Interdisciplinary Design and Analysis of a Warehouse

A Major Qualifying Project report submitted to the faculty of
Worcester Polytechnic Institute in partial fulfillment of the requirements
for the Degree of Bachelor of Science in Civil Engineering

Tanner Burke
Nicola DiLibero
Malina Ibelle
Julia MacLeod

Abstract

This project simulates the design and construction processes necessary to successfully repurpose an existing building. It compares the renovation of an existing warehouse into a school to the ground up construction of a similarly designed school. The comparison is based on the investigation of architectural, fire protection, structural, environmental, sustainability, and economical requirements. These factors guided recommendations on the opportunities provided in the renovation of existing buildings, the limitations, and the best practices used to overcome those constraints.

Authorship

Throughout the research, design, analysis, and writing of this report, each team member contributed equally within their respective areas of concentration. Details regarding the specific break down of the contribution of each student for this Major Qualifying Project (MQP) are listed below.

- Tanner Burke focused on the architectural and fire protection sections of this report. Specifically he concentrated on Chapters Three and Four and contributed to Chapter Five.
- Nicola DiLibero specialized in the structural aspects of the project and focused on Chapter Two and the structural *Revit* models.
- Malina Ibelle focused on the environmental components of the project. Specifically she concentrated on Chapter Six of the report and contributed towards the Capstone Design and Professional Licensure.
- Julia MacLeod concentrated on the fire protection aspects of the report, contributing towards Chapters Five and Seven.

Although sections of the report have primary authors, each section was reviewed and edited by all members. Collectively the team worked in a cooperative manner to produce the final product.

Tanner Burke

Nicola DiLibero

Malina Ibelle

Julia MacLeod

Scope of Work

The scope of this project involved the renovation of an existing, 295,000 square foot manufacturing facility to accommodate for a change of occupancy and use. The existing facility consists of a factory industrial moderate-hazard occupancy (Group F-1), with office space (Group B) provided in a remote area. A change of ownership was simulated, in which the building is renovated into a charter school for high school aged students. The building was designed to incorporate a variety of uses geared towards a diverse learning experience. The design also focused on both the opportunity to incorporate sustainable features into a building during a renovation phase and the ability for the building to be re-used for other purposes, if necessary, in the future.

The existing conditions of the building including its structural system, fire protection systems, interior finishes, and arrangement and enclosure of means of egress were analyzed. A code review for the new facility using the 8th Edition of the *Massachusetts State Building Code*, compared to the 6th Edition it was designed and constructed with, provided guidance as to which renovations need to be made to achieve code compliance.

Once the engineering drawings and outline specifications were created for the renovation of the warehouse, a cost analysis of the estimated materials, equipment, design, labor, and operation of the facility was performed. A design of a new building for the same purpose was then created. During the design for ground-up construction, any constructability issues that were not feasible in the renovation of the existing building were included. Another cost-analysis was performed to compare the cost of purchasing and renovating an existing building for the change in use versus purchasing a site and building a new facility, including any associated operating costs.

The incorporation of various LEED credits were analyzed for their effect on cost, constructability, and sustainability of the building. An environmental analysis was performed for the existing, renovation, and ground-up construction buildings. This analysis considered the life-cycle impact of the building over a 60-year period as well as the effect of incorporating a green roof into the design. The different methods for recycling construction and demolition waste were investigated as well to estimate potential project cost savings. Overall recommendations were made taking into consideration constructability, cost, and the sustainability of the design.

Capstone Design

The comparison between the structural and fire designs for the renovation of a warehouse facility and the new design and construction of a similar school facility explored six real world constraints that are elements of the Capstone Design. The constraints addressed are *Constructability, Economic, Environmental, Health and Safety, Social and Sustainability*.

Constructability

The concept of constructability influences each stage of design and development of a project because it refers to the ease of construction, subjected to the overall requirements for the design. The ability to renovate the existing conditions, as well as construct a new building with the same requirements, is initially affected by the materials considered during design. The shapes and sizes of sections and members were chosen in standard specifications to ensure simplified production and reduce cost and waste. Standardized shapes and sizes also help reduce construction time by limiting the potential for errors due to confusion in the field. During fabrication and erection, each section and member should be easily identifiable, in addition to moveable, for the construction laborers.

Economic

During project development, economic constraints must be evaluated in the early design stages, as well as repeatedly throughout the entire delivery process. Economic constraints are continuously re-evaluated to reduce the cost of construction while maintaining efficiency. The cost of renovation was compared to the cost of ground-up construction to determine the most efficient design alternative. The scope of the cost comparison included chosen materials, dimensions of structural elements, the layout of both design options (renovation and ground-up construction), cost of operation, and the time required to complete the project construction schedule.

Environmental

Both ground-up construction and the renovation of an existing building have environmental impacts that need to be considered during the project development phase. With the renovation of a building, the reuse and recycling of waste produced during construction and demolition is an important consideration. The effect of the actual building on its surrounding environment must also be considered. Taking precautions in the design phase of a project can help reduce the buildings' detrimental impact on the environment and reduce altered microclimates caused by urban heat island effects.

Health & Safety

In the design of any construction space, it is crucial to consider the health and safety of the potential occupants. All structural elements must be in compliance with the building codes and standards developed to ensure the integrity and safety of the building. Load requirements and member size restrictions were determined and evaluated based on the *Massachusetts State Building Code*, which references the *International Building Code*. Additionally, it is important to evaluate the design of the fire protection and suppression systems. The fire detection and sprinkler systems were evaluated based on the requirements specified in the *National Fire Protection Association* codes.

Social

The restoration and the ground-up construction of a charter school are affected by social implications of the surrounding area. The educational needs of the community must be evaluated for existing age groups and population demographics. The school's proximity to local businesses and facilities that can enhance educational development must also be considered. Prior to any renovation and construction, it is important for contract companies to address all social concerns presented by the community. Addressing such concerns early on ensures that the project runs smoothly and reduces the chance of backlash and resistance from members of the community.

Sustainability

The overall project conception was driven by the concept of sustainability. The renovation and repurpose of a large existing building was compared to the ground-up construction of a similar design in order to address the issue of the abandonment of large buildings. It's common practice to simply demolish these buildings and use the site for new construction. This project aimed to highlight the benefits of the renovation and repurpose of existing buildings and reuse of existing materials rather than new construction. The sustainability of a building is influenced by where and how the building is constructed. During the design phase, it is important to consider how the exterior environment affects the performance and service life of the chosen materials, as well as the effects the materials have on the environment. Service life was considered in the design decisions for renovation and ground-up construction of the warehouse facility to ensure that the building withstands environmental and load impacts for an extended period of time. To ensure that the materials and designs chosen are environmentally sustainable, LEED specifications were referenced. Specifically, a green roof design was considered to improve the shelf life of the roof and offset the adverse environmental effects associated with building hardscapes. A life-cycle analysis was also performed for each design to evaluate the environmental impact of the materials chosen for the buildings lifetime.

Professional Licensure

The intent of professional licensure is to protect the public by ensuring only qualified individuals work as engineers. Prior to reform in licensure laws, anyone had the capability to prepare, sign, seal, and submit engineering plans without the need to prove competence. Becoming licensed signifies a multifaceted understanding of both physical and engineering principles with a commitment to protecting the life, health, safety, property, economic interests, and welfare of the public. Professional engineers are licensed to be liable to the public for the work they produce and accountable for abiding by a strict code of ethics. This code of ethics ensures licensees place public welfare above any obligations to clients or employers while protecting confidential information and disclosing anything that could compromise their professional judgment. This loyalty to public interest and professional integrity requires a continual understanding of any advances in the engineering field as well as the competence to execute these changes.

Receiving professional licensure is governed by individual states and only valid in that specific state. The state of Massachusetts requires the completion of two eight-hour exams, the Fundamentals of Engineering (FE) exam and the Principles and Practice in Engineering (PE) exam in a designated discipline. Prior to the PE exam, four years of responsible engineering experience must be completed if a degree was received from an Accreditation Board for Engineering and Technology (ABET) accredited four-year college or eight years of experience if from an accredited four-year program in engineering technology.

This project requires a licensed professional engineer due to the change in occupancy of the building as well as an update in the applicable codes. When a building is constructed, it adheres to the current codes, regulations, and standards. However, codes and regulations are reactive laws and are therefore modified over time as knowledge and technology evolves. This building was designed and constructed under the 6th edition of the *Massachusetts State Building Code* in 2008; however, the 8th edition is currently followed. It is pertinent that the professional engineer is not only aware of the code change and how that affects the project, but also is qualified to implement those changes. The professional engineer must also understand how the change in occupancy affects the fire safety of the building. Currently the warehouse facility is used for the manufacture and storage of packaging materials and incorporates a two-story corporate office building space. Changing the occupancy to a charter school changes the occupancy rating from mixed occupancy Group B and Group F to Group E, which introduces the risk of an increase in the rate at which a fire would spread in the building. Having a professional engineer overseeing and advising on a project that ensures the integrity of the building is sustained and the public welfare is safeguarded.

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Chapter 1: Introduction

As technology continues to improve, time and efficiency become increasingly important during the design and construction of buildings. Building owners and developers not only need to take into consideration how quickly a project can be developed, but should now consider how the structural and fire suppression designs affect the environment. Buildings in the United States are associated with 38% of all carbon dioxide emissions, which is nearly 1/3 globally (USGBC, 2013). The awareness of such environmental implications has led to an increase in green construction worldwide. It is becoming more common for developers to investigate the renovation of buildings because it allows for the reuse of materials and produces less of a negative impact on the surrounding environment. A study performed in 2007 estimated that a shift in building design to incorporate zero to negative net life-cycle costs could offset up to 6 billion tons of carbon dioxide annually (Yudelson and Fedrizzi, 2008). Environmental engineers work with designers and builders to reduce the negative impact on the environment while still maintaining the essence of new design projects.

Renovation, however, is not always the most efficient method for time and cost of construction. When there is a change in occupancy within a building, it is crucial for the project team to ensure the new occupancy requirements are followed. Such buildings must comply with all codes including, but not limited to, structural design, fire protection, plumbing, and means of egress (International Building Code, 2006). In order to reduce the time and difficulty associated with renovations, owners may decide it is more efficient to start a building from the ground up. Tearing down an existing facility, however, generates debris and potential hazards to the surrounding environment. Even if the owner purchases a new plot of land, the time and resources necessary to survey and prepare the land for construction may outweigh the benefits.

To demonstrate the relationship between renovation and ground up construction, a storage warehouse facility was analyzed. The renovation of an existing warehouse was proposed to accommodate a change in occupancy, meeting the functional and safety needs of a charter school building. A new school building was then designed using similar constraints and occupant goals. The cost, time, and environmental impacts were analyzed and compared for both scenarios to determine the most efficient design alternative. During the analysis, *International and Massachusetts Building Codes*, National Fire Protection Association requirements, and LEED guidelines were investigated and incorporated.

The following chapters provide background information, results, and conclusions for each of the areas investigated. Chapter Two discusses the structural benchmarking process for the existing building as well as the structural design results and alterations made for the renovation and ground-up construction buildings. Chapter Three focuses on the architectural aspect of the project, including a detailed means of egress analysis for each new design. Chapters Four and Five examine passive and active fire protection for each design, including a discussion on the fire resistance of materials and sprinkler and fire alarm layouts. Chapter Six analyzes the environmental impact of each design through the incorporation of a green roof, life-cycle impact analysis, and construction recycling methods. Lastly, Chapter Seven presents a cost analysis and summarizes the results and recommendations for each design option.

Chapter 2: Structural

2.1 Structural Benchmarking

Repurposing a 200,000 square-foot warehouse requires an in depth understanding of the capabilities of the current structure in terms of loading. An understanding of the loads on the beams, columns, connections, and footings was necessary for redesigning the building. With the addition of a second floor, green roof, and modification of the roof diaphragm, a certain amount of structural changes are necessary to ensure the stability of the building. Benchmarking current critical members in areas of renovation was necessary to determine which structural components would need to be reinforced or replaced entirely. A set of structural engineering drawings for a warehouse were proved for analysis. This section reviews the process of analyzing the structural details starting with the creation of a building model in *Revit*, then an analysis of the dead and live loads and the forces they induced on the current components, followed by an analysis of the seismic and wind forces. Finally the cumulative effects of these forces on the components were defined and a list of components most likely to be changed was produced.

2.1.1 Scope of the Work

With the given warehouse design, the first step to understanding the building required an analysis of the structure. The building was divided into three separate sections, A, B, and C, by expansion joints shown in Figure 1. Section A was selected for benchmarking as it was nearly identical to Section B and Section C wasn't going to require major renovations. Dead, Live, Wind, and Earthquake loads were assumed to dictate design. Therefore, components would need to be gauged for their capacities based on these loading criteria. Their capacities' were compared to the new requirements in the following sections.

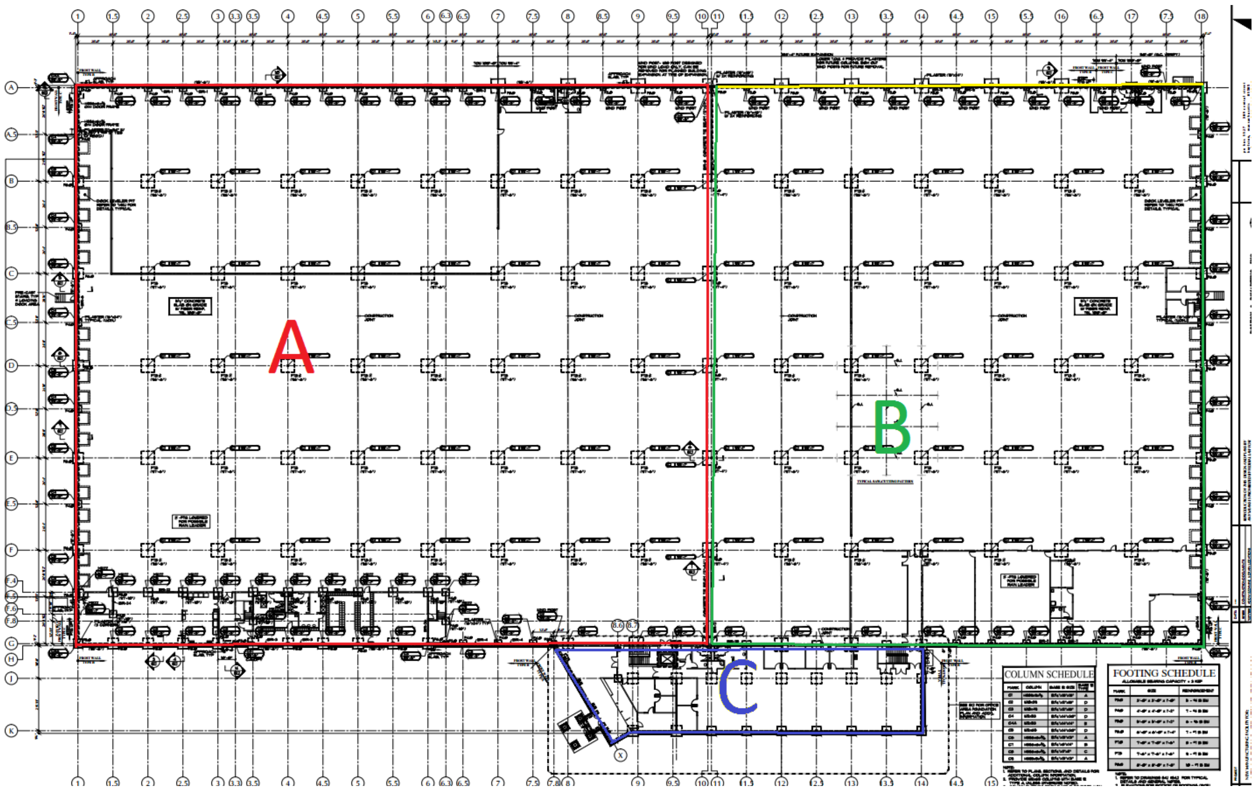

Figure 1: Structural Analysis Building Sections

2.1.2 *Revit* Model

A structural model of the building was created for multiple purposes, however; this section will strictly pertain to how it was used in the benchmarking process. The structural model contained the structural footings, beams, cross-bracing, columns, roof decking, joists, and girders. After completing the entire model, section A was isolated for the benchmarking. *Revit* software helped estimate unknown distances and dead loads which greatly aided analysis of the earthquake loads.

2.1.3 Roof Joists and Girders

After finishing the model, the process of benchmarking the system began. The work started with evaluating beams, specifically those on the roof which were the same for both sections A and B. The structure relies on joist beam and girder systems for the interior bays. *Vulcraft Steel Joists and Joist Girders Catalog* provided maximum vertical loading capacities in pounds per linear feet for the K-series joists used in the beam systems, as well as a design guide for joist girders. Appendix F details the service dead and live loads, which were all converted into plf and are displayed in

Table 1. The roof utilized bay systems consisting of 30K12 joists at spans between 52' 8" and 53' 5" at 5 feet on center. 40G 8N 17K joist girders support the joists for the interior bays. The joist which garnered the highest dead load was chosen for analysis as all joists were subject to a 30 psf snow load at a tributary width of 5 feet. The service loads are detailed in

Table 1 below along with the resulting factored loads on the joist and their capacities in Table 2.

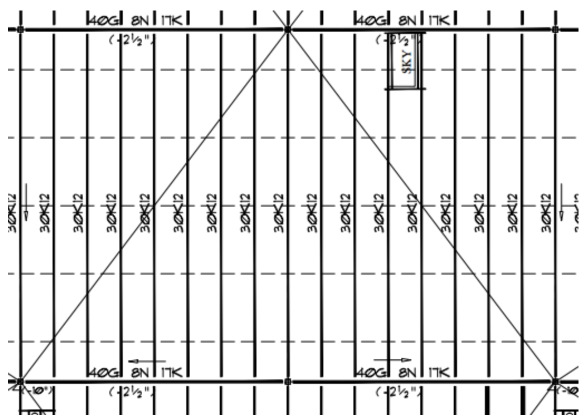

Figure 2: Typical Roof Bay Layout

Table 1: 30K12 Joist Dead and Live loads

Dead Loads		Live Loads	
Metal Decking	9 lb/ft	Snow Load	175 lb/ft
30 K 12 Joist	15 lb/ft	_	_
Roof Unit	6.8 lb/ft	_	_
TOTAL	**31 lb/ft**	**TOTAL**	**175 lb/ft**

Table 2: 30K12 Load Summary

Summary	
Total Factored Load 1.2D + 1.6L	318 lb/ft
Max Load Capacity for 30K12 at 53 ft.	495 lb/ft
Max Load Capacity for L/240 deflection	177 lb/ft

The Joist Girders were designed for supporting Joists and the self-weight of the Girders in a series of concentrated forces. This placed a concentrated force of 16.6 kips spaced at 5 feet with the addition of a 0.22 Kip concentrated dead load from the 5-foot length of girder responsible for that portion of loading as shown in Figure 3 below.

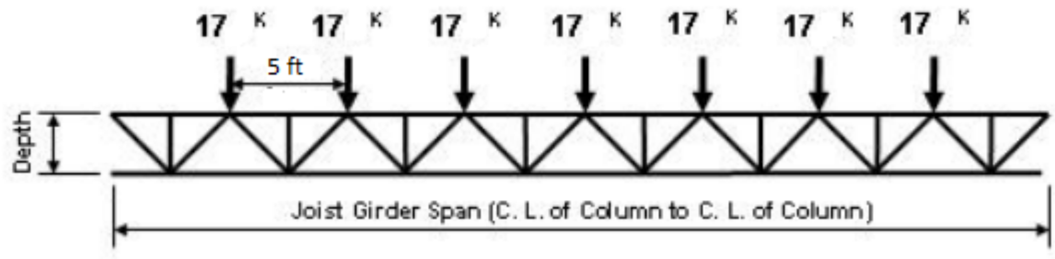

Figure 3: Typical Model for Joist Girder

2.1.4 Earthquake and Wind Loads

The next step was benchmarking the capacity of the roof diaphragm. Both Earthquake forces and Wind were considered in the structural design of the building and its roof diaphragm. The Earthquake forces were analyzed first. The structural notes in the drawings state the Equivalent Lateral Force procedure was used to design the frame of the building. The sequence of steps for the ELF procedure is provided in Figure 4. The values used in the process for Section A are listed in Table 3 below. Unknown values were estimated based off of ASCE 7-05 tables, shown in Figure 4, as they were not defined in the structural drawings. *Revit* schedules were used to calculate the dead load of the entire building. Refer to Appendix F for the calculations for these values.

Table 3: Equivalent Lateral Force Values

Variable	Value
W	1647.8K
S_s	.17
S1	0.7
Site Class	Soil Profile D
Fa	1.6
F_v	2.4
R	3*
I	1.0
Cs	0.06
V	100 K

ELF Procedure, ASCE 7-10

1. Determine weight of building, W.

2. Determine 0.2 second and 1 second response spectral acceleration, Ss and S1 from Figure 22-1 to 22-14

3. Determine Site class from Chapter 20 or from soil report.

4. Determine site coefficient, F_a, from Table 11.4.1.

5. Determine site coefficient, F_v, from Table 11.4.2

6. Determine adjusted maximum considered earthquake spectral response acceleration parameters for short period, SMS and at 1 second period, SM1.

$S_{MS} = F_a S_s$ (Eq. 11.4-1)

$S_{M1} = F_v S_1$ (Eq. 11.4.2)

7. Determine deign spectral response acceleration parameters for short period, SDS and at 1 second period, SD1.

$S_{DS} = (2/3) S_{MS}$ (Eq. 11.4.3)

$S_{D1} = (2/3) S_{M1}$ (Eq. 11.4.4)

8. Determine Importance factor, I, from Table 11.5.1

9. Determine Seismic design category from Table 11.6-1, & 11.6-2

10. Determine Response modification factor, R. from Table 12.2-1

check building height limitation

11. Determine seismic response coefficient from Eq. 12.8-1

$C_s = S_{DS} / (R/I)$

12. Determine approximate fundamental period from Eq. 12.8-7

$T = C_t h_n^x$

h_n is the height of building above base.

$C_t = 0.02$, $x = 0.75$

13. Check if $T < 3.5\, S_{D1}/S_{DS}$.

14. Determine Maximum seismic response coefficient Eq. 12.8-3 and 12.8-4

$C_{smax} = S_{D1} / [T(R/I)]$ for T £ T_L

$C_{smax} = S_{D1} / [T^2(R/I)]$ for $T \geq T_L$

where T_L is long-period transition period in Figure 22.15 to 22.20.

15. Minimum seismic response coefficient, Eq 12.8-5 & 12.8.6

C_{smin}³ 0.01

If S_1 ³ 0.6g, C_{smin}³ 0.5 S1 / (R/I)

16. Determine Seismic response for strength design from 12.8-1

Figure 4: Equivalent Lateral Force Procedure Flow Chart (ASCE 7-10)

After calculating the base shear, an elastic analysis was performed to develop an understanding of the deflections and the resulting story shears. Using *Risa 2-D* the four frames in the diaphragm were modeled and analyzed for North-South and East-West forces. An example of the East-West forces on the frame is shown below in Figure 5. The 100 kip earthquake force was distributed evenly through the frame be dividing the force by the span of the frame and applying that value as a distributed load. An example of the resulting joint deflections at the corresponding nodes can be found below in Table 4. Appendix F includes all of the models developed.

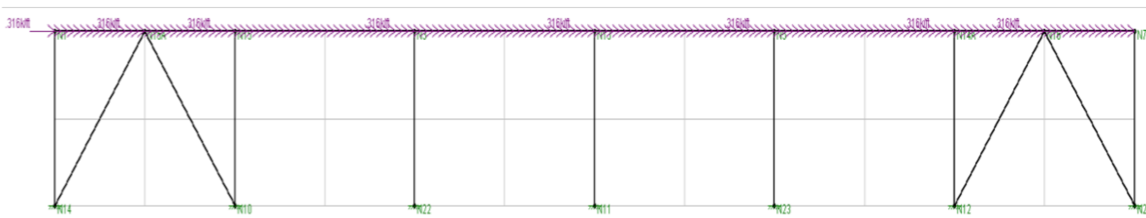

Figure 5: *RISA* Frame 10 Earthquake Force Model

Table 4: Frame 10 North to South Deflections Nodes in Order From Left to Right

Frame 10 Deflections North to South	
Node	**Horizontal Deflection (in.)**
N1	0.083
N15A	0.079
N15	0.111
N3	0.153
N13	0.167
N5	0.153
N14A	0.111
N16	0.08
N7	0.083

Story drifts were then calculated based on the average deflections per node with the equation $\delta x = \frac{C_x \delta_{xe}}{I}$ (eq 12.8-15 ASCE 7-05) with a maximum drift of 0.025hsx (Table 12.12-1 ASCE 7-05). The resulting story drifts were then used to calculate the P-Delta effects with the eq. 12.8-16 ASCE 7-05 $\theta = \frac{P_x \Delta I_e}{V_x h_{sx} C_d}$ with a maximum capacity of $\theta max = \frac{0.5}{\beta Cd} \leq 0.25$(eq 12.8-17 ASCE 7-05) . Table 5 below provides the story drifts and P-Delta effects for the four frames (A,G,1,and 10) with calculations provided in Appendix F.

Table 5: Diaphragm Story Drifts and P-Delta Values

	C_d	∂x (in.)	∂x Max (in.)	P_x (kips)	V_x (kips)	H_{sx} (in.)	θ	θ Max
Frame 10	4.5	0.510	9	2005	100	360	0.0063	0.111
Frame 1	4.5	1.687	9	2005	100	360	0.0209	0.111
Frame A	4.5	0.455	9	2005	100	360	0.0056	0.111
Frame G	4.5	0.500	9	2005	100	360	0.0062	0.111

The concentric braced frame system provides a stiffness to the frame which resulted in minimal story drifts and P-Delta effects so exceeding the capacity was not a major concern. The structural details included the wind pressure of 17 psf used for calculations, which produced a North to South shear of 91.8 kips and an East to West shear of 81.6 kips. Competing with the 100 kip earthquake force the following load combinations in Table 6 from ASCE 7-05 were explored.

Table 6: Wind and Earthquake Load (*ASCE 7-05*)

Load Combinations
1.2D + 1.6S + .8W
1.2D + 1.6 W + 0.5S
(1.2 +0.2SDS)D + 1.0E + 0.2S

An example of the diaphragm forces are shown in Figure 6 below. Axial forces carry through the girders in the chords A-B and C-D in Figure 6 while simultaneously moments are distributed to the columns along the face of A-C. The beam were analyzed using AISC Equations H1-1a/b. An overview of the process with written and spread sheet calculations found in Appendix F.

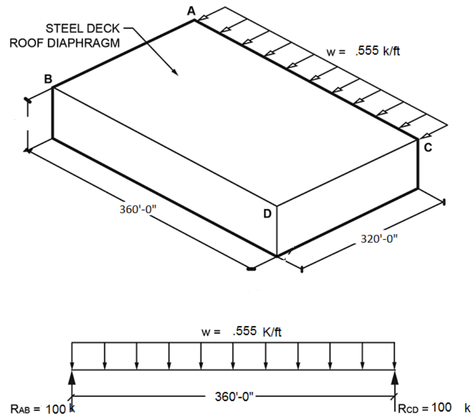

Figure 6: Earthquake Load on Diaphragm

Table 7 below provides a table to the results and capacities for both the beams and columns. The results show some additional capacity for the columns and beams. Especially the 21x62 exterior girders, which were designed to be able to carry additional loads in the event that the warehouse was expanded upon.

Table 7- Approximate Second Order Analysis Results for diaphragm members

Approximate Second Order Analysis Of Beam-Column Results		
Frame Columns		H1-1a/b
	C3	0.67
	C4	0.59
	C5	0.55
Beams	14X30	0.944
	21x62	0.38
	12X26	0.888
	21x44	0.58

In a braced frame, interior columns typically are not used to carry lateral loads caused by Wind and Earthquake forces. The columns carry the gravity loads into the footings and only require a simple analysis of axial compression caused by the dead and live loads. For a KL factor of 30 feet, the C1 HSS 9x9x3/8 columns have a maximum axial capacity of 241 kips (AISC Table 4-4), but with the given loads the largest design axial force any of these columns was 135 kips, leaving plenty of capacity for carrying the load of a second floor, especially with the corresponding reduction in the KL factor.

2.1.5 Footings and Baseplates

The column loads then directly transferred into the design of the column baseplates and footings. The structural drawings provide a list of base plate sizes and details for the different shapes, which are shown in Figure 7 and Figure 8 below. Hand calculations for the C1 interior columns can be found in Appendix G, and spread sheet calculations can be found in Appendix G as well. The results show an excess of thickness for the base plates for interior columns.

COLUMN SCHEDULE

MARK	COLUMN	BASE PL SIZE	BASE PL TYPE
C1	HSS9x9x⅜	PL1¼"x18"x18"	A
C2	W10x39	PL1¼"x12"x18"	D
C3	W10x49	PL1¼"x12"x18"	D
C4	W12x53	PL1¼"x14"x20"	D
C4A	W12x53	PL1¼"x14"x14"	E
C5	W12x65	PL1¼"x14"x20"	D
C6	HSS6x6x5/16	PL1¼"x13"x13"	A
C7	HSS6x6x5/16	PL1¼"x8"x14"	B
C8	HSS6x6x5/16	PL1¼"x11"x11"	C
C9	HSS5x5x5/16	PL1¼"x13"x13"	A

Figure 7: Structural Column Schedule

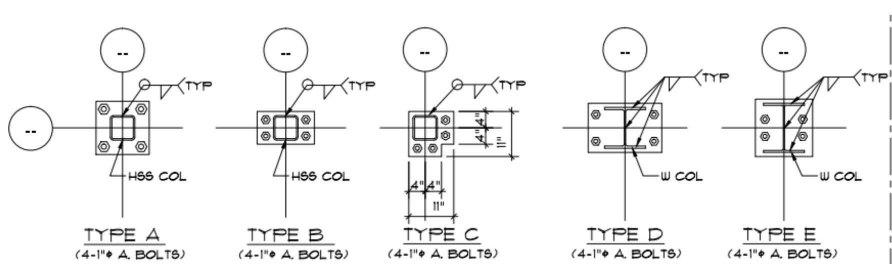

Figure 8: Structural Baseplate Details

For most of the columns the baseplates transferred loads to pedestals which then transferred to the footings. Concrete pedestals were calculated as short concrete columns where the object of concern was concrete crushing as opposed to buckling. The structural details call for 24"x24" concrete pedestals for typical pier design. This allowed for a total axial load of 1,220 Kips which exceeded any of the loads these pedestals would be subject to before or after renovations. The calculations for the concrete columns are located in Appendix G.

The final transfer of loads ended in the footings. The process of designing a footing and checking the different forms of stress is outlined in Figure 9. Variables such as soil bearing pressure and concrete strength of pedestals and footings were provided in the structural details along with a Footing Schedule and details for bar length development. Axial forces and moments were calculated for the columns in previous sections and used for their corresponding footings. Footings were designed for the specific loading of each column and as a result do not offer sufficient capacity for the additional design loads introduced by the renovation. Footings that will receive additional loads in renovations will need to be redesigned.

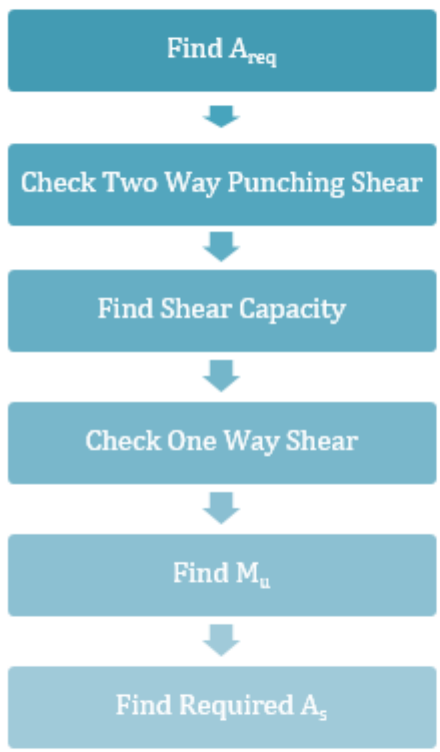

Figure 9: Flow Chart for Designing a Footing

2.1.6 Conclusions

The findings of the structural benchmarking provides insight to the current buildings capability of receiving additional loads. Considering the addition of a second floor, it was determined that changes are needed for the bracing system for the diaphragm, since the existing chevron bracing must be replaced with cross bracing to accommodate the installation of the second floor girders. New connections will need to be designed for the new bracing system as well. The columns have sufficient capacity for additional design loads, especially with the reduction of KL factors. Some girders will need to be replaced with the addition of loads on the roof; however, the joist beams used should provide sufficient capacities for minor additional loads. Furthermore, earthquake loading will change drastically with the addition of a second floor which may affect the diaphragm system used as well as the metal decking's capability of carrying the shear forces on the roof. The building will require some major structural renovations in order to satisfy increased load demands.

2.2 Structural Renovation

The renovated architectural plans provided a new layout for the first floor as well as the second floor. The renovations required several areas of alteration. This list includes additional columns, new footing sizes for nearly all of the current footings, new joist and girder bays for the second floor and the roof of the building.

2.2.1 Structural Bays

With the addition of new bay sizes, a second floor, and a green roof many revisions were made to accommodate the renovations. The second floor required the most revisions as opposed to the roof which required redesign of only 3 structural bays.

2.2.1.1 Second Floor

The first step in designing the second floor was to select a slab to span the two sections of the building. Vulcraft provides a steel deck catalog in which decking and corresponding slab thickness can be determined based on beam span and service loads. In this case, the span was five feet with a maximum factored service load of 152 psf. The lightest slab that offered an identical height to the preexisting mezzanine slab was chosen.

With the slab selected, a total service load was determined for classroom areas and corridor areas. The service loads for the second floor are shown in Table 8 below.

Table 8: Second Floor Service Loads

Second Floor Service Loads		
	Classroom	**Corridor**
Dead Load (psf)	75	65
Live Load (psf)	40	80

The method for calculating interior beam and girder layouts can be found in Appendix F with an example of the spreadsheet used to calculate the majority of the bays. Because of the large bay (53' x 40x) beams required a high Ix value to satisfy a serviceability deflection of L/240. This lead to the selection of the W24X62 beam for all the 53'x40' bays despite some of them having different service loads based on the classroom to corridor layout. Despite the beams being the same, the difference in service loads did have an effect on girder sizes. A full beam layout plan can be found in Appendix G.

2.2.1.2 Roof

A larger bay was designed to accommodate the high school gymnasium shown in Figure 10 in section 2.2.3. To stay consistent with the current roof design, Joist and Joist girders were used in the new bay design. Calculations for selecting sufficient joist and girder sizes are located in Appendix F. DLH long span joists fit the needs to sustain the 106' long bay. Essentially, the typical 53'X40' roof bays doubled in load so larger joist girders were needed as well.

Another renovation to consider was the green roof that was to occupy two bays. These added an additional load of 14.58 psf, which the current joists could easily handle, however; new girders were required to support the additional load.

2.2.2 Earthquake Analysis

As opposed to the benchmarking process, the design process required the use of ASCE 7-10 codes instead of ASCE-7-05 codes. Although some of the changes between the codes were minor, the building class did change along with its new expected usage. With the addition of more than twice the original building weight from the second floor, the seismic force increased drastically. The roof shear remained virtually the same due to most of the distribution of the base shears going into the second floor. The calculation in Appendix F conclude that all members from the original design were sufficient for the new lateral loading in the diaphragm. Although the old roof girders were sufficient, new cross bracing needed to be designed in order to compensate for additional force. Chevron bracing was used for the majority of the frame. Braces needed to be designed to account for a worst case scenario where the compression brace buckled and the tension members must carry the lateral loading. This causes uneven forces in the diaphragm members which must be accounted for when design the Girders. Calculations for the Lateral Bracing system can be found in Appendix F. The Bracing systems are shown in the elevations provided in Appendix G.

2.2.3 Column Renovations

The renovated designed required the additional columns to accommodate the new high school gymnasium. Figure 10 below was taken from the second floor architectural plan in Appendix K. This figure shows as built columns that needed to be removed circled in red, as built columns staying circled in blue, and the locations for new columns circled in green. Column sizes and their corresponding schedule are in Appendix G with Appendix F providing the calculations.

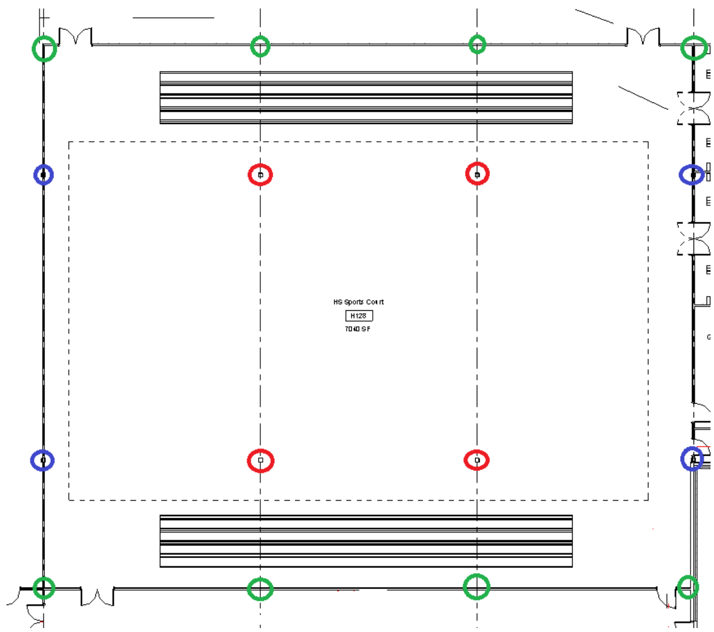

Figure 10: Basket Ball Court Column Renovations

As mentioned in section 2.1, the reduction of the KL factor for the as built columns from 30 feet to 14 feet greatly increased the columns capacity for sustaining the loads from the second floor. Considering that only two different types of interior columns were used in the existing design (C1 HSS 9X9X3/8 and C9 HSS 5X5X5/16) with the C1 being two story columns supporting the roof and C9 columns supporting the Mezzanine, only two calculations were made for the columns. The columns that had to support the highest possible loads were analyzed for sufficiency under the new loads. In both cases the columns were found to be sufficient which implied that all current columns were capable of sustaining the new loads. The calculations can be found in Appendix G.

2.2.4 Footings

Section 2.1 concluded that nearly every footing would require renovations in order to support the new loads from their respective columns. The same load for calculating the C1 column buckling was used to design the new footings for every C1 column in the building. The loads varied based on how much corridor space the columns supported on the second floor, but for the most part the loads were typically in the range of 580 to 595 kips. However, the footings positioned along the perimeter of the two gymnasiums, two courtyards, middle school cafeteria, and High School sustained far smaller loads and were designed accordingly. With so many columns and footings supporting similar loads, the same process was used for all exterior and interior columns. In total, only several footings needed to be redesigned as they were sufficient for all columns corresponding with each other. Footing calculations can be found in Appendix F and the Footing Plans and Schedule can be found in Appendix G.

2.3 Structural Ground-Up Construction

Material costs were compared for a renovation model and a ground up construction model. There were minor differences between the two models, the preexisting mezzanine section for the renovated model was removed for the ground up construction model. This allowed for a more streamlined second floor design. With two slightly different *Revit* models, three main construction materials were scheduled for each model and exported to *Microsoft Excel* giving a total volume of the concrete, column steel (Both HSS and Wide Flange Columns as they have different pricing), and steel used in beams in girders (again two volumes were found for Wide flange and Steel joists). Volumes of the material were then totaled in *Excel* and concrete volume was converted to yards and steel volume was converted to tons to fit unit costs found in the *2015 national Construction Estimator*. The results can be found in the Table 9 with supplementary unit costs and material properties found in Table 10.

Table 9: Material Costs Renovated Vs. Ground Up

			Renovated	Ground-Up
Foundations	Concrete Volume	(yd^3)	790.43	1,321.43
	Cost	($)	79,043.00	132,143.00
		($\$/ft^3$)	0.35	0.65
Beams and Girders	Steal Volume	(ft^3)	4,811.00	6,141.05
	Total Weight	(lbs.)	2,327,754.24	2,971,285.73
		(tons)	1,055.85	1,347.71
	Cost	($)	3,061,953.53	3,618,124.00
		($\$/ft^2$)	14.95	17.66
	W Flange Volume	(ft^3)	2.62	308.28
	Weight	(lbs.)	1,267.66	149,158.20
		(tons)	0.57	67.12
	Cost	($)	1,768.39	202,034.78
		($\$/ft^2$)	0.01	0.99
Columns	HSS Volume	(ft^3)	17.71	283.37
	Weight	(lbs.)	8,691.22	139,064.39
		(tons)	3.94	63.07
	Cost	($)	8,868.30	141,897.83
		($\$/ft^2$)	0.04	0.69
Total Costs		**($)**	**3,151,633.22**	**4,094,199.61**
		($\$/ft^2$)	**15.35**	**19.99**

Table 10: Material Properties and Cost (values based of *2015 National Constructor Estimator* and *AISC Steel Construction Manual Table 17-12)*

Material Properties and Cost		
Concrete	Cost	$100/ yd^3
Steel	Density	490 lb/ft^3
	Cost Beam	$2,900/ton
	Cost Joist	$1,470/ton
Cost per Column	HSS	$2,250/ton
	W Flange	$3,010/ton

In terms of materials there is a clear gap between costs. However, there are a few things to consider that are not provided in this assessment. With a $942,566 total estimated difference between the two costs, an argument could be made that it's the better option. However, it does not go into construction costs. Without a full analysis it will be difficult to decide which option would cost less money in total. Ground-up construction comes with the $900,000 material difference to begin with, and on top of that it would require site work, and the cost of labor to erect the entire building as opposed to just one floor. Renovation construction would entail the cost for demolition work, excavating pre-existing site work and slabs to provide utilities and foundation renovations, and the construction of the second floor.

Chapter 3: Architecture and Planning

This chapter illustrates the process for analyzing the existing architectural layouts and building materials as well as the modifications made to produce a preliminary layout for the educational facility. The strategy for completing this task involved looking at features present in the existing building and preservation methods to reduce the cost of renovation as much as possible. After the final layout was produced for the renovation, the architectural process was compared to the same design for ground-up construction. This involved a cost analysis for the two buildings, a code analysis, and any design changes based on specific restrictions inherent from the existing building.

3.1 Existing Building

The existing building layout primarily consists of warehouse space; with approximately 188,248 ft^2 of gross floor space dedicated to operations concerning manufacturing and other light industrial practices. The factory area is highlighted with the green hatch pattern in Figure 11.

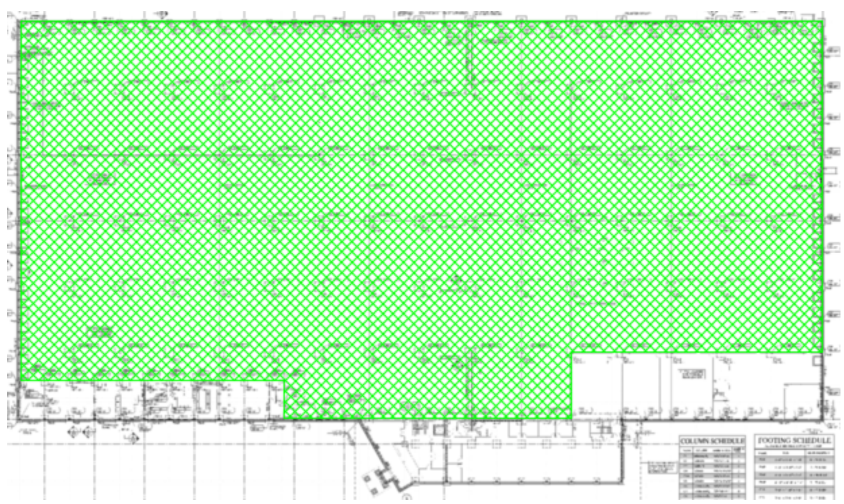

Figure 11: Factory Area of Existing Building

In this area there are thirty-four dock leveler pits, which are used to create a transition from the trucks shipping to and receiving from the building to the warehouse floor. At each of these pits, a steel overhead door is located to allow truck access to the loading docks. There are most likely no exterior windows in this area of the building, but there are several exterior doors aside from the overhead doors already mentioned. These doors do not lead directly to the grade level, but rather lead to precast exterior stairs or concrete approach slabs that slope down to grade level.

The areas with different uses are split into areas one, two, and three for discussion purposes as shown in Figure 12. Area 1 consists of large meeting areas that are used for discussions concerning warehouse operations, whereas Area 2 is a two-story area consisting of administrative offices. Area 3 is a non-enclosed mezzanine used as a platform to supervise operations and the space below the mezzanine houses locker rooms, break rooms, and mechanical space.

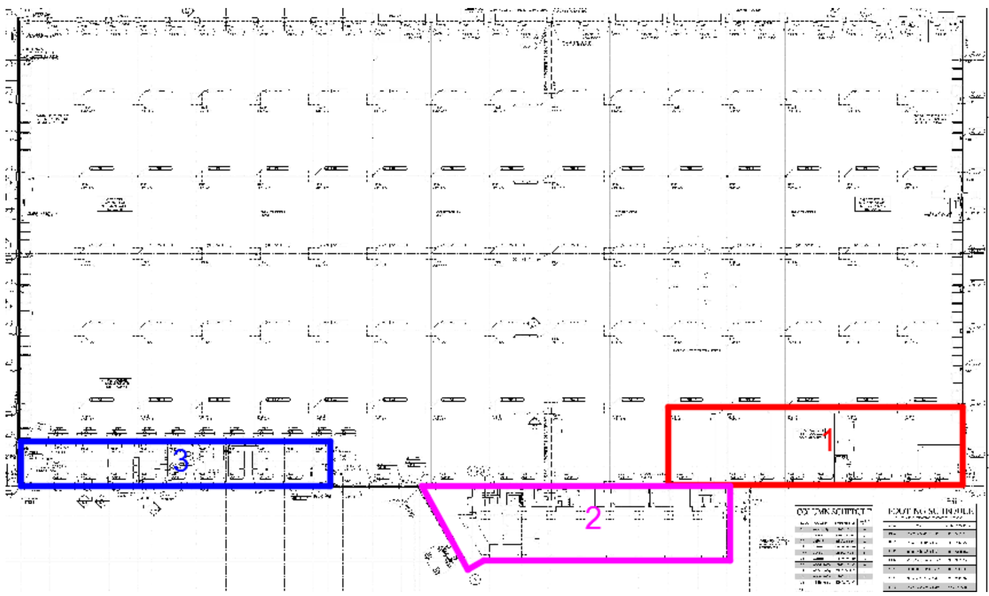

Figure 12: Office Areas of Existing Building

Some important information was obtained from the existing building to facilitate code compliance in terms of the proposed design. These are listed below in Table 11.

Table 11: Code Information from Existing Building

Category	Value
Height	30 ft.
Area	209,472 ft^2
Construction Type	IIB
Sprinkler System Present	Yes

3.2 Proposed Renovation

The planning and design for the adaptive reuse of the existing warehouse facility into the proposed school building consisted of several steps. First, an architectural program was performed. This focused on the basic configuration of the building to determine the enrollment size. Once the enrollment size was determined, calculations were performed to estimate the type, amount, and size of necessary spaces in the building. Following the space analysis, the recommendations and requirements of the *Massachusetts School Building Authority* (MSBA) were consulted. The initial programming of the building resulted in a conceptual layout that could then be modified.

After the conceptual block diagram was created, a code analysis was performed to specify the design criteria for fire and life-safety features. The 8th Edition of the *Massachusetts Building Code* (*780 CMR*) was initially consulted for the code analysis. *780 CMR* states that the 2009 Edition of the *International Existing Building Code* (*IEBC)* shall be used for the repair, alteration, change of occupancy, addition, and relocation of existing buildings. Chapter 13 of the *IEBC* provides a measurable process for achieving alternative compliance that was used for this design.

Once the design criteria for code compliance was developed, methods for selectively demolishing or reusing the materials from the existing building were considered. The scope of this analysis did not contain all of the building materials, but thorough analysis concerning constructability, sustainability, and economic feasibility were discussed for the materials and systems within the scope.

When the final architectural layout was produced, an egress analysis was performed. This was completed to ensure that the criteria selected in the performance compliance methods was met and the architectural layout was finalized to perform the design of the active and passive fire protection systems.

3.2.1 Architectural Programing

963 CMR 2.00 serves as the document for the *Massachusetts School Building Authority* (MSBA) regulations. The authority provides a grant called the Total Facilities Grant that has the potential to cover a significant amount of the construction costs in Massachusetts schools. In order to receive funds for this school, the provisions of this document were followed. The number and size were based on the enrollment of the school. Typically, stakeholders in the project will perform a number of studies to estimate the current enrollment when designing a building, as well as estimate the projected growth when planning for ways to expand the school. Since this project involves the

renovation of an existing building, the process was performed in a different order. The enrollment for the school was established based on the current size of the building. The statutes also provide requirements that reflect best practices for architectural design in order to provide a beneficial learning environment.

3.2.1.1 Enrollment Size

The size of the work area defined in the building is 206,856 ft^2. The area was divided in half to accommodate for the separation of the middle school and high school facilities, providing an area of 103,428 ft^2 on each side of separation wall. Additionally, courtyards were added to the building design by removing two adjacent structural bays near the center of each area created by the separation wall. This serves as a means of natural ventilation and open outdoor space to be utilized by students and faculty. It also decreases the gross building area to avoid any fire and life-safety issues. A conceptual drawing of the allotment of the space is shown in Figure 13.

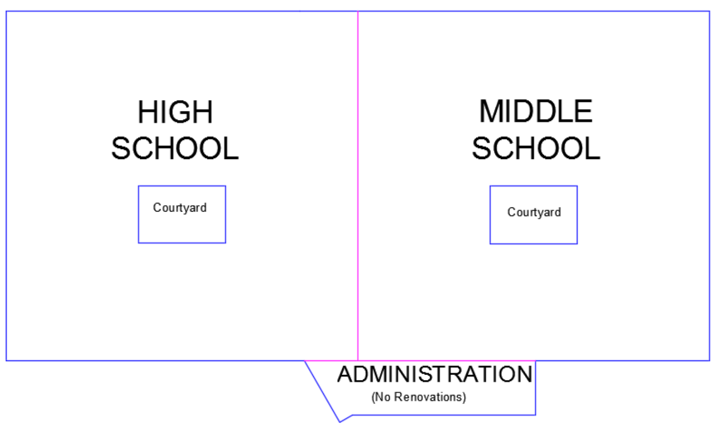

Figure 13: Conceptual Design of Proposed Renovation

The *MSBA* guidelines determine the enrollment of the school based on the gross area of the building. This included all spaces such as the office area, but excluding the courtyard. For simplicity, the office area was split so half of the area contributes towards the gross floor area of the middle school while half contributes to the gross floor area of the high school.

The gross area on both floors for each separate school was determined to be 197,743 ft^2 with an additional 9,725 ft^2 added to account for the office spaces. However, subtractions must also be made for the areas that are projected to account for both stories, which include auditoriums and cafeterias. A reasonable estimate for the size of a high school and middle school basketball courts and auditoriums was a combined 16,000 ft^2 for each school. Therefore, the gross floor area for each of the schools is 191,468 $ft.^2$. The range of enrollment can then be selected using Table 12 for the middle school and Table 13 for the high school, which were both obtained directly from 963 CMR.

Table 12: Area Per Student for Middle Schools (963 CMR – Table 3)

Projected Enrollment	GSF per Student	Projected Enrollment	GSF per Student
Less than 400	190	Between 580 and 589	175
Between 400 and 409	190	Between 590 and 599	174
Between 410 and 419	189	Between 600 and 609	173
Between 420 and 429	188	Between 610 and 619	172
Between 430 and 439	187	Between 620 and 629	171
Between 440 and 449	187	Between 630 and 639	170
Between 450 and 459	186	Between 640 and 649	169
Between 460 and 469	185	Between 650 and 659	169
Between 470 and 479	184	Between 660 and 669	168
Between 480 and 489	183	Between 670 and 679	167
Between 490 and 499	182	Between 680 and 689	166
Between 500 and 509	181	Between 690 and 699	165
Between 510 and 519	181	Between 700 and 709	164
Between 520 and 529	180	Between 710 and 719	163
Between 530 and 539	179	Between 720 and 729	163
Between 540 and 549	178	Between 730 and 739	162
Between 550 and 559	177	Between 740 and 749	161
Between 560 and 569	176	750 and greater	160
Between 570 and 579	175		

Table 13: Area Per Student for High Schools

Projected Enrollment	GSF per Student	Maximum Grossing Factor Limit	Projected Enrollment	GSF per Student	Maximum Grossing Factor Limit
Less than 600	*to be determined*	1.50	Between 1300 and 1319	175	1.44
Between 600 and 619	226	1.50	Between 1320 and 1339	174	1.44
Between 620 and 639	226	1.50	Between 1340 and 1359	173	1.43
Between 640 and 659	222	1.50	Between 1360 and 1379	172	1.43
Between 660 and 679	219	1.50	Between 1380 and 1399	171	1.42
Between 680 and 699	216	1.50	Between 1400 and 1419	171	1.42
Between 700 and 719	214	1.50	Between 1420 and 1439	170	1.42
Between 720 and 739	212	1.50	Between 1440 and 1459	169	1.41
Between 740 and 759	210	1.50	Between 1460 and 1479	167	1.41
Between 760 and 779	209	1.50	Between 1480 and 1499	166	1.40
Between 780 and 799	207	1.50	Between 1500 and 1519	165	1.40
Between 800 and 819	206	1.50	Between 1520 and 1539	165	1.40
Between 820 and 839	205	1.50	Between 1540 and 1559	165	1.40
Between 840 and 859	204	1.50	Between 1560 and 1579	164	1.40
Between 860 and 879	202	1.50	Between 1580 and 1599	163	1.40
Between 880 and 899	201	1.50	Between 1600 and 1619	162	1.40
Between 900 and 919	200	1.50	Between 1620 and 1639	162	1.40
Between 920 and 939	200	1.50	Between 1640 and 1659	162	1.40
Between 940 and 959	198	1.50	Between 1660 and 1679	162	1.40
Between 960 and 979	197	1.50	Between 1680 and 1699	162	1.40
Between 980 and 999	195	1.50	Between 1700 and 1719	161	1.40
Between 1000 and 1019	195	1.50	Between 1720 and 1739	160	1.40
Between 1020 and 1039	194	1.50	Between 1740 and 1759	160	1.40
Between 1040 and 1059	193	1.49	Between 1760 and 1779	160	1.40
Between 1060 and 1079	192	1.49	Between 1780 and 1799	160	1.40
Between 1080 and 1099	190	1.48	Between 1800 and 1819	160	1.40
Between 1100 and 1119	189	1.48	Between 1820 and 1839	160	1.40
Between 1120 and 1139	188	1.48	Between 1840 and 1859	159	1.40
Between 1140 and 1159	186	1.47	Between 1860 and 1879	159	1.40
Between 1160 and 1179	185	1.47	Between 1880 and 1899	159	1.40
Between 1180 and 1199	183	1.46	Between 1900 and 1919	158	1.40
Between 1200 and 1219	182	1.46	Between 1920 and 1939	158	1.40
Between 1220 and 1239	181	1.46	Between 1940 and 1959	158	1.40
Between 1240 and 1259	180	1.45	Between 1960 and 1979	158	1.40
Between 1260 and 1279	178	1.45	Between 1980 and 1999	157	1.40
Between 1280 and 1299	177	1.44	Greater than 2000	*to be determined*	1.40

The proper enrollment range is approximately 1,200 students for the middle school and between 980 and 999 students for the high school.

3.2.1.2 MSBA Requirements

The MSBA enforces design requirements along with the space recommendations. Some requirements that impacted the design approach of the building are listed below.

- Locate core classrooms (excluding laboratories, art, computer, vocational, and resource rooms, as well as any other rooms where daylight is not necessary) on the exterior walls of the building to provide interior daylighting and views.
- Provide interior partitions that extend from the top of the finished floor to the underside of the floor or roof deck above in spaces where chemical use occurs

such as housekeeping areas, chemical mixing areas, copying/printing rooms, and vocational spaces.

- Select a site with the spatial characteristics to accommodate future additions, outdoor educational programs, parking areas, bus turnarounds, and delivery setbacks.
- Design a layout to provide a net-to-gross square foot ratio less than 1.50.
- Provide special education spaces to support a program assuming that 8% of the enrollment will be enrolled in separate special education programs.
- Provide core classrooms with a net area between 825 ft^2 and 950 ft^2.
- Provide effective method of demolition practices in order to apply grant money toward demolition.

3.2.1.3 Space Planning

The MSBA provides an *Excel* file that calculates recommended spaces based on the enrollment capacity and gross building area. The allotted areas for the general use of the spaces are shown in Table 14 and the detailed spreadsheets showing the recommended number of spaces, area per space, and specific use of the spaces for each school are located in Appendix C.

Table 14: General Space Guidelines for School Designs

Space Type	High School Total Area	Middle School Total Area
Core Academic Spaces	42,360	56,430
Special Education	11,070	12,580
Art and Music	6,775	5,000
Vocational and Technology	9,600	9,600
Health and Physical Education	21,884	8,400
Media Center	6,244	7,280
Auditorium/Drama	9,670	-
Dining and Food Service	8,898	14,100
Medical	1,010	810
Administration and Guidance	4,541	4,450
Custodial and Maintenance	2,386	2,675
Other	2,000	-
Total	**126,438**	**121,325**

These areas were used to create a block diagram, which was used as a preliminary layout prior to designing the building to comply with the applicable building codes. The block diagram for the first floor is shown in Figure 14 and the block diagram for the second floor is shown in Figure 15.

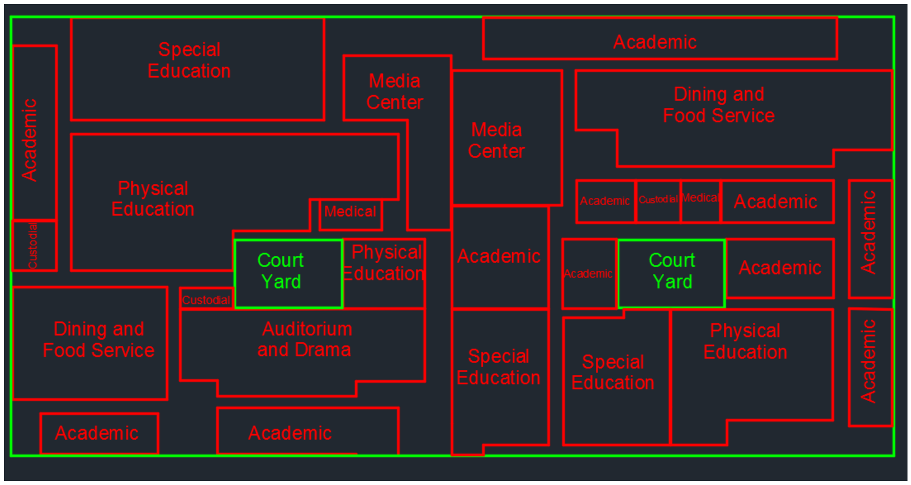

Figure 14: Preliminary First Floor Block Diagram

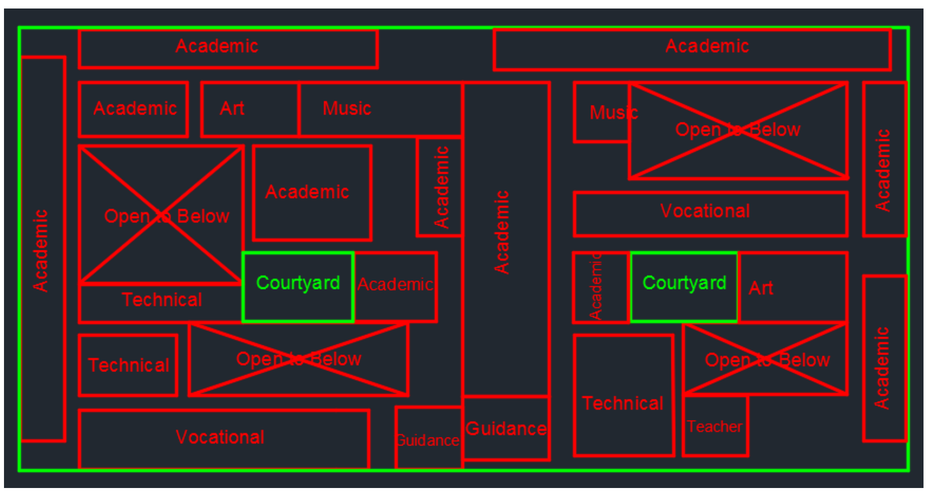

Figure 15: Preliminary Second Floor Block Diagram

3.2.2 Performance Compliance Alternative

The performance compliance method established by Chapter 13 of the *IEBC* was used to determine the fire and life-safety criteria of the renovated building. The provisions of the chapter offer an alternative method of achieving code compliance using a score system. This allows the substitution of a design feature that may be required by the prescriptive codes for one that provides an equivalent amount of fire and life safety at the convenience of the building owner or designer. The evaluation produces scores for fire safety, means of egress, and general safety. The categories involved in the production of these scores are listed below:

- Building Height
- Tenant Separation
- Fire Detection
- Means of Egress
- Elevator Control
- Automatic Sprinklers
- Building Area
- Corridor Walls
- Fire Alarm System
- Exit Access Travel
- Emergency Lighting
- Standpipes
- Compartmentation
- HVAC System
- Smoke Control
- Dead Ends
- Mixed Occupancies
- Incidental Occupancies

The goal of this design was to meet the minimum scores established in Table 1301.8 of the *IEBC*. Since the occupancy of the work area is classified as Group E, a fire-safety score of 29 and a means of egress score of 40 were the target scores for this design. The following evaluation is divided into sections concerning compartmentation, hazard separation, means of egress, and fire protection systems. The evaluation presents the initial trial followed by the solutions presented to increase the scores.

3.2.2.1 Compartmentation

The procedures for computing height, area, and compartmentation values are provided in Section 1301.6.1 through 1301.6.3 of the *IEBC*. The height and area of the building were computed using the existing construction type, which is Type IIB. Section 1301.6.1 of the *IEBC* prompts the lesser of the two values from calculations involving the building height and the number of stories to be used. These equations are shown in Equation 1 with the first equation using the building height and the second equation using the building stories.

$$Height\ Value = \frac{AH - EBH}{12.5} * CF$$

$$Height\ Value = (AS - EBS) * CF$$

Equation 1: Height Value for Performance Compliance Method

The allowable height and number of stories were obtained from the values in Table 503 of the *IBC* along with the automatic sprinkler system increase factors in Section 504.2, resulting in an allowable 70 feet at 3 stories. Using the existing building height of 30 feet, a height value of 3.6 was obtained. However, the value for the number of stories was computed as 1.

The area value was then computed with the allowable area and actual existing area using Equation 2, which was obtained from Equation 13-4 of the *IEBC*.

$$Area\ Value = \frac{A_a}{1200}\left(1 - \frac{A_e}{A_a}\right)$$

Equation 2: Area Value for Performance Compliance Method

The allowable area was computed based on the tabular value obtained from Table 503 of the *IBC*, the area increase for frontage, and the area increase for sprinklers. This equation is shown in Equation 3.

$$A_a = \left(1 + I_f + I_s\right) * A_t$$

Equation 3: Increased Allowable Area

The area increase for frontage was given as 75 percent since all sides of the building are provided with open space for a distance greater than 30 feet measured perpendicular from the edge of the building. The area increase for sprinklers was given as 200 percent since the building is more than one story above grade level. An exception in Section 912.5.3 of the *IEBC* allows the use of fire barriers having a fire-resistance rating of not less than that specified in Table 706.4 of the *IBC* in lieu of fire walls to separate areas into separate buildings for a change in occupancy classification.

The initial separation provided occupancies with an area per floor of 98,916 ft^2. The area value resulting from these variables was -37.1175. In order to decrease this value, more two-hour barriers were provided to decrease the area of the “separated” buildings. The new configuration is shown with the green walls representing two-hour fire barriers in Figure 16.

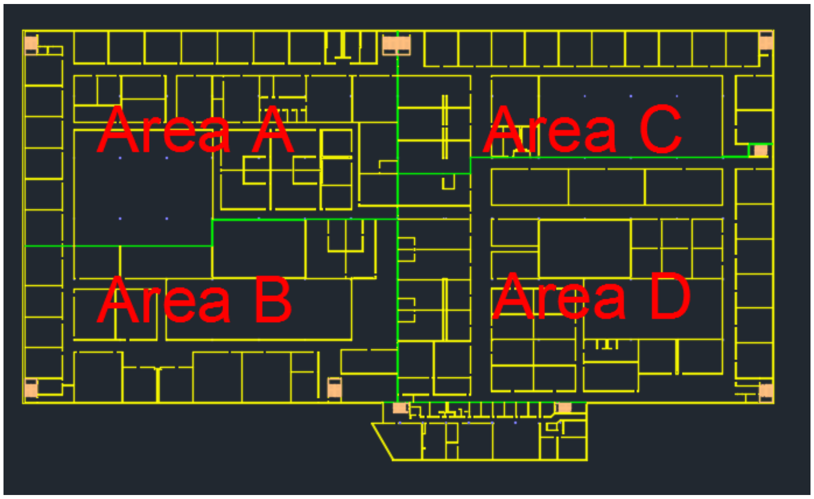

Figure 16: Fire Barrier Configuration for Area Value Calculation

The revised area computations were completed for each "separated building" in Table 15. The lowest value calculated was -7.5. Since the building will have uniform design features throughout, this was used as the controlling value.

Table 15: Area Value Calculations for Separated Areas

Area Label	Allowable Area (ft.^{2})	Actual Area (ft.^{2})	Area Value
A	54,375	55,896	-1.5
B	54,375	42,920	9.5
C	54,375	35,743	15.5
D	54,375	63,477	-7.5

Points are also provided for compartmentation of the building. The wall and floor/ceiling assemblies are required to possess a fire resistance rating of no less than two hours. The largest compartment size is the area designated as Area D in Figure 16. This compartment area exceeds 15,000 ft^2, in which case a value of 0 was awarded.

3.2.2.2 Hazard Separation

This section presents the results in determining the values for tenant separation, corridor walls, vertical enclosures, and mixed occupancies. The procedures for these categories are provided in Section 1301.6.4, 1301.6.5, and 1301.6.16 of the *IEBC*. The separation of tenants involves the separation of building space owned by another party. Since all spaces in the building have a single owner, the maximum value for Group E occupancies was earned. The value from Table 1301.6.4 of the *IEBC* is 4.

The value for corridors was earned by meeting the specifications of Category C of Table 1301.6.5 of the *IEBC*. Although the requirements states the construction of fire partitions with a fire resistance-rating between one-hour and two-hours, the construction in accordance with Section 1018 of the *IBC* is also accepted. Table 1018.1 of the *IBC* allows corridors without a fire-resistance rating in Group E occupancies, where a sprinkler system is provided throughout the building. This awarded a value of 0 for corridor walls.

The value for vertical openings was calculated from Equation 4, which was retrieved from Equation 13-5 of the *IEBC*.

$$VO = PV * CF$$

Equation 4: Vertical Opening Value

The vertical openings throughout the building, including interior exit stairs, hoistways, and other shafts were planned to have enclosures with fire-resistance ratings no less than one-hour. Therefore, the protection value (PV) derived from Table 1301.6.6 (1) of the *IEBC* was 1. The construction-type factor (CF) derived from Table 1301.6.6 (2) was 3.5. These values were used in Equation 4 to compute a vertical opening value (VO) of 3.5.

3.2.2.3 Means of Egress

The means of egress design considerations evaluated in the performance compliance method include smoke control, egress capacity, dead-ends, exit access travel distances, elevator control, and emergency lighting. The criteria used to assess the values earned are provided in Section 1301.6.10 through Section 1301.6.15.

The egress capacity value was awarded based on comparisons among the existing egress capacity, number of exits, and arrangement of exits and the provisions allowed by the *IBC*. The requirements for Category D state that the number of exits provided exceeds the number of exits required by Section 1021 of the *IBC*, and the exits are arranged in accordance with Section 1015.2 of the *IBC*. The number of exits per story is determined from the occupant load. The requirements from Table 1021.1 of the *IBC* are shown in Table 16 for different occupant load ranges.

Table 16: Minimum Number of Exits for Occupant Load (*IBC* - Table 1021.1)

Occupant Load (persons per story)	Minimum Number of Exits (per story)
1-500	2
501-1,000	3
More than 1,000	4

The arrangement of exits in accordance with Section 1015.2 of the *IBC* is used to ensure that a fire occurring at or near one of the exits will not block the other required exit(s). For building's protected throughout with an automatic sprinkler system, the distance between the centerline of exit doors must be no less than one-third of the maximum diagonal distance of the area which the exits are provided for. An example of this is shown in Figure 17.

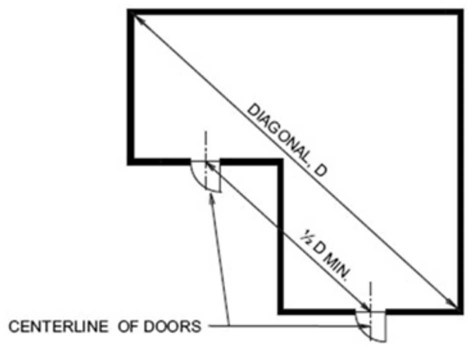

Figure 17: Example of Remoteness Between Exits (*IBC* - Figure 1015.2.1)

This design feature involves complying with the prescriptive requirements for exit doors in new buildings. Category E would require the egress capacity to meet or exceed the required egress capacity based on the occupant load. Since the occupant load is projected to be high, this requirement is not expected to be met. Since the modification of the building does not prevent code compliant exit door arrangement, Category D was selected.

Table 1301.6.12 of the *IEBC* permits an increase to 50 feet in Group B occupancies. Otherwise, the dead-end distance must be equal to or less than 20 feet to meet the requirements of Category B. Since the corridors and path of circulation is expected to be complex, the design criteria for Category B cannot confidently be met. As a result, the -2 value for Category A of Table 1301.6.12, was assigned to this building, which allows dead end distances to extend up to 70 feet.

The value assigned for exit access travel distances is a function of the allowable distance and the existing distance provided. It is provided in Equation 5, which was obtained from Equation 13-6 of the *IEBC*.

$$Value = 20 * \left(\frac{D_A - D_E}{D_A}\right)$$

Equation 5: Exit Access Travel Distance Value

According to Table 1016.1 of the *IBC*, the maximum exit access travel distance for Group E occupancies with an automatic sprinkler system is 250 feet. Therefore, a point may be obtained for every 12.5 feet less than 250 feet that the maximum exit access travel distance is. Since the building has large dimensions, the exit access travel distances are predicted to be high. In order to confidently meet the distance of 250 feet and provide flexibility in the building layout, a value of 0 was assigned, allowing a travel distance equal to the *IBC* requirements.

The elevator control values were assessed based on the passenger elevator equipment and controls available to the fire department to reach all occupied floors. 527 CMR does not require elevator recall for fire department operation for the proposed passenger elevators in this building. Therefore, unless necessary to meet the desired performance value, the addition of Phase I and Phase II elevator recall was not provided. Since the elevator does not have a travel distance of 25 feet or more above the primary level of access, a value of 2 may be provided according to Table 1301.6.14 of the *IEBC* if this feature is provided. The cost of adding this feature to the elevator is not significant, and therefore the design was adopted.

Section 1301.6.15 of the *IEBC* provides criteria for assessing the presence and reliability of emergency power for means of egress illumination and exit signs. Since more than two exits are provided in the building, the equipment must at a minimum have the emergency power capabilities provided in Section 2702 of the *IBC*. However, the minimum requirement is usually met by using batteries with no less than a 90 minute duration. Points are awarded for emergency power systems that provide power in the event of complete building or site power failure. Since this facility is not a critical facility such as a hospital, there would most likely not be an emergency generator capable of this. The minimum requirements were met resulting in an assigned value of 0.

3.2.2.4 Fire Protection Systems

This section presents the results in determining the values for fire protection systems. The categories involving fire protection systems are the HVAC, automatic fire detection, fire alarm, automatic sprinkler, and standpipe systems. The procedures for determining the values for these categories are provided in Section 1301.6.7, 1301.6.8, 1301.6.9, 1301.6.17, and 1301.6.18 of the *IEBC*.

Since the HVAC system is not in the scope of the project, an assumption was made that the renovated system will meet the applicable provisions of the 2009 Edition of the *International Mechanical Code* (*IMC*). According to Section 1301.6.7.1 of the *IEBC*, this neither penalizes, nor awards the building for fire-safety features, and the assigned value was 0.

Automatic fire detectors were not initially planned for in the design of the proposed school building. The prescriptive requirements of the *IEBC*, *IBC*, and 780 CMR do not require fire detectors with the installation of an automatic sprinkler system. However, the values assigned for automatic fire detection systems would aid in increasing the scores. From a fire and life-safety standpoint, these detectors would offer earlier detection of a fire incident, leading to earlier occupant notification. The redundancy of active fire detection is also important in the event that the thermal element of the sprinkler does not function properly. A rough estimate of the amount of smoke detectors needed for complete coverage of the building's work area can be estimated by dividing the building's gross floor area for both floors, not including the vertical openings and courtyards, by the typical spot-type smoke detector coverage area of 900 ft^2. This results in about 390 smoke detectors. Using the unit cost of $220 per detector for the installation of the device and all associated wiring, the cost to implement the system would be around $86,028 (RS Means, 2013). This is a significant cost, but the value provided by the system has the potential to offset the costs of other system designs. According to Table 1301.6.8 of the *IEBC*, a complete coverage smoke detector system earns the building a value of 8.

The fire alarm system initially planned for the building would conform to Section 907 of the *IBC*. An additional emergency/voice alarm communication system and fire command center classifies the system in Category D according to Section 1301.6.9.1 of the *IEBC*. Due to the low-cost and significant improvement of the system with these features, the decision was made to include them in the design allowing a value of 5 to be awarded.

The existing building has a sprinkler system located throughout the building, but sprinkler coverage is currently limited to the second floor level and select areas on the first floor level of the planned school. Additionally the position of the sprinkler must be modified to accommodate the additional floor level and partitions in the proposed renovation. NFPA 13 also recommends a level of protection where sprinklers are installed throughout the entire building when they are installed unless approved by the authority having jurisdiction, which is highly unlikely. Even if provisions were made to exempt an automatic sprinkler system, the existing system would have to be removed to accomplish this. Although the system would require modification for the new building layout and hazards, the fire safety value is essential, as it also effects other categories of the evaluation. Since the building already has an established water supply feeding the sprinkler system that will only serve the second floor of the educational area, the most cost-effective decision is to add additional sprinklers for the lower floor and modify the sprinkler locations and type on the second floor. Even though the sprinkler system is required by prescriptive codes, Category E of Table 1301.6.17 in the *IEBC* assigns a value of 6 to Group E occupancies when sprinklers are installed throughout the building.

The final category assessed had no impact on the means of egress score, but it influenced the fire safety and general safety scores. This category assessed the installation of a standpipe in accordance with Section 905 of the *IBC*. Since a standpipe was not required for the proposed building, and one was not provided, a value of 0 was assigned according to Table 1301.6.18 of the *IEBC*.

3.2.2.5 Final Evaluation

The results from the initial evaluation of the proposed school building design features resulted in means of egress score of 28 and a fire safety score of 22. The values discussed in the previous sections are listed in Table 17.

.

Table 17: Initial Performance Compliance Evaluation Summary Sheet

Category	Means of Egress Value	Fire Safety Value
Building Height	1	1
Building Area	-7.5	-7.5
Compartmentation	0	0
Tenant Separation	4	4
Corridor Walls	0	0
Vertical Openings	3.5	3.5
HVAC System	0	0
Fire Detection	8	8
Fire Alarm	5	5
Smoke Control	0	-
Means of Egress	8	-
Dead Ends	-2	-
Exit Access Travel	0	-
Elevator Control	2	2
Emergency Power	0	-
Mixed Occupancies	0	0
Automatic Sprinklers	6	6
Incidental	0	0
Standpipe	-	0
Total	**28**	**22**

According to Table 1301.8 of the *IEBC*, the mandatory means of egress and fire safety scores for Group E occupancies are 40 and 29 respectively. Therefore, design features needed to be implemented to increase the means of egress score by 12 and the fire safety score by 7.

The most impactful value on the chart is the one due to building area. This value decreased both scores by 7.5, which is significant in this system. By adjusting the location of the fire barrier in the middle school building, the gross floor area of Area D was decreased, thus increasing the building area value. The relocation of the barrier caused other design modifications in order to provide two interior exit stairs in each of the building areas. The revised fire barrier configuration is shown in Figure 18.

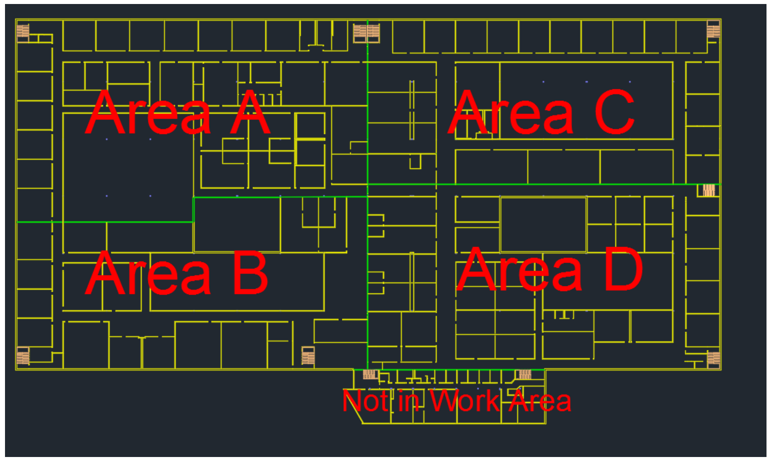

Figure 18: Revised Fire Barrier Configuration

The reconfiguration of the fire barriers created "separated buildings" that are closer to each other in size. This led to an increase in the lowest value as shown in Table 18.

Table 18: Revised Area Values

Area Label	Allowable Area (ft^2)	Actual Area (ft^2)	Area Value
A	54,375	55,896	-1.5
B	54,375	42,920	9.5
C	54,375	48,671	5.0
D	54,375	50,631	3.0

After the modification, the controlling building area value was -1.5. This increased both scores by 6. Following this revision, the means of egress score was 34 and the fire safety score was 28.

Another design modification that was made was an increase in the fire resistance ratings of all vertical enclosures. Although the prescriptive provisions require enclosures to have a one-hour fire resistance rating when connecting less than four stories, the improvement of the enclosure to a two-hour fire resistance rating increased both scores by 3.5. Following this revision the means of egress score was 37.5 and the fire safety score was 31.5.

In order to obtain the means of egress score of no less than 40, the smoke control category was consulted. Category F from section 1301.6.10.1 awards 5 points if one of the listed conditions is met. The options presented include constructing stairways as smokeproof enclosures, pressurized stairways, or to have operable exterior windows. The pressurization method was selected, as exterior balconies could not be provided for the smokeproof enclosure and operable exterior windows would require fire protection glazing in the exit enclosure. The pressurization method will be discussed in Chapter 5 of this paper using Section 909.6 of the *IBC*.

The final means of egress score was calculated to be 42.5, which exceeds the minimum required value by 2.5 points. Since the travel distances to an exit was a concern during the preliminary design, the travel distance value may be decreased to provide flexibility. The revised maximum travel distance was calculated by re-arranging Equation 5 and using -2.5 as the resulting value as shown in Equation 6.

$$D_e = D_a - \left[\left(\frac{Value}{20}\right) * D_a\right]$$

$$D_e = 250 - \left[\left(\frac{-2.5}{20}\right) * 250\right]$$

$$D_e = 281.25\ ft.$$

Equation 6: Revised Allowable Exit Access Travel Distance

The resulting performance compliance assessment that was used for the design of all fire and life-safety features of the renovated building is shown in Table 19.

Table 19: Final Performance Compliance Summary Sheet

Category	Means of Egress Value	Fire Safety Value
Building Height	1	1
Building Area	-1.5	-1.5
Compartmentation	0	0
Tenant Separation	4	4
Corridor Walls	0	0
Vertical Openings	7	7
HVAC System	0	0
Fire Detection	8	8
Fire Alarm	5	5
Smoke Control	5	-
Means of Egress	8	-
Dead Ends	-2	-
Exit Access Travel	-2.5	-
Elevator Control	2	2
Emergency Power	0	-
Mixed Occupancies	0	0
Automatic Sprinklers	6	6
Incidental	0	0
Standpipe	-	0
Total	**42.5**	**31.5**

3.2.3 Means of Egress

One of the most fundamental processes in designing a fire-safe building is providing a sufficient means of egress. This term is defined in Section 1002.1 of the *IBC*, as "A continuous and unobstructed path of vertical and horizontal egress travel from any occupied portion of a building or structure to a public way." The means of egress consists of three distinct parts: the exit access, exit, and exit discharge. The means of egress requirements that must be met for the renovated design, as selected from the performance compliance method, are listed in Table 20.

Table 20: Means of Egress Requirements from Performance Compliance Method

Category	Description
Number of Exits	Exceeds number of exits required by *IBC* 1021
Exit Remoteness	Exits located in accordance with *IBC* 1015.2
Dead-Ends	Dead-end corridors not exceeding 70 ft. in length
Exit Access Travel Distance	Exit Access Travel Distances not exceeding 281 ft.

3.2.3.1 Occupant Load

An occupant load factor was designated for each space of a building in order to determine the number of required exits. Codes intend to provide a conservative approach for defining the largest number of occupants that may occupy a space at any one time. Table 1004.1.1 of the *IBC* provides design occupant load factors for different functions of space. This does not account for all areas though, as the occupant load in areas with fixed seating is determined by the number of seats, as well as any additional spaces intended for accessible seating and/or standing space. In instances where seating does not have arm dividers, such as bleachers and benches, the occupant load can be taken as 18 inches in length per occupant as stated in Section 1004.7 of the *IBC*.

These numbers do not necessarily accurately depict the occupant load of an area due to the unlikeliness of multiple rooms being occupied to the same extent at the same time. This is the reason that an exception is listed in the *IBC* that permits the use of an occupant load less than that calculated when approved by the building official. The reduction in the occupant load may be used throughout this building design, since standard classrooms are designed for a capacity of 23 to 27 students, per the MSBA guidelines, but the occupant load for the minimum 850 ft^2 classrooms (using the *IBC* and NFPA 101 calculation methods) is 43 occupants. Therefore a more accurate occupant load factor of 25 square feet per occupant is still a conservative approach and was used throughout this design with the assumption that the building official would find this acceptable. Other occupant load factors from the *IBC* that were necessary for the egress analysis of this building are shown in Table 21.

Table 21: Design Occupant Load Factors

Function of Space	Occupant Load Factor (ft^2 per occupant)
Accessory Storage Area	300
Assembly (Concentrated – Chairs)	7 Net
Assembly (Standing Space)	5 Net
Assembly (Un-concentrated - Tables/Chairs)	15 Net
Business Areas	100
Classroom	25 Net
Vocational Classroom	50 Net
Exercise Rooms	50
Kitchen, Commercial	200
Library Stack Area	100
Library Reading Room	50 Net
Locker Room	50
Stages/Platform	15 Net

Unless specified otherwise, the occupant load was taken as the gross area, which includes spaces that are not necessarily occupied such as storage areas, corridors, bathrooms, and stairs. Since the building consists of mostly classrooms, the net classroom space was used and the bathrooms and corridors throughout the building were not taken into consideration. This is due to the probability of these occupants being accounted for in the calculation of the classroom occupant load. However, where a corridor or bathroom is dedicated to a business space, such as a teacher's lounge, the area was taken as part of the occupant load, since the gross square footage is applicable.

3.2.3.2 Exits

According to Section 1021.1 of the *IBC*, all spaces on each story of a building must have access to the amount of exits provided in Table 1021.1 of the code. The number of exits required in this building based on the more stringent requirement of the performance compliance method are shown in Table 22.

Table 22: Number of Exits Required for Renovated Building Based on Occupant Load

Occupant Load	Minimum Number of Exits
1-500	3
501-1,000	4
+1,000	5

At least two of these exit doors must be arranged at a required separation distance as shown by the example in Figure 19.

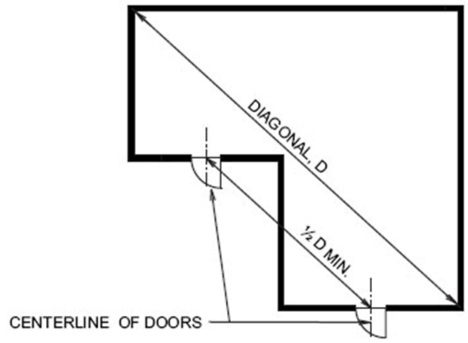

Figure 19: Example of Remote Exit/Exit Access Concept (*IBC* 2009: Figure 1015.2.1)

This distance is calculated by dividing the longest diagonal (corner to corner) in a space by three when the building is equipped with an automatic sprinkler system throughout and by two when a sprinkler system is not installed or partially installed. The distance between the centerline of the doors must meet or exceed this distance to provide remoteness in the scenario that a fire occurs at one of the doors.

Along with interior exit stairways and exterior exit doors, horizontal exits used in accordance with Section 1025 of the *IBC* may also be used to meet the requirements. Horizontal exits are designed by providing doors in a fire barrier with a fire resistance rating not less than two hours. Section 1025.1 also states that horizontal exits may not comprise more than one-half of the required exits.

3.2.3.3 Travel Distances

The two important travel distances to consider when designing this layout were exit access travel distance and dead end travel distance. Exit access travel distance is the distance traveled from the most remote point on each story to the nearest exit along a natural and unobstructed path of egress travel. This distance is measured at right angles and is modified based on the occupancy and the presence of a sprinkler system. Figure 20 shows an example of the exit access travel distance to an exterior exit doorway from the most remote point of the area.

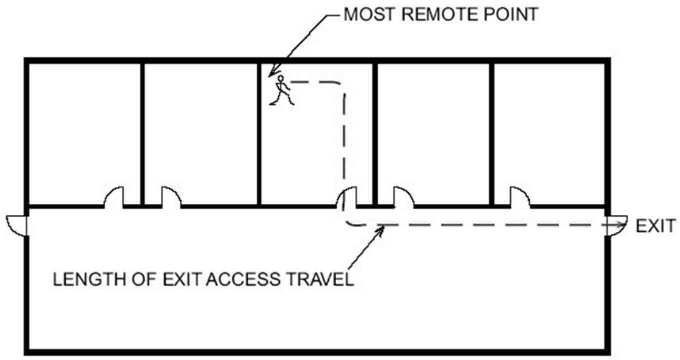

Figure 20: Example of Exit Access Travel Distance (*IBC* 2009: Figure 1016.1)

Dead end distances are commonly provided in corridors due to limitations in building layouts. These occur when travel down a corridor does not lead to exit access or an exit, and the occupant is required to turn around to travel back to the original location to maintain exit access. Figure 21 shows an example of dead end travel distances and common path of travel distances.

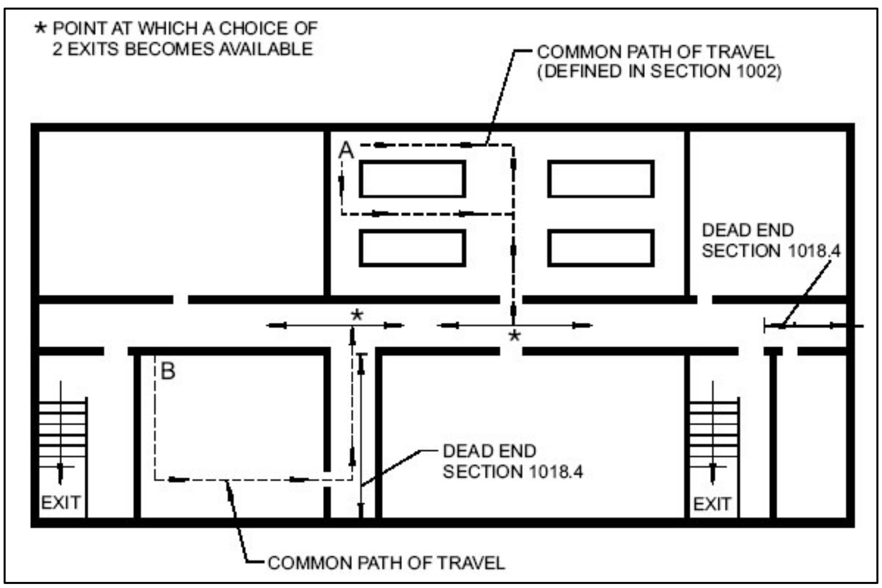

Figure 21: Examples of Common Path of Travel and Dead-End Travel Distances

3.2.3.4 Egress Analysis

An egress analysis was performed for the renovated building. This was completed by investigating the occupant loads of each area. Since the building was separated by fire barriers into four separate areas per floor, the number of exits for each area was computed separately. The designations for the separate areas are specified in Table 23.

Table 23: Designations for Separated Areas

Designation	Description
A	North First Floor of High School
B	South First Floor of High School
C	North First Floor of Middle School
D	South First Floor of Middle School
E	North Second Floor of High School
F	South Second Floor of High School
G	North Second Floor of Middle School
H	South Second Floor of Middle School

For each area, the occupant load was computed using the design occupant load factors from the *IBC*. Then the required number of exits was determined based onTable 16. After the number of exits was finalized, an evaluation of the travel distances was performed to verify that they were within their limitations.

3.2.3.4.1 Exit Evaluation

The occupant loads for the designated areas, along with the required number of exits from that areas of the renovated building are shown in Table 24.

Table 24: Number of Exits per Fire Compartment in Renovated Building

Area	Occupant Load	Exits Required	Horizontal Exits Permitted
A	1,617	5	2
B	1,530	5	2
C	1,503	5	2
D	1,171	5	2
E	947	4	2
F	772	4	2
G	783	4	2
H	826	4	2

An example layout of the exits is shown for Area A in Figure 22. The blue circles represent horizontal exits, and the red circles represent all other exits. The other layouts are provided in Appendix D.

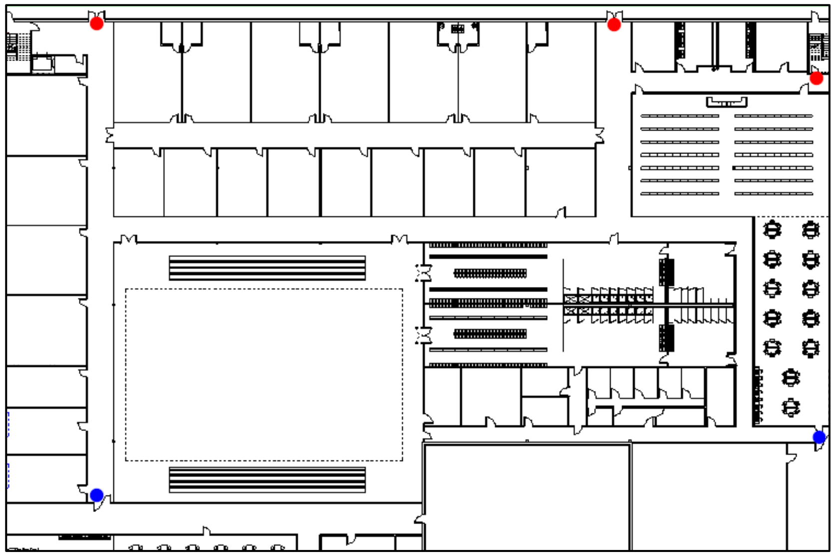

Figure 22: Area A Exit Layout

3.2.3.4.2 Travel Distance Evaluation

As stated in the performance compliance method, the exit access travel distance was extended from 250 feet to 281.25 feet. Additionally, no common path of travel distance was enforced, and the dead ends of corridors could extend to as long as 70 feet. The two-hour fire barrier also allowed the travel to exits from some areas to be reduced. Even the longest travel distances from each area of the building created travel distances that were within the limits of the requirements. Some of the longest travel distances are shown in Figure 23, Figure 24, and Figure 25. For each of these instances, the travel distance was met at a distance that is not acceptable by the prescriptive codes, but was allowed by the performance compliance method.

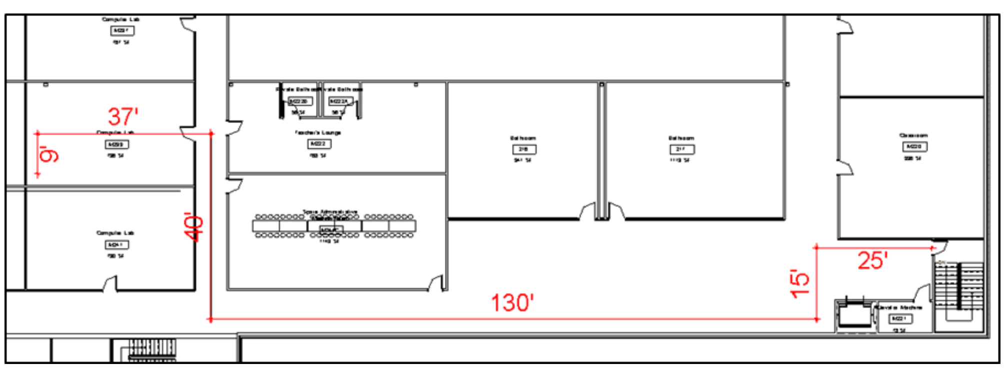

Figure 23: Travel Distance from Computer Lab on Second Floor of Middle School

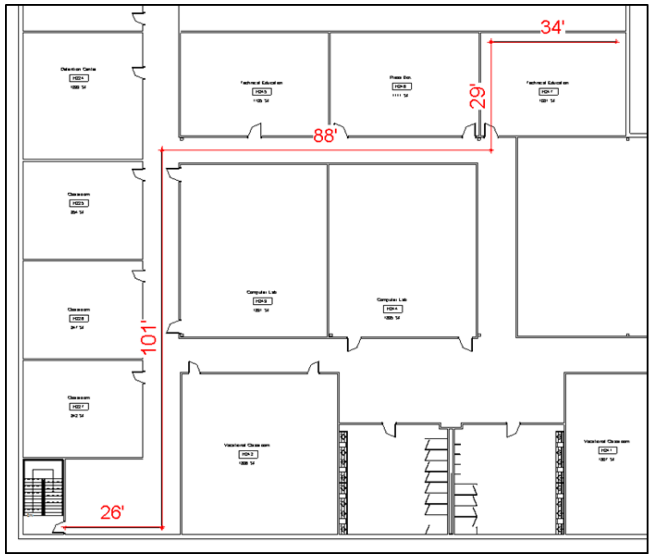

Figure 24: Travel Distance from Technical Education Classroom on Second Floor of High School

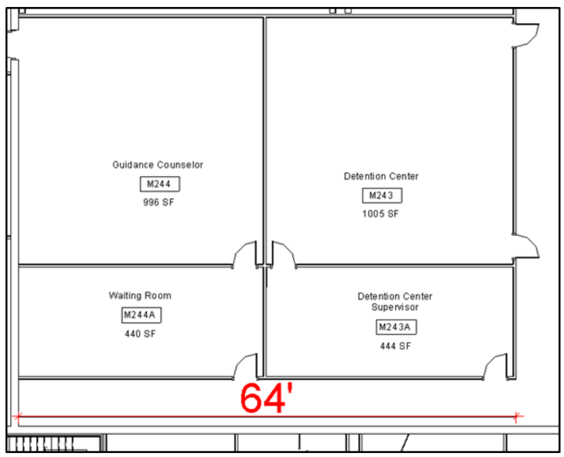

Figure 25: Dead-End Corridor on Second Floor of Middle School

3.2.4 Preservation vs. Demolition

How the existing architectural features should be demolished, recycled, or preserved was also considered The existing walls, doors, windows, and other key building materials were investigated to determine whether they could be reused directly within the building or if there are recycling markets available to make selectively demolishing cost effective and sustainable. Throughout these sections, cost estimates are made concerning the selective demolition of materials. These costs were then compared to the square footage cost estimate for the complete interior guy of a building.

The square footage values were obtained from the 2015 National Construction Estimator and RS Means 2013, which were \$6.21/ ft^2, \$5.29/ft^2 (minimum), and \$7.41/ft^2

(maximum) respectively. However, the cost provided by the 2015 National Construction Estimator assumes ceiling heights equal to 8 feet. Therefore, the maximum unit cost from RS Means 2013 was used. The area of the entire first floor, not including the office area wing, but including the mezzanine level, is about 213,000 ft^2. The cost estimate for a complete interior gut is estimated to be $1,578,321.

This may not be an accurate depiction since the cost involves stripping the building down to its load-bearing and sub-frame element. The estimate assumes that all interior finishes, electrical systems, and mechanical systems are demolished. The modification procedure for this building involves the replacement of structural elements in some cases, but the retention of building systems in other scenarios.

3.2.4.1 Interior Walls

Due to the careful planning that goes into the layout of an educational facility, the existing walls in the school area could not be utilized in their current locations. Also, the condition of the gypsum may not be suitable for the architectural aesthetic intended for the school. Given that the main purpose of the renovation is to preserve the shell of the building, the decision was made to preserve the steel studs that did not show deterioration, corrosion, or structural damage, but to replace the finish material with new gypsum wallboard. As a result, an alternative means of recycling the valuable material was necessary.

Gypsum wallboard, typically manufactured as drywall, has a presence in the construction recycling market due to its popularity as an interior wall material for most projects in the United States. Although most of the drywall waste is generated from new construction, the demolition of existing structures contributes to 14% of the waste, and the renovation of existing structures contributes to 10% of the waste (CIWMB, 2009). Typically, drywall-recycling programs are in place to reuse the leftover pieces from cuts in new construction. When careful processing procedures are in place, the material may be removed from existing structures for recycling. The potential uses for the recycled drywall are shown in Table 25 (Winkler, 2010).

Table 25: Gypsum Recycling Uses

Use	Description
New Drywall	Can be resold to drywall manufacturing facilities to produce new gypsum board
Portland Cement	Sell scraps to cement manufacturer, which is added to cement clinker before the ball mill process
Land Applications	Process gypsum to use as sulfur and calcium source for crops or use to improve drainage of clayey soils
Compost	Sell gypsum to compost facilities, which use the paper separated from gypsum to composting systems

Since feasible recycling methods are present for the drywall, all interior wall assemblies, except for those in the office area and those separating the office area from the warehouse, will be removed. This will allow flexibility in the renovation design while considering other reuse applications of the interior wall materials. The quantity take offs from the Revit model of the existing conditions showed that 60,383 ft^2 of wall was removed. Since drywall is present on each side of the metal studs, 120,766 ft^2 was removed. According to RS Means 2014, an estimated cost of labor for this activity is \$0.58 per square foot of wallboard in place. This estimate considers removal of the material using hand tools and piling them on the site (Pray, 2014). Based on this, the estimated labor cost is approximately \$70,044.

3.2.4.2 Swinging Doors

Doors located in the walls being removed would also be removed using hand tools and assessed for their reuse potential. Unlike gypsum wallboard, doors are heterogeneous building components, containing the frame, door, and associated hardware. The doors in this facility are most likely metal doors, which can be recycled with other approved materials in mixed loads. However, this practice is not as effective as processing other materials such as gypsum board (Winkler, 2010). However, there are opportunities for reusing swinging doors through architectural salvage practices. Companies specializing in material salvaging may write proposals for certain items they desire to have, and prior to demolition by the contractor, these companies will arrive at the site to deconstruct certain specialty items. Although this practice is more common in antique or historical materials, companies may specialize in certain building types, and want doors specific to warehouses.

Whether the doors are resold at salvage value, or reused in the building, they will be removed for the repositioning of walls. This is relatively inexpensive compared to other construction activities. Each 3’ x 7’ metal door in an interior wall has an estimated removal cost of $29.10, if it is intended to remove the door in a salvageable condition (Pray 101). If all of the doors positioned in the removed walls are also removed, then 41 doors would require removal per the takeoff quantity in the *Revit* model. This equals a cost of $1,193 prior to any re-sale considerations.

3.2.4.3 Masonry Walls

The majority of the CMU walls will remain from the existing building. However, the addition of exterior exit doors presents a more significant cost factor than simply accounting for the door material and the installation of the door. The cutting of the exterior wall to place doors in the wall must be planned. The unit cost provided assumes sections with areas up to 4 ft^2 cut out of the concrete block. An estimated cost per cutout for 8 inch thick CMU walls is $92.10. The process for computing the cutout cost estimate is shown in Table 26.

Table 26: Cost Estimate for CMU Wall Cutouts for Doors

Door Type	Height Opening	Width Opening	Area Opening	Cutouts Required	Quantity	Cost
Double-Door Two 3’x7’	7.33 ft.	6.33 ft.	46.4 ft^2	12	14	$15,472.80
Single Door 4’x7’	7.33 ft.	4.33 ft.	31.8 ft^2	8	8	$5,894.40
				Total Cost		**$21,367.20**

3.2.4.4 Building Systems

Although the sanitary water design is not in the scope of this project, it is still necessary to identify design features of the existing plumbing system. Since the building is not heavily occupied, there is a lack of bathroom facilities. Similar to the gypsum wallboard, even if certain situations allowed for plumbing fixtures to be incorporated into the new layout, the condition of the fixtures would not meet the needs of a new school building.

These facilities feed sanitary drain lines that lead to either a septic tank or a municipal system. After the system is carefully evaluated, additional pipe systems may be integrated into the building, which avoids the need for site work involving utilities. Although further evaluation would be necessary to ensure that the piping systems meet current codes, the codes have not changed significantly since 1950 (Rabun, 2009). Therefore, it is reasonable to assume that the plumbing work required for this building involves installing additional fixtures to meet the additional occupant load, and adding to the pipe system to accommodate for those fixtures.

The fixtures that are currently in the building will not be suitable for the proposed renovation. A common theme for sustainable design is to reduce the water use in plumbing fixtures. This is accomplished by installing fixtures with low flow operations or waterless flush functions. Therefore, the existing water closets, urinals, and washing sinks will be removed. Similar to doors, architectural salvage companies frequently target these items, for their value to particular construction projects. 14 water closets, 12 wash sinks, and 4 urinals must be removed without affecting the system supplying these fixtures. The careful removal of this equipment is accomplished using hand or pneumatic tools. The estimated time for removal of each fixture is between one-third to one-half the time it takes to install each fixture (RS Means, 30). Using a crew of one plumber and one laborer, which costs $49.73 per man-hour (Pray, 9), the cost estimates for the removal of plumbing fixtures is shown in Table 27. The total cost of removal is $1,472.

Table 27: Cost Estimates for Plumbing Fixture Removal

Fixture Removed	Quantity	Installation Man-hours	Estimated Removal Man-hours	Labor Cost
Urinal	4	2.35	1.00	198.92
Water Closet	14	2.60	1.10	765.84
Lavatory	12	2.00	0.85	507.25
			Total	**$1,472**

Although the plumbing fixtures were reassessed for their use outside of the renovated building, the plumbing systems themselves could be further investigated to directly reuse in the building.

3.3 Ground-Up Construction

Throughout the design of the adaptive reuse structure, several deficiencies were found that made the existing structure unfavorable for the intended purpose. Thus, the design would incorporate many changes if the flexibility of choosing a site and building from the ground-up were available. For comparison purposes, an analysis of the difference in the buildings was made using the same design that was hypothetically constructed from the ground up on a purchased site.

3.3.1 Preliminary Code Analysis

The Massachusetts State Board of Building Regulations and Standard (BBRS) enforces the 8th Edition of the *Massachusetts Building Code* (*780 CMR*), which includes the base code of the 2009 Edition of the *International Building Code* (*IBC* 2009), along with Massachusetts Amendments.

Massachusetts also enforces the *Massachusetts Comprehensive Fire Safety Code* (*527 CMR*), which adopts a base code of the 2012 Edition of NFPA 1, *Fire Code*. Though, according to Section 1.1.2 of the *527 CMR*, unless specific language is given referring to building construction, alteration, change of occupancy or any other related construction practices, the code serves as a reference to applicable portions of *780 CMR*. Therefore, unlike many jurisdictions where both NFPA 101, *Life Safety Code* and the *IBC* to new and existing buildings are applied, the *IBC* was the primary code referenced throughout the code analysis.

3.3.1.1 Occupancy Classification

Codes and standards primarily function by applying an occupancy classification to the building or space of a building and providing requirements specific to that occupancy classification. Section 305.1 of the *IBC* defines a Group E occupancy as the use of a building, or a portion thereof for educational purposes through the 12th grade. This is the most fitting description for most areas of the building, but there are also special uses such as the gymnasiums, cafeterias, and auditoriums. These spaces would typically be classified as Group A occupancies, but the Exception to Section 303.1 of the *IBC* states that assembly areas accessory to Group E occupancies are not considered separate occupancies except when applying the assembly requirements of Chapter 11, which provides provisions for accessibility.

The portion of the building dedicated to administration, which was referenced in Section 3.1 of this paper as “Area 2”, was designated as a Group B occupancy. Section

304.1 of the *IBC* describes this occupancy as the use of a building or part of a building for office, professional, or service-type transactions. Within this office space there are also conference rooms, which have an occupant load greater than 50 persons and an area greater than 750 ft^2. Therefore these spaces are considered Group A-3 occupancies, which include assembly uses not described in any of the other sub-classified assembly groups (*IBC* 2009 – Section 303.1).

3.3.1.2 Automatic Sprinkler System

Since the installation of a sprinkler system determines the ability to modify many of the code requirements, this code requirement was initially analyzed. Section 903.2.3 of the *IBC* requires that sprinklers be provided throughout all Group E fire areas exceeding 12,000 ft^2. This requirement is enhanced by *780 CMR*, which states that the existence of a fire area this large requires the entire building to have an automatic sprinkler system installed throughout. The design and construction of fire areas requires the area to be separated by fire barriers and horizontal assemblies, each with a two-hour fire resistance rating according to Table 707.3.9 of the Code. Although this can be accomplished, much consideration is required to ensure that openings, penetrations, and joints all maintain the integrity intended for the fire barriers.

Many trade-offs in the building code are possible with the installation of an automatic sprinkler system. This includes egress travel distances, interior finishes, fire alarm initiation, building heights and areas, and passive fire protection.

3.3.1.3 Height and Area

Using the same structural frame as the renovation design, one hour of fire protection must be provided to the building's structural elements to be considered Type IIA construction. In this case, a tabular area of 26,500 ft^2 is allowed. Section 506 allows the building area limitation to be modified using the allowances for frontage and sprinkler increase shown in Equation 7.

$$A_a = \{A_t + [A_t \times I_f] + [A_t \times I_s]\}$$

Equation 7: Allowable Building Area Per Story

The area increase factor due to frontage is applicable if the building has more than 30 ft. of open space on all sides. This can be calculated with the ratio of the building perimeter fronting on a public way to the total building perimeter using Equation 8, which was obtained from Section 506.2 of the *IBC*.

$$I_f = \left[\frac{F}{P} - 0.25\right] \times \frac{W}{30}$$

Equation 8: Area Increase Factor Due to Frontage

The open space must be accessed from a street or approved fire lane according to Section 506.2.2 of the *IBC*. Although the fire lane does not have to be 30 ft. in width, Section 10.03 of *527 CMR* states that all designated fire lanes should have a minimum width of 18 ft. The open space that must be accessed from the fire lanes is marked by the red border in Figure 26.

Figure 26: 30 ft. Wide Open Space on All Sides of the Building

Assuming the new building will have open space greater than 30 feet on all sides of the building, F/P is calculated as 1.0, and the frontage factor as 0.75. The area increase factor due to an automatic sprinkler system was 200% since the building has more than one story above grade plane. Therefore, the allowable area was computed below in Calculation 1 for Type IIB construction and Calculation 2 for Type IIA Construction.

Calculation 1: Allowable Area for Type IIB Construction

$$A_a = \{15{,}500 + [15{,}500 \times 0.75] + [15{,}500 \times 2]\}$$

$$A_a = 58{,}125\ ft^2$$

Calculation 2: Allowable Area for Type IIA Construction

$$A_{\alpha} = \{26{,}500 + [26{,}500 \times 0.75] + [26{,}500 \times 2]\}$$

$$A_{\alpha} = 99{,}375\ ft^2$$

Similar to the renovated design, the building was divided into two sections, and interior courtyards were provided. However, the high school and middle school areas require a firewall to permit the provision of separated buildings. This firewall was designed in accordance with Section 706 of the *IBC*. The design of the firewall is discussed in Section 4.3.1 Fire Wall of this report.

3.3.1.4 Means of Egress

As discussed in Section 3.2.3 Means of Egress the means of egress requirements of a building must be coordinated with the architectural layout early in the design process. The means of egress for the new building will generally be required to meet more stringent requirements, since all applicable sections of Chapter 10 in the *IBC* must be followed. Although all of the requirements will not be discussed, they were considered and implemented into the Revit model of the building. Many of these requirements were discussed for the renovated design. However, other requirements such as common path of travel, egress capacity, and egress from assembly spaces are discussed.

3.3.1.4.1 Egress Capacity

The capacity of all components of means of egress are based on the occupant load using the component, but there are also minimum standards for the width of these components. The minimum widths of egress components from the *IBC* are shown in Table 28. The only requirement specific to the Group E occupancy is the corridor width, which is increased due to the edge effect caused by the student lockers. It should be noted that the lockers may not cause an obstruction into the required width of the corridor, but that the increase is provided due to the frequency that the space will be occupied for reasons other than circulation.

Table 28: Minimum Width of Egress Components

IBC Section	Component	Minimum Width (in.)
1008.1.1	Door	32 (Clear Width)
1009.1	Stairway	44
1009.1	Stairway (< 50 Occupant Load)	36
1010.5.1	Ramps	36 (Between Handrails)
1018.2	Corridor (> 100 Occupant Load)	72
1018.2	Corridor (< 100 Occupant Load)	44

Additionally these components must meet the capacity requirements due to the occupant load. Here the *MBC* modifies the *IBC*, as an exception for Section 1005.1 is added, which allows an egress capacity of 0.2 inches per occupant for stairways, and 0.15 inches per occupant for all other egress components in buildings protected throughout with an automatic sprinkler system. Where there are multiple means of egress available from a space, the capacity is calculated to reduce the available capacity to not less than 50% of the required capacity in the event that one means of egress is lost from a fire in a single location. The capacity of the means of egress must not be reduced throughout the path of travel, with the exception of door encroachment, which is permitted to reduce the required width by 7 inches when fully opened.

3.3.1.4.2 Exit Access

Exit Access is defined in Chapter 10 of the *IBC* as the portion of a means of egress system that leads from any occupied portion of a building to an exit. The exit is separated from other interior spaces of a building by required fire-resistance rated construction to provide a path of egress to the exit discharge or directly to exit discharge. Exits can be provided in a variety of ways such as exterior exit doors, interior exit stairways, horizontal exits, or exit passageways.

Exit access is not permitted to pass through intervening rooms or areas unless the spaces are accessory to one another and there is a discernible path of egress travel to an exit (*IBC* 1014.2). An instance that is acceptable for passing through intervening spaces is from bathrooms serving a specific assembly space, through conjoined classrooms, or through the waiting area in the guidance counselor office.

The most common component of exit access in egress systems is corridors, which have several code provisions throughout Section 1018 of the *IBC*. Corridors consist of walls extending from the floor to the ceiling above, and may require a fire-resistance rating depending on the occupancy type, occupant loads, and other means of fire protection. However, in Group E occupancies, corridor walls are not required to possess a fire-resistance rating when a sprinkler system is provided throughout the building due to the absence of sleeping rooms (*IBC* Table 1018.1).

3.3.1.4.3 Travel Distances

The three important travel distances to consider when designing an architectural layout with a code compliant means of egress system are exit access travel distance, common path of travel distance, and dead end travel distance. The fundamentals for exit access and dead-end travel distances were already discussed. However common path of travel was not considered by the performance compliance method.

Common path of travel is the length of exit access travel in which occupants are forced to travel along the same path before the egress travel to more than one exit is available. This is typically present if one area is permitted to have only one exit access doorway, in which the maximum travel distance from the space will also be the common path of travel distance if multiple paths are available when the area is exited.

The travel distances permitted in the proposed school layout are listed in Table 29 based on the design consideration for a sprinkler system and the Group E occupancy.

Table 29: Allowable Travel Distances for Group E Occupancy

Travel Distance	Distance (ft.)	*IBC* Code Reference
Maximum Allowable	250	1016.1
Common Path	75	1014.3
Dead-End	50	1018.4

3.3.2 Egress Analysis

The egress analysis was a greater challenge in the new building than the renovated school building. This was due to the decreased allowable dead-end distances and maximum exit access travel distances. The common path of travel requirements also had to be met, which were not specified in the performance compliance method. Although the occupant loads remained the same as the existing modification, differences were provided in the travel distances and number of exit doors.

3.3.2.1 Occupant Load Analysis

The occupant load for the spaces on the first floor of the high school using the design occupant load factor method are displayed in Table 30. Some important notes to supplement the table are listed below it.

Table 30: Occupant Load for First Floor of High School

Space Type	Total Net Area (sf)	Load Factor (sf per person)	Occupant Load (persons)
General Classroom	16,662	25	666
Locker Rooms/Dressing Rooms	2,487	50	50
Mech./Elect./Storage	2,266	300	8
Kitchen	1,988	200	10
Offices	1,309	100	13
Library Study Area	2,462	50	49
Library Stack Area	3,693	100	37
Nurse Resting Areas	500	120	4
School Store	776	30	26
Resource/Small Group	5,017	25	201
Food Serving Area	594	5	119
Stage	1,000	15	67
Team Room	508	7	73
Waiting Area	113	15	8
Weight Room	2,996	50	60
Courtyard	3,881	50	78
		Total	**1,467**

- Rooms designated as small group conference, small group seminar, and resource rooms were all calculated using the same occupant load factor as for standard core classrooms.
- The serving area was calculated as an assembly standing space.
- The library was divided separately into the study area and the stack area, even though an actual partition separating the areas is not present.
- The sports court of the gymnasium was calculated using the occupant load for swimming pools and skating rinks.

- The interior courtyard will be used for outdoor classroom time for classes such as art and science. It will also be lightly used for recreational activities. Therefore a reasonable occupant load factor of 50 ft^2 per person was assigned for the area.

The areas which required further examination due to the presence of fixed seating includes the staff lunch room, student cafeteria, auditorium, and gymnasium. A simple display of these calculations is shown below.

- Staff Lunch Room: 6 tables x 8 seats = 48 occupants
- Student Cafeteria: 21 tables x 16 seats = 336 occupants
- Auditorium: 3 seating assemblies x 10 rows x 20 seats = 600 occupants
- Sports Court: 2 bleachers x 6 rows x 76ft. long/1.5 ft. per person = 608 occupants

The total occupant load between both methods is 3,059 occupants. This value was used to calculate the total egress capacity for the first floor of the high school.

The occupant load for the second story of the high school is significantly less than the occupant load of the first story due to the absence of assembly occupancies and some areas being extended through both stories. The total occupant load for this area of the building is 1,558 persons. The corresponding values for the occupant load per space type are shown in Table 31 with important notes to supplement the table listed below it.

Table 31: Occupant Loads for High School Second Floor

Space Type	Total Net Area (sf)	Load Factor (sf per person)	Occupant Load (persons)
General Classroom	5,965	25	239
Science Lab	7,368	50	147
Vocational Classroom	5,422	50	108
Technical/Computer Lab	5,852	50	117
Band/Chorus	3,434	7	491
Small Group Seminar	1,591	25	64
Art Room	2,418	50	48
Offices	3,355	100	34
Mech./Elect./Storage	2,929	300	10
Waiting Area	242	7	35
Press Box	1,111	5	222
Detention Center	1,099	25	44
		Total	**1,558**

- The science lab, technical education room, art room, and computer labs are all calculated using the same occupant load as vocational classrooms.
- The band and chorus spaces are calculated as assembly spaces with chairs only.

The occupant load for the first floor of the middle school was computed for the design occupant load factors for all of the rooms with the exception of the student cafeteria and faculty dining areas. These calculated figures are shown Table 32.

Table 32: Occupant Load for Middle School First Floor

Space Type	Total Net Area (sf)	Load Factor (sf per person)	Occupant Load (persons)
Classrooms	29,223	25	1,169
Science Labs	5,006	50	100
Locker Rooms	2,010	50	40
Offices	1,997	100	20
Small Group/Resource Room	5,142	25	206
Mech./Elec./Storage	1,811	300	6
Stage	1,600	15	107
Library Reading Area	3,847	20	192
Library Stack Area	4,197	50	84
Kitchen	1,371	200	7
Conference Room	358	15	24
Gymnasium	6,225	50	125
Courtyard	3,876	50	78
		Total	**2,157**

Along with the calculated occupant load based on the design occupant load factors, fixed seating plans in the student cafeteria and faculty dining room had to be added. The seating plan allowed for 640 seats in the student cafeteria and the faculty dining room had a seating plan with 48 seats. Therefore, the total occupant load for the first floor of the middle school portion of the building was computed as 2,845 persons.

The occupant load for the second floor of the middle school was computed in the same manner as the other spaces of the building. One important calculation to note is that the detention center was calculated using the occupant load prescribed by the *IBC* for classrooms. Even though the occupant load factor for classrooms was modified to be 25 square feet per person for this project, the reasoning for the decreased occupant load does not apply to the detention center, since no capacity is prescribed by the *MSBA* guidelines. The occupant loads calculated by the occupant load factor method are shown in Table 33.

Table 33: Occupant Load for Middle School Second Floor

Space Type	Total Net Area (sf)	Load Factor (sf per person)	Occupant Load (persons)
Classroom	17,673	25	707
Science Lab	12,465	50	249
Computer Lab	6,245	50	125
Vocational Classroom	6,195	50	124
Small Conference Room	3,980	25	159
Mech./Elect./Storage	835	300	3
Teacher's Lounge	880	100	9
Offices	1,889	100	19
Band/Chorus	1,779	10	178
Detention Classroom	996	20	50
		Total	**1,622**

Additionally, an occupant load of 48 persons was added for the administrative meeting room, which has a fixed seating plan with no additional standing space for occupants. Therefore, the total occupant load for the second floor of the middle school is 1,670 persons.

3.3.2.2 Egress Capacity Evaluation

Since no stairs are required to exit from the first floor, the number of required exits from the first floor was calculated using the 0.15 inches per person capacity factor. However, the second floor areas were primarily designed to exit the building using interior exit stairs. The capacity for these stairs were computed at 0.2 inches per person. The overall occupant load for each of the four areas previously discussed was used to specify the required number of exits from those areas, provided that they are arranged in a manner where all travel distance requirements are met. The width of doors and stairs determined for each area of the building, along with the calculated egress capacity are shown in Table 34.

Table 34: Egress Capacity for Different Areas

Space	Occupant Load	Total Width of Doors	Total Width of Stairs	Actual Egress Capacity
First Floor High School	3,059	504	N/A	3,360
Second Floor High School	1,558	72	240	1,680
First Floor Middle School	2,845	504	N/A	3,360
Second Floor Middle School	1,670	72	240	1,680

The process of arriving at suitable occupant loads involved adding double doors at all locations on the first floor and increasing the stair width from 3.5 feet to 5 feet. The doors accessing the exit stairs and discharging out of the exit stair enclosure also had to be increased to a size of 4.5 feet. Even though the stair width was increased in size, the second floor of both the high school and middle school required horizontal exits to comply with the required egress capacity. Since a two-hour fire barrier was already required to separate the areas, doors were added to allow access across the barrier as a temporary means of exiting an area where the fire incident occurs. The location of these horizontal exits are shown in Figure 27.

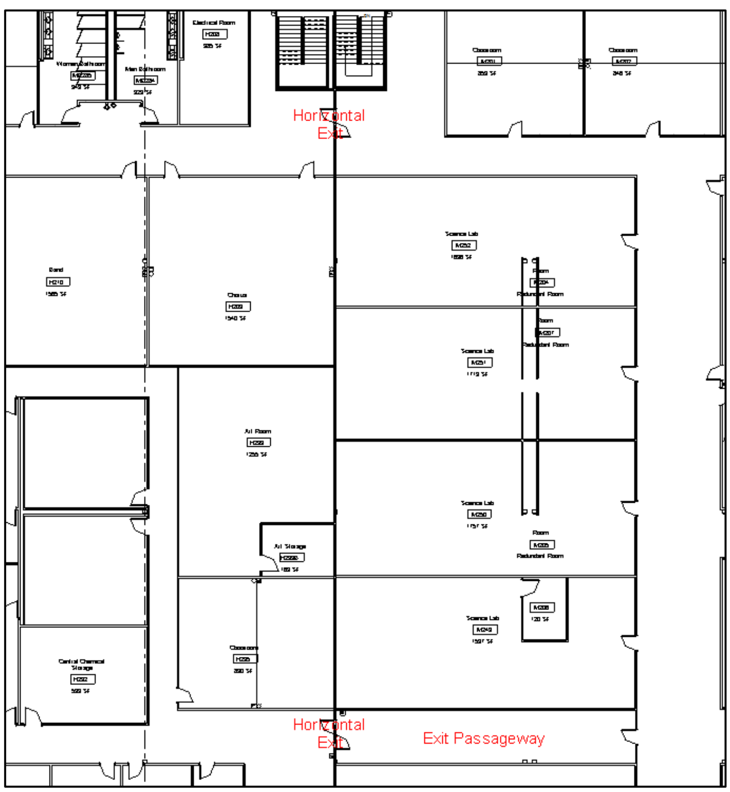

Figure 27: Horizontal Exits on Second Floor of Building

3.3.2.3 Travel Distance Evaluation

Initially, the spaces in all areas of the building appeared to have code compliant egress systems. However, a thorough evaluation of the travel distances showed that some areas could not meet either the common path, dead-end, or exit access travel distance requirements. The most common solution for these problems involved adding an exit passageway to create an extension to the exit that is separated from the rest of the building by fire-resistance rated construction. For example, the exit access travel distance from the interior courtyard of the high school first floor had an initial measurement of 267 feet as shown in Figure 28.

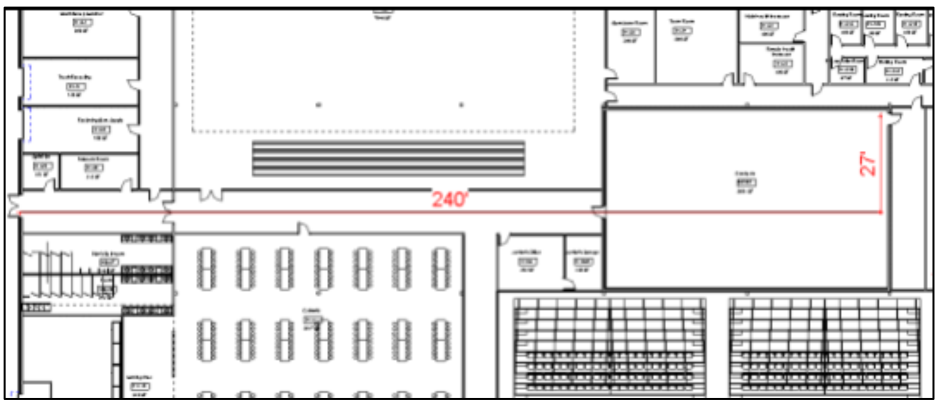

Figure 28: Initial Exit Access Travel Distance from Courtyard

As a vestibule was already planned here, the separation had to be provided with a one-hour fire resistance rated fire barrier that will be discussed the following sections. Additionally, 45-minute fire protection rated doors were required, and the openings had to be limited to those necessary for exit access from normally occupied areas. Since mechanical and electrical spaces that had doors opening onto the exit passageway were initially present, the space had to be reconfigured. The resulting layout and exit access travel distance from these corrections is shown in Figure 29.

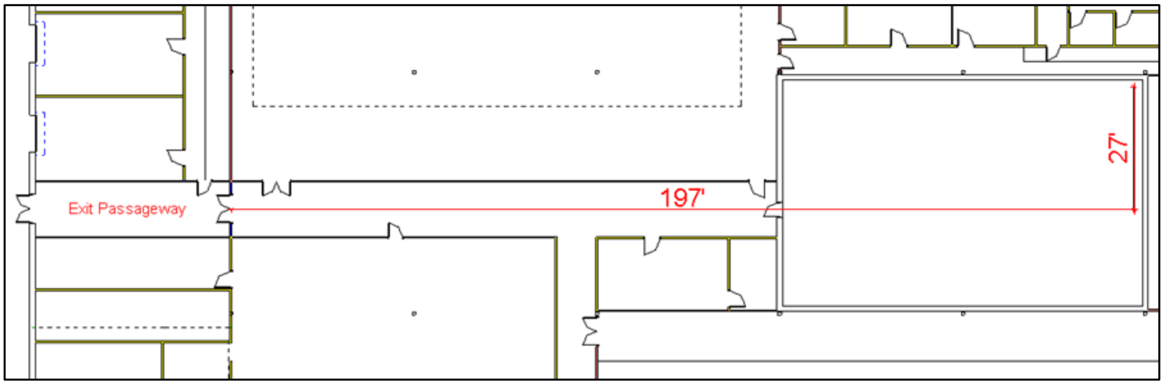

Figure 29: Revised Exit Access Travel Distance from Courtyard

Another prevalent problem became the dead-end distance of some corridors. The limitation of 50 feet was exceeded in several instances. One area in particular was the special needs wing on the first floor of the middle school. The initial layout had corridor lengths of 73 feet and 79 feet to provide exit access from classrooms. The initial layout is shown in Figure 30.

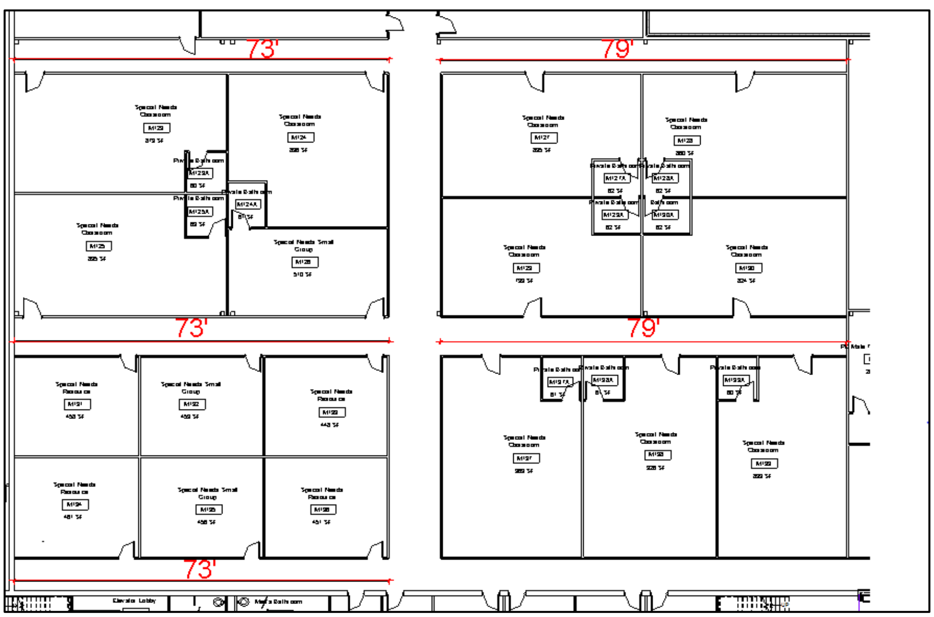

Figure 30: Initial Corridors of the Middle School Special Education Wing

These distances had to be reduced due to the possibility of an occupant traveling down the wrong end of the corridor for a long distance prior to realizing that he or she must change direction to access an exit. The solution for this was to extend the lengths of the room to use the spaces which were once part of the corridors. This caused come of the spaces to require egress though an intervening room, but it was not an issue since the rooms were accessory to one another. The resulting layout is shown in Figure 31.

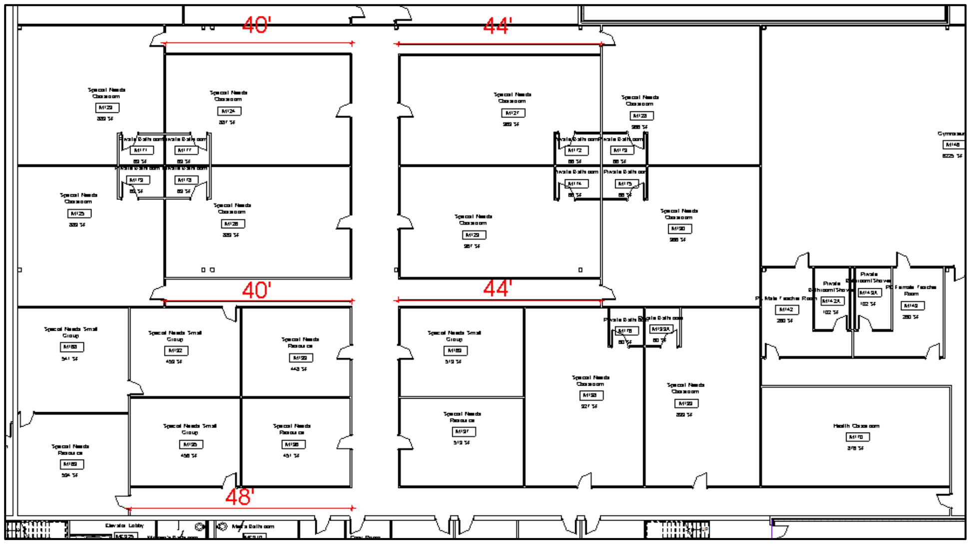

Figure 31: Revised Corridors of the Middle School Special Education Wing

The third type of travel distance that did not meet the requirements of the *IBC* was the common path of travel distance. This was evident in the means of egress from the guidance counselor waiting room on the second floor of the middle school. The path of travel from the most remote point in the room had an equivalent distance of 77 feet before access to multiple areas was provided. The initial layout of this area is shown in Figure 32.

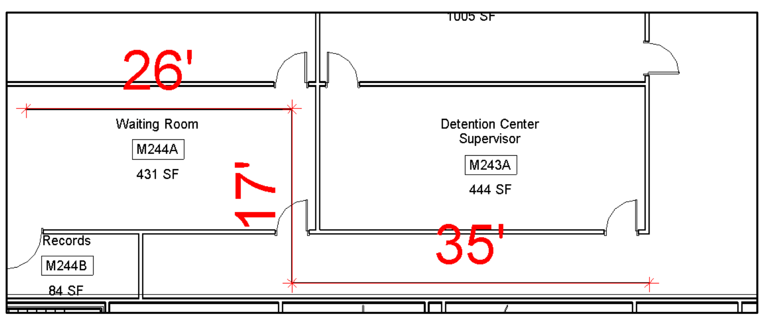

Figure 32: Initial Common Path of Travel from Middle School Guidance Counselor Waiting Room

Another significant deficiency concerning the common path of travel was discovered in the auditorium. Due to the fixed seating configuration, the occupant in the most remote seat has to travel a distance of 23 feet to reach the aisle, followed by a horizontal distance of 28 feet. The horizontal distance is converted into the actual distance traveled to equal 34 feet. Figure 33 shows the measured distance of this area.

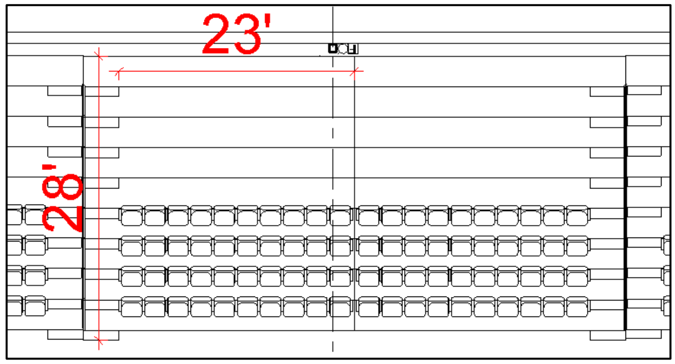

Figure 33: Common Path of Travel from High School Auditorium Seating

This results in a total travel distance of 57 feet before more than one exit access door may be accessed, which exceeds the maximum allowable distance for assembly areas by 27 feet. Unlike the solutions to the previously discussed travel distances, an engineering evaluation was provided to prove safe egress of all occupants from the auditorium under design fire conditions. This process is discussed in the next section.

Several other conflicts arose during the egress analysis that were related to the three travel distances discussed. A more extensive collection of figures displaying the layout before and after the solution was applied are shown in Appendix D.

3.3.2.4 Means of Egress Performance Based Analysis

The means of egress from the high school auditorium seating was completed under the use of Section 104.10 of 780 CMR, which states that modifications to the code acceptable to the building official may be granted if the intent and purpose of the code requirements are met in such a way that do not lessen the accessibility, fire and life-safety, or structural integrity of the building. Alternative compliance was proposed using the equations and methods from Chapter 12 of the 2008 Edition of the *SFPE Handbook* to prove that the available safe egress time (ASET) exceeds the required safe egress time (RSET) from the compartment. The concept of this model is shown graphically in Figure 34, which was obtained from the *SFPE Handbook*.

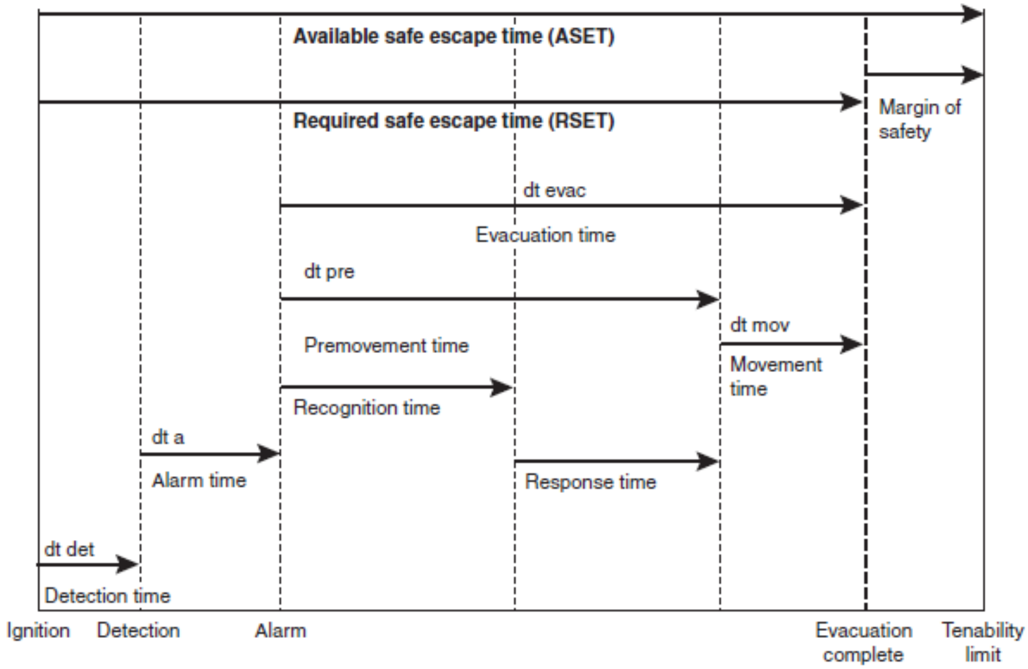

Figure 34: Egress Time Model (SFPE Handbook - Figure 3-12.1)

3.3.2.4.1 Pre-Evacuation Time

The RSET can be summarized as the sum of the time intervals between ignition, detection, notification, the beginning of evacuation, and the conclusion of evacuation as shown in Equation 9 (SFPE Handbook 3-13).

$$RSET = t_d + t_n + t_{p-e} + t_e$$

Equation 9: RSET Equation using Hydraulic Evacuation Model (SFPE Handbook, 2008)

The first variable is the time from ignition to detection, the detailed assessment of this is performed in Section 5.3.3.3 Roof Vent Activation. The time from ignition to the detection of the fire using the selected design fire scenario and sprinkler specifications was 225 seconds. The next variable is the time delay between detection of a fire scenario and the actuation of the fire alarm system. This requirement is enforced by NFPA 72. Section 23.8.1.1 of the code states that the actuation of alarm notification appliances and other fire alarm features shall occur within 10 seconds after the activation of an initiating device. However, actuation of an initiating device is considered the instant at which a complete digital signal is achieved. For instance, a time lag of 90 seconds is permitted between the time flow is detected in the sprinkler system waterflow alarm-initiating device and the actuation of the fire alarm. The pre-movement time is characterized by the delay of movement following the time that occupants are notified of an emergency. This delay can be caused by lack of awareness or familiarity with the building, as well as the probability that occupants engage in a variety of non-evacuation related actions.

Table 3-12.5 of the 2002 Edition of the SFPE Handbook, provides estimated occupant delay times based on the occupancy type, characteristics of the occupants, and notification strategy or system. Based on this table, offices, commercial and industrial buildings, and schools can be categorized together. This is due to the likelihood that occupants are awake and familiar with the building, alarm systems, and evacuation procedures. If speakers are placed in the auditorium to provide pre-recorded voice messages, a recognition time of three minutes is expected. Based on these methods, the total pre-evacuation time for the auditorium is summarized in Table 35.

Table 35: Summary of Pre-Evacuation Time for Auditorium RSET

Time Variable	Time (sec.)
Detection (t_d)	225
Notification (t_n)	100
Response/Recognition (t_{p-e})	180
Total	**505**

3.3.2.4.2 Evacuation Model

Occupant movement through rooms, corridors, doors, and stairs is dependent on crowd density, occupant abilities, and available clear width. Depending on these characteristics the movement time can either be calculated by the sum of the travel time for the first occupant to reach the door, stair, or similar feature and the occupant flow time, or the travel time for the last occupant to reach the exit. The configuration of the auditorium is shown in Figure 35. Since the model assumes that occupants travel on the closest exit route, the exit designated for each seating assembly and the stage is shown with a red arrow.

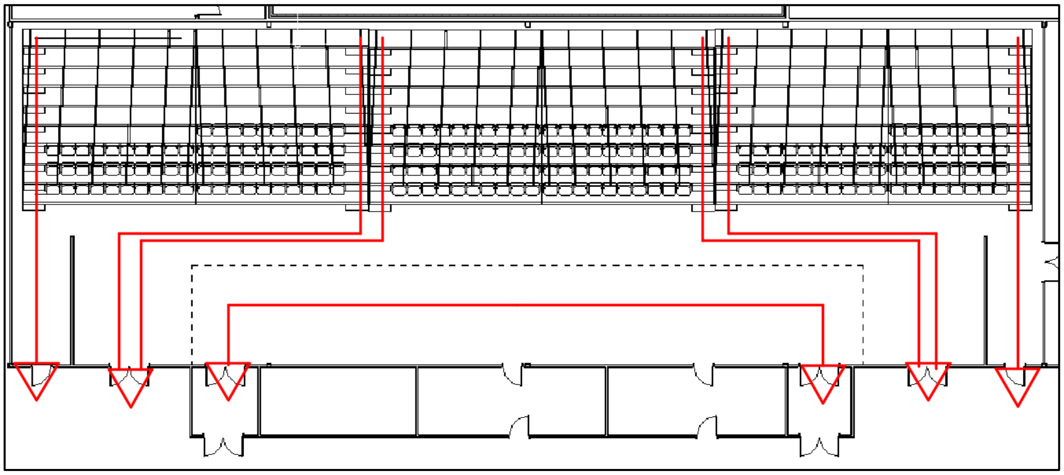

Figure 35: Exit Routes used in Egress Calculations from Auditorium

Another consideration for these calculations was the arrangement of the seating assemblies. There are six sets of seating structures that all share the same characteristics. Important dimensions and features of the structures are listed in Table 36.

Table 36: Features of the Fixed Seating Structures in the Auditorium

Feature	Dimension/Quantity
Aisle Length	22.5 ft.
Effective Aisle Width	1.5 ft.
Number of Aisles	10
Number of Seats per Aisle	10
Effective Stair Width	3.25 ft.
Stair Length (Horizontal)	30 ft.
Tread Depth	11 in.
Riser Height	7 in.
Total Occupied Area per Assembly	435 ft^2
Population Density	0.23 $persons/ft^2$

Due to the large population density on each set of auditorium seating, the flow discharging from the bleachers was calculated using Equation 10, which considers the exit route element and population density. The specific flow from each aisle of the seating assembly was computed using an aisle area of 33.75 square feet, an occupant load of 10 persons, and an evacuation speed constant of 275.

$$F_S = (1 - aD)kD$$

$$F_S = [1 - (2.86 \times 0.296)] \times 275 \times 0.296$$

$$F_S = \frac{12.42 \; \frac{persons}{ft}}{minute}$$

Equation 10: Specific Flow through Seating Aisles (SFPE Handbook, 2008)

Since a transition occurs at the stairs of the seating assembly involving the occupants from all ten rows merging, Equation 11 was used to calculate the specific flow down the stairs.

$$F_{S(Out)} = \frac{F_{S(in-1)}W_{e(in-1)} + F_{S(in-2)}W_{e(in-2)} + \cdots F_{S(in-n)}W_{e(in-n)}}{W_{e(Out)}}$$

$$F_{S(Out)} = \frac{10(12.42\times1.5)}{3.25}$$

$$F_{S(Out)} = \frac{57.3\ \frac{persons}{ft}}{minute}$$

Equation 11: Specific Flow Down Seating Stairs due to Merching Flows (SFPE Handbook, 2008)

However, this flow exceeded the maximum specific flow from Table 3-13.5 of the *SFPE Handbook*. The maximum specific flow of 18.5 persons/ft./minute was used due to the exit route consisting of stairs with 7-inch risers and 11-inch treads.

The change in specific flow at the transition points from the stairs of the seating assembly through the 9-foot wide aisle formed by the low-height partition, and then from the aisle through the exit access door were calculated using Equation 12.

$$F_{S(Out)} = \frac{F_{S(in)}W_{e(in)}}{W_{e(Out)}}$$

$$F_{S(Out-Aisle)} = \frac{18.5\ \times3.25}{7.67}$$

$$F_{S(Out-Aisle)} = 7.84$$

$$F_{S(Out-Door)} = \frac{7.84\times7.67}{2}$$

$$F_{S(Out-Door)} = 30.07$$

Equation 12: Specific Flow for Changed Terrain and Effective Width (SFPE Handbook, 2008)

The specific flow from the door exceeded the maximum value allowed, resulting in a specific flow of 24.0 persons/ft./minute through the door.

The time of discharge from the seating assembly was determined by the highest of these values. These time values were computed in Equation 13, which is based on the number of occupants using the route, and the specific flow and effective width of the route.

$$t_p = \frac{P}{F_S \times W_e}$$

Equation 13: Time of Passage Through Point in Exit Route (SFPE Handbook, 2008)

The controlling factor for the evacuation of the last occupant from the bleachers was the exit access door, which had a time of passage of 2.08 minutes for the occupant load of 100 persons. The time for passage computed for each exit route element is shown in Table 37.

Table 37: Egress Flow Model Summary for the Egress from One Seating Assembly in Auditorium

Exit Route Elements	Specific Flow (Persons/ft./min.)	Effective Width (ft.)	Occupant Load	Time for Passage (minutes)
Seating Aisle	12.42	1.50	10	0.54
Seating Stairs	18.50	3.25	100	1.66
Ground-Floor Aisle	7.84	7.67	100	1.66
Exit Access Door	28.00	2.00	100	2.08

In addition to the time required for the last occupant to move through this door, the travel time for the closest occupant to reach the exit access door was obtained and added to the evacuation time. This speed used for this time was computed using Equation 14, which factored the population density for the entire area traversed, which was 657 square feet.

$$S = k - akD$$

$$S = 275 - (2.86 \times 275 \times 0.15)$$

$$S = 155.3 \ \frac{ft}{minute}$$

Equation 14: Speed of Occupant Closest to the Exit Access Door (SFPE Handbook)

Since the distance from the closest seat to the exit access door was 29 feet, an additional 0.19 minutes was added to the previous time. This time prevailed as the longest evacuation, as the last occupants occupying the bleachers in the center of the room had evacuation times of 1.92 seconds, and the other bleacher located on the far side has identical dimensions, travel distances, and occupancy as the seating structure used in the calculations. This resulted in total evacuation of all occupants from the compartment in 136 seconds.

3.3.2.4.3 Tenability Criteria

The time values computed in Sections 3.3.2.4.1 Pre-Evacuation Time and 3.3.2.4.2 Evacuation Model resulted in a RSET of 641 seconds, or 10 minutes and 41 seconds. In order to provide a successful performance-based design, the ASET from this compartment, based on the tenability criteria, had to exceed 641 seconds. The tenability factors under consideration were those that posed significant risks to life such as reduced visibility, toxic gas exposure, heat exposure, and thermal radiation exposure (Klote, 2012). The tenability limits proposed for this performance-based design are listed in Table 38.

Table 38: Tenability Criteria for Performance-Based Design of Auditorium

Tenability Factor	Limit	Explanation and Reference
Visibility (Optical Density)	0.8 OD/m	Suggested tenability limit for large enclosures provide visibility range of 10 m or 32.8 ft. (SFPE Handbook Table 2-6.11)
Toxic Gas (CO)	3000 ppm	Loss of consciousness occurs after approximately 10 minutes of exposure to this concentration (SFPE Handbook Figure 2-6.6)
Convection	100 °C	Limiting Condition for 12 minute tolerance time (SFPE Handbook Table 2-6.20)
Radiation	1.7 kW/m^2	Critical Radiant Flux for initiation of pain is between 1.4 and 1.7 kW/m^2 (SFPE Handbook 3-314)

Along with these criteria limits, the smoke layer interface is also required to maintain a height of not less than six feet above occupants. The highest occupiable space in the auditorium is 12 feet from the ground level. Therefore, the design was required to keep the smoke layer 18 feet above the ground level for 641 seconds after fire ignition.

3.3.3 Disadvantages of Ground-Up Construction

3.3.3.1 Office Area

Since the office area was not modified in the renovation of the existing building, no costs had to be considered for those building elements. However, in the planning of the new building, the materials and assemblies that went into the design of this area must be accounted for in the cost. The major equipment and materials assessed included the interior walls, doors, stairways, plumbing fixtures, elevators, and rooftop HVAC units. Some assumptions that were made in the cost estimate are listed below:

- Typical interior partitions used ½ inch gypsum wallboard framed on 22 gauge 2.5 inch steel studs spaced 24 inches OC.
- The stairways were made of precast concrete
- The plumbing fixtures used plastic drain, waste, and vent piping, and copper water supply piping.
- The air handling units were single zone 12.5 ton cooling, 230 MBH heating units.

The quantity and cost of each of these items needed for new construction are displayed in Table 39. Following the table are supplementary notes concerning the process for determining some of the unit costs.

Table 39: Cost Estimates for New Construction of Office Wing

Item	Quantity (Units)	Unit Cost	Total Cost
Interior wall framing	22,946 SF	$0.84/SF	$19,274.64
1/2” Gypsum wallboard	45,892 SF	$0.86/SF	$39,467.12
Interior doors	46	$171.00 EA	$7,866.00
Exterior doors	4	$569.80 EA	$2,279.20
Stairways	48	$53.20/Step	$2,553.60
Elevator	1	$64,500 EA	$64,500.00
Water closets	8	$658.50 EA	$5,268.00
Urinals	4	$666.70 EA	$2,666.80
Lavatories	6	$861.20 EA	$5,167.20
Roof top units	2	$18,800 EA	$37,600.00

- The area quantities for the gypsum wallboard and the cementitious backer units were doubled to account for the materials being assembled on both sides of the frame assembly.
- The unit cost for the plumbing fixtures include a cost for the rough-ins of the pipes and fittings as well the final connection assembly.

3.3.3.2 Exterior Walls

The exterior walls of the existing building were left in place for the renovation design. The new design had to account for the construction of the exterior walls when estimating the cost of the building. According to the quantity takeoff from the *Revit* model, about 57,000 ft^2 of the exterior wall had to be accounted for in the ground-up construction. The exterior wall system used 8-inch thick concrete masonry unit construction for one-half the vertical height of the entire building, while the top half of the building comprised of a zee girt wall system. The typical cost for an 8-inch thick concrete block wall assembly is estimated as $8.89 per square foot (Pray, 2015).

The metal wall panel system used for the new construction was 8-inch wide beveled steel siding with vinyl coating. The unit cost for this assembly was obtained as $3.41 per square foot (RS Means, 2013). The estimated cost for this assembly was $350,550.

3.4 Architecture and Planning Results

The difference in the basic architectural layout and features of the building were a result in the method of achieving code compliance between the existing building and the new building. The design of the existing building was performed using the performance compliance method from the *IEBC*. This option allowed flexibility in specifying which fire-safety and means of egress measures would be incorporated into the design of the building, whereas the design of the new building essentially followed the prescriptive requirements of the *IBC* and 780 CMR unless a detailed performance-based design was provided. The most significant changes became evident in the means of egress. Since the active fire protection systems, most notably the fire detection and alarm system, were enhanced, the means of egress had less of an effect on the layout of the school building.

Another difference between the designs of the building was the cost estimate of the design. The design of the renovated existing building was capable of using some of the building materials and systems that were already present. However, necessary demolition increased the cost in some areas that were not necessary in ground-up construction. A summary of the construction costs taken into account for the buildings is provided in Table 40. The formation of this table considered basic architectural features and building systems that were not analyzed in detail. Further analysis was performed on the passive fire protection elements, active fire protection systems, and structural elements.

Table 40: Architectural Features and Building Systems Cost Comparison

	Renovated Building	New Building
Interior Wall Demolition	$70,044	-
New Interior Walls	$3,329,551	$3,388,293
Interior Door Demolition	$1,193	-
Overhead Door Demolition	$8,672	-
Exterior Wall Cut-Outs	$21,367	-
New Exterior Wall Assembly	-	$350,550
Plumbing Fixture Demolition	$1,472	-
New Elevators	$129,000	$193,500
Total	**$3,561,299**	**$3,932,343**

The results from Table 40 show that there is a close balance between the cost of constructing a building from the ground-up and the cost of selectively demolishing some building elements while preserving others. The complete architectural floor plans showing walls, doors, stairs, and select equipment and furniture are provided for the renovated design and the ground-up design in Appendix K.

Chapter 4: Passive Fire Protection

Even when an automatic sprinkler system is provided throughout the building, there are still requirements for passive fire protection that must be met including both structural elements and non-load bearing elements. Wherever possible, these requirements were met using calculations from ASCE 29-99 *Standard Calculation Methods for Structural Design for Fire Conditions* or Section 721 of the *IBC*.

4.1 Existing Passive Fire Protection

Due to the limitations in determining aspects of passive fire protection in the existing warehouse from the structural drawings, the building was assumed to comply with the 6th Edition of the *MBC*. This document adopted the 1993 Edition of the Building Officials and Code Administrators International, Inc. (BOCA) *National Building Code* (*NBC*). An existing conditions analysis was completed to determine the expected protection of the structural frame, fire barriers, and exterior walls.

The structural drawings do not provide any details with evidence of fire-resistance ratings for structural members. The code requirements at the time of the buildings construction were investigated and confirmed that passive fire protection was not required. There is a provision that permits an unlimited area of Group F-1 and Group B occupancies of Type 2C construction, if the building does not exceed one-story and an automatic sprinkler system is provided throughout the building. This is applicable in the Group F-1 occupancy, which is one-story. There is a floor area restriction for the Group B occupancy because it is a two-story assembly.

The most appropriate design strategy would have been to separate the Group B area from the Group F-1 area, in which both areas would have to meet the area requirements based on the sum of the ratios of actual area to allowable area not exceeding 1.00. According to Table 313.1.2 of the NBC, this fire barrier would have a fire resistance rating of 3-hours.

Although a fire-resistance rating is not required for load bearing exterior walls in Type 2C construction, a fire-resistance rating may be provided inherently in the walls' construction. Since details for the existing exterior walls were provided, calculations were utilized to determine a fire resistance rating for the load bearing elements. The only portion of the exterior wall system that supports other structural elements is the partial height concrete masonry unit (CMU) wall. Acceptable calculations for the fire resistance ratings of masonry assemblies are found in Chapter 4 of ASCE – SFPE 29.

The fire resistance rating of CMU walls is based on the equivalent thickness of the units, as well as the type of aggregate used in the assembly. Since the CMU uses solid grouted construction, as noted in the General Notes section of the plan, the equivalent thickness was taken as the actual thickness of the unit. In each case that the walls are load bearing, the thickness is 8 inches. Even though the aggregate type is not explicitly specified in the existing condition drawings, the thickness of the CMU blocks provides the assembly with a calculated fire resistance rating no less than four hours.

4.2 Proposed Renovation

The proposed renovation must meet the passive fire protection demands for the alterations taking place, as well as the change of occupancy classification. Since the performance compliance method was completed using Type IIB construction, fireproofing upgrades were not required for the primary structural frame. However, fire barriers were required in the renovation design. A fire barrier, as defined by Section 701 of the *IBC*, is "A fire-resistance rated wall assembly of materials designed to restrict the spread of fire in which continuity is maintained." The continuity that is referenced implies that the assembly is required to extend from the top of the floor assembly to the underside of the floor or roof sheathing, slab, or deck above. This includes continuity through concealed spaces formed above suspended ceilings. Along with providing the required fire-resistance rating and proper continuity, other construction requirements for fire barriers are shown in Table 41

Table 41: Summary of Code Provisions for Fire Barriers

IBC Section	Requirement	Description
707.5.1	Supporting Construction	Supporting construction of the fire barrier must be protected with the same fire-resistance rating
707.5.1	Fire Blocking	Vertical hollow spaces are fire blocked at every floor level
707.6	Openings	Openings cannot exceed an aggregate width of 25% of fire barrier length
Table 715.4	Openings	Fire door and shutter assembly fire protection rating of 1.5 hours
714.1	Joints	Joint system in between fire-resistance rated assemblies must have approved joint system
716	Ducts and Air Transfer Openings	A fire damper provided in a fire barrier must have a minimum damper rating of 1.5 hours for a 3-hour or less rated assembly and 3 hours for assemblies with a fire-resistance rating greater than 3 hours.

4.2.1 Area Separation Fire Barriers

The fire barriers separating the building into smaller areas are substitutions for fire walls, which were used to increase the area value in the performance compliance method. Table 706.4 of the *IBC* requires a two-hour fire resistance rating for this assembly. The fire resistance rating of these barriers also permits the use of horizontal exits in accordance with Section 1025.

Since the initial design of all interior partitions specifies the use of steel studs, and gypsum wallboard, a similar design for the fire barrier would be beneficial for constructability and material procurement practices. UL Design U404 was specified for the assembly, which is shown in Figure 36.

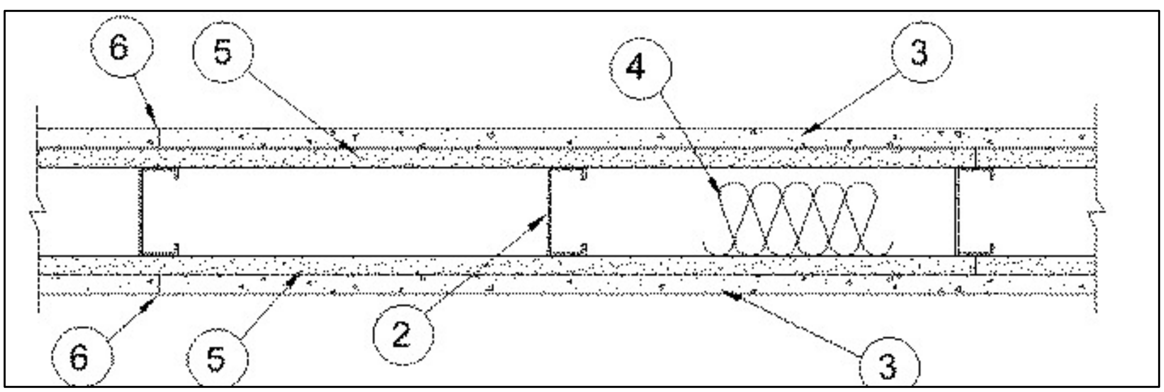

Figure 36: Two-Hour Fire Resistance Nonbearing Wall to Separate Schools (BXUV.U404)

The assembly is UL listed with the UL assembly code BXUV.U404 and requires steel studs with a width of at least 3-1/2 inches spaced a maximum of 16 inches O.C. The wall is attached to the floor and ceiling assemblies by steel, channel-shaped runners with steel fasteners spaced 24 inches O.C. The assembly uses gypsum board as the base layer on both sides with cementitious backer units applied as the finish on both sides as well. This design is simple, uses similar materials to other partitions in the building, and is symmetrical throughout.

Since the two-hour fire resistance rated fire barriers are such a significant construction feature of the building, the cost was estimated for this assembly. The estimate figures for the material and labor of framing 5/8-inch fire rated drywall was provided as $1.08 per ft^2 of wall area. Since the assembly also contains cementitious backer units, the unit cost was provided as $4.23 per square foot of ½-inch backboard installed. Since this figure only applied to the installation of the unit on one side of the wall, the area of the wall must be accounted for on both sides. The total cost of the entire assembly was computed and is displayed in Table 42.

Table 42: Cost Estimate for 2-Hour Fire Resistance Rated Fire Barrier Between Schools

Item	Area	Unit Cost	Total Cost
Interior Metal Stud Framing	23,045 ft^2	$0.84/ft^2	$19,357
5/8 inch Fire Rated Gypsum Board	46,090 ft^2	$1.08/ft^2	$49,778
1/2 inch cementitious backerboards	46,090 ft^2	$4.23/ft^2	$194,965
		Total Cost	**$264,101**

4.2.2 Vertical Opening Enclosures

Fire barriers with a two-hour fire resistance rating are required for the enclosures of all vertical openings in this building as stated in the design criteria of the performance compliance method. The USG Shaft Wall Systems Catalog was consulted for the design of these enclosures. These systems provide guidelines for selecting a non-load-bearing gypsum wall partition assembly to construct outside of the shaft at each floor. The assemblies that are provided consist of gypsum liner panels friction-fitted into C-H studs with gypsum panels or cement board applied to the face. The systems are effective since they are installed from one side early in construction to leave the shaft free of scaffolding.

A two-hour fire resistance rating that is listed in the catalog is UL Design U415 was selected. The design employ one layer of 1-inch gypsum liner panels with two layers of 5/8-inch gypsum panels attached to 2 ½-inch C-H shaped studs. The assembly detail is shown in Figure 37.

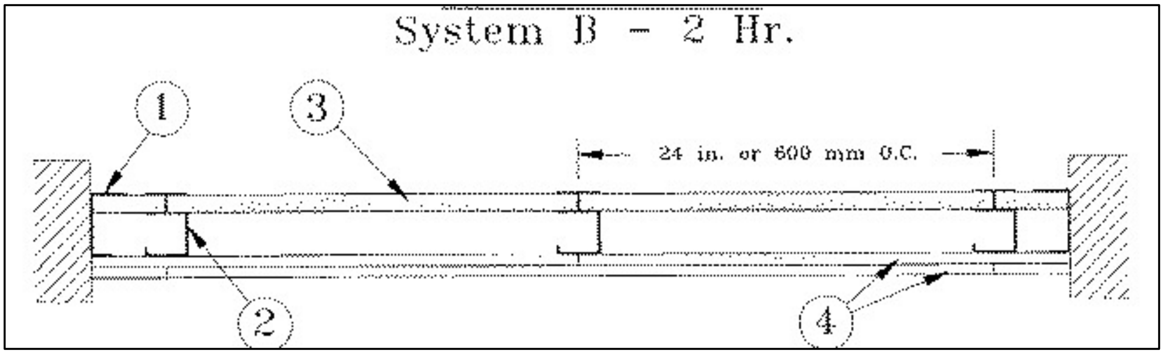

Figure 37: Two-Hour Fire Resistance Rated Assembly for Elevator Shaft Walls (BXUV.U415)

A cost estimate for a similar wall-assembly was provided in the 2015 Construction Estimator. The itemized costs for each component of the shaft wall are displayed in Table 43, which include costs for labor and material (Pray, 2015).

Table 43: Itemized Cost for Two-Hour Fire Resistance Rated Shaft Wall Assembly (Pray, 2015)

Item	Unit Cost ($ per SF)
2-1/2” C-Studs (24” O.C.)	2.00
1” Type X gypsum shaftboard	2.40
2 Layers 5/8” Type X gypsum wallboard	2.33
Fiberglass insulation	0.90
Total	**7.63**

The *Revit* quantity takeoff provided a total assembly area of 10,970 ft^2. This resulted in a total cost of $83,700 for the shaft wall assemblies.

4.2.3 Openings in Fire-Rated Construction

The doors in fire resistance rated assemblies must meet the requirements of Section 715 of the *IBC*. The fire door and fire shutter assembly must have a fire protection rating of 1-1/2 hours according to Table 715.4 of the code. Additionally, these elements must comply with the provisions of NFPA 80, *Standard for Fire Doors and Other Opening Protectives*. These doors would be self-closing with panic hardware in all instances. The specific fire door assembly selected for this design was the 90-minute Fib-R-Dor fire door assembly, which is manufactured by Chase Doors. The assembly is listed in accordance with UL 10B and UL 10C for positive and neutral pressure tests. A detail of the assembly is shown in Figure 38.

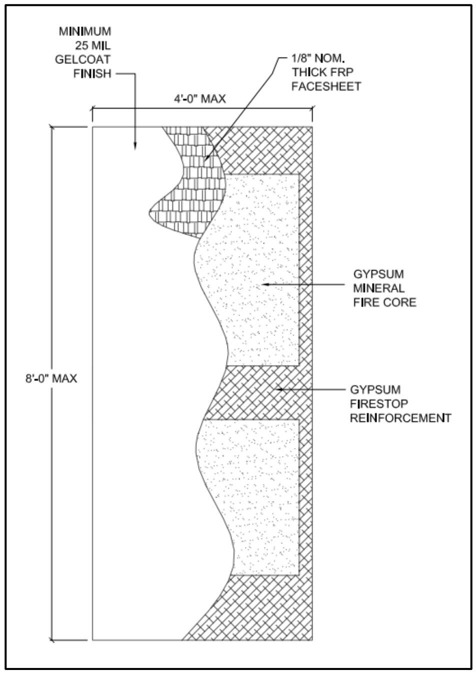

Figure 38: 90-Minute Fire Protection Rated Fib-R-Dor Fire Door Assembly (Chase Doors Product Catalog)

The cost estimate for the fire doors was computed using the itemized costs from the 2015 National Construction Estimator as shown in Table 44, which includes the costs for material, labor, and the additional fire protection rating.

Table 44: Itemized Costs for 90-Minute Fire Doors (Pray, 2015)

Item	Unit Cost ($ per door)
- 3'6" Wide, 7' High Hollow Metal Door Frame	171.00
+ 4' Wide, 7' High Hollow Metal Door Frame	195.00
90-Minute UL Frame	35.30
Prehung Steel door	556.80
90-Minute UL Door	26.10

The typical orientation of the fire doors in the area separation fire barrier is shown in Figure 39. This required one door frame 6 feet in width, along with two pre-hung steel doors. This typical orientation occurred eight times in the design.

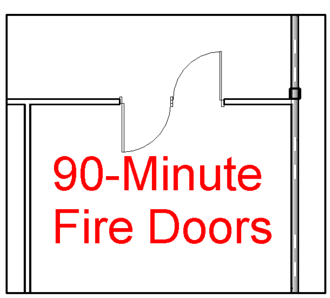

Figure 39: Typical Orientation of Fire Doors in Fire Barrier

Additionally, sixteen door frames less than 3' 6" wide were present in the interior exit stairs. The specification of all the 90-minute fire rated doors in the renovation design resulted in a cost of $16,918.

4.3 Ground-Up Construction

Similar to the discussion on other basic architectural features, some of the design decisions changed for the passive fire protection of a new building compared to the renovated design. The most significant requirement dictating these decisions was the use of Type IIA construction in the new building to meet the height and area requirements. Table 601 of the *IBC* requires all primary and secondary members of the structural frame, and load bearing walls to have fire-resistance ratings of no less than one hour. Additionally, the design of a fire wall required a design procedure unlike the design of a fire barrier.

Since the prescriptive methods are typically conservative, the cost for an assembly may be greater than needed to provide the necessary protection. Rather than use the assemblies discussed in Section 720 of the *IBC* for prescriptive fire resistance, the provisions of Section 721 of the code were used for calculated fire resistance. Additionally, ASCE 29-99 *Standard Calculation Methods for Structural Design for Fire Conditions* was used when certain information was not provided in the *IBC*.

4.3.1 Fire Wall

The design for the warehouse renovation used an exception to meet the allowable area requirements under the provisions of the *IEBC*. Typically, portions of connected buildings may be considered separate buildings for the purpose of applying the requirements of the *IBC*, where a firewall is provided between the portions of the building. Since the building existed for the renovation, a fire barrier with the same fire resistance rating as the normally required firewall was permitted. However, designing a new building with a firewall is a much greater challenge. The firewall must be constructed with the structural stability to allow the collapse of the structure on either side without the collapse of the wall for the indicated fire-resistance duration.

4.3.1.1 Fire Wall Types

The three types of firewall designs that are utilized to accomplish the goals mentioned in the previous section, are cantilever firewalls, double firewalls, and tied firewalls (Destefano 22-23). A firewall design was selected after a thorough analysis for each type based on architectural and structural layouts,

A cantilever firewall is entirely self-supporting with the absence of any ties to the adjacent structures on either side. It is cantilevered vertically from the foundation where there is a complete break in structural framing. A typical detail for this type of firewall is shown in Figure 40.

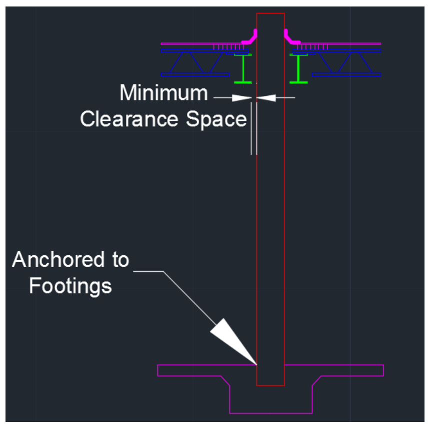

Figure 40: Cantilever Fire Wall Detail

A double firewall is designed by positioning two one-way walls back to back. This type of firewall provides the required stability by attaching each wall to a separate structural system. This allows a fire on one side of the double wall to cause the collapse of one of the structural systems, while only bringing down the part of the firewall attached to that system. The system attached to the other one-way wall would remain standing and should resist the fire for the specified time it is rated for. A schematic detail for a double firewall is shown in Figure 41.

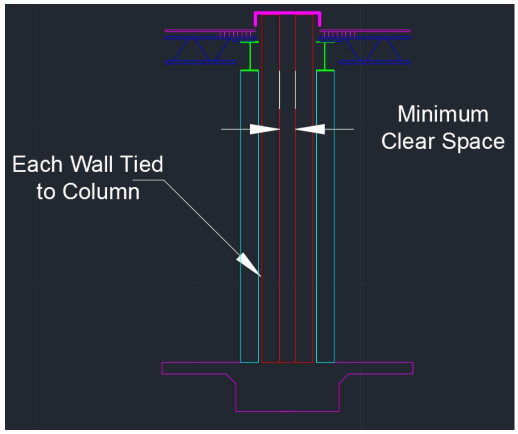

Figure 41: Double Fire Wall Detail

Double firewalls are typically considered where an addition is added to an existing building and a firewall is required between the two areas to meet the construction type requirements.

Tied fire walls are laterally supported by the steel structure on both sides of the wall. Section 6.4.1 of NFPA 221 requires that these walls be centered on a single column line or constructed between double column lines. The required stability is provided by the strength of the structural frame, which must be designed to resist the maximum lateral pull from a fire on either side of the assembly. Since the fire may occur on either side of the wall, the fire should be located at the center of strength of the building frame (Stuart). A typical detail of a column encased by a tied firewall is shown in Figure 42.

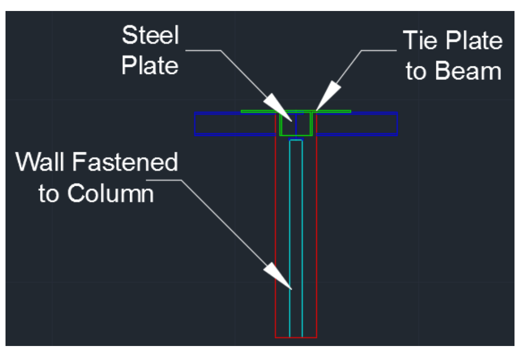

Figure 42: Tied Fire Wall Detail

4.3.1.2 Fire Wall Selection

Since the building requires an expansion joint, the wall types that fit this requirement best are the cantilever firewall or the double firewall. In each case, the wall is positioned so it is centered between the double columns. However, the location of the expansion joint in the renovated building is not centered to provide equal areas for the high school and middle school. The expansion joint is recommended for buildings of a certain length, and therefore, moving the expansion joint to the midpoint along the length of the building will decrease the building length on one side of the expansion joint and would not pose any problems to the structural design.

Another consideration that was addressed was the effect either type of firewall has on the openings in the wall. This was important since the renovated design has several instances where openings allow a horizontal exit to either side of the building. The use of openings in double firewalls is inconvenient since each door is required to have a fire protective rating and the space between the separate walls must also be enclosed by 2-hour fire resistance rated construction. Therefore, the most feasible firewall type to use was the freestanding cantilever firewall.

4.3.1.3 Fire Wall Design

Although Section 706.2 of the *IBC* requires firewalls to have the structural stability to allow the collapse of construction on one side of the assembly without the collapse of the wall or the structural frame on the other side of the wall, no design standards are referenced to provide necessary safety factors or design loads. However, the commentary "Footnote p" of Table 720.1 of the *IBC* permits the use of NCMA TEK 5-8A for the design of fire walls. This document states to cantilever the wall from the foundation by grouting and reinforcing or by pre-stressing (NCMA TEK 5-8B).

In order to anchor this building to the foundation, CMU, brick masonry, or reinforced concrete walls are typically utilized. The wall must be designed to remain stable against horizontal forces during fires, which may be induced by the pull of flashing or due to the collapse of a portion of the building on one side of the wall. This lateral strength may be provided with the use of vertical reinforcement members in the wall or reinforced pilasters. Failures of the fire wall may arise due to unreinforced pilasters or reinforced pilasters on only one side of the wall (Stuart).

The use of CMU construction required consultation with Chapter 4 of *ASCE 29-99* as well as references to Factory Mutual Loss Prevention Data Sheet 1-22 (FM 1-22). Table 1 of FM 1-22 provides a minimum clearance that must be obtained between a cantilever firewall and the steel frame based on the length of the structural bays, which is shown in Table 45.

Table 45: Minimum Clearance Between Structural Steel and Firewall (FM Data Sheet 1-22: Table 1)

Length of Bay Perpendicular to the Fire Wall		Minimum Clearance Between Wall and Steel	
ft	m	in.	mm
20	6.1	2½	64
25	7.6	3¼	83
30	9.1	3¾	95
35	10.7	4½	114
40	12.2	5	127
45	13.7	5¾	146
50	15.2	6¼	159
55	16.8	7	178
60 or longer	18.3	7½	191

According to this table a clearance of 5 inches is recommended between the wall and the steel structure to obtain a suitable cantilever firewall. The double column configuration from the existing building use W10 x 49 columns that are spaced two feet on center. This allows room for a four-inch thick firewall while maintaining the clearance recommendation. A detail showing the configuration of the firewall is shown in Figure 43.

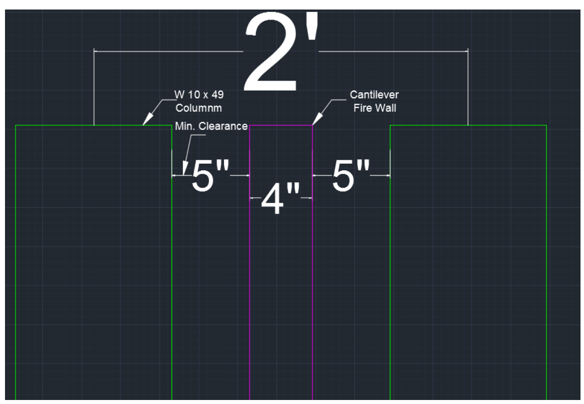

Figure 43: Proposed Firewall Allowable Thickness and Clearance

Since it is desirable to allow a finish on both sides of the wall for aesthetic purposes, the thickness of the finish must also be taken into consideration. According to Table 4.3 of *ASCE 29-99*, the use of 5/8 inch Type X gypsum wallboard will provide an additional 0.67 hours of fire-resistance when attached to both sides of the firewall, resulting in a fire resistance rating of 1.34 hours. However, this would result in a concrete masonry block size that is less than four inches, which is typically the minimum available block size. Therefore, a 100% solid unit using a limestone aggregate would be used and a thin application of Portland cement-sand plaster could be applied directly to the masonry to achieve the desired finish appearance.

The cost of the fire wall was estimated using unit costs for typical concrete masonry block assemblies of the thickness used. The typical cost for standard gray medium weight masonry block walls, including mortar and typical reinforcement for a four-inch thick wall, was provided as $6.46 per square foot of the wall face including labor (Pray, 2015). Additionally, the cost of the plaster finish that was prescribed for the wall was estimated using a two coat application of Keene's cement plaster to both sides of the wall. The cost for this, including labor, was listed as $34.10 per square yard. The Total cost for the masonry unit wall is shown in Table 46.

Table 46: Cost Estimate for Cantilever Fire Wall in New Building

Item	Area	Unit Cost	Total Cost
Concrete Block Wall	9496 ft^2	$6.46/$ft^2$	$101,396
Cement Plaster	2110 yd^2	$34.10/$yd^2$	$118,941
		Total Cost	**$220,337**

4.3.2 Structural Frame

The primary structural frame, when referenced by the *IBC*, includes the columns, structural members with direct connections to the columns, members of floor and roof construction with direct connections to the columns, and bracing members that are essential to the vertical stability of the primary structural frame. All of these building elements carry the gravity loads of the building, and therefore it is essential that the materials are effectively protected using the methods presented in the *IBC*.

The four basic types of fireproofing of steel framed structures are concrete encasement, gypsum wallboard protection, spray-applied fireproofing, and intumescent coatings. Another method that may be used, even though it is not recognized by the *IBC*, is concrete filled hollow steel columns. Each of these methods was considered in terms of characteristics such as installation difficulty, material cost, and constructability. The advantages and disadvantages are listed in Table 47 (Rakik, 2007).

Table 47: Advantages and Disadvantages of Fireproofing Methods

Method	Advantages	Disadvantages
Concrete Encasement	• Durable and robust • May be designed as composite members to enhance load resistance	• Significant increase in building weight • High costs for installation when applied to existing facilities • Decreases usable space of building
Gypsum Board	• Easy to install around columns • Does not require specialist contractors • Columns can be incorporated into walls • Beams can be incorporated into soffits	• May be difficult to fit around complex details • Susceptible to vandalism or natural cracking and spalling
SFRM	• Relatively low cost to apply • Easy to apply onto complicated detailing and connections • Low density resulting in low weight increase of structural members	• Thorough investigation of existing members to ensure proper surface treatment • Typically not considered aesthetically pleasing • Wet trade that requires surrounding areas to be sealed off • Requires specialist contractors
Intumescent Coatings	• Low Thickness • Aesthetically pleasing	• Steel must be prepared prior to application

4.3.2.1 Columns

Columns, unlike other members of the structural frame, are required to have a fire-resistant protection in which the entire member is encased on all four sides for the full column length. The connections with other structural members must also be encased with a method of the same fire-resistance rating. The column must also maintain its encasement through the concealed space above a ceiling, regardless of the fire-resistance rating the assembly may have.

These calculation methods are dependent on the heated perimeter of the column, which is calculated differently for hollow square section (HSS) columns and wide-flanged columns. The configuration of the encasement types and the corresponding calculations for the heated perimeters are shown in Figure 44.

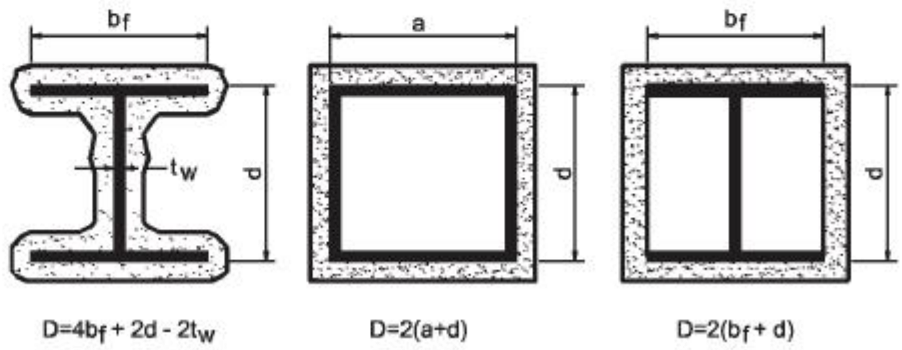

Figure 44: Heated Perimeters of Steel Columns

4.3.2.1.1 Gypsum Board

Per Section 721.5.1.2 of *IBC*, the fire resistance of structural steel columns with weight-to-heated perimeter ratios less than or equal to 3.65 and which are protected with Type X gypsum wallboard can be calculated by Equation 15.

$$R = 130\left[\frac{h\left(\frac{W'}{D}\right)}{2}\right]^{0.75}$$

Equation 15: Fire Endurance of Gypsum Covered Steel Column

Since Type IIA construction requires 1 hour fire-resistance ratings for the primary structural frame members, this equation was solved for h using R = 60. Table 48 shows the minimum nominal thicknesses of gypsum board for each column size requiring fire-resistance rated protection.

Table 48: Thickness Required for Gypsum Board Covered Steel Columns

Column	Nominal Thickness (Inches)	Calculated Endurance (Minutes)
HSS9x9x3/8	5/8	70
W10x49	5/8	72
W12x53	5/8	71
W12x65	1/2	63

The estimated cost for the labor of attaching one layer of gypsum wallboard of any size to columns is \$0.89 per square foot (Pray 427). However, the material cost for 5/8-inch thick Type X gypsum board is \$0.36 per square foot, whereas ½-inch Type X gypsum board has a material cost of $0.26 per square foot. For constructability and procurement purposes, it may be advantageous to encase all columns with the same size gypsum wallboard. The increase in material cost for the 1,250 square feet of gypsum needed for the W12 x 65 columns only resulted in $87.50 when 5/8-inch gypsum board was selected over ½-inch gypsum board. The estimated overall cost of encasing all of the columns in gypsum wallboard is shown in Table 49.

Table 49: Cost for Gypsum Wallboard Column Encasement

Column Size	Height (ft.)	Area of Gypsum per Column (sf)	Quantity	Total Area of Gypsum (sf)	Cost
HSS9x9x3/8	30	96.25	80	7,700	$9,625.00
HSS9x9x3/8	16	51.3	4	205.3	$256.67
W 10 x 49	14	49.6	1	49.6	$62.00
W 10 x 49	30	106.29	50	5,314.3	$6,642.86
W 12 x 53	30	116.25	16	1,860.0	$2,325.00
W 12 x 65	30	125	10	1,250.0	$1,562.50
				Total:	**$20,474.00**

4.3.2.1.2 Concrete Encasement

Concrete encasement is the most traditional method of fireproofing steel structures, but it can have its drawbacks and limitations as listed in Table 47 Per Section 721.5.1.4 of the *IBC*, the fire resistance of structural steel columns protected with concrete can be determined from Equation 16.

$$R = R_0(1 + 0.3_m)$$

Equation 16: Fire Endurance for Concrete Encased Steel Column

The fire endurance at zero moisture content can be calculated from Equation 17.

$$R_0=10\left(\frac{W}{D}\right)^{0.7}+17\left(\frac{h^{1.6}}{k_c^{0.2}}\right)\times\left[1+26\left\{\frac{H}{p_c c_c(L+h)}\right\}^{0.8}\right]$$

Equation 17: Fire Endurance for Concrete Encased Steel Column at Zero Moisture Content

The columns can be encased in either lightweight concrete or normal weight concrete, which have different densities, thermal conductivities, and moisture contents. Normal weight concrete has carbonate or siliceous aggregate, whereas lightweight concrete is made with aggregates of expanded clay, shale, slag, or slate (ASCE 29-99). The differences in typical properties are shown in Table 50.

Table 50: Lightweight vs. Normal Weight Concrete Properties

Property	Lightweight Concrete	Normal Weight Concrete
Density (pcf)	110	145
Thermal Conductivity (BTU/lb F)	0.35	0.95
Moisture Content (Percent)	5	4

The minimum required thickness of concrete, when measured from the edge of the column face in the HSS column and the flange in the W-shaped columns, is shown in Table 51, with detailed calculations shown in Appendix E

Table 51: Thickness Required for Concrete Encased Steel Columns

	Normal Weight		Lightweight	
Column	Thickness (in.)	Endurance (min.)	Thickness (in.)	Endurance (min.)
HSS9x9x3/8	1-1/2	64	1-1/4	66
W10x49	1-1/4	64	1	64
W12x53	1-1/4	60	1	64
W12x65	1-1/4	63	7/8	60

The estimated costs for cast-in place fireproofing takes into consideration a cubic yard unit cost, which includes the concrete, reinforcing bars, embedded steel, and concrete cylinder tests. The total unit cost for the material, labor, and equipment of this item is $331.41 per cubic yard of concrete needed. A square footage unit cost was available that includes the forms needed for the concrete work. This unit cost was $10.40 per square foot of contact area with the column. The quantity and cost computations for the concrete and formwork are shown in Table 52 and Table 53 respectively.

Table 52: Concrete Quantity and Cost for Column Fireproofing

Column Size	Unit Area of Concrete (sy per yard)	Column Length (Yard)	Quantity	Total Concrete Volume (cy)	Concrete Total Cost
HSS9x9x3/8	0.0486	10.0	80	38.888	$12,887.87
HSS9x9x3/8	0.0486	5.3	4	1.037	$343.68
W10x49	0.1096	4.7	1	0.511	$169.46
W10x49	0.1096	10.0	50	54.785	$18,156.30
W12x53	0.2414	10.0	16	38.630	$12,802.25
W12x65	0.2387	10.0	10	23.873	$7,911.90
				Total	**$52,271.45**

Table 53: Formwork Quantity and Cost for Column Fireproofing

Column Size	Unit Surface Area (sf per ft.)	Column Length (ft.)	Quantity	Total Surface Area (sf)	Total Formwork Cost
HSS9x9x3/8	3	30	80	7200	$72,288.00
HSS9x9x3/8	3	16	4	192	$1,927.68
W10x49	4.87	14	1	68.18	$684.53
W10x49	4.87	30	50	7305	$73,342.20
W12x53	5.2	30	16	2496	$25,059.84
W12x65	5.87	30	10	1761	$17,680.44
				Total	**$190,982.69**

Therefore, the total cost for encasing all of the columns in concrete was estimated as $243,254.

4.3.2.1.3 Intumescent Coating

Unlike the other methods of fire-proofing the steel columns, the *IBC* explicitly states that the application of intumescent or mastic fire-resistant coatings are determined in accordance with the fire-resistance tests stated in Section 703.2 of the code. The UL directory for fire-resistance rated assemblies was consulted to determine the best design that could be applied in the design. UL Design No. X630 specifies a design for hollow square section columns. According to the table provided on the data sheet, HSS 10 x 10 x 3/8 columns require a coating with a dry thickness of 0.127 inches to achieve a one-hour fire resistance rating. Additionally, a primer coat and topcoat of 0.003 inches thick would be applied. A detail from the data sheet is shown in Figure 45.

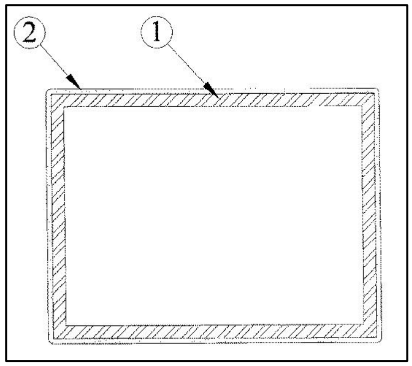

Figure 45: One-Hour Fire Resistance Rated HSS Column with Intumescent Coating (BXUV.X630)

The cost for intumescent fireproof paint applied at a thickness of 3/16 inches for a fire resistance rating of one-hour is provided at $5.97 per square foot of surface area covered (RS Means, 2002). This process would be completed off-site and then shipped to the site for installation, which provides an advantage as far as maintaining a clean site. The total cost for the fireproofing of the steel columns using this figure is shown in Table 54.

Table 54: Cost Estimates for Intumescent Coating for New Steel Columns

Column Size	Length (ft.)	Surface Area per ft. of Length	Quantity	Total Surface Area Coated	Cost
HSS9x9x3/8	30	3	80	7,200	$42,984.00
HSS9x9x3/8	16	3	4	192	$256.67
W 10 x 49	14	4.87	1	68.18	$62.00
W 10 x 49	30	4.87	50	7,305	$6,642.86
W 12 x 53	30	5.2	16	2,496	$2,325.00
W 12 x 65	30	5.87	10	1,761	$1,562.50
				Total Cost:	**$53,833.03**

4.3.2.2 Beams

Most of the beams and girders in the warehouse area currently only support the roof structure. This allows them to be protected with a roof-ceiling assembly that has a fire resistant rating of one-hour when tested or calculated as a complete system. However, the girders that support the diaphragm and exterior walls of the building require individual encasement. These include spandrel girders with member sizes W14x30, W12x26, and W24x68. Similar to the columns, the existing spandrel girders had fire protection specifications calculated only for gypsum board protection. Although spray-applied fire resistive material is an advantageous fire proofing method for beams that are not readily visible by the building's occupants, the anticipated performance in a renovation project was not promising.

Although some of the beams will be exposed since a suspended ceiling is unnecessary in places such as the basketball court, auditorium, and middle school gym, a provision of the *IBC* allows the omission of fire-resistance ratings in these structural members. Footnote b of Table 601 in the *IBC* permits the omission of fire-resistance rating in roof construction that is 20 feet or more above any floor immediately below.

4.3.2.2.1 Spray-Applied Fire Resistant Material

A popular method of fire-proofing structural steel beams is applying SFRM directly to the member. Since the members will be concealed in a horizontal assembly, the visual appearance of the fireproofed member is not a concern. This can be advantageous compared to encasing the member due to labor costs and undesirable weight increases to the structural members (Cote 19-51). The materials used are typically low-density, cementitious, and mineral fiber coatings. The procedure for calculating the thickness of the spray-applied material is different from the previous calculation methods in that an approved assembly must be referenced. This is due to extensive research at Underwriters Laboratories that proves the heat transfer to a protected beam or girder is a direct function of the weight-to-heated perimeter ratio (*IBC* 2009 Commentary: Section 721.5.2.1.2). Therefore an approved assembly must be specified, and the equivalent thickness can be calculated from Equation 18.

$$h_2 = h_1 \left[\frac{\left(\frac{W_1}{D_1}\right) + 0.6}{\left(\frac{W_2}{D_2}\right) + 0.6} \right]$$

Equation 18: Thickness of Substituted SFRM Protected Beam or Girder (*IBC* 2009 Equation 7-17)

UL Design No. S701 (BXUV.S701) was the baseline assembly selected. According to the data sheet, a one-hour fire resistance rating is provided for a W8x18 beam when the spray applied material has a finished minimum thickness of 1-1/8 inches. A detail of the design is shown in Figure 46.

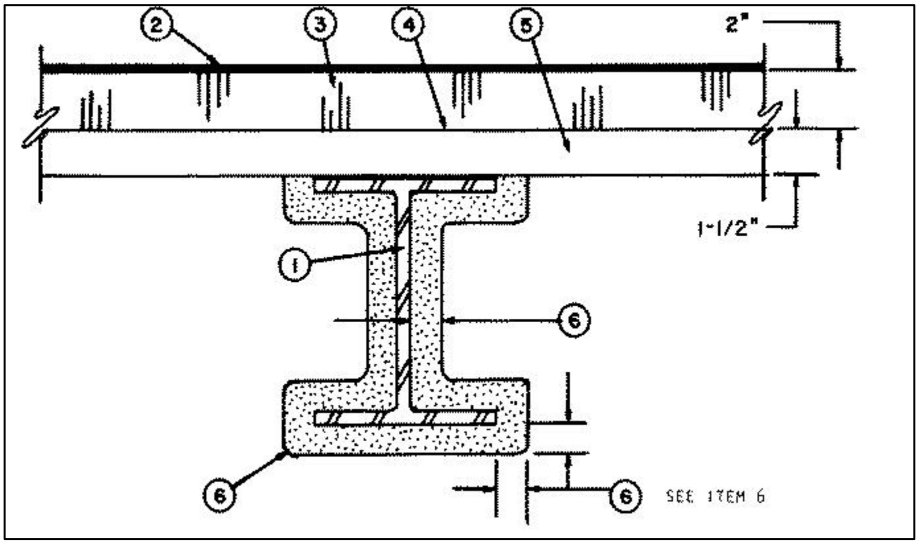

Figure 46: SFRM Protection of Wide Flange Steel Beam (BXUV.S701)

The W/D ratio for a W8 x 18 beam with a contour profile is 0.57 as obtained from Table 721.5.1 (4) of the *IBC*. Table 55 shows the calculated thickness corresponding to this design for each wide-flange beam size requiring individual protection. Note that the thicknesses are rounded up to the nearest 1/8 inch for constructability purposes.

Table 55: SFRM Thickness for Individually Protected Beams

Beam Size	W/D Ratio	Thickness of SFRM (in.)
W14 x 30	0.63	1-1/8
W12 x 26	0.60	1-1/8
W24 x 68	0.92	7/8

The unit cost for spray-applied fire resistant materials assumes the coating is made from inorganic vermiculite and portland cement. It also assumes a covered thickness of one inch, which corresponds to the unit called a board foot, which is one square foot covered one inch thick. In order to obtain accurate figures for the actual required thicknesses, the equivalent to a board foot for each beam size is shown in Table 56. The table also shows the computed board foot per beam of spray applied material needed.

Table 56: Equivalent Board Foot for SFRM Thickness Cost Estimate

Beam Size	Thickness of SFRM (in.)	BF Equivalent	Surface Area (ft^2)	Length (ft.)	Total BF per Beam
W14 x 30	1-1/8	0.89 ft^2	3.89	20	87.4
W12 x 26	1-1/8	0.89 ft^2	3.58	26.4	106.2
W24 x 68	7/8	1.14 ft^2	6.05	40	212.3

The cost estimates based on the unit cost of $1.86 per the board foot equivalent were then computed in Table 57.

Table 57: Cost Estimate for SFRM Protected Beams

Beam Size	Total BF per Beam	Quantity	Total BF	Cost
W14 x 30	87.4	34	2971.6	$5527.18
W12 x 26	106.2	24	2548.8	$4740.77
W24 x 68	212.3	10	2123.0	$3948.78
			Total	**$14,217.00**

4.3.2.2.2 Mineral and Fiber Boards

Another method of fireproofing beams that require individual encasement is the use of mineral and fiber boards. Although there are no calculation methods referenced by the *IBC*, a UL listed assembly is available that provides one hour of fire resistance. The detail for UL Design No. S301 (BXUV.301) is provided in Figure 47.

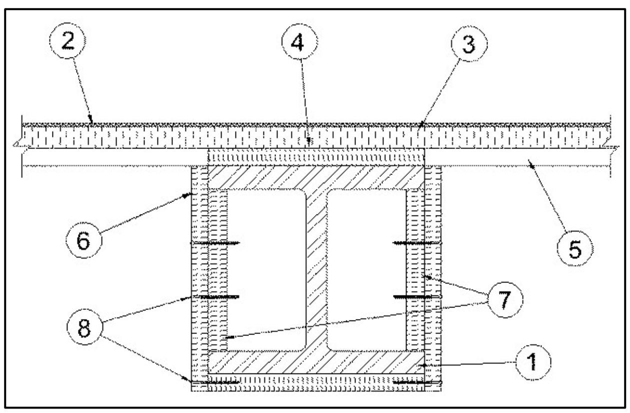

Figure 47: Mineral and Fiber Board Protection for Steel Beams (BXUV.301)

The data sheet specifies a minimum nominal thickness of ¾ inches to provide a fire resistance rating of one hour. The unit cost of $8.79 per square foot of mineral fiberboard panels was used for the estimate of fireproofing the beams (RS Means, 2013). The square footage of mineral board required to protect all of the beams that require protection and the associated cost were computed in Figure 56.

Table 58: Cost Estimate for Beam Protection with Mineral and Fiber Board

Beam Size	Unit Area (SF per LF)	Length (LF)	Quantity	Total Cost
W14x30	2.9925	20	34	$18,253
W12x26	2.7025	26.4	24	$15,359.37
W24x68	4.8225	40	10	$17,303
			Total	**$50,9015**

4.3.3 Fire Barriers

4.3.3.1 Exit Passageways

There were several instances where an exit passageway was incorporated into the design floor layout to ensure exit access travel distances were met. Section 1023.3 of the *IBC* requires exit passageways to be enclosed with fire barriers that have a one-hour fire resistance rating. Since these walls do not require a two-hour fire resistance rating, a different fire barrier was specified that required less materials. The same UL assembly sheet (BXUV.U404) used for the two-hour fire barrier also has a one-hour configuration that can be used. This assembly is constructed of one layer of gypsum wallboard framed on 3-1/2 inch wide steel studs spaced a maximum of 16 inches O.C. The other side is constructed with cementitious backer units. Figure 48 shows the design that was specified for the exit passageways.

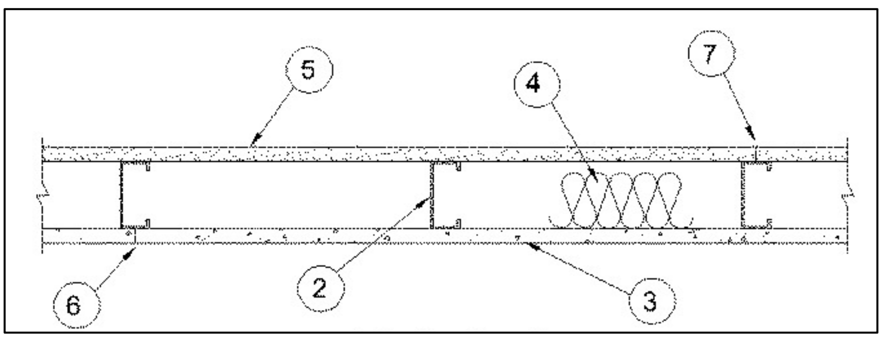

Figure 48: One-Hour Fire Resistance Rated Fire Barrier for Exit Passageways (BXUV.U404)

The quantity takeoff from the Revit model resulted in 6,774 ft^2. The cost estimate for this assembly was computed using the same unit costs from Table 42. However, this cost estimate only took one layer each of the gypsum board and cementitious backerboard. These cost estimates were computed in Table 59.

Table 59: Itemized Cost Estimate for One-Hour UL 404 Fire Barrier

Item	Area	Unit Cost	Total Cost
Interior Metal Stud Framing	6,774 ft^2	\$0.84/ft^2	\$5,690
5/8 inch Fire Rated Gypsum Board	6,774 ft^2	\$1.08/ft^2	\$7,316
1/2 inch cementitious backerboards	6,774 ft^2	\$4.23/ft^2	\$28,654
		Total Cost	**\$41,660**

4.3.3.2 Exit Stair Enclosures

Similar to the procedure for selecting wall enclosures for vertical opening protection in the modified building, the USG Shaft Wall Systems Catalog was used to determine the fire barriers used for the exit stair enclosures in the new building. However, unlike the stair enclosures in the renovated building, an assembly with a one-hour fire resistance rating was prescribed. Section 1022.1 of *IBC* permits interior exit stairways connecting less than four stories to be enclosed with one-hour fire resistance rated fire barriers. Using the same UL design assembly as used for the two-hour enclosure in the renovated building, system A was selected, which provides a one-hour rating. A detail of this assembly is shown in Figure 49.

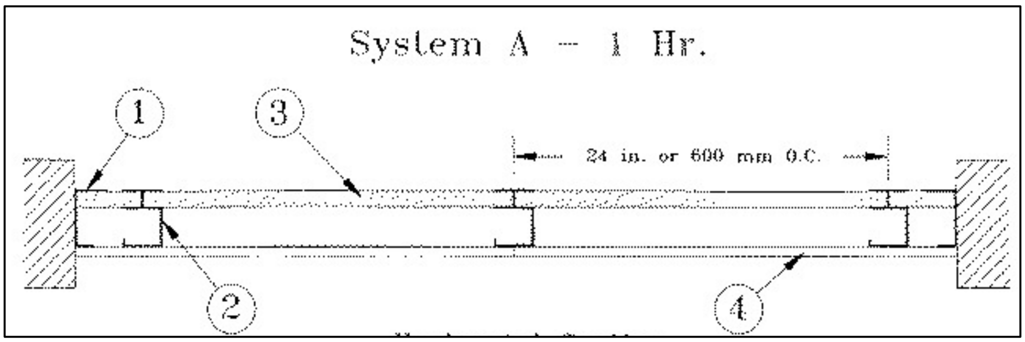

Figure 49: One-Hour Fire Resistance Rated Shaft Enclosure (BXUV.U415)

This assembly requires less material than the two-hour assembly, since only one layer of 5/8 inch gypsum wallboard is required. The cost estimate for this assembly was performed by reducing the cost associated with the gypsum wallboard by one-half the initial value stated in

Table 43. The cost for the shaft enclosures in ground-up construction was computed by multiplying the unit cost of $6.47 per square foot by the total area of shaft walls, which was 10,970 ft^2. This resulted in an estimated cost of $70,921.

4.3.3.3 Stage Separation

Another area of the building that requires the use of a fire barrier is the auditorium. According to Section 410.5 of the *IBC*, dressing and appurtenant rooms associated with stages require special consideration for fire-safety. The rooms accessory to the stage require separation with a one-hour fire resistance rated fire barrier. Additionally, the rooms must be separated from each other by the equivalent. This requirement helps to contain a fire that might ignite in any of the rooms that likely have a significant amount of combustibles.

The one-hour fire resistance rated fire barrier from UL Design No. 404 was also specified for this separation. The detail for the figure can be found in Figure 48. The walls requiring this separation are highlighted in blue in Figure 50.

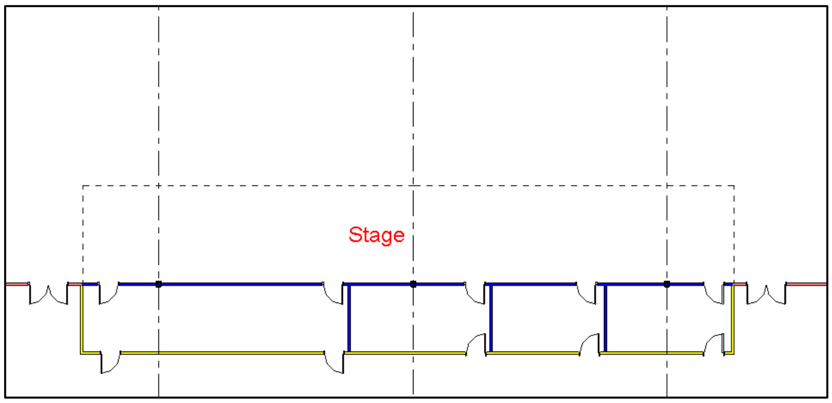

Figure 50: Room Separation from Stage

The total quantity of these fire barriers is 1,957.5 ft^2. Using the unit cost estimates from Table 59, the total cost for these fire barriers resulted in $12,039.

4.3.4 Horizontal Assemblies

In order to avoid the individual protection of each structural member of a floor/ceiling or floor/roof system that does not require individual encasement, a horizontal assembly will be designed to provide the required one-hour fire resistance rating. These assemblies must be continuous without unapproved penetrations, openings, or joints. However, skylights and other penetrations through the fire resistance rated roof deck are permitted without protection if the structural integrity of the roof assembly is maintained.

4.3.4.1 Floor/Ceiling Assembly

The floor-ceiling assembly was selected using the proposed joist, girder, and concrete slab properties. Since a sprinkler system and other mechanical, electrical, and plumbing systems will be installed in the concealed space, a floor-ceiling assembly was selected that is deep enough to allow piping to run through it. Using the Design Information Guide for ANSI/UL 263 “Fire Tests of Building Construction and

Materials," the parameters for identifying an approved system were outlined. Some key supplemental information is listed below.

- The concrete compressive strength specified in the designs may be reduced 500 psi to obtain the minimum value.
- A 5% tolerance may be applied to the minimum steel deck thickness.
- The steel joists must meet or exceed both the depth and weight per foot specified in the design.
- The spacing between joists specified in the design may be increased to a maximum of 4 ft. on centers if the spacing of the hanger wires supporting the ceiling is not increased.

Therefore a UL design was sought that allows the use of steel joists with a minimum depth not exceeding 22 inches and a weight of 9 lbs/ft., a concrete slab with a compressive strength not exceeding 3,500 psi and thickness of 3 inches, and steel beams and girders with criteria not exceeding that of W18x35 beams. The most feasible design was UL Design No. G529, which provides a two-hour fire resistance rating. The ceiling assembly is shown in Figure 51.

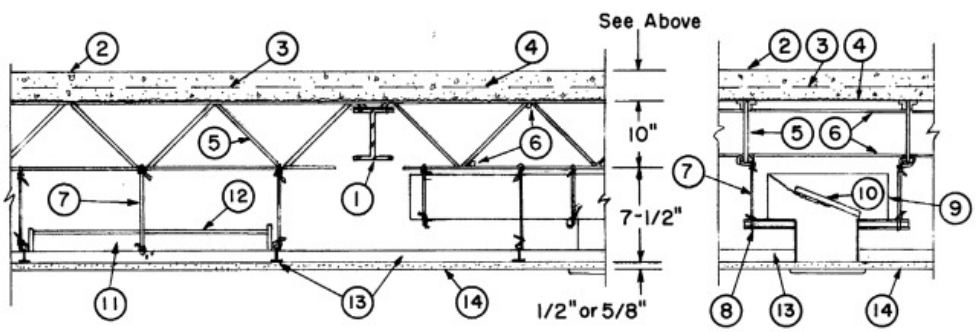

Figure 51: Two-Hour Fire Resistance Rated Floor/Ceiling Assembly (BXUV.G29)

The cost estimate for the floor-ceiling assembly was computed using separate unit costs for the ceiling suspension ceiling and the gypsum panels. The unit cost for the suspension system was determined for a system with 1-5/8 inch deep channels, spaced 24 inches O.C. This unit cost was $1.74 per square foot. The estimated cost for the gypsum panels was determined for 5/8 inch thick fire resistant panels on ceilings. This unit cost was $0.93 per square foot. Therefore, the total cost for the floor-ceiling assembly was computed at \$2.67 per square foot. The *Revit* model provided the total square footage of the first-floor ceiling as 172,788 ft^2, which resulted in a total cost of \$461,344.

4.3.4.2 Roof/Ceiling Assembly

Similar to floor/ceiling assemblies, individual encasement of secondary structural members may be avoided if roof/ceiling assemblies are used. These elements are tested and rated like floor/ceiling assemblies, but it is important to consider the thickness of insulation in place during tests. The insulation thickness that is in place must not be increased, as it would result in a decrease in the fire-resistance rating.

There were not many options available for the selection of the roof-ceiling assembly since most UL Listed assemblies require a maximum steel joist spacing of 4 feet. In order to retain the existing spacing of the joists, the assembly needed specifications that allow a spacing of at least 5 feet O.C. An assembly that permits joists spaced at a maximum of 6 feet O.C. is UL Design No. P514 (BXUV.P514). A detail of the assembly is shown in Figure 52.

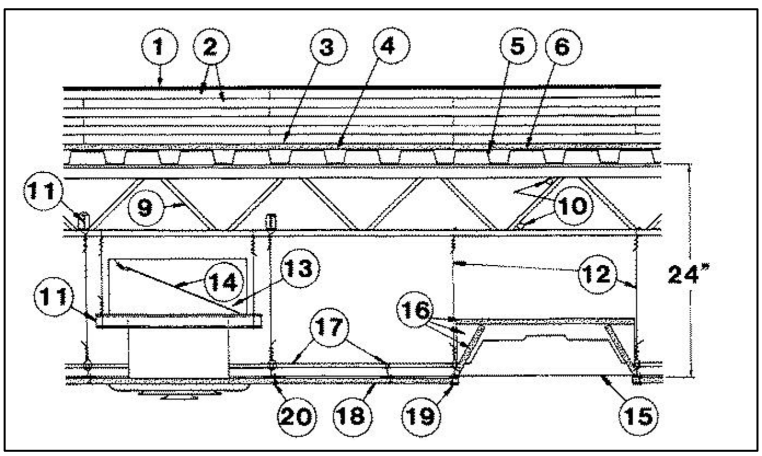

Figure 52: One-hour Fire Resistance Rated Roof-Ceiling Assembly (BXUV.P514)

The assembly also has several other design features that were examined. The joist girders had to have a minimum depth of 20 inches with a minimum weight per linear foot of 13 lbs/ft. The steel deck had to be a minimum of 1 ½ inches deep and each roof joist required horizontal bridging on the top and bottom chord.

4.3.5 Openings in Fire-Rated Construction

Similar to the passive fire protection design of the renovated building, openings in fire-rated construction were considered for ground-up construction. The design contained a variety of fire door assemblies due to the different requirements for doors in different assemblies. The required fire protection ratings, which were obtained from Table 715.4 of the *IBC* for the fire doors in this building are listed in Table 60, and the quantity take-off from the Revit model, along with cost estimates are listed in Table 61.

Table 60: Fire Protection Ratings for Fire Doors in Different Assemblies

Assembly	Required Fire Door Rating (Hours)
2-Hour Fire Wall	1-1/2
1-Hour Shaft Enclosure	1
1-Hour Exit Passageway	1
1-Hour Exterior Wall	3/4
1-Hour Fire Barrier	3/4

Table 61: Cost Estimate for Fire Doors in New Building

Door Assembly	Quantity	Unit Cost	Total Cost
1 ½ Single Door	8	$789.20	$6,313.60
1 ½ Double Door	2	$1,396.10	$2,792.20
1 Single Door	19	$779.93	$14,818.67
1 Double Door	2	$1,360.73	$2,721.46
¾ Single Interior Door	2	$777.80	$1,555.60
¾ Single Exterior Door	8	$800.80	$6,406.40
¾ Double Exterior Door	14	$1,434.60	$20,084
	Total Fire Door Cost		**$54,692**

4.4 Passive Fire Protection Results

The dissimilarity between the passive fire protection elements in the renovated building and the new building produced variations in cost. Although, multiple methods were proposed for the fireproofing of structural members, the assemblies with the lowest construction costs were selected. This included the steel columns encased in gypsum board and the steel beams protected with SFRM. The cost estimate for the passive fire protection systems in each of the different building designs is displayed in Table 62.

Table 62: Cost Comparison for Passive Fire Protection

Element	Cost for Renovated Building	Cost for New Building
Fire Wall	-	$220,337
Column Fireproofing	-	$20,474
Beam Fireproofing	-	$14,217
Fire Barrier	$264,101	$53,699
Shaft Enclosure	$83,700	$70,921
Fire Door	$16,918	$54,692
Total	**$364,719**	**$434,340**

The total cost for the passive fire protection elements in the scope of this report for the new building design was $69,621 greater than the total cost for the passive fire protection of the renovated building. This was due to the difference in construction type between the two buildings. Since the renovated design used fire barriers in lieu of fire walls to increase the building's performance compliance method score, the structural elements did not require additional fire-resistance ratings. However, it is apparent that the cost of fire barriers is still significant and can impact the economic decisions for a project.

Chapter 5: Active Fire Protection Systems

Many buildings often require fire protection features that supplement the passive fire protection design and fire department strategy in place. This additional protection is accomplished through active fire protection systems, which are designed to perform their intended functions through some type of mechanical or electrical interface. Active fire protection systems include water-based fire protection systems, alternative fire suppression systems, fire detection and alarm systems, and smoke control systems. The requirements for the presence of these systems and some of their key features are found in Chapter 9 of the *IBC*. Additionally, the code may reference different standards specific to the system for more detailed provisions. Since plans were not provided for active fire protection systems of the existing building, the process for predicting the presence and design of certain systems is documented in the proceeding section. Design changes resulting from modification of the existing building for the renovation design option as well as changes for the ground-up construction are discussed in the following sections.

5.1 Existing Benchmark Building

Based on the code provisions provided in the 6th Edition of the *Massachusetts Building Code* at the time this building was constructed, the original design was assumed to have an automatic suppression system according to Section 904.7 of the *NBC*, which requires systems throughout buildings with Group F-1 fire areas larger than 12,000 ft^2. However, it appeared this building did not require a complete fire alarm system since the only notification device requirement specified by Section 906.5 was an approved audible or visual alarm device actuated by the automatic sprinkler system. This section does not state specific provisions pertaining to the quantity of devices, and therefore only one sprinkler water gong was assumed on both the interior and exterior of the building.

5.1.1 Automatic Sprinkler System

The feasibility of modifying an automatic sprinkler system to meet the design demands of a new occupancy with modified spaces involves a survey of the as-built system. Unfortunately, a field survey could not be performed on the building and the methodology for using the existing sprinkler system components had to be adjusted.

Assuming that all applicable code requirements were met at the time of the design and installation of the automatic sprinkler system, a reasonable estimate of the layout and configuration of the system may be performed. According to the 6th Edition of the *Massachusetts Building Code*, any code provisions requiring compliance with NFPA 13 *Installation of Sprinkler Systems*, referenced the 2002 Edition of the standard.

5.1.1.1 Water Supplies

In order to assess the ability of the sprinkler system or any other fixed water-based fire protection system, the water supply information was evaluated. The most cost-effective way to renovate a building that requires an automatic sprinkler system is to select a site with existing infrastructure that can provide a water supply that meets the design demand of the new system. The most preferable supply for an automatic sprinkler system is a connection to a reliable public waterworks system with adequate capacity and pressure.

The existing building has a water connection from a public waterworks system that appears to serve most buildings within the town. Figure 53 shows an overview of the system with water lines of various sizes, hydrants, and gate valves controlling the flow of water.

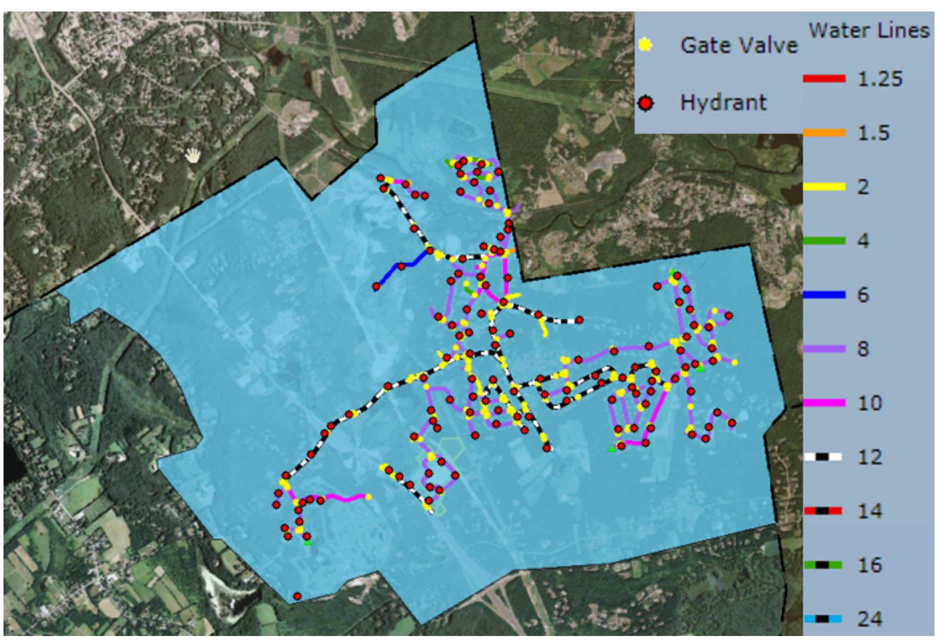

Figure 53: Water District of Building Location (CAI Technologies)

The building site layout consists of a 12-inch street main feeding an 8-inch line, which branches out to form a grid around the building using check valves. This layout is shown visually in Figure 54. There are also five fire hydrants on the site, which would be used for the water-flow test data as required by Section 23.2.1.2 of NFPA 13.

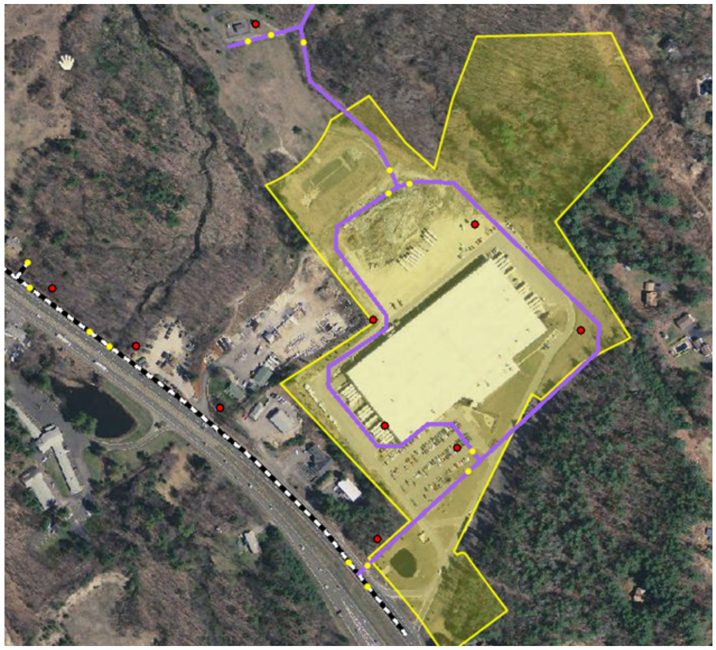

Figure 54: Water Lines Supplying Building (CAI Technologies)

The layout of the water system shows that the main enters the building in the southwest corner of the building. A check of the drawings indicates that a room that resembles a sprinkler riser room is located in that area. Since water supply information could not be obtained for the hydrants on the site of the existing building, an alternative report was obtained that simulates a possible water supply curve that had to be met during the design of the existing sprinkler system.

A water analysis conducted by an engineering consulting firm containing water-flow data from hydrants was used for the benchmark design. This analysis was performed for a nearby town, in which a public department serves buildings similar to a large school. The analysis provides results from two separate water-flow tests.

The main capacity flow test is completed by using a gauge cap on the residual hydrant to record the static pressure and residual pressure, while recording the nozzle pressure on the flow from the hydrant at the same moment. The test results were plotted as a water supply curve, as shown in Figure 55, using PingFIRE's web-based graph tool for water supply and demand information. The supply shows a static pressure of 74 psi with a flow of 3,432 GPM at the residual pressure of 20 psi.

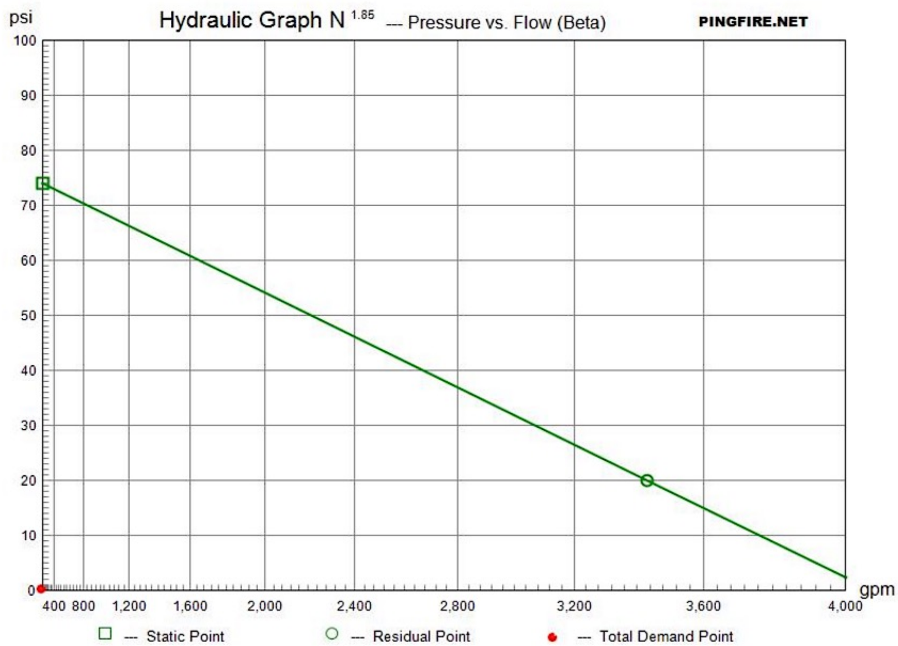

Figure 55: Simulation Water Supply Curve for Existing Building

5.1.1.2 Existing Sprinkler System Requirements

The hazards for the warehouse area of the building were not classified based on its storage of commodities due to the limited knowledge of the exact contents and storage arrangements and the primary use as a manufacturing facility. Therefore, in accordance with Section 5.3.2 of NFPA 13, the system should have been designed as one protecting an ordinary hazard (Group 2) area, while the office space, and several spaces auxiliary to the manufacturing area could have been protected as light hazard occupancies. Assuming standard coverage, pendent or upright sprinklers were used; the maximum coverage area per sprinkler allowed is 130 ft^2 for the ordinary hazard areas and 225 ft^2 for the light hazard areas.

According to Section 8.2.1, the maximum floor area that one sprinkler riser may supply sprinklers for is 52,000 ft^2. Since the area of the building is approximately 230,000 ft^2, five risers are required. As stated in Section 5.1.1.2 of this report, it appears that an underground connection to the water supply is only present in one area of the building. A requirement in *527 CMR* supports this observation. Section 915.2 of the code states that connection to any one fire department connection must serve all sprinklers in a building. This requirement would be achieved by configuring the multiple sprinkler risers in a manifold arrangement. A schematic detail of this arrangement is shown in Figure 56.

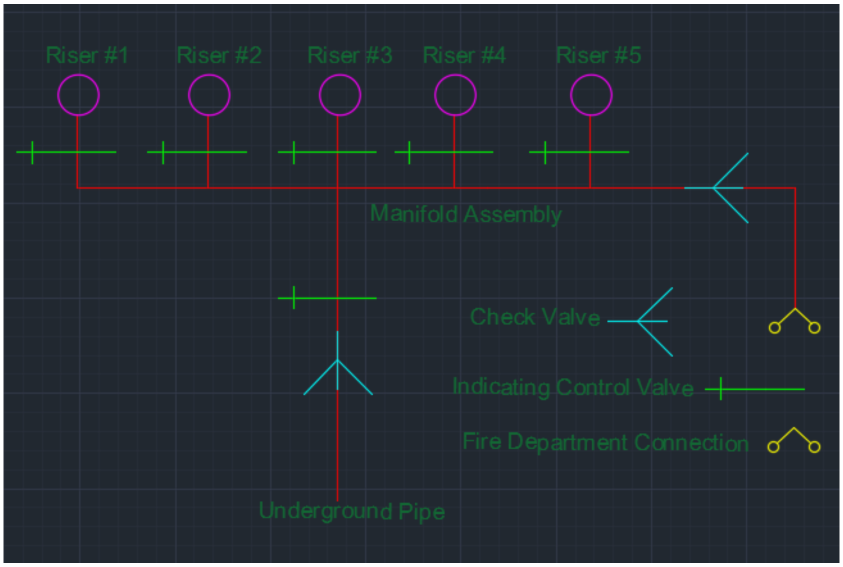

Figure 56: Sprinkler Riser Manifold Detail

The existing roof/ceiling assembly consists of 30-inch deep open web bar joists spaced 5 feet on center. According to the 2002 Edition of NFPA 13, this is considered unobstructed construction, which allows the sprinkler layout to have fewer restrictions concerning sprinkler positioning. Since the assembly is unobstructed construction, Section 8.6.4.1.1.1 of NFPA 13 requires the sprinkler deflector to be located at a distance between 1 inch and 12 inches vertically from the steel deck above. The steel joist is still an obstruction that needs to be considered, as Section 8.6.4.5.2.1.3 requires the sprinkler to be located a minimum distance of three times the maximum dimension of the truss, but it is not required to be located more than 24 inches away from the member as shown in graphically in Figure 57.

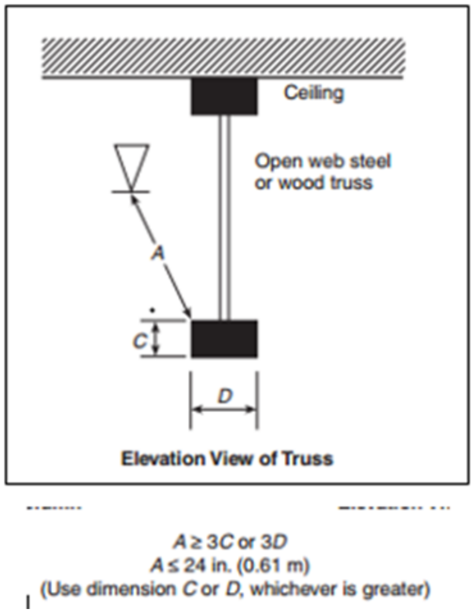

Figure 57: Requirements for Sprinkler Positioning from Steel Joist (NFPA 13 – Figure 8.6.5.2.1.3)

Along with the structural members, the structural drawings show several instances where rooftop air handling units and pipe penetrations are present, which can obstruct both piping arrangements and sprinkler locations. These were identified on a case-by-case basis if they posed a problem to the predicted layout.

5.1.1.3 Existing Sprinkler Layout

The existing sprinkler layout was developed based on a predicted design, best practices, engineering judgment, and code compliance with the 2002 Edition of NFPA 13. Prior to the detailed spacing of sprinklers in a sprinkler system, a rough prediction of the branch line logic was made. The best practice used in the industry is to install branch lines perpendicular to bar joists allowing increased flexibility for branch line spacing; It also facilitates the spacing of hangers for the pipe system (Gagnon 91). Following the determination of the branch line direction, the system configuration was determined. The major configurations consist of tree, grid, and loop systems. The tree system, which uses a cross-main to feed a series of dead-end branch lines is most commonly used, an example of this type of system is shown in Figure 58.

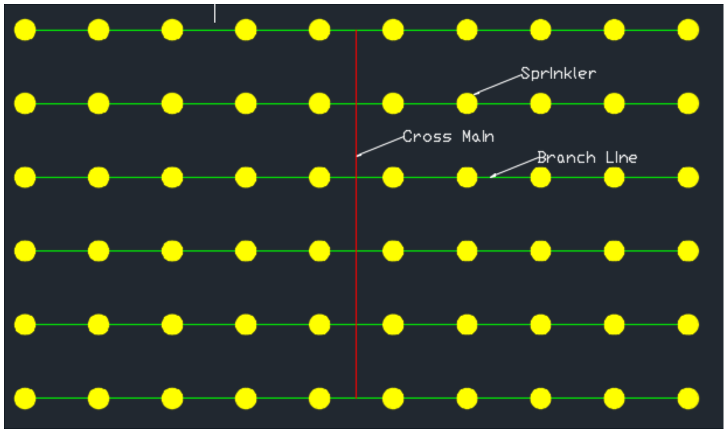

Figure 58: Example of Center-Fed Tree System

In comparison, a grid system uses cross-mains to feed branch lines on both ends. This typically gives the system a hydraulic advantage, which may be necessary for systems with numerous branch lines. However, this system is more time consuming to design since the most remote sprinklers are difficult to determine. Additionally, labor costs may increase due to the need to install two mains for a system that typically requires one. Therefore, a rule of thumb is to use tree configurations for systems with less than eight branch lines and less than 10 sprinklers per branch line. An example of this type of system is shown in Figure 59.

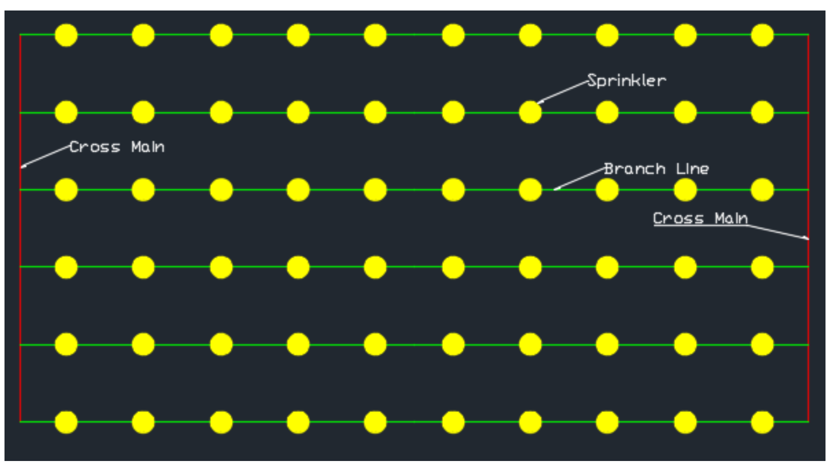

Figure 59: Example of Grid Sprinkler System

Since the building contains a significant amount of open space, and the length of branch lines fed from each cross main do not exceed 100 feet in length, a grid system may be beneficial. However, a center-feed tree system can be used if the sprinkler zones are divided into areas that allowed fewer sprinklers per branch line. The need to run an additional cross-main for each system poses a significant increase in material cost.

Additionally, the use of open web joists makes hanging the multiple cross-mains and feeds difficult. For these reasons, the system layout was performed using center-fed tree systems. A schematic diagram showing the areas divided into the five required systems is shown in Figure 60.

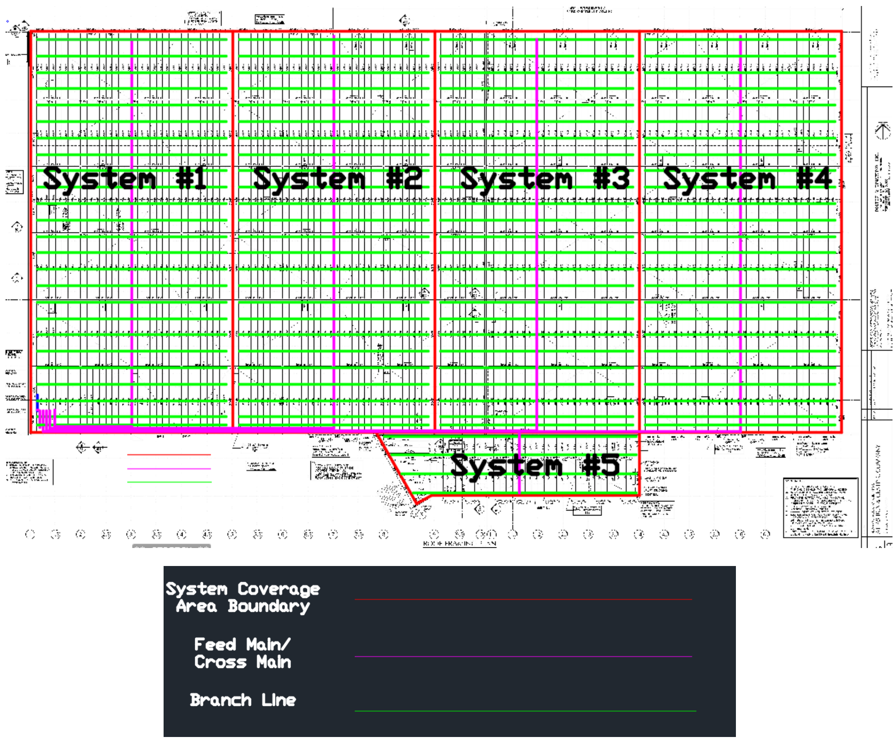

Figure 60: Schematic Pipe Configuration for Existing Building

Since most of the building consists of open space, a reasonable assumption was made that the sprinklers maintain uniform spacing throughout. In order to ensure that the sprinklers continuously meet the requirements involving the joist obstruction, the sprinklers on each branch line may be spaced 10 feet apart, centered between the bays formed by the joists. Therefore, each branch line is permitted to have a spacing 13 feet apart. This configuration was desirable since the structural bays, which are approximately 52 feet in length, could be divided evenly to accommodate four branch lines per bay. This general spacing was used, except for several instances that needed modifications. A partial plan of sprinkler system #1 is shown in Figure 61 to provide evidence of this.

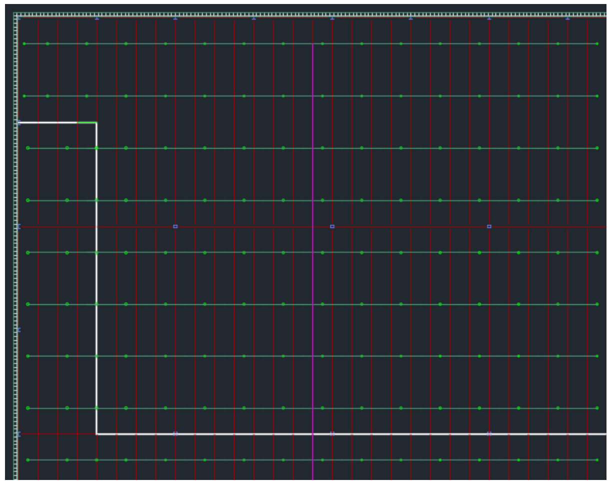

Figure 61: Partial Sprinkler Plan of Sprinkler Zone #1

5.1.1.4 Hydraulic Analysis

In order to confirm that the predicted system would work under the simulated water supply data, hydraulic calculations were performed. This also determined the probable K-factors for the sprinklers and pipe diameters. The calculations were performed using the Design/Area method established in Section 11.2.3 of NFPA 13. This required a point on the Density/Area curve to be selected for an ordinary hazard (Group 2) occupancy. The curve is shown in Figure 62.

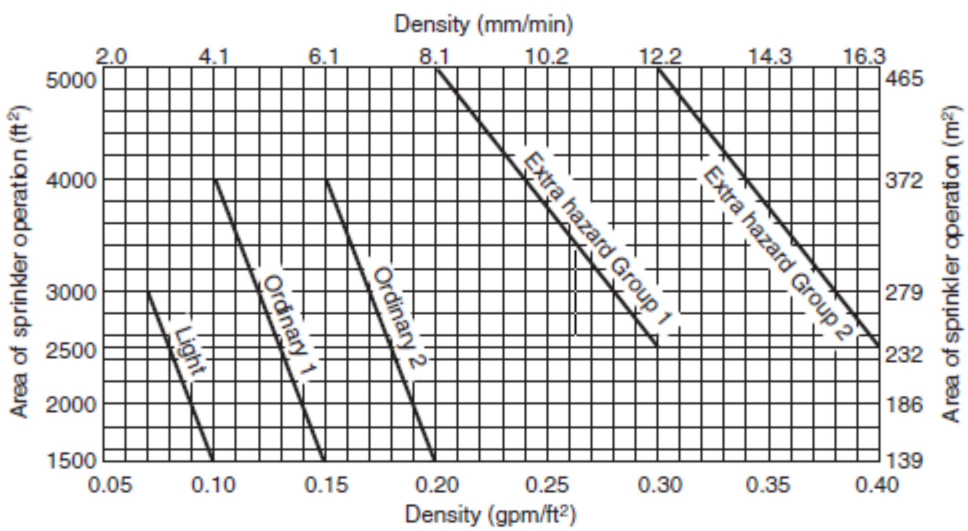

Figure 62: Density/Area Curve for Hydraulic Calculations (NFPA 13 - Figure 11.2.3.1.1)

The density of 0.20 GPM/ft^2 over an area of 1500 ft^2 was selected. The number of sprinklers and sprinklers per branch line required for the remote design areas were calculated using Equation 19 and Equation 20.

$$N_S = \frac{A_D}{A_S}$$

$$N_S = \frac{1500\ ft^2}{130\ ft^2}$$

$$N_S = 11.54 \approx 12\ sprinklers$$

Equation 19: Number of Sprinklers in Design Area (NFPA 13 – Figure A.23.4.4)

$$N_B = \frac{1.2\sqrt{A_D}}{S}$$

$$N_B = \frac{1.2\sqrt{1500\ ft^2}}{10\ ft.}$$

$$N_B = 4.65 \approx 5\ sprinklers$$

Equation 20: Number of Sprinklers on Each Branch Line (NFPA 13 – Figure A.23.4.4)

Since the system is a tree system, the most hydraulically demanding sprinkler is considered the most remote sprinkler furthest away from the cross main on the branch line furthest away from the feed main. The design area includes the five most remote sprinklers on the two most remote branch lines and an additional two sprinklers on the third most remote branch line. Figure 63 shows the remote design area that was selected from a view that shows the entire system and a view that shows the node designation for the hydraulic calculations.

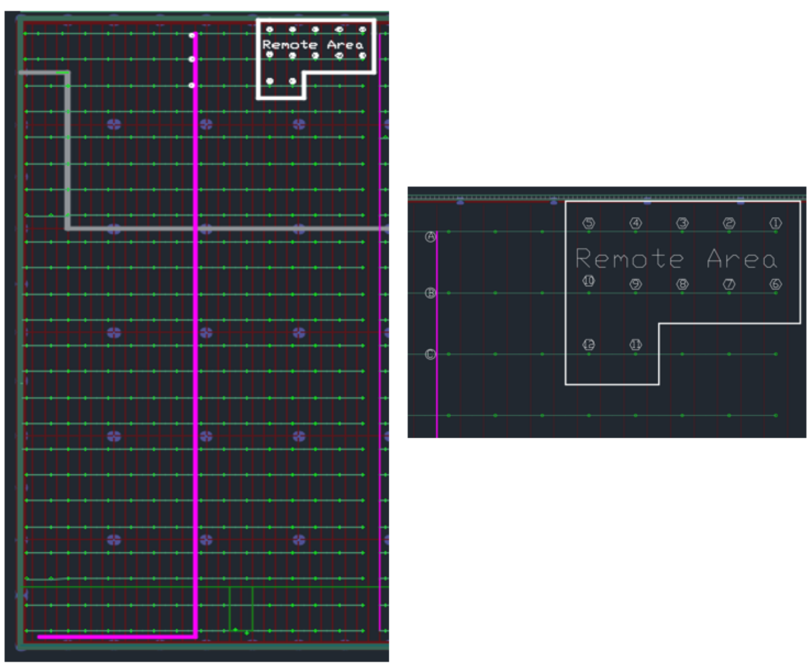

Figure 63: Remote Area for Existing Sprinkler Zone #1

The calculations begin by calculating the flow required at Sprinkler #1. This is calculated in Equation 21.

$$Q = D * A_S$$

$$Q = 0.2\frac{GPM}{ft^2} * 130\,ft^2$$

$$Q = 26\,GPM$$

Equation 21: Flow Required at First Sprinkler in Hydraulic Calculations

The pressure resulting from the discharge is then calculated based on the k-factor of the sprinkler in Equation 22. The operating pressure must be no less than 7 psi according to Section 22.4.4.10.1 of NFPA 13. Since a K-factor of 11.0 provided an operating pressure of 5.4, a nominal k-factor of 8.0 was selected.

$$P = \left(\frac{Q}{K}\right)^2$$

$$P = \left(\frac{26\,GPM}{8.0}\right)^2$$

$$P = 10.6\,psi$$

Equation 22: Operating Pressure at First Sprinkler in Hydraulic Calculation

The pressure loss accounting for friction and elevation was then calculated for the water traveling from sprinkler # 2 to sprinkler #1. The pressure loss due to elevation is not dependent on flow or pipe size and is always found by multiplying 0.833 by the change of elevation in feet. The frictional resistance was calculated using the Hazen-Williams formula from Section 22.3.2.1.1 of NFPA 13. The calculation for pressure losses from sprinkler # 2 to sprinkler #1 is shown in Equation 23, which used a C-factor of 120 for schedule 40 steel pipe, and a 1.5 inch nominal pipe size, the pressure lost traveling through the 10 foot section of pipe was then calculated using Equation 24.

$$p = \frac{4.52Q^{1.85}}{C^{1.85}d^{4.87}}$$

$$p = \frac{4.52(26)^{1.85}}{(120)^{1.85}(1.610)^{4.87}}$$

$$p = 0.026\frac{psi}{ft.}$$

Equation 23: Frictional Resistance for Flow through Pipe

$$P_f = pL$$

$$P_f = (0.026\,\frac{psi}{ft.})(10\,ft.)$$

$$P_f = 0.26\,psi$$

Equation 24: Pressure Loss from Sprinkler # 2 to Sprinkler #1

This pressure was then added to the operating pressure of sprinkler #1 to get the required pressure at sprinkler #2. The flow at sprinkler #2 was then calculated by re-arranging Equation 22. This process was then completed until the flow from all sprinklers on the first branch line are accumulated and the pressure needed to produce this flow at Node A are calculated. The entire branch line can then be considered to have the discharge characteristic of a single orifice, and the discharge coefficient K was determined using Equation 25.

$$K = \frac{Q}{\sqrt{P}}$$

$$K = \frac{173.73}{\sqrt{33.1}}$$

$$K = 30.19$$

Equation 25: K-Factor for Branch Line #1

The pressure losses are then calculated to account for the water traveling from Node B, which is located at the start of Branch Line #2, to Node A, which is located at the start of Branch Line #1. The flow for the entire Branch Line #2 was then calculated using the pressure at Node B and the branch line K-factor. The flows were added and the same process was repeated for Branch Line #3. This procedure was used even though less sprinklers were selected on Branch Line #3 since the flow calculation is based on the pressure entering the branch line.

The resulting flow and pressure at Node C was 523 GPM at 33.7 psi. The pressure losses were then calculated flowing down the cross-main, feed-main, riser, and underground pipe until the required pressure and flow at the water supply was determined. NFPA 13 also requires a hose allowance to be accounted for at any time in the calculation. Per Table 11.2.3.1.2 of NFPA 13, a hose allowance of 250 GPM is required for ordinary hazard occupancies. This hose allowance was added at the outside hydrant to avoid the increasing pressure losses that occur due to an increased flow. The resulting demand of 773 GPM at a pressure of 55.7 psi was plotted on the water supply curve, as shown in Figure 64. The calculations arriving at this demand can be found in Appendix H.

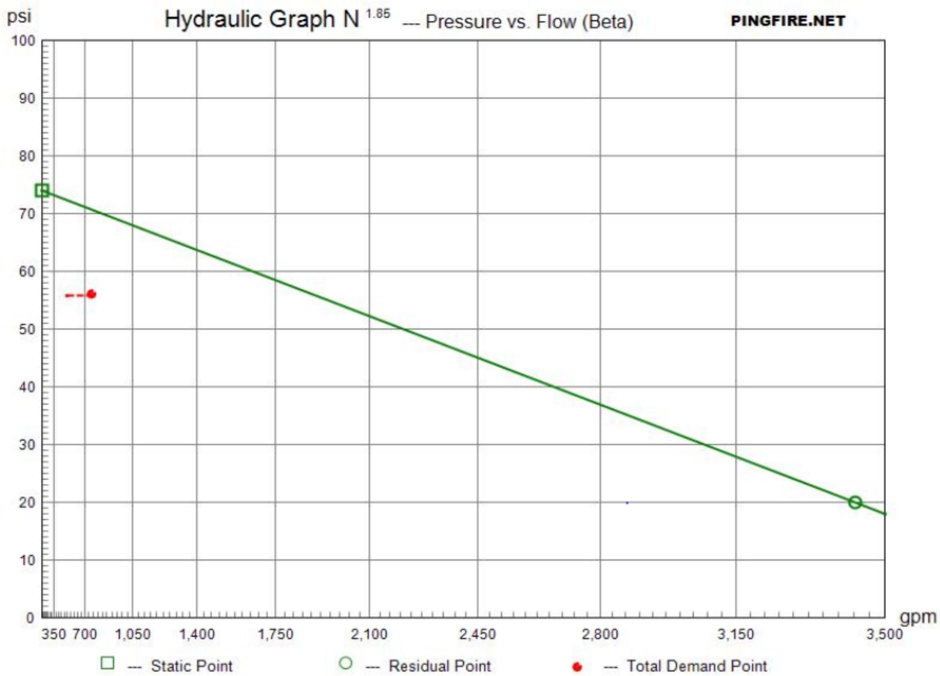

Figure 64: Water Supply Curve with Demand from Existing Sprinkler Zone #1

Since the demand is below the supply curve, the supply is adequate. In order to make this possible the pipe sizes that were used are shown in Table 63. Additionally, a sprinkler k-factor of 8.0 was used and it was assumed that this k-factor was applied throughout the entire system.

Table 63: Pipe Size Selection for Existing Sprinkler System Zone #1

Pipe Description	Nominal Diameter (in.)
Sprinkler #1 to Sprinkler #5	1.5
Sprinkler # 5 to Cross-Main	2.0
Cross-Main	5.0
Feed-Main	6.0
Riser	8.0
Underground Pipe	12.0

5.2 Proposed Renovation

The requirements for fire protection systems in the proposed renovation of the existing building were investigated in the *IEBC*. According to Section 912.2 of the code, both fire sprinkler systems and fire alarm and detection systems must be provided in accordance with the *IBC* for the areas where the change of occupancy classification occurs. Additionally, areas with classified special uses such as stages and platforms must meet the requirements of the *IBC*. The proceeding sections outline the requirements, design processes, and resulting designs for the automatic sprinkler system, fire alarm system, and smoke control system.

5.2.1 Automatic Sprinkler System

According to Table 903.2 of the MBC, buildings having a Group E occupancy with an aggregate floor area greater than 12,000 ft^2 are required to be sprinklered throughout the entire building in accordance with the 2013 Edition of NFPA 13. Additionally, the 2011 Edition of NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems* must be followed. Section 4.1.6 of NFPA 2011 states that the property owner cannot make changes in the occupancy without the evaluation of the fire protection systems for their capability to protect the new occupancy, use, or materials. Section 4.1.6.2 of the standard goes on to state that the evaluation must consider factors such as occupancy changes, material changes, relocated walls, added ceilings, and changes in heating systems. An evaluation of the system previously discussed and its potential to modify is discussed in the following sections.

5.2.1.1 Modification of Existing System

Section 6.1.2.1 of NFPA 13 allows the use of reconditioned valves and devices as replacement equipment in existing systems, but the standard prohibits the use of reconditioned sprinklers in new or existing installations. This provision permits the re-use of check valves, water-flow devices, and other necessary equipment for modifying nearly every existing automatic sprinkler system but once the sprinklers are removed, they are not permitted for reuse in any way. This does not pose a significant issue for construction of materials because certain sprinkler heads are fairly inexpensive, but the issue of labor to remove and install sprinklers may be a more significant cost.

NFPA 13 also discusses the revamping of systems. Since the proposed renovation involves adding a suspended ceiling from the roof structure in most areas of the building, the provisions in Section 8.15.20.3 of NFPA 13 are of particular importance. It states that sprinkler outlets utilized for new arm-over or drop nipples must be used, provided that hexagonal bushings are removed from the fitting(s). Furthermore, Section 8.15.20.4.1 discusses the revamping of a pipe schedule system permits a nipple with a maximum length of 4 in. to be installed in the branch line fitting. This can either be performed using an arm-over as shown in Figure 65 or a straight drop nipple. Due to the need for sprinkler relocation throughout the existing system, many instances will use an arm-over to provide greater flexibility in moving the sprinkler to a more desirable location.

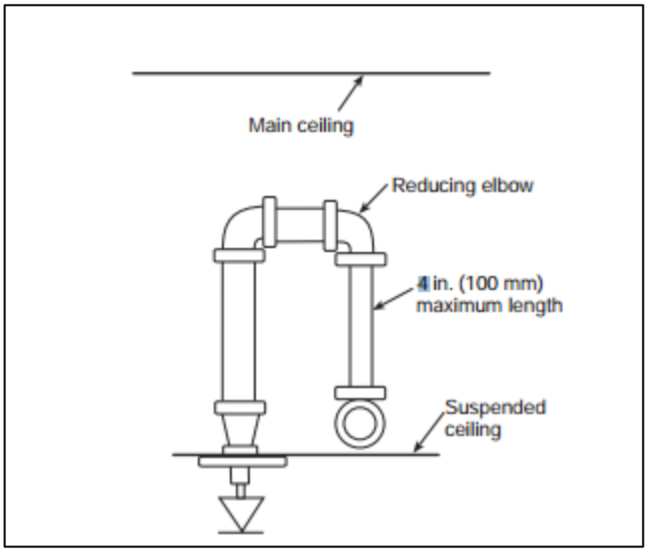

Figure 65: Armover Design for Sprinkler System Modification (NFPA 13 – Figure 8.15.19.4.2)

The same requirements mentioned for the revamping of existing pipe schedule systems are applicable to hydraulically designed system, as stated in Section 8.15.20.5 of NFPA 13, though calculations must be provided to determine that the system flow rate will be achieved. However, there are limitations in using armovers, as Section 9.2.3.5.1 of the standard states that the cumulative horizontal length of an unsupported armover may not exceed 2 feet when steel pipe is used.

5.2.1.2 Hazard Classifications

Since there will not be a significant amount of commodities stored in the proposed school facilities, all of the areas can be classified based on the hazard classifications in Chapter 5 of NFPA 13. The rooms throughout the building were primarily classified as light hazards (LH), which are occupancies where the quantity and combustibility of contents is low, but some occupancies were classified as ordinary hazard group 1 (OH1) and ordinary hazard group 2 (OH2) areas. The distinction between these two groups is that the combustibility of contents in OH1 is low compared to OH2, which has contents with moderate to high combustibility. The spacing between sprinklers in OH1 and OH2 areas is not affected by the sub-classification, but the classification of an OH2 area requires a greater density of water. The individual hazard classification for each area is represented in Table 64.

Table 64: NFPA 13 Hazard Classifications for Various Rooms

Room Type	Hazard Classification	Maximum Coverage (SR Pendent) (ft^2)
Standard Classroom	Light	225
Library	Light	225
Cafeteria	Light	225
Auditorium	Light	225
Computer Lab	Light	225
Administrative Office Space	Light	225
Nurse	Light	225
Bathroom	Light	225
Corridor	Light	225
Weight Room	Ordinary (I)	130
Vocational Classroom	Ordinary (I)	130
Janitor Storage	Ordinary (I)	130
Mechanical Room	Ordinary (I)	130
Sprinkler Room	Ordinary (I)	130
Science Laboratory	Ordinary (I)	130
Chemical Storage for Lab	Ordinary (I)	130
Kitchen	Ordinary (I)	130
Gymnasium	Ordinary (I)	130
Locker Room	Ordinary (I)	130
Network/Telecomm	Ordinary (I)	130
Trash Room	Ordinary (I)	130
Shipping/Receiving	Ordinary (I)	130
School Store	Ordinary (I)	130
Stage	Ordinary (II)	130

Additionally, there are several areas in the building, which require special consideration to properly protect with the sprinkler system. This information is provided in Table 65.

Table 65: Special Considerations for Sprinkler System

Area	Requirement	NFPA 13 Reference
Stairs	Sprinkler installed at top of shaft and under first accessible landing above bottom of shaft	8.15.3.2.1
Elevator Hoistway	Sprinkler installed at top of hoistway	8.15.5.4
Elevator Pit	Sidewall sprinkler installed no more than 2 ft. above elevator pit	8.15.5.1
Library Stack Areas (Clearance < 18 in.)	Sprinklers installed at top of stacks and in every aisle with a distance not exceeding 12 ft., and in every tier of books	8.15.9
Stages containing combustible materials or construction	Sprinklers installed underneath stage	18.15.16

5.2.1.3 Sprinkler Criteria

Sprinklers for this layout were selected based on specific characteristics, which are listed and discussed in Table 66.

Table 66: Sprinkler Characteristics

Characteristic	Description	Requirements
K-Factor	Orifice size; Controls the pressure of discharge at a given flow.	Increased due to greater flow required to control the fire; Large K-Factors used for storage
Temperature Rating	Temperature at which activation occurs	Increased ratings due to proximity to heat sources
Response Time Index	The response of the thermal element to a change in temperature	Quick-Response sprinklers required for light hazard occupancies
Coverage Area	The area of coverage ability of sprinkler deflector	Extended Coverage sprinklers not permitted in obstructed construction.

A sprinkler's k-factor is a constant applied based on its orifice size, as previously noted in the design of the existing sprinkler system. The k-factor is selected based on the flow discharge of the most remote sprinkler. Since the operating pressure of a sprinkler is not permitted to be less than 7 psi, the k-factor is selected to require the lowest possible pressure exceeding 7 psi. The k-factor is then maintained throughout the design to avoid unnecessary hydraulic calculation procedures to prove that the demand of all areas meets the water supply.

Unless the sprinkler is located in a manner which increases the ambient temperature of the ceiling above 100ºF or it is located in an area described in Table 8.3.2.5 (a) or Table 8.3.2.5 (b) of NFPA 13, then the temperature rating must be of ordinary or intermediate ratings throughout the building (NFPA 13 8.3.2). Since many of these locations contain mechanical equipment, which is not in the scope of the design, the only consideration that must be made is the location in relation to skylights.

The requirements in Section 8.3.3.1 require the use of quick-response sprinklers in light-hazard areas unless a modification or addition is being made to an existing light-hazard system. Since the previous occupancy was not a light-hazard classification, the sprinklers must be replaced assuming that standard-response sprinklers were previously installed. For ease of installation and design, quick-response sprinklers were selected throughout instead of the use of standard response sprinklers in ordinary-hazard spaces.

The option of selecting standard coverage sprinklers or extended coverage sprinklers depended on a combination of the room sizes and the existing sprinkler placement. As previously discussed, the length of an armover was limited, which caused dilemmas in positioning new standard overage sprinklers. Therefore, extended coverage sprinklers, which have spacing up to 20 feet by 20 feet, were prescribed to properly protect some of the rooms.

The aesthetics of the layout were also considered. For architects, aesthetics are extremely important, especially in a school environment. As a result, the renovated sprinkler layout consists of concealed sprinkler heads for both the middle and high schools where a concealed ceiling was provided.

5.2.1.4 Sprinkler System Layout

The basis of design for modifying the existing sprinkler system was to utilize the existing cross main and branch line configuration, since these items are the most costly in the installation of a sprinkler system. The cost to demolish sprinkler piping is also a costly activity, and it was avoided whenever possible. Due to the existing sprinklers being upright heads, the areas with suspended ceilings required armovers with drops to position sprinklers to protect the areas under the ceiling. Since the concealed space above the ceiling is not combustible, it was not necessary to leave these devices in place. Therefore, in many locations the existing upright sprinklers were removed and replaced with an armover in that existing outlet. Although this led to some conservative spacing in some areas, it was more effective to have a greater number of sprinklers rather than install new branch lines or find a method to hang additional pipe. In some cases, the coverage could not be met using standard coverage pendent sprinklers with a 2 foot armover. This led to the use of extended coverage sprinklers and sidewall sprinklers in certain locations.

Areas without suspended ceilings were able to reuse the existing sprinklers without any modifications. This was the case for the gymnasium in the high school, where the sprinklers were already positioned in optimal locations. Other areas, like the vocational classrooms on the second floor of the high school did not have suspended ceilings, but the sprinklers had to be replaced with extended coverage sprinklers due to room location relative to the existing sprinklers. The pipe from branch lines was also replaced in certain locations. This was due to the required fire barriers, or other interior walls that had to extend to the underside of the floor or roof sheathing above. A recommended practice would be to investigate the pipe size and condition prior to re-installation once the walls were in place. The resulting layout due to the modifications of sprinkler zone #1, along with a legend indicating the various symbols is shown in Figure 66.

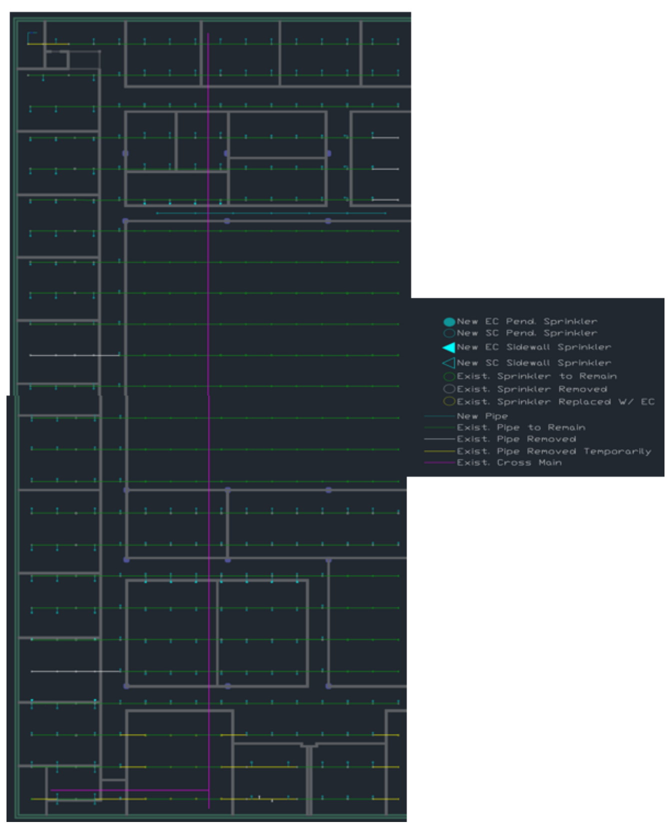

Figure 66: Layout for Second Floor of Modification of Sprinkler Zone #1

5.2.1.5 System Hydraulic Calculations

The hydraulic calculations for the modified Sprinkler Zone #1 were performed to ensure that the demand still met the supply and that a fire pump was not required to increase the pressure of the supply. Since the sprinkler zone consists of both light hazard and ordinary hazard (Group 1) occupancies, hydraulic calculations were required for both instances.

The Density/Area curve from Figure 62 was used to determine the criteria for the hydraulic calculations. Additionally, Section 11.2.3.2.3 of NFPA 13 allows a decrease of the sprinkler operation area without increasing the required discharge density when quick response sprinklers are used for an area with a floor-to-ceiling height that is less than 20 feet. This equation is modeled in Figure 67.

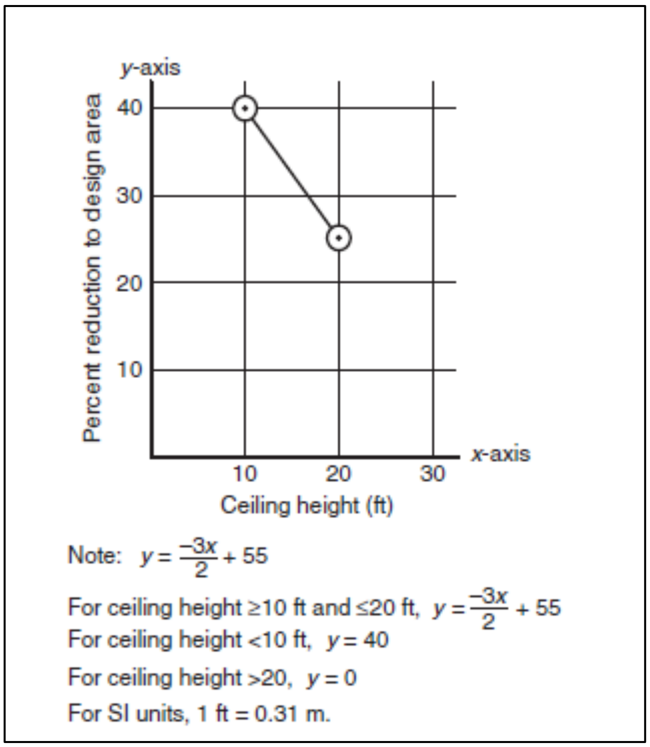

Figure 67: Remote Design Area Reduction (NFPA 13 - Figure 11.2.3.2.3.1)

Since the ceiling height for the light hazard remote area is 11 feet and 8 inches from the floor, a 37.5 percent area reduction factor was used to permit a design area of 937.5 ft^2. It was determined that seven sprinklers were required for the design area with four of them being on the most remote areas. The remote design area is shown in.

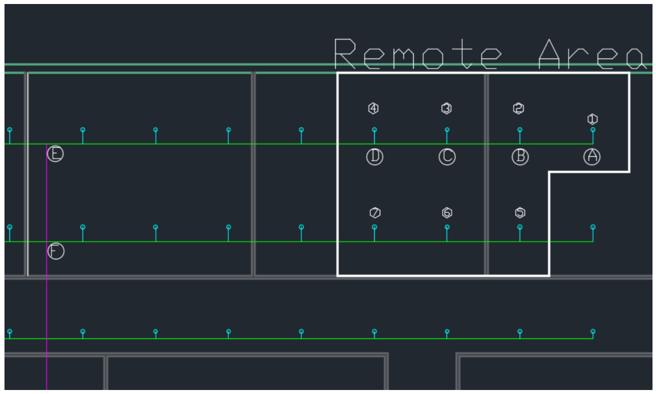

Figure 68: Remote Design Area for Light Hazard in Modified Sprinkler Zone #1

The hydraulic calculation for this remote area had a different procedure than the hydraulic analysis of the existing sprinkler system. This was due to the hydraulic junction points such as the one labeled "B" in Figure 68, which are areas that the flow may travel in one or more different directions. Therefore, the discharge of sprinkler #2 was calculated using the k-factor that was calculated from the flow and pressure at Node B. The resulting demand from this area was calculated to be a flow of 124.5 GPM at a pressure of 26.2 psi. The calculations were performed in a spreadsheet that can be found in Appendix H. The data was plotted on the water supply curve to include the 100 GPM hose allowance required by NFPA 13. The curve is shown Figure 69.

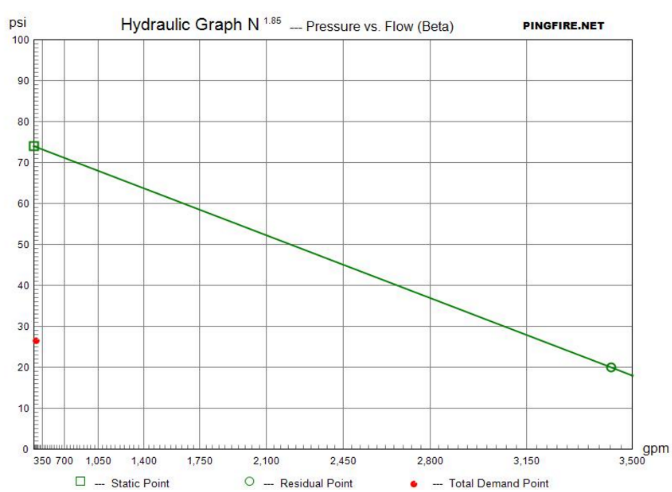

Figure 69: Demand of Light Hazard Remote Area for Renovated Sprinkler Zone #1

The most hydraulically demanding ordinary hazard occupancy was the gymnasium, which was classified as a group 1 ordinary hazard. Using the Density/Area graph, a density of 0.15 GPM/ft^2 was selected over an area of 1500 ft^2. The design area requires twelve sprinklers with five sprinklers per branch line for the two most remote branch lines. The remote design area is shown in Figure 70.

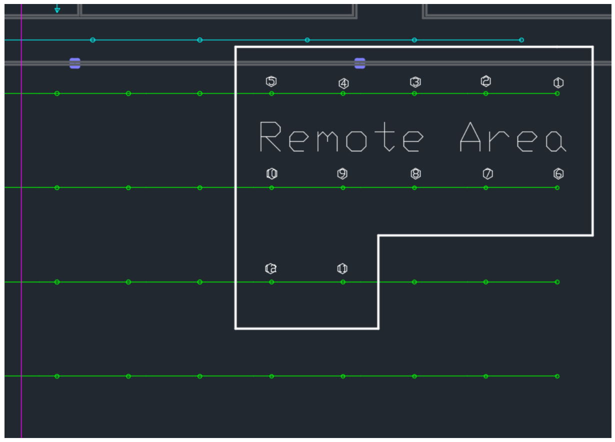

Figure 70: Ordinary Hazard Design Remote Area for Renovated Sprinkler Zone #1

Since the initial flow for a density of 0.15 GPM/ft^2, did not produce an operating pressure exceeding 7 psi for a sprinkler with a k-factor of 8.0, a required flow of 21.20 GPM was established. The demand resulted in a flow of 427.2 GPM at a pressure of 42.3 psi. The data was plotted on the water supply curve including the 250 GPM hose allowance. The curve is shown in Figure 71.

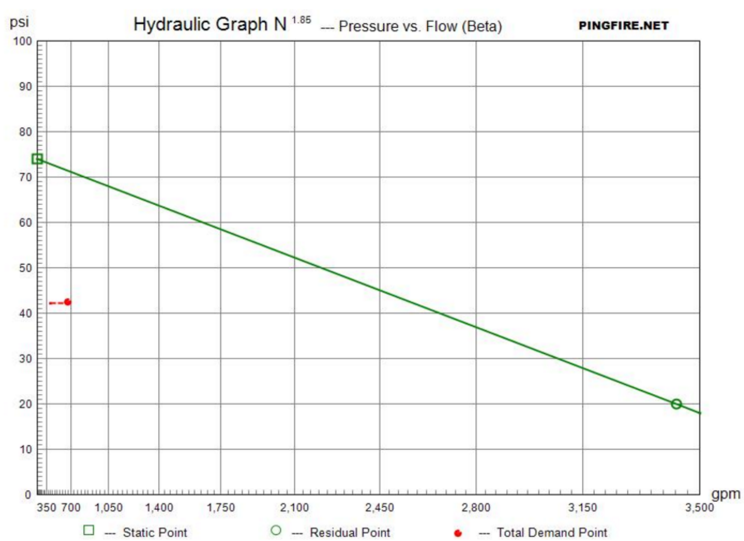

Figure 71: Ordinary Hazard Design Area Demand for Modified Sprinkler Zone #1 on Supply Curve

5.2.1.6 Sprinkler Modification Cost Estimate

The cost estimate was an important consideration for the modification of the existing sprinkler since it can be seamlessly compared to the sprinkler system design for the new building. The cost estimate utilized figures for new items, as well as labor for demolition. Since most of the piping was reused, the most detrimental cost was the need to relocate sprinkler heads on drops. The unit cost per sprinkler relocated was provided as $130.10. Other factors such as pipe removal, new pipe installation, and capping sprinklers were assessed as well. The cost estimate for the modification to Sprinkler Zone #1 is show in Table 67.

Table 67: Cost Estimate for Modified Sprinkler Zone #1

Activity	Unit Cost (Material/Labor)	Units	Cost
Relocate Sprinkler with Branch Drop	$130.10	239 EA	$31,093.90
Remove Sprinkler and Cap	$38.68	34 EA	$1,315.12
New Sprinkler	$28.65	15 EA	$429.75
Pipe Removal	$2.23	251 LF	$559.73
Pipe Installation (Using Existing Materials)	$6.65	249 LF	$1,655.85
		Total Cost	**$35,053**

Since the first floor was not provided with sprinkler coverage on the lower floor by the existing system, the modified costs were not accurate. Therefore, the sprinkler layout for the first floor of Sprinkler Zone #1 was provided. This layout is shown in Figure 72.

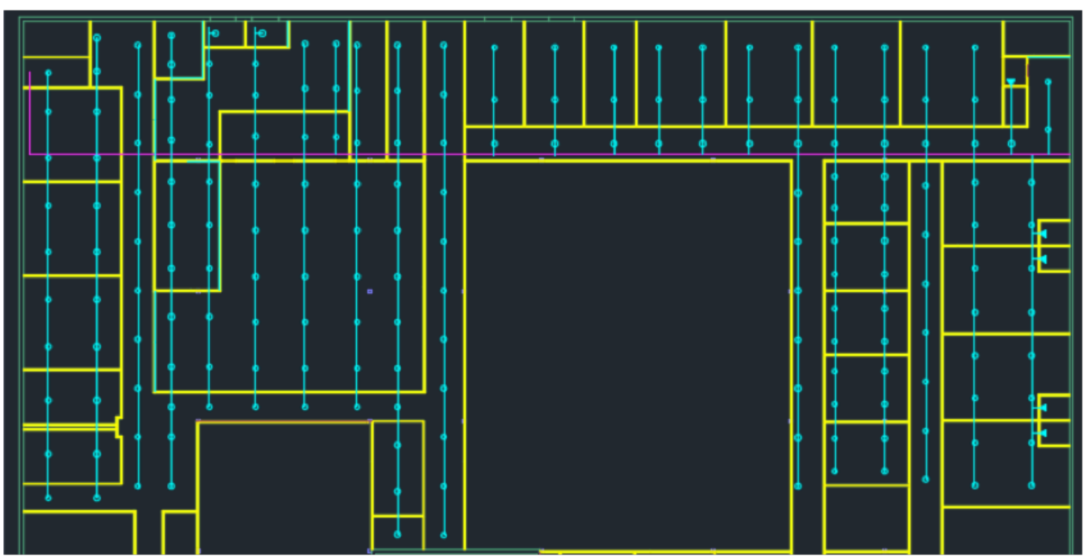

Figure 72: Layout of First Floor Sprinkler Zone #1

The extension of the sprinkler system to the first floor of the renovated building primarily incorporated cost estimates for new construction. However, the need to cut into the existing sprinkler riser to install a feed main at a lower level was also accounted for.

The cost estimate for the system covering Sprinkler Zone #1 on the first floor is summarized in Table 68.

Table 68: Cost Estimate for First Floor Sprinkler Zone #1

Activity	Unit Cost (Material/Labor)	Units	Cost
Pendent Sprinkler Head	$28.65	193 EA	$5,529.45
Horizontal Sidewall Sprinkler Head	$35.55	5 EA	$177.75
Branch-Line (1-1/2 inch)	$17.69	2331 LF	$41,235.39
Cross-Main Piping (4-inch)	$38.00	318 LF	$12,084.00
Feed-Main Piping (6-inch)	$68.20	25 LF	$1,705.00
Riser Section Remove and Replace (12-inch)	$107.35	10 LF	$1,073.50
Welded Flange for Riser Connection	$383.00	1 EA	$383.00
		Total Cost	**$62,188**

Additional costs were also computed for miscellaneous sprinkler system components and design procedures. These cost figures are shown in Table 69.

Table 69: Miscellaneous Sprinkler System Costs for Renovated Building

Activity	Unit Cost (Material/Labor)	Units	Cost
Field Testing and Flushing	$199.00	LS	$199.00
Existing Conditions Field Survey	$199.00	LS	$199.00
Waterflow Alarm Valve	$1,168.00	4 EA	$4,672.00
		Total Cost	**$5,070.00**

The total cost of the sprinkler system in the renovated design was estimated by multiplying the cost estimate for the first and second floor of sprinkler zone #1 by the number of zones. The miscellaneous system costs were then added separately as shown in Equation 26.

$$C_T = 4C_{A1} + 4C_{A2} + C_S$$

$$C_T = 4(\$62{,}188) + 4(\$35{,}053) + 5{,}070$$

$$C_T = \$394{,}034$$

Equation 26: Final Cost Estimate for Renovated Sprinkler System

5.2.2 Fire Alarm System

The renovated building is required to have a fire alarm system in accordance with Section 907 of the *IBC* due to the performance compliance evaluation. Another condition of the assessment was that the system must be provided with an associated emergency voice/alarm communications system. Additionally, a fire command center must also be provided for the building. The fire command center is intended for fire department operations of the building's fire alarm system and its interconnections. Some applicable features required in the fire command center, which were obtained from Section 911.1.5 of the *IBC*, are listed below:

- Emergency voice/alarm communication system control unit
- Fire department communications system
- Fire detection and alarm system annunciator
- Sprinkler valve and waterflow detector display panels
- Emergency and standby power status indicators
- Elevator fire recall switch
- Smoke control panel

5.2.2.1 Initiating Devices

Since the compliance performance method was met, the fire alarm requirements for the *IBC* were met rather than the requirements for 780 CMR. The effective provision of Section 907.2.3 of the *IBC* allows the elimination of manual fire alarm boxes where an automatic sprinkler system is provided throughout. Yet a minimum of one manual fire alarm box must be installed in a location approved by the AHJ. The most likely location of this is outside of the fire command center. Other initiating devices for this fire alarm system include the supervisory devices of each automatic sprinkler system and the smoke detectors installed to meet the heat detection criteria from the performance compliance method. Rather than create fire alarm zones, which are limited to 22,500 ft^2 per Section 907.6.3 of the *IBC*, addressable devices were selected to indicate the precise location of the alarm condition at the fire alarm control unit (FACU).

5.2.2.1.1 Sprinkler System Supervision

Section 903.4 of the *IBC* requires waterflow switches on automatic sprinkler systems to be electrically supervised by the fire alarm control unit. A waterflow alarm device must be installed on each sprinkler system, and it indicates a flow of water in the system. According to Section 17.12.2 of NFPA 72, the device must be installed to initiate an alarm signal within 90 seconds of flow occurring at the waterflow switch that is equal to or greater than that from a single sprinkler of the smallest orifice size installed in the system. However Section 17.12.3 requires an analysis of the device to determine that the movement of water due to waste, surges, or variable pressure will not initiate an alarm signal. The waterflow device specified for this design is the Tyco Model AV-1-300 Alarm Check Valve, which works for system pressures up to 300 psi, and has sizes available to accommodate 2.5, 4, 6, and 8 in. risers. This product is shown in Figure 73.

Figure 73: Waterflow Alarm Device (Tyco AV-1-300 Alarm Check Valve)

5.2.2.1.2 Smoke Detection System

As stated in the performance compliance method, a complete coverage automatic smoke detection system was specified for the renovated building. The design and layout of this system was required to meet the provisions of the 2010 Edition of NFPA 72, *National Fire Alarm and Signaling Code*. Section 17.5.3.1 of NFPA 72 defines complete coverage as the installation of detectors in all accessible compartments or spaces.

When Annex B: Engineering Guide for Automatic Fire Detector Spacing of NFPA 72 is not used to design the detection system according to specific performance-based design criteria, the location of spot-type smoke detectors on smooth ceilings shall be in accordance with Section 17.7.3.2.3.1 through 17.7.3.2.3.4. These provisions identify a nominal spacing of 30 feet with detectors located no more than one-half the nominal spacing from walls. The nominal 30 foot spacing includes all detector spacing configurations on or inside the circle formed by the spacing of four detectors 30 feet apart, as shown graphically in Figure 74.

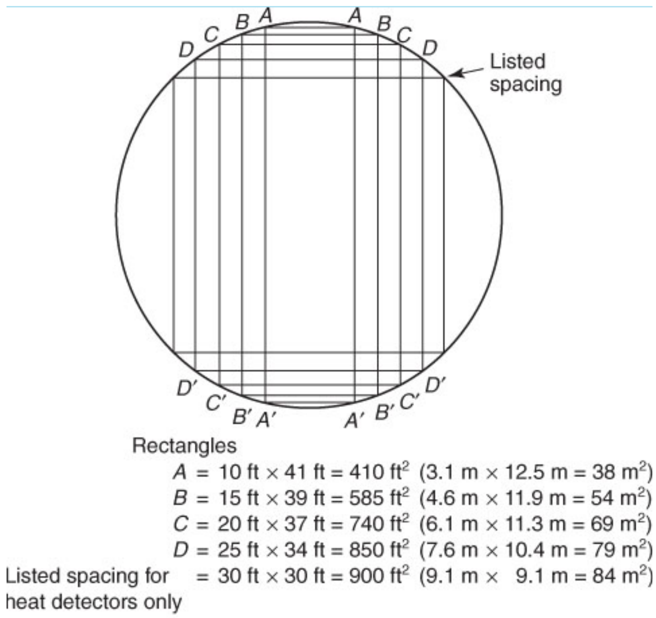

Figure 74: Equivalent Spacing for 30 ft. Nominal Spaced Detectors (NFPA 72 – Figure A.17.6.3.1.1)

Additionally, all points on a ceiling must have a detector within a distance of no greater than 0.7 times the nominal 30 ft. spacing. This technique is used in irregularly shaped areas where the spacing between detectors may be greater than the nominal spacing. However, the spacing of detectors should still take into consideration the ceiling shape, surface, and height, the configuration of the area's contents, the combustion characteristics of the fuel loads, compartment ventilation, and ambient conditions.

A majority of the design consisted of positioning spot-type smoke detectors on the underside of smooth, flat ceilings. Even in areas where the structural frame remained exposed such as the vocational classrooms, the open web joists are not expected to affect smoke flow unless the solid part of the top cord exceeds four inches in depth. This is not the case and the detectors were positioned to mount directly to the underside of the roof sheathing above. The more difficult challenge came where smoke detection had to be designed for high ceiling areas such as the high school gymnasium, which has a height of 30 feet from the finished floor to the underside of the roof structure. Section 17.7.1.10 of NFPA 72 states that the effect of stratification below the ceiling shall be taken into account for the design of the detection system.

Stratification occurs when air containing smoke particles is heated by smoldering to a point where the smoke-filled air becomes less dense than the surrounding cooler air. The smoke rises until it reaches a level where the difference in temperature is not significant enough to activate the device. In the high-ceiling areas where stratification is likely to occur, projected beam-type smoke detectors were utilized. These detectors operate based on the light obscuration principle, in which a light source is projected onto a photosensitive device. When smoke obscures the beam, the light reaching the photosensitive device is reduced and the alarm is activated (Cote, 2008). Figure A.17.7.3.7 from NFPA 72 is shown in Figure 75 to provide a typical layout of the projector and receiver devices.

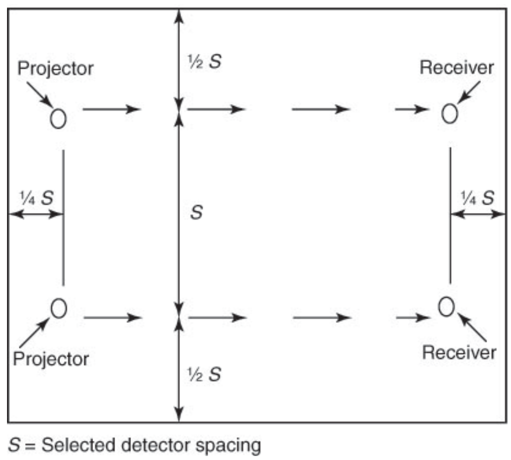

Figure 75: Typical Arrangement of Light Projector and Receiver (NFPA 72 – Figure A.17.7.3.7)

The advantage of these detectors is their ability to operate over a long range and the designer's ability to locate the devices at several levels of the compartment. The device selected for these scenarios was the System Sensor Model 6424 Projected Beam Smoke Detector, which is shown in Figure 76.

Figure 76: System Sensor Model 6424 Projected Beam Smoke Detector for High-Ceiling Areas

The assembly has a protection range of 30 feet to 330 feet and a maximum spacing of 60 feet between projected beams and 30 feet between projected beams and sidewalls. The device is also capable of ceiling and wall mounted configurations.

The distance from the top of the fuel package to the point where stratification will occur can be computed using the predicted heat release rate of a fire scenario and estimating the ambient temperature difference at a rate as the distance from the floor increases as shown below in Equation 27 which was obtained from Annex B.4.6.3.2 of NFPA 72.

$$Z_m = 14.7(Q_c)^{1/4}\left(\frac{\Delta T_0}{dZ}\right)^{-3/8}$$

Equation 27: Height of Stratification (NFPA 72 - B.4.6.3.2b)

Two assumptions are required to perform this equation. The first assumption that was made was the temperature differential. Since sufficient evidence could not be obtained for a constant increase in ambient temperature of a room at an increased height, designs from the Section 4 – Chapter 1 of the SFPE Handbook were evaluated. The two example problems showed an increase of between 0.5625 and 0.7826°F per foot of height increase. Therefore an estimated differential of 0.6°F per foot was used for this calculation. The second assumption was based off of the selection of a design fire scenario. Since the goal of the detection system was to provide the most conservative amount of protection, a reasonably probable fire with the lowest heat release rate was selected. Since trash barrels are typically located on the sides of bleachers, a design fire involving a large barrel filled with milk cartons was selected. According to Table B.2.3.2.2(b) of NFPA 72, this fuel package has a maximum heat release rate of approximately 140 Btu/sec. According to Annex B.4.6.3.2.1 of NFPA 72, the convective portion of the heat release rate can be estimated as 70 percent of the total heat release rate. These values were used to compute the maximum height of smoke rise in Equation 28.

$$Z_m = 14.7(0.7 * Q)^{1/4}\left(\frac{\Delta T_0}{dZ}\right)^{-3/8}$$

$$Z_m = 14.7(0.7 * 140)^{1/4}(0.6)^{-3/8}$$

$$Z_m = 56\ ft.$$

Equation 28: Calculation of Stratification Height of Fire Scenario in Gymnasium

5.2.2.2 Notification Appliances

The fire alarm system is required to annunciate at the FACU and must initiate the occupant notification system. Section 907.5.2.1.1 of the *IBC* requires the notification system to consist of audible devices with a minimum sound pressure of 60 decibels (dBA) in all occubiable building spaces and 75 dBA in mechanical equipment rooms. Additionally, an emergency voice/alarm communication system was be installed in accordance with Section 907.5.2.2 of the IBC and NFPA 72. This system operates to sound an alert tone followed by voice instruction giving information and directions for evacuation in accordance with the building's evacuation plans. The speakers dedicated to this system were provided at paging zones at each elevator, exit stairway, and floor. The system must also be capable of providing manual override and live voice message features and have an emergency power source due to its critical aid in evacuation.

Visible notification appliances were provided in all public and common areas. Section 907.5.2.3 of the *IBC* allows the exemption of visible notification appliances from private offices, mechanical and storage rooms, exits, and elevator cars. These devices must meet the requirements of NFPA 72, which focuses on the spacing of such devices. According to Section 18.5.4.2 of NFPA 72, visual notification devices may be located on the ceiling or the walls of a space. Where located on the walls, they must be mounted in a manner that the entire lens is between 80 inches and 96 inches above the floor. The spacing requirements for wall-mounted devices are shown in Table 70 and the requirements for ceiling-mounted devices are shown in Table 71, which were both retrieved directly from the NFPA 72 document.

Table 70: Room Spacing for Wall-Mounted Visible Appliances (NFPA 72 – 2010: Table 18.5.4.3.1 (a))

Table 18.5.4.3.1(a) Room Spacing for Wall-Mounted Visible Appliances

Maximum Room Size		Minimum Required Light Output [Effective Intensity (cd)]		
ft	m	One Light per Room	Two Lights per Room (Located on Opposite Walls)	Four Lights per Room (One Light per Wall)
20 × 20	6.10 × 6.10	15	NA	NA
28 × 28	8.53 × 8.53	30	Unknown	NA
30 × 30	9.14 × 9.14	34	15	NA
40 × 40	12.2 × 12.2	60	30	15
45 × 45	13.7 × 13.7	75	Unknown	19
50 × 50	15.2 × 15.2	94	60	30
54 × 54	16.5 × 16.5	110	Unknown	30
55 × 55	16.8 × 16.8	115	Unknown	28
60 × 60	18.3 × 18.3	135	95	30
63 × 63	19.2 × 19.2	150	Unknown	37
68 × 68	20.7 × 20.7	177	Unknown	43
70 × 70	21.3 × 21.3	184	95	60
80 × 80	24.4 × 24.4	240	135	60
90 × 90	27.4 × 27.4	304	185	95
100 × 100	30.5 × 30.5	375	240	95
110 × 110	33.5 × 33.5	455	240	135
120 × 120	36.6 × 36.6	540	305	135
130 × 130	39.6 × 39.6	635	375	185

NA: Not allowable.

Table 71: Room Spacing for Ceiling-Mounted Visible Appliances (NFPA 72 – 2010: Table 18.5.4.3.1 (b))

Table 18.5.4.3.1(b) Room Spacing for Ceiling-Mounted Visible Appliances

Maximum Room Size		Maximum Lens Height		Minimum Required Light Output (Effective Intensity); One Light (cd)
ft	m	ft	m	
20 × 20	6.1 × 6.1	10	3.0	15
30 × 30	9.1 × 9.1	10	3.0	30
40 × 40	12.2 × 12.2	10	3.0	60
44 × 44	13.4 × 13.4	10	3.0	75
50 × 50	15.2 × 15.2	10	3.0	95
53 × 53	16.2 × 16.2	10	3.0	110
55 × 55	16.8 × 16.8	10	3.0	115
59 × 59	18.0 × 18.0	10	3.0	135
63 × 63	19.2 × 19.2	10	3.0	150
68 × 68	20.7 × 20.7	10	3.0	177
70 × 70	21.3 × 21.3	10	3.0	185
20 × 20	6.1 × 6.1	20	6.1	30
30 × 30	9.1 × 9.1	20	6.1	45
44 × 44	13.4 × 13.4	20	6.1	75
46 × 46	14.0 × 14.0	20	6.1	80
50 × 50	15.2 × 15.2	20	6.1	95
53 × 53	16.2 × 16.2	20	6.1	110
55 × 55	16.8 × 16.8	20	6.1	115
59 × 59	18.0 × 18.0	20	6.1	135
63 × 63	19.2 × 19.2	20	6.1	150
68 × 68	20.7 × 20.7	20	6.1	177
70 × 70	21.3 × 21.3	20	6.1	185
20 × 20	6.1 × 6.1	30	9.1	55
30 × 30	9.1 × 9.1	30	9.1	75
50 × 50	15.2 × 15.2	30	9.1	95
53 × 53	16.2 × 16.2	30	9.1	110
55 × 55	16.8 × 16.8	30	9.1	115
59 × 59	18.0 × 18.0	30	9.1	135
63 × 63	19.2 × 19.2	30	9.1	150
68 × 68	20.7 × 20.7	30	9.1	177
70 × 70	21.3 × 21.3	30	9.1	185

5.2.2.3 System Layout

The system layout is primarily dominated by the smoke detection system that was selected as part of the performance compliance method. However, it was still critical to space the notification appliances strategically to require the least devices and conduit as possible. The smoke detectors spaced throughout are ionization spot-type detectors, whereas the detectors in the auditorium and gymnasium are light beam-projected detectors located below the exposed roof joists. Figure 77 shows a zoomed view to display a detailed view of the spacing,

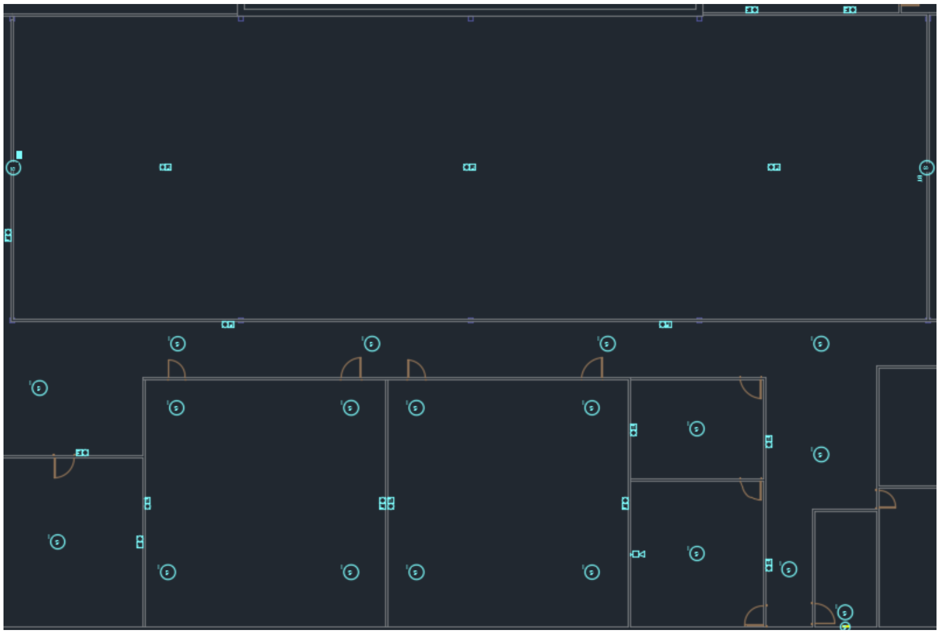

Figure 77: Close-Up View of Fire Alarm Devices in Renovated Design

5.2.2.4 Fire Alarm System Cost Estimate

Although the fire alarm system for the renovated building was a new system, the decisions made in the performance compliance method resulted in a system that was much different from the ground-up construction. The quantity of fixtures on the second floor of the high school, along with the associated cost estimate is shown in Table 72.

Table 72: Cost Estimate for Second Floor of High School in Renovated Building

Activity	Unit Cost (Material/Labor)	Units	Cost
Spot-Type Smoke Detector	$175.50	167	$29,308.50
Beam-Type Smoke Detector	$203.30	3	$609.90
Strobe and Horn	$226.00	145	$32,770.00
Horn	$120.50	17	$2,048.50
Elevator Recall Actuation	$376.50	1	$376.50
		Total Cost	**$65,113.00**

An estimated quantity takeoff for the fire alarm devices on the first floor of the high school was obtained by eliminating the devise in the spaces that extend two stories high. Additionally a manual fire alarm box was added, since no less than one could be provided in the building. The revised cost estimate for the first floor of the high school is shown in Table 73.

Table 73: Projected Cost Estimate for First Floor of High School in Renovated Building

Activity	Unit Cost (Material/Labor)	Units	Cost
Spot-Type Smoke Detector	$175.50	167	$29,308.50
Manual Fire Alarm Box	$46.50	1	$46.50
Strobe and Horn	$226.00	136	$30,736.00
Horn	$120.50	17	$2,048.50
Elevator Recall Actuation	$376.50	1	$376.50
		Total Cost	**$62,516.00**

The cost estimates for other system components dedicated to the overall function of the fire alarm system are presented in Table 74.

Table 74: Cost Estimate for Fire Alarm System Features in Renovated Building

Activity	Units	Cost
Wireless Fire Command Center	1	$4,120.00
Remote Supervision of Devices	1	$2,375.00
Intercom Systems (25 Stations)	1	$32,100.00
	Total Cost	**$38,595.00**

The final cost estimate for the fire alarm system in the existing building was then computed by multiplying the costs estimates for each floor by two and adding them to the value in Table 74. This resulted in a cost estimate of $293,853 for the fire alarm system in the renovated building.

5.3 Ground-Up Construction

Both the fire alarm and smoke control system were not significantly affected when comparing the renovated design to a design using the same features but constructed from the ground up. This was not the case for the automatic sprinkler system, which was designed with consideration for the existing system. Also, the sprinkler system was designed based on existing underground pipe from a public water supply. Depending on the site selection, sufficient water supply may not be available. Assuming this possibility, the sprinkler system for the new building was designed based on the need to also install a fixed water-supply and fire pump.

5.3.1 Sprinkler System

The design of the sprinkler system for the ground-up construction involved several design comparisons to the modification of the existing sprinkler system. While the pipe system may have appeared more efficient, the system was assessed for its hydraulic ability. Since the construction of a new building does not guarantee a sufficient water supply, the simulated use of an on-site water storage tank was performed. Once the design of the system and the water supplies was complete, a cost analysis was performed to compare the new sprinkler system to the modified sprinkler system discussed in Section 5.2.1 Automatic Sprinkler System.

5.3.1.1 Sprinkler System Layout

The ability to design the sprinkler system without the restrictions of modifying an existing system provides much more flexibility. The spacing of the sprinklers were more efficient, as was proved by less being used for the second floor of Sprinkler Zone #1. The layout for this area is shown in Figure 78.

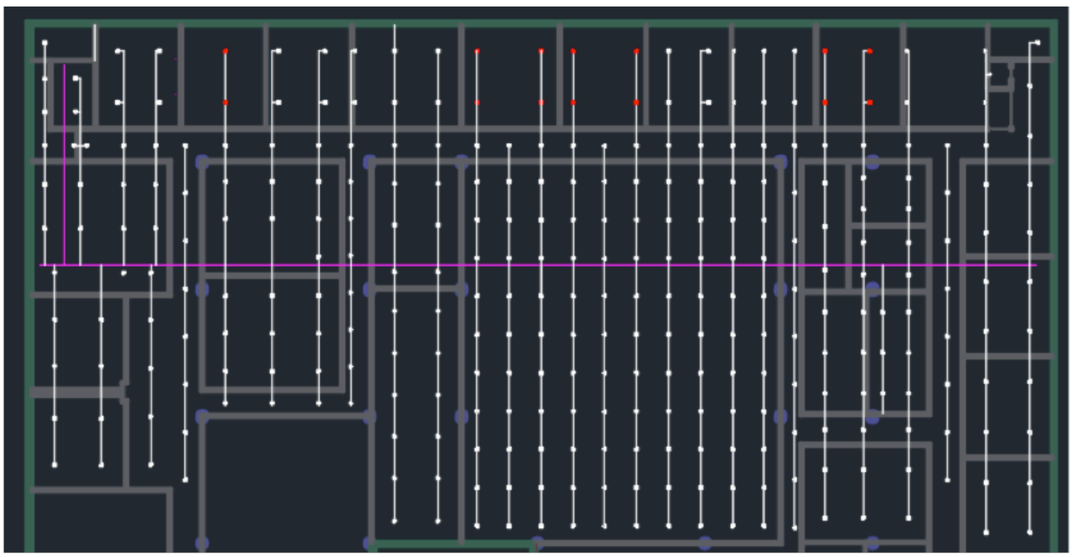

Figure 78: Ground-Up Sprinkler System Layout for Sprinkler Zone A

Although using the same feed main and cross main layout, the design incorporated significantly less armovers, resulting in sprinklers being fed with drops straight from the branch line. This allowed for better hydraulic results and a design with improved constructability.

5.3.1.2 New Sprinkler Cost Estimates

The cost to install a new sprinkler system may seem like a better option economically since the unit cost to install a sprinkler, without incorporating the cost for piping, is $28.65 per sprinkler head, compared to the unit cost of $130.10 per sprinkler to relocate with a branch drop. However, this system lacked the cost advantage of using existing materials. Throughout the design of the renovated system, many key features were retained. All significant piping, including the branch lines, cross-mains, risers, and underground pipe were not modified under the assumed sizes and physical conditions. The cost estimate for this sprinkler system zone used estimated pipe sizes as listed in Table 75.

Table 75: Pipe Sizes used for Cost Estimate of Ground-Up Sprinkler System

Pipe Description	Nominal Size (in.)
Drops	1
Branch Line	1.5
Cross Main	4
Feed Main	6
Riser	8

The total cost estimate also took into consideration a check valve, alarm valve package, zone valve, inspector's test connection, and the fire department connection, all which were assumed to be present in the modification to the existing sprinkler system. The estimated cost is shown in Table 76.

Table 76: Cost Estimate for Second Floor of Sprinkler Zone #1 in New Sprinkler System

Item	Unit Cost (Material/Labor)	Units		Cost
Drops	$10.82	148.5	LF	$1,606.77
Branch Lines	$12.09	3756.5	LF	$45,416.09
Sprinklers	$28.65	297	EA	$8,509.05
Cross Main	$38.60	310	LF	$11,966.00
Feed Main	$69.20	62.5	LF	$4,325.00
Riser	$58.60	30	LF	$1,758.00
			Total Cost	**$73,581.00**

The cost estimate for the first floor of sprinkler zone #1, used the same quantities. However, the cost to cut into an existing riser to connect the feed main was not necessary. These revised cost estimates are provided in Table 77.

Table 77: Cost Estimate for 1st Floor of Sprinkler Zone #1 in New Sprinkler System

Activity	Unit Cost (Material/Labor)	Units	Cost
Pendent Sprinkler Head	$28.65	193 EA	$5,529.45
Horizontal Sidewall Sprinkler Head	$35.55	5 EA	$177.75
Branch-Line (1-1/2 inch)	$17.69	2331 LF	$41,235.39
Cross-Main Piping (4-inch)	$38.00	318 LF	$12,084.00
Feed-Main Piping (6-inch)	$68.20	25 LF	$1,705.00
		Total Cost	**$60,732.00**

The new sprinkler system had a greater amount of miscellaneous components, which had to be accounted for in the cost estimate. Table 78 displays the quantities and costs of these components.

Table 78: Cost Estimate for Miscellaneous Components for New Sprinkler System

Activity	Unit Cost (Material/Labor)	Units	Cost
Alarm Valve	$1,168.00	5 EA	$5,840.00
OS&Y Gate Valve	$1,155.00	5 EA	$5,775.00
Fire Department Connection	$713.00	1 EA	$713.00
Backflow Preventer	$4,062.00	1 EA	$4,062.00
Inspector's Test Connection	$137.10	5 EA	$685.50
		Total Cost	**$17,076.00**

The total cost estimate of the sprinkler system for ground-up construction was performed in the same manner as performed for the renovated sprinkler system. This resulted in a total cost of $554,328.

5.3.2 Fire Alarm System

Section 907.2.3 of the *IBC* is replaced in its entirety by the amendment of 780 CMR. The code provision in 780 CMR requires all Group E occupancies with an occupant load greater than 50 occupants to have a manual fire alarm system installed with emergency voice/alarm capabilities in accordance with Section 907.5. The code provision states that all installed smoke detectors and automatic sprinkler systems must be connected to the fire alarm system to initiate it upon activation of such systems. Additionally, no exception for the elimination of manual fire alarm boxes is mentioned, and therefore it was anticipated that they were a requirement of the system. The following sections outline the design of the system by determining the initiation device, notification appliance, and fire-safety function requirements.

5.3.2.1 Initiation

The fire alarm system in the new building was designed for initiation by the automatic sprinkler system and manual fire alarm boxes. The manual fire alarm boxes are required not more than 5 feet from the entrance to each exit and at sufficient locations so the travel distance to the nearest box does not exceed 200 feet. Other requirements for each fire alarm box are listed in Table 79, and the model selected for the school facility is shown in Figure 79.

Table 79: Manual Fire Alarm Box Requirements

Requirement	Description	Reference
Height	42 in. to 48 in. from floor level	907.4.2.2
Color	Red	907.4.2.3
Cover	Transparent with proper operating instructions	907.4.2.5

Figure 79: Simplex Manual Fire Alarm Device

Additionally, protective covers were specified for the manual fire alarm boxes to prevent malicious false alarms and to provide the device with protection from physical damage. The covers will be installed in accordance with Section 907.4.2.5 of the *IBC*, which states that the cover must be transparent and include proper operating instructions.

5.3.2.1.1 Smoke Detectors

Smoke detectors are required in several locations in this building. Although the *IBC* permits the exemption of smoke detectors from locations of each fire alarm control unit, Section 10.15 of NFPA 72 requires smoke detectors at the location of each fire alarm control unit (FACU), notification appliance circuit power extenders, and supervising station transmitting equipment. Also, as stated in Section 4.2.4.1, doors in certain locations, which are not self-closing, must be smoke automatic-closing by the actuation of a smoke detector. These include the doors in walls that are capable of resisting the passage of smoke. Rooms with walls that require the capability of resisting the passage of smoke include laboratories and vocational shops per Section 508.2.5.2 of the *IBC*.

Section 17.7.5.3 of NFPA 72 requires the detectors to be either photoelectric or ionization type detectors that are listed for releasing service. The smoke detector selected for this design was the Simplex TruAlarm Photolectric Smoke detector as shown in Figure 80.

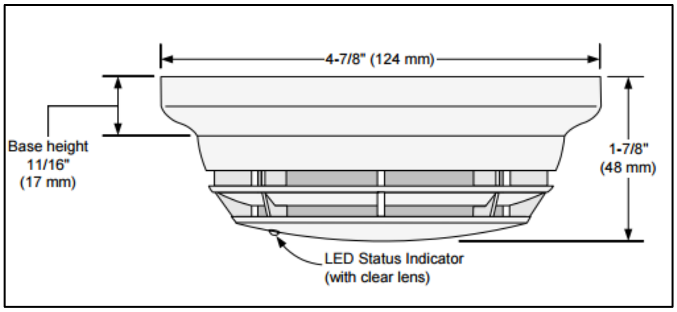

Figure 80: Simplex TruAlarm Photoelectric Smoke Detector for Door Release Service

Since a ceiling-mounted smoke detector was selected, Section 17.7.5.6.6.1 of NFPA 72 requires the devices to be located on the centerline of the doorway, at a distance between 1 foot and 5 feet measured perpendicular to the doorway.

5.3.2.2 Notification

The occupant notification systems for the new building followed the same provisions discussed in Section 5.2.2.2 Notification of this report. Although the layout slightly changed due to minor differences in the spaces, the same principles were performed to design and position the audible, visible, and speaker appliances.

5.3.2.3 System Layout

The fire alarm system primarily consisted of notification devices since the sprinkler heads themselves act as fire detection devices. Also, the manual pull stations had to be carefully designed in order to place them at distances where the travel distance does not exceed 200 feet. After the evaluation of the travel distances, it was evident that more pull stations were necessary than those just at the exits. The fire alarm layout for the second floor of the high school is shown in Figure 81 with a close-up view shown in Figure 82 and a legend shown in Figure 83.

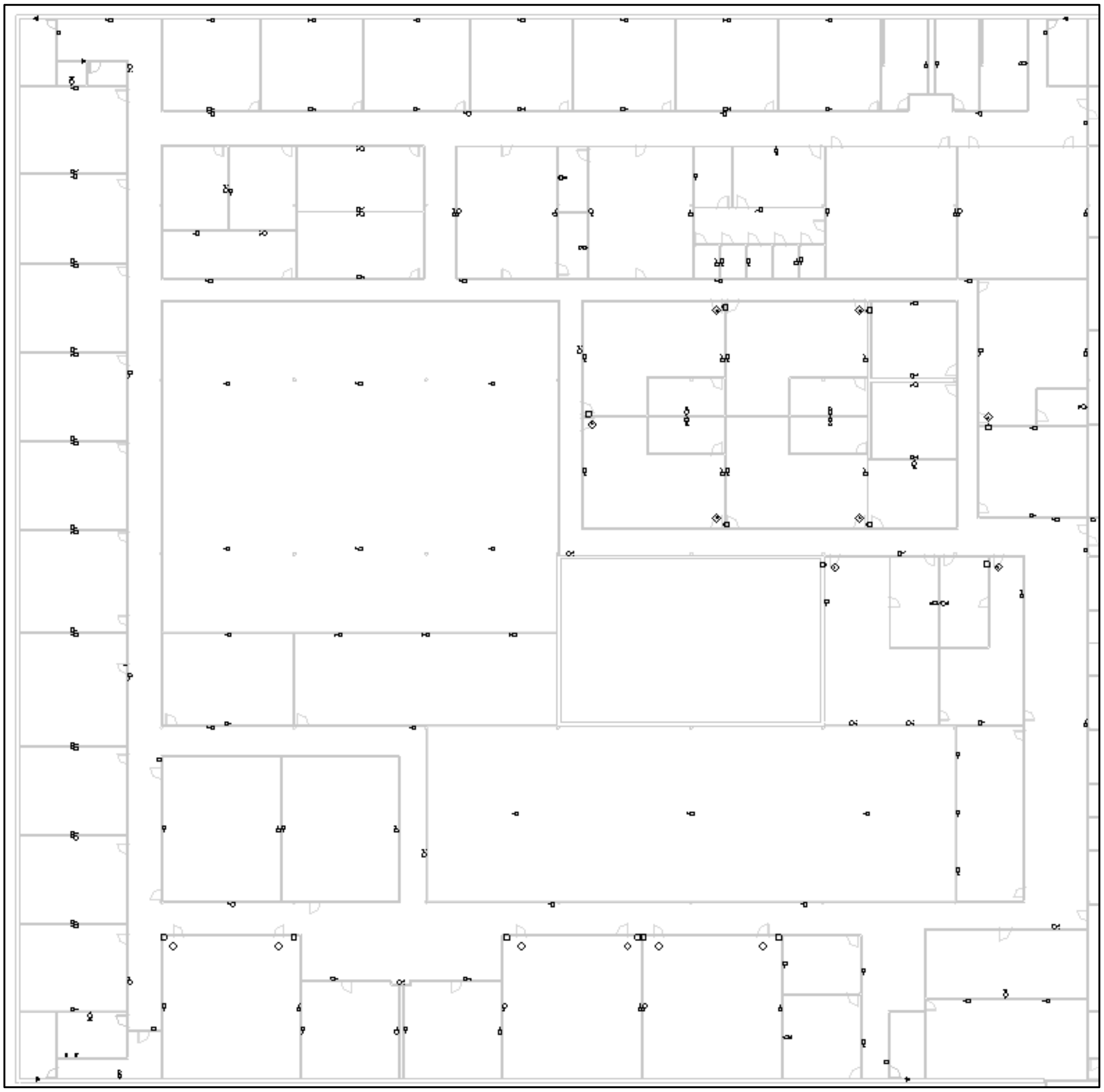

Figure 81: Fire Alarm Device Layout for Second Floor of Middle School

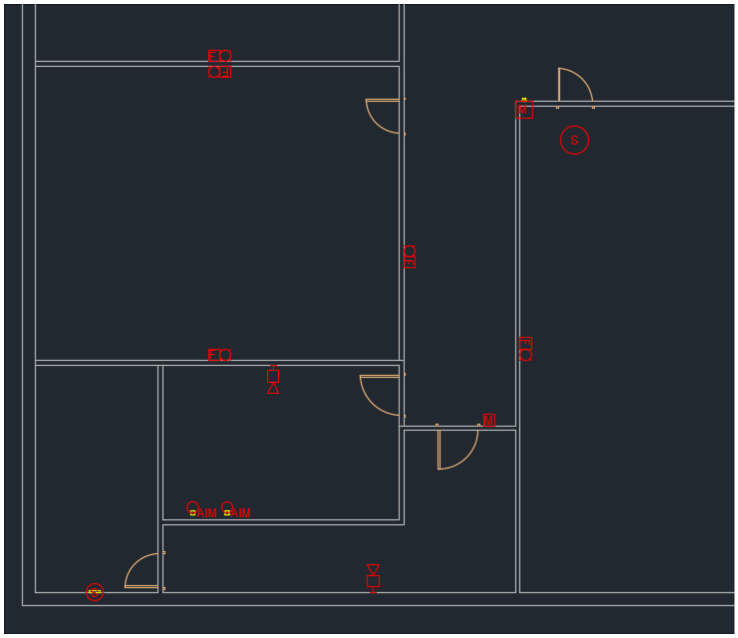

Figure 82: Close-Up View of Fire Alarm Plan

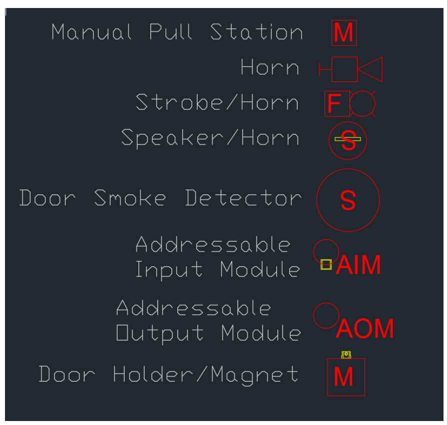

Figure 83: Fire Alarm Symbol Legend

The addressable input monitor on the plan represents the sprinkler waterflow devices that initiate the activation of the occupant notification system. The quantity of devices on the second floor of the high school was recorded and is displayed in Table 80

Table 80: High School Second Floor Fire Alarm Device Quantities

Device	Quantity
Manual Pull Stations	7
15 Cd Wall Horn/Strobe	47
30 Cd Wall Horn/Strobe	68
60 Cd Wall Horn/Strobe	21
110 Cd Ceiling Horn/Strobe	9
Door Holder/Magnet	14
Door Smoke Detector	14
Speaker	5

5.3.2.4 Fire Alarm System Cost Estimate

Although the fire alarm system for the renovated building was a new system, the decisions made in the performance compliance method resulted in a system that was much different from the ground-up construction. The quantity of fixtures on the second floor of the high school, along with associated cost estimates are shown in Table 81.

Table 81: Cost Estimate for Fire Alarm for Second Floor of High School in New Building

Activity	Unit Cost (Material/Labor)	Units	Cost
Spot-Type Smoke Detector	$175.50	14	$2,457.00
Combination Door Holder and Closer	$249.90	14	$3,498.60
Manual Fire Alarm Box	$46.50	7	$325.50
Strobe and Horn	$226.00	145	$32,770.00
Horn	$120.50	17	$2,048.50
Smoke Control Input Module	$376.50	1	$376.50
		Total Cost	**$41,476.00**

A cost estimate was also performed for the devices on the first floor of the high school. The only devices provided were horns, strobes, and manual fire alarm boxes. The quantity takeoff and cost estimate for the devices in this area are shown in Table 82.

Table 82: Fire Alarm Cost Estimate for First Floor of High School in the Renovated Building

Activity	Unit Cost (Material/Labor)	Units	Cost
Manual Fire Alarm Box	$46.50	7	$325.50
Strobe and Horn	$226.00	139	$31,414.00
Horn	$120.50	5	$602.50
		Total Cost	**$32,342.00**

The cost estimates for other system components dedicated to the overall function of the fire alarm system are presented in Table 83.

Table 83: Cost Estimate for Fire Alarm System Features in Renovated Building

Activity	Units	Cost
Fire Alarm Annunciator	1	$648.00
Fire Alarm Control Panel	1	$884.00
Intercom Systems (25 Stations)	1	$32,100.00
	Total Cost	**$33,632.00**

The final cost estimate for the fire alarm system in the ground-up constructed was computed using the same method performed for the existing building. This resulted in a cost estimate of $181,268 for the fire alarm system in the new building.

5.3.3 Smoke Control System

Since there are stages in both the high school auditorium and middle school cafetorium with floor areas greater than 1,000 ft^2 each, the provisions of Section 410 in the *IBC* must be met. The requirements concerning smoke control system include compliance with either of the two options in Section 410.3.7. Section 410.3.7.1 permits the use of roof vents, whereas Section 410.3.7.2 permits the use of a performance-based system that maintains the smoke layer interface not less than 6 feet above the highest level of the assembly seating. Although the prescriptive option seems the most reasonable when considering the design process, the common path of travel from the auditorium seating causes an engineering evaluation for both methods.

5.3.3.1 Natural Ventilation Method

Section 410.3.7.1 of the *IBC* permits roof vents as means of ventilation for the stage. These must be constructed as automatic vents that operate when heat-detection devices are activated. Although the required specifications for the heat-activated devices are not referenced, Section 910 of the *IBC* provides requirements for smoke and heat vents, which state that an automatic means of opening the vent should be performed by using gravity-operated drop-out vents. This type of vent is designed using heat-sensitive glazing that shrinks and drops out of the vent opening when exposed to fire. The heat-sensitive element is designed to fully open the vent within five minutes after the vent cavity is exposed to a simulated design fire with a time-temperature gradient that reaches an air temperature of 500ºF within five minutes (*IBC* 910.3.2.1). Other direct requirements include the use of no less than two separate vents with an aggregate area of not less than 5% of the stage area and the capability of operating the vents manually as a supplement to the automatic operation. The vent product must be listed in compliance with UL 793 *Standard for Automatically Operated Roof Vents for Smoke and Heat*. The product selected for this instance is the Bilco Type ACDSH Smoke vent, as shown in Figure 84.

Figure 84: ACDSH Smoke Vent (UL 793 Listed)

This smoke vent model is intended for concert halls and theaters, which have a STC 45 sound rating that is ideal for preventing unnecessary daylighting and sound from the outside. The product is provided with interior and exterior pull release cables to manually operate the vent, which is required by code. The positive hold/release mechanism is controlled by a 165ºF fusible link that is also UL listed.

The prescriptive method of smoke control does have complications and is a controversial topic of discussion in the fire protection industry when used in sprinklered buildings. Although not included in any jurisdictional requirements, NFPA 204 *Standard for Smoke and Heat Venting* provides guidance in the use of performance-based design. Section 11.1 of the code states, "Where provided, the design of venting for sprinklered buildings should be based on an engineering analysis acceptable to the AHJ demonstrating that the established objectives are met" (NFPA 204 11.1). This is due to the coordination between the heat-sensitive element in the vent material and the heat-operating element in the sprinkler system. The conflict arises in research that has been performed showing that the operation of the vent, which is intended for smoke control in occupant evacuation, delays the operation of the sprinkler due to the dissipation of smoke and other combustion products to the exterior of the building.

5.3.3.2 Roof Vent Design

As previously stated, two roof vents must be provided that provide an aggregate opening area of no less than five percent of the stage area. The layout of the auditorium in the high school where one of the stage resides is shown in Figure 85.

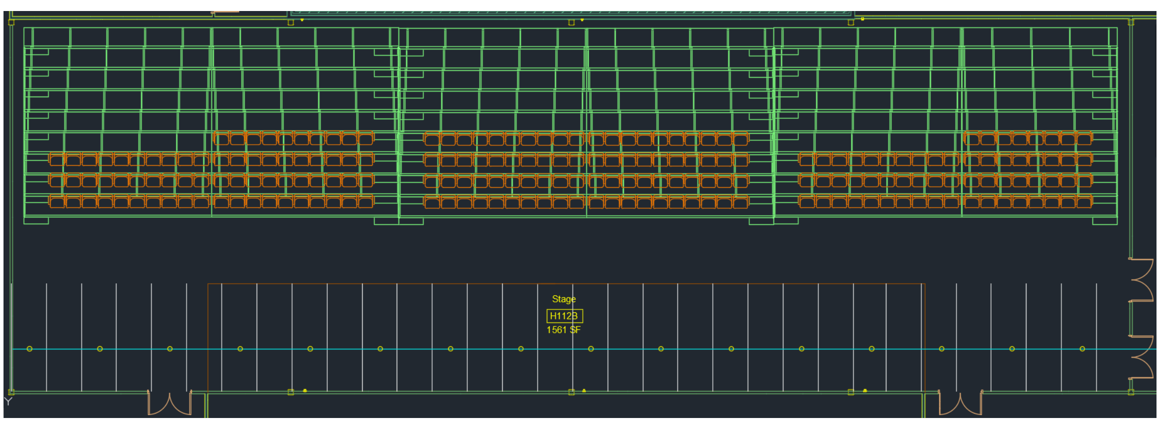

Figure 85: Layout of Auditorium and Stage in High School

As shown in Figure 85, the area of the stage is 1,561 ft^2. Therefore, 78 ft^2 of openings must be provided by the roof vents. Potential obstructions to the roof vents included the roof joists, which are represented by the white lines, the sprinklers, which are represented by the yellow circles, and the sprinkler piping, which is represented by the blue lines. The roof joists are spaced five feet on center, which means that the roof vents had to have a width less than five feet to account for the framing dimensions. The lowest opening dimension of ACDSH smoke vents is 4 ft. with an overall width of 4.5 ft. This led to the selection of 4 ft. x 7.5 ft. roof vents, which had overall dimensions of 4.5 ft. x 8 ft. The opening area provided by one vent of this size is 30 ft. Therefore, three vents of this size were provided to meet the minimum opening area requirement. The layout of these vents is shown in Figure 86.

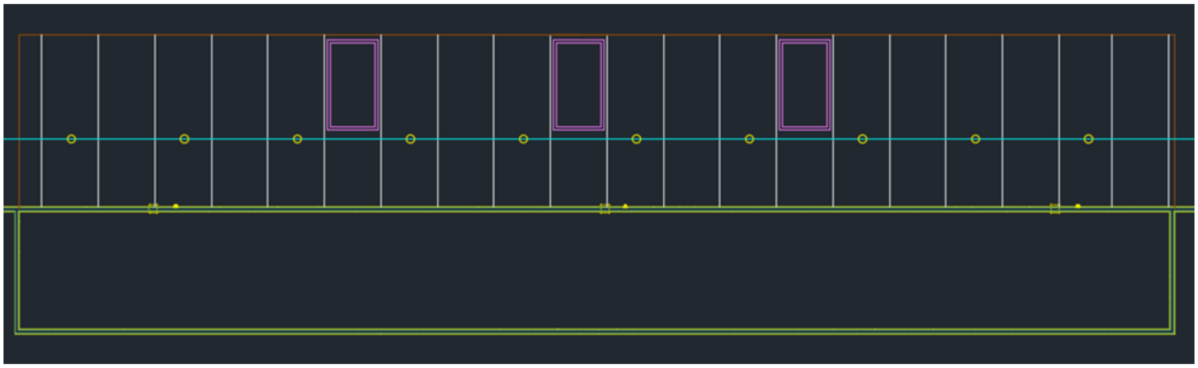

Figure 86: Smoke Vent Layout for Auditorium Stage

Since the common path of travel from the auditorium seating did not meet the acceptable distance prescribed by Section 1028.8 of the *IBC*, an engineering analysis was performed to ensure that the available safe egress time meets exceeds the required safe egress time. This was accomplished using the Consolidated Model of Fire and Smoke Transport (CFAST), which is a two-zone fire model used to calculate the evolving distribution of smoke, fire gases, and temperature throughout a compartment.

5.3.3.3 Roof Vent Activation

Since the vents will not be opened at the initial time of ignition, a preliminary hand calculation was performed to determine the time after fire ignition that the vents open. Although the vents have their own thermal actuating elements, they may also be connected to the fire alarm. This results in the vents opening upon actuation of an initiating device on the same circuit. Upon this decision, sprinkler activation was considered the primary method of actuation due to the lower RTI that they possess. An RTI of approximately 160 m-s$^{1/2}$ was used for the roof vent, which was used in a previous study for the interaction between fire curtains, sprinklers, and smoke vents in theaters, which exceeds the RTI of 80 m-s$^{1/2}$ for a standard response sprinkler (Ove Arup & Partners PC, 2009).

In order to perform the calculation of sprinkler activation, a design fire scenario was established. According to a survey involving over thirty-two theatre professionals the three primary locations of ignition for stages are at the center of the stage, the wing of the stage, and in the rigging within the fly tower (Ove Arup & Partners PC, 2009). Although the exact fuel load was not described, a fast-growing t-squared fire was assumed for this design due to the large fuel load of combustibles such as stage curtains, theater props, and the stage construction itself. A common approach is to assume that the fire growth ceases at the time of sprinkler activation, at which point it either maintains a steady heat-release-rate, or it enters a decay period (Kwon, 2014). The fire growth curve specified is shown in Figure 87. The y-axis represents the heat-release-rate in kilo-watts and the x-axis represents the time after ignition in seconds

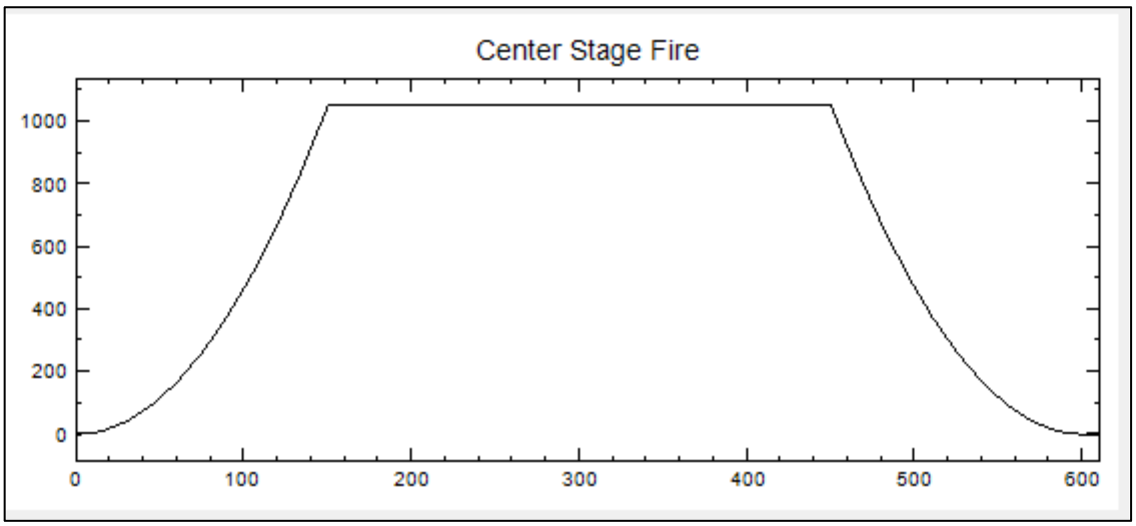

Figure 87: Design Fire Curve for Sprinkler Activation Calculation

The time to sprinkler activation was performed using the Quasi-Steady-State Model for the Heat Detection of Growing Fires, which assumes the fire behavior as a series of increasing steady heat-release rates (SFPE Handbook, 2008). The exact location of the fire was based on the worst-case scenario, in which the fire is located equidistant from four sprinklers as shown in Figure 88.

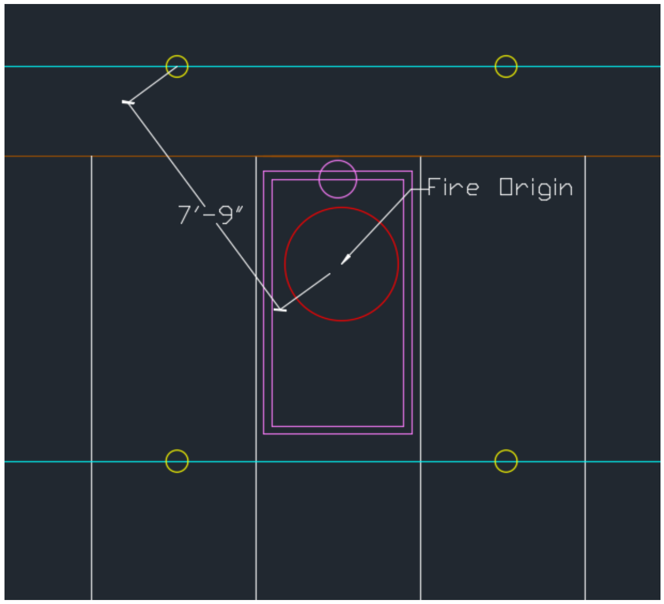

Figure 88: Location of Fire Origin in Design Fire Scenario

This method of computing the temperature of the sprinkler at a given time after ignition began by establishing a time interval to evaluate the heat-release rate at. The average heat release rate was computed at each interval of five seconds using Equation 29.

$$\text{First Step (t=0 to t=5): } Q = \alpha\left(\frac{\Delta t}{2}\right)^2$$

$$\text{Second Step (t=5 to t=10): } Q = \alpha\left(t_1 + \frac{\Delta t}{2}\right)^2$$

Equation 29: Mid-Point Heat Release Rate for Given Time Step (SFPE Handbook, 2008)

For each iteration, the ceiling jet velocity and ceiling jet gas temperature must be calculated, which are shown in Equation 30 and Equation 31 respectively. These equations are dependent on the total heat release rate computed in Equation 29 as well as the radial and vertical distances between the sprinkler and the fire origin.

$$T_g = \frac{\left[5.38\left(\frac{Q}{r}\right)^{2/3}\right]}{H}$$

Equation 30: Ceiling Jet Gas Temperature in °C (SFPE Handbook, 2008)

$$u = \frac{\left(0.20Q^{1/3}H^{1/2}\right)}{r^{5/6}}$$

Equation 31: Ceiling Jet Velocity in m/sec (SFPE Handbook, 2008)

The temperature of the detector was then calculated using the ceiling jet temperature and ceiling jet velocity, along with the temperature of the detector at the previous time interval as shown in Equation 32.

$$T_{d,n} = \left[\frac{u^{1/2}\left(T_{g,n} - T_{d,n-1}\right)}{RTI}\Delta t\right] + T_{d,n-1}$$

Equation 32: Detector or Sprinkler Temperature in °C (SFPE Handbook, 2008)

Table 84 lists all of the assumptions and design variables incorporated into the calculation.

Table 84: Design Inputs for Sprinkler Activation Calculation

Variable	Value
Sprinkler RTI	80 m-s$^{1/2}$
Sprinkler Operation Temperature	68.3 °C (155 °F)
Sprinkler Height from Floor	8.84 m (29 ft.)
Fire Height from Floor	0.91 m (3 ft.)
Height Distance Between Fire and Sprinkler	7.93 m (26 ft.)
Radial Distance Between Fire and Sprinkler	2.38 m (7.75 ft.)
Fire Growth Factor	0.044 kw/sec^2
Ambient Ceiling Temperature	20 °C (68 °F)

The calculation provided the activation of a sprinkler 225 seconds after ignition. The spreadsheets with complete calculations up to detector activation are displayed in Appendix J.

5.3.3.4 Natural Ventilation Fire Model

CFAST required several inputs to get the desired results from the fire model. The inputs for the compartment geometry are shown in Table 85.

Table 85: Compartment Geometry Inputs for CFAST Model

Property	Value
Width	160 ft.
Depth	53 ft.
Height	30 ft.
Wall Material	5/8 inch Gypsum Board
Ceiling Material	3/8 inch Carbon Steel
Floor Material	Normal Weight Concrete

The next required input values involved the details of the vertical flow vents. As stated in Section 5.3.3.2 Roof Vent Design three vents were provided, each covering of an area of 30 ft^2. The vents will open directly to the exterior of the building, and they were set to fully open 240 seconds after ignition to account for a time lag caused by the fire alarm control modules.

Other fuel properties that were specified in the model were based on a combination of natural and synthetic materials commonly present in stage scenery. These included muslin, wood, plywood, vinyl, medium-density-fiberboard, Masonite, cardboard, and wool draperies (Kwon, 2014). The fuel properties used in the model are listed in Table 86.

Table 86: Fuel Properties for Design Fuel Load of Stage Fire

Property	Value
Heat of Combustion	15,630 kJ/kg
Soot yield	0.0356 kg/kg
Carbon monoxide yield	0.021 kg/kg
Radiative fraction	0.35

The simulation was completed for 650 seconds, which was slightly longer than the calculated RSET. The highest values computed from the simulation that are related to the tenability criteria are provided in Table 87.

Table 87: Output Values from Natural Vent CFAST Model

Measurement	Time (sec)	Value
Upper Layer Height	650	14 ft.
Upper Layer Temperature	420	103 °F
CO Concentration	650	1177 ppm
Optical Density	650	0.83

Both the upper layer height and the optical density at that height did not meet the tenability criteria provided in Section
3.3.2.4.3 Tenability Criteria of this report.

5.3.3.5 Mechanical Ventilation

One of the options provided by Section 410.3.7 of the *IBC* to fulfill the emergency ventilation for stages larger than 1,000 square feet in area, is the use of a smoke control system in accordance with Section 909 of the code. The prescriptive requirement also states that the system shall be designed to maintain a smoke layer interface not less than six feet above the highest level of assembly seating. The primary method for performing this is using the mechanical exhaust method.

The design approaches that were considered for the auditorium include steady mechanical exhaust and unsteady mechanical exhaust. Steady mechanical smoke exhaust involves the design of a system sized to keep the bottom of the smoke layer at a predetermined height for the design fire, whereas unsteady mechanical smoke exhaust uses a flow rate less than steady exhaust to slow the rate of the smoke layer descent for a time that allows occupants to egress from the space (Klote, 2012). In order to obtain a conservative design a steady smoke exhaust method was used.

5.3.3.5.1 Smoke Management Calculation Procedure

The analytical methods from the 2012 Edition of NFPA 92 were used to design the smoke control system for the auditorium. Chapter 5 of the standard, provides smoke management calculation procedures that may be performed with using either algebraic equations, compartment fire models, or a combination of both. Using the same design fire scenario as used to model the natural ventilation design in Section 5.3.3.1 Natural Ventilation Method this report with the exception of the vents. The time after ignition it took for the smoke layer to descend to the initial indication of smoke was computed as 350 seconds. At this time, the height of the flame (2.50 m) was less than the distance from the base of the fire to the smoke layer interface (4.57 m). These results then required the smoke production rate to be calculated in accordance with Equation 33, which is a function of the convective heat release rate and the distance from the base of the fire to the smoke layer interface.

$$m = \left(0.071 {Q_C}^{1/3} z^{5/3}\right) + 0.0018 Q_C$$

$$m = \left(0.071(487.02)^{1/3}(4.57)^{5/3}\right) + (0.0018 \times 0.487)$$

$$m = 7.907\ kg/sec$$

Equation 33: Smoke Production Rate (NFPA 92 - Equation 5.5.1.1b)

In order to convert this the mass production rate of smoke into a volumetric flow rate, the density of the smoke at 350 seconds after ignition was computed using Equation 34, which is a function of the absolute smoke temperature, atmospheric pressure, and a gas constant.

$$\rho = \frac{P_{atm}}{RT}$$

$$\rho = \frac{4728.8}{(53.34)(42.34 + 273)}$$

$$\rho = 0.281\ kg/m^3$$

Equation 34: Density of Smoke (NFPA 92 - Equation 5.8b)

The volumetric flow rate of smoke required to maintain the height of the smoke layer interface was then computed using Equation 35.

$$V = \frac{m}{\rho}$$

$$V = \frac{7.907}{0.281}$$

$$V = 28.14\ m^3/sec$$

Equation 35: Volumetric Flow Rate of Smoke Exhaust (NFPA 92 - Equation 5.7b)

After the flow rate of the exhaust system was calculated, the minimum number of exhausts inlets providing this flow was examined. This serves the purpose of avoiding plugholing, which indicates an inefficient system as part of the exhaust fan will become occupied by clean ambient air from below the smoke layer. The maximum volumetric flow rate that can be exhausted by a single exhaust without plugholing was calculated using Equation X, which is a function of the depth of the smoke layer below the lowest point of the exhaust inlet, the absolute temperature of the smoke layer, and the absolute ambient temperature.

$$V_{max} = 4.16\gamma d^{5/2}\left(\frac{T_s - T_0}{T_0}\right)$$

$$V_{max} = 4.16(1.0)(8.23 - 4.57)^{\frac{5}{2}}\left(\frac{(42.34 - 26.02}{26.02 + 273}\right)$$

$$V_{max} = 5.82\ m^3/sec$$

5.3.3.5.2 Smoke Control Equipment

The minimum number of exhaust inlets was required for the smoke control system of the auditorium was determined by dividing the total exhaust flow required by the minimum exhaust flow required to avoid plugholing. This resulted in the need for no less than five fans. Since the products offered for this system are typically sized in cubic feet per minute (CFM), the minimum flow required was converted to 59,640 CFM, and the maximum flow provided by a single inlet could not exceed 12,335 CFM. The system specified for the auditorium was selected to consist of five centrifugal roof fans that each provide a volumetric flow rate of 12,000 CFM. The unit cost for each of these fixtures is $5,955, which resulted in a total cost of $29,775. The system also requires several other controls that are provided in the total cost estimate of the system located in Table 88.

Table 88: Total Smoke Control Equipment Cost Estimate

Activity	Unit Cost (Material/Labor)	Units	Cost
12,000 CFM Centrifugal Roof Fan	$5,955.00	5	$29,775.00
8,000 CFM Axial Flow Fan (Return Air)	$3,340.00	5	$16,700.00
Beam-Type Smoke Detector	$203.30	1	$203.30
Manual Actuating Device	$46.50	1	$46.50
Firefighter's Smoke Control Station	$1,050.00	1	$1,050.00
Input Module	$376.50	5	$1,882.00
		Total Cost	**$49,657.00**

5.4 Active Fire Protection System Results

The dissimilarity between the active fire protection system designs in the renovated building and the new building produced variations in cost. The itemized cost for each element discussed is displayed in Table 89.

Table 89: Cost Comparison for Active Fire Protection Systems

System	Renovated Design	Ground-Up Design
Sprinkler System	$394,034	$554,328
Fire Alarm System	$293,853	$181,268
Smoke Control System	-	$49,657
Total	**$687,887**	**$785,253**

The cost differences in the sprinkler systems came from the use of existing sprinkler components in the renovated design. The cost of sprinklers and the fittings required to relocate sprinklers was relatively low compared to the cost of large pipes such as cross mains, feed mains, and risers.

The fire alarm system for the renovated building was much higher due to the design criteria selected in the performance compliance method. The addition of a smoke detection system, a fire command center, and elevator recall controls resulted in a cost increase.

The smoke control system was only present in the design of the auditorium in ground-up construction. The existing building did not have to meet the provisions of Chapter 4 in the *IBC*, which requires a smoke control system for stages, nor did it have to prove that successful egress could be provided from the auditorium seating. Although the smoke vents would have been a more cost effective option for the auditorium, a CFAST fire model proved that it could not be accomplished in conjunction with the timed egress calculation, sprinkler system specifications, and compartment size. Thus, a cost of almost $50,000 was added for the active system that only protected the auditorium compartment.

The total cost was more favorable for the renovated building due to the existing sprinkler system material and the omission of the smoke control system. However, both systems could have been modified to change the cost based on the goals of the designer.

6.1.2 Renovation

6.1.2.1 Extensive vs. Intensive

The two main types of green roofs are extensive and intensive, varying in required maintenance, accessibility, material selection, additional load bearing, and associated costs. Table 90 compares the different components of extensive, simple-intensive, and intensive green roof designs. In general, extensive roofs require less maintenance, weigh less, are non-accessible, and primarily serve as a protection layer. Intensive roofs in comparison require more regular maintenance, can support a wider range of plant types, weigh more, and operate as accessible gardens and parks.

Table 90: Comparison of Different Types of Green Roof Systems

	Extensive	Simple-Intensive	Intensive
Maintenance	Low	Periodic	High
Irrigation	Just start up	Periodic	Regular
Plant Communities	• Moss, sedum, herbs, grasses • Low growing plants, hardy, self-sufficient, self-propagating	• Grasses-herbs, and shrubs	• Lawn/perennials, shrubs & trees, larger species
Plant Heights	2-12"	12-24"	12-36"+
Growing Media Depth	1.5-8" (4-6" typical)	4-20"	4-79" +
Costs	Less	Medium	More
Use/Accessibility	Ecological protection layer, non-accessible	Designed green roof	Park like garden, accessible
Storm Water Reduction	Low	Medium	High
Roof Slopes	Up to 30 degrees	--	Only on low slope/terraced
General Saturated Weights	13-30 psf	25-40 psf	35-100 + psf
Estimated Cost	$10-14 per sf.	$14-25 per sf.	$25+ per sf.

6.1.2.1.1 Green Roof Type Results

An extensive green roofing system was selected for this design. Incorporating an extensive design into the retrofit of an existing building limits the extent of structural alterations necessary to support the additional roof loading. Extensive roofs are typically non-accessible, which reduces the school's exposure to liability if students were to have access to the green roof.

6.1.2.3 Extensive Green Roof Layers

After the extensive green roof is selected, the next areas of work involve the roof cross section and its placement on the existing roof. Extensive green roof assemblies consist of the roofing membrane, a root barrier, protection layer, drainage layer, filter layer, growing medium, and vegetation. Figure 89 shows the typical assembly of an extensive system, and Table 91 explains the function of each layer.

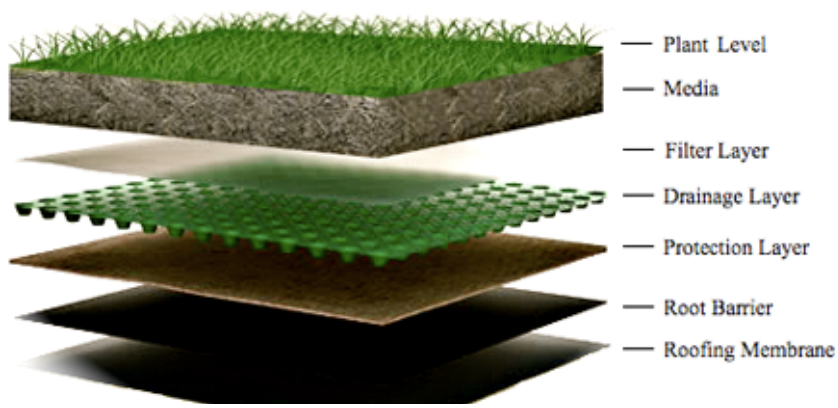

Figure 89: Extensive Green Roof Assembly (http://godfreyroofing.com)

Table 91: Functions of Extensive Roof Layers

Layer	Function
Roofing Membrane	Weathering surface, prevents leaks
Root Barrier	Prevents plant roots from damaging roof membrane
Protection Layer	Protects roof from moisture retention and decomposition
Drainage Layer	Retains water, provides outlets for excess water and aeration for plants
Filter Layer	Separates media and drainage layers, retains particles for plants, prevents drainage layer from clogging
Growing Medium	Provides optimal growing conditions over time, provides necessary root coverage, retain adequate amounts of water
Vegetation Layer	Improves aesthetic appearance, weather tolerant, reduces heat island effects

6.1.2.3.1 Roofing Membrane

There are several types of roofing membranes including Ethylene Propylene Diene Terpolymer (EPDM), Thermoplastic Polyolefin (TPO), Polyvinyl Chloride (PVC), Built-Up Roofing (BUR), Modified Bitumen, and Liquid Applied Membrane. Appendix B includes detailed description of each type. Due to their popularity in warehouse design, out of the options, EPDM and modified bitumen were considered for this design. Modified bitumen membranes consist of asphalt with added modifiers in order to give it properties similar to plastic or rubber and come in one to three ply systems. The two types of modifiers are Atactic Polypropylene (APP) and Styrene Butadiene Styrene (SBS). APP modified bitumen membranes use polyester as reinforcement and are torch applied by melting the extra layer of asphalt on the sheet so it adheres to the roof. SBS modified bitumen can use fiberglass, polyester, scrims, or a combination for reinforcement and can be applied by hot asphalt, torch, or cold process. EPDM membranes are durable, synthetic rubber, single-ply membranes comprised primarily of ethylene and propylene, which originate from oil and natural gas.

Table 92 outlines the pros and cons of both types of roofing membranes.

Table 92: Characteristics of EPDM and Modified Bitumen Roofing Membranes

Characteristic	EPDM	Modified Bitumen
Applicable for Flat Roofs	• Yes	• Yes
Pros	• Large sized sheets minimizes seams • Good root resistance • Material is moderately light • Weather resistance	• Low cost • Peel-and-stick option has easy installation • Light colored surface reflects heat • Pre-coated at factory to be reflective • Self-cleaning surface
Cons	• Poor chemical and oil resistance • Standard black absorbs heat • Light-colored coatings add 30% more to cost • Both finishes cost more than modified bitumen • Vulnerable to punctures • Delaminates with foot traffic • Must be formulated to be reflective	• Poor chemical and oil resistance • Requires root barrier • Torch down application is a fire hazard • Not as scuff resistant as rubber membrane
Common Thickness/Weight	• 45 mil., 0.29 lb/ft^2 • 60 mil., 0.40 lb/ft^2	• 1.00 – 1.75 lb/ft^2

In order to count towards LEED credits, the roofing membrane must meet certain standards to be considered a high-reflectance roof. For the portions of the roof not covered by the vegetation portion of the green roof, the membrane is exposed to solar radiation and therefore must meet LEED SRI standards. A Solar Reflectance Index (SRI) is used to measure the roofing material's ability to reject solar heat. In addition to the initial SRI value of the membrane material, LEED takes into consideration the three-year aged SRI value in order to ensure the material adequately meets standards over time. Table 93 from the LEED v4 manual outlines the SRI values that high-reflectance roof membrane materials must meet or exceed to in order to contribute towards the credit.

Table 93: Minimum Solar Reflectance Index Values by Roof Slope (LEED v4 Manual)

Roof Type	Slope	Initial SRI	3-Year Aged SRI
Low-Sloped	≤ 2:12	82	64
Steep-Sloped	> 2:12	39	32

6.1.2.3.2 Root Barrier

The two main categories of root barriers are fabrics and thermal plastics, which differ primarily in the type of root structure each can protect against. Root barriers are required if the underlying membrane is not certified as root-resistant, or if the type of membrane is unknown in the retrofit of a building. Table 94 compares the favorable and unfavorable characteristics of each type.

Table 94: Characteristics of Fabric and Thermal Plastic Root Barriers

	Fabrics	Thermal Plastic
Description	• Contains chemicals to repel root growth • Suited for shallower green roofs with sedums and succulents	• Has similar characteristics as thermal plastic roofing membranes • Placed below drainage layer
Pros	• Acts as a root barrier and retains particles of growth media • Doesn't add significant weight to the roof design	• Protects against larger plants like trees and shrubs • Creates surface resistant to water and roots when heat welded
Cons	• Doesn't protect against larger plants	• More expensive than fabrics

6.1.2.3.3 Protection Layer

The purpose of a protection layer is to ensure the roof is not damaged by moisture or decomposition over time. The most common type is Extruded polystyrene (XPS) boards, but other forms include gypsum-based cover boards and fesco boards. Table 95 outlines the pros and cons of these three types of protection layers.

Table 95: Comparison of Types of Protection Layers

	Gypsum-Based	Fesco Board	Extruded Polystyrene
Pros	• Protects insulation during membrane installation • High point load durability	• Protects insulation during membrane installation • Lighter than Gypsum-Based	• Serves as insulation and protection board when installed above membrane • Recyclable product • Long-term R-value
Cons	• Must be dry • Installed below roof membrane • Requires an insulation layer	• Must be dry • Installed below roof membrane	• Will deteriorate if exposed to sunlight • Can't handle temperatures > 250 F

6.1.2.3.4 Drainage & Filter Layer

The drainage layer of an extensive green roofing system serves multiple purposes that can include water retention, drainage, aeration, and soil hydration. Certain systems retain water to aid in growing medium hydration as well as reduce storm water runoff. Drainage layers are designed to direct excess water off of the roof in order to reduce additional roofing loads during high precipitation events and avoid over hydration of the vegetation. The main types are aggregate, geo-textiles, and combination drain core and root barriers. Aggregate drainage layers are primarily popular in Europe and not in the US due to their labor intensity, high cost, and weights exceeding 4 pounds per square foot (Luckett, 2009) and will not be considered for this design. Table 96 compares geo-textile and combination drainage layer materials.

The filter layer of a drainage system serves to separate growing media and drainage in order to prevent clogging. Filter layers also retain necessary nutrient particles to support plant growth. It is common practice for manufacturers to combine the filter layer with the drainage system.

Table 96: Comparison of Drainage Layer Systems

	Geo-Textiles	Combination Drain Core/Root Barriers
Pros	• Lightweight • Unrolls on roof surface for application • Provides drainage passageways	• Simple and most common • Unrolls on roof for application • Serves as protection board, drainage layer, and root barrier • Provides water retention, drainage passage, and root protection
Cons	• Requires a root protection barrier layer • Requires a filter fabric layer • Does not store water	• Drainage cups must be placed facing upwards in order to retain water

6.1.2.3.5 Growing Media

The growth media serves to support the vegetation and varies in depth based on roof type and plant selection. Engineered growth medias are divided into two categories: commercial blend and custom blend. Commercial blends tend to be more expensive but can include additional unnecessary ingredients for the specific design. They also have readily available saturated weights, making additional load bearing calculations simpler for ensuring structural integrity. Custom blends, in comparison, allow for a greater control of ingredients in order to be designed to specifically match the needs of the project.

In general, growing medias should be lightweight and sustainable in order to support vegetation growth over long periods of time. In order to prevent the breakdown of material over time and provide enough nutrients to the vegetation, medias are designed to be of 80% mineral material and 20% organic material (Lundholm and Maclvor, 2010). For extensive roofs, expanded age pumice and volcanic rock are commonly used as lightweight minerals that have enough pore space to hold adequate amounts of water for plant growth. Organics tend to decompose over time resulting in a loss of media depth, which can expose plants roots and be detrimental to the sustainability of the green roof system. Typically the organic material will breakdown after three to five years, but the continual decomposition of plant foliage provides enough additional organic materials to sustain the depth of the growth media (Lundholm and Maclvor, 2010).

The growing media depth varies with the type of green roof being designed. For an extensive roof, the depth is typically between three and six inches and can support low growing plants with 2 to 12 inch heights with shorter roots. In comparison, media depths for intensive systems range from approximately 4 to 80 inches and can therefore support larger plants with heights around three feet. This difference in media depth is the main factor in the additional roof loads the system will impose.

6.1.2.3.6 Vegetation

The selection of proper vegetation for a design is primarily based on the type of green roof and the climate of the region it is being designed for. According to Section 6.1.2 of ASTM Standard E-2400, "extensive green roofs are limited to using herbs, grasses, mosses, and drought tolerant succulents such as sedum." The aesthetic goals of the project also influence the selection of which of the acceptable plant species to use. Typically annuals, perennial flowering plants, and grasses require additional irrigation and maintenance in order to uphold their appearance in varying weather conditions year round. Succulent plants such as sedum, sempervivum, and delosperma do not require additional irrigation and have a higher tolerance to varying weather. Due to their ability to store large amounts of water in their leaves, succulents also do not pose a fire risk during extended dry weather spells. The type of plants used also influences the load impact of the design. Table 97 summarizes the typical weights of three plant categories based on height.

Table 97: Weights of Green Roof Plant Types

Plant Type	Typical Weight
Sedums and Succulents	2 lb/ft^2
Grasses and Bushes – Up to 6 in. High	3 lb/ft^2
Shrubs and Bushes – Up to 3 ft. High	4 lb/ft^2

Climate is one of the largest influences in plant selection for green roof systems. The United States Department of Agriculture (USDA) has developed a plant hardness zone map that shows which plants are likely to thrive in each location based on average annual, minimum winter temperatures. Massachusetts is comprised of hardiness zones 5a through 7b, ranging in minimum temperatures from -20^{o}F in the northwest corner of the state to 10^{o}F in the southeast coastline, as shown in Figure 90. The school is located in zone 5b or 6a, and the plant choices must be capable of withstanding harsh winters and cold temperatures so they grow back each year to encourage sustainability of the design.

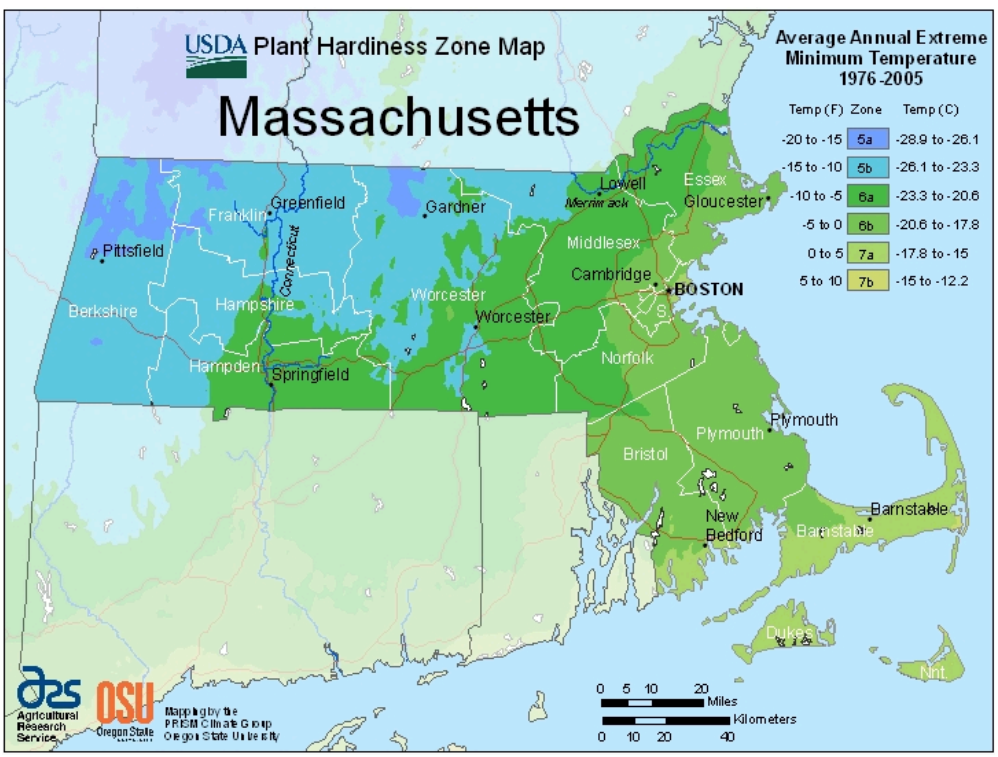

Figure 90: USDA Plant Hardiness Zone Map for Massachusetts (http://planthardiness.ars.usda.gov)

6.1.2.4 Green Roof Layer Results

Based on the information outlined in the above sections, materials were selected for each layer of the green roof design. The resulting design incorporates a modified bitumen roofing membrane underlying an extruded polystyrene protection layer. A combination drain core system was specified to address the drainage, root barrier, and filter fabric layers. To ensure proper growth during each season, various species of sedum were selected for the vegetation layer which is supported by a three-inch commercial blend growing media.

6.1.2.4.1 Roof Membrane

A modified bitumen roofing membrane was chosen over an EPDM membrane due to its lower cost and not requiring an additional coating in order to be reflective. For the retrofit of the existing building, it was assumed that this membrane layer is pre-existing based off Google map images and literature review. From this assumption, Polykool's White Reflective Modified Bitumen Roofing Membrane was selected. The Polykool membrane consists of a white reflective cap sheet that helps reduce building energy costs and mitigates the heat island effect. Other benefits of this material include the Adeso self-adhered technology that doesn't produce fumes during installation and a self-cleaning surface that reduces maintenance requirements (Polyglass, 2011). The SRI value is 92 and the 3-Year Aged SRI value was estimated to be 64.46 using Equation 36 below, both of which comply with the minimum values for low-sloped roofs in Table 93. Equation 36 was obtained from *Guidelines for Selecting Cool Roofs* by Urban and Roth.

$$SRI_{Aged} = 0.7(SRI_{initial} - 0.2) + 0.2$$

Equation 36: Aged Solar Reflectance Index Estimation

6.1.2.4.2 Protection Layer

For the retrofit of the building, the protection material must be installed above the pre-existing roofing membrane. Extruded Polystyrene (XPS) is the only option out of the three most commonly used protection materials with this capability. XPS was also chosen for its recyclability, high thermal resistance, and ability to also serve as an insulation layer when installed above the roofing membrane. Specifically, a Kingspan GreenGuard PB4 XPS Protection Board was selected for this project. This XPS board has plastic capsheets capable of resisting puncture and a high compressive strength. It also resists both moisture and decomposition due to exposure to chemicals present in the growth media (Green Guard, 2015). Table 98 lists some specific product data for the material.

Table 98: Protection Material Product Data (http://www.trustgreenguard.com)

Property	Value
Thermal Resistance, R (^oF-ft^2-h/Btu)	1.00
Thermal Conductivity (Btu-in/hr-ft^2-^oF)	0.25
Water Vapor Permeance (perm)	0.60
Water Absorption (Max % by Volume)	0.40
Compressive Strength (psi @ 10% Deflection)	16.00
Flame Spread	25
Max Recommended Use Temp. (^oF)	165
Weight (lbs/1,000 ft^2)	80

6.1.2.4.3 Drainage Layer/Root Barrier/Filter Fabric

Although geotextile drainage layers are lightweight, this perceived advantage is often offset by the need for both a filter fabric layer and a root barrier layer. Due to this, a combination drain core system was chosen for this design. This type of system is also most common due to its easy installation and combined ability to retain water for plant hydration while offering drainage for excess water. Other favorable features of this type of system are the incorporation of a root barrier to protect the membrane and a filter layer to prevent clogging and retain necessary particles for plant growth.

The Henry DBR50 Water Retention & Drainage with Root Barrier system was selected for this design. Most products have similar core properties such as compressive strength and water storage capacity. The Henry DBR50 was compared to the Ram Drain 1241, as shown in

Table 99, and was chosen due to a high recycled content of 63%, which can help further contribute to LEED credits. The root barrier fabric is comprised of a polypropylene material with a copper hydroxide coating, the core drainage of a high impact polystyrene, and the protection fabric of needle-punched non-woven polypropylene.

Table 99 outlines more detailed product data information.

Table 99: Drainage Layer Product Data (http://us.henry.com, http://barrettroofs.com)

Property	Henry DBR50	Ram Drain 1241
Thickness (inches)	0.44	0.44
Compressive Strength (lbs/ft^2)	15,000	15,000
Water Storage Capacity (gal/ft^2)	0.06	0.06
Horizontal Flow, Gradient 1 (gpm/ft^2)	16	16
Recycled Content (%)	63	Not Listed

6.1.2.4.4 Growing Media

For simplicity a commercial blend growing media from WaterGrip was chosen over a custom blend. This type of growth media is delivered in lightweight, ready-to-plant blocks that reduce labor costs for installation and is ideal for retrofit projects. The media is capable of holding up to eight times its weight in water, resulting in high stormwater retention, enhancing vegetation growth. WaterGrip media also maintains adequate porosity levels over time, inhibiting compaction that could expose plant roots. This media comes in three-inch thick blocks, which are capable of supporting the short roots typical of extensive roof plants (Water Grip, 2013). Table 100 compares WaterGrip growth media to estimations for a typical aggregate media that would be used for an extensive roof system.

Table 100: Growing Media Product Comparison (http://watergripmedia.com)

Property	WaterGrip Media	Common Aggregate Media
Media Thickness	3 in.	4 in.
Saturated Weight at Max WHC	11.8 lb/ft^2	22.7 lb/ft^2
Water Held	10.5 lb/ft^2	5.4 lb/ft^2
Percent Water Held	892%	131%

6.1.2.4.5 Vegetation

As per ASTM standard E-2400, extensive roofs are capable of supporting herbs, grasses, mosses, and drought tolerant succulents. However, due to their ability to thrive in weather extremes and most climates, sedums were selected for this design. The Worcester area falls under a Hardiness Zone 5b and 6a. Table 101 represents a small portion of the sedum species that are applicable for this project based on hardiness zone. Although some of the earlier ones in the list have better drought tolerance and disease resistance, they also die off in the winter. For aesthetic purposes it is important to incorporate a mixture between high drought and disease tolerance as well as sedums that remain blooming in the wintertime.

Table 101: Sedum Species Options for Design (http://www.greenroofplants4u.com)

Sedum Species	Hardiness Zone	Description	Dimensions (Height x Diameter)
Allium Schoenpraesum	4-9	• Pale purple flowers in spring • Excellent drought tolerance • Dies in winter • Excellent disease resistance	12in. x 6in.
Sedum Ellecombianum	4-9	• Blooms yellow in summer • Dies in winter • Excellent drought tolerance • Disease resistant	6in. x 8in.
Sedum Spurium Fuldaglut	4-9	• Foliage red/green • Burgundy leaflets in winter • Moderate drought tolerance • Moderate disease resistance	4in. x 8in.
Sedum Kamtschaticum	4-9	• Yellow flowers in summer • Dies back in winter • Moderate drought tolerance • Moderate disease resistance	3in. x 12in.
Sedum Rupestre Angelina	4-9	• Colorful without flowering • Yellow/Orange/Red in winter • Moderate drought tolerance • Moderate disease resistance	4in. x 6in.+
Sedum Album France	4-9	• Blooms white in summer • Turns yellow/pink in winter • Moderate drought tolerance • Moderate disease resistance	4in. x 8in.
Sedum Reflexum Blue Spruce	4-9	• Yellow flowers in summer • Turns gray/pink in winter • Excellent drought tolerance • Moderate disease resistance	5in. x 6in.

6.1.2.2 Roof Layout Design

Once the materials for each layer were selected, the layout of the green roof was determined. This design took into consideration the additional load of the vegetated sections and focused on placement that minimized structural alteration needed. Two options of varying vegetation area were considered.

6.1.2.2.1 Additional Loads

From the selected materials, a list of the additional load each roof layer would impose on the roof structure was compiled in Table 102. Since it was assumed the modified bitumen roofing membrane is pre-existing, the weight of that layer was excluded.

Table 102: Saturated Weight of Each Roof Layer

Green Roof Layer	Saturated Weight (lbs/ft^2)
Protection Material	0.08
Drainage, Root Barrier, & Filter Fabric	0.70
Growth Media	11.80
Vegetation	2.00
Total	**14.58**

6.1.2.2.2 Design Options

The design of the green roof took into consideration additional loads, locations of pre-existing structural columns, accessibility for maintenance, and aesthetics. Both design options place the vegetated green roof towards the front of the building behind the office space section, as shown in Figure 91. This allows visibility of the vegetation from street level. Design option one includes 21,000 square feet of vegetated roof while option two accounts for 28,800 square feet.

Figure 91: Green Roof Design Options

To reduce the structural alterations needed to support the added weight of a green roof, the vegetation was divided into 36-foot by 50-foot sections to be placed in between the pre-existing structural columns. This allows for roughly three-foot wide pathways between the sections East to West and four-foot wide pathways North to South in order to increase accessibility for maintenance and repair purposes. Design option one divides the 21,600 square feet into twelve sections while option two splits the 28,800 square feet into sixteen sections. This is illustrated in Figure 92 and Figure 93.

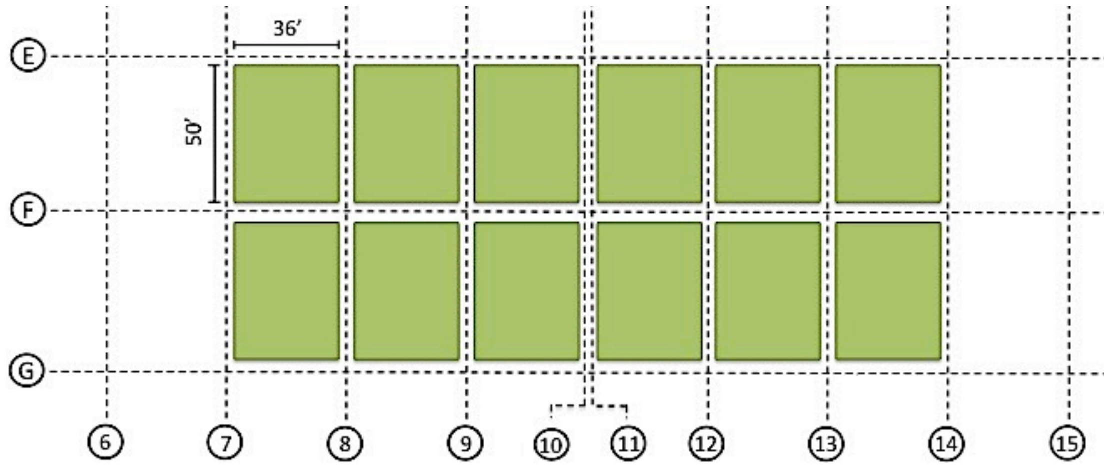

Figure 92: Detailed Sketch of Green Roof Design Option 1

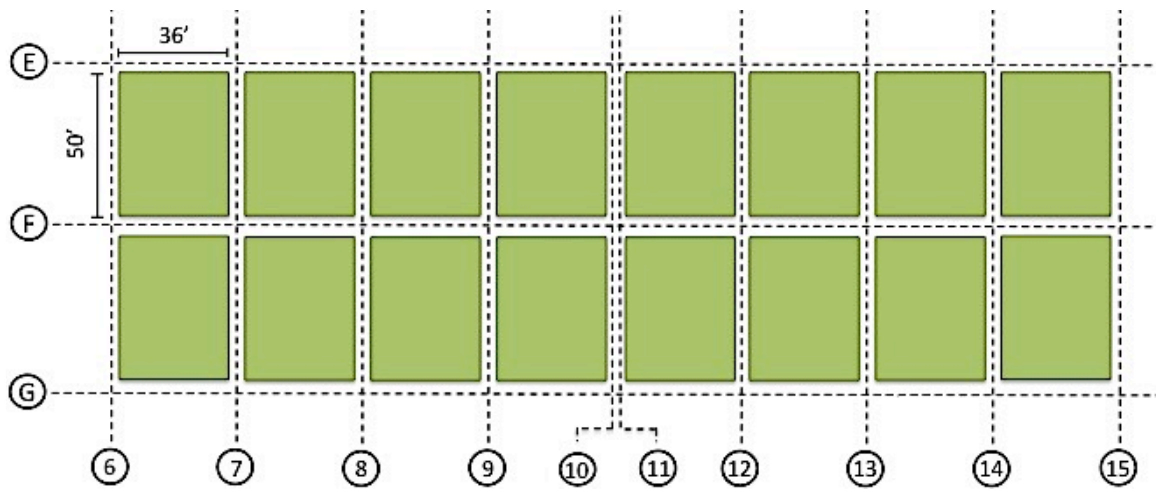

Figure 93: Detailed Sketch of Green Roof Design Option 2

The total additional load for each design option was then calculated using the previously calculated unit weight of 14.58 lbs/ft^2 for the green roof layers. The results are summarized in Table 103.

Table 103: Area and Loads of Green Roof Design Options

Design Option	Area of High Reflectance Roof (ft^2)	Area of Vegetated Roof (ft^2)	Total Added Load (lb)
1	207,312	21,600	314,928
2	200,112	28,800	419,904

Due to the placement of the vegetated section within the bays, the structural alterations for both designs are fairly minimal, reducing the significance of additional loading between the two options. Since vegetation is more effective in mitigating the urban heat island affect than reflective roofing, design Option 2 was selected since it incorporates a larger area of vegetation.

6.1.2.3 LEED Credit Achievement

In order to determine whether or not the chosen green roof design would meet the requirements to achieve the Heat Island Reduction LEED Credit, Equation 37 was used. For this equation, areas of non-roof measures include shading with plants, vegetated planters, shading structures with energy generation, shading architectural structures, vegetated shading structures, high-reflectance paving, and open-grid paving. Specifics on each can be found in Appendix B.

$$\frac{A_{Nonroof\ Measures}}{0.5} + \frac{A_{High\ Reflectance\ Roof}}{0.75} + \frac{A_{Vegetated\ Roof}}{0.75} \geq A_{Total\ Site\ Paving} + A_{Total\ Roof}$$

Equation 37: Standard Roof Calculation (LEED v4)

To reduce the total amount of paving on the site, a 125-foot by 275-foot section of the existing pavement located by the middle school area was replaced with a grass-covered recreational area for the students. Taking this into account, Google Maps was used to estimate the total area of paving on the site. To contribute towards non-roof measures, trees will be planted in the pre-existing islands in the front parking lot and along the edges of the lot. The shading these trees would contribute was estimated to be 4,500 square feet. Based on LEED non-roof strategies, high reflectance paving must have a three-year aged SR value of at least 0.28 or initial SR of at least 0.33. Therefore, it was assumed the walkways located along the edge of the building have a three-year SR value of 0.30 in order to contribute towards non-roof measures. LEED outlines Using Google Maps, this area was estimated to be 2,500 square feet. Table 104 summarizes the calculated areas that contribute towards this credit. Figure 94 further illustrates these areas on a view of the site layout.

Table 104: Design Areas for Green Roof Options

		Area (ft^2)	
		Option 1	Option 2
Non-roof Measures	Shading By Tree Canopy	4,500	4,500
	Walkway w/ SR of 0.30	2,500	2,500
High Reflectance Roof		207,312	200,112
Vegetated Roof		21,600	28,800
Total Site Paving		88,300	88,300
Total Roof		228,912	228,912

Figure 94: Site View of the Areas Contributing to the Heat Island Reduction LEED Credit

Using Equation 37 and the data from Table 104, the summation of area contributing towards the credit for both options was calculated to be 319,216 square feet, which is greater than 317,212 square feet, the sum of total site paving and roof areas. Therefore, both Option 1 and 2 will contribute towards this LEED credit. Sample calculations are located in Appendix B.

6.1.3 Ground-Up Construction

A green roof design similar to that for the renovation was considered for the ground-up construction with the roof membrane layer material being the only alteration. An EPDM roof membrane was incorporated into the design of the new construction instead of the modified bitumen membrane used for the renovation design. Using the LCA software, it was determined an EPDM membrane has an overall lower environmental impact than a modified bitumen membrane as explained in the following section.

6.2 Materials and Resources-Building Life Cycle Impact Reduction

The Building Life-Cycle Impact Reduction LEED credit addresses the local, regional, and global environmental effects buildings have during their lifetime. A Life-Cycle Assessment (LCA) identifies different strategies for reducing the detrimental effects of a building on the environment. For a whole building analysis, this assessment takes into consideration global warming potential, stratospheric ozone depletion, use of land and water sources, eutrophication, formation of tropospheric ozone, and the depletion of nonrenewable energy sources. The Athena EcoCalculator for Commercial Assemblies was utilized as an LCA tool to determine the affects the existing building has on the environment over a 60-year period. These results were then used to pinpoint areas of improvement for the renovation of the warehouse into a middle and high school. The following section summarizes these results.

To determine if the designs for both the renovation and ground up construction meet the requirements of this LEED credit, Option 4 for whole-building life-cycle assessment was followed. This method requires a new design to achieve at least a 10% reduction in at least three impact categories, one of which must be global warming potential, in comparison with the baseline design. It also states that no impact category can increase by more than 5% from the baseline results. In order to ensure comparable results, the baseline and proposed building designs have to be of similar size considering a lifetime of at least 60 years using the same LCA software.

6.2.1 Environmental Impact Categories

The seven impact categories the Athena EcoCalculator takes into consideration for the sixty-year environmental impact assessment are as follows (Athena Software, 2014):

1. **Fossil Fuel Energy Consumption** – An estimated total fossil fuel energy consumption used for the extraction, processing, transportation, construction, and disposal of each material.
2. **Global Warming Potential –** An estimated amount of total greenhouse gases generated.
3. **Acidification Potential** – An estimated amount of acid-forming chemicals created.
4. **Human Health Criteria –** An estimated quantity of airborne particles linked to asthma, bronchitis, acute pulmonary disease, and other respiratory diseases.
5. **Aquatic Eutrophication Potential –** An estimated amount of water-nitrifying substances that result in the proliferation of photosynthetic aquatic species.
6. **Ozone Depletion Potential** – An estimated amount of ozone-depleting substances generated, such as CFC's, HFC's, and halons.
7. **Smog Potential** – An estimated amount of chemicals that produce photochemical smog and ground-level ozone if exposed to sunlight.

The various material options for each assembly were assessed based on their contribution towards these seven impact categories to determine the best options based on the lowest environmental impacts. The following sections outline the life-cycle assessment process and results for the existing, renovation, and ground-up construction buildings.

6.2.2 Baseline Life-Cycle Assessment

The Athena EcoCalculator generates an environmental impact summary based on areas and volumes of seven building assemblies: foundations and footings, columns and beams, intermediate floors, exterior walls, windows, interior walls, and the roof. Due to limited availability of information, the square footage of windows for the existing building only includes those in the office portion of the building. A window frame type also had to be assumed based on characteristics of each option. Table 105 summarizes the disadvantages and advantages of each frame type. Based on these specifications, an aluminum frame type was assumed due to its durability and common use in commercial and institutional buildings.

Table 105: Advantages/Disadvantages of Window Frame Types (Allen and Iano, 2009)

Frame Type	Advantages	Disadvantages
Aluminum	• Strong, easy to form and join • Less susceptible to moisture damage than wood • Durable finishes don't require repainting • Popular for commercial/institutional buildings • Extrusion process results in aesthetically pleasing profiles	• Conducts heat rapidly, requires a plastic or synthetic rubber thermal break • More expensive than wood or plastic
Wood	• Moderate thermal insulator • Consistently strong if knot free	• Shrinks/swells with moisture content changes • Requires periodic repainting • Decay from exposure to weather, leakage, and condensation • Knot free wood is becoming rare and expensive
Vinyl-Clad Wood	• Improves the weather resistance of wood frames • Reduces maintenance requirements • Most popular type out of wood framed windows	• Not as aesthetically pleasing
Plastic	• Never requires painting • Good thermal insulators • Less expensive than wood or wood clad frames	• Not as stiff/strong as other frame types • Has a high coefficient of thermal expansion
Vinyl	• Most common is polyvinyl chloride (PVC, vinyl) • Made with a high proportion of inert filler material to minimize thermal expansion/contraction	• Expands 15 times more than wood and 3 times more than aluminum frame types

For the foundation slab, the calculator assumes a four-inch concrete slab. However, the existing building involves a five-inch slab so the equivalent square footage was input, accounting for an equivalent volume of concrete. For the columns and beams assembly, the square footage of roof or floor slab supported by each column/beam system was input assuming non-load bearing exterior walls. Since the existing building does not have any intermediate floors, this assembly was not incorporated into the environmental impact summary. Material schedules were generated from the structural *Revit* model to calculate these values, which are summarized in Table 106.

Table 106: LCA Baseline Assembly Type Inputs

Assembly Type	Description	Square Footage	Volume (yd^3)
Foundations & Footings	Foundation Wall – Concrete Block	4,305.0	-
	Foundation Slab - 4" Poured Concrete	21,371.9	-
	Footing - Poured Concrete	-	218.2
Columns & Beams	HSS Column / WF Beam	159,00.0	-
	WF Column / WF Beam	44,520.0	-
Exterior Walls	Brick Cladding, 8" Concrete Black, Continuous Insulation + Polyethylene Membrane	21,381.4	-
	Brick Cladding, R-7.5 Continuous Insulation Sheathing, 2x4 Steel Stud 16" o.c., R-13 Cavity Insulation + Polyethylene Membrane, Gypsum Board + Latex Paint	3,562.9	-
	EIFS, Gypboard Sheathing, 2x4 Steel Stud 16" o.c., Polyethylene Membrane + Gypsum Board + Latex Paint	30,149.6	-
	Curtainwall: Opaque Glazing, w/ Insulated Backpan	5,220.7	-
Windows	Aluminum Frame	108.0	-
Interior Walls	1-5/8" x 3-5/8" Steel Stud 16" o.c., 5/8" Gypsum Board + 2 Coats Latex Paint	41,322.7	-
Roofs	Modified Bitumen Membrane, R-20 Continuous Insulation + Polyethylene Membrane, Open-Web Steel Joist w/ Steel Decking, Gypsum Board + Latex Paint	214,137.0	-

6.2.2.1 Baseline LCA Results

The results of the benchmark life-cycle assessment for the existing warehouse are summarized in

Table 107 and Table 108. The top three areas of environmental impact are fossil fuel consumption, eutrophication potential, and acidification potential while the roof, columns and beams, and exterior walls are the primary assemblies contributing to these impact categories. The breakdown of the results in

Table 107 shows the roof has the largest impact on fossil fuel consumption and acidification potential while the column and beam assemblies impact the eutrophication potential of the building the most. Since the LEED credit focuses on an improvement in impact categories between proposed and baseline designs, there is not a threshold for the desired values for each impact category. The values summarized in Table 108 will therefore be utilized to determine if the proposed renovation and ground-up construction designs meet the credit requirements for reduction percentages. Full results from this assessment are located in Appendix B.

Table 107: Baseline LCA Total Environmental Impact Categories

Environmental Impact Category	Total
Fossil Fuel Consumption (FF), MJ	68,644,862
Global Warming Potential (GWP), tons CO_2eq	2,986
Acidification Potential (AP), moles of H^+eq	1,024,468
Human Health Criteria (HH), kg PM10 eq	16,672
Eutrophication Potential (EP), g N eq	1,385,016
Ozone Depletion Potential (ODP), mg CFC-11 eq	10,848
Smog Potential (SP), kg No_x eq	113,267

Table 108: Contributions to the Baseline LCA by Assembly Type

Assembly Type	Percentage of Total Contribution						
	FF	GWP	AP	HH	EP	ODP	SP
Foundations & Footings	2%	6%	5%	4%	3%	15%	9%
Columns & Beams	16%	19%	19%	5%	48%	0%	13%
Exterior Walls	20%	25%	25%	58%	12%	22%	38%
Windows	0%	0%	0%	0%	0%	0%	0%
Interior Walls	2%	3%	2%	5%	2%	1%	2%
Roof	60%	47%	48%	27%	35%	62%	37%

6.2.3 Renovation Life-Cycle Assessment

Reducing the environmental impact of an existing building through renovation serves as a challenge. The three largest assembly types contributing to the detrimental environmental impact of this building are areas that won't necessarily be changed through the renovation. The existing open-web steel joist roof cannot be changed to a different roof type without significant demolition that would add unnecessary costs and construction time to the project. Currently, the warehouse has a high reflective modified bitumen membrane that contributes to the Heat Island Reduction LEED category. Although this membrane could be replaced with a different high reflective membrane with a lower environmental impact, this process would also add to construction cost and time. Similarly, the replacement of the existing exterior walls would also require substantial demolition that is not necessary from a structural point of view since they sufficiently enclose the building. The existing design incorporates WF beams and HSS and WF columns. Since changing these would require unnecessary demolition and associated expenses these two assembly types will not be altered. Any additions or changes necessary to maintain structural integrity for the renovation will incorporate the use of WF beams and either HSS or WF columns to ensure design continuity.

Although the scope is limited for reducing the environmental impact of the building, there are some measures that can be taken. For example, the renovation from a warehouse to a middle and high school requires the addition of windows throughout the building in order to provide daylight in the classrooms and foster a suitable learning environment. However, according to the National Renewable Energy Laboratory, solar heat gain and cold weather heat loss from windows accounts for approximately one third of U.S. building heating and cooling electrical loads (Allen and Iano, 2009). Therefore, the type of window frame chosen must be thermally efficient while still minimizing environmental impacts as well as associated maintenance and installation costs. Since the existing office area will primarily be maintained with few alterations, the existing aluminum frame windows will be preserved. However, all new windows will incorporate PVC vinyl frames. Currently, PVC vinyl frames are the most popular frame type due to their thermal efficiency and recycling capability, which increases their sustainability factor (Allen and Iano, 2009). Although aluminum frames are also recyclable, they have higher environmental impacts than vinyl frames in each impact category. They also must be thermally broken in order to be thermally efficient, which complicates the wall detail and construction process. Although vinyl clad wood frames have lower fossil fuel, acidification, and ozone depletion impacts than vinyl frames, there are several issues surrounding wood sustainability in construction. In most cases with buildings being demolished that incorporate wood frames into the design, the windows and frames are sent to landfills or incinerators rather than being recycled.

6.2.3.1 Renovation LCA Results

Using the *Revit* model created for the design for the renovated building, material schedules were created to input into the LCA calculator. This information is summarized in Table 109. As stated previously, the existing aluminum window frames in the office section were kept for the renovation design. Since a full schedule of windows throughout the existing warehouse portion of the building was not available, the location and quantity of new PVC windows was not included in any of the new designs for consistency purposes.

Table 109: LCA Renovation Assembly Type Inputs

Assembly Type	Description	Square Footage	Volume (yd^3)
Foundations & Footings	Foundation Wall – Concrete Block	4,305.0	-
	Foundation Slab - 4” Cast-in-Place Concrete	22,410.6	-
	Footing - Cast-in-Place Concrete	-	413.3
Columns & Beams	HSS Column / WF Beam	271,400.0	-
	WF Column / WF Beam	89,040.0	-
Intermediate Floor	Elevated Concrete Slab	156,393.4	
Exterior Walls	Brick Cladding, 8” Concrete Black, Continuous Insulation + Polyethylene Membrane	21,381.4	-
	Brick Cladding, R-7.5 Continuous Insulation Sheathing, 2x4 Steel Stud 16” o.c., R-13 Cavity Insulation + Polyethylene Membrane, Gypsum Board + Latex Paint	3,562.9	-
	EIFS, Gypboard Sheathing, 2x4 Steel Stud 16” o.c., Polyethylene Membrane + Gypsum Board + Latex Paint	30,149.6	-
	Curtainwall: Opaque Glazing, w/ Insulated Backpan	5,220.7	-
Windows	Aluminum Frame (existing)	108.0	-
Interior Walls	1-5/8” x 3-5/8” Steel Stud 24” o.c., 2 x 5/8” Gypsum Board + 2 Coats Latex Paint	323,635.0	-
	6” Concrete Block, 2 Coats Latex Paint	162.3	
Roofs	Modified Bitumen Membrane, R-20 Continuous Insulation + Polyethylene Membrane, Open-Web Steel Joist w/ Steel Decking, Gypsum Board + Latex Paint	214,137.0	-

Table 110 and Table 111 below summarize the results from the LCA calculations, showing fossil fuel consumption, eutrophication potential, and acidification potential are the main contributors towards the buildings overall environmental impact. The roof, intermediate floors, and exterior walls are the main contributors towards the overall environmental impact of the building. The baseline building had the same results for largest areas of impact with the exception of the column and beams assembly contributing largely towards the overall impact since an intermediate floor was not present. For the renovation building, the roof remained the main contributor towards fossil fuel consumption, however, the main contributor towards acidification potential and eutrophication potential shifted to the intermediate floor assembly. Table 110 shows the percent change between the renovation and baseline designs for each impact category. It is important to note that the large percent change is primarily due to significant change in design. The addition of a second floor largely contributed towards the buildings environmental impact, making it difficult to compare the two designs solely on the percent change in impact categories. According to LEED guidelines, the two buildings must be of similar size and function for comparison. Therefore, to ensure a credible comparison, the renovation LCA results will be compared to the ground-up construction results later in this report.

Table 110: Renovation LCA Total Environmental Impact Categories

Environmental Impact Category	Renovation Total	Baseline Total	Percent Change
Fossil Fuel Consumption (FF), MJ	113,992,747	67,230,145	69.6%
Global Warming Potential (GWP), tons CO_2eq	6,446	2,914	54.8%
Acidification Potential (AP), moles of H^+eq	2,024,622	999,543	50.6%
Human Health Criteria (HH), kg PM10 eq	32,100	16,560	48.4%
Eutrophication Potential (EP), g N eq	2,867,200	1,299,205	54.7%
Ozone Depletion Potential (ODP), mg CFC-11 eq	30,642	10,848	64.6%
Smog Potential (SP), kg No_x eq	292,003	111,336	61.9%

Table 111: Contributions to the Renovation LCA by Assembly Type

Assembly Type	Percentage of Total Contribution						
	FF	GWP	AP	HH	EP	ODP	SP
Foundations & Footings	2%	4%	3%	3%	2%	7%	5%
Columns & Beams	17%	15%	17%	5%	41%	0%	9%
Intermediate Floors	20%	35%	29%	27%	22%	59%	47%
Exterior Walls	12%	12%	13%	30%	6%	8%	15%
Windows	0%	0%	0%	0%	0%	0%	0%
Interior Walls	13%	12%	13%	21%	12%	4%	10%
Roof	36%	22%	25%	14%	17%	22%	14%

6.2.4 New Construction Life-Cycle Assessment

Utilizing the Athena EcoCalculator during the design process for the ground-up construction of the same layout for the middle and high school allows the materials to be chosen based on their corresponding environmental impacts. The material options for each assembly type can be assessed and compared for their effect in each impact category. These results can then be incorporated into the material selection process in order to further reduce the extended environmental impact of the building.

6.2.4.1 Foundations and Footings

If ground-up construction of the school uses a design similar to the renovation, then similar quantities of materials for foundations and footings will be used. Therefore, the associated impacts for this assembly will remain the same. Since this assembly type contributed less than 15% towards each environmental impact category, it is not a primary concern for reducing the overall impact of the new construction for the building.

6.2.4.2 Columns and Beams

The ground-up construction design will continue the use of WF and HSS beams and columns in order to ensure structural integrity is maintained. By using the same materials as the baseline design, only the quantity used will affect the environmental impact of this assembly.

6.2.4.3 Intermediate Floors

A steel joist intermediate floor structure will be utilized for the second floor. In order to maintain an aesthetically appealing design, only intermediate floor assemblies with gypsum board and latex paint ceiling finishes were considered in the LCA comparison. The options were also limited to those comprised of steel to maintain continuity in material use throughout the building design. Based on these limitations, four assembly types remained. Taking into consideration all six impact categories, these options were ranked from least detrimental environmental impact to most, which is reflected in the list below.

1. **Steel Joist** - gypsum board & latex paint ceiling finish
2. **Open-Web Steel Joist** - gypsum board & latex paint ceiling finish
3. **Steel Joist w/ Plywood Decking** - gypsum board & latex paint ceiling finish
4. **Open-Web Steel Joist w/ Concrete Topping** - gypsum board & latex paint ceiling finish

6.2.4.4 Exterior Walls

The existing structure type of a two-by-four steel stud wall will be incorporated into the design for ground up construction. The different subcategories for cladding options for two-by-four steel stud, spaced 16 inches on center, were compared to determine which option had the least adverse environmental impacts. These results are summarized in Table 112. Here “A” represents the existing exterior walls, which includes both brick cladding and EIFS cladding and “B” represents a wood cladding wall. Options 2 and 5 were worse than existing, while options 1, 3, 4, and 6 were better than the existing but not better than the wood cladding. The next best options for minimizing environmental impacts in order of increasing impact are vinyl cladding, stucco cladding, and brick cladding.

Table 112: Comparison of the Environmental Impacts of Exterior Wall Types Versus the Existing Brick and EIFS Clad Wall and a Wood Clad Wall

Structure Type		FF		GWP		AP		HH		EP		ODP		SP	
		A	B	A	B	A	B	A	B	A	B	A	B	A	B
1	2x4 Steel Stud Wall, Brick Cladding	Lower	Higher	Lower	Higher	Lower	Higher	Lower	Higher	Lower	Higher	Higher	Higher	Lower	Higher
2	2x4 Steel Stud Wall, Steel Cladding (26 ga.)	Lower	Higher	Higher	Higher	Higher	Higher	Lower	Higher	Higher	Higher	Higher	Higher	Lower	Higher
3	2x4 Steel Stud Wall, Stucco Cladding	Lower	Higher	Lower	Higher	Lower	Higher	Lower	Higher	Lower	Higher	Higher	Higher	Lower	Higher
4	2x4 Steel Stud Wall, Vinyl Cladding	Lower	Higher	Lower	Higher	Lower	Higher	Lower	Higher	Lower	Higher	Higher	Higher	Lower	Higher
5	2x4 Steel Stud Wall, EIFS Cladding	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher
6	2x4 Steel Stud Wall, Precast Concrete Cladding	Lower	Higher	Lower	Higher	Lower	Higher	Lower	Higher	Lower	Higher	Higher	Higher	Lower	Higher

6.2.4.5 Windows

As discussed in the renovation section, PVC vinyl window frames provide the best thermal efficiency and lowest environmental impact. This frame type will therefore be utilized throughout the whole building, including the office area.

6.2.4.6 Interior Walls

In order to minimize the interior wall contribution towards the environmental impact of the building, each wall type was compared using the Athena EcoCalculator. The existing steel stud interior wall type was first compared to a similar wood stud structure to determine which had the lowest environmental impact. The remaining wall types were then compared to these two options to determine the best assembly. These results are summarized in Table 113 where “A” represents the existing 1-5/8 by 3-5/8 inches steel stud, spaced 16 inch on center with 5/8 inches of gypsum board and two coats of latex paint, and “B” the 2 by 4 wood stud wall, spaced 24 inch on center with 5/8 inches of gypsum board and two coats of latex paint. From these results, it was determined options 2, 4, 5, 6, and 7 were not better than the existing assembly while options 1 and 3 had lower impacts than the existing type but higher impacts than option B.

Table 113: Comparison of the Environmental Impacts of Interior Wall Types

	Structure Type	FF		GWP		AP		HH		EP		ODP		SP	
		A	B	A	B	A	B	A	B	A	B	A	B	A	B
1	2x4 Wood Stud Wall 16" o.c. 5/8" Gyp. Board, 2 Coats Latex Paint	Lower	Higher	Lower	Equal	Lower	Higher	Equal	Higher	Lower	Higher	Equal	Equal	Higher	Higher
2	2x4 Wood Stud Wall 24" o.c. 2x 5/8" Gyp. Board, 2 Coats Latex Paint	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher
3	1-5/8"x3-5/8" Steel Stud 24" o.c. 5/8" Gyp. Board, 2 Coats Latex Paint	Lower	Higher	Lower	Higher	Lower	Higher	Lower	Equal	Lower	Higher	Equal	Equal	Lower	Lower
4	1-5/8"x3-5/8" Steel Stud 24" o.c. 2x5/8" Gyp. Board, 2 Coats Latex Paint	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher
5	6" Concrete Block, 5/8" Gyp. Board, 2 Coats Latex Paint	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher
6	6" Concrete Block, 2 Coats Latex Paint	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher
7	Clay Brick 4", Unpainted	Higher	Higher	Higher	Higher	Higher	Higher	Lower	Higher	Higher	Higher	Higher	Higher	Higher	Higher

6.2.4.7 Roof

Each roof type was compared to determine the best option for minimizing the environmental impact of the roof. In order to ensure the roof would contribute towards the Heat Island Reduction LEED credit, only roof types with modified bitumen or EPDM roof membranes were considered. The impact of the existing open-web steel joist roof structure with a modified bitumen membrane was compared to the impacts associated with an EPDM membrane on the same structure. This comparison proved that an EPDM roof membrane has a lower overall environmental impact than modified bitumen. The impacts of each structure type with an EPDM membrane were then compared to determine the best option. These results are summarized in Table 114 below where “A” represents the existing open-web steel joist structure with modified bitumen membrane and “B” the same structure with EPDM membrane. These results show roof structure options 1 and 3 are not better than the existing roof type while options 2, 4,5,6,7, and 8 are better than the existing structure but not better than the existing structure with an EPDM membrane.

Table 114: Comparison of the Environmental Impacts of Roof Structure Types

	Structure Type	FF		GWP		AP		HH		EP		ODP		SP	
		A	B	A	B	A	B	A	B	A	B	A	B	A	B
1	Precast Hollow-Core Concrete, EPDM	Lower	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher
2	Precast Concrete Double-T, EPDM	Lower	Higher	Higher	Higher	Lower	Higher	Lower	Higher	Lower	Lower	Higher	Higher	Higher	Higher
3	Suspended Concrete Slab, EPDM	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher	Higher
4	Glulam Joist w/ Plank Decking, EPDM	Lower	Higher	Lower	Higher	Lower	Higher	Lower	Higher	Lower	Lower	Higher	Equal	Higher	Higher
5	Wood I-Joist w/ WSP Decking, EPDM	Lower	Lower	Lower	Lower	Lower	Higher	Lower	Higher	Lower	Higher	Higher	Equal	Higher	Higher
6	Solid Wood Joist w/ WSP Decking, EPDM	Lower	Lower	Lower	Higher	Lower	Higher	Lower	Higher	Lower	Lower	Higher	Equal	Higher	Higher
7	Wood Chord/Steel Web Truss w/ WSP Decking, EPDM	Lower	Higher	Lower	Higher	Lower	Higher	Lower	Higher	Lower	Higher	Higher	Equal	Higher	Higher
8	Wood Truss (Flat) w/ WSP Decking	Lower	Lower	Lower	Higher	Lower	Higher	Lower	Higher	Lower	Lower	Higher	Equal	Higher	Higher

6.2.4.8 Ground-Up Construction Results

Since a complete *Revit* model was not designed for the ground-up construction building, the same area values from the renovation building for each assembly were input into the LCA calculator. The top contributors towards the overall environmental impact of the renovation building were identified as the roof, intermediate floors, and exterior walls. The design of the roof and exterior walls was largely inhibited during the renovation building by what was pre-existing. To address these limitations, the comparison for the ground-up construction focused on altering these two assemblies to reflect the materials determined to be least detrimental in the previous section. If the materials for each assembly were changed for the ground-up design to the best options determined previously, the design would be idealized and the comparison unrealistic. Therefore, the materials for all assemblies other than the roof and exterior walls were kept constant between the renovation and the ground-up designs. For the exterior walls, it was determined a 2x4 steel stud design with wood cladding was optimal. The next best options used vinyl, stucco, and brick cladding. However, wood, vinyl, and stucco cladding are not commonly used in the design of schools so brick cladding was selected. These values are reflected in

Table 115. Since a full schedule of windows throughout the existing warehouse portion of the building was not available, the window quantity was kept consistent throughout each design. The aluminum frame windows in

Table 115 represent what was originally existing in the administration space. In the final design and construction of the ground-up construction school, PVC window frames would be used since they were determined to have the smallest adverse environmental impact.

Table 115: LCA Ground-Up Construction Assembly Type Inputs

Assembly Type	Description	Square Footage	Volume (yd^3)
Foundations & Footings	Foundation Wall – Concrete Block	4,305.0	-
	Foundation Slab - 4" Cast-in-Place Concrete	22,410.6	-
	Footing - Cast-in-Place Concrete	-	413,3
Columns & Beams	HSS Column / WF Beam	271,400.0	-
	WF Column / WF Beam	89,040.0	-
Intermediate	Elevated Concrete Slab	156,393.4	

Floor			
Exterior Walls	2x4 Steel Stud Wall 16 o.c., Brick Cladding, R-7.5 Continuous Insulation Sheathing, R-13 Cavity Insulation & Polyethylene Membrane, Gypsum Board & Latex paint	55093.9	-
	Curtainwall: Opaque Glazing, w/ Insulated Backpan	5,220.7	-
Windows	Aluminum Frame (existing)	108.0	-
Interior Walls	1-5/8" x 3-5/8" Steel Stud 24" o.c., 2 x 5/8" Gypsum Board + 2 Coats Latex Paint	323,635.0	-
	6" Concrete Bock, 2 Coats Latex Pain	162.3	
Roofs	EPDM Membrane, R-20 Continuous Insulation + Polyethylene Membrane, Open-Web Steel Joist w/ Steel Decking, Gypsum Board + Latex Paint	214,137.0	-

Table 116 and

Table 117 below summarize the LCA results, showing fossil fuel consumption, eutrophication potential, and acidification potential are still the main contributors towards the buildings overall environmental impact. The main contributors are the intermediate floors, columns and beams, and roof. This differs slightly from the renovation where the main assemblies contributing towards the building's environmental impact were the roof, intermediate floors, and exterior walls.

Table 116: Ground-Up Construction LCA Total Environmental Impact Categories

Environmental Impact Category	Total
Fossil Fuel Consumption (FF), MJ	986,633,743
Global Warming Potential (GWP), tons CO_2eq	6,113
Acidification Potential (AP), moles of H^+eq	1,875, 559
Human Health Criteria (HH), kg PM10 eq	24,358
Eutrophication Potential (EP), g N eq	2,832,647
Ozone Depletion Potential (ODP), mg CFC-11 eq	30,451
Smog Potential (SP), kg No_x eq	272,811

Table 117: Contributions to the Ground-Up Construction LCA by Assembly Type

Assembly Type	Percentage of Total Contribution						
	FF	GWP	AP	HH	EP	ODP	SP
Foundations & Footings	2%	4%	4%	4%	2%	7%	5%
Columns & Beams	20%	16%	18%	6%	41%	0%	10%
Intermediate Floors	23%	37%	32%	36%	23%	59%	50%
Exterior Walls	6%	7%	10%	12%	4%	5%	8%
Windows	0%	0%	0%	0%	0%	0%	0%
Interior Walls	15%	13%	14%	27%	12%	4%	11%
Roof	33%	23%	22%	15%	18%	24%	16%

6.2.5 LCA LEED Credit

In order to achieve the LEED credit points, the proposed new design must demonstrate a minimum improvement of five percent in three environmental impact categories, one of which much be global warming potential. In addition, no impact category can increase by ten percent or more in comparison to a baseline building. To calculate the percent change in each impact category Equation 38 was used.

$$P_n = \frac{PB_n - RB_n}{RB_n} * 100$$

Equation 38: Percent Change in Environmental Impact Categories

Where,

P_n is the percent reduction/increase of the Ground-Up Building with respect to the Renovation Building, for the impact category n

RB_n is the LCA result of the Renovation Building, for the impact category n

PB_n is the LCA result of the Proposed Ground-Up Building, for the impact category n

The credit requires that the two buildings being compared are of similar size, design, and serve a similar function. Although the existing building and the renovation are the same size, due to the drastic changes in function and design, they are not comparable for this LEED credit. The inclusion of a second floor in the renovation impacted the structural design greatly requiring significant alterations in the design. Therefore, the renovation design and ground-up construction design will be compared in compliance with the LEED credit specifications to determine the changes in environmental impact between the two buildings. Table 118 summarizes these results and Figure 95 displays them graphically.

Table 118: Comparative LCA Results Between Renovation and Ground-Up Construction Designs

Impact Category	Renovation Building	Ground-Up Construction Building	% Change
Fossil Fuel Consumption (FF), MJ	113,992,747	98,633,743	-13.47%
Global Warming Potential (GWP), tons CO_2eq	6,446	6,113	-5.17%
Acidification Potential (AP), moles of H^+eq	2,024,622	1,875,559	-7.36%
Human Health Criteria (HH), kg PM10 eq	32,100	24,358	-24.12%
Eutrophication Potential (EP), g N eq	2,867,200	2,832,647	-1.21%
Ozone Depletion Potential (ODP), mg CFC-11 eq	30,642	30,451	-0.62%
Smog Potential (SP), kg No_x eq	292,003	272,811	-6.57%

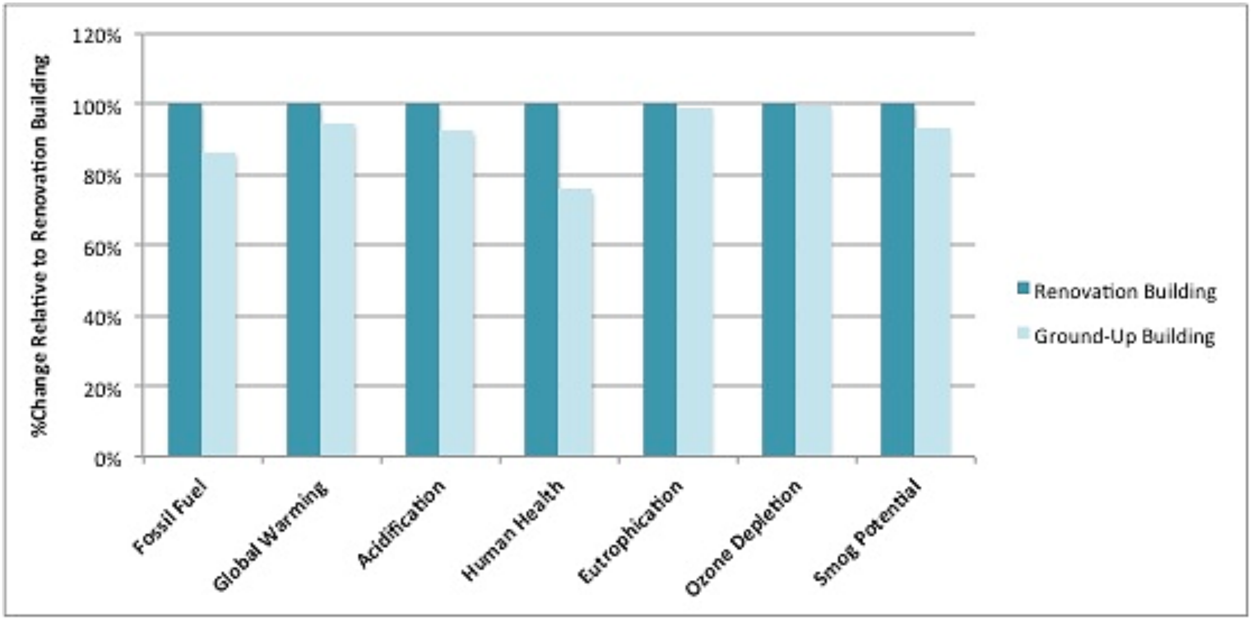

Figure 95: Comparative Results of the Renovation and Ground-Up LCA's

6.2.6 Results

These LCA results highlight the effect constraints associated with renovating a building have on the overall environmental impact of the design. Although the three largest areas of impact remained constant between the three different designs as fossil fuel consumption, eutrophication potential, and acidification potential, the amount each assembly contributed did not. For the existing building, the assemblies that contributed the most towards the environmental impact were the roof, columns and beams, and the existing walls. With the addition of the second floor in the design for the renovation, this shifted to the roof, intermediate floors, and exterior walls. Since the roof and exterior walls were consistently large contributors, they were targeted in the design for ground-up construction. For the renovation design, these two areas could not be changed to decrease their detrimental effect on the environment without extensive and unnecessary demolition. By changing these two assemblies to be constructed with environmentally friendly materials and retaining the same materials for all other assemblies, the intermediate floors, columns and beams, and roof became the largest contributing areas. This small alteration in material use also successfully decreased the ground-up building's environmental impact in comparison to the renovation in every impact category. The ground-up design met the LEED requirements of decreasing at least three impact categories by 5%, one of which had to be global warming potential, without increasing any areas by more than 10%. The ground-up design had the largest impact on the buildings contribution towards human health, fossil fuel consumption, and acidification potential.

The renovation of a building places constraints on areas that can be altered to reduce a building's environmental impact over its lifetime, limiting the designs capability of increasing its overall sustainability. Areas typically of large impact, such as roofs and exterior walls, cannot be altered to more environmentally friendly systems without major demolition that would add unnecessary costs and time to the project. Ground-up construction projects create more leeway for focusing material selection on decreasing the environmental impact of the building.

6.3 Materials and Resources – Construction & Demolition Waste Management

The USGBC estimates that approximately 40% of the total solid waste stream in the United States comes from waste produced during construction and demolition. The Construction and Demolition Waste Management LEED credit addresses this issue by encouraging projects to focus on recycling waste rather than disposing it. For years, conventional practice has been to simply dispose of waste produced on construction sites, resulting in over 75% of site waste being brought to landfills or incinerators. Although disposal of waste has historically been less costly than recycling, as landfills have reached their capacity and raw materials have become scarcer, economics have shifted in favor of recycling. By shifting the focus of construction waste management from disposal to eliminating waste where possible, minimizing where feasible, and reusing materials that would otherwise become waste, the construction industry can reduce their contribution to the U.S.'s solid waste stream (WBDG). The EPA estimates demolition accounts for 53% of the waste generated by the construction industry while renovation accounts for 38% and new construction 9% (Winkler, 2010). Therefore, projects that are primarily renovations or heavy in demolition must take special care to properly recycle waste to aid the industry in becoming more sustainable. The following section discusses the concerns regarding C&D waste management, the waste stream options available, and requirements for recyclable items.

6.3.1 Waste Stream Options

The three waste stream options for construction and demolition projects are directly to a landfill, commingled recycling, and source separation recycling. Direct disposal to landfills and incinerators used to be the predominant method used on construction sites due to the availability of landfills and cost. However, as landfills started to reach capacity and the development of new ones was resisted, the price to directly dispose waste became more expensive than the recycling rates. In commingled recycling, different types of waste are collected into common containers for transportation to recyclers for separation by materials. The source separated recycling method sorts materials directly on the jobsite into distinct bins based on material and market availability for transportation to their respective recyclers. As illustrated in Figure 96-Figure 98 source separated recycling results in the least amount of waste to landfills at 0-50% of the total project waste. In comparison, commingled recycling sends 20-50% of project waste to landfills while the disposal waste stream sends all project waste to the landfill.

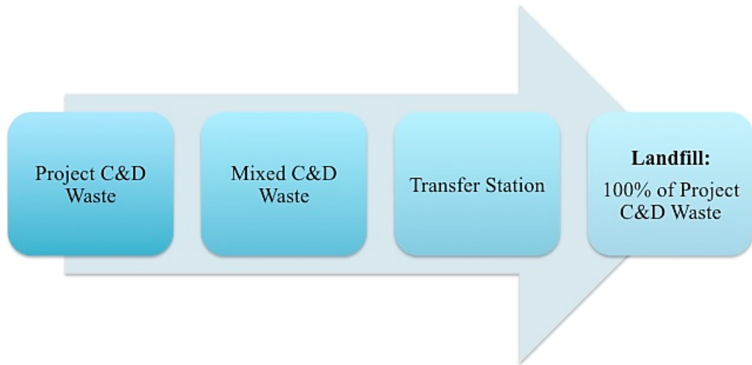

Figure 96: Landfill Waste Stream Process

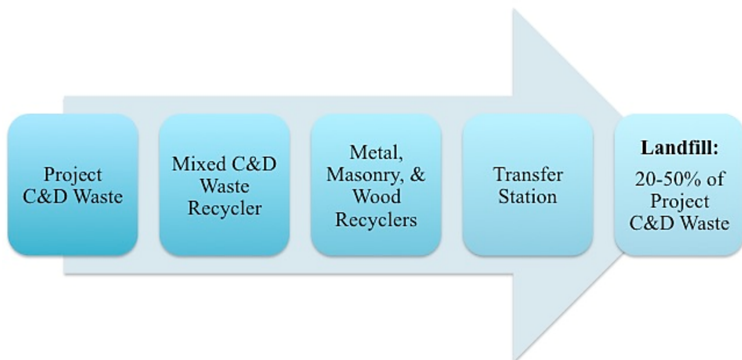

Figure 97: Single Stream/Commingled Waste Stream Process

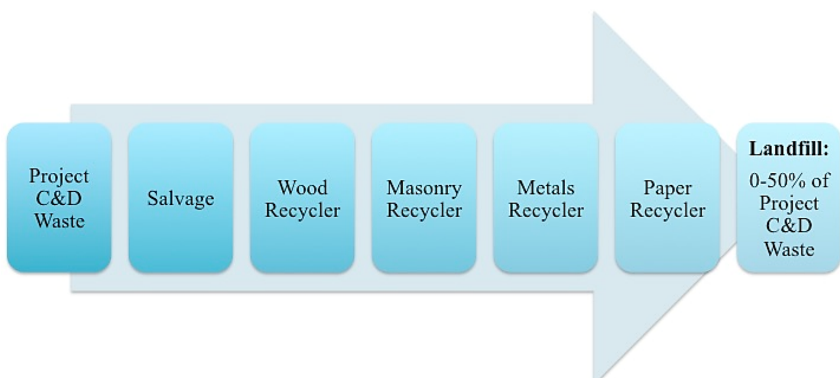

Figure 98: Source Separated Waste Stream Process

Table 119 outlines the advantages and disadvantages for source separated and commingled recycling methods. Although commingled recycling is often viewed as simpler to conduct on site, it is less common in application since some materials cannot be commingled and source separation offers increased savings.

Table 119: Advantages and Disadvantages of Source Separated and Commingle Recycling

Recycling Method	Advantages	Disadvantages
Source Separation	• Higher recycling rates • Lower recycling costs • Cleaner, safer work site • Sends least amount of waste to landfill	• Multiple containers onsite • Workers must separate materials • More complex logistics • Multiple markets, more information to manage
Commingled	• Only 1-2 containers onsite • Workers don't need to separate materials • Easier logistics • One market, less information to manage	• Lower recycling rates • Higher recycling costs • Materials not accepted in commingled loads must be source separated

6.3.2 Construction & Demolition Waste Recycling Concerns

In 2003, only 20% of waste generated at construction sites was being recycled or reused (Winkler, 2010). Although this rate has improved, misconceptions surrounding recycling on a jobsite still hinder its involvement in projects. Some common misconceptions regarding the recycling process is that it slows down jobs and there is a lack of room onsite for it. However, with proper planning these beliefs are false. By identifying the main waste materials for each job phase and ensuring the correct containers are present for each stage in advance, the recycling process does not differ much from the basic disposal process. In most cases, recycling actually opens up room on a site since recycling containers are often smaller than mixed debris containers (Winkler, 2010). One legitimate obstacle is that some products either do not have markets for recycling or the only recycling opportunities for that product exist in select areas. For cases like this, projects can still implement a waste recycling system into their procedure and dispose of products unable to be recycled. By doing so, products that do have recycling markets in the area that would otherwise be disposed of can be recycled, significantly reducing the costs associated with the removal of construction and demolition waste.

The main concern for contractors is that recycling costs too much and will add unnecessary expenses to the project budget. Although this used to be true, recycling significantly reduces waste management costs as shown in Figure 99. This graph uses data from The Institution Recycling Network to compare the cost of construction and demolition recycling versus disposal in the Boston area (ISN, 2005). Here, the lighter blue bars represent the transportation cost, or cost per ton to get the material to the designated market. The darker blue bars represent the cost per ton to process and recycle the material once it has reached the appropriate market. In the case of the first bar, C&D Disposal, the red represents the disposal cost per ton for the landfill-tipping fee. Analyzing the highest tonnage material for construction sites, the concrete, brick, and block section, it costs $10.00 per ton to recycle plus an additional $11.00 per ton for transportation, which is an overall cost of $21.00 per ton. In comparison, the disposal rate is $105.00 per ton plus $31.00 per ton for transportation, amounting to a cost of $136.00 per ton for disposal. Therefore, the choice of recycling over disposal of concrete, brick, and block can save a project $115.00 per ton of these materials. Although not all waste materials provide such significant savings, this data shows the lowest cost savings would be $42.00 per ton for the recycling of mixed debris rather than the disposal of it.

Figure 99: Boston Area Cost of C&D Recycling vs. Disposal (Modified from ISN, 2005)

6.3.2.1 Construction and Demolition Waste Reduction Case Study

A case study was conducted by the Massachusetts Department of Environmental Protection on the different techniques for cost savings for construction and demolition waste management. The study was performed on the Douglas School renovation and new construction project headed by Consigli Construction. The project entailed the renovation of the existing building and a two-story addition of a new high school to accommodate 700 students totaling 137,000 square feet of new construction and 6,800 square feet of renovation and addition. To encourage source separated recycling onsite, recycling containers were placed throughout the project site while disposal containers were located further away, increasing the convenience of recycling. This resulted in a 57% waste reduction with 444 tons recycled and 338 tons disposed, for a 66% cost savings of $31,812. Table 120 further breaks down the total cost savings achieved through source separated recycling for this project.

Table 120: Case Study C&D Cost Savings (Modified From ISN, 2005)

Materials	Tons	Recycling Cost	Avoided Disposal Cost	Savings
Concrete	285	$8,265	$31,065	$22,800
Metal	69	$1,380	$7,521	$6,141
Wallboard	49	$2,559	$5,450	$2,891
Cardboard	0.67	$67	$70	$3
Wood	40	$4,381	$4,358	$23
TOTALS	**443.67**	**$16,652**	**$48,464**	**$31,812**

Using the total savings and total square footage of this project, a total savings from recycling versus disposal was calculated to be $0.22 per square foot. This was then used to estimate a construction and demolition cost savings of $50,640.81 for the renovation building based on a total area of 228,912 square feet.

6.3.3 Requirements for Recyclable Materials

The USGBC estimates that 95% of waste produced on a typical construction site can be recycled, including concrete, plastics, ceiling tiles, and plumbing. (Winkler, 2010). Table 121 and Table 122 summarize a complete list of recyclable materials, their main source, available recycling markets, and any special limitations on their recycling. In general, metal is brought to scrap dealers for feedstock for creating new products while wood is often used as a fuel source for plants and manufacturers. Some products, such as bricks and engineered wood have high reuse values. These tables also highlight the increased recycling limitations that result from mixed debris collection rather than source separation. Oftentimes the hazardous materials present in mixed debris bins will prevent the possibility of recycling. In cases where hazardous materials are present, the costs associated with recycling increase. Overall, the source separation of construction and demolition waste reduces the number of recycling limitations increasing overall project savings.

Table 121: Recyclable Construction and Demolition Materials and Markets (Modified from IRN, 2005)

Material	Description & Sources	Markets	Recycling Limitations
Brick	• Mainly from demolition & renovation • Some from new construction	• High-value re-use markets for certain types • Often placed in mixed aggregate markets (concrete & block) • Used in aggregate production	Few
Concrete, Formed	• Mainly from demolition & renovation • Some from new construction	• Mixed aggregate markets (brick & block) • Used in aggregate production	Concrete w/rebar must be separated from brick, block, & concrete w/out rebar. Lead paint is an issue if present
Concrete, Block	• Mainly from demolition & renovation • Some from new construction	• Mixed aggregate markets (brick & concrete)	Few
Asphalt Pavement	• Almost exclusively from parking areas • Limited from new construction	• Recycled separately from other materials • Used in new asphalt production	Few
Metals, Ferrous	• Demolition - Structural & framing steel • New Construction/Renovation – Framing scrap (typically small amounts	• Scrap markets • Used in production of new steel	Few
Metals, Non-Ferrous	• Significant amounts in new construction • Aluminum, copper, brass & alloys from MEP	• Scrap markets • Highest value if source separated • Can be mixed and marketed w/ ferrous metals	Few
Wood, Dimensional	• New construction/Renovation- two-by ends • Renovation/Demolition- Whole boards • Pre-fabbed walls & trusses greatly reduce waste	• Reuse markets in most areas for whole boards • Scrap is mainly used for mulch and boiler fuel	Few (some markets will refuse nails and screws)
Wood, Flooring & Trim	• Mainly from demolition and renovation • Ends and scraps from new construction and renovation	• High re-use value in hardwood & softwood floor, trim, and molding • Painted/treated, scrap, and damaged wood goes to boiler fuel	Limited markets for painted/treated wood, must be tested for lead

Table 122: Recyclable Construction and Demolition Materials and Markets, Continued (Modified from ISN, 2005)

Material	Description & Sources	Markets	Recycling Limitations
Wood, Engineered	• Renovation/Demolition/New construction- significant amounts of plywood, OSB, glu-lam beams, etc. • Pre-fabbed walls & trusses greatly reduce waste	• Some re-use value from deconstruction • Most recycled as boiler-fuel	Few
Gypsum Wallboard	• Clean scrap from renovation and new construction • No markets for demolition wallboard	• GP Gypsum & U.S. Gypsum offer markets in NE • Some grinded as soil amendment	Clean scrap from new installation only without tape, nails, screws, or corner bead
Ceiling Tiles	• Mainly from demolition & renovation • Some from new construction	• Armstrong Ceiling accepts and recycles most	No mold, asbestos or other hazmat, vinyl/fabric/foil faced, visible pulp. Must be tested prior to recycling
Porcelain Fixtures	• Demolition and renovation only • Generally non from new construction	• Ground and used as aggregate or decorative chip	Requires removal of seats and plastic/metal fixtures
Roofing, Asphalt Shingles	• Large quantities from demolition, renovation, and new construction	• Used for asphalt and other paving materials	No asbestos or other hazmat. Metal (flashings, dripedge, etc.) typically accepted
Roofing, Membrane	• Large quantities from demolition, renovation, and new construction	• Used for asphalt and other paving materials	No asbestos or other hazmat. Metal (flashings, dripedge, etc.) typically accepted
Roofing, Metal	• Large quantities from demolition, renovation, and new construction	• Scrap markets	Few
Roofing, Slate	• Large quantities from demolition, renovation, and new construction	• Often reusable • Damaged roofing is ground and used as aggregate	Few
Carpet	• Large quantities from demolition, renovation, and new construction	• Some manufacturers will accept it back • Often taken apart and materials recycled separately	Must be dry/mold free, high cost, most feasible with replacement installation
Mixed Debris	• Large quantities from demolition and renovation • Small-large for new construction	• Sorted mechanically or by hand into constituents: wood, metal, aggregate, and residual	Hazmats may preclude recycling/increase cost. Recycling rates less than source-separated, higher costs

6.3.4 Results

The construction and demolition waste management results demonstrate the potential savings from the implementation of a recycling program in a project. The most profitable waste stream option for projects is a source separated process. This method requires the separation of construction and demolition materials directly on the jobsite into bins based on market availability. In doing so, only 0-50% of the total project waste is sent to landfills. Although the execution of an effective construction and demolition recycling program requires pre-planning by the contractor, the cost savings in comparison to disposal makes it worthwhile. According to data collected by The Institution Recycling Network it is estimated in the worst case scenario, the cost to recycle is half the cost of disposal in the Boston area. By comparing this renovation building to a similar school project, a potential construction and demolition cost savings of $50,640.81 was estimated. These results show the benefit of recycling for the renovation design. These cost savings could be crucial if the project was on a tight budget and needed to identify areas to cut spending. The money saved from recycling waste could also be utilized to incorporate more expensive architectural design components into the design to improve aesthetics and enhance the learning environment of the school.

Chapter 7: Results and Discussion

This project simulated the design and construction processes necessary to repurpose an existing building. It investigated the structural, architectural, fire protection, environmental, sustainability, and economical requirements to compare the renovation of an existing warehouse into a school to the ground-up construction of various design alternatives. These factors guided recommendations for the renovation of existing buildings, the limitations, and the best practices used to overcome those constraints. The proceeding sections provide the results and recommendations based on the conclusions from the previous chapters.

7.1 Result Comparisons

During the renovation of the existing warehouse facility, some design aspects of the intended school building were adjusted according to the requirements, as explained in previous chapters. In order to reduce the cost and time of construction, compromises were made to the structural, architectural, and environmental aspects of the renovated design. The design for the renovated building was created with certain aspects already determined, such as total area and construction materials. Additional engineering principles were used to coordinate the best layout and design for the middle school and high school.

For the structural and architectural aspects of the building, the total area of the warehouse posed an issue for renovation. As previously stated in Chapter 4, the total area of the warehouse was approximately 229,000 $ft^{2,}$ which exceeds the maximum allowable area for school buildings. As a result, courtyards were added to both the middle school and the high school layouts. This reduced the amount of total area and ensured the designs complied with the building codes and specifications. The area of the building also influenced the projected student enrollment totals. Such a large building also required a large student population. According to the Massachusetts School Building Authority (MSBA), a school of this size should enroll approximately 1,200 students for the middle school and between 980 to 999 students for the high school. Another structural aspect that influenced the design was the ceiling heights. The high ceiling heights paired with the relatively large student enrollment led to the insertion of a second floor between the existing slab on grade and roof line for both the middle school and high school. Including a second floor ensured the gross area for both schools complied with MSBA but the additional loads required redesign of some of the structural elements including columns and footings.

The options of ground-up construction allowed for the design to be defined and constructed as desired. While still utilizing the same site area, the new design would consist of two separate buildings: one for the high school and one for the middle school. A sports field was placed between the two buildings to reduce the amount of interaction between the older and younger kids, reducing potential risks. Allowing both schools to utilize the field at varying times reduces the necessary site area, ultimately reducing the cost. Both the middle school and high school are two-story buildings of approximately 76,000 ft^2. With a gross floor area of approximately 152,000 ft^2 the target enrollment dropped to just over 600 students. According to the Massachusetts Charter Public School Association, there are currently 71 charter schools educating over 32,000 students (about 3 percent of the total) in Massachusetts (MCPSA, N.D.). Using this estimate and the Massachusetts Department of Elementary and Secondary Education district database, an intended enrollment was determined. Table 123 below shows the breakdown for districts surrounding, and including, Sutton, MA based on the student enrollment for 2015-2016.

Table 123: School Population by District

District	PK-12	Charter School (3%)
Sutton	1,468	44
Oxford	1,797	54
Douglas	1,471	44
Uxbridge	1,898	57
Northbridge	2,373	71
Grafton	3,206	96
Millbury	1,732	52
Auburn	2,454	74
Webster	1,894	57
Blackstone-Millville	1,738	52
Total	**-**	**601**

The total intended enrollment is based on the assumption that 3% of the students in the above stated districts attend the public school for both middle and high school. A smaller student enrollment corresponds to a smaller school building and therefore requires less construction material, fire protection elements and has a smaller detrimental impact on the environment.

A third design scenario would be to combine the middle and high school into one building for the ground-up construction. In this case, both schools could share common spaces including the gymnasium, auditorium and the kitchen/cafeteria area. Although combining the schools would increase the necessary gross floor area to 239,799 ft^2, the shared rooms would help to reduce the overall area. The table below shows the floor area requirements of various room types for the separate schools and the combined school scenarios.

Table 124: Floor Area Requirements by Room Type

Room Type	MS Area	HS Area	Combined Area
Core Academic Space	27,680	29,090	56,770
Special Education	7,550	8,050	15,600
Art & Music	3,250	6,625	6,625
Vocations & Technology	6,400	6,400	6,400
Health & Phys. Ed	8,400	19,566	19,566
Media Center	3,836	3,656	3,836
Auditorium/Drama	-	6,807	6,807
Dining & Food Services	8,659	6,206	8,659
Medical	610	710	710
Administration & Guidance	3,401	3,521	6,922
Custodial & Maintenance	2,076	2,076	2,076
Total Net Floor Area	**71,862**	**92,707**	**133,971**
Total Gross Floor Area	**103,836**	**135,826**	**239,799**

These values were determined using the projected enrollment total, 601 students for each the middle school and the high school, and the proposed spatial requirements from the Massachusetts School Building Authority. For the combined school areas, many of the spaces can be flexibly shared such as the cafeteria and health and physical education areas. When comparing such spaces between the middle school and high school, the larger area was chosen as the minimum requirement for the combined alternative to ensure all requirements were met.

Once the necessary areas were determined for the separate schools and combined school scenarios, potential layouts were created in AutoCAD. The layouts were developed as block diagrams to show that the total areas for the variety of room uses were met. The first design alternative considered was constructing separate buildings for the middle school and high school. Figure 100 and Figure 101below, show the layouts of the middle school and high school for the first design alternative. In this scenario, the same amount of land area was used as the existing warehouse facility. Based on the design, the new site would consist of both schools and a high school regulation size football field separating the two buildings. The separation reduces the interaction between the younger and older students, which increases the safety of the students and reduces parental and community concern.

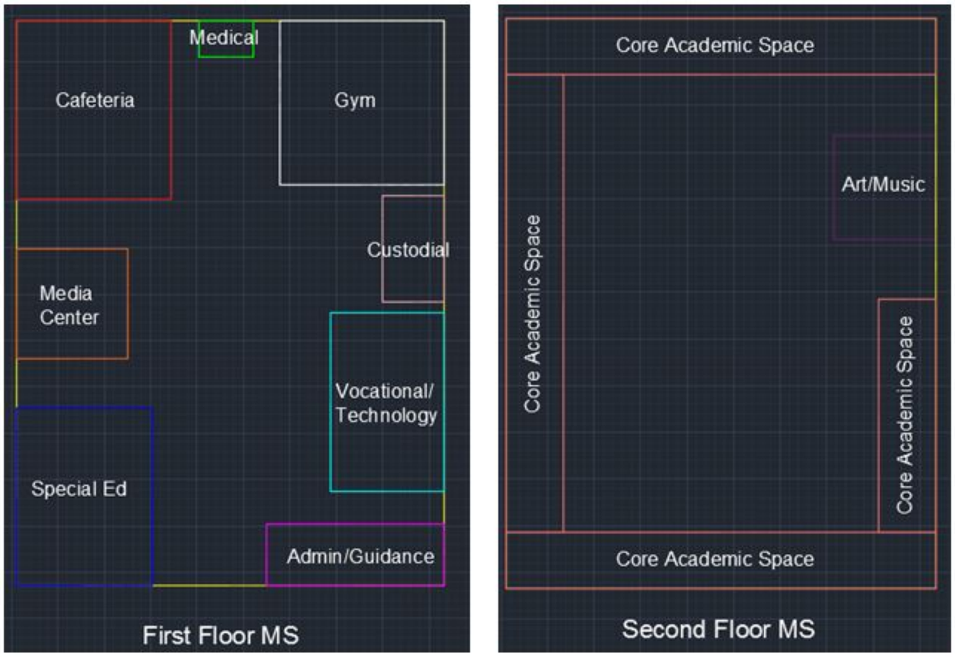

Figure 100: Block Diagram for Middle School Building

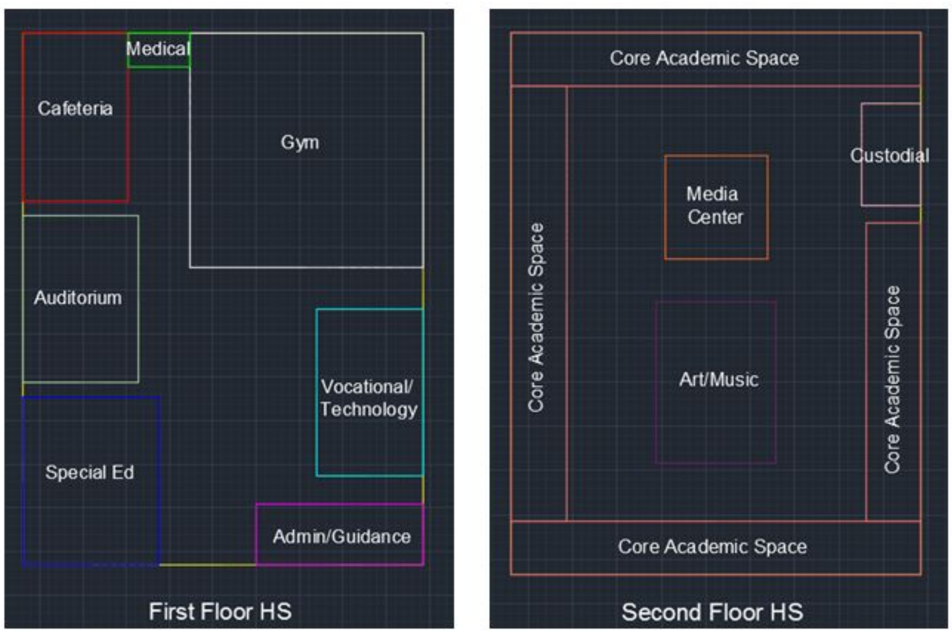

Figure 101: Block Diagram for High School Building

The layouts for both the middle school and high school include the minimum requirements for room types and the corresponding areas. Areas that are currently unoccupied can be utilized by expanding the existing rooms or including additional, specialty rooms. Specialty rooms could include science or computer labs, foreign language departments, or an area for home economics.

For simplicity of construction, the middle school and high school were designed to have the same building area, 76,200 ft^2. By including two floors in each building, the total gross floor area became 152,400 ft,^{2} which exceeds the minimum requirements for both schools. Although the excess area increases the amount of materials needed for construction, it makes the design more symmetric and more aesthetically appealing.

The second design alternative considered the construction of one building to the house the combined middle school and high school. This design allows for some of the spaces to overlap and be used by both schools. Figure 102 below, shows the proposed layout for the combined school alternative. For example, only one cafeteria and one gymnasium are needed in the building, which results in a reduction of the total area used for construction. Based on the area requirements previously stated in Table X above, the combined school must have a gross floor area of 240,000 ft^2. By including a second floor, this allowed for the construction area to be reduced from 152,400 ft^2 to 120,000 ft^2. The smaller building area results in the use of fewer materials and therefore the cost of construction for this alternative would be lower.

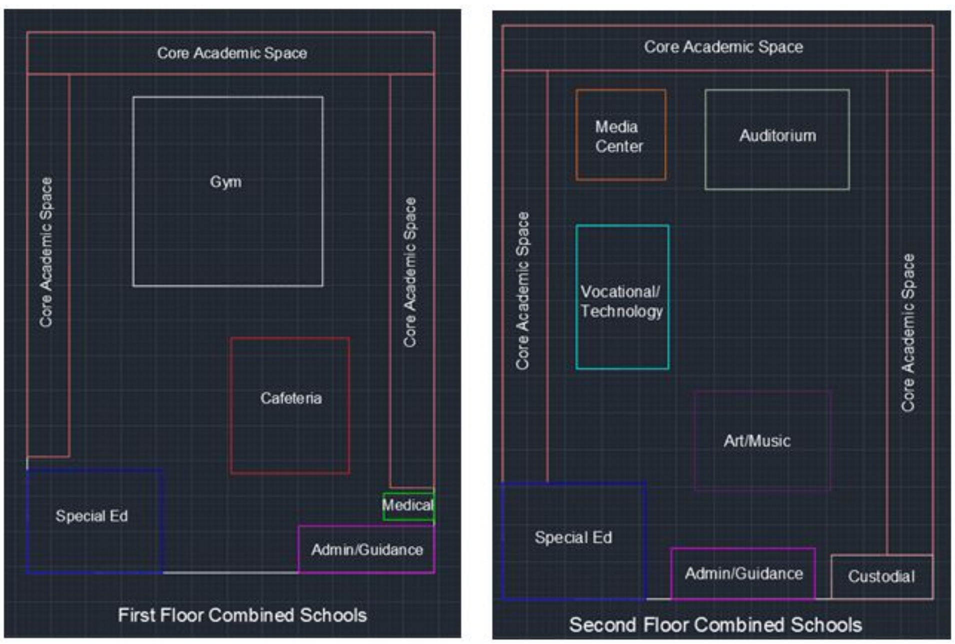

Figure 102: Block Diagram for Combined School Building

Similar to the first design alternative, minimum requirements were used for room types and the corresponding areas and the spaces can be utilized as previously stated. Although this scenario increases the opportunity for interaction between the younger and older students, the layout does separate the major learning areas. The core academic spaces on the first floor would be used exclusively by the middle school while the second floor spaces would be used exclusively by the high school. Only the shared areas such as the gymnasium, media center, or the medical area would be accessed by both schools. Even with the dual access, scheduling could be arranged to ensure the students use is staggered.

7.2 Discussion and Future Work

Based on the scope of the project, four design alternatives were developed to determine the most efficient method of construction. The alternatives included (1) the renovation of an existing facility, (2) the ground-up construction of the same building design, (3) the ground-up construction of two separate buildings, and (4) the ground-up construction of a combined school building. Each scenario was evaluated based on structural components, fire protection elements, and environmental concerns. From this evaluation, cost estimates were compared and utilized to develop recommendations for the most beneficial method of construction. Table 125 below, provides details for the cost estimates considered during the comparison.

Table 125: Cost Comparison

	Associated Costs					
Option	**Green Roof ($)**	**Construction ($)**	**Fire Protection($)**	**Total ($)**	**$/ft^2**	**$/student**
1	403,200	4,247,299	266,787	4,917,286	21.47	2,256
2	403,200	6,358,074	502,898	7,264,172	31.72	3,332
3	268,333	4,231,312	334,679	4,834,324	31.72	4,022
4	211,283	3,331,742	263,527	3,806,552	31.72	3,167

Based on this cost analysis, the final recommendation is to renovate the existing warehouse into a combined school building for the middle and high school. The adaptive reuse of the existing building allows for the potential reduction in the number of vacant warehouses. These results provide a basis for the renovation of such buildings and show that it would be more cost efficient in terms of $/ft^2 and $/student. The renovation design would also allow the contractors to develop a waste separation and recycling process in order to reduce construction debris and generate additional savings. Renovation also allows for the reuse of structural and fire protection elements. Although some of the structural members would need to be reinforced or replaced to support the insertion of a second floor, the construction costs for renovation are over $2 million less than that of ground-up construction. Similarly, new sprinklers would need to be purchased to meet the NFPA requirements of the new occupancy but most of the piping system can be reused. This reduced the cost by almost half of the ground-up construction total. The recommendation for the renovation of existing warehouses is based on the scope of work and the findings of this project.

As a result of this study, there are additional areas that can be further investigated. Detailed layouts of the ground-up construction design alternatives could be created to include corridors and specialty areas in replacement of the block diagrams presented in the previous section. Using *Revit* software, full material schedules could be exported from these detailed designs for the completion of a full cost comparison. This could also include a more comprehensive look into renovation versus ground up construction. An actual bid comparison could be a viable option to compare construction time and cost. Giving an in depth analysis of the scope of the work necessary to complete each project would allow for a more accurate comparison between the two costs, especially with time as a major factor. Faster construction times could prove to be more compelling than a cost analysis alone. Additional LEED credits could also be explored to determine other areas in which the project could achieve points. Further investigation into the sourcing and recycling content of materials used within the building could increase the building's sustainability and help for the Materials and Resources LEED category. Another area that could be explored in further detail is the comparison of fireproofing methods between retrofitting buildings and new construction. In order to increase the effectiveness of building renovation projects, a strategy could be developed for analyzing buildings for their adaptive reuse potential prior to the design process. This strategy could take into consideration the performance compliance methods outlined in the IEBC for renovating existing buildings as well.

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Appendix A: Proposal

Interdisciplinary Design and Analysis of a Warehouse

A-Term Project Proposal

A Major Qualifying Project submitted to the faculty of Worcester Polytechnic Institute in partial fulfillment of the requirements for the Degree of Bachelor of Science in Civil Engineering

Tanner Burke
Nicola DiLibero
Malina Ibelle

Abstract

This project will compare and contrast renovating an existing warehouse versus ground-up construction for a change in occupancy through six distinct phases: the existing conditions, predicting existing fire protection systems, the proposed renovation, ground-up construction, an analysis and comparison of two approaches, and the proposed recommendations. The analysis will take into consideration real-world constraints that affect the design and construction process. The cost, time, and environmental impacts will be analyzed and compared for both scenarios to determine the most effective design alternative.

Introduction and Problem Statement

As technology continues to improve, time and efficiency become increasingly important during the design and construction of buildings. Building owners and developers not only need to take into consideration how quickly a project can be developed, but now need to consider how the structural and fire suppression designs affect the environment. Buildings in the United States are associated with 38% of all carbon dioxide emissions, which is nearly 1/3 globally (USGBC, 2013). The awareness of such environmental implications has led to an increase in green construction worldwide. It is becoming more common for developers to investigate the renovation of buildings because it allows for the reuse of materials and produces less of a negative impact on the surrounding environment. A study performed in 2007 estimated that a shift in building design to incorporate zero to negative net life-cycle costs could offset up to 6 billion tons of carbon dioxide annually (Yudelson and Fedrizzi, 2008). Environmental engineers work with designers and builders to reduce the negative impact on the environment while still maintaining the essence of new design projects.

Renovation, however, is not always the most efficient method for time and cost of construction. When there is a change in occupancy within a building, it is crucial for the project team to ensure the new occupancy requirements are followed. Such buildings must comply with all codes including, but not limited to, structural design, fire protection, plumbing, and means of egress (International Building Code, 2006). In order to reduce the time and difficulty associated with renovations, owners may decide it is more efficient to start a building from the ground up. Tearing down an existing facility, however, generates debris and potential hazards to the surrounding environment. Even if the owner purchases a new plot of land, the time and resources necessary to survey and prepare the land for construction may outweigh the benefits.

To demonstrate the relationship between renovation and ground up construction, a storage warehouse facility will be analyzed. The existing warehouse will be renovated to accommodate a change in occupancy, meeting the functional and safety needs of a charter school building. A new school building will then be designed using similar constraints and occupant goals. The cost, time, and environmental impacts will be analyzed and compared for both scenarios to determine the most efficient design alternative. During the analysis, International and Massachusetts Building Codes, National Fire Protection Association requirements, and LEED guidelines will be investigated and incorporated.

Scope of Work

The scope of this project involves the renovation of an existing, 295,000 square foot manufacturing facility to accommodate for a change of occupancy and use. The existing facility consists of a factory industrial moderate-hazard Occupancy (Group F-1), with Business (Group B) space. A change of ownership will be simulated, in which the building is renovated into a charter school for high school aged students. The building will be designed to incorporate a variety of uses geared towards a diverse learning experience. The design will also focus on the opportunity to incorporate sustainable features into a building during a renovation phase and the ability for the building to be re-used for other purposes if necessary in the future.

The existing conditions of the building including its structural system, fire protection systems, interior finishes, and arrangement and enclosure of means of egress will be analyzed. A code review for the new facility using the 8th Edition of the *Massachusetts State Building Code*, compared to the 6th Edition it was designed and constructed with, will provide guidance as to which renovations need to be made to achieve code compliance.

Once the specifications are created for the renovation of the warehouse, a cost analysis of the estimated materials, equipment, design, labor, and operation of the facility will be performed. A design of a new building for the same purpose will then be created. During the design for ground-up construction, any constructability issues that were not feasible in the renovation of the existing building will be included. Another cost-analysis will be performed to compare the cost of purchasing and renovating an existing building for the change in use versus purchasing a site and building a new facility including any associated operating costs.

The incorporation of various LEED credits will be analyzed for their effect on cost, constructability, and sustainability of the building. An environmental analysis will be performed for the building that is selected as the more feasible, sustainable, and cost-effective design. This analysis will consider the life-cycle impact of the building as well as the effect of incorporating a green roof and building on a brownfield site. Based on these results, a recommendation for the best design options will be made.

Capstone Design

The comparison between the structural and fire designs for the renovation of a manufacturing facility and the new design and construction of a similar school facility, will explore six real world constraints that are elements of the Capstone Design. The constraints addressed are *Constructability, Economic, Environmental, Health and Safety, Social and Sustainability*.

Constructability

The concept of constructability influences each stage of design and development of a project because it refers to the ease of construction, subjected to the overall requirements for the design. The ability to renovate the existing conditions, as well as construct a new building with the same requirements, will initially be affected by the materials considered during design. The shapes and sizes of sections and members will be chosen in standard specifications to ensure simplified production and reduce cost and waste. Standardized shapes and sizes also help reduce construction time by limiting the potential for errors due to confusion in the field. During fabrication and erection, each section and member should be easily identifiable, in addition to moveable, for the construction laborers.

Economic

During project development, economic constraints must be evaluated in the early design stages, as well as repeatedly throughout the entire delivery process. Economic constraints are continuously re-evaluated to reduce the cost of construction while maintaining efficiency. The cost of renovation will be compared to the cost of ground-up construction to determine the most efficient design alternative. The cost comparison will include chosen materials, dimensions of structural elements, the layout of both design options (renovation and ground-up construction), life-cycle costs, cost of operation, and the time required to complete the project construction schedule.

Environmental

Both ground-up construction and the renovation of an existing building have environmental impacts that need to be considered during the project development phase. With the renovation of a building, the reuse and recycling of materials as well as the impact of the demolition on the environmental air quality are important factors. The site implications, such as the remediation of a brownfield, are aspects of new construction that can impact the environment. The state of Massachusetts does not prohibit the development of schools on a brownfield site, but outlines specific siting factors and requires an environmental evaluation and site remediation to be performed.

Health & Safety

In the design of any construction space, it is crucial to consider the health and safety of the potential occupants. All structural elements must be in compliance with the building codes and standards developed to ensure the integrity and safety of the building. Load requirements and member size restrictions will be determined and evaluated based on the *Massachusetts State Building Code*, which references the *International Building Code*. Additionally, it is important to evaluate the design of the fire protection and suppression systems. The fire detection and sprinkler systems will be evaluated based on the requirements specified in the *National Fire Protection Association* codes.

Social

The restoration and the ground-up construction of a charter school will be affected by social implications of the surrounding area. The educational needs of the community must be evaluated for existing age groups and population demographics. The school's proximity to local businesses and facilities that can enhance educational development must also be considered. Prior to any renovation and construction, it is important for contract companies to address all social concerns presented by the community. Addressing such concerns early on, will ensure the project runs smoothly and reduce the chance of backlash and resistance from members of the community.

Sustainability

The sustainability of a building is influenced by where and how the building is constructed. During the design phase, it is important to consider how the exterior environment will affect the materials chosen, as well as the effects the materials will have on the environment. The designs for renovation and ground-up construction of the warehouse facility will ensure the building withstands environmental and load impacts for an extended period of time. To ensure the materials and designs chosen are environmentally sustainable, LEED specifications will be referenced.

Background

Vacant Warehouse Facilities

Big-box buildings and warehouse structures are generally owned by one entity and maintain only one operation. These buildings are built for one purpose whether a warehouse with a niche in its industry or a big-box store such as Target. When large corporations are then forced to shut down locations, it is difficult for a replacement tenant to be found, resulting in a vacant building. Depending on the economic situation, even popular retail stores such as Walmart may not have use for these oversized buildings in suburban areas. Despite a space being suitable for a corporate warehouse or big-box retail store, competitors in the same market sector have unique prototype stores, and reject vacant space with the preference of building on open land rather than incurring the cost to rehabilitate the existing building (Sochar, 2008).

The problem associated with these large vacant buildings is not only attributed to their waste of materials and space, but also pose a fire hazard. A key event that brought light to this issue was the fire in a cold storage warehouse in Worcester, Massachusetts in December of 1999. The 43,000 square foot building was originally constructed in 1906 and had been abandoned for over 10 years prior to the fire. During the attack on the fire, six firefighters tragically lost their lives while trying to search for the homeless couple believed to be living there. Several issues were investigated from this event that have now been utilized in the adoption of certain NFPA codes and standards. The lack of security in this building after its operations had ceased allowed unrestricted access into the building. Therefore the integrity of the building was not left up to owners or tenants, but rather to the discretion of people with unpredictable behavior (USFA Report). The building had also not been maintained and fire department personnel were not familiar with the building's contents nor the automatic suppression within it. It is evident that the lack of records and upkeep of a structure along with potential damage from vandals make these vacant buildings a danger to the built environment.

The professionals responsible for designing an urban landscape and its built environment are responsible for solving this problem. Although sustainability is often associated with a small carbon footprint and low energy usage in buildings, adaptive reuse of these abandoned buildings is a sustainable measure that can be taken to prevent overcrowding and urban sprawl. As more adaptive reuse projects for large vacant structures are completed, designers will begin to realize the flexibility that can be incorporated into buildings to allow for different ownership and use in the future.

Renovation/Repurposing

Many commercial and industrial developers disregard the potential there is in the United States to repurpose buildings. Rather, a common practice is to find a buildable site that suits the needs of the building's purpose in mind. Site selection must be very specific, and with the preservation of a large amount of the open space in desirable urban and suburban areas, the perfect site may not be available to the developer. Another common practice is to purchase a site that has already been built upon and has the infrastructure capabilities to support the desired building. In many cases these existing buildings do not provide the features to support the operations of the new owner and will be completely or partially demolished to erect a new structure. This is not a sustainable practice, as the materials and debris of the old structure commonly end up in a landfill.

Over the last few decades, protecting the environment has become a much larger concern for architects and contractors. As a result, there is a growing emphasis on reducing the environmental impacts of renovation and new construction. LEED and other green guidelines have provided ranking systems to help improve sustainability during construction and development. One of the most important aspects of sustainable building is Recycling Construction and Demolition Debris (C&D). Through C&D recycling, developers can provide materials to local vendors and processors for reuse. By recycling these materials, the cost of materials is greatly reduced while conserving raw materials such as energy and water (Lennon, 2005). Almost 90% of C&D waste can be recycled including concrete and bricks, plumbing fixtures, and even asphalt. By recycling these materials, the prices for supplies will decrease for the entire industry (Alton Materials, 2013). Reducing the amount of waste and increasing the amount of recycled C&D materials conserves landfill space, reduces the environmental impact of producing new materials, creates jobs, and reduces overall building project expenses (EPA, 2015). Prior to construction, architects and contractors must weigh the alternatives of recycling old job sites versus starting new construction.

A solution to these practices is to carefully investigate and survey available buildings to determine how they can be repurposed to meet the needs of the new occupancy. In some cases this requires a more involved planning process to ensure the building fits the size, location, and quality of the desired building and operations. The applicable building codes must be used to preliminarily assess the requirements for the design in mind for the new building. This will include the construction type, size requirements, and fire-safety features that the surveying agent will look for when finding the right building to repurpose. Ideally multiple buildings will be preliminarily assessed due to the specific code requirements that could prevent a building's feasibility due to expensive reconstruction and modifications.

The team of architects and engineers must develop a feasibility study in which zoning codes, building codes, sketches, calculations, and expert consultation are provided to prove that the building is worth pursuing further.

Charter School Design

Charter schools are unique in that they are public schools, making them available to all children without special entrance requirements or tuition costs. The schools are operated by private organizations, and thus provide flexibility for the learning opportunities and culture that can be implemented. Since they are operated by private organizations, funding is typically received from the local school district or the state board of education, and a performance-based contract is established. Therefore, the design of the building itself plays a significant role in the learning capabilities, student safety, and initial attraction to the building.

When considering the potential locations for a school, the site must meet educational needs while minimizing possible adverse educational, environmental, social, or economic impacts on the community. Negative implications that must be considered include, but are not limited to, new sewers, road construction, transportation facilities, new water supplies and/or water connections. The size of the land plot must be large enough to efficiently and safely serve the intended population. Project developers must ensure sufficient land to accommodate the design of the building, as well as potential additions in the future, outdoor educational programs, parking areas, bus turnarounds, and delivery areas. The soil condition of the site must also be evaluated because it may cause development costs to increase (Mass DOE, 2004).

Potential construction sites for a school are also required to undergo an environmental site assessment conforming to ASTM Phase I Standards (ASTM, 2014). Phase I consists of four parts: records review, site reconnaissance, interviews, and a final report. The records review is intended to obtain information that will help identify recognized environmental conditions in connection with the property. Site reconnaissance is evaluated through a site visit in which the property must be visually and/or physically observed along with any structure located on the property. Interviews must be conducted with past and present land owners and occupants to obtain information about previous uses and conditions of the property. Once all the information previously mentioned is obtained, it must be composed in a final report that includes all documentation of findings, opinions, and conclusions (ASTM, 2014).

Leadership in Energy and Environmental Design

The environmental movement of the 1960's and 1970's brought a newfound attention to the detrimental effects of human actions on Earth's limited resources. Along with this came an understanding of how buildings use resources and negatively impact the environment. Buildings in the United States are associated with 38% of all carbon dioxide emissions, which is nearly 1/3 globally (USGBC, 2013). A study performed in 2007 estimated that a shift in building design to incorporate zero to negative net life-cycle costs could offset up to 6 billion tons of carbon dioxide annually (Yudelson and Fedrizzi, 2008). Currently, Earth is in an ecological overshoot where resources are being converted into waste faster than they can be replenished. Due to an increase in human population, an overreached use of resources, and increase in both commercialism and industrialism, it takes eighteen months to regenerate what was consumed in one year (USGBC, 2013).

The Leadership in Energy and Environmental Design (LEED) rating system was created in response to this with the understanding that the design and construction trades already had the resources and ability to transform the industry's approach to building in order to promote sustainability. The LEED rating system created a process for implementing and measuring green building practices while providing a certification procedure for commercial, residential, and institutional buildings. This project will focus on four of the credits necessary for the certification process of a school: High Priority Site, Rainwater Management, Heat Island Reduction, and Building Life-Cycle Impact Reduction. It will also adapt the approach outlined in the Materials and Resources section to incorporate the recycled content pre- and post- consumer as well as the manufacturing and extraction distances in the selection process of materials.

High Priority Site

The concept of restoring contaminated sites for reuse emerged in the 1960's when environmentalists connected a series of toxic waste catastrophes to the detrimental effect hazardous chemicals have on Earth's resources. Prior to the 1960's, hazardous waste was disposed of outside of city limits. By the 1970's, manufacturing plants were unable to comply to new, stricter disposal regulations and began to shut down leaving behind polluted land. Increased urban development resulted in the eventual expansion of housing, businesses, and infrastructure to these areas. These contaminated areas became valuable for development due to an increase in population and the government's inability to tax unused land.

The Environmental Protection Agency (EPA) estimates between 500,000 to 1 million brownfield sites currently exist in the United States as a result of fuel, chemical or solvent, and heavy metal contamination (Maczulak, 2009). Oftentimes brownfield sites sit unused due to the high cost of remediation that oftentimes ends up being greater than the land worth after cleanup. The process for site assessment begins with a site visit to assess current condition, then a review of records and property inspection, followed by air, soil, and water testing for chemicals. A cleanup plan that takes into consideration land topography, erosion patterns, sediment movement, surface and underground water flow is then established. This plan outlines safety measures as well as which technology is most suitable for use, bioremediation or phytoremediation. Bioremediation utilizes naturally occurring organisms to either remove or neutralize pollutants present on a contaminated site while phytoremediation uses plants to detoxify hazardous substances in the soil and water of a site. In order to simplify cleanup processes, the EPA classified brownfields by industry type as displayed in *Figure 1* below. Integrated cleanup redevelopment, where field developers coordinate with new construction so building can occur on sections already cleaned, is a cost effective technique used to speed up the remediation process.

EPA Brownfield Categories	
Type of Brownfield	**Cleanup Tasks**
community	small-scale projects needing excavation and removal or on-site containment
mill sites	removal of asbestos, VOCs, PCBs, metals (textile mills); wood treating chemicals, VOCs, fuels, metals, creosote, dioxins (wood and paper mills); petroleum-based products, PCBs, slag, underground storage tanks (iron and steel mills); Numerous buildings on large sites
mining sites	acid tailings, PCBs, heavy metals in remote sites; surface and groundwater contamination
portfields (ports and harbors)	oils, ballast, ship scrapings, paints, solvents in large underwater areas
petroleum sites	refineries, storage tanks, automotive plants, service stations; numerous structures on large areas connected with tanker shipping ports and railways
railfields	petroleum products, herbicides, pesticides, metals, creosote, industrial cargo on large areas covered with rails and buildings; right-of-way stipulations
underground storage tank (UST) sites	buried storage tanks with mixed contents, contaminated soils, sediments, and groundwaters

Figure 103: EPA Brownfield Categories from "Cleaning Up the Environment"

The LEED High Priority Site contains an option for brownfield development in order to promote sustainability through the reuse of abandoned land. Development on a brownfield site not only removes and treats harmful substances, but can increase local property values, avoid urban sprawl, and reduce human and wildlife exposure to environmental pollution. Redevelopment on a contaminated site also reduces the project footprint by using 78% less land on average than on a greenfield (USGBC, 2013).

Heat Island Reduction

At the beginning of the twentieth century approximately 15% of the world's population lived in cities and by 2011 this increased to 50%, encompassing 2.8% of Earth's total land (Dell'Osso, 2011). This continuous increase in urban development has resulted in the urban heat island phenomenon where cities alter their natural climates with increased temperatures. Dark, non-reflective surfaces that are commonly used in urban infrastructure for parking, roofs, and walkways absorb thermal energy during the day and slowly re-emit stored heat at night creating heat islands that can cause urban neighborhoods to experience temperatures 1.8 to 5.4 degrees

Fahrenheit warmer than that of surrounding suburban areas (USGBC, 2013). With this change in natural temperature increasing at a rate of 0.25 to 2 degrees Fahrenheit per decade, the heat island effect could double in fifty years (Rodgers and Stone, 2001). *Figure 2* below illustrates a temperature profile of a typical urban heat island profile.

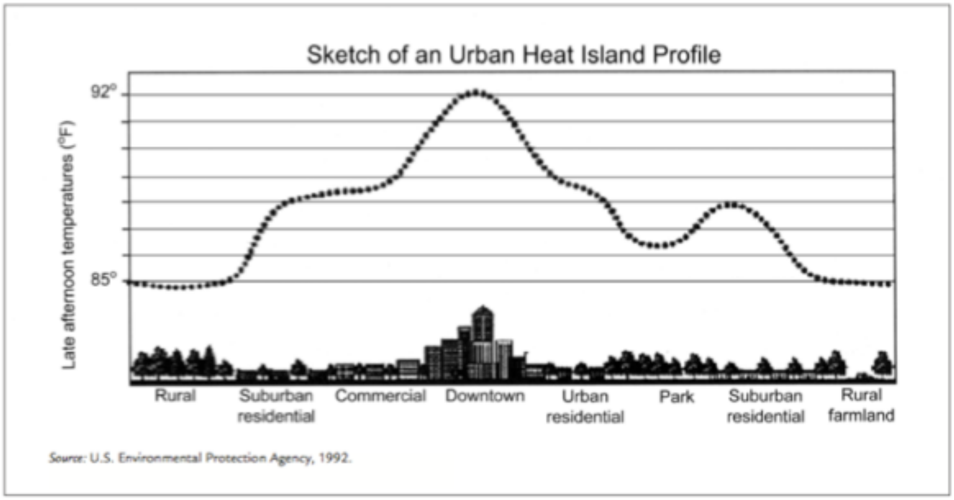


Figure 104: Urban Heat Island Temperature Profile from "Urban Form & Thermal Efficiency"

Urban development involves significant removal of vegetation, replacing it with materials of higher heat capacity that limit evapotranspiration, a natural cooling process that converts water to vapor and reduces the amount of radiation available for absorption by hard surfaces. Since roofs encompass 20 to 25% of urban surfaces the conversion to green and cool roofs can reduce heat islands in addition to improving air quality, stormwater management, biodiversity, and building life-span (Dell'Osso, 2011). Green roofs increase the evapotranspiration in urban areas by an increase in vegetation while cool roofs increase the reflection of solar radiation by improving the albedo of the roof surface.

It is estimated that urban heat islands have contributed to one third of New York City's increase in temperature over the past century. According to a study performed in NYC that analyzed three types of roofing systems (standard black, high-reflective white, and extensive green) the installation of white and green roofs results in a decrease in energy use. The construction process of a green roof generates less kilograms of carbon dioxide equivalent and requires less replacement of building materials than a black roof, decreasing their overall environmental loads.

Urban heat islands have detrimental effects on human, animal, and plant health by changing habitats and increasing exposure to ground-level pollution. By increasing temperatures, more greenhouse gas pollution is generated due to inflated cooling loads. In an attempt to mitigate these effects, the LEED Heat Island credit provides an outline of how to incorporate green and cool roofing techniques into the design process while creating incentive to do so. The energy savings correlated with the reduction of heat island effects through inclusion of integrated green roof systems are between $4-15 million per year with a reasonable payback period (USGBC, 2013). The credit uses the Solar Reflectance Index (SRI) and Solar Reflectance (SR) to measure roofing and non-roofing materials ability to resist solar heat respectively. In order to evaluate material performance over time, it additionally takes into account the three year aged SRI and SR values of the material.

Building Life-Cycle Impact Reduction

The beginning stages of moving towards sustainable building focused primarily on the impacts of products and processes during the construction phase. As technology progressed, a greater understanding of a building's local, regional, and global effects on the environment over its lifetime evolved. Life-cycle Analysis (LCA) tools were created in response to this in order to assess the cradle-to-grave impacts of each component of a building and its construction, and to identify areas where harm to the environment can be reduced. The popularity of utilizing LCA in the design stages of projects has grown due to a shift in belief that manufacturers are responsible for both the direct impacts of production and the environmental impacts of the use, transportation, and disposal of the products. Environmental preference has also become a criteria in both the consumer market and government guidelines for procurement.

Assessing a building's life-cycle impact is comprised of four stages: goal definition, life-cycle inventory, impact analysis, and improvement analysis. During the design stage, boundaries need to be established regarding the scope of the project. From there, the energy and raw material inputs for each stage of a project need to be calculated in order to evaluate the effects on human and environmental health. Various areas for reducing energy and environmental impacts for each stage can be evaluated using a LCA tool. This entire process takes into consideration the raw material procurement, manufacturing, distribution, consumer use, and post-consumer use of each product as outlined in *Figure 3* below.

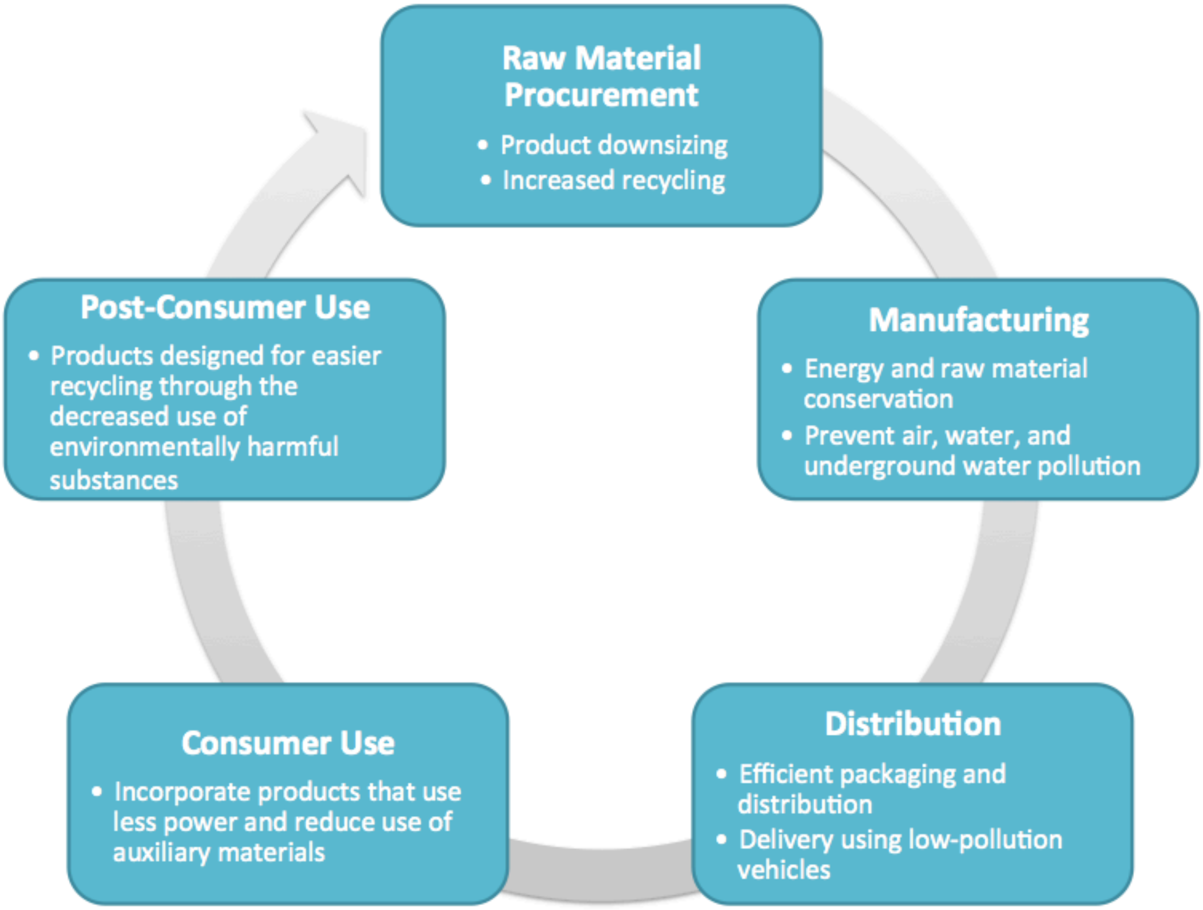


Figure 105: Life-Cycle Assessment Process Considerations, Adapted from "Defining Life-Cycle Assessment"

In order to encourage the use of life-cycle analysis in projects, LEED developed a credit devoted to the impact reduction of a building's lifetime for restoring existing buildings, reusing building components, and reducing a building's environmental footprint (USGBC, 2013. For the restoration of an existing building, the energy use and associated waste can be reduced. According to a report by the National Trust for Historic Preservation, the reuse of a building offers environmental savings compared to new construction the majority of the time (USGBC, 2013). For new construction, LCA analysis can be utilized to determine which materials are most effective for a project through its lifetime as well as identify any tradeoffs between the selection of materials and the energy performance of the building.

This project will be utilizing the Athena EcoCalculator for Commercial Assemblies in the New York City ASHRAE climate zone 4 for low-rise structures to analyze the life-cycle impact of both the renovation and new construction of the building. Each pre-defined assembly analyzed by this software is embedded with LCA results from the ATHENA Impact Estimator for

Buildings, producing immediate results. These results take into consideration each life-cycle stage including maintenance and replacement over a sixty year time period. Although the EcoCalculator cannot provide scoring for LEED credits, it is beneficial for comparing explicit assemblies and evaluating all of the assemblies of a specific structure. Any assumptions the calculator uses for simplification purposes can be found in *Appendix B*. The foundations and footings, columns and beams, intermediate floors, exterior walls, windows, interior walls, and roof components will all be input to determine the environmental footprint of each design. The data for each assembly is based on common practices within industry standards, and variations between products falling within this practice are accounted for by sensitivity studies. These designs will be analyzed for seven impact categories as outlined in *Figure 4* below. Based on the results, recommendations will be made for the best design option.

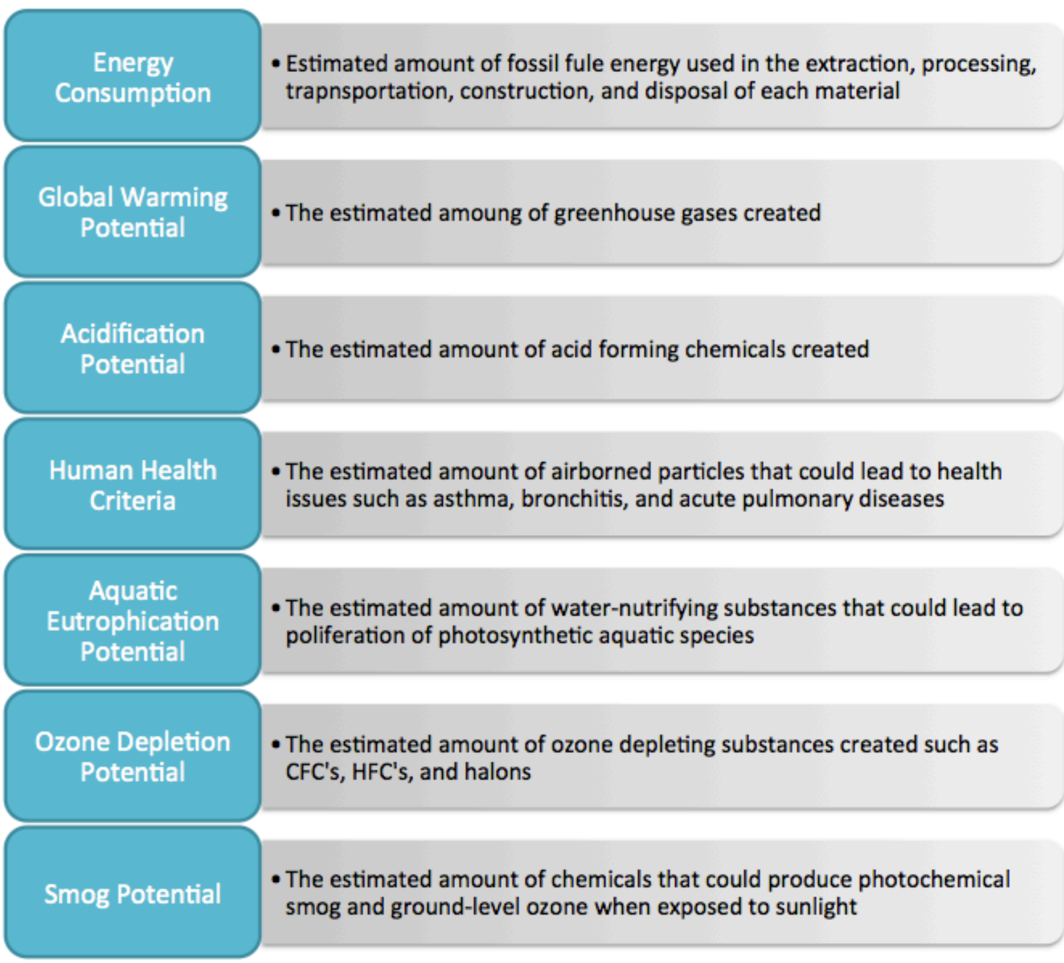


Figure 106: Impact Categories for the ATHENA EcoCalculator Software, Adapted from "Life-Cycle Assessment Software"

Materials and Resources

The environmental impression of manufacturing processes for products encompasses the extraction, processing, and transportation of the materials and their associated energy impact. The extraction of raw materials results in deforestation, degradation of water sources, habitat loss, threats to rare and endangered species, release of toxic chemicals, and infringement on domestic people's rights. For example, conventional logging practices are responsible for 70% of resource depletion in Latin America and subtropical Asia and mining practices represent another 18% of deforestation worldwide (USGBC, 2013). In addition to the imprint product manufacturing leaves on the environment, construction and demolition waste represents 40% of the solid waste stream in the United States, creating a waste hierarchy (USGBC, 2013).

In order to address this issue, the Environmental Protection Agency (EPA) identified the principle techniques for reducing waste as source reduction, building and material reuse, recycling, and conversions to energy. By focusing on source reduction, the adverse impacts of a project on the environment can be decreased through innovative construction methods such as prefabrication design that caters to the dimensions of materials to reduce cutoffs further decreasing the amount of waste. The production of greenhouse gasses associated with manufacturing processes can be mitigated through the reuse of both buildings and materials. Although common practice is to landfill waste from project sites, most landfills are reaching capacity requiring contractors to export waste to remote areas increasing transportation requirements and environmental harm. With advancements in recycling technology, the amount of product considered waste is decreased and the life time of materials in the production stream is increased. For materials that don't have a secondary service, procedures for converting product waste to energy have been developed.

The LEED Material Resources credit category encourages the responsible sourcing of raw materials and selection of reused or recycled materials. The manufacturing industry has also become more candid through the requirement of Corporate Sustainability Reports (CSR's) based on accepted standards and methods for supply chains and material extraction. These reports allow for practices within companies to be assessed, improved, and compared based on their associated environmental effects. Through these tactics, the LEED framework has contributed to diverting over 80 million tons of waste from landfills, which is expected to reach 540 million by the year 2030 (USGBC, 2013).

Building Codes (Purpose/Importance)

Building codes were established to provide minimum regulations for the construction and development of buildings. They ensure a building is structurally sound and will serve its intended purpose over its lifetime. The codes were developed based on principles intended to adequately protect public health, safety, and welfare while maintaining the integrity of the scope of the building (International Code Council, 2015). While the codes provide minimum specifications, they do not unnecessarily increase construction costs nor do they restrict the use of/or give preference to specific materials, products, or methods of construction. Over time, the codes have developed and improved along with the progressions of technology and research. Today, building codes vary with the intended purpose of a structure. For example, a warehouse facility is subjected to different codes than a public building or private school, as shown in *Table 1*.

Table 126: Facility Type Comparison

Building Type	Code Requirements	Design Considerations	Commentary
Factory (Industrial)	- Occupational Safety and Health Admiration (OSHA) - NFPA 230 Standard for the Fire Protection of Storage - Department of Defense (Covered Storage/Depots)	Durable/Functional Energy Efficient Safety/Security	More straightforward, needs to store items sufficiently
Secondary School (grades 9-12)	**- National Clearinghouse for Educational Facilities (NCEF) - Advanced Energy Design Guide for School Buildings - American National Standards Institute (ANSI) - State School Facilities Planning and Design Guidelines**	**Accessibility Aesthetics Cost-Effective Safety/Security**	**Consider the safety and interaction of the students**
Chemical Storage Warehouse	- National Fire Protection Association (NFPA) - International Building Code (IBC) - International Fire Code (IFC) - International Mechanical Code (IMC) - National Electric Code (NEC) (NFPA 70) - Hazardous Chemicals	Safety/Security Risk Assessment Accessibility	Higher risk therefore higher attention to detail. More codes regarding employee and fire safety

As shown in *Table 1*, the codes and standards that govern various facility types cover a wide range of components including building materials, systems, equipment, testing, and more (EPA, 2015). When there is a change in occupancy within a building, it is crucial for contractors to ensure the new occupancy requirements are followed. A change in occupancy classification can include a change of classification within a group as well as a change of occupancy classification from one group to a different group. Such buildings must comply with all codes including, but not limited to, structural design, fire protection, plumbing, and means of egress (International Building Code, 2006). Due to the various building codes and regulations, it is difficult, time consuming, and potentially a larger cost to renovate a building to withstand a change in occupancy classification.

Structural Design

A building's structural design greatly influences the ability to repurpose a building. The existing structural elements are typically inadequate if the structure is repurposed to an occupancy that requires higher service loads. When dealing with a building designed with older building codes, one must also question the building's ability to comply with modern standards of design. These factors require a benchmark study of the structural design of the warehouse. Understanding the loads, costs, and purpose of the structural design allows for the exploration of alternative design options. These options include designing a building with higher capability for repurposing, which allows for a more sustainable design. A sustainable design requires a combination of the following: “minimizing material use, minimizing material production energy, minimizing embodied energy, life-cycle analysis/inventory/assessment, and maximizing structural system reuse (Danatzko 2011)”. Understanding the thought process behind the design is crucial to understanding the sustainability of the current building. With construction taking place in 2008, only 7 years ago, one may assume sustainability was considered in the original design. This draws into question whether or not a new building design will be necessary to accommodate the change in occupancy. This investigation will explore how sustainable design has evolved within the last decade.

Fire Safety in Schools

Schools, like other building uses, have been subjected to fire issues in the past that have become mitigated through the development of codes based on the analysis of tragic incidents. Since the NFPA was founded in 1896, there has been a total of nine school building fires involving the death of at least ten people (Cote 20-12, 2008). The problems stemming from the earlier school fires proved to be an inadequate egress design and poor evacuation planning, whereas later incidents took place due to unlikely explosions and flash fires. Despite fire officials believing all issues had been addressed, the reconsideration of code provisions occurred in 1958 as a result of a fire that occurred in Our Lady of the Angels School in Chicago, IL killing ninety-two children and three nuns. Post-fire investigations showed the building did not provide sufficient features of fire protection, fire prevention, and life-safety. Though the building's structural design was non-combustible, the interior was filled with combustible wood materials, ceiling tiles, and personal belongings. Life-safety was not achieved as the exit capacity exceeded that of the occupant load, interior stairways were not enclosed, and teachers did not have an evacuation strategy in place. The building also lacked fire suppression and detection, and the occupant notification system strictly relied on manual pull stations that were unreachable by some students since it was mounted at a height of 6 ft. above the floor (Carella, 2008). The accumulation of these factors has led to reassessment of codes and standards to recognize the hazards that schools present such as the provisions against the storage of personal items in a corridor that does not have either automatic smoke detection or fire suppression.

Since the Our Lady of the Angels fire, there have been no documented incidents of a fire in a school killing more than ten people. Even so, more recent statistics show that an average of 5,320 fires occurred annually between 1999 and 2002 in K-12 educational facilities, contributing to an average of 88 civilian injuries and $74 million worth of property damage. An important result to take away from these reported fires is that no deaths occurred over the three-year period. A majority of these fires were caused intentionally (38%), originated in lavatories, bathrooms, and locker rooms (19%), and had trash or waste be the first items ignited (12%) (Cote 20-12, 2008). Therefore, it is evident that the status of fire safety in schools is based off human behavior rather than actual hazards in the building. As a result code provisions are based on the behavior and capabilities of younger children.

Some unique design challenges presented in the study of schools include open plan designs, in which spaces are delineated using movable fixtures and low height partitions. This prevents passive fire and smoke control, but the flexibility is valuable to educational goals and could prevent re-construction to adapt to certain programs. The open plan concept has the ability to work, but proper design and consideration must go into planning for egress requirements. Another existing challenge is the false manual activation of the fire alarm system that is prevalent in schools. Several solutions have been proposed including substitution for other systems, relocating pull stations to classrooms, and providing covers that activate distinct audible alarms prior to the alarm being pulled (Cote 4-5, 2008). The development of an advanced evacuation plan must also be examined, as possible designs such as horizontal exits into temporary areas of refuge (zoned evacuation) may be effective for large schools. The occupants in a school presents difficult fire-safety design challenges in an adaptive reuse project that must be overcome with prescriptive code compliance and sound engineering judgment.

Revit as a BIM Tool

Building Information Modeling (BIM) is still in the early growth period in the design, planning, and construction industry. The overall process of BIM encompasses all data of a building through its early design stages through changes that occur, or are predicted during its lifecycle. *Revit* is a software developed by Autodesk that is mainly used as a design tool to produce a digital representation of the structure, but it has capabilities that far exceed the typical use. *Revit* building design software is specifically built for Building Information Modeling (BIM), including features for architectural design, MEP, structural engineering, and construction. Some capabilities of *Revit 2016* that have the capability to be implemented in this project are shown in *Table 2*. The most effective features that are packaged into the software allow collaboration of different design disciplines and the storage and manipulation of building data related to materials, sizes, and assemblies, and their relationships to each other.

Table 127: Applicable Capabilities of Revit 2016

Discipline	Feature	Description
Architectural Design	Energy Analysis	Perform energy analysis and find potential opportunities for energy savings; Refine analysis with different data input
	Solar Studies	Model impact of natural light and shadows
Site Engineering	Site Designer	Model alternatives for site elements
Structural Engineering	Links with Autodesk Advance Steel	Weld definition properties; Steel connection design
	Structural Analytical Model	Simplified 3D representation of structural system
	Rebar Design	Constraints; Detailing; Scheduling; Path reinforcement shapes
Construction	Material Takeoff	Estimate takeoff quantities for any Revit family
	Construction Modeling	Support construction workflows by dividing model element into parts or assemblies
	Displaced Views	Create exploded building design views to illustrate model relationships
MEP	Pipe Placement	Control slope, size, elevation, and justification of piping
	Place Sprinklers	Insert sprinklers with pre-defined specifications

A case study in which *Revit* was optimally used was performed on the integrated design of a medical Facility in New York, NY. The project was completed by WASA/Studio A, which was a firm using *Revit* and BIM for the first time. Instead of easing into the software platform, the firm completely adopted BIM to successfully design the architectural, MEP, lighting, and interior design layouts. Throughout the design process, problems, per usual practice, came up between different design disciplines. For instance, the structural engineer's initial design of the steel frame did not meet the requirements of the floor-to-floor height. *Revit* allowed the design team to model this structure quickly and determine an alternative structural system. The 3D modeling capabilities of *Revit* also facilitated the coordination of mechanical equipment and components above the hung ceilings, which had limited spacing. A feature in *Revit* that WASA/Studio A found practical in this scenario was clash detection, which determined if the layout of equipment, piping, and conduit crossed caused them to cross each other (Autodesk). Unlike typical projects where the architect designs a building substantially before involving the specialized consultation of engineers, this firm used a common *Revit* design model to incorporate the consultant's expertise early on in the project.

Integrated design is a process that involves collaboration of stakeholders of different expertise. The successful design of a building is dependent on the balance of opinions and decisions among these stakeholders. The desire to use *Revit* as a BIM tool in integrated design has come from the lack of success in traditional project delivery and the increased drive for sustainability and innovation. *Revit* has shown the ability to plan construction more efficiently to create less material and labor waste, conflicts amongst parties, and associated risk (Deutsch, 2011). It is also a necessary tool to meet the needs of increasingly complex building processes and systems, and deliver projects on time and within budget. The study of *Revit* and its role in the design, construction, and operation of buildings show how it has advanced integrated design and should be applied across the board for future projects.

Professional Licensure

The intent of professional licensure is to protect the public by ensuring only qualified individuals work as engineers. Prior to reform in licensure laws, anyone had the capability to prepare, sign, seal, and submit engineering plans without the need to prove competence. Becoming licensed signifies a multifaceted understanding of both physical and engineering principles with a commitment to protecting the life, health, safety, property, economic interests, and welfare of the public. Professional engineers are licensed to be liable to the public for the work they produce and accountable for abiding by a strict code of ethics. This code of ethics ensures licensees place public welfare above any obligations to clients or employers while protecting confidential information and disclosing anything that could compromise their professional judgment. This loyalty to public interest and professional integrity requires a continual understanding of any advances in the engineering field as well as the competence to execute these changes.

Receiving professional licensure is governed by individual states and only valid in that specific state. The state of Massachusetts requires the completion of two eight-hour exams, the Fundamentals of Engineering (FE) exam and the Principles and Practice in Engineering (PE) exam in a designated discipline. Prior to the PE exam, four years of responsible engineering experience must be completed if a degree was received from an Accreditation Board for Engineering and Technology (ABET) accredited four-year college or eight years of experience if from an accredited four-year program in engineering technology.

This project requires a licensed professional engineer due to the change in occupancy of the building as well as an update in the applicable codes. When a building is constructed, it adheres to the current codes, regulations, and standards. However, codes and regulations are reactive laws and are therefore modified over time as knowledge and technology evolves. This building was designed and constructed under the 6th edition of the *Massachusetts State Building Code* in 2008; however, the 8th edition is currently followed. It is pertinent that the professional engineer is not only aware of the code change and how that effects the project, but also is qualified to implement those changes. The professional engineer must also understand how the change in occupancy affects the fire safety of the building. Currently the warehouse facility is used for the manufacture and storage of packaging materials and incorporates a two-story corporate office building space. Changing the occupancy to a charter school will change the occupancy rating from mixed occupancy Group B and Group F to Group E the increase in the rate at which a fire would spread in the building. Having a professional engineer overseeing and advising on a project ensures the integrity of the building is sustained and the public welfare is safeguarded.

Methodology

Initial background research will focus on building codes, green construction, adaptive building reuse, and common design practices for school buildings. The purpose of building codes as well as how the governing code provisions will change between the existing occupancy of factory industrial and the proposed change to an educational facility will be considered. How both the existing building and the new building comply with zoning regulations will be determined. In addition to a general background on green building and the LEED accreditation process, specifics on its application to a school and renovation will be researched. A comprehensive understanding of the uses of fire suppression systems as well as an examination of past structural and fire related failures will be fundamental for this project. This project will be broken down into six phases: existing conditions, predict existing fire protection systems, proposed renovation, ground-up construction, analysis and comparison, and proposed recommendations.

Existing Conditions

The existing conditions will include an analysis of the building's structural system, fire protection systems, interior finishes, and means of egress. The warehouse was originally designed using the 6th edition *Massachusetts State Building Code*. Over the past few years, Massachusetts has adopted the 8th Edition of its building code, which primarily references the 2009 Edition of the *International Building Code* with amendments provided (BBRS, 2010)**.** The Load combinations are significantly different between the current IBC and the 6th edition building code.

The analysis of the existing building conditions will be conducted using the structural drawings completed for the construction of the building. These drawings provide the building floor plan showing basic architectural components such as windows, doors, interior walls, and location of plumbing fixtures. They also provide the plans for the first floor foundation, and the second floor, mezzanine, and roof framing. Material sections, details, and notes are also included for all structural components.

With the given information, a detailed study of the structure for fire safety, structural integrity, and load requirements will be performed. This will involve benchmarking the current building using the 6th edition *Massachusetts State Building Code* as well as the current edition.

Benchmarking allows for a comparison between the codes as well as a starting point for designing an entirely new building.

Since architectural, electrical, mechanical, civil, and fire protection drawings have not been provided, some assumptions must be made about the building to get a complete assessment of the existing conditions. These assumptions will be done using the code provisions that were applicable at the time of design and an engineering understanding of how the building should be constructed. The assumptions that need to be made are listed below:

- Mechanical, electrical, and plumbing (MEP) dead loads
- Fire resistance of structural components, exterior walls, and interior walls.
- Fire protection systems including fire alarm and fire suppression systems
- Use of rooms and spaces
- Type and height of interior walls/partitions
- Interior finishes
- Stair, elevator, and shaft enclosures

With the use of Building Design handbooks many of the items listed above can be easily estimated as they are common construction materials; however, items such as the MEP cannot be properly estimated without more detailed drawings. In order to account for these loads, representative values will be used for the interior of the building as well as the weights for roofing units from the structural drawings.

Predict Existing Fire Protection Systems

For the renovation to withstand a change in occupancy, it is crucial to first understand the existing conditions of the fire detection and suppression systems present in the warehouse. Plausible sprinkler and fire alarm layouts will be created using *AutoCAD* and *Revit* drawings based on the assumption that the both layouts comply with code requirements for F-1 moderate hazard, as provided in NFPA. Using the existing structural design drawings, the layout will be designed in compliance with the *Massachusetts Comprehensive Fire Safety Code* (MCFSC), which at the time referenced NFPA 13 (1993) as the base code for the installation of sprinkler systems. By recreating the existing fire protection systems, the amount of reconstruction required for renovation to obtain suitable fire protection can be determined.

Proposed Renovation

Once the existing conditions of the warehouse are determined, potential renovation designs will be considered. Proposed spatial layouts for the charter school will be analyzed for their structural impacts. Based on these results, the structural design of the warehouse will be altered to withstand the change in dead and live loads. This may include alterations of column sizes, structural bays, and the analysis of the footing capacity. Interior layouts will include learning spaces, supporting spaces such as offices, restrooms, storage, and dining, paths of travel, and means of egress. Changes to the exterior enclosure of the warehouse will be proposed and analyzed. Several alternatives will be developed using *AutoCAD* and *Revit* design software. Once various options are produced, a construction schedule will be developed based on specific design phases in order to determine the amount of time and man power required. Alternatives will then be compared based on the cost, time of completion, and environmental impacts to select the most efficient design option.

Ground-Up Construction

With the completion of the proposed renovation, a design for the ground-up construction of a building for the same purpose will be created. We will first perform a review of the repurposed design to identify any constraints that interfered with the desired design. We will also give examples of costly project activities that would not need to be performed in the construction of the new building. Finally, any apparent constructability issues will be discussed and solutions will be proposed as to how they can be resolved in the new design. The same steps will then be taken to produce a code compliant building, identifying all of the major concerns in our scope of work. A construction schedule will be created for comparison to the time required for renovation.

Analysis and Comparison

A baseline cost analysis will be performed on each building taking into consideration the estimated materials, equipment, design, labor and operation of the facility. From there, components of LEED-based design for Heat Island Reduction, High Priority Sites, and Material and Resources credits will be analyzed through the inclusion of the development on a brownfield, a green roof, and material selection for both design options. Another cost analysis will be completed taking into consideration the incorporation of each of these environmental elements. A life-cycle impact analysis on the individual options will be completed using the Athena EcoCalculator for Commercial Assemblies. This tool will aid in determining the best designs by taking into consideration energy consumption, global warming potential, acidification potential, human health criteria, aquatic eutrophication potential, ozone depletion potential, and smog potential.

Proposed Recommendations

Based on the results from comparing the different design options, a proposed recommendation will be determined. This will examine renovation versus ground-up construction considering the baseline cost-analysis, the incorporation of environmental components, and the life-cycle impact analysis. A ranking system for constructability, economics, the environment, health and safety, social implications, and sustainability will be developed and applied to each design alternative to determine the most effective option.

Deliverables

The fulfillment of the Major Qualifying Project requirement will generate a considerable number of deliverables. Both structural and architectural drawings in *AutoCAD* and *Revit* will be created for the existing layout and proposed new layouts showing any necessary structural modifications. Adhering to NFPA 13, predicted arrangements for the fire protection systems of the warehouse and charter school will be designed in *AutoCAD*. Designs and considerations for addressing the LEED credit categories of Heat Island Reduction, High Priority Site, and Materials and Resources will be produced. Results from a life-cycle analysis using the Athena EcoCalculator will be presented in graphical and tabular form for each design option in accordance with the Building Life-Cycle Impact Reduction LEED credit category. A complete cost analysis of the renovation and ground-up construction will be summarized in tables using RSMeans data. A written report including the analysis completed, relevant background information, and various design alternatives will be produced to supplement the proposed recommendations.

Conclusion

The completion of this project will merge together structural, fire protection, and sustainability components that directly impact the civil engineering field. Structural engineering will be implemented to benchmark the current design and evaluate any modifications needed to maintain the structural integrity for the change in occupancy from a warehouse to a charter school. Fire protection engineering will be addressed through the design of the existing and proposed sprinkler systems in compliance with applicable codes. Through the incorporation of green engineering technologies, the sustainability of each design option will be considered and analyzed based on their practicality and economic impact. The completion of a construction and life-cycle cost estimation of each proposed design will aid in the recommendation process. The goal of this project is to demonstrate the connections between structural, fire protection, sustainability, and civil engineering components and how they impact each other. These results will then determine whether ground up construction or a renovation is more effective for a change in occupancy according to constructability, economic, environmental, health and safety, social, and sustainability constraints.

Schedule

Full Year Schedule

Full Year MQP Schedule

Term	Task	Primary Author	Start Date	End Date	Week 0 8/27 - 8/28	Week 1 8/31 - 9/4	Week 2 9/7 - 9/11	Week 3 9/14 - 9/18	Week 4 9/21 - 9/25	Week 5 9/28 - 10/3	Week 6 10/5 - 10/9	Week 7 10/12 - 10/15
A Term	Break Down of Project Tasks	All	8/27/15	9/9/15								
	Site Visit	All	9/9/15	9/9/15								
	Benchmark Existing Warehouse	Cola/Tanner	8/27/15	10/15/15								
	A Term Proposal	All	8/27/15	10/15/15								
	Abstract	Malina	9/22/15	9/22/15								
	Introduction & Problem Statement	Julia	8/27/15	9/23/15								
	Scope of Work	Tanner	8/27/15	9/23/15								
	Capstone Design Statement	Julia	9/7/15	9/23/15								
	Background-Vacant Warehouse Facilities	Tanner	9/23/15	9/29/15								
	Background-Renovation/Repurposing	Tanner/Julia	9/7/15	9/23/15								
	Background-Charter School Design	Tanner/Julia	9/23/15	9/30/15								
	Background-LEED	Malina	9/7/15	10/7/15								
	Background-Building Codes	Julia	9/7/15	9/23/15								
	Background-Structural Design	Cola	9/7/15	9/23/15								
	Professional Licensure Statement	Malina	9/7/15	9/22/15								
	Methodology	All	9/7/15	9/23/15								
	Deliverables	Malina	9/30/15	10/7/15								
	Conclusion	Malina	9/30/15	10/7/15								
	A Term Submittal	All	10/15/15	10/15/15								

Term	Task	Primary Author	Start Date	End Date	Week 0 10/27 - 10/30	Week 1 11/2 - 11/6	Week 2 11/9 - 11/13	Week 3 11/16 - 11/20	Week 4 11/23 - 11/27	Week 5 11/30 - 12/4	Week 6 12/7 - 12/11	Week 7 12/14 - 12/17
B Term	Revit Model of Structural Drawings		10/27/15	11/6/15								
	Written Report		10/27/15	12/17/15								
	Analyze Current Warehouse		10/27/15	10/30/15								
	New Layout Plan for Renovation		11/4/15	11/20/15								
	Design/Analyze New Building		11/12/15	11/27/15								
	Analyze Environmental Components		11/25/15	12/17/15								
	B Term Submittal		12/17/15	12/17/15								
	Presentation		12/17/15	12/17/15								

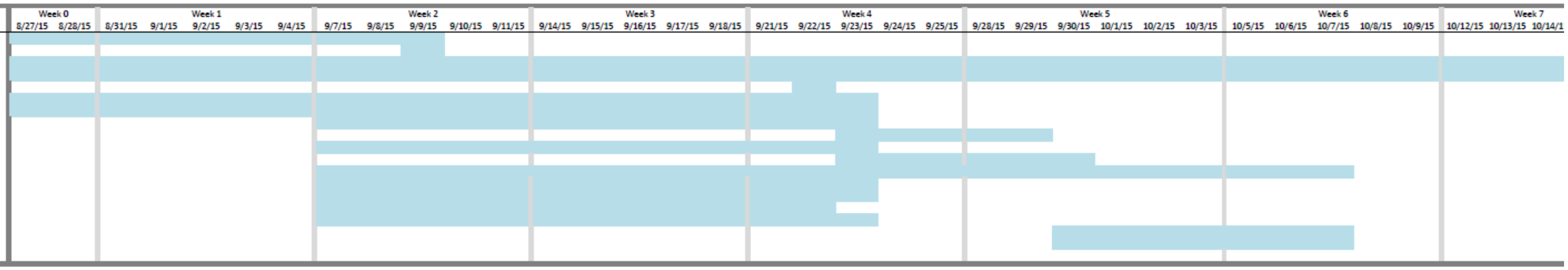
Term	Task	Primary Author	Start Date	End Date	Week 0 1/14 - 1/15	Week 1 1/18 - 1/22	Week 2 1/25 - 1/29	Week 3 2/1 - 2/5	Week 4 2/8 - 2/12	Week 5 2/15 - 2/19	Week 6 2/22 - 2/26	Week 7 2/29 - 3/4
C Term	Compare Renovation vs. New Construction		1/14/16	1/22/16								
	Analyze Environmental Components		1/14/16	1/22/16								
	Determine Best Design Option		1/25/16	2/3/16								
	Executive Summary		2/4/16	2/12/16								
	Written Report		1/14/16	3/3/16								
	Final Presentation		2/4/16	3/3/16								
	C Term Submittal (Final MQP)		3/4/16	3/4/16								
	Final Presentation Submittal		3/4/16	3/4/16								

Term	Task	Primary Author	Start Date	End Date	Week 0 3/14 - 3/18	Week 1 3/21 - 3/25	Week 2 3/28 - 4/1	Week 3 4/4 - 4/8	Week 4 4/11 - 4/15	Week 5 4/18 - 4/22	Week 6 4/25 - 4/29	Week 7 5/2 - 5/3
D Term	Prepare Poster		3/14/16	4/15/16								
	Finalize Poster		4/18/16	4/21/16								
	Present Poster		4/21/16	4/21/16								

A Term Detailed Schedule

Detailed A-Term Schedule

Term	Task	Primary Author	Start Date	End Date
	Break Down of Project Tasks	All	8/27/15	9/9/15
	Site Visit	All	9/9/15	9/9/15
	Benchmark Existing Warehouse	Cola/Tanner	8/27/15	10/15/15
	A Term Proposal	All	8/27/15	10/15/15
	Abstract	Malina	9/22/15	9/22/15
	Introduction & Problem Statement	Julia	8/27/15	9/23/15
	Scope of Work	Tanner	8/27/15	9/23/15
	Capstone Design Statement	Julia	9/7/15	9/23/15
	Background-Vacant Warehouse Facilities	Tanner	9/23/15	9/29/15
A Term	Background-Renovation/Repurposing	Tanner/Julia	9/7/15	9/23/15
	Background-Charter School Design	Tanner/Julia	9/23/15	9/30/15
	Background-LEED	Malina	9/7/15	10/7/15
	Background-Building Codes	Julia	9/7/15	9/23/15
	Background-Structural Design	Cola	9/7/15	9/23/15
	Professional Licensure Statement	Malina	9/7/15	9/22/15
	Methodology	All	9/7/15	9/23/15
	Deliverables	Malina	9/30/15	10/7/15
	Conclusion	Malina	9/30/15	10/7/15
	A Term Submittal	All	10/15/15	10/15/15



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Appendix B: Environmental

Green Roof Calcs

Roof Membrane – Aged SRI Value

$$SRI_{Aged} = 0.7(SRI_{Initial} - 0.2) + 0.2$$

$$SRI_{Aged} = 0.7(92 - 0.2) + 0.2$$

$$\boxed{SRI_{Aged} = 64.46}$$

Drainage Layer – Saturated Weight

Unsaturated Weight = 40 lbs/200ft²
Water Storage Capacity = 0.06 gal/ft²

$$0.06\ gal/ft^2 * \frac{8.35\ lb\ H_2O}{1\ gal\ H_2O} = 0.5\ lb/ft^2$$

$$0.5\ lb/ft^2 * 200 = 100\ lb/200ft^2$$

$$W_{saturated} = W_{unsaturated} + W_{water\ storage}$$

$$W_{saturated} = (40\ lbs/200ft^2) + (100\ lb/200ft^2) * 1/200$$

$$\boxed{W_{saturated} = 0.70\ lb/ft^2}$$

LEED Credit Achievement

Total Site Paving Area:

Left Loading Docks Lot:	100 ft	x	225 ft	=	22,500 ft²
Front Parking Lot:	200 ft	x	275 ft	=	55,000 ft²
Front Drive:	20 ft	x	450 ft	=	9,000 ft²
Administration Parking Lot:	20 ft	x	90 ft	=	1,800 ft²
					TOTAL = 88,300 ft²

Option 1:

$$\frac{A_{Nonroof\ Measures}}{0.50} + \frac{A_{High\ Reflectance\ Roof}}{0.75} + \frac{A_{Vegetated\ Roof}}{0.75} \geq A_{Total\ Site\ Paving} + A_{Total\ Roof}$$

$$\frac{(4,500\ ft^2 + 2,500\ ft^2)}{0.50} + \frac{207,312\ ft^2}{0.75} + \frac{21,600\ ft^2}{0.75} \geq 88,300\ ft^2 + 228,912\ ft^2$$

$$14,000\ ft^2 + 276,416\ ft^2 + 28,800\ ft^2 \geq 88,300\ ft^2 + 228,912\ ft^2$$

$$\boxed{319,216\ ft^2 \geq 317,212\ ft^2}\ \checkmark$$

Option 2:

$$\frac{(4,500\ ft^2 + 2,500\ ft^2)}{0.50} + \frac{200,112\ ft^2}{0.75} + \frac{28,800\ ft^2}{0.75} \geq 88,300\ ft^2 + 228,912\ ft^2$$

$$14,000\ ft^2 + 266,816\ ft^2 + 38,400\ ft^2 \geq 88,300\ ft^2 + 228,912\ ft^2$$

$$\boxed{319,216\ ft^2 \geq 317,212\ ft^2}\ \checkmark$$

Table 128: Green Roof Membrane Options

Membrane Type	Description
EPDM	• Most commonly used • Low cost • Large sheet size minimizes seams • Excellent durability and root resistance • Poor chemical and oil resistance • Thickness/Weight: 45 mil/0.29 lb/ft^2, 60 mil/0.4 lb/ft^2,
TPO	• Increasingly popular membrane • Reflective white surface with heat-welded seams • Excellent durability and root resistance • Good chemical and oil res • Expensive • Thickness/Weight: 45 mil/0.232 lb/ft^2, 60 mil/0.314 lb/ft^2, 80 mil 0.42/ft^2
PVC	• Reflective white surface with heat-welded seams • Excellent durability and root resistance • Excellent chemical and oil resistance • Expensive • Thickness/Weight: 45 mil/0.232 lb/ft^2, 60 mil/0.314 lb/ft^2, 80 mil 0.42/ft^2
Built-Up Roofing (BUR)	• Commonly used roofing strategy • Low cost • Poor root resistance • Poor chemical and oil resistance • Thickness/Weight: 2-3 lb/ft^2, add 4lb for gravel surface
Modified Bitumen	• Popular roof system • Available in torch down (APP) and adhered (SBS) formulas • Low cost • Poor chemical and oil resistance • Weight: 1.00-1.75 lb/ft^2
Liquid-Applied Membrane	• Increasingly popular waterproofing strategy • In hot rubber-modified asphalt and synthetic liquid membrane formulas • Excellent for monolithic concrete substrates • Poor root resistance • Poor chemical and oil resistance • Weight: 0.75-1.5 lb/ft^2

Table 129: Nonroof Strategies for Heat Island Reduction LEED Credit (LEED v4)

Strategy	Rules & Suggestions
Shading With New/Existing Plant Material	• Plants must be in place at occupancy • Assume 10-year canopy width at noon
Vegetated Planters	• Artificial turf grass does not count • Plants must be in place at occupancy
Shading Structures With Energy Generation	• Paved area (not roof area) shaded by covering with energy generation equipment, such as solar thermal collectors
Shading Architectural Devices/Strategies	• Materials must have 3-year aged SR value of at least 0.28 or initial SR of at least 0.33
Vegetated Shading Structures	• Plants must be in place at occupancy
High-Reflectance Paving	• Materials must have 3-year aged SR value of at least 0.28 or initial SR of at least 0.33 • Consider maintenance required to keep those materials from losing reflectivity over time
Open-Grid Paving	• Must be at least 50% unbound

4.2 Assumptions Global Assumptions

- The Impact Estimator requires a definition of building type, whether rental or owner occupied and expected life. This affects the maintenance schedule and repair/replacement of certain building assemblies. For the purposes of the commercial EcoCalculator, we assumed an "owner occupied office" building type, either high-rise or low-rise, with a 60-year life, and for the residential EcoCalculator we assumed a "single family residential" building type with a 60-year life.
- An assumption was made that all assemblies would be installed in either low- or high-rise office or residential buildings using components and loadings typical for central areas of the United States but with differentiations between locations for the purposes of properly defining assemblies in terms of thermal performance and related code requirements.
- The life cycle stages considered in the LCA results include resource extraction, resource transportation, building product manufacturing and component manufacturing (components incorporate two or more building products), transportation from manufacturing plant to building site by various modes, on-site construction, maintenance and replacement of components over a 60-year period, end of life (demolition) effects for those materials replaced over the 60-year life and transportation to landfill of those materials currently landfilled.
- Commercial buildings' exterior walls were assumed to have 40% windows by area and residential 20% windows by area.
- All windows were assumed to be inoperable in commercial buildings and operable in residential buildings.
- All window glazing was assumed to be double-glazing with low-E silver coating and argon filled cavity. Viewable curtain wall was assumed to be two panes of 6 mm glazing.
- All concrete (except floor topping) was assumed to be 4000 psi (30 MPa) in commercial buildings and 3000 psi (20 MPa) in residential buildings.
- All cast-in-place concrete was assumed to contain 25% fly ash in place of Portland cement; although this is not necessarily typical, it was considered more appropriate to use an environmentally beneficial formulation.
- All concrete masonry was assumed to contain 0% fly ash.
- All gypsum board was assumed to be 5/8" thick regular gypsum board in commercial buildings and 1/2" thick regular gypsum board in residential buildings, taped and finished with two coats of latex paint.
- In commercial buildings, all wood structural panels (WSP) used data for softwood plywood, and in residential buildings plywood and OSB are available as decking and sheathing choices.
- All vapor barriers were assumed to be 6 mil polyethylene, and air barrier is assumed to be derived from a spun polypropylene derivative.
- All cavity insulation is modeled as fiberglass batt.

Foundations and Footings Assumptions

- Cast-in-place concrete walls were assumed to be 8" thick, with 4000 psi (30 MPa) concrete for commercial buildings and 3000 psi (20 MPa) for residential buildings. Both have 25% fly ash content; #5 rebar reinforcement included; allowance for form-ties, wire, etc.
- Concrete masonry exterior walls were assumed to be standard weight, 8"x8"x16" hollow concrete blocks; every third vertical core was assumed to be grouted and reinforced with one steel bar.
- Concrete slab-on-grade are assumed to be 4" thick, 4000 psi (30 MPa) for commercial buildings and 3000 psi (20 MPa) for residential buildings, 25% fly ash concrete with welded wire mesh reinforcement.
- Footings are assumed to be 4000 psi (30 MPa) with #5 rebar for commercial buildings and 3000 psi (20 MPa) with #4 rebar for residential buildings each with , 25% fly ash content. The user is required to calculate the volume of his/her footing assembly and input the total volume of concrete in the EcoCalculator. This value should reflect local soil conditions

Column and Beam Assumptions

- Live load for structural systems was assumed to be 75 psf/3.6 kPa for commercial buildings and 50 psf/2.4 kPa for residential buildings.
- Commercial bay sizes were set at 30'x30' and residential at 10' x15' for the purpose of assessing columns and beams.
- Column heights were set at 10' for commercial assemblies and 8' for residential.
- Glulam beams assumed 24F grade (2400 psi allowable bending stress) beams.
- HSS steel columns assumed 5"x 5" steel tube, 1⁄4" tube thickness.
- Wood columns assumed 6"x 6" (nominal) built-up columns.

Intermediate Floor and Roof Assumptions

- The live load for roofs was set at 50 psf (2.4 kPa).
- The live load for intermediate floors was set at 75 psf (3.6 kPa) for commercial buildings and 50 psf (2.4 kPa) for residential buildings
- Wood trusses were assumed to be 2"x4" or 2"x 6" (nominal)/38 x 89 mm or 38 x 140 mm solid lumber fastened with galvanized steel nail plates. Trusses were assumed to be spaced at 24"/600 mm o.c. and bridging included at 6'-6"/2000 mm o.c.
- Open web steel joists were assumed to be 4'/1200 mm o.c.
- Precast double-T assemblies were assumed to be 8'/2400 mm wide.
- Steel joists were assumed to be 16 gage steel "C" joists.
- Composite wood and steel joists (TJM, TJL, TJW and TJH type) were assumed to be 4'/1200 mm o.c. Joist chords were assumed to consist of one or two 2"x4"(nominal)/38 mm x 89 mm wood members with tubular steel webs. Nails and other steel connectors except bridging are included.

- Wood I-joists were assumed to be 1⁄2” OSB web with either 2”x3” (nominal) LVL flanges for commercial buildings or 2”x2” (nominal) MSR flanges for residential buildings.
- Solid wood joists were assumed to be 2”x (nominal)/38 mm wood joists (SPF #2 grade) at 16”/400 mm o.c. and include solid lumber bridging at 6’-6”/2000 mm o.c
- Steel decking was assumed to be 22 ga. 1.56”/39 mm metal deck.
- Concrete topping assumed 3 1⁄2”/89 mm thick concrete reinforced with 6”x6”/150 mm x 150 mm no. 10 metal mesh.
- EPDM roofing membrane assumed ethylene-propylene-diene monomer used as roofing membrane application density of 4.5 kg/m2 or 92 lbs/square (100 sq.ft.).
- Modified bitumen roofing membrane assumes 2-ply roofing application density of 34 kg/m2 or 695 lbs/square (100 sq.ft.).

Exterior Wall Assumptions

- Concrete masonry exterior walls were assumed to be standard weight, 8"x8"x16" hollow concrete blocks; every third vertical core was assumed to be grouted and reinforced with one steel bar.
- ICF exterior walls were assumed to be 8” in total thickness with a finished R- value of 20. 4000 psi concrete with 25% fly ash content was assumed; steel reinforcement included; wood sill plates and rough opening framing included. Concrete tilt-up walls were assumed to be 8” thick, with 4000 psi concrete with average (25%) fly ash content; #5 rebar reinforcement included; allowance made for CIP steel angle, lifting inserts/accessories, etc.
- Curtainwall assemblies assumed self-supporting grid comprising most of the exterior wall envelope area. Grid system was assumed to be aluminum (100 mm deep mullions) on 2 m centers vertically and 1.5 m horizontally. Provided take-off assumed every vertical mullion in the curtain wall is structurally connected via structural steel at every floor.
- Wood studs were assumed to be kiln dried, 2x6 (nom.). Double top plates (single top plates for interior non-load bearing walls) and a single bottom plate included. Fasteners included. For residential buildings, there is also one extra corner or nailing stud included every 30 ft.
- Structural Insulated Panels are modeled on a 3 1⁄2” expanded polystyrene core, with 2x4 lumber splines and framing, sheathed on both sides in 7/16” OSB.
- Steelstudswereassumedtobe15/8”x35/8”or 15/8”x 6”20 ga.Studs top and bottom tracks included; fasteners included. For residential buildings, there is also one extra corner or nailing stud included every 30 ft.
- Brick cladding was assumed to be standard 7.6"x 3.5"x 2.3" cored clay brick; includes brick ties and mortar.
- Steel cladding assumed 26 ga. galvanized steel siding for commercial buildings, and 30 ga. For residential buildings, each with one coat of latex paint.
- Stucco was assumed to be Portland cement based traditional stucco with steel mesh reinforcement. Galvanized flashing and 15# felt moisture barrier included.

- Vinyl cladding was assumed to include j-channels and 15# felt moisture barrier.
- Wood siding used data from beveled lap siding, pine for commercial buildings and cedar for residential buildings. One coat of latex paint included.
- Natural stone cladding assumes 0.5m x 0.5m x 0.03m slabs, including brick ties and mortar.
- Fiber cement siding includes #15 felt moisture barrier.
- Exterior wall rigid insulation was assumed to be polyisocyanurate foam board with foil facing at R-7 per inch, with thickness dependent on required R-value as per ASHRAE 90.1 for commercial buildings, and extruded polystyrene at R-5 per inch, with thickness dependent on required R-value as per 2009 IECC for residential buildings.
- All batt insulation in exterior walls was assumed to be fiberglass at R-3.13 per inch, with the thickness dependent on the required R-value per ASHRAE 90.1for commercial buildings and 2009 IECC for residential buildings.

Interior Wall Assumptions

- Interior concrete masonry walls were assumed to be 8” thick.
- Wood studs were assumed to be 2”x 4”, kiln dried. Non-load bearing walls (24” o.c.) include a single top and bottom plate, and load bearing walls (16” o.c.) include two top and one bottom plate; fasteners included.
- Steel studs were assumed to be 1 5/8” x 3 5/8”. Non-load bearing walls (24” o.c.) 25 ga., and load bearing walls (16” o.c.) are 20 ga. Top and bottom tracks and fasteners included.

Benchmark LCA Results

Athena EcoCalculator for Commercial Assemblies

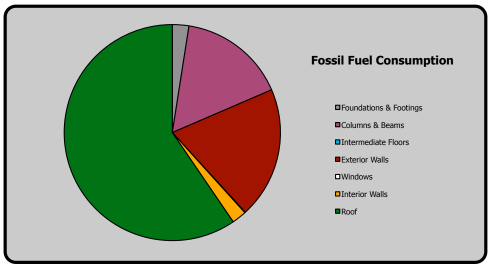
Version 3.71
Location: New York City
ASHRAE climate zone 4
Low-rise structures (Up to 4 stories)

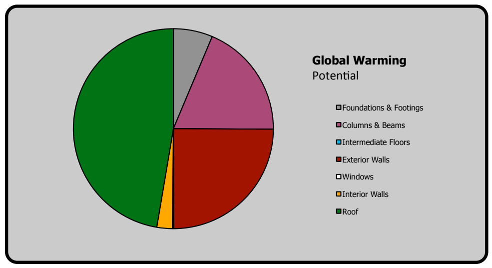
ENVIRONMENTAL IMPACT SUMMARY

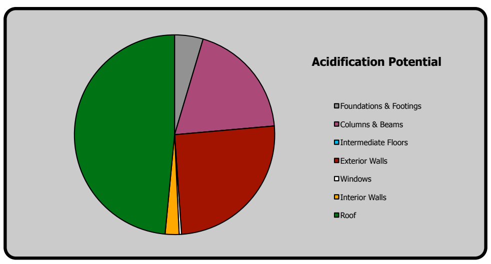
ASSEMBLY	Total area	Fossil Fuel Consumption (MJ) TOTAL	GWP (tonnes CO2eq) TOTAL	Acidification Potential (moles of H+ eq) TOTAL	Human Health Criteria (kg PM10 eq) TOTAL	Eutrophication Potential (g N eq) TOTAL	Ozone Depletion Potential (mg CFC-11 eq) TOTAL	Smog Potential (kg NOx eq) TOTAL
Foundations & Footings	25,677	1,694,381	190	47,229	656	42,045	1,623	10,578
Columns & Beams	203,520	11,023,252	559	194,551	877	660,784	2	14,951
Intermediate Floors	0	0	0	0	0	0	0	0
Exterior Walls	60,315	13,510,129	743	259,011	9,728	159,982	2,405	43,127
Windows	108	62,488	6	3,947	71	957	23	389
Interior Walls	41,323	1,495,395	75	23,004	782	32,670	93	2,701
Roof	214,137	40,859,218	1,413	496,727	4,559	488,578	6,703	41,522
TOTALS		68,644,862	2,986	1,024,468	16,672	1,385,016	10,848	113,267

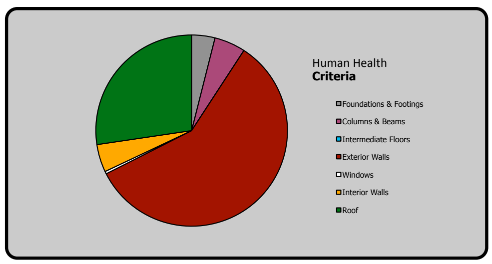
Percentages by assembly groups
(these results are shown in the pie charts below)

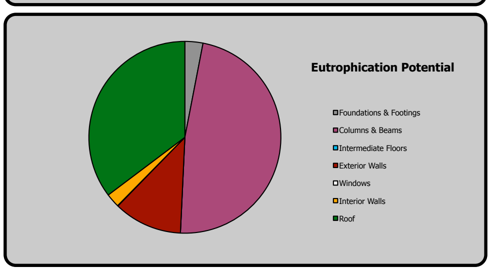
Fossil Fuel Consumption	Global Warming Potential	Acidification Potential	Human Health Criteria	Eutrophication Potential	Ozone Depletion Potential	Smog Potential
2%	6%	5%	4%	3%	15%	9%
16%	19%	19%	5%	48%	0%	13%
0%	0%	0%	0%	0%	0%	0%
20%	25%	25%	58%	12%	22%	38%
0%	0%	0%	0%	0%	0%	0%
2%	3%	2%	5%	2%	1%	2%
60%	47%	48%	27%	35%	62%	37%

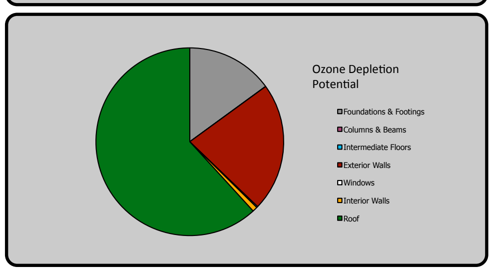


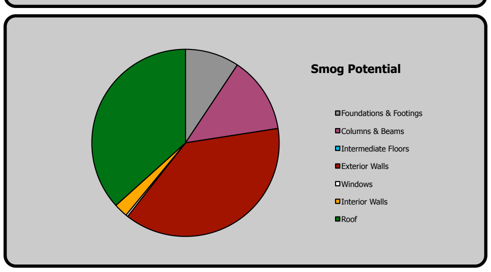












Renovation LCA Results

Athena EcoCalculator for Commercial Assemblies

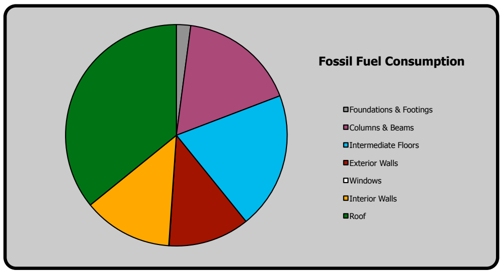
Version 3.71
Location: New York City
ASHRAE climate zone 4
Low-rise structures (Up to 4 stories)

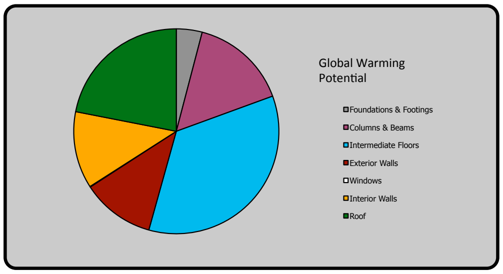
ENVIRONMENTAL IMPACT SUMMARY

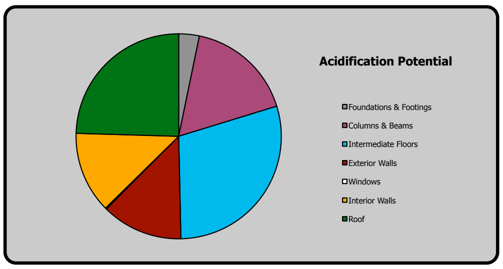
ASSEMBLY	Total area	Fossil Fuel Consumption (MJ) TOTAL	GWP (tonnes CO2eq) TOTAL	Acidification Potential (moles of H+ eq) TOTAL	Human Health Criteria (kg PM10 eq) TOTAL	Eutrophication Potential (g N eq) TOTAL	Ozone Depletion Potential (mg CFC-11 eq) TOTAL	Smog Potential (kg NOx eq) TOTAL
Foundations & Footings	26,716	2,373,518	262	65,700	907	61,672	2,248	14,548
Columns & Beams	360,440	19,510,607	990	344,292	1,551	1,170,781	4	26,478
Intermediate Floors	156,393	22,792,477	2,250	595,366	8,649	638,387	18,098	136,264
Exterior Walls	60,315	13,510,129	743	259,011	9,728	159,982	2,405	43,127
Windows	108	62,488	6	3,947	71	957	23	389
Interior Walls	323,797	14,884,311	783	259,580	6,635	346,842	1,162	29,676
Roof	214,137	40,859,218	1,413	496,727	4,559	488,578	6,703	41,522
TOTALS		113,992,747	6,446	2,024,622	32,100	2,867,200	30,642	292,003

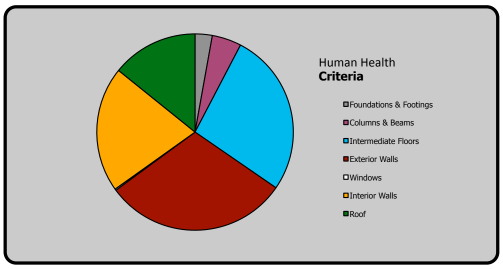
Percentages by assembly groups
(these results are shown in the pie charts below)

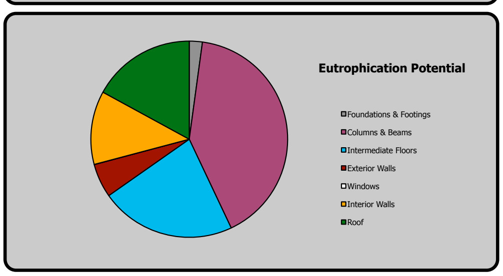
Fossil Fuel Consumption	Global Warming Potential	Acidification Potential	Human Health Criteria	Eutrophication Potential	Ozone Depletion Potential	Smog Potential
2%	4%	3%	3%	2%	7%	5%
17%	15%	17%	5%	41%	0%	9%
20%	35%	29%	27%	22%	59%	47%
12%	12%	13%	30%	6%	8%	15%
0%	0%	0%	0%	0%	0%	0%
13%	12%	13%	21%	12%	4%	10%
36%	22%	25%	14%	17%	22%	14%

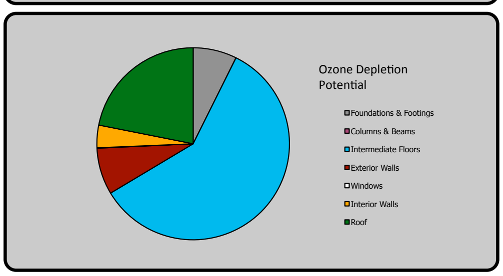


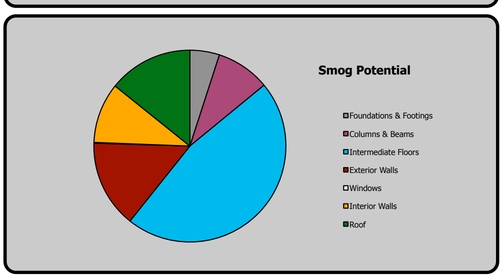












Ground-Up LCA Results

Athena EcoCalculator for Commercial Assemblies

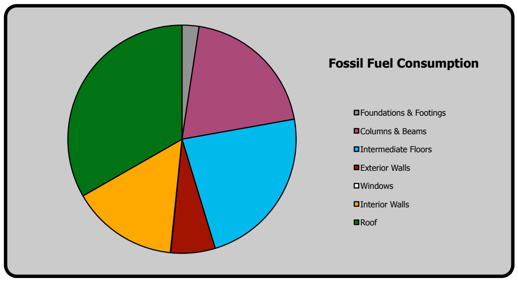
Version 3.71
Location: New York City
ASHRAE climate zone 4
Low-rise structures (Up to 4 stories)

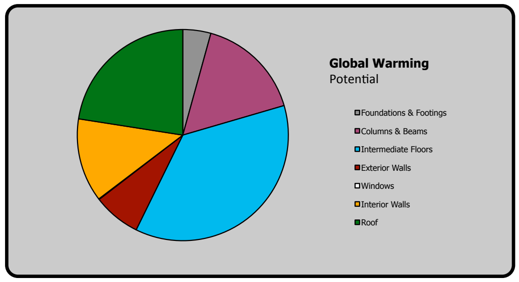
ENVIRONMENTAL IMPACT SUMMARY

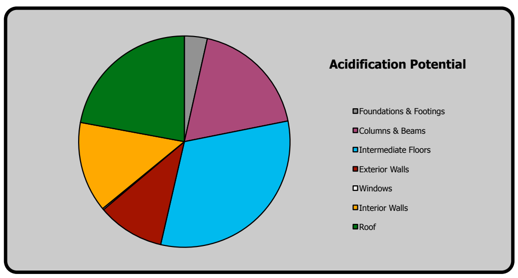
ASSEMBLY	Total area	Fossil Fuel Consumption (MJ) TOTAL	GWP (tonnes CO2eq) TOTAL	Acidification Potential (moles of H+ eq) TOTAL	Human Health Criteria (kg PM10 eq) TOTAL	Eutrophication Potential (g N eq) TOTAL	Ozone Depletion Potential (mg CFC-11 eq) TOTAL	Smog Potential (kg NOx eq) TOTAL
Foundations & Footings	26,716	2,373,390	262	65,697	907	61,668	2,248	14,547
Columns & Beams	360,440	19,510,607	990	344,292	1,551	1,170,781	4	26,478
Intermediate Floors	156,393	22,792,477	2,250	595,366	8,649	638,387	18,098	136,264
Exterior Walls	60,315	6,191,187	446	192,496	2,953	106,380	1,604	23,053
Windows	108	62,488	6	3,947	71	957	23	389
Interior Walls	323,797	14,884,311	783	259,580	6,635	346,842	1,162	29,676
Roof	214,137	32,819,285	1,377	414,182	3,592	507,632	7,312	42,404
TOTALS		98,633,743	6,113	1,875,559	24,358	2,832,647	30,451	272,811

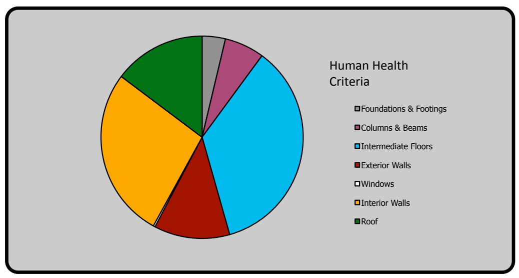
Percentages by assembly groups
(these results are shown in the pie charts below)

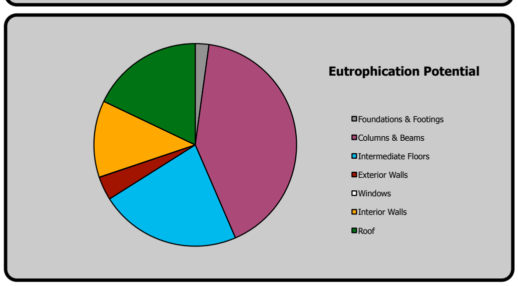
Fossil Fuel Consumption	Global Warming Potential	Acidification Potential	Human Health Criteria	Eutrophication Potential	Ozone Depletion Potential	Smog Potential
2%	4%	4%	4%	2%	7%	5%
20%	16%	18%	6%	41%	0%	10%
23%	37%	32%	36%	23%	59%	50%
6%	7%	10%	12%	4%	5%	8%
0%	0%	0%	0%	0%	0%	0%
15%	13%	14%	27%	12%	4%	11%
33%	23%	22%	15%	18%	24%	16%

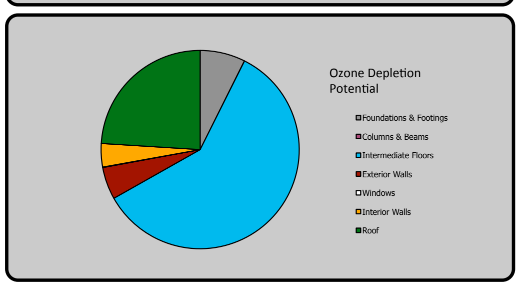


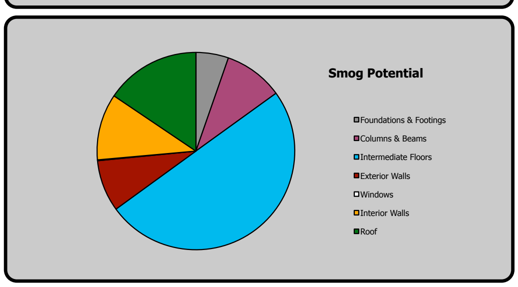












Appendix C – Space Programming

Table 130: Middle School Space Recommendations (MSBA Space Summary Template)

	ROOM TYPE	ROOM NFA [1]	# OF RMS	area totals
CORE ACADEMIC SPACES				**41,520**
	(List classrooms of different sizes separately)			
	Classroom - General	950	30	28,500
	Small Group Seminar (20-30 seats) / Resource	500	3	1,500
	Science Classroom / Lab	1,200	9	10,800
	Prep Room	80	9	720
SPECIAL EDUCATION				**12,580**
	(List classrooms of different sizes separately)			
	Self-Contained SPED	950	8	7,600
	Self-Contained SPED Toilet	60	8	480
	Resource Room	500	6	3,000
	Small Group Room / Reading	500	3	1,500
ART & MUSIC				**5,000**
	Art Classroom	1,200	2	2,400
	Art Workroom w / Storage & kiln	150	2	300
	Band / Chorus - 100 seats	1,500	1	1,500
	Music Practice / Ensemble	200	4	800
VOCATIONS & TECHNOLOGY				**9,600**
	Tech Clrm. - (E.G. Drafting, Business)	1,200	3	3,600
	Tech Shop - (E.G. Consumer, Wood)	2,000	3	6,000
HEALTH & PHYSICAL EDUCATION				**8,400**
	Gymnasium	6,000	1	6,000
	Gym Storeroom	150	1	150
	Health Instructor's Office w / Show er & Toilet	250	1	250
	Locker Rooms - Boys / Girls w / Toilets	1,000	2	2,000
MEDIA CENTER				**7,261**
	Media Center / Reading Room	7,261	1	7,261
DINING & FOOD SERVICE				**14,069**
	Cafetorium / Dining	8,975	1	8,975
	Stage	1,600	1	1,600
	Chair / Table / Equipment Storage	599	1	599
	Kitchen	2,497	1	2,497
	Staff Lunch Room	399	1	399
MEDICAL				**810**
	Medical Suite Toilet	60	1	60
	Nurses' Office / Waiting Room	250	1	250
	Examination Room / Resting	100	5	500

ADMINISTRATION & GUIDANCE				4,447
	General Office / Waiting Room / Toilet	698	1	698
	Teachers' Mail and Time Room	100	1	100
	Duplicating Room	200	1	200
	Records Room	200	1	200
	Principal's Office w / Conference Area	375	1	375
	Principal's Secretary / Waiting	125	1	125
	Assistant Principal's Office - AP1	150	1	150
	Assistant Principal's Office - AP2	150	2	300
	Supervisory / Spare Office	150	1	150
	Conference Room	350	1	350
	Guidance Office	150	6	900
	Guidance Waiting Room	100	1	100
	Guidance Storeroom	50	1	50
	Teachers' Work Room	748	1	748
CUSTODIAL & MAINTENANCE				2,672
	Custodian's Office	150	1	150
	Custodian's Workshop	250	1	250
	Custodian's Storage	375	1	375
	Recycling Room / Trash	400	1	400
	Receiving and General Supply	499	1	499
	Storeroom	798	1	798
	Network / Telecom Room	200	1	200
OTHER				0
	Other *(specify)*			
	Total Building Net Floor Area (NFA)			106,359
	Proposed Student Capacity / Enrollment			1,197
	Total Building Gross Floor Area (GFA)[2]			191,468
	Grossing factor (GFA/NFA)			1.80

Table 131: Recommended High School Areas (MSBA Space Summary Template)

CORE ACADEMIC SPACES			**42,360**
(List classrooms of different sizes separately)			
Classroom - General	825	28	23,100
Teacher Planning	100	28	2,800
Small Group Seminar (20-30 seats)	500	3	1,500
Science Classroom / Lab	1,440	9	12,960
Prep Room	200	9	1,800
Central Chemical Storage Rm	200	1	200
SPECIAL EDUCATION			**11,070**
(List classrooms of different sizes separately)			
Self-Contained SPED	950	7	6,650
Self-Contained SPED Toilet	60	7	420
Resource Room	500	4	2,000
Small Group Room	500	4	2,000
ART & MUSIC			**6,775**
Art Classroom - 25 seats	1,200	2	2,400
Art Workroom w/ Storage & kiln	150	2	300
Band - 50 - 100 seats	1,500	1	1,500
Chorus - 50 - 100 seats	1,500	1	1,500
Ensemble	200	1	200
Music Practice	75	5	375
Music Storage	500	1	500
VOCATIONS & TECHNOLOGY			**9,600**
Tech Clrm. - (E.G. Drafting, Business)	1,200	3	3,600
Tech Shop - (E.G. Consumer, Wood)	2,000	3	6,000
HEALTH & PHYSICAL EDUCATION			**21,884**
Gymnasium	12,000	1	12,000
PE Alternatives	3,000	1	3,000
Gym Storeroom	300	1	300
Locker Rooms - Boys / Girls w/ Toilets	5,684	1	5,684
Phys. Ed. Storage	500	1	500
Athletic Director's Office	150	1	150
Health Instructor's Office w/ Shower & Toilet	250	1	250
MEDIA CENTER			**6,244**
Media Center / Reading Room	6,244	1	6,244
Computer Lab			
AUDITORIUM / DRAMA			**9,670**
Auditorium	6,767	1	6,767
Stage	1,600	1	1,600
Auditorium Storage	504	1	504
Make-up / Dressing Rooms	300	2	600
Controls / Lighting / Projection	200	1	200

DINING & FOOD SERVICE			**8,898**
Cafeteria / Student Lounge / Break-out	5,075	1	5,075
Chair / Table Storage	404	1	404
Scramble Serving Area	600	1	600
Kitchen	2,315	1	2,315
Staff Lunch Room	504	1	504
MEDICAL			**1,010**
Medical Suite Toilet	60	1	60
Nurses' Office / Waiting Room	250	1	250
Interview Room	100	2	200
Examination Room / Resting	100	5	500
ADMINISTRATION & GUIDANCE			**4,541**
General Office / Waiting Room / Toilet	508	1	508
Teachers' Mail and Time Room	100	1	100
Duplicating Room	200	1	200
Records Room	200	1	200
Principal's Office w/ Conference Area	375	1	375
Principal's Secretary / Waiting	125	1	125
Assistant Principal's Office - AP1	150	1	150
Assistant Principal's Office - AP2	150	1	150
Supervisory / Spare Office	120	1	120
Conference Room	450	1	450
Guidance Office	150	6	900
Guidance Waiting Room	100	1	100
Guidance Storeroom	100	1	100
Career Center	404	1	404
Records Room	152	1	152
Teachers' Work Room	508	1	508
CUSTODIAL & MAINTENANCE			**2,386**
Custodian's Office	150	1	150
Custodian's Workshop	250	1	250
Custodian's Storage	375	1	375
Recycling Room / Trash	400	1	400
Receiving and General Supply	404	1	404
Storeroom	608	1	608
Network / Telecom Room	200	1	200
OTHER			**0**
Other (specify)			
Total Building Net Floor Area (NFA)			**124,438**
Proposed Student Capacity / Enrollment			**1,015**
Total Building Gross Floor Area (GFA)[2]			**191,468**
Grossing factor (GFA/NFA)			**1.54**

Appendix D – Means of Egress

Renovation Building Exits

Figure 107: Exits from Area A of Renovated Building

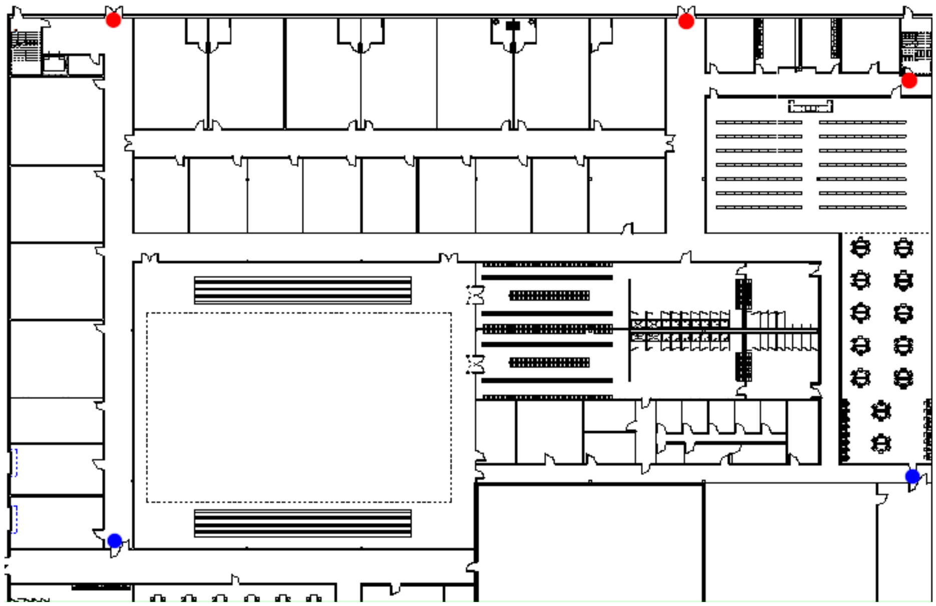


Figure 108: Exits from Area B of Renovated Building

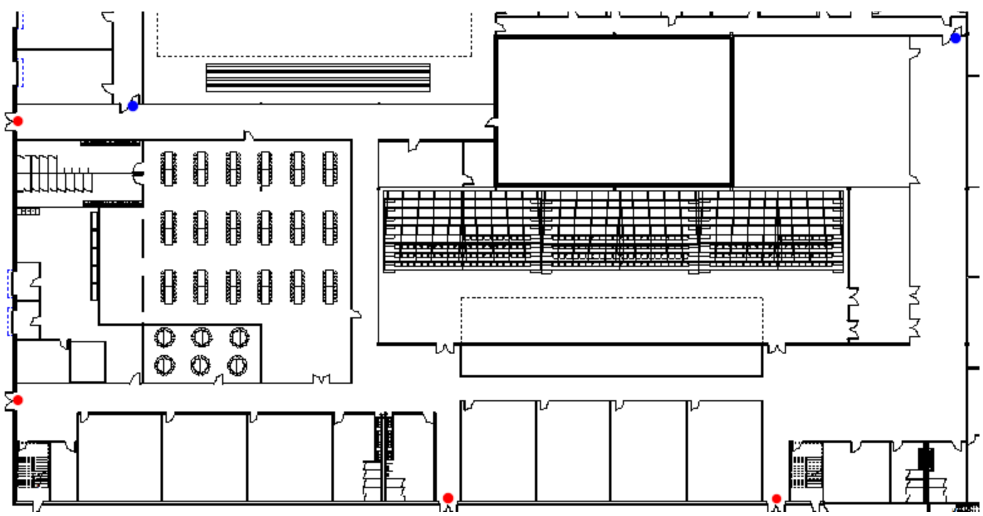


Figure 109: Exits from Area C of Renovated Building

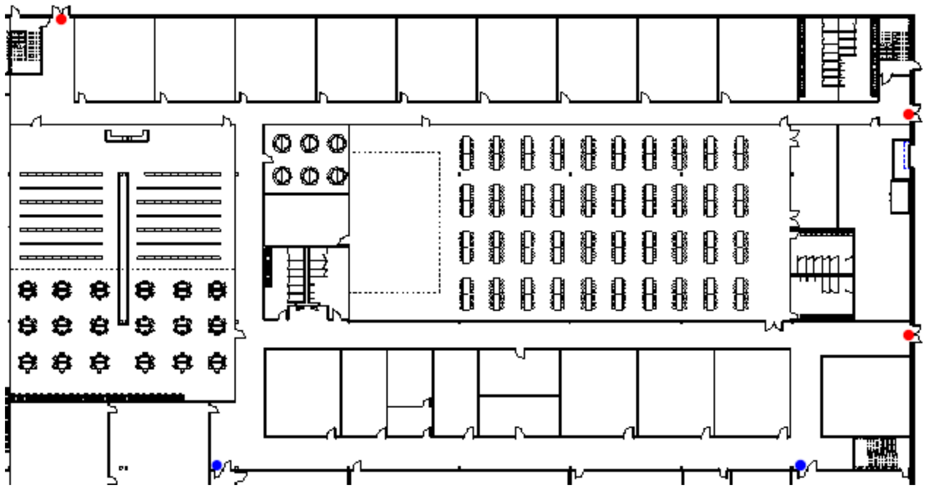
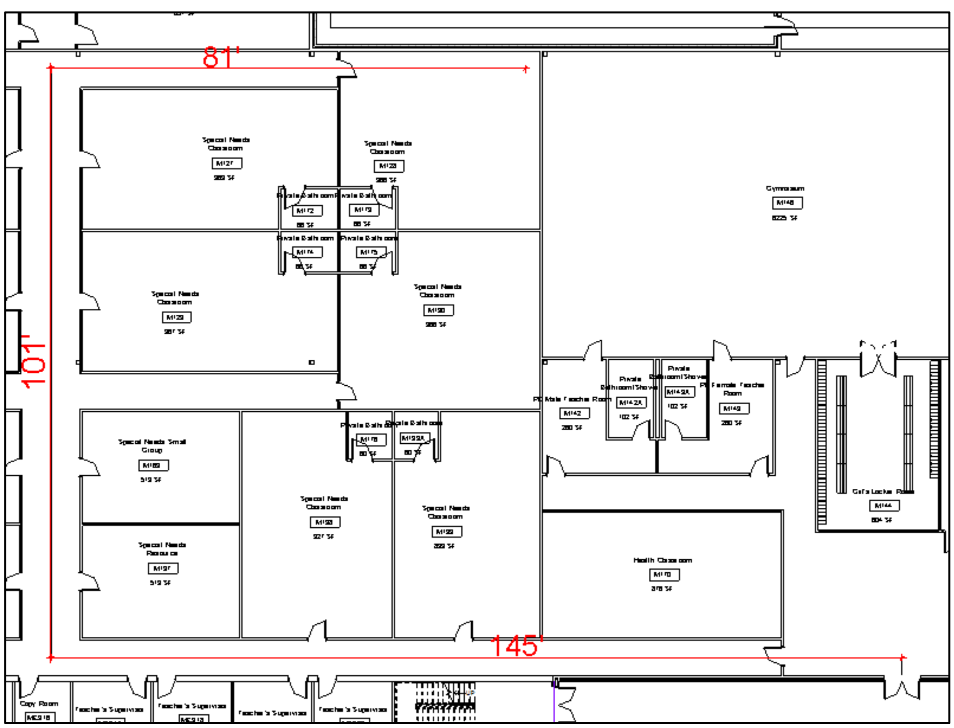


Figure 110: Exits from Area D of Renovated Building

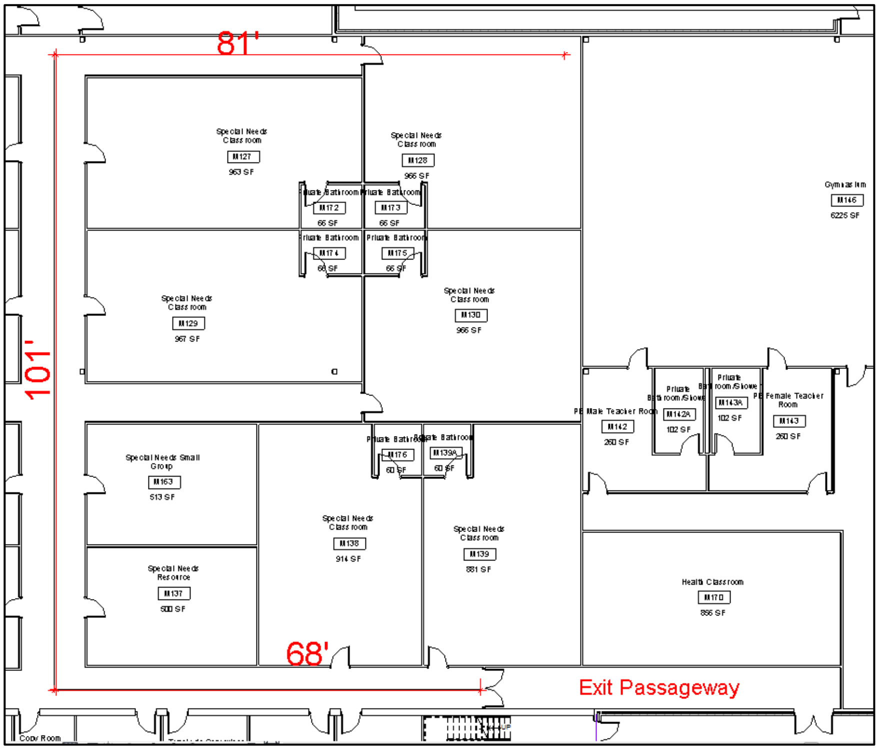
Egress Solutions Performed

Special Needs Wing – Middle School First Floor

- Before: Exit access travel distance = 327 ft.

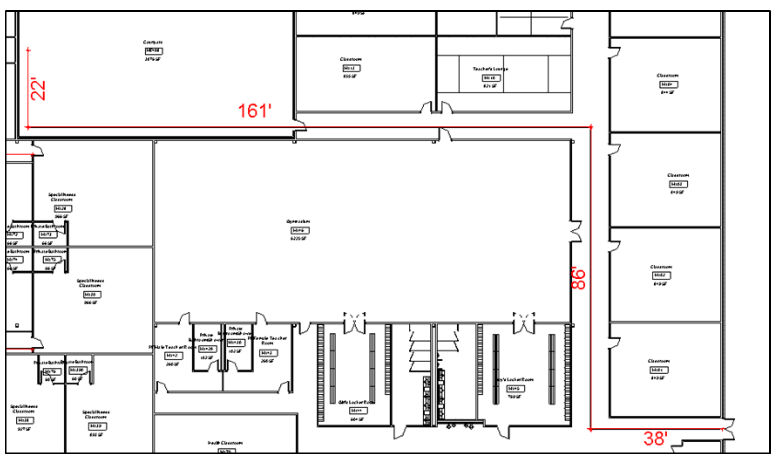


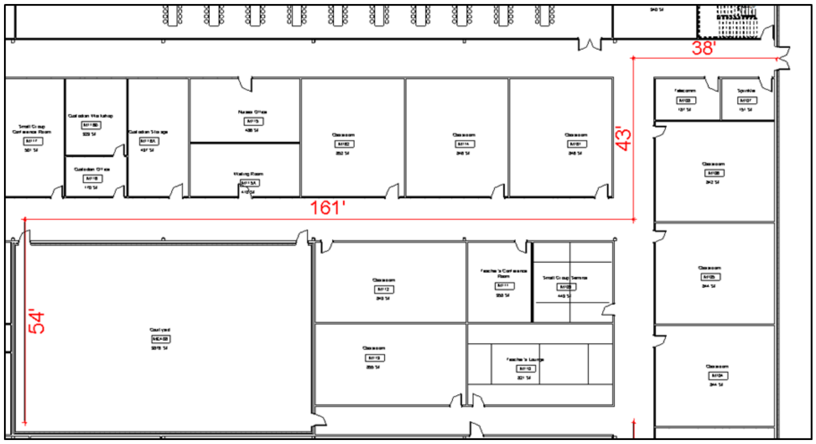
- After: Exit passageway added to reduce distance to 250 ft.



Courtyard – Middle School First Floor

- Before: Exit access travel distance exceeded 250 ft.

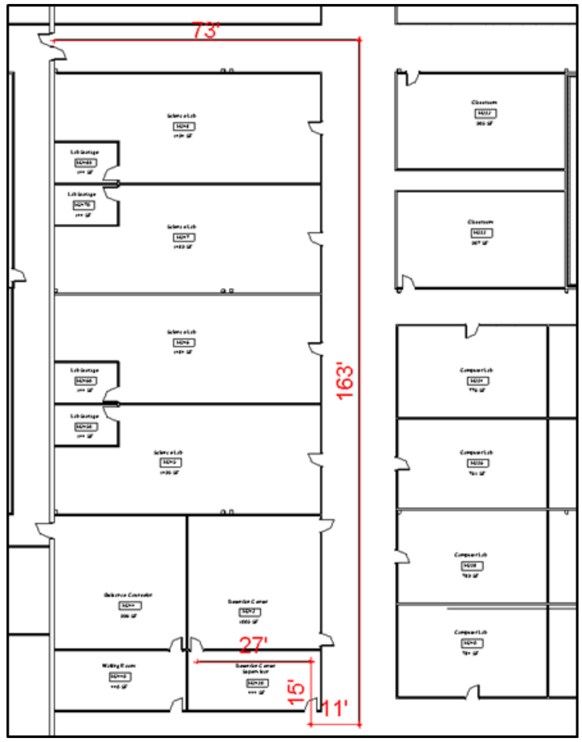




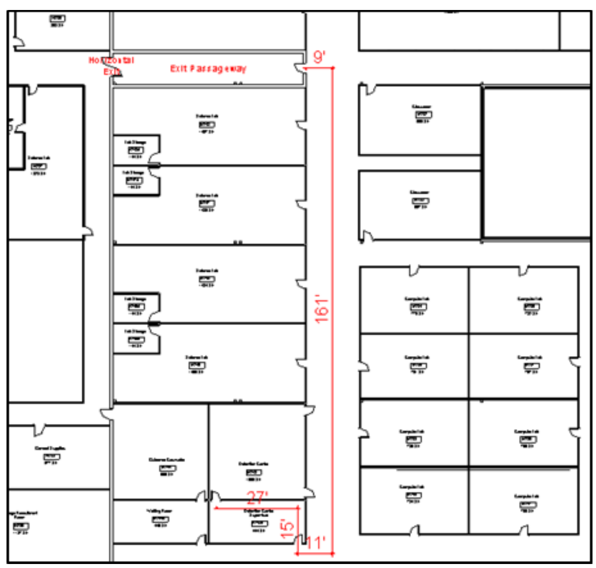
- After: Exit location reconfigured to provide travel distance of 243 ft.

Detention Supervisor Office – Middle School Second Floor

- Before: Exit access travel distance was 289 ft.

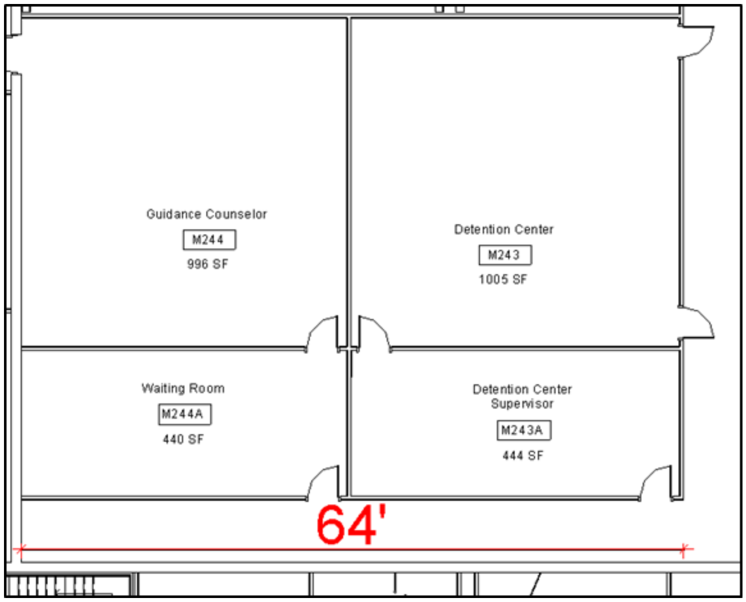


- After: Exit passageway added to decrease travel distance to 213 ft.



Guidance Counselor Wing: Middle School Second Floor

- Before: Dead-end corridor distance was 64 ft.



- After: Closet added to room to decrease distance to 49 ft.

Occupant Loading

Name	Room #	Area	Load Factor	Occupant Load
Athletic Director	H120	247 SF	100 SF	3
Auditorium Storage	H112A	406 SF	300 SF	2
Classroom	H101	853 SF	25 SF	35
Classroom	H102	862 SF	25 SF	35
Classroom	H103	851 SF	25 SF	35
Classroom	H104	855 SF	25 SF	35
Classroom	H105	851 SF	25 SF	35
Classroom	H106	848 SF	25 SF	34
Classroom	H107	848 SF	25 SF	34
Classroom	H133	863 SF	25 SF	35
Classroom	H134	852 SF	25 SF	35
Classroom	H135	850 SF	25 SF	34
Classroom	H136	848 SF	25 SF	34
Controls/Lights	H115	181 SF	300 SF	1
Detention Center	H154	303 SF	25 SF	13
Dry Storage	H108B	255 SF	200 SF	2
Elevator Machine Room	H137	83 SF	300 SF	1
Female Health Instructor	H122	196 SF	100 SF	2
Gym Store Room	H125	296 SF	300 SF	1
Health Classroom	H153	691 SF	25 SF	28
HS Library Stack Area	H119B	3693 SF	100 SF	37
HS Library Study Area	H119A	2462 SF	50 SF	50
Janitor's Office	H156	282 SF	100 SF	3
Janitor's Storage	H156A	158 SF	300 SF	1
Kitchen	H108	1368 SF	200 SF	7
Librarian Office	H155	255 SF	100 SF	3
Makeup Room	H116	180 SF	50 SF	4
Male Health Instructor	H123	196 SF	100 SF	2
Men's Dressing Room	H113	197 SF	50 SF	4
Men's Locker Room	H127	2110 SF	50 SF	43
Nurse Station	H121	133 SF	100 SF	2
Receiving	H108C	98 SF	200 SF	1
Recieving/Gen. Supply	H130	408 SF	300 SF	2
Resting Room	H121C	100 SF	120 SF	1
Resting Room	H121D	99 SF	120 SF	1
Resting Room	H121E	100 SF	120 SF	1
Resting Room	H121F	100 SF	120 SF	1
Resting Room	H121G	100 SF	120 SF	1
School Store	H110	776 SF	30 SF	26
Serving Area	H111A	594 SF	5 SF	119
Small Group Conference	H117	454 SF	25 SF	19
Small Group Seminar	H132	506 SF	25 SF	21
Special Needs Classroom	H139	950 SF	25 SF	38
Special Needs Classroom	H141	941 SF	25 SF	38
Special Needs Classroom	H143	940 SF	25 SF	38
Special Needs Classroom	H145	941 SF	25 SF	38
Special Needs Classroom	H147	944 SF	25 SF	38
Special Needs Classroom	H149	932 SF	25 SF	38
Special Needs Classroom	H151	942 SF	25 SF	38
Special Needs Resource	H138	506 SF	25 SF	21
Special Needs Resource	H142	508 SF	25 SF	21
Special Needs Resource	H146	513 SF	25 SF	21
Special Needs Resource	H150	504 SF	25 SF	21
Special Needs Small Group	H140	506 SF	25 SF	21
Special Needs Small Group	H144	508 SF	25 SF	21
Special Needs Small Group	H148	508 SF	25 SF	21
Special Needs Small Group	H152	504 SF	25 SF	21
Sprinkler	H129	101 SF	300 SF	1
Stage	H112B	947 SF	15 SF	64
Team Room	H124	508 SF	7 SF	73
Telecom Room	H128	213 SF	300 SF	1
Trash Room	H108D	99 SF	300 SF	1
Trash/Recycling	H131	420 SF	300 SF	2
Waiting Room	H121A	113 SF	15 SF	8
Walk-In Refrigerator	H108A	168 SF	200 SF	1
Weight Room	H118	2996 SF	50 SF	60
Women's Dressing Room	H114	198 SF	50 SF	4
Women's Locker Room	H126	2170 SF	50 SF	44
Teacher's Lunch Room	Fixed-Seating			48
Student Cafeteria				336
Courtyard				58
Gymnasium				749
Auditorium				600
			Total:	3267

Name	Number	Area	Load Factor	Net Occupant Load
Classroom	H201	855 SF	25 SF	35
Classroom	H202	852 SF	25 SF	35
Classroom	H203	877 SF	25 SF	36
Classroom	H204	856 SF	25 SF	35
Classroom	H205	849 SF	25 SF	34
Classroom	H206	845 SF	25 SF	34
Classroom	H207	854 SF	25 SF	35
Electrical Room	H208	385 SF	300 SF	2
Chorus	H209	1494 SF	7 SF	214
Band	H210	1565 SF	7 SF	224
Band Storage	H210A	497 SF	300 SF	2
Ensemble	H210B	208 SF	300 SF	1
Band Practice1	H210C	75 SF	7 SF	11
Band Practice 2	H210D	75 SF	7 SF	11
Band Practice 3	H210E	74 SF	7 SF	11
Band Practice 4	H210F	76 SF	7 SF	11
Band Practice 5	H210G	75 SF	7 SF	11
Art Room	H211	1231 SF	50 SF	25
Art Storage	H211A	179 SF		
Art Room	H212	1187 SF	50 SF	24
Art Storage	H212A	177 SF		
Teacher's Work Room	H213	735 SF	100 SF	8
Teacher's Work Room	H214	758 SF	100 SF	8
Small Group Seminar	H215	509 SF	25 SF	21
Small Group Seminar	H216	506 SF	25 SF	21
Small Group Seminar	H217	576 SF	25 SF	24
Classroom	H218	847 SF	25 SF	34
Classroom	H219	857 SF	25 SF	35
Classroom	H220	847 SF	25 SF	34
Classroom	H221	853 SF	25 SF	35
Classroom	H222	853 SF	25 SF	35
Mechanical	H223	986 SF	300 SF	4
Detention Center	H224	1099 SF	25 SF	44
Classroom	H225	854 SF	25 SF	35
Classroom	H226	847 SF	25 SF	34
Classroom	H227	842 SF	25 SF	34
Science Lab	H228	1200 SF	50 SF	24
Lab Storage	H228A	257 SF		
Science Lab	H229	1201 SF	50 SF	25
Lab Storage	H229A	255 SF		
Science Lab	H230	1157 SF	50 SF	24
Lab Storage	H230A	257 SF		
Science Lab	H231	1159 SF	50 SF	24
Lab Storage	H231A	255 SF		
Central Chemical Storage	H232	539 SF	300 SF	2
Art Room	H233	1217 SF	50 SF	25
Art Storage	H233B	151 SF		
Classroom	H235	858 SF	25 SF	35
Science Lab	H236	1328 SF	50 SF	27
Lab Storage	H236A	394 SF		
Science Lab	H237	1323 SF	50 SF	27
Lab Storage	H237A	396 SF		
General Supplies	H238	977 SF	300 SF	4
College Recruitment Room	H239	1137 SF	100 SF	12
Waiting Room	H239A	401 SF	100 SF	5
Voacational Classroom	H240	1809 SF	50 SF	37
Vocational Classroom	H241	1807 SF	50 SF	37
Vocational Classroom	H242	1806 SF	50 SF	37
Computer Lab	H243	1831 SF	50 SF	37
Computer Lab	H244	1835 SF	50 SF	37
Technical Education	H245	1105 SF	50 SF	23
Press Box	H246	1111 SF	15 SF	75
Technical Education	H247	1081 SF	50 SF	22

Appendix E – Passive Fire Protection Calculations

Gypsum Encased Column – W10x49

R (minutes)	D (inches)	W (pounds per foot)	h (inches)	W' (pounds per foot)	bf (inches)	d (inches)
0.0	39.96	49	0	49.00	10	9.98
19.4	39.96	49	1/8	50.73	10	9.98
33.5	39.96	49	1/4	52.47	10	9.98
46.6	39.96	49	3/8	54.20	10	9.98
59.2	39.96	49	1/2	55.94	10	9.98
71.5	39.96	49	5/8	57.67	10	9.98

Gypsum Encased Column – W12x65

R (minutes)	D (inches)	W (pounds per foot)	h (inches)	W' (pounds per foot)	bf (inches)	d (inches)
0.0	48.12	65	0	65.00	12	12.06
20.8	48.12	65	1/8	67.09	12	12.06
35.9	48.12	65	1/4	69.18	12	12.06
49.7	48.12	65	3/8	71.27	12	12.06
63.1	48.12	65	1/2	73.35	12	12.06

Gypsum Encased Column – W12x53

R (minutes)	D (inches)	W (pounds per foot)	h (inches)	W' (pounds per foot)	bf (inches)	d (inches)
0.0	48.12	53	0	53.00	12	12.06
18.0	48.12	53	1/8	55.09	12	12.06
31.1	48.12	53	1/4	57.18	12	12.06
43.3	48.12	53	3/8	59.27	12	12.06
55.1	48.12	53	1/2	61.35	12	12.06
66.9	48.12	53	5/8	63.44	12	12.06

Gypsum Encased Column – HSS9x9x3/8

R (minutes)	D (inches)	W (pounds per foot)	h (inches)	W' (pounds per foot)
0.0	36	42.79	0	42.8
19.0	36	42.79	1/8	44.4
32.8	36	42.79	1/4	45.9
45.6	36	42.79	3/8	47.5
58.0	36	42.79	1/2	49.0
70.1	36	42.79	5/8	50.6

Lightweight Concrete Encased Column – W10x49

R (minutes)	Ro (minutes)	W (pounds per foot)	D (inches)	h (inches)	d (inches)

17.0	14.8	49	59.28	1/8	9.98
23.1	20.1	49	59.28	1/4	9.98
29.4	25.6	49	59.28	3/8	9.98
35.9	31.2	49	59.28	1/2	9.98
42.5	37.0	49	59.28	5/8	9.98
49.5	43.0	49	59.28	3/4	9.98
56.7	49.3	49	59.28	7/8	9.98
64.1	55.7	49	59.28	1	9.98

Normal Weight Concrete Encased Column – W10x49

R (minutes)	Ro (minutes)	W (pounds per foot)	D (inches)	h (inches)	d (inches)
14.4	12.8	49	59.28	1/8	9.98
18.6	16.6	49	59.28	1/4	9.98
23.0	20.5	49	59.28	3/8	9.98
27.6	24.6	49	59.28	1/2	9.98
32.4	28.9	49	59.28	5/8	9.98
37.4	33.4	49	59.28	3/4	9.98
42.7	38.1	49	59.28	7/8	9.98
48.2	43.0	49	59.28	1	9.98
53.9	48.1	49	59.28	1 1/8	9.98
60.0	53.3	49	59.28	1 1/4	9.98

Lightweight Concrete Encased Column – W12x65

R (minutes)	Ro (minutes)	W (pounds per foot)	D (inches)	h (inches)	d (inches)
18.2	15.8	65	71.46	1/8	12.12
24.7	21.5	65	71.46	1/4	12.12
31.3	27.2	65	71.46	3/8	12.12
38.1	33.1	65	71.46	1/2	12.12
45.1	39.2	65	71.46	5/8	12.12
52.3	45.5	65	71.46	3/4	12.12
60.0	52.0	65	71.46	7/8	12.12

Normal Weight Concrete Encased Column – W12x65

R (minutes)	Ro (minutes)	W (pounds per foot)	D (inches)	h (inches)	d (inches)
15.4	13.7	65	71.46	1/8	12.12
19.8	17.7	65	71.46	1/4	12.12
24.4	21.8	65	71.46	3/8	12.12
29.2	26.1	65	71.46	1/2	12.12
34.2	30.6	65	71.46	5/8	12.12
39.5	35.2	65	71.46	3/4	12.12

44.9	40.1	65	71.46	7/8	12.12
50.6	45.2	65	71.46	1	12.12
56.5	50.4	65	71.46	1 1/8	12.12
62.6	55.9	65	71.46	1 1/4	12.12

Lightweight Concrete Encased Column – W12x53

R (minutes)	Ro (minutes)	W (pounds per foot)	D (inches)	h (inches)	d
17.0	14.8	53	63.41	1/8	12.06
23.1	20.1	53	63.41	1/4	12.06
29.3	25.5	53	63.41	3/8	12.06
35.7	31.0	53	63.41	1/2	12.06
42.4	36.9	53	63.41	5/8	12.06
49.3	42.9	53	63.41	3/4	12.06
56.5	49.1	53	63.41	7/8	12.06
63.9	55.6	53	63.41	1	12.06

Normal Weight Concrete Encased Column – W12x53

R (minutes)	Ro (minutes)	W (pounds per foot)	D (inches)	h (inches)	d (inches)
14.4	12.8	53	63.41	1/8	12.06
18.6	16.6	53	63.41	1/4	12.06
22.9	20.5	53	63.41	3/8	12.06
27.5	24.5	53	63.41	1/2	12.06
32.3	28.8	53	63.41	5/8	12.06
37.3	33.3	53	63.41	3/4	12.06
42.6	38.0	53	63.41	7/8	12.06
48.1	42.9	53	63.41	1	12.06
53.8	48.0	53	63.41	1 1/8	12.06
60.0	53.3	53	63.41	1 1/4	12.06

Lightweight Concrete Encased Column – HSS9x9x3/8

R (minutes)	Ro (minutes)	W (pounds per foot)	D (inches)	h (inches)
16.8	15.0	42.79	36	1/8
20.9	18.7	42.79	36	1/4
25.4	22.7	42.79	36	3/8
30.3	27.0	42.79	36	1/2
35.5	31.7	42.79	36	5/8
41.0	36.6	42.79	36	3/4
46.8	41.8	42.79	36	7/8
53.0	47.3	42.79	36	1
59.4	53.1	42.79	36	1 1/8

66.2	59.1	42.79	36	1 1/4

Normal Weight Concrete Encased Column – HSS9x9x3/8

R (minutes)	Ro (minutes)	W (pounds per foot)	D (inches)	h (inches)
15.5	13.8	42.79	36	1/8
18.5	16.5	42.79	36	1/4
21.8	19.5	42.79	36	3/8
25.5	22.8	42.79	36	1/2
29.4	26.3	42.79	36	5/8
33.7	30.1	42.79	36	3/4
38.2	34.1	42.79	36	7/8
43.0	38.3	42.79	36	1
48.0	42.8	42.79	36	1 1/8
53.2	47.5	42.79	36	1 1/4
58.7	52.4	42.79	36	1 3/8
64.4	57.5	42.79	36	1 1/2
70.4	62.8	42.79	36	1 5/8
76.5	68.3	42.79	36	1 3/4

Appendix F – Structural Calculations

Benchmarking

30K12 Beam | 53' x 40' Bay | Highest loading case

DL Metal Deck 1.78 psf x 5 ft 9 lb/ft
Joist 30K12 15 lb/ft
MEP 350 lb point load @ 12 ft
DL = 26 lb

LL SNOW 35 psf x 5 ft LL = 175 lb

1.2D + 1.6L = 311 lb/ft

Adjusted factored load w/ point load 318 lb/ft
Found using Volcraft software

For 30 K12 Max Uniform Factored load = 495 lb/ft

40G 8N (Spacing of joists @ 5ft) 17 K (Load in kips) Girder

53 ft * 318 lb/ft = 16854 lb → 16.85 kips
1" depth for 1' of span

Green Roof + 14.58 lb/sq ft
factored D+L = 396.4 lb/ft

Girder needs to change to 40G 8N 21.3 K

Top Girders Need to change to 40G 8N 19.2K

22K9 Span 27'

DL- 3" concrete w/ 3/16" 24 GA Metal Deck 31 psf x 2.5 ft 77.5 lb/ft

Joist 10.2 lb/ft

LL 125 psf - Light storage x 2.5 ft 312.5 lb/ft

$1.6L + 1.2D = 605$ lb/ft

22K9 Max load @ 27 ft = 825 lb/ft ✓

W16x26

DL - 87.7 lb/ft $\quad W_u = 1.6L + 1.2D = 605$ lb/ft

LL - 312.5 lb/ft

$$M_u = \frac{.605 \text{ k/ft} \cdot 27 \text{ ft}^2}{8} = 55.13 \text{ k-ft}$$

$\phi M_{px} = 166$ ✓

W 14x30 girder @ span 20 ft

DL	Metal Deck	1.78 lb/ft² x 26.7 ft	=	47.5 lb/ft
	MEP	10 psf x 26.7 ft	=	267 lb/ft
	Metal Siding	1.78 psf x 30 ft	=	53.4 lb/ft
	wt of Beams	3.5 30K12 + W14x30	=	90 lb/ft
			DL	457.5 lb/ft
LL	SNOW	35 psf · 26.7 ft	=	934.5 lb/ft

LRFD Load $1.2D + 1.6L = 1.2(457.5) + 1.6(934.5)$

$W_u = 2044.2$ lb/ft

$$M_u = \frac{(2.04)(20\text{ ft})^2}{8} = 102\text{ K-ft}$$

$$Z_x \doteq \frac{102\text{ K-ft} \times 12}{.9 \times 50} = 27.2\text{ in}$$

Fits W12 X22

Deflection

$$\frac{\Delta L}{240} = 1''$$

$M_u = 102$ K-ft

$$\Delta = \frac{5wL^4}{384EI_x} = \frac{5 \cdot 2.04 \cdot (20 \times 12)^4}{384 \times 29 \times 10^6 \times 291} = .01'' \checkmark$$

Shear W14X30 Girder

$A = 8.85$ $d = 13.8$ $t_w = .27$ $K_{des} = .785$ $Z_x = 47.3$

$h = 13.8 - 2(.785) = 12.23$

$\frac{h}{t_w} = \frac{12.23}{.270} = 46.3 < 59.23$ $c_v = 1.0$

$1.10\sqrt{\frac{29{,}000 \times 5}{50}} = 59.23$

$A_w = d t_w = 13.8 \cdot .27 = 3.726 \text{ in}^2$

$V_n = 0.6 \cdot 50 \text{ ksi} \cdot 3.726 \text{ in} \cdot 1 = 111.78 \text{ kips}$

$W_u = 2.04 \text{ kips}$

$V_u = \frac{2 \text{ k/ft} \times 20 \text{ ft}}{2} = 20 \text{ kips}$

Diaphram F_p of F_p load in Diaphrams from seismic

W12x26 Beam @ span 26.7 ft

DL Deck 1.78 psf x 2.5 ft — 4.45 lb/ft
MEP 10 psf x 2.5 ft = 25 lb/ft
Wt of Beam — 26 lb/ft
Siding 1.78 psf x 30 ft — 53.4 lb/ft

DL 108.9 lb/ft

LL 35 psf · 2.5 ft — 87.5

$W_u = 1.2(D) + 1.6(L) = 270.68$ lb/ft

$$M_u = \frac{(.271\text{ K})(26.7\text{ ft})^2}{8} = 24\text{ k-ft}$$

$$Z_x = \frac{24\text{ k-ft}\cdot 12}{.9\cdot 50} = 6.45\text{ in}^3$$

Check for lateral torsional Buckling
Cb = 1.14 Unbraced length 8.8 feet

$1.14[140 - 5.46(8.8 - 5.33)]$
$= 138 \rightarrow$ No Change

Deflection

$$\frac{\Delta L}{240} = 1.23''$$

$$\Delta = \frac{5\cdot .271(26.7\times 12)^4}{384\cdot 29\times 10^6\times 204} = .006''$$

Building Diaphram | Seismic Design | Equivalent lateral Forces

size: 280′ × 320.4′
height: 30′
Wind Zone 2 wind pressure 17 psf Soil profile 1.2 Cl[illegible]
[illegible] $S_S = 1.17$ $S_1 = 0.7$
3 story Building $h_n = 30 ft$ Soil profile D

$V = C_S \cdot W$

W → total dead Load
+10 lb/ft² partition load
+35 psf snow load
+25% floor live loads

$S_{MS} = F_a S_S$ $F_a = 1.$ $1.6 \cdot .171 = .272$

$S_{M1} = F_v S_1$ $F_v = 2.4$ $2.4 \cdot .07 = .168$

$S_{DS} = 2/3\, S_{MS} = .181$

$S_{D1} = 2/3\, S_{M1} = .112$

$I_e = 1.25$ class II

R - Response modification factor - 3 $C_d = 4\tfrac{1}{2}$

$$C_S = \frac{S_{DS}}{R/I_e} = \frac{.181}{3/1} = .06$$

$T_a = C_t h_n^x$ $C_t = 0.02$ $x = 0.75$

$T_a = 0.02 \cdot 30ft^{0.75} = .256\ s$

Building-A | Seismic Loads

$C_s = .06$ total factored Wt 4125188 lbs

$V = C_s \cdot W = .06 \cdot 1647.8\,K = 100\ K$

= 584 Kips

Verticle Distribution of Forces

~~Roof~~

~~$F_x = C_{vx} V$~~

~~$C_{vx} = \frac{W_x h_x^k}{\sum_{i=1}^{N} w_i h_i^k}$~~

w_{xi} = portion of total seismic wt W located or Assigned to level i or x

$h_{x/i}$ = height from base level to i or x

K = 1 for T ≤ .5 s ∴ INTERPOLATE

= 2 for T ≤ 2 s

~~Roof W = 1201 Kips~~

~~$C_{vRoof} = \frac{1201\ Kips \cdot 30ft^1}{1648\ Kips \cdot 45ft^1}$~~ = .49

~~F_{xRoof} = 632 Kips · .59 = 367.5 Kips~~

~~F_x Mezz W = 446.5~~

~~$\frac{446.5 \cdot 14ft}{1648 \cdot 45} = .08$~~

~~F_x = 632 · .084 = 53.3 Kips~~

Building A | Verticle Lateral Forces

Verticle Distribution

$F_1 = V = 100$ Kips ∴ Virtually 1 story

Story Shear

$M_x = (100)(30ft) = 18982.5$ ft-K

$T = .256$ s

$\Delta_a = 0.025\, h_{sx}$ h_{sx}

$\Delta_a = 0.025(180'') = 4.5''$ $C_d = 3.25$

$\delta_{xe} = 1''$

$$\delta_x = \frac{C_d\, \delta_{xe}}{I_e}$$

Over strength $\Omega_o = 2$

$E = E_h + E_v$ $E = 131$ K

$E_h = 100$ K

$E_v = 31$ K

$$\theta = \frac{P_x\, \Delta\, I_e}{V_x\, h_{sx}\, C_d}$$

C1 Column Non-Diaphragm | HSS 9x9x3/8

Tributary Area - 53 ft x 40 ft

DL - 1.78 psf x 40 ft x 53 ft — 3773.6 lbs

RTU 350 lb — 350 lbs

Joist Beam Wt 9 x 53 ft x 15 lb/ft — 7155 lbs

Girder Wt 40 ft x 48 lb/ft — 1920 lb

13198.6 lb

LL 53 ft x 40 ft x 35 psf

74200 lb

$$W = 1.2D + 1.6L = \frac{1.2 \times 13198.6 + 1.6 \times 74200}{1000\ lb/k}$$

$W = 134.56K$ $F_y = 46$ ksi

K value = 1 pinned connections $A = 11.8$ $b/t = 22.8 = h/t$

min $r = 3.51$ $1.4\sqrt{\frac{E}{F_y}} = 35$ ∴ Non Slender

$$\frac{L}{r} = \frac{30ft}{3.51 in} \times 12in/1ft = 102.7 in$$

$$4.71\sqrt{\frac{E}{F_y}} = 118.2 in \therefore F_{cr} = \left[0.658^{\frac{F_y}{F_e}}\right]F_y$$

$$F_e = \frac{\pi^2 \times 29000\ ksi}{102.7 in^2} = 27.1$$

$$F_{cr} = \left[0.658^{\frac{46}{27.1}}\right] 46 ksi = 22.6 ksi$$

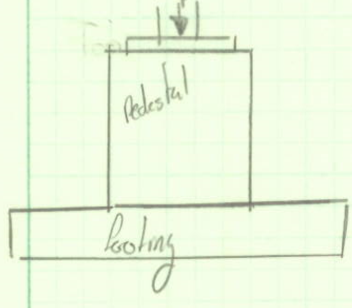
$$P_n = F_{cr} A_g = 22.6 Ksi \times 11.8 in^2 = 266.68K$$

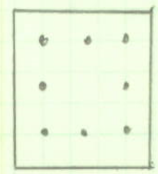
$$\phi P_n = .9(266.68) - 240 \text{ Kips}$$

Footing Pedestal F.7S

2' x 2' x 2' pedestal

Base plate 18" x 18" + 3" d. length both sides





8#7 Bars → $A_s = 4.81$"

$A_s/A_g = \frac{4.81 in^2}{576 in^2} = .00835$

$f'_c = 4$ ksi

$f_c = 2$ ksi

$E_c = 57{,}000\sqrt{4000} = 3.6 \times 10^6$ psi

$E_s = 29 \times 10^6$ psi

$n = 8 = \frac{E_s}{E_c}$

$P = f_c \left(A_g + (n-1) A_s\right) = 2000\left(576 + (8-1) \times 4.81\right)$

$P_n = 1220$ Kips

Max Force 135 Kips ✓

Footing design | 7.5′ x 7.5′ x 1.5′

soil Bearing Pressure 3 ksf

$F_y = 46$ ksi

Page 560

$F_u = 58$ ksi

$f'_c = 3$ ksi

$P = 135 +$

Max $P_u = 168$ kips

$$A_2 = \frac{135{,}000}{3000\ lb/ft^2} = \sqrt{45 ft^2} = 6.7 ft \times 6.7 ft = 8100 in^2$$

(7.5′ x 7.5′)

$$A_1 = BN = 24'' \times 24'' = 576 in^2$$

$$P_p = 0.85(3ksi)(576 in^2)\sqrt{\frac{8100 in^2}{576 in^2}} \leq 1.7(3ksi)(169 in^2)$$

$$5508 \leq 861.9K \therefore$$

$$\phi P_p = .65(861.9K)$$

Base Plate 18″ x 18″ x 1.25″ (Attached to Pier)

$F_y = 36$ ksi

$$m = n = \frac{N - 0.95(\text{outer dimension})}{2} = \frac{18'' - 0.95(9'')}{2}$$

$$m = n = l = 4.725''$$

$$f_{pu} = \frac{P_u}{A_1} \quad \frac{135K}{576 in^2} = .23 \text{ Kips}$$

$$M_u = \frac{f_{pu} l^2}{2} = \frac{.23(4.725)^2}{2} = 2.56$$

$$Z = \frac{t_p^2}{4} = \frac{M_n}{F_y} = \frac{2.56K}{36} = \frac{t_p^2}{4} \qquad t_p = .53'' \checkmark \text{o.k}$$

Transfer Load

ϕ dowels $= P_u - \phi P_n$

$\phi P_n \geq P_u$ Nominal Dowels Required

min 4 bars

min $A_s = 0.005 A_g = 2.88''$ → 5 #7 min

∴ Drawings call for 9 #7 → 5.41 in² As

Footing Design Cont.

dowel embedment

$l_{dc} = \frac{0.02 f_y d_b}{\sqrt{f'_c}} = \frac{0.02(36000)(.875)}{\sqrt{3000}} = 11.5''$

Length of lapped splices

$l_{dc} \leq 0.005 f_y d_b = 20.7''$

Check Two Way Shear

$A = 576 \text{ in}^2$

$b_o = 2(c+d) + 2(b+d) =$

$b_o = 2(14''+24'') + 2(14''+24)'' = 152 \text{ in}$

factored $q_u = \frac{P_u}{B^2} = \frac{135,000}{56.25} = 2400 \text{ lbs} = 2.4 \text{ kips}$

$V_{u2} = P_u - q_u(c+d)(b+d) = 135 - 2.4(10 ft^2)$

$V_{u2} = 105k$

$\phi = .75$

$V_{u2} \leq \phi(6)\sqrt{f'_c}\, b_o d \leq \phi 4\sqrt{f'_c}\, b_o d$

$105k \leq 0.75(6)\sqrt{3000psi}(152in)(14in) \leq .75 \cdot 4\sqrt{3000psi}(152in)(14in)$

$105k \leq 524.5k \leq 350.66k$ ✓ o.k.

One Way Shear

$L' = \frac{B}{2} - (d + \frac{b}{2}) = \frac{90in}{2} - (14in + \frac{24in}{2})$

$L' = 19''$

$V_{u1} = BL'q_u = 7.5ft \cdot 1.6ft \cdot 3.0ksf = 36k$

$36k \leq \phi\sqrt{f'_c}Bd = .75\sqrt{3000psi} \cdot 90in \cdot 14in = 51.8k$ ✓ ok

Footing Design Cont II

Bending Stress

$$L_m = \frac{B}{2} - \frac{b}{2} = \frac{90in}{2} - \frac{24in}{2} = 33in$$

$$M_u = q_u \frac{BL_m^2}{2} = 3ksf \frac{(7.5ft)(2.75ft)^2}{2} = 85 \text{ k-ft}$$

Req A_s

$$R_n = \frac{M_n}{bd^2} = \frac{M_u}{\phi bd^2} \quad \phi = .9$$

guess $a \rightarrow 4''$

$$A_s = \frac{M_u}{\phi f_y (d - \frac{a}{2})} \quad b = 90''$$

*M_u in k-in

$$a = \frac{A_s f_y}{.85 f'_c b} \quad A_s = 2.6 \text{ in}^2$$

$$A_s = \frac{1020 \text{ k-in}}{.9 \cdot 60 (14 - \frac{4}{2})} = 1.57 \text{ in}^2$$

$$a = \frac{1.57 in^2 \cdot 60 ksi}{.85 \cdot 3 ksi \cdot 24''} = 1.54 in^2$$

$A_s = 1.43$ for 24"

$a = 1.53$ 3 #7 dowels

Exterior column C3

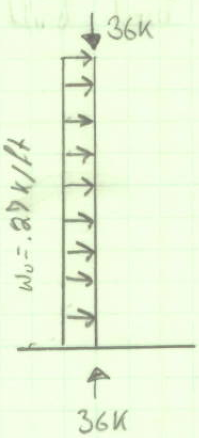
W 10 x 49

$A = 14.4$ $I_x = 272$ $\phi_b M_{px} = 227$ k-ft

$L_p = 8.97$ $L_r = 31.6$ $BF = 4.12$

DL = MD	1.78 x 26.7ft x 20ft	=	95 lb
Siding	2.74 x 15 ft x 20ft	=	822 lb
Masonry	5.2 x 15ft x 20ft	=	1560 lb
Girder	30 lb/ft x 20	=	600 lb
Joists	4.5 · 26.7 · 15 lb/ft	=	1802 lb
			4.879 K
LL	26.7 x 20 x 35 psf	=	18.69 K

$P_u = 1.2D + 1.6L = 36$ K



$w_u = .8WL = .8 \cdot 17 \text{ psf} \cdot 20\text{ft} = 272$ lb/ft

$$M_u = \frac{.272 \cdot 30\text{ft}^2}{8} = 30.6 \text{ K-ft}$$

$(KL_x) = (KL_y) = 30$ft

$$B_1 = \frac{C_m}{1 - \alpha \frac{P_r}{P_{e1}}}$$

$$P_{e1} = \frac{\pi^2 EI}{(K_1 L)^2} = \frac{\pi^2 29 \times 10^3 \cdot 272 \text{ in}^4}{360^2} = 600 \text{ K}$$

$P_r = 36k + \sout{B_2(0)P_r} = 36K$

$$C_m = 1 - .04\left(\frac{36K}{162K}\right) = .99$$

$$B_1 = \frac{.99}{1 - \frac{36K}{600K}} = 1.05 \quad M_{rx} = 1.05 \cdot 30.6\text{K-ft} = 32.13$$

Zone II $L_p \leq L \leq L_r$

$$\phi M_{px} = 1\left[227 - (4.12)(30 - 8.97)\right] = 140 \text{ Kips}$$

$$\frac{P_r}{2P_c} + \frac{8}{9}\left(\frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}}\right)$$

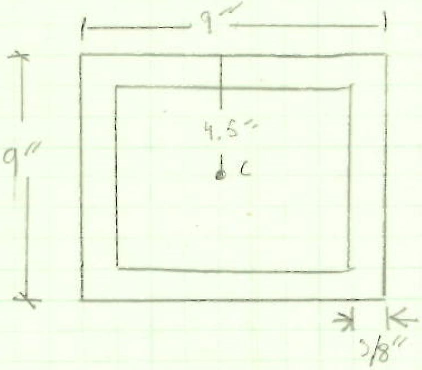
$$\frac{36K}{162K} + \frac{8}{9}\left(\frac{32.13 \text{ k-ft}}{140 \text{ k-ft}}\right) = .43 \leq 1.00K$$

∴ section is Satisfactory

Or $p_x = 6.7 \times 10^{-3}$

$b_x = 5.96 \times 10^{-3}$

Stress in HSS 9x9x 3/8



$F_y = 46$ ksi

$M = 795$ K-ft $\cdot$ 12in/ft = 7950 K-in

$C = 4.5''$

$I = 145$ in^4

$$\sigma = \frac{Mc}{I}$$

$$46 = \frac{M \cdot 4.5in}{145in^4}$$

$M_{max} = 1482$ K-in $<$ 7950 K-in

Wind Forces

V= 80 MPH

Reference Wind Pressure = 17 psf

Left side loading

X→ 320 ft * 30ft x 17psf = 163.2 K

Y→ Minimal?

Top Frame

360ft * 30 ft * 17 psf = 183.6 K

Wind loads Won't Be changing and niether will the forces of the Roof Diaphram

DESIGN GUIDE WEIGHT TABLE FOR JOIST GIRDERS
U. S. CUSTOMARY

Based on a 50ksi maximum yield strength

Girder Span (ft)	Joist Spaces (ft)	Girder Depth (in)	Joist Girder Weight – Pounds Per Linear Foot: Load on Each Panel Point																					
		LRFD	6K	7.5K	9K	10.5K	12K	13.5K	15K	16.5K	18K	21K	24K	27K	30K	37.5K	45K	52.5K	60K	75K	90K	105K	120K	150K
		ASD	4K	5K	6K	7K	8K	9K	10K	11K	12K	14K	16K	18K	20K	25K	30K	35K	40K	50K	60K	70K	80K	100K
40	3N@ 13.33	32	22	23	23	23	24	24	25	26	27	30	34	38	40	51	60	69	81	94	108	124	150	185
		36	23	23	23	23	23	24	25	25	27	27	32	34	39	46	54	61	70	87	104	111	126	164
		40	23	23	23	23	23	23	24	25	27	27	28	32	35	43	49	55	62	84	93	107	125	156
		44	23	23	23	24	24	24	24	26	26	28	28	32	33	42	47	55	63	73	89	99	115	131
		48	23	24	24	24	24	24	24	26	26	29	29	29	32	38	44	51	57	70	80	92	102	131
	4N@ 10.00	32	16	16	19	22	25	26	28	30	33	39	45	50	53	68	77	90	104	129	152	173	202	252
		36	16	17	18	21	25	25	26	29	31	34	40	44	48	62	71	79	93	115	143	166	179	230
		40	17	17	17	19	23	25	26	27	29	32	38	41	46	56	68	77	93	109	119	150	172	212
		44	16	16	18	18	20	21	23	24	28	30	34	37	40	51	57	66	76	104	111	126	150	189
		48	17	17	18	18	19	20	23	25	26	28	32	34	37	49	58	66	74	87	108	116	139	178
	5N@ 8.00	32	16	18	22	25	28	31	34	37	40	46	54	58	65	78	100	106	130	157	188	227	255	
		36	16	17	20	23	25	27	31	34	35	41	46	54	59	71	91	102	107	143	167	196	230	298
		40	16	16	18	21	23	27	28	30	33	37	42	47	53	64	80	93	104	128	159	182	210	262
		44	17	17	17	20	23	24	28	29	31	35	39	46	49	60	73	81	96	116	138	161	186	245
		48	17	17	17	19	23	25	25	28	29	33	37	41	47	57	67	80	93	111	122	152	178	217
	6N@ 6.67	32	17	20	24	28	32	35	39	42	47	54	62	69	77	99	108	140	151	189	220	266		
		36	17	20	23	26	28	31	35	38	41	48	55	62	70	83	102	115	142	167	197	232	275	
		40	17	18	21	25	28	29	32	36	38	44	49	56	64	79	94	105	118	147	185	215	245	313
		44	17	18	21	22	27	29	30	33	36	42	49	53	58	74	86	105	111	148	177	199	227	294
		48	17	18	20	24	25	28	29	31	33	40	44	52	55	72	79	98	108	130	156	180	204	271
	7N@ 5.71	32	19	24	28	32	34	40	45	47	54	62	70	77	91	105	130	152	175	218	255			
		36	18	21	26	28	32	35	40	43	48	56	63	71	79	102	115	143	155	197	232	276		
		40	18	20	25	28	31	33	36	41	45	51	57	65	72	94	108	118	145	184	214	255	300	
		44	18	21	23	27	29	31	34	37	41	50	58	63	67	82	106	113	127	167	199	237	272	
		48	18	22	24	27	30	33	37	39	42	48	57	63	71	81	99	114	125	169	195	234	267	
	8N@ 5.00	32	21	27	31	36	39	47	50	58	62	70	83	100	101	121	152	175	197	241				
		36	21	25	29	32	37	40	48	51	56	64	72	84	93	111	144	156	182	222	277			
		40	20	23	27	30	35	38	41	46	51	61	69	76	86	105	119	148	171	203	257	294		
		44	20	24	29	30	34	38	41	45	50	58	66	75	78	98	113	129	153	193	240	278	320	
		48	19	24	26	29	32	35	40	43	46	55	60	72	76	90	111	118	144	183	218	261	295	
	10N@ 4.00	32	27	33	40	43	51	58	63	70	78	92	103	110	122	168	190	218	246					
		36	27	30	35	41	48	55	62	64	72	79	94	107	116	145	181	199	240	306				
		40	25	28	33	39	43	50	56	57	65	74	86	95	109	134	160	186	212	277				
		44	23	28	31	37	40	48	51	57	59	74	81	88	98	120	150	175	190	255	302			
		48	22	26	29	34	38	42	50	54	59	67	76	83	98	114	140	157	182	230	277	324		
42	3N@ 14.00	32	29	29	29	30	31	31	32	33	34	35	38	40	45	53	60	69	81	94	118	140	160	185
		36	29	29	30	30	30	31	32	34	33	35	36	38	40	47	57	64	70	87	109	122	141	173
		40	30	30	30	30	30	30	31	34	34	34	35	37	39	46	53	61	71	85	97	112	126	156
		44	30	30	30	30	30	30	32	32	33	35	35	36	37	43	48	56	63	73	89	99	115	146
		48	30	30	30	30	31	31	32	32	33	35	35	36	39	43	48	53	61	74	88	99	110	132
	4N@ 10.50	32	16	17	20	23	25	28	30	33	35	42	45	50	57	68	89	99	104	140	161	186	214	274
		36	16	16	18	21	23	25	28	30	33	37	44	46	52	66	75	91	101	115	143	175	191	240
		40	17	17	18	21	22	24	26	28	30	34	38	45	47	59	68	79	94	109	134	159	177	214
		44	17	17	18	19	21	25	25	27	29	32	36	42	46	54	65	74	82	106	120	138	164	202
		48	18	18	18	18	20	25	27	25	28	31	35	39	43	50	63	71	81	98	114	139	153	192
	5N@ 8.40	32	17	20	23	26	28	33	36	39	44	47	54	61	68	90	103	113	130	172	197	225	256	
		36	16	17	21	23	26	28	32	34	37	44	48	54	62	74	91	105	115	152	177	207	233	
		40	16	18	20	22	24	27	29	32	34	40	45	52	55	67	79	93	107	133	156	186	210	266
		44	16	18	19	21	25	26	28	30	32	38	41	47	53	64	77	93	104	119	148	171	200	238
		48	17	18	18	20	24	24	27	29	30	36	39	43	49	57	70	81	96	111	137	162	187	220
	6N@ 7.00	32	18	21	26	29	33	37	40	45	47	57	65	73	81	99	119	140	160	190	236	289		
		36	17	20	24	27	30	34	36	39	43	51	58	62	70	91	106	121	142	177	209	240	293	
		40	17	19	21	26	28	32	34	36	40	47	55	59	64	79	103	109	123	167	192	222	253	
		44	17	18	21	24	26	29	32	34	36	43	50	57	60	76	95	105	113	148	176	202	227	303
		48	17	18	21	24	26	29	30	33	35	41	46	52	58	70	83	106	108	139	163	188	208	270
	7N@ 6.00	32	20	24	29	34	37	42	47	53	54	68	77	90	99	113	140	162	187	226	289			
		36	20	23	27	30	35	38	41	46	51	59	70	78	83	102	122	142	166	205	248	292		
		40	18	22	25	28	32	35	39	42	47	56	63	71	79	95	109	134	147	182	222	272	303	
		44	18	21	24	27	30	32	36	40	43	51	57	65	73	87	106	119	137	176	202	246	283	
		48	18	20	24	26	29	32	34	37	41	47	52	59	67	83	98	113	122	164	191	220	255	
	8N@ 5.25	32	22	28	33	38	43	47	54	58	65	77	83	100	105	140	163	188	216	268				
		36	20	26	29	34	40	43	49	55	59	67	79	84	101	116	143	167	190	231	290			
		40	20	24	28	33	36	41	45	50	53	61	69	81	86	107	126	151	175	215	264	326		
		44	21	23	28	31	34	37	43	47	52	58	66	79	83	107	116	141	157	201	239	291	333	
		48	21	25	28	29	32	35	39	44	48	56	64	69	78	100	111	130	156	182	214	278	315	
	11N@ 3.82	32	31	37	45	53	61	69	77	82	91	104	114	130	151	189	218	267						
		36	27	35	41	48	55	62	70	72	79	92	106	115	132	166	197	232	270					
		40	27	32	37	42	49	56	64	65	73	84	103	108	117	149	182	209	243	310				
		44	25	31	35	40	48	51	58	65	66	81	95	106	111	139	167	190	218	281				
		48	24	29	34	38	45	50	54	60	67	76	84	98	108	122	154	180	205	259	318			
Bearing Depth			7 1/2 in.														10 in.							

Joist Girder weights between the heavy black and blue lines have 7 1/2 inch bearing depths.
Joist Girder weights to the right of the heavy blue line have 10 inch bearing depths. Check with Vulcraft for material availability.

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STANDARD LOAD TABLE FOR OPEN WEB STEEL JOISTS, K-SERIES
Based On A 50 ksi Maximum Yield Strength - Loads Shown In Pounds Per Linear Foot (plf)

Joist Designation	10K1	12K1	12K3	12K5	14K1	14K3	14K4	14K6	16K2	16K3	16K4	16K5	16K6	16K7	16K9
Depth (in.)	10	12	12	12	14	14	14	14	16	16	16	16	16	16	16
Approx. Wt (lbs./ft.)	5.0	5.0	5.7	7.1	5.2	6.0	6.7	7.7	5.5	6.3	7.0	7.5	8.1	8.6	10.0
Span (ft.) ↓															
10	825 550														
11	825 542														
12	825 455	825 550	825 550	825 550											
13	718 363	825 510	825 510	825 510											
14	618 289	750 425	825 463	825 463	825 550	825 550	825 550	825 550							
15	537 234	651 344	814 428	825 434	766 475	825 507	825 507	825 507							
16	469 192	570 282	714 351	825 396	672 390	825 467	825 467	825 467	825 550	825 550	825 550	825 550	825 550	825 550	825 550
17	415 159	504 234	630 291	825 366	592 324	742 404	825 443	825 443	768 488	825 526	825 526	825 526	825 526	825 526	825 526
18	369 134	448 197	561 245	760 317	528 272	661 339	795 397	825 408	684 409	762 456	825 490	825 490	825 490	825 490	825 490
19	331 113	402 167	502 207	681 269	472 230	592 287	712 336	825 383	612 347	682 386	820 452	825 455	825 455	825 455	825 455
20	298 97	361 142	453 177	613 230	426 197	534 246	642 287	787 347	552 297	615 330	739 386	825 426	825 426	825 426	825 426
21		327 123	409 153	555 198	385 170	483 212	582 248	712 299	499 255	556 285	670 333	754 373	822 405	825 406	825 406
22		298 106	373 132	505 172	351 147	439 184	529 215	648 259	454 222	505 247	609 289	687 323	747 351	825 385	825 385
23		271 93	340 116	462 150	321 128	402 160	483 188	592 226	415 194	462 216	556 252	627 282	682 307	760 339	825 363
24		249 81	312 101	423 132	294 113	367 141	442 165	543 199	381 170	424 189	510 221	576 248	627 269	697 298	825 346
25					270 100	339 124	408 145	501 175	351 150	390 167	469 195	529 219	576 238	642 263	771 311
26					249 88	313 110	376 129	462 156	324 133	360 148	433 173	489 194	532 211	592 233	711 276
27					231 79	289 98	349 115	427 139	300 119	334 132	402 155	453 173	493 188	549 208	658 246
28					214 70	270 88	324 103	397 124	279 106	310 118	373 138	421 155	459 168	510 186	612 220
29									259 95	289 106	348 124	391 139	427 151	475 167	570 198
30									241 86	270 96	324 112	366 126	399 137	444 151	532 178
31									226 78	252 87	304 101	342 114	373 124	415 137	498 161
32									213 71	237 79	285 92	321 103	349 112	388 124	466 147

LRFD

STANDARD LOAD TABLE FOR OPEN WEB STEEL JOISTS, K-SERIES
Based On A 50 ksi Maximum Yield Strength - Loads Shown In Pounds Per Linear Foot (plf)

Joist Designation	18K3	18K4	18K5	18K6	18K7	18K9	18K10	20K3	20K4	20K5	20K6	20K7	20K9	20K10	22K4	22K5	22K6	22K7	22K9	22K10	22K11
Depth (In.)	18	18	18	18	18	18	18	20	20	20	20	20	20	20	22	22	22	22	22	22	22
Approx. Wt. (lbs./ft.)	6.4	7.2	7.7	8.4	8.9	10.1	11.6	6.5	7.2	7.7	8.4	8.9	10.1	11.6	7.3	7.7	8.5	9.0	10.2	11.7	11.9
Span (ft.) ↓																					
18	825 550	825 550	825 550	825 550	825 550	825 550	825 550														
19	771 494	825 523	825 523	825 523	825 523	825 523	825 523	825 550	825 550	825 550	825 550	825 550	825 550	825 550							
20	694 423	825 490	825 490	825 490	825 490	825 490	825 490	775 517	825 550	825 550	825 550	825 550	825 550	825 550							
21	630 364	759 426	825 460	825 460	825 460	825 460	825 460	702 453	825 520	825 520	825 520	825 520	825 520	825 520	825 550	825 550	825 550	825 550	825 550	825 550	825 550
22	573 316	690 370	777 414	825 438	825 438	825 438	825 438	639 393	771 461	825 490	825 490	825 490	825 490	825 490	825 548	825 548	825 548	825 548	825 548	825 548	825 548
23	523 276	630 323	709 362	774 393	825 418	825 418	825 418	583 344	703 402	793 451	825 468	825 468	825 468	825 468	777 491	825 518	825 518	825 518	825 518	825 518	825 518
24	480 242	577 284	651 318	709 345	789 382	825 396	825 396	535 302	645 353	727 396	792 430	825 448	825 448	825 448	712 431	804 483	825 495	825 495	825 495	825 495	825 495
25	441 214	532 250	600 281	652 305	727 337	825 377	825 377	493 266	594 312	669 350	729 380	811 421	825 426	825 426	657 381	739 427	805 464	825 474	825 474	825 474	825 474
26	408 190	492 222	553 249	603 271	672 299	807 354	825 361	456 236	549 277	618 310	673 337	750 373	825 405	825 405	606 338	682 379	744 411	825 454	825 454	825 454	825 454
27	378 169	454 198	513 222	558 241	622 267	747 315	825 347	421 211	508 247	573 277	624 301	694 333	825 389	825 389	561 301	633 337	688 367	768 406	825 432	825 432	825 432
28	351 151	423 177	477 199	519 216	577 239	694 282	822 331	391 189	472 221	532 248	579 269	645 298	775 353	825 375	522 270	588 302	640 328	712 364	825 413	825 413	825 413
29	327 136	394 159	444 179	483 194	538 215	646 254	766 298	364 170	439 199	495 223	540 242	601 268	723 317	825 359	486 242	547 272	597 295	664 327	798 387	825 399	825 399
30	304 123	367 144	414 161	451 175	502 194	603 229	715 269	340 153	411 179	462 201	504 218	561 242	675 286	799 336	453 219	511 245	556 266	619 295	745 349	825 385	825 385
31	285 111	343 130	387 146	421 158	469 175	564 207	669 243	318 138	384 162	433 182	471 198	525 219	631 259	748 304	424 198	478 222	520 241	580 267	697 316	825 369	825 369
32	267 101	322 118	363 132	396 144	441 159	529 188	627 221	298 126	360 147	406 165	442 179	492 199	592 235	702 276	397 180	448 201	489 219	544 242	654 287	775 337	823 355
33	252 92	303 108	342 121	372 131	414 145	498 171	589 201	280 114	339 134	381 150	415 163	463 181	556 214	660 251	373 164	421 183	459 199	511 221	615 261	729 307	798 334
34	237 84	285 98	321 110	349 120	390 132	468 156	555 184	264 105	318 122	358 137	391 149	435 165	523 195	621 229	352 149	397 167	432 182	481 202	579 239	687 280	774 314
35	223 77	268 90	303 101	330 110	367 121	441 143	523 168	249 96	300 112	339 126	369 137	411 151	493 179	585 210	331 137	373 153	408 167	454 185	546 219	648 257	741 292
36	211 70	253 82	286 92	312 101	348 111	417 132	495 154	235 88	283 103	319 115	348 125	388 139	466 164	553 193	313 126	354 141	385 153	429 169	516 201	612 236	700 269
37								222 81	268 95	303 106	330 115	367 128	441 151	523 178	297 116	334 130	364 141	406 156	487 185	579 217	663 247
38								211 74	255 87	286 98	312 106	348 118	418 139	496 164	280 107	316 119	345 130	384 144	462 170	549 200	628 228
39								199 69	241 81	271 90	297 98	330 109	397 129	471 151	267 98	300 110	327 120	364 133	438 157	520 185	595 211
40								190 64	229 75	258 84	282 91	313 101	376 119	447 140	253 91	285 102	310 111	346 123	417 146	495 171	565 195
41															241 85	271 95	295 103	330 114	396 135	471 159	538 181
42															229 79	259 88	282 96	313 106	378 126	448 148	513 168
43															219 73	247 82	268 89	300 99	360 117	427 138	489 157
44															208 68	235 76	256 83	286 92	343 109	408 128	466 146

LRFD

STANDARD LOAD TABLE FOR OPEN WEB STEEL JOISTS, K-SERIES
Based On A 50 ksi Maximum Yield Strength - Loads Shown In Pounds Per Linear Foot (plf)

Joist Designation	24K4	24K5	24K6	24K7	24K8	24K9	24K10	24K12	26K5	26K6	26K7	26K8	26K9	26K10	26K12
Depth (In.)	24	24	24	24	24	24	24	24	26	26	26	26	26	26	26
Approx. Wt. (lbs./ft.)	7.8	7.9	8.5	9.0	9.4	10.3	11.7	13.5	8.1	8.6	9.0	9.7	10.4	11.8	13.7
Span (ft.) ↓															
23	825 550	825 550	825 550	825 550	825 550	825 550	825 550	825 550							
24	780 516	825 544	825 544	825 544	825 544	825 544	825 544	825 544							
25	718 456	810 511	825 520	825 520	825 520	825 520	825 520	825 520	825 550	825 550	825 550	825 550	825 550	825 550	825 550
26	663 405	748 453	814 493	825 499	825 499	825 499	825 499	825 499	813 535	825 541	825 541	825 541	825 541	825 541	825 541
27	615 361	693 404	754 439	825 479	825 479	825 479	825 479	825 479	753 477	820 519	825 522	825 522	825 522	825 522	825 522
28	571 323	643 362	700 393	781 436	825 456	825 456	825 456	825 456	699 427	762 464	825 501	825 501	825 501	825 501	825 501
29	531 290	600 325	652 354	727 392	804 429	825 436	825 436	825 436	651 384	709 417	790 463	825 479	825 479	825 479	825 479
30	496 262	559 293	609 319	679 353	750 387	816 419	825 422	825 422	607 346	661 377	738 417	816 457	825 459	825 459	825 459
31	465 237	523 266	570 289	636 320	702 350	765 379	825 410	825 410	568 314	619 341	690 378	763 413	825 444	825 444	825 444
32	435 215	490 241	535 262	595 290	658 318	717 344	823 393	823 393	534 285	580 309	648 343	715 375	778 407	823 431	823 431
33	409 196	462 220	502 239	559 265	619 289	673 313	798 368	798 368	501 259	546 282	609 312	672 342	732 370	798 404	798 404
34	385 179	435 201	472 218	526 242	582 264	634 286	753 337	774 344	472 237	514 257	573 285	633 312	688 338	774 378	774 378
35	363 164	409 184	445 200	496 221	549 242	598 262	709 308	751 324	445 217	484 236	540 261	597 286	649 310	751 356	751 356
36	343 150	387 169	421 183	469 203	519 222	565 241	670 283	730 306	420 199	457 216	510 240	564 263	613 284	729 334	730 334
37	324 138	366 155	399 169	444 187	490 205	534 222	634 260	711 290	397 183	433 199	483 221	534 242	580 262	690 308	711 315
38	307 128	346 143	378 156	421 172	465 189	507 204	601 240	691 275	376 169	411 184	457 204	505 223	550 241	654 284	691 299
39	292 118	328 132	358 144	399 159	441 174	480 189	570 222	673 261	357 156	390 170	433 188	480 206	522 223	619 262	673 283
40	277 109	312 122	340 133	379 148	420 161	456 175	541 206	657 247	340 145	370 157	412 174	456 191	496 207	589 243	657 269
41	264 101	297 114	324 124	361 137	399 150	435 162	516 191	640 235	322 134	352 146	393 162	433 177	472 192	561 225	640 256
42	252 94	283 106	309 115	343 127	379 139	414 151	490 177	625 224	307 125	336 136	373 150	412 164	450 178	534 210	625 244
43	240 88	270 98	294 107	328 118	363 130	394 140	468 165	609 213	294 116	319 126	357 140	394 153	429 166	508 195	610 232
44	229 82	258 92	280 100	313 110	346 121	376 131	447 154	580 199	280 108	306 118	340 131	376 143	409 155	486 182	597 222
45	219 76	246 86	268 93	298 103	330 113	360 122	427 144	555 185	268 101	291 110	325 122	360 133	391 145	465 170	583 212
46	208 71	235 80	256 87	286 97	316 106	345 114	408 135	531 174	256 95	279 103	310 114	343 125	375 135	444 159	570 203
47	199 67	225 75	246 82	274 90	303 99	330 107	391 126	508 163	246 89	267 96	298 107	328 117	358 127	426 149	553 192
48	192 63	216 70	235 77	262 85	291 93	316 101	375 118	487 153	235 83	256 90	285 100	315 110	343 119	408 140	529 180
49									225 78	246 85	274 94	303 103	330 112	391 131	508 169
50									216 73	235 80	262 89	291 97	316 105	375 124	487 159
51									208 69	226 75	252 83	279 91	304 99	361 116	469 150
52									199 65	217 71	243 79	268 86	292 93	346 110	451 142

LRFD

STANDARD LOAD TABLE/OPEN WEB STEEL JOISTS, K-SERIES
Based On A 50 ksi Maximum Yield Strength - Loads Shown In Pounds Per Linear Foot (plf)

Joist Designation	28K6	28K7	28K8	28K9	28K10	28K12	30K7	30K8	30K9	30K10	30K11	30K12
Depth (In.)	28	28	28	28	28	28	30	30	30	30	30	30
Approx. Wt. (lbs./ft.)	8.9	9.2	9.8	10.5	11.8	14.5	9.6	10.0	10.6	11.9	13.3	15.0
Span (ft.) ↓												
27	825 550	825 550	825 550	825 550	825 550	825 550						
28	822 541	825 543	825 543	825 543	825 543	825 543						
29	766 486	825 522	825 522	825 522	825 522	825 522	825 550	825 550	825 550	825 550	825 550	825 550
30	715 439	796 486	825 500	825 500	825 500	825 500	825 543	825 543	825 543	825 543	825 543	825 543
31	669 397	745 440	825 480	825 480	825 480	825 480	801 508	825 520	825 520	825 520	825 520	825 520
32	627 361	699 400	772 438	823 463	823 463	823 463	751 461	823 500	823 500	823 500	823 500	823 500
33	589 329	657 364	726 399	790 432	798 435	798 435	706 420	780 460	798 468	798 468	798 468	798 468
34	555 300	618 333	684 364	744 395	774 410	774 410	664 384	735 420	774 441	774 441	774 441	774 441
35	523 275	583 305	645 333	702 361	751 389	751 389	627 351	693 384	751 415	751 415	751 415	751 415
36	495 252	550 280	609 306	663 332	730 366	730 366	592 323	654 353	712 383	730 392	730 392	730 392
37	468 232	522 257	576 282	627 305	711 344	711 344	559 297	619 325	673 352	711 374	711 374	711 374
38	444 214	493 237	546 260	594 282	691 325	691 325	531 274	586 300	639 325	691 353	691 353	691 353
39	420 198	469 219	519 240	564 260	670 306	673 308	504 253	556 277	606 300	673 333	673 333	673 333
40	399 183	445 203	492 222	535 241	636 284	657 291	478 234	529 256	576 278	657 315	657 315	657 315
41	379 170	424 189	468 206	510 224	606 263	640 277	454 217	502 238	547 258	640 300	640 300	640 300
42	361 158	403 175	445 192	486 208	576 245	625 264	433 202	480 221	522 240	619 282	625 284	625 284
43	345 147	385 163	426 179	463 194	550 228	610 252	414 188	457 206	498 223	591 263	610 270	610 270
44	330 137	367 152	406 167	442 181	525 212	597 240	394 176	436 192	475 208	564 245	597 258	597 258
45	315 128	351 142	388 156	423 169	501 198	583 229	376 164	417 179	454 195	538 229	583 246	583 246
46	301 120	336 133	372 146	405 158	480 186	570 219	361 153	399 168	435 182	516 214	570 236	570 236
47	288 112	321 125	355 136	387 148	459 174	558 210	345 144	382 157	415 171	493 201	558 226	558 226
48	276 105	309 117	340 128	370 139	441 163	547 201	331 135	366 148	399 160	472 188	543 215	547 216
49	265 99	295 110	327 120	355 130	423 153	535 193	318 127	351 139	382 150	454 177	520 202	535 207
50	255 93	283 103	313 113	342 123	405 144	525 185	304 119	337 130	367 141	436 166	499 190	525 199
51	244 88	273 97	301 106	328 115	390 136	507 175	292 112	324 123	352 133	418 157	480 179	514 192
52	235 83	262 92	289 100	315 109	375 128	487 165	282 106	312 116	339 126	402 148	462 169	504 184
53	226 78	252 87	279 95	304 103	360 121	469 156	271 100	300 109	327 119	387 140	444 159	495 177
54	217 74	243 82	268 89	292 97	348 114	451 147	261 94	286 103	313 112	373 132	427 150	486 170
55	210 70	234 77	259 85	282 92	334 108	435 139	252 89	277 98	303 106	360 125	412 142	468 161
56	202 66	226 73	249 80	271 87	322 102	420 132	243 84	268 92	292 100	346 118	397 135	451 153
57							234 80	259 88	282 95	334 112	384 128	435 145
58							226 76	250 83	271 90	322 106	370 121	420 137
59							219 72	241 79	262 86	312 101	358 115	406 130
60							211 69	234 75	253 81	301 96	346 109	393 124

Approximate Second Order Analysis Benchmarking

C3 W10X49		Tributary Area	
L	30	Roof /Floor	Siding
)(ltb)	30	530	520
)(elb)	30	Loads	plf
E	29000	Snow Load (psf)	45
A	14.4	Dead Loads	
Ix	272	Roof Deck	1.78
Iy	93.4	Girder	1.3
Lp	9.04	4.5 30 k 12 joists	3.4
Lr	31.6	MEP	5
Pc	162	column	
ry	2.54	Siding	6
rx	5.73	Live Loads	
kly/ry	141.7323		
klx/rx	62.82723		
J	0.38		
rts	1.77	Input For Revit File	
ho	13.4	Unfactored DL k	9.2044
Sx	42	Unfactored LL K	23.85
Fcr		Earthquake Load (k)	104.940255
Mc	149	Wind Load (klf)	0.34
b/t	\	Wind Load Sory shear	91.8

Load Combination											
(1.2 + 0.2SDS)D + 1.0E +0.2S											
Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δoh	Pestory	pstory	B2	Mlt	Mu
33.0544		0.204	0.98	600	1.035	0.797	47430.6	1645.06	1.0359	2.1	2.175
1.2D + 1.6S + .8W											
Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δoh	Pestory	pstory	B2	Mlt	Mu
49.2053	2.1	0.304	0.97	600	1.0536	0.266	124241	7289.86	1.0623	43.6	48.16
1.2D + .5S + 1.6W											
Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δoh	Pestory	pstory	B2	Mlt	Mu
22.9703	2.1	0.162	0.98	600	1.0239	0.266	124241	2854.66	1.0235	84.0	88.16

Pe1x	EI/(KL)^2 AISC A-8-5
B1x	Cm/1-α(Pr/Pex) A-8-3
Δoh	Story Drift from RISA Model
Pestory	Rm(HL/ΔH) A-8-7
pstory	Totol factored axial load for entire story
B2	1/(1-(Pestory/Pstory)) A-8-6
Mlt	Moment from lateral force
Mu	Moment from gavity Load
H1-1a	Pr/Pc +8/9(Mr/Mc)
H1-1b	Pr/2Pc + Mr/Mc
Cm	Based of AISC Table C-8-8.1

Out Of Plane (y)			In Plane X		
Q E7-4	13.48659	*>b/t*	Q E7-4	13.4866	*>b/t*
Q E7-5	24.80568	*>b/t*	Q E7-5	24.8057	*>b/t*
Q	#VALUE!		Q	#VALUE!	
E7-2	#VALUE!	*<KL/r*	E7-2	#VALUE!	*<KL/r*
E3-3Fcr	#VALUE!		E3-3 Fcr	#VALUE!	
E3-4Fe	14.23376		E3-4 Fe	72.4372	

C4W12X53		Tributary Area		Load Combination												
L	30	Roof /Floor	Siding	*(1.2 + 0.2SDS)D + 1.0E +0.2S*												
Lb(ltb)	30	530	689	Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δ_{oh}	Pestory	pstory	B2	Mlt	Mu	H1-1b
Lb(elb)	30	Loads	plf	19.0758		0.115	0.99	938	1.0125	0.797	47888.9	1645.06	1.0356	2.1	2.1747	0.070426
E	29000	Snow Load (psf)	45	1.2D + 1.6S + .8W												
A	14.6	Dead Loads		Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δ_{oh}	Pestory	pstory	B2	Mlt	Mu	H1-1b
Ix	425	Roof Deck	1.78	50.4221	2.1	0.305	0.98	938	1.0341	0.527	55332.1	7289.86	1.1517	47.3	51.298	0.571734
Iy	93.4	Girder	1.3	1.2D + .5S + 1.6W												
Lp	8.76	4.5 30 k 12 joists	3.4	Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δ_{oh}	Pestory	pstory	B2	Mlt	Mu	H1-1b
Lr	28.2	MEP	5	24.1871	2.1	0.167	0.99	938	1.0159	0.88	33136.4	2854.66	1.0943	84.0	87.673	0.596019
Pc	165.2757	column														
ry	2.48	Siding	6	Pe1x	EI/(KL)^2 AISC A-8-5											
rx	5.23	Live Loads		B1x	Cm/1-α(Pr/Pex) A-8-3											
kly/ry	145.1613			Δ_{oh}	Story Drift from RISA Model											
klx/rx	68.83365			Pestory	Rm(HL/ΔH) A-8-7											
J	0.38			pstory	Totol factored axial load for entire story											
rts	1.77	Input For Revit File		B2	1/(1-(Pestory/Pstory)) A-8-6											
ho	13.4	Unfactored DL k	10.2184	Mlt	Moment from lateral force											
Sx	42	Unfactored LL K	23.85	Mu	Moment from gavity Load											
Fcr		Earthquake Load (k)	105.954255	H1-1a	Pr/Pc +8/9(Mr/Mc)											
Mc	171	Wind Load (klf)	0.45	H1-1b	Pr/2Pc + Mr/Mc											
b/t	17.38	Wind Load Sory shear	81	Cm	Based of AISC Table C-8-8.1											
Out Of Plane (y)			In Plane X													
Q E7-4	13.48659	*>b/t*	Q E7-4	13.4866	*>b/t*											
Q E7-5	24.80568	*>b/t*	Q E7-5	24.8057	*>b/t*											
Q	0.880968		Q	0.88097												
E7-2	106.467	*<KL/r*	E7-2	106.467	*<KL/r*											
E3-3Fcr	11.32025		E3-3 Fcr	32.4526												
E3-4Fe	13.56924		E3-4 Fe	60.347												

C5 W12X65		Tributary Area	
L	30	Roof /Floor	Siding
Lb(ltb)	30	795	583
Lb(elb)	30	Loads	plf
E	29000	Snow Load (psf)	45
A	19.1	Dead Loads	
Ix	533	Roof Deck	1.78
Iy	174	Girder	1.3
Lp	11.9	4.5 30 k 12 joists	3.4
Lr	35.1	MEP	5
Pc	304	column	
ry	3.09	Siding	6
rx	5.44	Live Loads	
kly/ry	116.5049		
klx/rx	66.17647		
J	-		
rts	-	Input For Revit File	
ho	-	Unfactored DL k	12.6246
Sx	-	Unfactored LL K	35.775
Fcr	-	Earthquake Load (k)	105.428383
Mc	258	Wind Load (klf)	0.45
b/t	-	Wind Load Sory shear	81

Load Combination

(1.2 + 0.2SDS)D + 1.0E +0.2S

Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δoh	Pestory	pstory	B2	Mlt	Mu	H1-1b
48.3996		0.159	0.98	1176	1.0258	1.3	29195.6	1645.06	1.0597	24	25.433	0.178182

1.2D + 1.6S + .8W

Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δoh	Pestory	pstory	B2	Mlt	Mu	H1-1a
72.3895	2.1	0.238	0.98	1176	1.0394	0.527	55332.1	7289.86	1.1517	39.6	43.598	0.388331

1.2D + .5S + 1.6W

Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δoh	Pestory	pstory	B2	Mlt	Mu	H1-1a
33.037	2.1	0.284	0.99	1176	1.0173	0.88	33136.4	2854.66	1.0943	75.3	78.889	0.555366

Pe1x	EI/(KL)^2 AISC A-8-5
B1x	Cm/1-α(Pr/Pex) A-8-3
Δoh	Story Drift from RISA Model
Pestory	Rm(HL/ΔH) A-8-7
pstory	Totol factored axial load for entire story
B2	1/(1-(Pestory/Pstory)) A-8-6
Mlt	Moment from lateral force
Mu	Moment from gavity Load
H1-1a	Pr/Pc +8/9(Mr/Mc)
H1-1b	Pr/2Pc + Mr/Mc
Cm	Based of AISC Table C-8-8.1

Out Of Plane (y)			In Plane X		
Q E7-4	13.48659	*>b/t*	Q E7-4	13.4866	*>b/t*
Q E7-5	24.80568	*>b/t*	Q E7-5	24.8057	*>b/t*
Q	#VALUE!		Q	#VALUE!	
E7-2	#VALUE!	*<KL/r*	E7-2	#VALUE!	*<KL/r*
E3-3Fcr	#VALUE!		E3-3 Fcr	#VALUE!	
E3-4Fe	21.06538		E3-4 Fe	65.2905	

W12x26		Tributary Area		Load Combination												
L	26.5	Roof /Floor	Siding	*(1.2 + 0.2SDS)D + 1.0E +0.2S*												
Lb(ltb)	8.83	66.25		Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δ_{oh}	Pestory	pstory	B2	Mlt	Mu	H1-1b
Lb(elb)	8.83	Loads	plf	52.1106	12.5	**0.213**	1.00	**5195**	**1.0061**	0.797	**40616.6**	**1645.06**	**1.0422**	6.7	**19.575**	**0.26824**
E	29000	Snow Load (psf)	112.5	1.2D + 1.6S + .8W												
A	7.65	Dead Loads		Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δ_{oh}	Pestory	pstory	B2	Mlt	Mu	H1-1a
Ix	204	Roof Deck	4.45	86.7139	24.32525	**0.354**	0.99	**5195**	**1.0102**	0.613	**47622.2**	**7289.86**	**1.1807**	14.0	**38.3**	**0.63574**
Iy	17.3	Girder	26	1.2D + .5S + 1.6W												
Lp	5.33	4.5 30 k 12 joists		Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δ_{oh}	Pestory	pstory	B2	Mlt	Mu	H1-1a
Lr	14.9	MEP	25	166.925	16.70626	**0.682**	0.99	**5195**	**1.0199**	1.228	**23772.3**	**2854.66**	**1.1365**	26.9	**28.0**	**0.88816**
Pc	**244.7171**	column														
ry	1.51	Siding	90	Pe1x	EI/(KL)^2 AISC A-8-5											
rx	5.17	Live Loads		B1x	Cm/1-α(Pr/Pex) A-8-3											
kly/ry	**70.17219**			Δ_{oh}	Story Drift from RISA Model											
klx/rx	**20.49516**			Pestory	Rm(HL/ΔH) A-8-7											
J	0.3			pstory	Totol factored axial load for entire story											
rts	1.75	Input For Revit File		B2	1/(1-(Pestory/Pstory)) A-8-6											
ho	11.8	DL klf	0.14545	Mlt	Moment from lateral force											
Sx	33.4	LL Klf	0.1125	Mu	Moment from gavity Load											
Fcr	31.98917	Earthquake Load (k)	101.732983	H1-1a	Pr/Pc +8/9(Mr/Mc)											
Mc	121	Wind Load (klf)	0.45	H1-1b	Pr/2Pc + Mr/Mc											
b/t	17.48	Wind Load Sory shear	91.8													

W14x30		Tributary Area		Load Combination												
L	20	Roof /Floor	Siding	*(1.2 + 0.2SDS)D + 1.0E +0.2S*												
Lb(ltb)	5	530		Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δ_{oh}	Pestory	pstory	B2	Mlt	Mu	H1-1b
Lb(elb)	20	Loads	plf	52.6791	110.4	**0.15**	0.99	**1445**	**1.0227**	0.797	**32346.4**	**1645.06**	**1.0536**	6.7	**119.97**	**0.949293**
E	29000	Snow Load (psf)	927.5	1.2D + 1.6S + .8W												
A	8.85	Dead Loads		Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δ_{oh}	Pestory	pstory	B2	Mlt	Mu	H1-1a
Ix	291	Roof Deck	47.17	73.4172	71.42321	**0.21**	0.98	**1445**	**1.0321**	0.313	**62108.6**	**7289.86**	**1.133**	6.9	**78.3**	**0.71691**
Iy	19.6	Girder	30	1.2D + .5S + 1.6W												
Lp	5.26	4.5 30 k 12 joists	90	Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δ_{oh}	Pestory	pstory	B2	Mlt	Mu	H1-1a
Lr	14.9	MEP	132.5	148.833	31.25	**0.425**	0.96	**1445**	**1.0689**	0.88	**22090.9**	**2854.66**	**1.1484**	79.0	**80.2**	**0.944322**
Pc	**350.0306**	column														
ry	1.49	Siding	90	Pe1x	EI/(KL)^2 AISC A-8-5											
rx	5.73	Live Loads		B1x	Cm/1-α(Pr/Pex) A-8-3											
kly/ry	**40.26846**			Δ_{oh}	Story Drift from RISA Model											
klx/rx	**41.88482**			Pestory	Rm(HL/ΔH) A-8-7											
J	0.38			pstory	Totol factored axial load for entire story											
rts	1.77	Input For Revit File		B2	1/(1-(Pestory/Pstory)) A-8-6											
ho	13.4	DL klf	0.38967	Mlt	Moment from lateral force											
Sx	42	LL Klf	0.9275	Mu	Moment from gavity Load											
Fcr	39.55148	Earthquake Load (k)	107.349469	H1-1a	Pr/Pc +8/9(Mr/Mc)											
Mc	137.2541	Wind Load (klf)	0.34	H1-1b	Pr/2Pc + Mr/Mc											
b/t	17.48	Wind Load Sory shear	81													

W21x44		Tributary Area		Load Combination												
L	53	Roof /Floor	Siding	*(1.2 + 0.2SDS)D + 1.0E +0.2S*												
Lb(ltb)	8.83	159		Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δ_{oh}	Pestory	pstory	B2	Mlt	Mu	H1-1b
Lb(elb)	8.83	Loads	plf	51.0305	28.1	0.134	0.97	595.9	1.0562	0.797	81464.5	1645.06	1.0206	2.8	32.487	0.184948
E	29000	Snow Load (psf)	112.5	1.2D + 1.6S + .8W												
A	13	Dead Loads		Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δ_{oh}	Pestory	pstory	B2	Mlt	Mu	H1-1a
Ix	843	Roof Deck	4.45	79.7147	74.47564	0.209	0.95	595.9	1.0927	0.613	84039.2	7289.86	1.095	4.0	78.5	0.389846
Iy	20.7	Girder	44	1.2D + .5S + 1.6W												
Lp	6.25	4.5 30 k 12 joists		Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δ_{oh}	Pestory	pstory	B2	Mlt	Mu	H1-1a
Lr	14.9	MEP	25	156.231	46.39295	0.409	0.90	595.9	1.2132	1.228	41951.1	2854.66	1.073	7.9	54.3	0.584597
Pc	381.8774	column														
ry	1.26	Siding		Pe1x	EI/(KL)^2 AISC A-8-5											
rx	8.06	Live Loads		B1x	Cm/1-α(Pr/Pex) A-8-3											
kly/ry	84.09524			Δ_{oh}	Story Drift from RISA Model											
klx/rx	13.1464			Pestory	Rm(HL/ΔH) A-8-7											
J	0.77			pstory	Totol factored axial load for entire story											
rts	1.6	Input For Revit File		B2	1/(1-(Pestory/Pstory)) A-8-6											
ho	20.3	DL klf	0.07345	Mlt	Moment from lateral force											
Sx	81.6	LL Klf	0.1125	Mu	Moment from gavity Load											
Fcr	29.37518	Earthquake Load (k)	102.022764	H1-1a	Pr/Pc +8/9(Mr/Mc)											
Mc	275	Wind Load (klf)	0.34	H1-1b	Pr/2Pc + Mr/Mc											
b/t	14.44	Wind Load Sory shear	81													

W21x62		Tributary Area		Load Combination						
L	40	Roof /Floor	Siding	*(1.2 + 0.2SDS)D + 1.0E +0.2S*						
Lb(ltb)	5	1060		Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δ_{oh}
Lb(elb)	20	Loads	plf	51.223	26.9	**0.061**	1.00	**6602**	**1.0047**	0.7
E	29000	Snow Load (psf)	927.5	1.2D + 1.6S + .8W						
A	18.3	Dead Loads		Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δ_{oh}
Ix	1330	Roof Deck	47.17	73.215	80.96109	**0.087**	1.00	**6602**	**1.0067**	0.6
Iy	18.1	Girder	62	1.2D + .5S + 1.6W						
Lp	6.25	4.5 30 k 12 joists	90	Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δ_{oh}
Lr	14.9	MEP	132.5	142.443	41.36007	**0.169**	0.99	**6602**	**1.0132**	1.2
Pc	**843.7035**	column								
ry	1.77	Siding	90	Pe1x	EI/(KL)^2 AISC A-8-5					
rx	8.54	Live Loads		B1x	Cm/1-α(Pr/Pex) A-8-3					
kly/ry	**33.89831**			Δ_{oh}	Story Drift from RISA Model					
klx/rx	**28.10304**			Pestory	Rm(HL/ΔH) A-8-7					
J	1.83			pstory	Totol factored axial load for entire story					
rts	1.75	Input For Revit File		B2	1/(1-(Pestory/Pstory)) A-8-6					
ho	20.4	DL klf	0.42167	Mlt	Moment from lateral force					
Sx	127	LL Klf	0.9275	Mu	Moment from gavity Load					
Fcr	46.10402	Earthquake Load (k)	114.326841	H1-1a	Pr/Pc +8/9(Mr/Mc)					
Mc	283.5	Wind Load (klf)	0.34	H1-1b	Pr/2Pc + Mr/Mc					
b/t	13.4	Wind Load Sory shear	81							
Out Of Plane (y)			In Plane X							
Q E7-4	**13.48659**	*>b/t*	Q E7-4	**13.4866**	*>b/t*					
Q E7-5	**24.80568**	*>b/t*	Q E7-5	**24.8057**	*>b/t*					
Q	**1.003261**		Q	**1.00326**						
E7-2	**113.6166**	*<KL/r*	E7-2	**113.617**	*<KL/r*					
E3-3Fcr	**46.10402**		E3-3 Fcr	**47.3366**						
E3-4Fe	**248.8292**		E3-4 Fe	**362.035**						

Renovation Calculations

Flexure Design

DESIGN FOR BENDING STRENGTH

Span 53X40

Scheme 1

DATA INPUT

# OF BEAMS	8	-
LENGTH	53	ft
WIDTH	5	ft
DEAD LOAD	73	psf
LIVE LOAD	60	psf

CALCULATIONS FOR THE BEAM

DEAD LOAD	365	lbs/ft	
LIVE LOAD	300	lbs/ft	
LOAD COMBINATION EQUATIONS:			
1.4D	365	lbs/ft	
1.2D+1.6L	918	lbs/ft	
MOMENT CALCULATION:			
M_u	322.33275	ft*kips	
DESIGN EQUATION:			
Z_x	85.9554	in^3	
Value from the table			
	62	lbs/ft	W24X62
UPDATED W_u			
W_u	992.4	lbs/ft	
UPDATED M_u			
M_u	348.45645	ft*kips	
UPDATED Z_x			
Z_x	92.92172	in^3	
Ix	1550	in^4	
New value from the table			
	62		W24X62
DEFLECTION			
			LIMITS
Deflection .5LL			
w(.5LL)	150	lb/ft	
Δ(0.5LL)	0.59244435		1.766666667
Deflection .5LL+D			
w(D)	427	lb/ft	
Δ(D)	1.68649157		
Δ(0.5LL)+Δ(D)	2.27893592		2.65

CALCULATIONS FOR THE GIRDER

Length	40	ft		
Width	53	psf		
UPDATED DEAD LOAD FOR GIRDER				
WU				
	10519.44	lbs/ft		
MOMENT CALCULATION:				
M_u	2103.888	ft*kips		
DESIGN EQUATION:				
Z_x	561.0368	in^3		
Value from the table				
	141	lbs/ft		W33X141
UPDATED W_u				
	10688.64			
UPDATED M_u				
	2137.728			
Ix	7450			
Total Uniform Load				
	427.5456	Kips		
DEFLECTION				
				LIMITS
Deflection .5LL				
w(.5LL)	1590	lb/ft		
Δ(0.5LL)	0.42390187			1.33333333
Deflection .5LL+D				
w(D)	4667.2	lb/ft		
Δ(D)	1.24429863			
Δ(0.5LL)+Δ(D)	1.66820051			2

DESIGN FOR BENDING STRENGTH

Span 53x40

Scheme 2

DATA INPUT

# OF BEAMS	3	-
LENGTH	53	ft
WIDTH	5	ft
DEAD LOAD	58	psf
LIVE LOAD	80	psf

CALCULATIONS FOR THE BEAM

DEAD LOAD	290	lbs/ft	
LIVE LOAD	400	lbs/ft	
LOAD COMBINATION EQUATIONS:			
1.4D	290	lbs/ft	
1.2D+1.6L	988	lbs/ft	
MOMENT CALCULATION:			
M_u	346.9115	ft*kips	
DESIGN EQUATION:			
Z_x	92.5097333	in^3	
Value from the table			
	62	lbs/ft	W14X22
UPDATED W_u			
W_u	1062.4	lbs/ft	56.3072 K
UPDATED M_u			
M_u	373.0352	ft*kips	
UPDATED Z_x			
Z_x	99.4760533	in^3	
Ix	1330	in^4	
New value from the table			
	62		W24X62
DEFLECTION			
			LIMITS
Deflection .5LL			
w(.5LL)	200	lb/ft	
Δ(0.5LL)	0.92059021		1.766666667
Deflection .5LL+D			
w(D)	352	lb/ft	
Δ(D)	1.62023877		
Δ(0.5LL)+Δ(D)	2.54082899		2.65

CALCULATIONS FOR THE GIRDER

Length	15	ft	
Width	14.5	psf	
UPDATED DEAD LOAD FOR GIRDER			
WU			
	3080.96	lbs/ft	
MOMENT CALCULATION:			
M_u	86.652	ft*kips	
DESIGN EQUATION:			
Z_x	23.1072	in^3	
Value from the table			
	62	lbs/ft	W24X62
UPDATED W_u			
	3155.36		
UPDATED M_u			
	88.7445		
Zx	23.6652		
Ix	1550		
Total Uniform Load			
	47.3304	Kips	
DEFLECTION			
			LIMITS
Deflection .5LL			
w(.5LL)	580	lb/ft	
Δ(0.5LL)	0.01469758		0.5
Deflection .5LL+D			
w(D)	1082.8	lb/ft	
Δ(D)	0.02743886		
Δ(0.5LL)+Δ(D)	0.04213644		0.75

DESIGN FOR BENDING STRENGTH

Span 40x41

DATA INPUT

# OF BEAMS	8	-
LENGTH	53	ft
WIDTH	5	ft
DEAD LOAD	73	psf
LIVE LOAD	60	psf

CALCULATIONS FOR THE BEAM

DEAD LOAD	365	lbs/ft	
LIVE LOAD	300	lbs/ft	
LOAD COMBINATION EQUATIONS:			
1.4D	365	lbs/ft	
1.2D+1.6L	918	lbs/ft	
MOMENT CALCULATION:			
M_u	322.33275	ft*kips	
DESIGN EQUATION:			
Z_x	85.9554	in^3	
Value from the table			
	62	lbs/ft	W24X62
UPDATED W_u			
W_u	992.4	lbs/ft	
UPDATED M_u			
M_u	348.45645	ft*kips	
UPDATED Z_x			
Z_x	92.92172	in^3	
Ix	1550	in^4	
New value from the table			
	62		W24X62
DEFLECTION			
			LIMITS
Deflection .5LL			
w(.5LL)	150	lb/ft	
Δ(0.5LL)	0.59244435		1.766666667
Deflection .5LL+D			
w(D)	427	lb/ft	
Δ(D)	1.68649157		
Δ(0.5LL)+Δ(D)	2.27893592		2.65

CALCULATIONS FOR THE GIRDER

Length	39	ft	
Width	40	ft	
UPDATED DEAD LOAD FOR GIRDER			
WU			
	8142.76923	lbs/ft	
MOMENT CALCULATION:			
M_u	1548.144	ft*kips	
DESIGN EQUATION:			
Z_x	412.8384	in^3	
Value from the table			
	116	lbs/ft	W16X40
UPDATED W_u			
	8281.96923		
UPDATED M_u			
	1574.6094		
Ix	4930		
DEFLECTION			
			LIMITS
Deflection .5LL			
w(.5LL)	1200	psf	
Δ(0.5LL)	0.4368952		1.33333333
Deflection .5LL+D			
w(D)	3544.71795	psf	
Δ(D)	1.29055855		
Δ(0.5LL)+Δ(D)	1.72745375		1.95

DESIGN FOR BENDING STRENGTH

Span 29x40

Scheme 1

DATA INPUT

# OF BEAMS	8	-
LENGTH	29	ft
WIDTH	5	ft
DEAD LOAD	73	psf
LIVE LOAD	42.2	psf

CALCULATIONS FOR THE BEAM

DEAD LOAD	365	lbs/ft		
LIVE LOAD	211	lbs/ft		
LOAD COMBINATION EQUATIONS:				
1.4D	365	lbs/ft		
1.2D+1.6L	775.6	lbs/ft		
MOMENT CALCULATION:				
M_u	81.53495	ft*kips		
DESIGN EQUATION:				
Z_x	21.7426533	in^3		
Value from the table				
	22	lbs/ft	W14X22	
UPDATED W_u				
W_u	802	lbs/ft	23.258	K
UPDATED M_u				
M_u	84.31025	ft*kips		
UPDATED Z_x				
Z_x	22.4827333	in^3		
Ix	199	in^4		
New value from the table				
	22		W14X22	
DEFLECTION				
			LIMITS	
Deflection .5LL				
w(.5LL)	105.5	lb/ft		
Δ(0.5LL)	0.29092155		0.966666667	
Deflection .5LL+D				
w(D)	387	lb/ft		
Δ(D)	1.06717195			
Δ(0.5LL)+Δ(D)	1.3580935		1.45	

CALCULATIONS FOR THE GIRDER

Length	40	ft		
Width	14.5	psf		
UPDATED DEAD LOAD FOR GIRDER				
WU				
	2325.8	lbs/ft		
MOMENT CALCULATION:				
M_u	465.16	ft*kips		
DESIGN EQUATION:				
Z_x	124.042667	in^3		
Value from the table				
	62	lbs/ft		W24X62
UPDATED W_u				
	2400.2			
UPDATED M_u				
	480.04			
Zx	128.010667			
Ix	1550			
Total Uniform Load				
	96.008	Kips		
DEFLECTION				
				LIMITS
Deflection .5LL				
w(.5LL)	305.95	lb/ft		
Δ(0.5LL)	0.39205161			1.33333333
Deflection .5LL+D				
w(D)	1184.3	lb/ft		
Δ(D)	1.51759021			
Δ(0.5LL)+Δ(D)	1.90964182			2

DESIGN FOR BENDING STRENGTH

Stair Case 11x6

Scheme 1

DATA INPUT

# OF BEAMS	2	-
LENGTH	6	ft
WIDTH	5	ft
DEAD LOAD	70	psf
LIVE LOAD	40	psf

CALCULATIONS FOR THE BEAM

DEAD LOAD	350	lbs/ft		
LIVE LOAD	200	lbs/ft		
LOAD COMBINATION EQUATIONS:				
1.4D	350	lbs/ft		
1.2D+1.6L	740	lbs/ft		
MOMENT CALCULATION:				
M_u	3.33	ft*kips		
DESIGN EQUATION:				
Z_x	0.888	in^3		
Value from the table				
	10	lbs/ft	W8x10	
UPDATED W_u				
W_u	752	lbs/ft		
UPDATED M_u				
M_u	3.384	ft*kips		
UPDATED Z_x				
Z_x	0.9024	in^3		
Ix	30.8	in^4		
New value from the table				
	62		W24X62	
DEFLECTION				
			LIMITS	
Deflection .5LL				
w(.5LL)	100	lb/ft		
Δ(0.5LL)	0.00326467			0.2
Deflection .5LL+D				
w(D)	360	lb/ft		
Δ(D)	0.0117528			
Δ(0.5LL)+Δ(D)	0.01501747			0.3

CALCULATIONS FOR THE GIRDER

Length	10	ft		
Width	3	ft		
UPDATED DEAD LOAD FOR GIRDER				
WU				
	451.2	lbs/ft		
MOMENT CALCULATION:				
M_u	5.64	ft*kips		
DESIGN EQUATION:				
Z_x	1.504	in^3		
Value from the table				
	141	lbs/ft		W33X141
UPDATED W_u				
	620.4			
UPDATED M_u				
	7.755			
Ix	7450			
Total Uniform Load				
	6.204	Kips		
DEFLECTION				
				LIMITS
Deflection .5LL				
w(.5LL)	60	lb/ft		
Δ(0.5LL)	6.2486E-05			0.33333333
Deflection .5LL+D				
w(D)	357	lb/ft		
Δ(D)	0.00037179			
Δ(0.5LL)+Δ(D)	0.00043427			0.5

DESIGN FOR BENDING STRENGTH

Span 29x40

Scheme 2

DATA INPUT

# OF BEAMS	8	-
LENGTH	29	ft
WIDTH	5	ft
DEAD LOAD	70	psf
LIVE LOAD	60	psf

CALCULATIONS FOR THE BEAM

DEAD LOAD	350	lbs/ft		
LIVE LOAD	300	lbs/ft		
LOAD COMBINATION EQUATIONS:				
1.4D	350	lbs/ft		
1.2D+1.6L	900	lbs/ft		
MOMENT CALCULATION:				
M_u	94.6125	ft*kips		
DESIGN EQUATION:				
Z_x	25.23	in^3		
Value from the table				
	26	lbs/ft	W14X26	
UPDATED W_u				
W_u	931.2	lbs/ft	27.0048	K
UPDATED M_u				
M_u	97.8924	ft*kips		
UPDATED Z_x				
Z_x	26.10464	in^3		
Deflection .5LL+D				
w(D)	376	lb/ft		
Δ(D)	1.01142618			
Δ(0.5LL)+Δ(D)	1.41492066		1.45	

CALCULATIONS FOR THE GIRDER

Length	40	ft	
Width	14.5	psf	
UPDATED DEAD LOAD FOR GIRDER			
WU			
	2700.48	lbs/ft	
MOMENT CALCULATION:			
M_u	540.096	ft*kips	
DESIGN EQUATION:			
Z_x	144.0256	in^3	
Value from the table			
	68	lbs/ft	W24X68
UPDATED W_u			
	2782.08		
UPDATED M_u			
	556.416		
Zx	148.3776		
Ix	1830		
.5LL+D			
w(D)	1158.4	lb/ft	
Δ(D)	1.25727982		
Δ(0.5LL)+Δ(D)	1.72941097		2

Lateral Loading Calculations

Earth Quake Story Shear

Section A

Class II	Ie	1.25	
	R	3.25	
	Cd	3.25	
	Ω	2	
	SDS	0.181	
	SD1	0.112	
	Ta	0.256	seconds
Adjusted T=CuTa	T	0.4224	
	T0	0.123757	
	Ts	0.618785	
Cs=(SDS/(R/Ie)	Cs	0.069615	
Cs=SD1/(T(R/I)	Cs max	0.101981	
Base Shear	V	779.9956	
	k	1	

Level	Wx	hx	Wxhx^k	Cvx	Fx	Vx
Roof	1723.08	30	51692.4	0.280282	218.6184	218.6184
2nd	9481.276	14	132737.9	0.719718	561.3772	779.9956
SUM	11204.36	_	184430.3		779.9956	

Section B

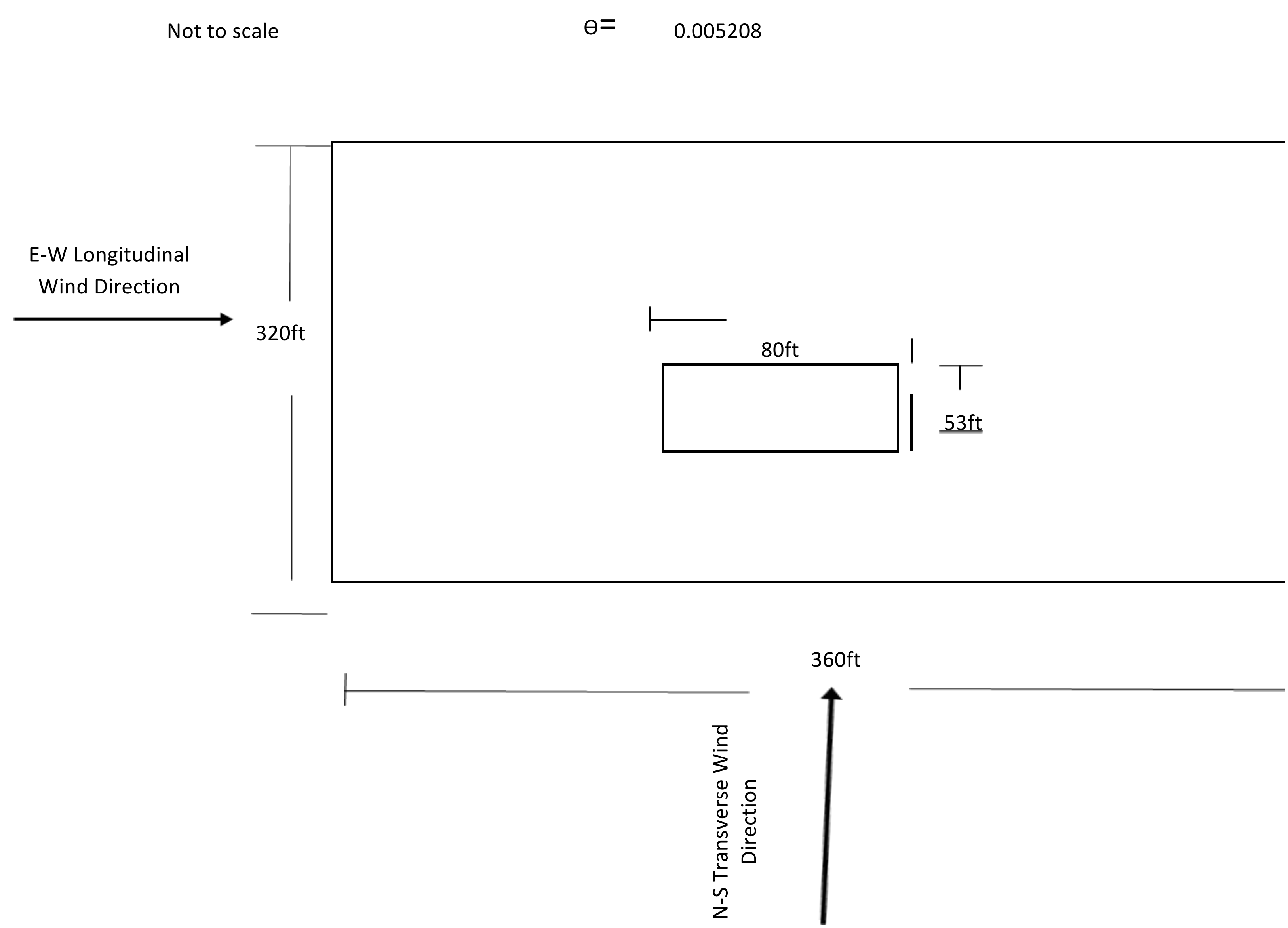
Level	Wx	hx	Wxhx^k	Cvx	Fx	Vx
Roof	1195.782	30	35873.46	0.247197	154.8642	154.8642
2nd	7803.411	14	109247.8	0.752803	471.6181	626.4823
SUM	8999.193	_	145121.2		626.4823	

Wind Loads

WIND LOADING DIRECTIONAL PROCEDURE

Wind Velocity	120	mph			
Building Risk Category	II				
Structure Type	MWFRS				
K_d	0.85	TABLE 26.6-1			
Exposure Category	B	SEC 26.7.3			
Total Wall Height	30	ft			
Mean Roof Height	30	ft			
α	7	TABLE 26.9-1	Hill Dimensions Via Google Maps		
Zg	1200	TABLE 26.9-1		N-S	E-W
K1	0.95	FIGURE 26.8-2	Lh	475	420
K2	0.777778	FIGURE 26.8-1	H1	10	15
K3	0.866878	FIGURE 26.8-0	H2	10	10
K_{zt}	1	FIGURE 26.8-1	H/Lh<.2		
G	0.85				
Gcpi	0.18	Table 26.11			
Kz 0-15	0.57	Table 27.3-1			
20	0.62	Table 27.3-2			
25	0.66	Table 27.3-3			
30	0.7	Table 27.3-4			
K_z	0.700591				
K_h	0.7				
q_z(0-15)	17.86061	$q=0.00256K_zK_{zt}K_dV^2$ (lb/ft^2)			
q_z(20)	19.42733				
q_z(25)	20.6807				
q_z(30)	21.93408				
q_h	21.93408				

Building Dimensions



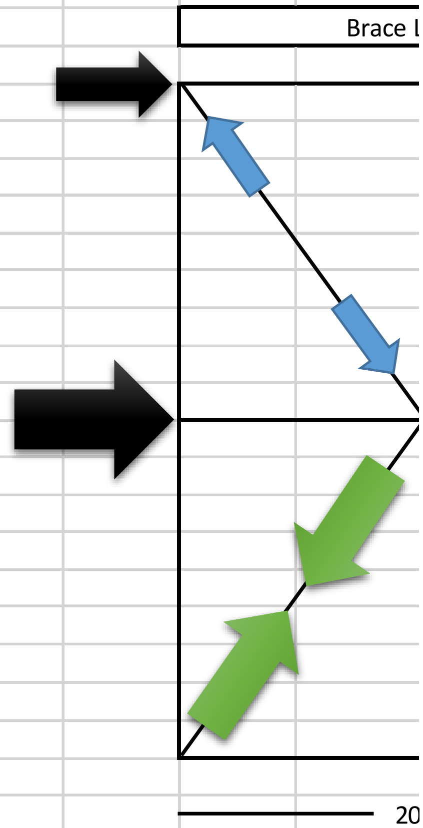
Longitudinal Direction		Sec 26.9.4							
		Area (ft^2)	q (psf)	q_i	G	Long. C_p	Trans. C_p	GC_{pi} (+)	G
Windward Wall	0'-15'	4800	17.8606	21.9	0.85	0.8	0.8	0.18	-
	15'-20'	1600	19.4273	21.9	0.85	0.8	0.8	0.18	-
	20'-25'	1600	20.6807	21.9	0.85	0.8	0.8	0.18	-
	25'-30'	1600	21.9341	21.9	0.85	0.8	0.8	0.18	-
Leeward Wall	0'-15'	4800	17.8606	21.9	0.85	-0.5	-0.3	0.18	-
	15'-20'	1600	19.4273	21.9	0.85	-0.5	-0.3	0.18	-
	20'-25'	1600	20.6807	21.9	0.85	-0.5	-0.3	0.18	-
	25'-30'	1600	21.9341	21.9	0.85	-0.5	-0.3	0.18	-

Transverse Direction		Sec 26.9.4							
		Area (ft^2)	q (psf)	q_i	G	Long. C_p	Trans. C_p	GC_{pi} (+)	G
Windward Wall	0'-15'	5400	17.8606	21.9	0.85	0.8	0.8	0.18	-
	15'-20'	1800	19.4273	21.9	0.85	0.8	0.8	0.18	-
	20'-25'	1800	20.6807	21.9	0.85	0.8	0.8	0.18	-
	25'-30'	1800	21.9341	21.9	0.85	0.8	0.8	0.18	-
Leeward Wall	0'-15'	5400	17.8606	21.9	0.85	-0.5	-0.3	0.18	-
	15'-20'	1800	19.4273	21.9	0.85	-0.5	-0.3	0.18	-
	20'-25'	1800	20.6807	21.9	0.85	-0.5	-0.3	0.18	-
	25'-30'	1800	21.9341	21.9	0.85	-0.5	-0.3	0.18	-

Diaphragm Brace Design

Frame 1

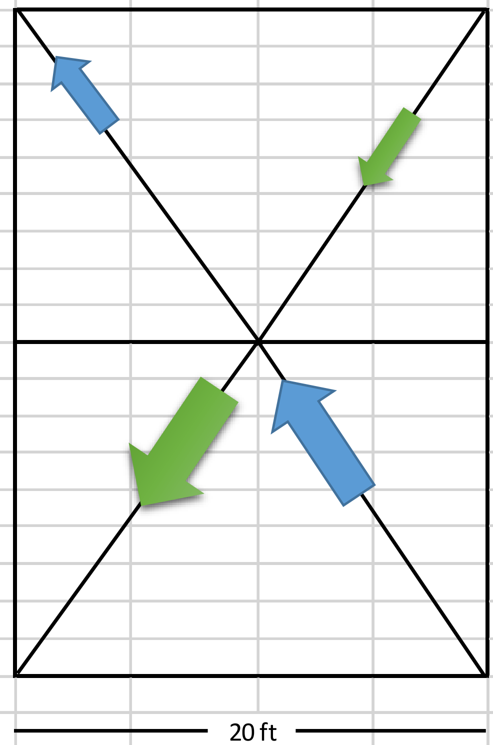
Brace Design								
Frame 1 Brace 2								Forces Taken From RISA Model
Factored Compressive Forces				Factored Tensile Forces				
Top Brace								
D	L	E	W	D	L	E	W	
0	0	108	16.7	0	0	81.1	14.2	
(1.2 + 0.2SDS)D + 1.0E +0.2S + L				(1.2 + 0.2SDS)D + 1.0E +0.2S + L				
P_u (k)		108		T_u (k) =		81.1		
1.2D + 1.6S or L + .5W				1.2D + 1.6S or L + .5W				
P_u (k)=		13.36		T_u (k) =		11.36		
1.2D + .5S or L + 1.6W				1.2D + .5S or L + 1.6W				
P_u (k)=		26.72		T_u (k) =		22.72		
Bottom Brace								
D	L	E	W	D	L	E	W	
2.2	2.2	332	29.4	-2.5	-2.5	302	26.4	
(1.2 + 0.2SDS)D + 1.0E +0.2S or L				(1.2 + 0.2SDS)D + 1.0E +0.2S or L				
P_u (k)=		338.16		T_u (k) =		295		
1.2D + 1.6S or L + .8W				1.2D + 1.6S or L + .8W				
P_u (k)=		29.68		T_u (k) =		21.12		
1.2D + .5S or L + 1.6W				1.2D + .5S or L + 1.6W				
P_u (k)=		50.78		T_u (k) =		42.24		
Member Properties								
Top Brace				Bottom Brace				
Horizontal Length=		10	ft	Horizontal Length=		26.5	ft	
Vertical Length=		15	ft	Vertical Length=		15	ft	
Θ		0.9827937	radians	Θ		0.515073	radians	
Brace Legth L=		18.027756	ft	Brace Legth L=		30.45078	ft	
P_u=		108	k	P_u=		338.16	k	
T_u=		81.1	k	T_u=		295	k	
Member Selection		HSS 6x6x1/4		Member Selection		HSS 8x8x1/2		
A_g		5.24	in^2	A_g		13.5	in^2	AISC SM Tbl 1-12
F_y		46	ksi	F_y		46	ksi	
AISC Tbl 4-4		AISC Tbl 5-5		AISC Tbl 4-4		AISC Tbl 5-5		
ΦP_n (k) =	122	ΦT_n (k) =	217	ΦP_n (k) =	398	ΦT_n (k) =	559	
Brace Reactions to Beam								
Top Brace				Bottom Brace				
R_y		1.4		R_y		1.4		AISC 341-10 Tbl A3.1
P_t=		337.456	k	P_t=		869.4	k	($P_t=R_yF_yA_g$) AISC 341-10 F1.4.4.a(1)(i)(a)
Load Effect T_u=		81.1	k	Load Effect T_u=		295	k	Frame A RISA EQ
$T_u=P_t$=		81.1	k	$T_u=P_t$=		295	k	
P_{tx}		44.986186	k	P_{tx}		256.7258	k	Pt*cos(Θ)



Forces Taken From RISA Model

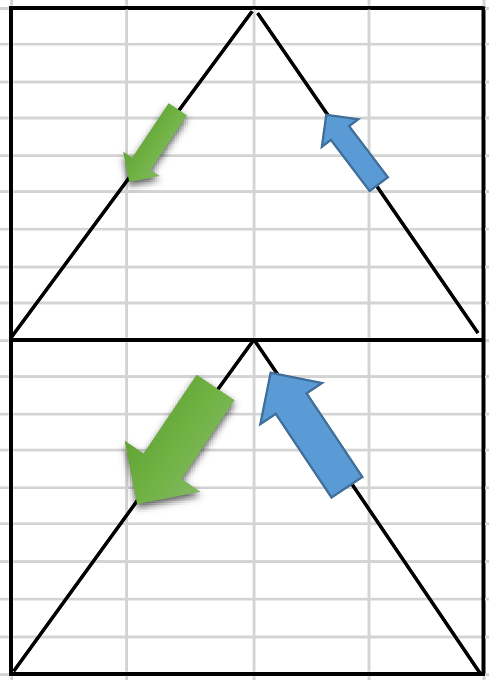
Brace Design							
Frame A							
tored Compressive Forces			**Factored Tensile Forces**				
Top Brace							
L	**E**	**W**	**D**	**L**	**E**	**W**	
8.8	68.8	16.7	0	0	44.6	14.2	
+ 0.2SDS)D + 1.0E +0.2S or L			**(1.2 + 0.2SDS)D + 1.0E +0.2S or L**				
(k)	71.1		**T_u (k) =**		74.6		
1.2D + 1.6S or L + .8W			**1.2D + 1.6S or L + .8W**				
(k)=	32.72		**T_u (k) =**		11.36		
1.2D + .5S or L + 1.6W			**1.2D + .5S or L + 1.6W**				
(k)=	36.4		**T_u (k) =**		22.72		
Bottom Brace							
L	**E**	**W**	**D**	**L**	**E**	**W**	
15.46	225	29.4	0	0	224.6	26.4	
+ 0.2SDS)D + 1.0E +0.2S or L			**(1.2 + 0.2SDS)D + 1.0E +0.2S or L**				
(k)=	233		**T_u (k) =**		236		
1.2D + 1.6S or L + .8W			**1.2D + 1.6S or L + .8W**				
(k)=	62.944		**T_u (k) =**		21.12		
1.2D + .5S or L + 1.6W			**1.2D + .5S or L + 1.6W**				
(k)=	69.458		**T_u (k) =**		42.24		
Member Properties							
Top Brace			**Bottom Brace**				
al Length=	10	**ft**	**Horizontal Length=**	10	**ft**		
Length=	15	**ft**	**Vertical Length=**	15	**ft**		
Θ	0.9827937	radians	Θ	0.982794	radians		
egth L=	18.027756	**ft**	**Brace Legth L=**	18.02776	**ft**		
u=	71.1	**k**	**P_u=**	233	**k**		
u=	74.6	**k**	**T_u=**	236	**k**		
Selection	**HSS 6x6x3/16**		**Member Selection**	**HSS 8x8x5/16**			
g	3.98	**in^2**	A_g	7.1	**in^2**	AISC SM Tbl 1-12	
y	46	**ksi**	F_y	46	**ksi**		
bl 4-4	**AISC Tbl 5-5**		**AISC Tbl 4-4**		**AISC Tbl 5-5**		
94.2	**ΦT_n (k) =**	165	**ΦP_n (k) =**	254	**ΦT_n (k) =**	363	
Brace Reactions to Beam							
Top Brace			Bottom Brace				
y	1.4		Ry	1.4		AISC 341-10 Tbl A3.1	
t=	256.312	k	P_t=	457.24	k	($P_t=R_yF_yA_g$) AISC 341-10 F1.4.4.a(1)(i)(a)	
fect Tu=	71.1	k	Load Effect Tu=	236	k	Frame A RISA EQ	
Pt=	71.1	k	Tu=Pt=	236	k		
tx	39.439184	k	P_{tx}	130.9092	k	Pt*cos(Θ)	
ty	59.158776	k	P_{ty}	196.3639	k	Pt*sin(Θ)	
.3Pu	21.33	k	P_c=.3P_u	69.9	k	F1.4.4a(1)(ii)	
cx	11.831755	k	P_{cx}	38.77354	k	Pc*cos(Θ)	
cy	17.747633	k	P_{cy}	58.16032	k	Pc*sin(Θ)	

Brace Layout



Forces Taken From RISA Model

Brace Layout



53 ft

Brace Design							
Frame 10							
tored Compressive Forces			**Factored Tensile Forces**				
Top Brace							
L	**E**	**W**	**D**	**L**	**E**	**W**	
3.8	64	16.7	-2.4	3.8	63	14.2	
+ 0.2SDS)D + 1.0E +0.2S + L			**(1.2 + 0.2SDS)D + 1.0E +0.2S + L**				
(k)	68.12		**Tu (k) =**		58.88		
1.2D + 1.6S or L + .5W			**1.2D + 1.6S or L + .5W**				
(k)=	22.32		**Tu (k) =**		11.36		
1.2D + .5S or L + 1.6W			**1.2D + .5S or L + 1.6W**				
(k)=	31.5		**Tu (k) =**		22.72		
Bottom Brace							
L	**E**	**W**	**D**	**L**	**E**	**W**	
6.1	220	29.4	-7.6	-6.1	220	26.4	
+ 0.2SDS)D + 1.0E +0.2S + L			**(1.2 + 0.2SDS)D + 1.0E +0.2S + L**				
(k)=	236.74		**Tu (k) =**		203.26		
1.2D + 1.6S or L + .8W			**1.2D + 1.6S or L + .8W**				
(k)=	42.4		**Tu (k) =**		21.12		
1.2D + .5S or L + 1.6W			**1.2D + .5S or L + 1.6W**				
(k)=	59.21		**Tu (k) =**		42.24		
Member Properties							
Top Brace			**Bottom Brace**				
al Length=	26.5	**ft**	**Horizontal Length=**	26.5	**ft**		
Length=	15	**ft**	**Vertical Length=**	15	**ft**		
ϴ	0.5150728	radians	ϴ	0.515073	radians		
egth L=	30.45078	**ft**	**Brace Legth L=**	30.45078	**ft**		
u=	68.12	**k**	**Pu=**	236.74	**k**		
u=	58.88	**k**	**Tu=**	203.26	**k**		
Selection	**HSS 7x7x1/2**		**Member Selection**	**HSS 9x9x5/8**			
Ag	11.6	**in^2**	Ag	15.3	**in^2**	AISC SM Tbl 1-12	
Fy	46	**ksi**	Fy	46	**ksi**		
bl 4-4	**AISC Tbl 5-5**		**AISC Tbl 4-4**	**AISC Tbl 5-5**			
140	**ΦTn (k) =**	480	**ΦPn (k) =**	364	**ΦTn (k) =**	774	
Brace Reactions to Beam							
Top Brace			Bottom Brace				
y	1.4		Ry	1.4		AISC 341-10 Tbl A3.1	
t=	747.04	k	Pt=	985.32	k	(Pt=RyFyAg) AISC 341-10 F1.4.4.a(1)(i)(a)	
fect Tu=	68.12	k	Load Effect Tu=	203.26	k	Frame A RISA EQ	
Pt=	68.12	k	Tu=Pt=	203.26	k		
tx	59.281897	k	Ptx	176.8884	k	Pt*cos(ϴ)	
ty	33.555791	k	Pty	100.1255	k	Pt*sin(ϴ)	
.3Pc	46.666667	k	Pc=.3Pu	121.3333	k	F1.4.4a(1)(ii)	
cx	40.611987	k	Pcx	105.5912	k	Pc*cos(ϴ)	
cy	22.987917	k	Pcy	59.76858	k	Pc*sin(ϴ)	

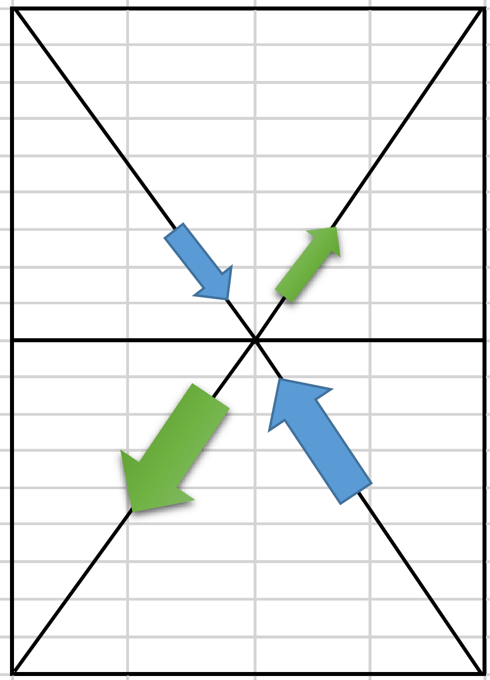
ce 1

Forces Taken From RISA Model

Frame G Brace 1						
tored Compressive Forces			Factored Tensile Forces			
Top Brace						
L	E	W	D	L	E	W
4.9	34	16.7	-0.8	-4.9	38	14.2
+ 0.2SDS)D + 1.0E +0.2S + L			(1.2 + 0.2SDS)D + 1.0E +0.2S + L			
(k)	36.1		T_u (k) =		35.9	
1.2D + 1.6S or L + .5W			1.2D + 1.6S or L + .5W			
(k)=	22.16		T_u (k) =		11.36	
1.2D + .5S + L + 1.6W			1.2D + .5S + L + 1.6W			
(k)=	30.13		T_u (k) =		22.72	
Bottom Brace						
L	E	W	D	L	E	W
11.8	153.6	29.4	-8.2	-11.8	157	26.4
+ 0.2SDS)D + 1.0E +0.2S or L			(1.2 + 0.2SDS)D + 1.0E +0.2S or L			
(k)=	176.88		T_u (k) =		133.72	
1.2D + 1.6S or L + .8W			1.2D + 1.6S or L + .8W			
(k)=	52.24		T_u (k) =		21.12	
1.2D + .5S or L + 1.6W			1.2D + .5S or L + 1.6W			
(k)=	62.78		T_u (k) =		42.24	
Member Properties						
Top Brace			Bottom Brace			
al Length=	10	ft	Horizontal Length=		10	ft
Length=	15	ft	Vertical Length=		15	ft
ϴ	0.9827937	radians	ϴ		0.982794	radians
egth L=	18.027756	ft	Brace Legth L=		18.02776	ft
u=	36.1	k	P_u=		176.88	k
u=	35.9	k	T_u=		133.72	k
Selection	HSS 4x4x1/2		Member Selection		HSS 7x7x1/2	
Ag	6.02	in^2	A_g		6.17	in^2
Fy	46	ksi	F_y		46	ksi
bl 4-4	AISC Tbl 5-5		AISC Tbl 4-4		AISC Tbl 5-5	
58	ΦT_n (k) =	136	ΦP_n (k) =	305	ΦT_n (k) =	480

AISC SM Tbl 1-12

Brace Layout



20 ft

Top Brace			Bottom Brace				
y	1.4		Ry	1.4		AISC 341-10 Tbl A3.1	
t=	387.688	k	P_t=	397.348	k	($P_t=R_yF_yA_g$) AISC 341-10 F1.4.4.a(1)(i)(a)	
fect Tu=	36.1	k	Load Effect T_u=	133.72	k	Frame A RISA EQ	
Pt=	36.1	k	$T_u=P_t$=	133.72	k		
tx	20.024677	k	P_{tx}	74.17451	k	Pt*cos(ϴ)	
ty	30.037016	k	P_{ty}	111.2618	k	Pt*sin(ϴ)	
.3Pu	19.333333	k	$P_c=.3P_u$	101.6667	k	F1.4.4a(1)(ii)	
cx	10.724204	k	P_{cx}	56.39452	k	Pc*cos(ϴ)	
cy	16.086306	k	P_{cy}	84.59178	k	Pc*sin(ϴ)	
bv	13.95071	k	Q_{bv}	26.66999	k	$Q_{bv} = P_{ty}-P_{cy}$ On 2nd Floor Beam	Vertical Unbalanced Lo
bh	15.37444	k	Q_{bh}	65.28452	k	$Q_{bp} = (P_{tx}+P_{cx})/2$ On 2nd Floor Beam	Horizontal Unbalanced

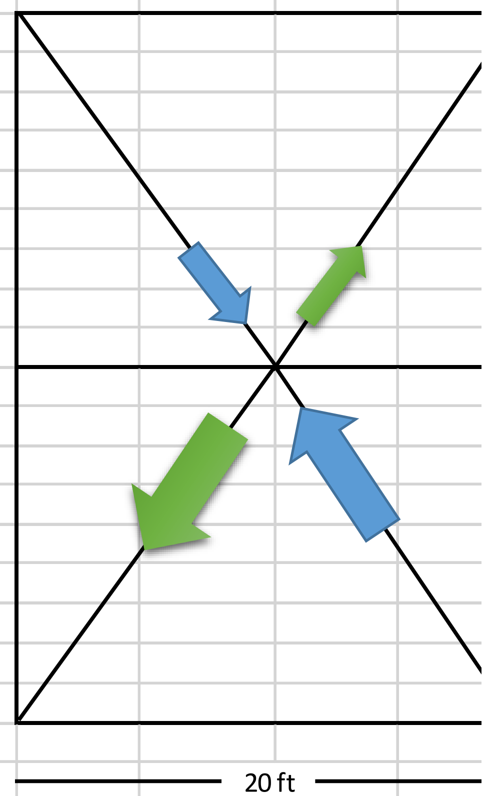
ce 2

Forces Taken From RISA Model

Brace Design						
Frame G Brace 2						
·d Compressive Forces			Factored Tensile Forces			
Top Brace						
L	E	W	D	L	E	W
4.9	53.9	16.7	-0.8	-4.9	46	14.2
.2SDS)D + 1.0E +0.2S + L			(1.2 + 0.2SDS)D + 1.0E +0.2S + L			
	56		Tu (k) =		43.9	
D + 1.6S or L + .5W			1.2D + 1.6S or L + .5W			
	22.16		Tu (k) =		11.36	
2D + .5S + L + 1.6W			1.2D + .5S + L + 1.6W			
	30.13		Tu (k) =		22.72	
Bottom Brace						
L	E	W	D	L	E	W
11.8	206	29.4	-8.2	-11.8	197	26.4
2SDS)D + 1.0E +0.2S or L			(1.2 + 0.2SDS)D + 1.0E +0.2S or L			
	229.28		Tu (k) =		173.72	
D + 1.6S or L + .8W			1.2D + 1.6S or L + .8W			
	52.24		Tu (k) =		21.12	
D + .5S or L + 1.6W			1.2D + .5S or L + 1.6W			
	62.78		Tu (k) =		42.24	
Member Properties						
Top Brace			Bottom Brace			
ength=	10	ft	Horizontal Length=		10	ft
gth=	15	ft	Vertical Length=		15	ft
	0.9827937	radians	ϴ		0.982794	radians
h L=	18.027756	ft	Brace Legth L=		18.02776	ft
	56	k	Pu=		229.28	k
	43.9	k	Tu=		173.72	k
ection	HSS 5x5x3/16		Member Selection		HSS 7x7x1/2	
	2.23	in^2	Ag		6.17	in^2
	46	ksi	Fy		46	ksi
-4	AISC Tbl 5-5		AISC Tbl 4-4		AISC Tbl 5-5	
60	ΦTn (k) =	136	ΦPn (k) =	305	ΦTn (k) =	480

AISC SM Tbl 1-12

Brace Layout



Top Brace			Bottom Brace			
	1.4		Ry	1.4		AISC 341-10 Tbl A3.1
	143.612	k	Pt=	397.348	k	(Pt=RyFyAg) AISC 341-10 F1.4.4.a(1)(i)(a)
Tu=	56	k	Load Effect Tu=	173.72	k	Frame A RISA EQ
	56	k	Tu=Pt=	173.72	k	
	31.063211	k	Ptx	96.36252	k	Pt*cos(ϴ)
	46.594816	k	Pty	144.5438	k	Pt*sin(ϴ)
	20	k	Pc=.3Pu	101.6667	k	F1.4.4a(1)(ii)

r Analysis for Diaphragm Girders

f/Frame G Roof

4x30	Tributary Area		Load Combination										
20	Roof /Floor	Siding	(1.2 + 0.2SDS)D + 1.0E +0.2S										
5	530	520	Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δ_{oh}	Pestory	pstory	B2	Mlt
5	Loads	plf	115.286	35.1	0.312	0.97	1445	1.052	1.4	30169.6	1645.06	1.05767	21.4
29000	Snow Load (psf)	927.5	1.2D + 1.6S + .5W										
8.85	Dead Loads		Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δ_{oh}	Pestory	pstory	B2	Mlt
291	Roof Deck	47.17	36.2554	101.42281	0.098	0.99	1445	1.0154	0.313	62108.6	7289.86	1.13298	0.0
19.6	Girder	30	1.2D + .5S + 1.6W										
5.26	4.5 30 k 12 joists	90	Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δ_{oh}	Pestory	pstory	B2	Mlt
14.9	MEP	132.5	73.4976	48.95	0.199	0.98	1445	1.0322	0.88	22090.9	2854.66	1.1484	7.3
370	column												
1.49	Siding	132	Pe1x	EI/(KL)^2 AISC A-8-5									
5.73	Live Loads		B1x	Cm/1-α(Pr/Pex) A-8-3									
40.26846			Δ_{oh}	Story Drift from RISA Model									
10.4712			Pestory	Rm(HL/ΔH) A-8-7									
0.38			pstory	Totol factored axial load for entire story									
1.77	Input For Revit File		B2	1/(1-(Pestory/Pstory)) A-8-6									
13.4	DL klf	0.43167	Mlt	Moment from lateral force									
42	LL Klf	0.9275	Mu	Moment from gavity Load									
0	Earthquake Load (k)	175.989469	H1-1a	Pr/Pc +8/9(Mr/Mc)									
197	Wind Load (klf)	0.34	H1-1b	Pr/2Pc + Mr/Mc									
17.48	Wind Load Sory shea	81											

ond Floor Girder

x62	Tributary Area		Load Combination										
20	Roof /Floor	Siding	(1.2 + 0.2SDS)D + 1.0E +0.2S										
0	530		Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δ_{oh}	Pestory	pstory	B2	Mlt
0	Loads	plf	33	417.7	0.046	1.00	7694.254	1.0026	0.652	206503	11047.8	1.05652	64.6
29000	Snow Load (psf)												
18.2	Dead Loads												
1550	Desks,walls, etc	265											
29.1	Girder	76											
4.87	Slab	1007											
14.4	MEP	265											
724	Siding	159											
1.38			Pe1x	EI/(KL)^2 AISC A-8-5									
9.23	Live Loads		B1x	Cm/1-α(Pr/Pex) A-8-3									
0	Corridor/classroom	1325	Δ_{oh}	Story Drift from RISA Model									
0	Partitions	530	Pestory	Rm(HL/ΔH) A-8-7									
1.71			pstory	Totol factored axial load for entire story									
1.75	Input For Revit File		B2	1/(1-(Pestory/Pstory)) A-8-6									

ce 1 2nd Floor=

5x36	Tributary Area		Load Combination										
20	Roof /Floor	Siding	*(1.2 + 0.2SDS)D + 1.0E +0.2S*										
0	265		Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δoh	Pestory	pstory	B2	Mlt
0	Loads	plf	100	176.3	0.228	0.98	2223.888	1.0283	0.442	304615	5523.88	1.01847	0
29000	Snow Load (psf)												
10.6	Dead Loads												
448	Desks,walls, etc	132.5											
24.5	Girder	38											
5.37	Slab	503.5											
15.2	MEP	132.5											
438	Siding	79.5											
1.52			Pe1x	EI/(KL)^2 AISC A-8-5									
6.51	Live Loads		B1x	Cm/1-α(Pr/Pex) A-8-3									
0	Corridor/classroom	662.5	Δoh	Story Drift from RISA Model									
0	Partitions	265	Pestory	Rm(HL/ΔH) A-8-7									
0.545			pstory	Totol factored axial load for entire story									
1.83	Input For Revit File		B2	1/(1-(Pestory/Pstory)) A-8-6									
15.5	DL klf	0.886	Mlt	Moment from lateral force									
56.5	LL Klf	0.9275	Mu	Moment from gavity Load									
0	Earthquake Load (k)	561	H1-1a	Pr/Pc +8/9(Mr/Mc)									
273.9	Wind Load (klf)	0.343	H1-1b	Pr/2Pc + Mr/Mc									
16.24	Wind Story shear	108											

ce2 2nd Floor

1x62	Tributary Area		Load Combination										
20	Roof /Floor	Siding	*(1.2 + 0.2SDS)D + 1.0E +0.2S*										
0	530		Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δoh	Pestory	pstory	B2	Mlt
0	Loads	plf	192	372.2	0.265	0.99	7694.254	1.0154	0.652	206503	11047.8	1.05652	
29000	Snow Load (psf)												
18.2	Dead Loads												
1550	Desks,walls, etc	265											
29.1	Girder	76											
4.87	Slab	1007											
14.4	MEP	265											
724	Siding	159											
1.38			Pe1x	EI/(KL)^2 AISC A-8-5									
9.23	Live Loads		B1x	Cm/1-α(Pr/Pex) A-8-3									
0	Corridor/classroom	1325	Δoh	Story Drift from RISA Model									
0	Partitions	530	Pestory	Rm(HL/ΔH) A-8-7									
1.71			pstory	Totol factored axial load for entire story									
1.75	Input For Revit File		B2	1/(1-(Pestory/Pstory)) A-8-6									
23.1	DL klf	1.772	Mlt	Moment from lateral force									

ernate Roof Girder

40	Roof /Floor	Siding	*(1.2 + 0.2SDS)D + 1.0E +0.2S + L*										
5	1060		Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δ_{oh}	Pestory	pstory	B2	Mlt
5	Loads	plf	112.37	258.4	0.139339	0.96	1046	1.0722	0.797	77997	1645.06	1.02155	2.8
29000	Snow Load	927.5	*1.2 D +1.6S +.5 W*										
13	Dead Loads		Mn (K-ft)		527.14								
843	Roof Deck	47.17											
20.7	Girder	68											
6.61	8 30 k 12 joists	80											
14.9	MEP	132.5											
806.45	Green Roof	397.5											
1.26	dry wall+metal studs	45	Pe1x	EI/(KL)^2 AISC A-8-5									
8.06	ceiling+insulation	79.5	B1x	Cm/1-α(Pr/Pex) A-8-3									
47.61905	Live Loads		Δ_{oh}	Story Drift from RISA Model									
7.444169			Pestory	Rm(HL/ΔH) A-8-7									
0.77			pstory	Totol factored axial load for entire story									
1.6	Input For Revit File		B2	1/(1-(Pestory/Pstory)) A-8-6									
20.3	DL klf	0.84967	Mlt	Moment from lateral force									
81.6	LL Klf	0.9275	Mu	Moment from gavity Load									
0	Earthquake Load (k)	129.426223	H1-1a	Pr/Pc +8/9(Mr/Mc)									
664	Wind Load (klf)	0.34	H1-1b	Pr/2Pc + Mr/Mc									
14.44	Wind Load Sory shear	81											

f

2x26	Tributary Area		Load Combination										
26.5	Roof /Floor	Siding	*(1.2 + 0.2SDS)D + 1.0E +0.2S*										
8.83	66.25		Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δ_{oh}	Pestory	pstory	B2	Mlt
26.5	Loads	plf	111.949	19.0	0.348	0.92	577	1.1445	1.11	62454.1	1645.06	1.02705	8.7
29000	Snow Load (psf)	112.5	1.2D + 1.6S + .5W										
7.65	Dead Loads		Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δ_{oh}	Pestory	pstory	B2	Mlt
204	Roof Deck	4.45	37.6378	31.04814	0.117	0.97	577	1.0419	0.28	140147	7289.86	1.05487	10.3
17.3	Girder	26	1.2D + .5S + 1.6W+L										
5.33	4.5 30 k 12 joists		Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δ_{oh}	Pestory	pstory	B2	Mlt
14.9	MEP	25	78.3601	19.75991	0.243	0.99	5195	1.0092	1.228	31955.4	2854.66	1.0981	22.7
322	column												
1.51	Siding	90	Pe1x	EI/(KL)^2 AISC A-8-5									
5.17	Live Loads		B1x	Cm/1-α(Pr/Pex) A-8-3									
70.17219			Δ_{oh}	Story Drift from RISA Model									

Floor

3x46	Tributary Area	
26.5	Roof /Floor	Siding
0	66.25	
0	Loads	plf
29000	Snow Load (psf)	
13.5	Dead Loads	
712	Desks,walls, etc	25
82.5	Girder	76
5.33		
14.9	MEP	25
568.2		
1.29	Siding+Metal Studs	48
7.25	Live Loads	
246.5116	Corridor/classroom	125
43.86207	Partitions	50
340.5		
	Input For Revit File	
	DL klf	0.174
	LL Klf	0.175
	Earthquake Load (k)	561
	Wind Load (klf)	0.343
	Wind Load Story shear	108

Load Combination										
(1.2 + 0.2SDS)D + 1.0E +0.2S						Braced				
Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δoh	Pestory	pstory	B2	Mlt
140.563	275.2	**0.247**	0.97	**2013.18**	**1.045**	0.992	**179837**	**21702.3**	**1.13724**	0
					Non Braced					
Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δoh	Pestory	pstory	B2	Mlt
267.706	36.3	0.471	0.98	5937.76	1.0283	0.992	179837	21702.3	1.13724	0

Pe1x	EI/(KL)^2 AISC A-8-5
B1x	Cm/1-α(Pr/Pex) A-8-3
Δoh	Story Drift from RISA Model
Pestory	Rm(HL/ΔH) A-8-7
pstory	Totol factored axial load for entire story
B2	1/(1-(Pestory/Pstory)) A-8-6
Mlt	Moment from lateral force
Mu	Moment from gavity Load
H1-1a	Pr/Pc +8/9(Mr/Mc)
H1-1b	Pr/2Pc + Mr/Mc

of

1x44	Tributary Area	
53	Roof /Floor	Siding
8.83	159	
8.83	Loads	plf
29000	Snow Load (psf)	112.5
13	Dead Loads	
843	Roof Deck	4.45
20.7	Girder	44
6.25	4.5 30 k 12 joists	
14.9	MEP	25
333	column	
1.26	Siding	
8.06	Live Loads	
84.09524		
13.1464		
0.77		

Load Combination										
(1.2 + 0.2SDS)D + 1.0E +0.2S										
Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δoh	Pestory	pstory	B2	Mlt
61.2366	190.9	**0.184**	0.96	**595.9**	**1.0687**	0.797	**81464.5**	**1645.06**	**1.02061**	2.8

Pe1x	EI/(KL)^2 AISC A-8-5
B1x	Cm/1-α(Pr/Pex) A-8-3
Δoh	Story Drift from RISA Model
Pestory	Rm(HL/ΔH) A-8-7
pstory	Totol factored axial load for entire story

Floor

x76	Tributary Area		Load Combination										
53	Roof /Floor	Siding	*(1.2 + 0.2SDS)D + 1.0E +0.2S+L*										
6	132.5		Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δ_{oh}	Pestory	pstory	B2	Mlt
6	Loads	plf	189	700.7	0.223009	1.00	115827	1.001	0.7	509709	35356.1	1.07454	0
29000	Snow Load (psf)												
22.4	Dead Loads												
2100	Desks,walls, etc	25											
82.5	Girder	76											
5.33	Slab	95											
14.9	MEP	25											
847.5													
1.92			Pe1x	EI/(KL)^2 AISC A-8-5									
9.23	Live Loads		B1x	Cm/1-α(Pr/Pex) A-8-3									
37.5	Corridor/classroom	125	Δ_{oh}	Story Drift from RISA Model									
7.80065	Partitions	50	Pestory	Rm(HL/ΔH) A-8-7									
2.68			pstory	Totol factored axial load for entire story									
2.33	Input For Revit File		B2	1/(1-(Pestory/Pstory)) A-8-6									
23.2	DL klf	0.221	Mlt	Moment from lateral force									
176	LL Klf	0.175	Mu	Moment from gavity Load									
0	Earthquake Load (k)	561	H1-1a	Pr/Pc +8/9(Mr/Mc)									
851	Wind Load (klf)	0.343	H1-1b	Pr/2Pc + Mr/Mc									
13.22	Wind Load Story shea	108											

Column Design

10X49	Tributary Area		Load Combination										
15	Roof /Floor	Siding	*(1.2 + 0.2SDS)D + 1.0E +0.2S*										
15	530	105	Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δ_{oh}	Pestory	pstory	B2	Mlt
15	Loads	plf	76.64	10.2	0.171	0.99	2400	1.0198	0.541	186654	11814.1	1.06757	74
29000	Snow Load (psf)		1.2D + 1.6S + .8W										
14.4	Dead Loads		Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δ_{oh}	Pestory	pstory	B2	Mlt
272	Slab	38	137.36	10.2	0.307	0.98	2400	1.0364	0.08	238500	12487.6	1.05525	7.9
93.4	Girder + beam	17.8	1.2D + .5S + 1.6W										
9.04	MISC	10	Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δ_{oh}	Pestory	pstory	B2	Mlt
31.6	MEP	5	72.8148	10.2	0.163	0.99	2400	1.0188	0.16	119250	20392.4	1.20628	18.1
448	column	1.4											
2.54	Siding	6	Pe1x	EI/(KL)^2 AISC A-8-5									
5.73	Live Loads		B1x	Cm/1-α(Pr/Pex) A-8-3									
70.86614	Classroom	50	Δ_{oh}	Story Drift from RISA Model									
31.41361	Partitions	20	Pestory	Rm(HL/ΔH) A-8-7									
0.38			pstory	Totol factored axial load for entire story									
1.77	Input For Revit File		B2	1/(1-(Pestory/Pstory)) A-8-6									
13.4	Unfactored DL k	38.154	Mlt	Moment from lateral force									
42	Unfactored LL K	37.1	Mu	Moment from gavity Load									
	Earthquake Load (k)	561	H1-1a	Pr/Pc +8/9(Mr/Mc)									
100	Wind Load (klf)	0.34	H1-1b	Pr/2Pc + Mr/Mc									

12X53	Tributary Area		Load Combination										
15	Roof /Floor	Siding	*(1.2 + 0.2SDS)D + 1.0E +0.2S*										
15	66.25	212	Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δ_{oh}	Pestory	pstory	B2	Mlt
15	Loads	psf	97.8695	1.2	0.205	0.99	3751	1.0161	0.992	101794	15148.5	1.17483	77
29000	Snow Load (psf)	45											
14.6	Dead Loads												
425	slab	38											
93.4	Girder	30.4											
8.76	MISC	10											
28.2	MEP	5											
478	column	12											
2.48	Siding	6	Pe1x	EI/(KL)^2 AISC A-8-5									
5.23	Live Loads		B1x	Cm/1-α(Pr/Pex) A-8-3									
72.58065	classroom	50	Δ_{oh}	Story Drift from RISA Model									
34.41683	partitions	20	Pestory	Rm(HL/ΔH) A-8-7									
0.38			pstory	Totol factored axial load for entire story									
1.77	Input For Revit File		B2	1/(1-(Pestory/Pstory)) A-8-6									
13.4	Unfactored DL k	6.79725	Mlt	Moment from lateral force									
42	Unfactored LL K	4.6375	Mu	Moment from gavity Load									

2X65	Tributary Area		Load Combination										
15	Roof /Floor	Siding	*(1.2 + 0.2SDS)D + 1.0E +0.2S+ L*										
15	795	185.5	Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δ_{oh}	Pestory	pstory	B2	Mlt
15	Loads	plf	197.925		0.298980363	0.98	4704	1.0264	1.3	77676.9	12843.177	1.19809	77
29000	Snow Load (psf)	35	1.2D + 1.6S + .5W										
19.1	Dead Loads		Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δ_{oh}	Pestory	pstory	B2	Mlt
533	MISC	10	232.88	2.1	0.351782477	0.98	4704	1.0313	0.055	352174	21274.437	1.06429	9.5
174	Girders + beams	25.14	1.2D + .5S + 1.6W + L										
11.9	Slab	38	Pu	Mn (K-ft)	Pr/Pc	Cm	Pe1x	B1x	Δ_{oh}	Pestory	pstory	B2	Mlt
35.1	MEP	5	133.66	2.1	0.201903323	0.99	4704	1.0175	0.11	176087	13369.617	1.08216	19.2
662	column	1.22											
3.09	Siding	6	Pe1x	EI/(KL)^2 AISC A-8-5									
5.44	Live Loads		B1x	Cm/1-α(Pr/Pex) A-8-3									
58.25243	Classrooms	50	Δ_{oh}	Story Drift from RISA Model									
33.08824	Partitions	20	Pestory	Rm(HL/ΔH) A-8-7									
-			pstory	Totol factored axial load for entire story									
-	Input For Revit File		B2	1/(1-(Pestory/Pstory)) A-8-6									
-	Unfactored DL k	64.2042	Mlt	Moment from lateral force									
-	Unfactored LL K	55.65	Mu	Moment from gavity Load									
-	Earthquake Load (k)	561	H1-1a	Pr/Pc +8/9(Mr/Mc)									
160.7	Wind Load (klf)	0.45	H1-1b	Pr/2Pc + Mr/Mc									
-	Wind Story shear	108	Cm	Based of AISC Table C-8-8.1									

Checked Interior Columns C1 on left C9 on right

Design		
		2nd
Width	**ft**	33.4
Length	ft	33.4
Area	ft^2	1115.56
rea		
L		
	psf	70
	psf	80
	lbs	78089.2
	lbs	89244.8
m		
Width	**ft**	31.6
Length	ft	31.6
Area	ft^2	998.56
rea		
L		
	psf	90
	psf	40
	lbs	89870.4
	lbs	39942.4
6L	Kips	408.25104
	ft	
		1
	ft	14
	ft	14
	in	11.8
	in	22.8
	in	
	ksi	29000
	ksi	46
(E/Fy)	in	35.15184453
		3.51
	in	47.86324786
		124.8110289
	ksi	39.42427185
	Kips	465.2064079
	Kips	418.6857671

Column Design		
Foor		**2nd**
Corridor		
Tributary Width	**ft**	20
Tibutary Length	ft	13
Tributary Area	ft^2	260
Siding Area		
Siding DL		
DL	psf	60
LL	psf	80
DL	lbs	15600
LL	lbs	20800
Classroom		
Tributary Width	**ft**	20
Tibutary Length	ft	13
Tributary Area	ft^2	260
Siding Area		
Siding DL		
DL	psf	85
LL	psf	40
DL	lbs	22100
LL	lbs	10400
1.2D +1.6L	Kips	95.16
Height	ft	
K		1
L	ft	14
KL	ft	14
A	in	11.8
b/t	**in**	22.8
h/t	in	
E	ksi	29000
Fy	ksi	46
1.4SQRT(E/Fy)	in	35.15184453
r		3.51
L/r	in	47.86324786
Fe		124.8110289
Fcr	ksi	39.42427185
Pn	Kips	465.2064079
Phi(Pn)	Kips	418.6857671

ot need to be replaced only minor loads added			Process followed from Design Of Concrete Concrete Structures Arthur H. Nilson Davic			
GIVEN INFORMATION						
f_c	3000			trib area	66.25	ft^2
f_y	60000	60		Roof Area	66.25	
q all	3000			Roof DL	10.7	psf
w_c	150			Roof LL	35	psf
DL	12037.625			2nd DL	75	psf
LL	10003.75			2nd LL	76	psf
S	2318.75			Siding Area	795	ft^2
p tot (1.6L+1.2D+.5Lr)	31610.525	31.610525		Siding DL	8	psf
				Footing Depth	8.5	ft
Φs	0.75					
Φf	0.9					
Φb	0.65					
column f_c	4000					
A_{req}	11.3302907					
Columns length	24					
b trial	3.366					
q_u	2789.912973					
CEHCK PUNCHING SHEAR						
Vu1	-5.05067515					
d	19.5	1.625	in			
b_o	174	14.5	in			
A_v	3393		in^2			
V_c	743.369055					
$ΦV_n$	557.5267913	0.55752679				
CHECK ONE WAY SHEAR ALONG THE FACE OF THE FOOTING						
V_u	-8.84607515					
Vc	86.28335163					
$ΦV_c$	64.71251373					
FLEXURAL DESIGN						
l	7.25					
M_u	26.28666273					
try a=2in						
A_s	0.026312976					
A_s min	2.157083791	>	2.6			
s	-1.9930142					
7 #7 Pr exsisting						
Additional 8 #8						
h	24	inches				

al Forces were negligable

GIVEN INFORMATION						
f_c	3000			trib area	260	ft^2
f_y	60000	60		Roof Area	530	
q all	3000			Roof DL	10.7	psf
w_c	150			Roof LL	35	psf
DL	29971			2nd DL	75	psf
LL	59510			2nd LL	76	psf
S	9100			Siding Area	600	ft^2
p tot (1.6L+1.2D+.5Lr)	135731.2	135.7312		Siding DL	8	psf
				Footing Depth	4	ft
Φs	0.75					
Φf	0.9					
Φb	0.65					
column f_c	4000					
A_{req}	37.91576923					
Columns length	24					
V_{u1}						
Trial d						
b trial	6.158					
q_u	3579.808685					
CEHCK PUNCHING SHEAR						
Vu1	104.4016591					
d	11.5	0.95833333	in			
b_o	142	11.8333333	in			
A_v	1633		in^2			
V_c	357.7723746					
$ΦV_n$	268.3292809	0.26832928				
CHECK ONE WAY SHEAR ALONG THE FACE OF THE FOOTING						
V_u	24.69815252					
Vc	93.08498757					
$ΦV_c$	69.81374068					
FLEXURAL DESIGN						
l	5.916666667					
M	3518.136177					

cement							
	GIVEN INFORMATION						
	f_c	3000			trib area	1404.5	ft^2
	f_y	60000	60		Roof Area	927.5	
	q all	3000			Roof DL	10.7	psf
	w_c	150			Roof LL	35	psf
	DL	121621.75			2nd DL	75	psf
	LL	176304.5			2nd LL	76	psf
	S	49157.5			Siding Area	795	ft^2
	p tot (1.6L+1.2D+.5Lr)	452612.05	452.61205		Siding DL	8	psf
					Footing Depth	8.5	ft
	Φs	0.75					
	Φf	0.9					
	Φb	0.65					
	column f_c	4000					
	A_{req}	161.4343023					
	Columns length	24					
	b trial	12.706					
	q_u	2803.691926					
	CEHCK PUNCHING SHEAR						
	Vu1	415.7697858					
	d	19.5	1.625	in			
	b_o	174	14.5	in			
	A_v	3393		in^2			
	V_c	743.369055					
	$ΦV_n$	557.5267913	0.55752679				
	CHECK ONE WAY SHEAR ALONG THE FACE OF THE FOOTING						
	V_u	132.7961429					
	Vc	325.6899751					
	$ΦV_c$	244.2674813					
	FLEXURAL DESIGN						
	l	7.25					
	M_u	6124.180329					
	try a=2in						
	A	6.130310639					

GIVEN INFORMATION				
f_c	3000	psi		
f_y	60000	psi	60	
q all	3000	lb/ft^2		
Loads				
DL	98042	Lbs		
LL	80560	Lbs		
S	37100			
.6L+1.2D+.5Lr)	265096.4	Lbs	265.1	
Reduction Factors				
Φs	0.75			
Φf	0.9			
Φb	0.65			
olumn f_c	4000	psi		
A_{req}	100.3265116	ft^2		
mns length	24	in		
b trial	10.016	ft		
q_u	2642.336464	lbs/ft^2		
CEHCK PUNCHING SHEAR				
Vu1	236.4665009			
d	15.5	in		
b_o	158	in		1.291666667
A_v	2449	in^2		13.16666667
V_c	536.5490173	Kips		
$ΦV_n$	402.411763	Kips		
ONE WAY SHEAR ALONG THE FACE OF THE FOOTING				
V_u	71.89587941	kips		
Vc	204.0851586	kips		
$ΦV_c$	153.0638689	kips		
FLEXURAL DESIGN				
M_u	2551.152892	in-kips		

Loads	
trib area	1060
Roof Area	1060
Roof DL	10.7
Roof LL	35
2nd DL	75
2nd LL	76
Siding Area	900
Siding DL	8
Footing Depth	8.5

Courtyard Corner							
	GIVEN INFORMATION						
psi	f_c	3000			Roof trib area	1590	ft^2
psi	f_y	60000	60		2nd Trib Area	1590	
lb/ft^2	q all	3000			Roof DL	2.42	psf
pcf	w_c	150			Roof LL	35	psf
Lbs	DL	101632.8			2nd DL	61.5	psf
Lbs	LL	176490			2nd LL	76	psf
Lbs	p tot (1.6L+1.2D)	404343.36			Footing Depth	4.5	ft
	Φs	0.75					
	Φf	0.9					
	Φb	0.65					
psi	column f_c	4000					
ft^2	A_{req}	109.0677647					
in	Columns length	24					
	Vu1						
	Trial d						
	b trial	10					
	q_u	3707.267322					
Kips	Vu1	365.1853489					
	CEHCK PUNCHING SHEAR						
in	d	15	1.25	in			
in	b_o	156	13	in			
	A_v	2340		in^2			
	V_c	512.6683138					
	$ΦV_n$	384.5012354	0.38450124				
	CHECK ONE WAY SHEAR ALONG THE FACE OF THE FOOTING						
kips	V_u	115.0583476					
	Vc	205.9260715					
	$ΦV_c$	154.4445536					
	FLEXURAL DESIGN						
	l	6.5					
in-kips	M_u	20716.86575					
	try a=2in						
	A_s	27.40326157		As6:	0.44		

	3000			Roof trib area	1060	ft^2
	60000	60		2nd Trib Area	1060	
ll	3000			Roof DL	2.42	psf
	150			Roof LL	35	psf
	67755.2			2nd DL	61.5	psf
	117660			2nd LL	76	psf
ɔt (1.6L+1.2D)	269562.24			Footing Depth	4.5	ft
	0.75					
	0.9					
	0.65					
ımn f_c	4000					
ı	72.71184314					
umns length	24					
ıl d						
·ial	9					
	3707.267322					
L	238.0247228					

ɪCK PUNCHING SHEAR

	11	0.91666667	in
	140	11.6666667	in
	1540		in^2
	337.3970954		
n	253.0478216	0.25304782	

ECK ONE WAY SHEAR ALONG THE FACE OF THE FOOTING

	74.1908246
	123.3011511
c	92.47586331

XURAL DESIGN

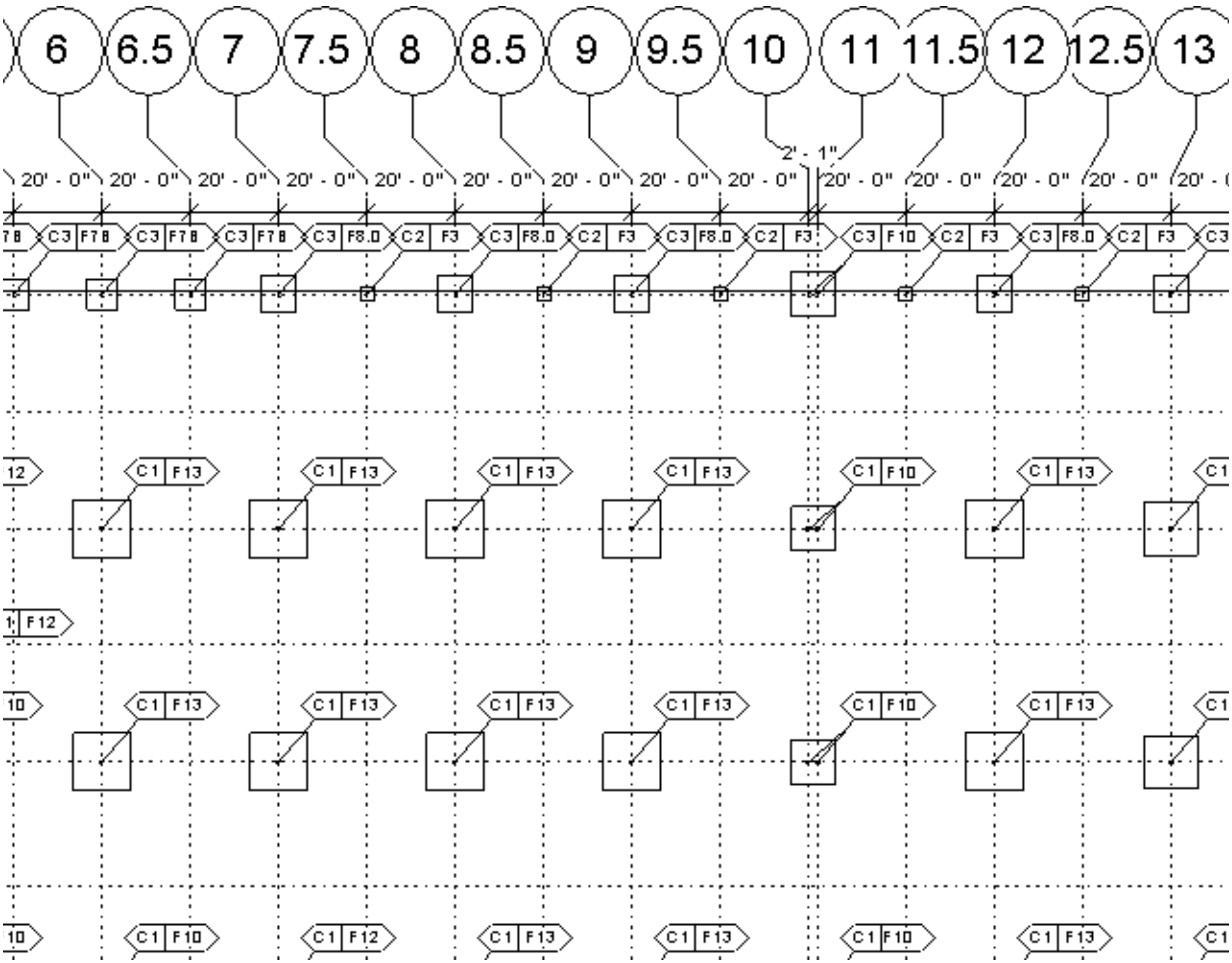
	5.833333333		
	10746.47091		
a=2in			
	19.90987306	AsSt	0.44

3all Court non corner							
	GIVEN INFORMATION						
	f_c	3000			Roof trib area	2650	ft^2
	f_y	60000	60		2nd Trib Area	1060	
	q all	3000			Roof DL	5.7	psf
	w_c	150			Roof LL	35	psf
	DL	94605			2nd DL	75	psf
	LL	173310			2nd LL	76	psf
	p tot (1.6L+1.2D)	390822			Footing Depth	4.5	ft
	Φs	0.75					
	Φf	0.9					
	Φb	0.65					
	column f_c	4000					
	A_{req}	105.0647059					
	Columns length	24					
	V_{u1}						
	Trial d						
	b trial	10					
	q_u	3719.821958					
	Vu1	347.3982451					
	CEHCK PUNCHING SHEAR						
	d	17	1.41666667	in			
	b_o	164	13.6666667	in			
	A_v	2788		in^2			
	V_c	610.8201961					
	$ΦV_n$	458.1151471	0.45811515				
	CHECK ONE WAY SHEAR ALONG THE FACE OF THE FOOTING						
	V_u	103.2669429					
	Vc	229.0599782					
	$ΦV_c$	171.7949836					
	FLEXURAL DESIGN						
	l	6.833333333					
	M_u	19574.71277					
	try a=2in						
	A_s	22.65591756		As6:	0.44		

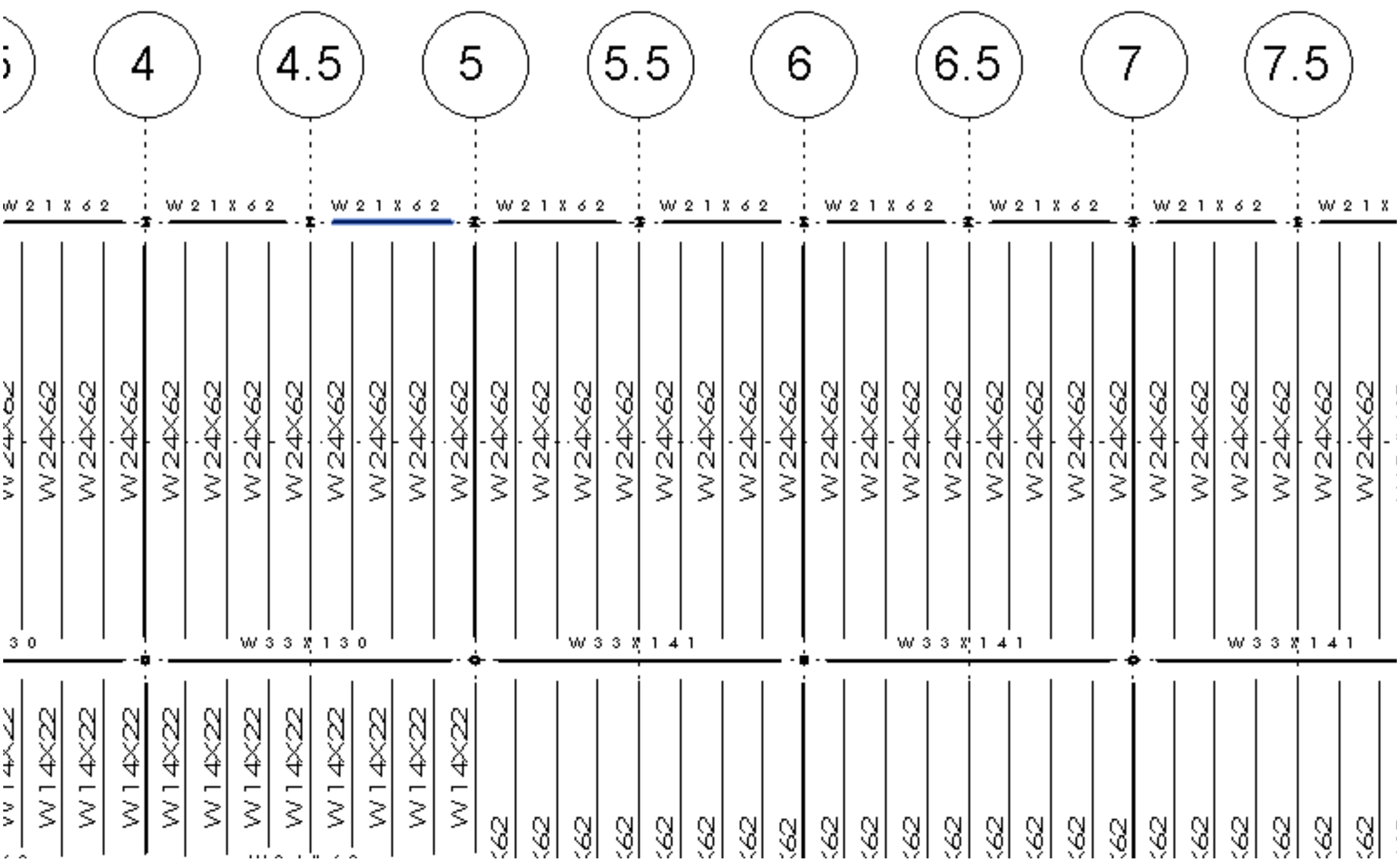
Girder Support 53X40ft'							
	GIVEN INFORMATION						
	f_c	3000			trib area	2120	ft^2
	f_y	60000	60		Roof DL	10.7	psf
	q all	3000			Roof LL	35	psf
	w_c	150			2nd DL	75	psf
	DL	181684			2nd LL	76	psf
	LL	235320			Footing Depth	4.5	ft
	p tot (1.6L+1.2D)	594532.8	594.5328		siding Area		ft^2
	Φs	0.75			Siding DL	3	psf
	Φf	0.9					
	Φb	0.65					
	column f_c	4000					
	A_{req}	163.5309804					
	Columns length	24					
	V_{u1}						
	Trial d						
	b trial	12.788					
	q_u	3635.597356					
	Vu1	551.0508031					
	CEHCK PUNCHING SHEAR						
	d	17.5	1.45833333	in			
	b_o	166	13.8333333	in			
	A_v	2905		in^2			
	V_c	636.4536118					
	$ΦV_n$	477.3402089	0.47734021				
	CHECK ONE WAY SHEAR ALONG THE FACE OF THE FOOTING						
	V_u	182.9742062					
	Vc	294.1778286					
	$ΦV_c$	220.6333714					

Appendix G Structural Plans

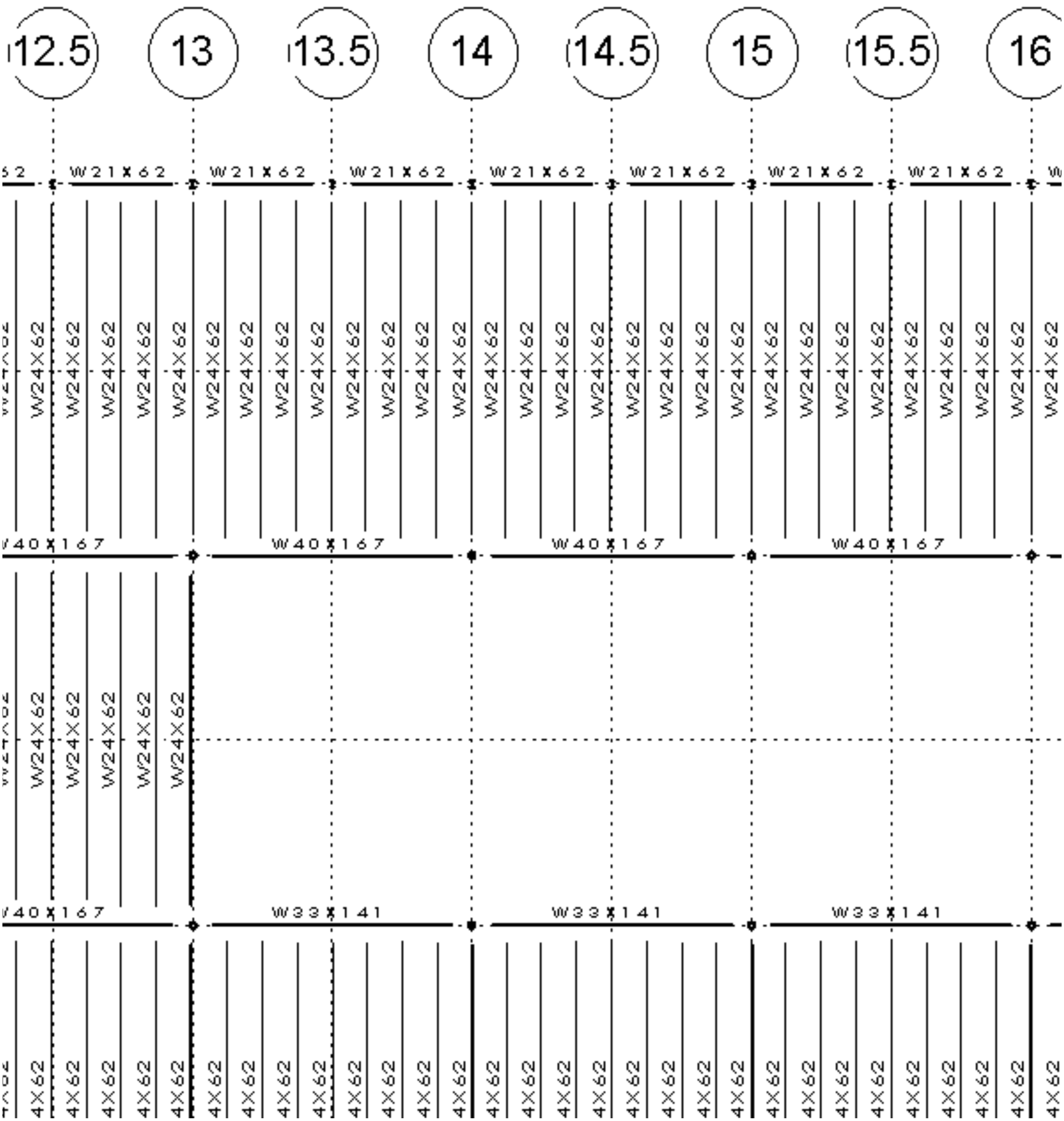
Footing and Column Layout

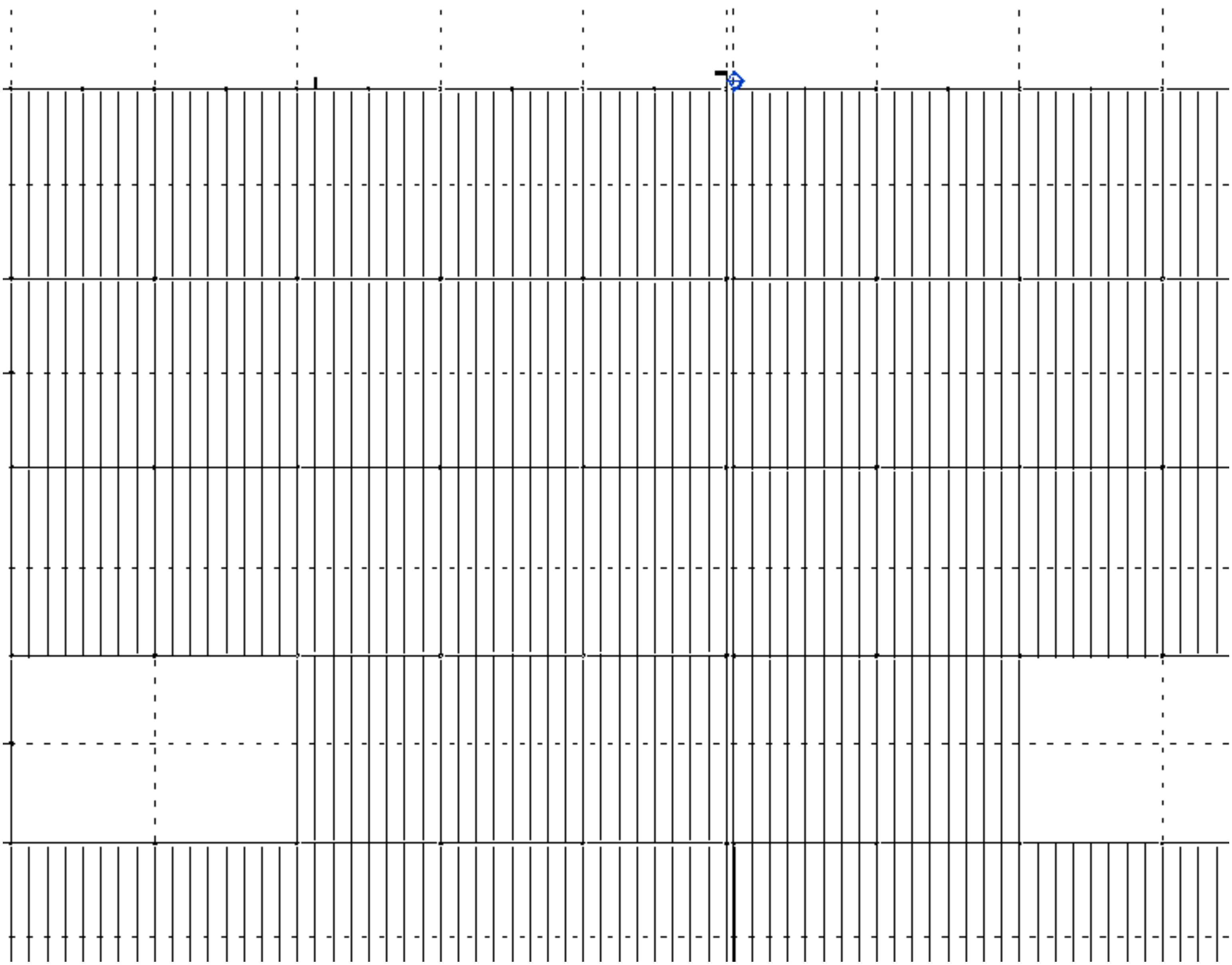


Second Floor Beam Layout 1-10



Second Floor Beam Layout 11-18





Frame 1

Frame 10

A

Frar

Table 132: Existing Building Sprinkler Zone #1

Pipe		K	Added Flow	Act	Fittings	L	C		Notes
From Node	EL	Previous P	Prev. Flow	Nom		F		Pe	
To Node	EL	Total P	Total Flow			T	Pf/ft	Pf	
Pipe 1		8.0	26.00	1.610		10	120.00		Q = 0.2 GPM * 130 ft^2
2	29	10.6	0.00	1.500		0		0.00	
1	29	10.8	26.00			10	0.026	0.26	
Pipe 2		8.0	26.32	1.610		10	120.00		
3	29	10.8	26.00	1.500		0		0.00	
2	29	11.8	52.32			10	0.10	0.96	
Pipe 3		8.0	27.46	1.610		10	120.00		
4	29	11.8	78.32	1.500		0		0.00	
3	29	15.3	105.78			10	0.35	3.52	
Pipe 4		8.0	31.29	1.610		10	120.00		
5	29	15.3	105.78	1.500		0		0.00	
4	29	21.0	137.08			10	0.57	5.69	
Pipe 5		8.0	36.65	2.067		32.5	120.00		
RN1	29	21.0	137.08	2.000		0		0.00	
5	29	29.5	173.73			32.5	0.26	8.48	
Pipe 6			0.00	2.067	1T: 10	1.5	120.00		
A	27.5	29.5	173.73	2.000		10		0.65	Branch Line K-Factor = 173.73/(33.1)
RN1	29	33.1	173.73			11.5	0.26	3.00	30.2
Pipe 7			0.00	5.047	1T: 25	13	120.00		
B	27.5	33.1	173.73	5.000		25		0.00	
A	27.5	33.3	173.73			38	0.003	0.13	
Pipe 8			173.73	5.047	1T: 25	13	120.00		Branch Line 2 Flow = 30.2 (33.3^0.5)
C	27.5	33.3	174.06	5.000		25		0.00	174.06
B	27.5	33.7	347.79			38	0.012	0.46	
Pipe 9			347.79	5.047	1T: 25	285	120.00		Branch Line 3 Flow = 30.2 (33.7^0.5)
FM	27.5	33.7	175.27	5.000		25		0.00	175.27
C	27.5	41.8	523.06			310	0.026	8.05	
Pipe 10			0.00	6.065	1E: 14	67	120.00		
TOR	27.5	41.8	523.06	6.000		14		0.00	
FMJ	27.5	42.6	523.06			81	0.011	0.86	
Pipe 11			0.00	7.981	1 T: 35	28.5	120.00		
BOR	0	42.6	523.06	8.000		35		11.91	
TOR	27.5	54.7	523.06			63.5	0.003	0.18	
Pipe 12			0.00	11.938		266	120.00		RN1 = Riser Nipple at Branch Line 1
UG	-2	54.7	523.06	12.000				0.87	FM = Feed Main
TOR	0	55.7	523.06			266	0.000	0.10	TOR = Top of Riser
Hose			250.00						BOR = Bottom of Riser
			523.06						UG = Underground Main
		55.7	773.06						Hose = Hose Allowance at Supply

Table 133: Renovated Building Sprinkler Zone #1 (Light Hazard)

Pipe		K	Added Flow	Act	Fittings	L	C		Notes
From Node	EL	Previous P	Prev. Flow	Nom		F		Pe	
To Node	EL	Total P	Total Flow			T	Pf/ft	Pf	
Pipe 1		5.6	15.00	1.049	1 T: 5	4.25	120.00		Q = 0.1 GPM * 150 ft^2
A	29	7.2	0.00	1.000	2 E: 4	9		-0.87	
1	27	7.3	15.00			13.25	0.076	1.01	
Pipe 2			0.00	1.610		10	120.00		
B	29	7.3	15.00	1.500		0		0.00	
A	29	7.4	15.00			10	0.01	0.09	
Pipe 3		5.5	15.10	1.049	1 T: 5	4.25	120.00		Armover K-Factor = 15/(7.3^0.5)
B	29	7.4	0.00	1.000	2 E: 4	9		-0.87	
2	27	7.6	15.10			13.25	0.08	1.02	
Pipe 2			15.10	1.610		10	120.00		
C	29	7.6	15.00	1.500		0		0.00	
B	29	7.9	30.10			10	0.03	0.34	
Pipe 5		5.5	15.60	1.049	1 T: 5	4.25	120.00		
C	29	7.9	0.00	1.000	2 E: 4	9		-0.87	
3	27	8.1	15.60			13.25	0.08	1.09	
Pipe 6			30.10	1.610		10	120.00		
D	29	8.1	15.60	1.500		0		0.00	
C	29	8.9	45.70			10	0.07	0.75	
Pipe 7		5.5	16.53	1.049	1 T: 5	4.25	120.00		
D	29	8.9	0.00	1.000	2 E: 4	9		-0.87	
4	27	9.2	16.53			13.25	0.091	1.21	
Pipe 8			16.53	1.610		10	120.00		
E	29	9.2	45.70	1.000		0		0.00	
D	29	10.6	62.22			10	0.132	1.32	
Pipe 9			0.00	2.067		30	120.00		
F	29	10.6	62.22	2.000		0		0.00	
E	29	11.7	62.22			30	0.039	1.17	
Pipe 9			0.00	2.067	1T: 10	1.5	120.00		
RN1	27.5	11.7	62.22	2.000		10		0.65	
E	29	12.8	62.22			11.5	0.039	0.45	
Pipe 9			0.00	5.047	1T: 25	1.5	120.00		Branch Line K-Factor = 62.22/(12.8^0.5)
F	27.5	12.8	62.22	5.000		25		0.00	
RN1	27.5	12.8	62.22			26.5	0.001	0.01	
Pipe 9			0.00	5.047		15	120.00		
G	27.5	12.8	62.22	5.000		0		0.00	
F	27.5	12.8	62.22			15	0.001	0.01	
Pipe 9		17.4	62.24	5.047		280	120.00		
FM	27.5	12.8	62.22	2.000				0.00	
G	27.5	13.4	124.47			280	0.002	0.51	
Pipe 10			0.00	6.065	1T: 30	67	120.00		
TOR	27.5	13.4	124.47	6.000		30		0.00	
FM	27.5	13.4	124.47			97	0.001	0.07	
Pipe 11			0.00	7.981	1 E: 18	27.5	120.00		
BOR	0	13.4	124.47	8.000		18		11.91	E = Standard Elbow
TOR	27.5	25.3	124.47			45.5	0.000	0.01	T = Tee or Cross
Pipe 12			0.00	11.938	1E: 27	266	120.00		RN1 = Riser Nipple at Branch Line 1
UG	-2	25.3	124.47	12.000	1T: 60	87		0.87	FM = Feed Main
BOR	0	26.2	124.47			353	0.000	0.01	TOR = Top of Riser
Hose			100.00						BOR = Bottom of Riser
			124.47						UG = Underground Main
		26.2	224.47						Hose = Hose Allowance at Supply

Table 134: Renovated Building Sprinkler Zone #1 (Ordinary Hazard)

Pipe		K	Added Flow	Act	Fittings	L	C		Notes
From Node	EL	Previous P	Prev. Flow	Nom		F		Pe	
To Node	EL	Total P	Total Flow			T	Pf/ft	Pf	
Pipe 1		8.0	22.50	1.049		10	120.00		
2	27.5	7.9	0.00	1.500		0		-0.22	
1	27	9.3	22.50			10	0.162	1.62	
Pipe 2		8.0	24.41	1.610		10	120.00		
3	29	9.3	22.50	1.500		0		0.00	
2	29	10.1	46.91			10	0.08	0.78	
Pipe 3		8.0	25.42	1.610		10	120.00		
4	29	10.1	69.41	1.500		0		0.00	
3	29	13.0	94.83			10	0.29	2.88	
Pipe 4		8.0	28.81	1.610		10	120.00		
5	29	13.0	94.83	1.500		0		0.00	
4	29	17.7	123.64			10	0.47	4.70	
Pipe 5		8.0	33.63	2.067		32.5	120.00		
RN1	29	17.7	123.64	2.000		0		0.00	
5	29	24.7	157.27			32.5	0.22	7.06	
Pipe 6			0.00	2.067	1T: 10	1.5	120.00		
A	27.5	24.7	157.27	2.000		10		0.65	
RN1	29	27.9	157.27			11.5	0.22	2.50	
Pipe 7			0.00	5.047	1T: 25	13	120.00		Branch Line K-Factor = 142.07/(33.1)
B	27.5	27.9	157.27	5.000		25		0.00	29.7
A	27.5	28.0	157.27			38	0.003	0.11	
Pipe 8		29.7	157.27	5.047	1T: 25	13	120.00		Branch Line 2 Flow = 30.2 (33.3^0.5)
C	27.5	28.0	157.27	5.000		25		0.00	157.27
B	27.5	28.4	314.53			38	0.010	0.38	
Pipe 9		29.7	314.53	5.047	1T: 25	285	120.00		Branch Line 3 Flow = 30.2 (33.7^0.5)
FM	27.5	28.4	158.34	5.000		25		0.00	158.34
C	27.5	35.0	472.88			310	0.022	6.68	
Pipe 10			0.00	6.065	1E: 14	67	120.00		
TOR	27.5	35.0	472.88	6.000		14		0.00	
FM	27.5	35.8	472.88			81	0.009	0.71	
Pipe 11			0.00	7.981	1 T: 35	28.5	120.00		
BOR	0	35.8	472.88	8.000		35		11.91	
TOR	27.5	47.8	472.88			63.5	0.002	0.15	
Pipe 12			0.00	11.938	1T: 50	266	120.00		RN1 = Riser Nipple at Branch Line 1
UG	-2	47.8	472.88	12.000		50		0.87	FM = Feed Main
TOR	0	48.8	472.88			316	0.000	0.10	TOR = Top of Riser
Hose			250.00						BOR = Bottom of Riser
			472.88						UG = Underground Main
		48.8	722.88						Hose = Hose Allowance at Supply

Appendix I – Egress Analysis Solutions

Appendix J – Smoke Control Calculations

Equation 39: Manual Calculation for Sprinkler Activation Time

t (seconds)	Q (kW)	Tg (Deg. C)	U (m/s)	Td (Deg. C)
0	0	20	0	20.0
5	0.3	20.161	0.178	20.0
10	2.5	20.696	0.370	20.0
15	6.9	21.376	0.520	20.1
20	13.5	22.154	0.650	20.2
25	22.3	23.012	0.769	20.3
30	33.3	23.936	0.879	20.6
35	46.5	24.918	0.983	20.8
40	61.9	25.952	1.081	21.2
45	79.5	27.033	1.175	21.6
50	99.3	28.157	1.266	22.0
55	121.3	29.322	1.353	22.6
60	145.5	30.524	1.437	23.2
65	171.9	31.761	1.520	23.8
70	200.5	33.032	1.600	24.5
75	231.3	34.335	1.678	25.3
80	264.3	35.668	1.754	26.2
85	299.5	37.030	1.829	27.1
90	336.9	38.420	1.902	28.1
95	376.5	39.836	1.974	29.1
100	418.3	41.279	2.044	30.2
105	462.3	42.746	2.113	31.3
110	508.5	44.237	2.181	32.5
115	556.9	45.752	2.249	33.8
120	607.5	47.289	2.315	35.1
125	660.3	48.848	2.380	36.4
130	715.3	50.429	2.444	37.8
135	772.5	52.030	2.508	39.2
140	831.9	53.652	2.570	40.6
145	893.5	55.293	2.632	42.1
150	957.3	56.954	2.694	43.6
155	1023.3	58.634	2.754	45.2
160	1091.5	60.332	2.814	46.8
165	1161.9	62.048	2.873	48.4
170	1234.5	63.782	2.932	50.0
175	1309.3	65.533	2.990	51.7
180	1386.3	67.301	3.048	53.4

185	1465.5	69.086	3.104	55.1
190	1546.9	70.887	3.161	56.9
195	1630.5	72.705	3.217	58.7
200	1716.3	74.538	3.272	60.5
205	1804.3	76.386	3.327	62.3
210	1894.5	78.250	3.382	64.1
215	1986.9	80.129	3.436	66.0
220	2081.5	82.023	3.490	67.8
225	2178.3	83.931	3.543	69.7

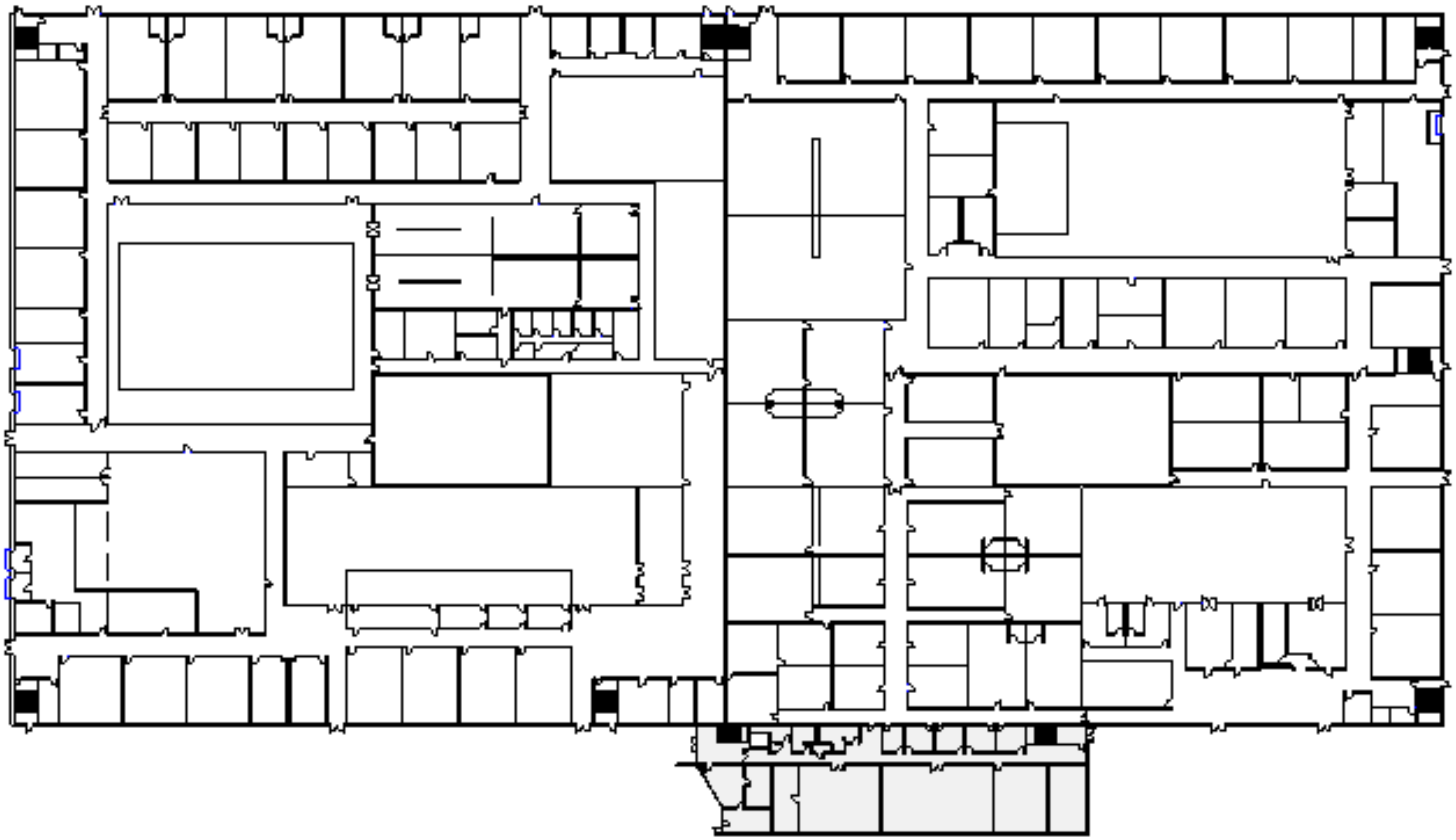


Figure 111: First Floor Architectural Plans

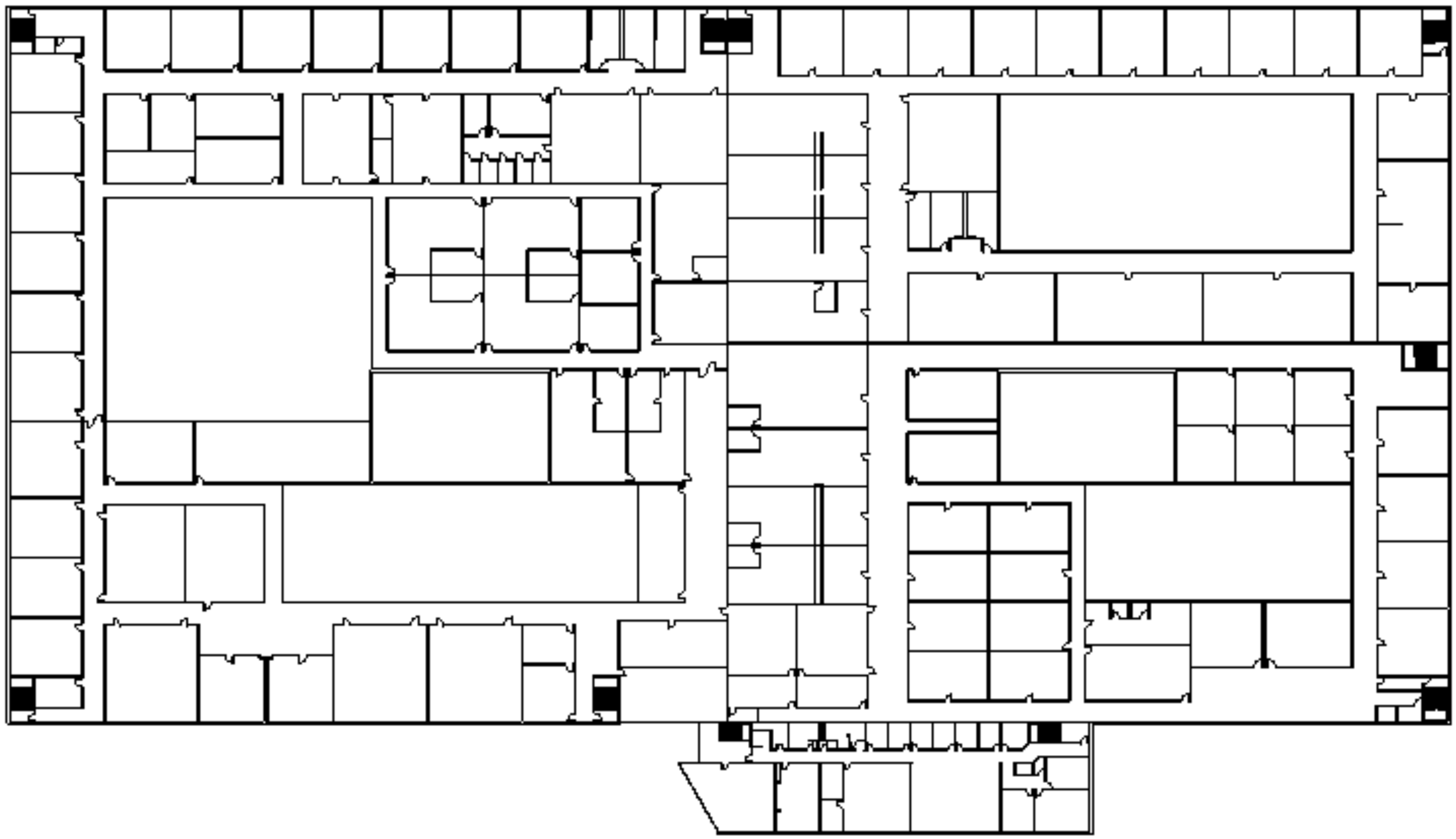


Figure 112: Second Floor Architectural Plan