MQP LDA-1901

WPI Replacement to Kaven Hall: Structural Design

A Major Qualifying Project Submitted to the Faculty of Worcester Polytechnic Institute in Partial Fulfillment of the requirements for the Bachelor of Science Degree

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Abstract

Kaven Hall has housed the Civil and Environmental Engineering Department for over 60 years. Growing class sizes and a lack of technology in meeting spaces demand a new CEE building. The scope of this project includes the design of a functional floor plan to maximize square footage and to limit cost. The design explores the possibilities of steel and reinforced concrete framing to decide which framing method best fits the goal of the project.

Capstone Design Statement

To complete the requirements produced by the Accreditation Board for Engineering and Technology (ABET) for a Capstone Design experience, numerous realistic constraints must be thoroughly evaluated during the design process. This project addresses constructability, environmental, sustainability, social, economic, health and safety, and ethics. Each of these constraints is described below.

Constructability:

Constructability is an important consideration to be aware of throughout the design process. If a design presented is challenging to construct, then there could be a loss in materials and time to redesign the structure. The team's goal was to make the new Kaven Hall easily buildable. Standard beam and column sizes are specified for ease of construction and affordability. In the reinforced concrete design alternative, the beams, columns, and floor slabs are designed to have only a few different sizes to limit the amount of formwork needed for the job, which also lowers the cost of construction.

Environmental:

When working with an old building, such as Kaven Hall, there are a lot of environmental issues to be concerned with. Building materials, such as lead paint and asbestos tiles or insulations, are some of the critical elements that should be monitored as the old building is torn down. Water runoff is not impacted in this design since the new building foot print will not be much bigger than the existing layout. Runoff was accounted for in the building process and handled appropriately with erosion control.

Sustainability:

Sustainability has been a growing topic over the last 20 years and for WPI as a growing campus in an urban area. WPI needs a building that is durable and can last another 60 plus years with minimal maintenance. Producing the most efficient design and limiting the unnecessary resources used was another way that sustainability was encompassed in the final design.

Social:

A building on any campus must be socially accepted by its users for it to be efficiently used. Surveys were the main tool used to collect the needs of the students and faculty. Ideally, the professors will now have class rooms that adequately meet their needs. The building will be more accessible for all students, with ADA Compliant rooms, and the addition of an elevator. The facilities staff will enjoy working in this building as it is tied into the loading dock already present at the base of Fuller Labs with easy access to the elevator. This will help the custodial staff to facilitate the distribution of paper goods and cleaning products and for easy removal of trash and recyclables.

Economic:

Although economic analysis of the proposed building focused mainly on the structural components, there was an estimated allowance for other elements of the building to understand the total cost of the project. Cost is an important consideration since projects are funded by WPI, and the Board of Trustees will want the most economical design that meets their needs. This cost estimate was compiled using similar construction projects completed by WPI in the past.

Health and Safety:

Health and safety need to be considered for the duration of the project, especially during the construction period. The United States Department of Labor states that in 2016 that there were more than 14 deaths a day (United, 2018). Accident rates can be reduced by having the majority of the components pre-fabricated by manufacturers at their warehouse. Long-term safety factors that have been evaluated are snow load, occupancy load and fire restrictions to name a few. To do this, the *Massachusetts Building Code* (780 CMR), *International Building Code* (IBC 2015), American Concrete Institute (ACI 318-19), American Institute of Steel Construction (AISC 2016), and The American Society of Civil Engineers Standards (ASCE 7-10) were utilized to make sure all safety requirements were met.

Ethics:

When it comes to ethics, proper decisions must always be made based on building codes, OSHA regulations, and technical competence. This ensures that Kaven Hall is designed and built ethically and complies with all the required provisions. Understanding the appropriate licensure requirements for structural design gives us, the design team, insight and ethical values when it comes to executing this project. Provisions and regulations must always be followed and should never be abused, even if there may be any potential loopholes. Building quality and the safety of the occupants are the most important concerns when it comes to design and construction.

Licensure Statement

In the world of civil engineering obtaining licensure is the mark of being a professional and is the standard in todays' society. Only a licensed engineer may prepare, sign, seal, and submit engineering work and drawings to a public authority for approval. Professional Engineers (PEs) are also responsible for the work of others in the engineering field, making sure that they follow high ethical standards of practice. Obtaining licensure is necessary for engineers who are aspiring to hold upper-level management positions in a civil engineering firm.

Obtaining licensure is a major milestone in the career of any engineer and is very rewarding. However, there is a level of difficulty that is involved with it, and it does take a significant amount of time to fulfill all the requirements necessary. To obtain licensure, aspiring engineers must first graduate from a four-year university engineering program accredited by EAC/ABET. Following graduation, engineers must take and pass the Fundamentals of Engineering Exam (FE). This is a 6-hour long exam that consists of 110 multiple choice questions that cover the basics learned throughout an engineer's college career. Topics include mathematics, statics, structural analysis, chemistry, and surveying just to name a few.

Once the FE Exam is passed, an aspiring engineer is now recognized as an Engineer-In-Training (EIT). EIT's must then complete four years of work experience under the supervision of a Professional Engineer. After four years of experience are completed, an EIT can then register for the Principles and Practice Engineering Exam (PE). This exam lasts 8-hours and consists of 80 multiple choice questions. The PE exam is based on which discipline of civil engineering an individual wishes to practice in and in which state they want to be licensed. Each state has a different set of standards and qualifications.

Aspiring engineers may also register and take the Structural Engineering Exam also known as the "SE". This exam is a 16-hour long test that tests for the competency in the field of structural engineering. The SE exam is designed for engineers who practice in jurisdictions that license structural engineers separately from other professional engineers. This 16-hour exam uses separate gravity and lateral components to test one's ability to safely design buildings or bridges, especially in areas of high seismicity and high wind.

In the practicing world of civil engineering it is necessary for an engineer to obtain the appropriate licensure in his/her discipline. Through the numerous amounts of structural calculations and designs a licensed engineer works to ensure the safety of those who interact with and occupy a building or structure.

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1.0 Introduction

Kaven Hall is located on the corner of Salisbury Street and Boynton Street and is home to the Civil and Environmental Engineering Department at Worcester Polytechnic Institute (WPI). It was built in 1954, and named after a graduate of the 1865 class, Moses Kaven, who was a generous benefactor for WPI. Kaven Hall's exterior was built out of brick and limestone creating a sturdy exoskeleton. The floor plan of the building accommodates a limited amount of class sizes and a minimal amount of faculty office. Kaven Hall has provided for the WPI community for over sixty years, and it is approaching the time for a new facility. Kaven Hall is getting small for the growing class sizes that WPI has, and its use is limited by the fact it does not have an elevator.

The project is a design for a new building to replace Kaven Hall that meets the building code, fits typical class sizes at WPI, and is welcoming to the end users within the Civil Engineering department. The proposed building is a four-story, I-shaped building selected from multiple designs based on a grading system. This building includes multiple 70-student class rooms, 25-student class rooms, tech suites, offices, testing laboratories, and computer labs. Both a steel and concrete frame were compared for constructability and economics. Other aspects of the project include a survey of existing conditions, project schedule for demolition and new construction, cost estimates, and foundation design.

2.0 Background

This project is a complete redesign of Kaven Hall with the designs for both steel and concrete frames that compare constructability and economics. The most constructible, cost effective and efficient design was identified and selected. The ultimate goal of this design is to provide students and professors with the amenities and space needed to further their education and research in Civil Engineering and beyond. By developing this new design, the proposed Kaven Hall will accommodate the larger classes of sixty-plus students for the CE 2000 level classes. It can also support research projects and house laboratory classes on the bottom floor of the building. In order to properly deliver this project, certain background knowledge and understanding was required. This background section provides an overview of the necessary information regarding the factors that were taken into consideration in the design of a new Kaven Hall. Information regarding the current status of the project site, regulatory provisions and design parameters, and the properties of the materials used are presented in this section.

2.1 Construction Materials

Over thousands of years of construction history, some of the building materials have changed drastically, and some have stood the test of time and are still used today. When designing a building it is crucial that the best materials are selected to make the outcome a resilient building that lasts for the end users with as little maintenance as possible.

2.1.1 Concrete

Concrete is a composite material that is formed from a hydration reaction, which reaches its optimal strength at 28 days. Concrete normally is made with Portland cement, aggregate, water, and admixtures (as needed) to produce the desired material properties and quality. Concrete is used in most cases because of its workability and versatility on jobs that require high compressive strength.

Reinforced concrete consists of reinforcing bars, or *rebar,* embedded in concrete. The rebar is generally made of steel with nobbles or ridges that anchor firmly into the concrete, in order to promote a mechanical bond and to avoid slipping. There are many techniques used to reinforce concrete, but one technique consists of tying rebar together with wire to form a cage, which the wet concrete is then placed on and hardens over. The concrete and rebar combine to resist compressive, tensile, and shear forces. The rebar can increase the compression capacity of the reinforced concrete while also absorbing most of the tensile and shear forces.

The use of reinforcement increases compression capacity, enhances ductility, and reduces long-term deflections of concrete elements. It also increases the flexural capacity of beams. Another technique for reinforcing concrete uses stirrups, ties, and hoops to provide lateral reinforcement, which resists principle stresses resulting from shear. This technique provides confinement to columns, beams, and joints in highly stressed areas of compression zones. Confinement is especially important in structures located in high seismic risk zones because it improves their strength and ductility.

Steel is the common choice for reinforcement because it expands and contracts in the heat and cold roughly as much as concrete. This reduces the likelihood of the steel cracking the concrete due to varying temperatures. However, if the concrete cracks and water penetrates the reinforced concrete structure, it can rust the steel rebar. This process ruins the durability of concrete structures, and it is difficult to detect and repair. Deterioration due to rusting can begin in as little as 10 years and has resulted in shorter life spans of 50-100 years in reinforced concrete structures (Keulemans).

2.1.2 Steel

Steel is a common material used for constructing high-occupancy buildings since it can carry very high compressive and tensile forces. Steel is used over other materials due to its speed of construction with the use of bolts or welds. Smaller, easily transportable beams and columns can come together on-site to produce a strong, lightweight building frame. These beams and columns are typically wide flange beams or W-shapes, which can carry high tension and compressive forces in a lighter, more compact shape.

Steel structures tend to have longer spans between columns than concrete structures. Normally, buildings that have steel structures allow for more flexibility in spatial layouts. They can be divided up into interior spaces with metal stud and gypsum boards. When compared to concrete, steel has more available open space due to the reduced number of columns which allows for the space to be easily repurposed. Steel structures also produce generally more variability in design since they can accommodate large overhangs and glass-faced walls more easily.

One of the properties that makes steel a great structural framing component is its ductility. With increased ductility, steel greatly reduces the seismic loads that must be accounted for compared to the seismic loads that a rigid concrete frame must carry. The steel members rely heavily on their inelastic behavior to sustain these seismic loads. This allows for smaller members to be chosen, reducing the cost of the project, and making the self-weight of the frame lower.

For this design, composite construction instead of traditional non-composite steel design was used. Composite construction has numerous advantages, with some of them being:

- A high utilization of construction material (steel and concrete).
- Ability to cover a large column-free area, leading to more usable space.
- Faster construction by utilizing rolled and/or pre-fabricated components.
- Smaller Structural sections required compared to non-composite construction.
- Reduction in overall weight of the composite structure compared to the reinforced concrete construction (RCC), resulting in lesser foundation

Cambering beams is another option when designing a steel structure. Cambered beams allow for smaller beams sizes to be selected thus reducing cost and providing ease for the steel manufacturers. A cambered beam is a beam that has a curve in the upward direction in its vertical plane. Cambering allows for beams to be selected with a deflection greater than one inch. The smaller beams will then be able to settle thus reaching an acceptable deflection that passes L/360.

2.2 Design Tools

There are many engineering tools that can be utilized in the design process for a structure or building. Autodesk Revit, RAM Structural System, Microsoft Excel, Tekla's TEDDs, and Primavera are the applications that were used to perform calculations, structural analysis, and ultimately redesign Kaven Hall.

2.2.1 Revit

Autodesk Revit is a 3D modeling software typically used for creating structural and architectural models of buildings or structures. The software allows a design to be created in 2D as well as a 3D representation. This software is great for adding architectural and structural members to a structure proposed building. For example, the selected beam and column sizes can be implemented within the software to give an actual representation of the building frame. Once all structural members are properly sized and added to the model, a schedule with material takeoffs for each type of member can be created. These types of members include shear walls/bracing, structural framing, structural columns, structural foundations, and floors. Each schedule can contain several columns of information including member lengths, areas, and volumes. Creating these material takeoff schedules are very beneficial because they can be exported into Microsoft Excel to assist in creating a cost analysis.

2.2.2 RAM Structural System

RAM Structural System is a structural analysis software provided by Bentley that allows users to create computer models of the structural members they have designed. For example, a steel framing system for a building design can be implemented in RAM. Loads and load factors may then be applied to the structure in both the vertical and horizontal directions to simulate the various load combinations that must be considered for design. Once the design loads and loading combinations are defined, this software can size all the structural members to adequately resist the applied loads. The software is also capable of analyzing the effects of the loads on the given structure by determining moment, shear, and deflection values. RAM has made itself very convenient for structural engineers by providing printable reports for each individual component of the building's shell (e.g., an exterior beam) along with the entire structural frame.

2.2.3 Microsoft Excel and Tekla's TEDDs

Hand-calculations can become repetitive when designing multiple components of a building with numerous loads and loading combinations. Microsoft Excel software provides the ability to create spreadsheets capable of performing the necessary calculations for multiple iterations of similar member types. The software makes use of data and formulas to output the necessary design values. The sheets can be repeated, increasing the speed and efficiency of the design process. Microsoft Excel can be very helpful when trying to calculate the snow and wind loading on a specific part of the building through the easy development and implementation of the design equations in Microsoft Excel.

Just like Microsoft Excel, TEDDs is another software that can be used to complete repetitive calculations, and it can be linked back to Microsoft Excel. Created by Tekla, TEDDs is a fast and easy software to learn, and is widely used in the field by structural engineers. TEDDs can perform 2-D structural frame analysis, generate loads and loading combinations, and determine properties for sections.

2.2.4 Primavera

Primavera is an application that creates a realistic schedule for projects. A list of activities paired with their durations can be imported into Primavera from a Microsoft Excel spreadsheet. Once imported into Primavera, these activities can be linked to one another to create a timeline for the project. After all of the activities are linked together, Primavera calculates the total duration and float of the project, displaying this information in a Gantt chart.

2.3 Design Parameters

When it comes to designing any structure or building, safety and constructability are the ultimate underlying responsibilities of any engineer. It is an essential requirement for a building project to comply with all national, state, and local rules and regulations to ensure a safe design and building practice. In Massachusetts, all current and future buildings must be in compliance with provisions of *Minimum Design Loads for Buildings and Other Structures (ASCE 7-10),* the *International Building Code (IBC 2015),* the *Americans with Disabilities Act (ADA)* and the *Massachusetts State Building Code (780 CMR)*. The uses and how an engineer can reference each provision are shown in Table 1.

Table 1: Design Parameters

Design Reference	**Use**
Minimum Design Loads for Buildings and Other Structures (ASCE 7-10)	Snow Loads Wind Loads Seismic Loading Floor and Roof Live Load
International Building Code (IBC 2015)	General Building Heights and Area Foundation Inspections General Structural Design Occupancy Requirements Quality Control of Materials
Americans with Disabilities Act (ADA)	Hallway Widths Door Widths Elevator Requirements Ramp Slopes
Massachusetts State Building Code (780 CMR)	Adopts IBC and ASCE 7 by reference, as well as provides certain provisions unique to Massachusetts
American Concrete Institute (ACI 318-19)	Design Parameters according to *ACI 318-19: Building Code Requirements for Structural Concrete*
American Institute of Steel Construction (AISC 2016)	Design Parameters according to *2016 AISC Specification for Structural Steel Buildings, 2014 RCSC Specification for Structural Joints Using High-Strength Bolts, 2016 AISC Code of Standard Practice for Steel Buildings and Bridges*

3.0 Methodology

The goal of this project was to develop a new design to revitalize the aging Kaven Hall. This chapter outlines the methods used to accomplish this goal. To achieve the new design, the project scope was divided into three objectives:

Objective 1: Develop an architectural program to create and compare layouts based on community sentiment, the current condition of the building, and academic necessity.

Objective 2: Design a building frame with steel and concrete alternatives based on gravity and lateral loads.

Objective 3: Determine the cost effectiveness of each building frame and decide the best option for the building.

Each objective is discussed below.

3.1 Objective 1: Develop an architectural program to create and compare layouts based on community sentiment, the current condition of the building, and academic necessity.

Objective 1 is where the problems of Kaven Hall came to light. To develop an architectural program for the building, the wants and needs of the WPI community needed to be discovered. Student and faculty surveys were initiated through WPI's Qualtrics near the beginning of the project. The questions found in Appendix C asked for specific feedback about spaces, like Question 6 in the student survey: "Do you use the Student Lounge as a workplace?" The survey also asked broad questions in hopes of detailed responses on inadequate components of the building that might be hidden to most, like Question 13 on the faculty survey: "What do you dislike the most about Kaven Hall?" Thoughtful responses to these surveys were an important step to designing a layout that best fit the WPI community.

Another method of gathering information for the building program was interviewing the academic scheduler, Cathy Battelle. While the surveys are good for getting personal opinions, an interview with the academic scheduler provided numbers: numbers for how many large spaces are needed for classes, how many classes take place in Kaven Hall, etc. This interview was also essential to the completion of Objective 1.

Once community sentiment and scheduling information from Cathy Battelle were compiled, the architectural program was prepared. The list of spaces included required utility space, classroom spaces, meeting spaces, faculty offices, and others. Each alternative design layout created needed to incorporate all aspects listed on the architectural program.

Using the architectural program, the team then split up to design alternative layouts. Each layout incorporated every aspect on the architectural program. The layouts also needed to use space effectively, have a flow conducive to the students and faculty needs, and have the relationship between spaces make sense. Additionally, all layouts had to conform to building code requirements addressing the minimum widths for egress and maximum capacities of rooms. Once the three alternative designs were created, they were graded using the architectural program. Each layout was assigned a grade of 1-3 for each category on the program. The design with the highest score was chosen as the final layout moving forward.

3.2 Objective 2: Design a building frame with steel and concrete alternatives based on gravity and lateral loads.

After the layout was chosen, the building frames were designed. A reinforced concrete frame and steel frame were both designed in order to compare alternative options. Each design included footings, beams, columns, slabs, roofs, and a lateral-load-resisting system. In Figure 1 the overall design process for both the steel and concrete frames is shown.

Figure 1: Flowchart of Design Process

For the column grid the layout for the steel and concrete spacing had to be different to support the loads with a reasonably sized set of columns and beams. Some of the assumptions used for the design of these frames included:

- Simply Supported Connections
- Tributary area
- LRFD design

When designing for gravity loads, members were sized to maintain a uniform member size throughout the building. This ensured to keep the product cost down on the steel and the formwork cost down on the concrete design. During the sizing of the members design criteria from ACI and AISC were followed.

After the gravity loads were evaluated, lateral loads were analyzed for both structures. In the New England area, there is moderate seismic activity. The seismic load was evaluated for this site and the results can be found in Appendix G. The base shear force from the seismic analysis is less than the shear force created by the wind force, which makes the wind loads the governing load case. From the load combinations the full wind force is applied on each side of the building was used to design the lateral bracing. There are many styles of bracing that could be used in these structures. Such as chevrons, shear walls, single diagonal bracing, X bracing, and knee bracing. Each one has its own strengths and weaknesses. For this project, the shear wall worked best for the concrete building, and X bracing was used for the steel building.

3.3 Objective 3: Determine the cost effectiveness of each building frame and decide the best option for the building.

Using the Revit model of the two building frame designs, the amount of material needed was calculated through the material takeoff function. Then, using *2019 Building Construction Costs with RSMeans data* textbook the square foot costs for categories in the Uniformat were calculated (Mewis, 2019). The categories included in the Uniformat are substructure, shell, interiors, services, equipment and furnishings, special construction, and building site work (Charette, 2019).

Using the material takeoffs exported from Autodesk Revit, the quantities of concrete and steel needed for their respective frames were calculated using the unit costs for each material from the RS Means books. All of the other sections were calculated by using an average square-foot cost for a typical college lab building made of concrete and steel.

Once the best method of construction was identified, a schedule was created for it. By using the *2019 Building Construction costs with RSMeans data* book and the schedule for the WPI Bartlett Center the duration of tasks was predicted and assigned in Primavera. The schedule for the WPI Bartlett Center was provided in the WPI course CE3025, Project Management. Using Primavera the tasks were organized by completion date, and a critical path for the project was formed. Once the timeframe was identified the start date was chosen to maximize the time that students and faculty would not be at WPI to complete construction.

4.0 Results

This section contains the results of the project. Similar to the methods, the results section is organized according to the three objectives that were used to achieve the end goal.

4.1 Objective 1 Results

4.1.1 Existing Building

Kaven Hall sits at the corner of Boynton Street and Salisbury Street, housing the Civil and Environmental Engineering Department. This building was completed in 1954, and over the 60 years that it has serviced WPI, it has had a couple of major renovations that have changed the configuration of rooms and how space was utilized. Copies of the original blue prints are in the Gordon Library's Curation, Preservation, and Archives, so the initial design and layout is well documented.

The building was designed in the shape of a C for Civil Engineering, and it has three floors in service with an attic space. The C-shape of the building can be seen in Figure 2. The basement floor is approximately at grade level and has not changed in use over the years. It has been an area for lab testing for various classes and research. On the other two floors of the building there were three individually dedicated rooms for sophomores, juniors, and seniors. In these rooms, each student in the department would have their own desk, and they could leave work at school. Additionally, there were classrooms, coat rooms, offices, and other special dedicated rooms. One feature that was common on campus at this time was one library for each department so they can maintain their own reference books.

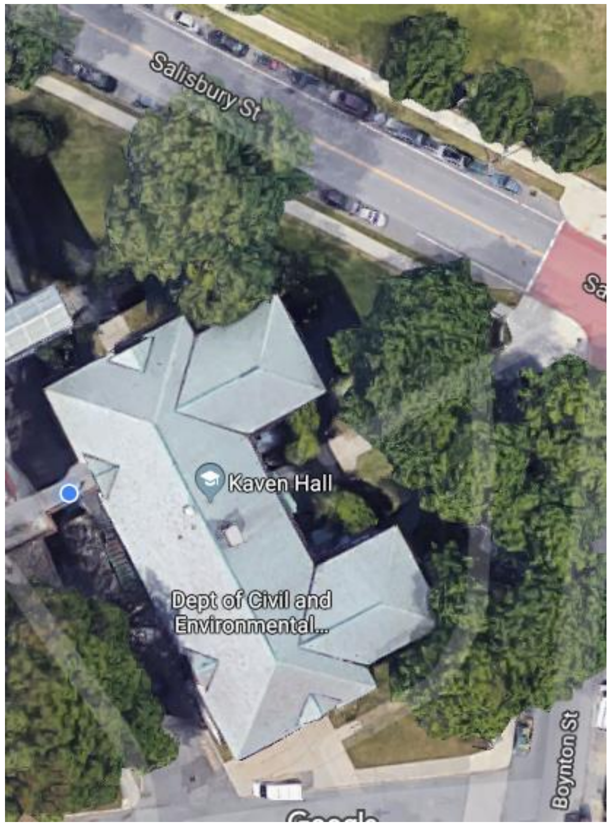


Figure 2: Existing Kaven Hall via Google Earth

Kaven Hall is located at the base of Boynton Hill, so grading of the site is one of the important design features that was considered. In Figure 3 it can be seen that the grade elevation starts higher at the close end of the building and it gradually gets lower. Also, to note, Fuller Laboratories is less than twenty feet away from the edge of the existing building. A picture of this can be seen in Figure 4 with Fuller Labs on the right and Kaven Hall on the left.

Figure 3: Exterior Grading of Existing Building

Figure 4: Fuller labs and Kaven Hall

The grade elevations around the building were surveyed using the known bench mark on the right side of the main stair case. This bench mark can be seen in Figure 5. This bench mark has been assigned an elevation of 506.35’. All the elevations around the building are referenced to this bench mark. A list of these elevations can be seen in Table 2 with their corresponding locations seen in Figure 6.

Figure 5: Bench Mark on Stairs

Table 2: List of Survey Points and Elevations

Point	Elevation	Point	Elevation
BM1	506.35	P.6	499.896
P.1	504.63	P.7	499.635
P.2	506.75	P.8	514.157
P.3	505.375	P.9	514.455
P.4	504.43	P.10	503.97
P.5	502.465	P.11	500.801

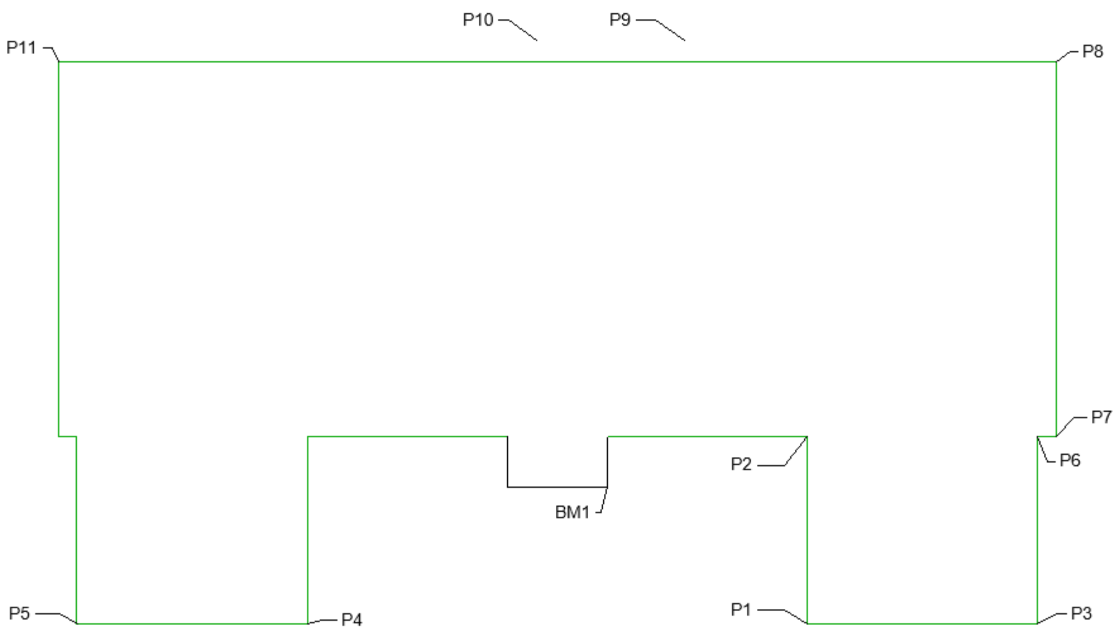


Figure 6: Surveying Point Locations

4.1.2 Criteria for New Design

When designing a new building there are many different constraints, parameters, and necessities that need to be considered.

4.1.2.1 Site constraints

The Worcester zoning ordinance was evaluated, and Table 3 shows the hard restraints that needed to be enforced in the new design (Unites States, 1991). These restraints dictated where the building had to be in reference to the lot.

Table 3: Zoning Requirements

LOT		Yard Setbacks			Height	
Minimum Area	Frontage	Front(ft)	Side(ft)	Rear(ft)	Max Stories	Max Height (ft)
NA	NA	15	10	10	NA	NA

LOT		Yard Setbacks			Height	
Minimum Area	Frontage	Front(ft)	Side(ft)	Rear(ft)	Max Stories	Max Height (ft)
NA	NA	15	10	10	NA	NA

Another constraint to consider is the slower demolition and construction time because of the extra precautions that are necessary for protecting Fuller Labs. It also means that the new building must align with the base of Fuller Labs to make the walkways between the buildings efficient. Two other significant design parameters that are a result of the existing configuration are the required setbacks and the loading dock on the west side of the existing building.

When designing this building, the locations of the utilities are also a major constraint. WPI heats most of its buildings through steam pipes. Kaven Hall is one building that receives these steam pipes underground, which run perpendicular to the building, and are centrally located. This is not a utility that would be easily relocated, so when designing the new building, a mechanical room must be positioned in the correct location. Other utilities considered are water, sewer, and electrical. The gas and the water service locations are known and can be seen in Figure 7.

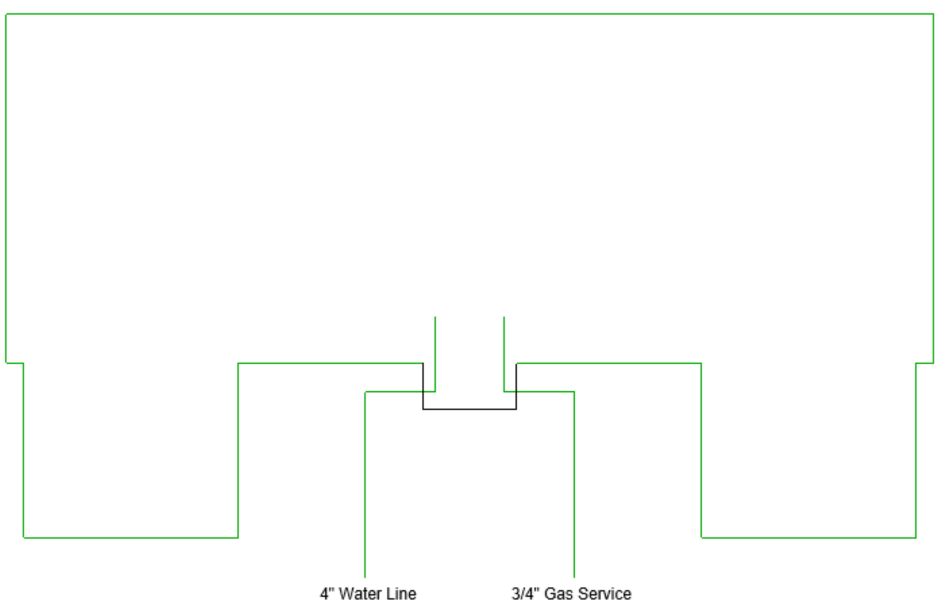


Figure 7: Gas and Water Service Locations

4.1.2.2 Recommended Spaces and Functional Areas

An interview was conducted with the academic scheduler, Cathy Battelle. This interview along with personal experiences and the student/ faculty surveys provided the information necessary to derive the occupancy and types of academic spaces needed. The student faculty survey provided over 100 thoughtful responses to help develop this list. With this information a list was developed of necessities based on community feedback. Below is the list of necessities in no particular order:

- 20 faculty offices
- 70-student class rooms
- 50-student computer labs
- Testing laboratories
- Tech suites
- Multiple 25-student classrooms
- Bathrooms
- Janitor closets
- Student lounge
- Elevator
- Loading dock platform
- Storage closets
- Conference rooms
- Mechanical rooms

In order to evaluate the layouts created, this list was transformed into categories. These categories combined to create an architectural program for choosing the final layout.

4.1.2.3 Occupancy and Egress

The building code has many rules about spaces and egress. These restrictions are all based upon occupancy. After sizing the rooms based on the recommended functional spaces and desired capacities, the occupant load for fire safety and egress was calculated by dividing the gross area of each space by 20, allocating each occupant at least 20 square feet of space for usage. (IBC 2015) In Table 4, the occupant load per floor is presented with an approximate total occupant load of 1200 people. In Table 5, minimum areas are presented for classrooms and office space. This was used to design the floorplan layouts.

Table 4: Occupancy

Floor	Gross area (sqft)	Occupancy
Basement	6,200	310
1st	6,200	310
2nd	5,100	255
3rd	5,960	298
Approximate Total	**24,000**	**1200**

Table 5: Minimum Area Criteria (IBC 2015)

Parking Spots	Loading Dock	Classroom Size			Office Size
10/Classroom	1 - 12x50'	25 Person	50 Person	70 Person	1 Faculty
	Min Dimensions	500	1000	1400	120sq/ft

These occupancy calculations defined the dimensions for many areas throughout the building, such as the stairways, hallways, and exits. Using the building code to find the design ratios, each design incorporated the appropriate amount of space for egress based upon the criteria in Table 6.

Table 6: Egress Requirements

Area	Max Occupancy	Ratio	Code Reference	Min
Stairs	310	.2"/Occupant	IBC 2015	5.16'
Hallways	310	.2"/Occupant	IBC 2015	5.16'
Exits	1200	1 Exit/500 Occupants	IBC 2015	4 Exits

4.1.3 Alternative Layouts

Three different designs were produced incorporating as many of the necessities within the defined restrictions. One design reworked the classic "C" shape layout, while the other two explored new possibilities. Each design incorporates an elevator, a mezzanine level connected to the loading dock, and at least two 70-person classrooms.

4.1.3.1 T-Shape

The first alternative layout is a T-shape in plan. This building includes four total floors of combined academic class rooms and collaborative space for students to do work, with all the parameters and recommended assets accounted for. Some of the major additions were the three rooms that were put on the third floor. These rooms are a senior room, grad lounge, and a study hall. These three rooms work as an area for the students to come and go, with tables and a few computers to work on projects. With the proposed increases to 4 total floors and to the building footprint, two elevators were installed, one on the north end of the building and the other one on the south end, allowing for easy flow throughout the building.

4.1.3.2 C-Shape

The second design is essentially the same shape as the current Kaven Hall in order to consider the option of preserving the iconic “C” shape building. There are major changes to the spaces and, of course, the addition of the third floor. The overall arrangement in the basement is similar. The major change is the new mezzanine level in the Northeast corner of the building. This mezzanine is flush to the loading dock outside and access is only permitted to faculty and staff. In this design the first floor has two large classrooms. New additions also include tech suites and much larger spaces for the TA office, the student lounge, and faculty lounge. Both lecture halls have two exits in case of an emergency, and the elevator is strategically located next to the Fuller entrance.

The second floor is now home to all of the faculty offices. Students no longer have to search the corners of the building for their professor's office as they are all conveniently located on one floor. This floor also hosts two computer labs and two classrooms. Located in the Northwest corner is the graduate TA office as well as another tech suite. This floor also has a student lounge area that overlooks the Kaven courtyard.

The third floor has a much larger architectural studio than what is available now in KH 207. There are also storage units available to the different programs that are based in the Civil and Environmental Engineering Department.

All the documents in the current attic can now be stored in the new civil engineering archive. Also, on the fourth floor is a building code and civil reference library. To finish off the building the floor has a café and a practice room for the ASCE student competition teams. This design maximizes space while keeping the historical “C” shape layout.

4.1.3.3 I-Shape

The final layout that was produced is an "I" shaped building. The first three floors keep the "C" shape with slightly different dimensions, while the third floor is an "I" shape with a large cutout that can become a greenhouse/outdoor patio space. The major changes to this building from the existing building design are the amount of open space, the addition of tech suites, and more classrooms. The first-floor entrance next to Fuller has been kept completely open for dining options and collaboration. Also found on the first floor are two 70-person lecture halls, a 50-person computer lab, and a new project presentation/display room. The idea of this room is to present past MQP's and highlight other civil, environmental, and architectural engineering projects.

On the second floor, one can find most of the faculty offices, two additional classrooms, and a larger architectural engineering lab. Finally, the third floor is home to a larger, more open student lounge space that transitions into a greenhouse/outdoor patio. This floor also features a new virtual reality room, in which students have the capability of seeing their CAD/Revit models come to life.

4.1.3.4 Recommended Layout

An architectural program was developed using the criteria from Section 4.1.2.2 and its elements are listed in Table 7. The three alternative layouts were evaluated on how many of the desired spaces they had and how these spaces were incorporated. The best design for each category got a score of three, and the least desirable layout got a score of one. The scores were than totaled, and it was determined that the I-Shape design was the best layout with a total score of 33 out of a possible 45 points.

Table 7: Evaluation of Design Alternatives

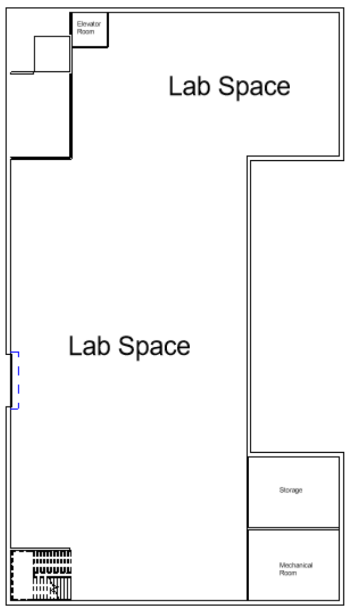
	I Shape	T Shape	C Shape
Faculty offices	3	2	1
70-student class rooms	2	1	3
50-student computer labs	3	2	1
Testing laboratories	1	2	3
Tech suites	3	2	1
Multiple 25-student classrooms	2	3	1
Bathrooms	1	3	2
Janitor closets	3	1	2
Student lounge	1	3	2
Elevator	3	1	2
Loading dock platform	3	2	1
Storage closets	3	1	2
Conference rooms	3	1	2
Mechanical rooms	1	2	3
Misc.	1	2	3
Total	**33**	**28**	**29**

The I-Shape design incorporates all the different spaces required and maximizes their efficiency. All the designs included all the required spaces, but the I-Shape layout uses them the most efficiently. The I-shaped layout can be seen in Figure 8. For example, one of the major complaints recorded from the student survey was the difficulty in finding faculty offices. The I-Shape design has two major hubs of offices on the second and third floors. This gives students clarity in the sense that the office that they're looking for can only be in two distinct areas.

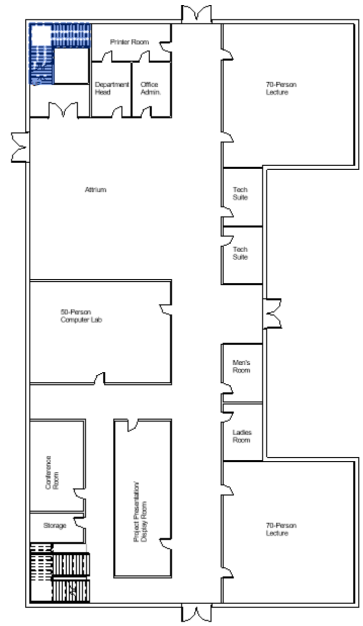
Another complaint recorded is that there is not an even mix of large and small classrooms. The T-Shape design had the most classrooms by far, but the number of available classrooms is beyond the program's needs within the CEE department, and the space could have been used for other things. The I-Shape design has two large classrooms and three smaller classrooms. With this mix, professors don't have to scramble to reserve a classroom similar to KH 116, and there are also classrooms for smaller classes and clubs to meet.

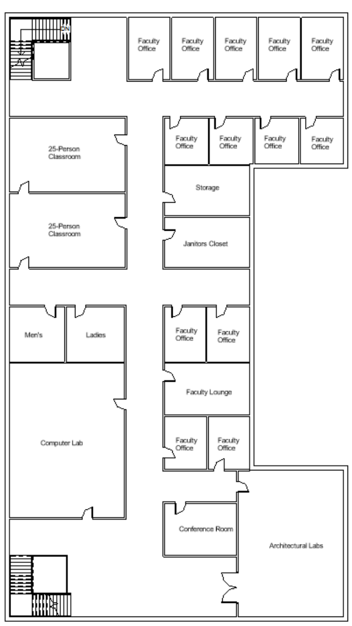
Last, the major reason the I-Shape design is best is the amount of open space it provides. The most common complaint on the surveys was that Kaven Hall feels like a high school building. The long narrow hallway, closed spaces, and uniformity does not sit well with the student body. The I-Shape design uses unique spaces and open concepts such as the new student lounge to turn Kaven Hall into a modern and sheik learning space.

Basement

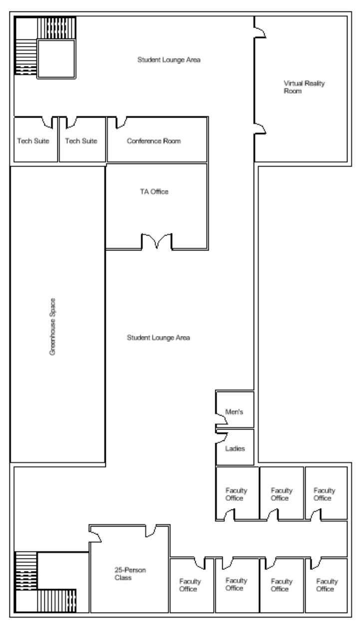


First Floor





Second Floor



Third Floor

Figure 8: Final Layout

4.2 Objective 2 Results

To determine the best structural frame for the proposed building both a reinforced concrete frame and a structural steel frame were designed for gravity loads and lateral loads. Both materials have advantages when compared to one another. These advantages entail cost, strength, fire-resistance, and sustainability. In this section, the loads and the design of both structures are evaluated.

4.2.1 Design Loads and Load Combinations

Design loads for both structural frames were determined in compliance of ASCE 7-10. The load combinations, 1.4D and 1.2D +1.6L + 0.5S, were used to design for gravity loads. Load values can be seen in the Table 8.

Table 8: Applicable Gravity Loads

Type	Value
Dead Load	Variable
Service Live Load	First Floor 100 PSF, Other Floors 80 PSF, Roof 20 PSF
Snow Load for Flat Roof	Deck & Roof 38.115 PSF
Drift Snow Load	Deck 80.37 PSF
Wind Load	Gradient from 19.8-16 PSF from top to bottom

4.2.2 Structural Steel Design

For the steel design, a beam system with a 5.5-inch slab (3-inch concrete slab on 2.5-inch metal decking) was utilized for composite construction. Composite construction was used because it allows for larger spans between columns and generally lighter beams compared to traditional beam construction. This system allowed for an almost uniform design on all floors besides the additional support located on the third floor under the outside rooftop patio of the building. The patio section requires larger beam sizes to support the additional snow drift load.

When designing specific beams some deflection issues arose. This was due to the architectural layout having large amounts of open space. To counteract this issue, larger beam sizes were selected, and the idea of cambering during the fabrication process was also used. Cambering beams compensates for the deflection issue because it allows for smaller beams to settle once placed and offsets the impact of heavy loads. However, after analyzing all the beams for deflection and span length, it was noticed, in the calculations that only a specific beam size can be cambered at five separated locations throughout the layout. This is because when looking back at the calculations the beam sizes were governed by moment capacity instead of deflection. The common beam sizes used on each floor can be seen in Table 9.

The steel column grid utilizes a column at each outside vertex plus a few more along the widths and under where the outside roof top patio is located. The location of these columns can be seen in Figure 9. Columns were selected to be W14 x 99 at all locations to ease the fabrication and erection process even though some could have been smaller due to smaller gravity loads.

Table 9: Structural Steel Building Components

Component	Size	
Slab on Grade	5-inch depth	
Composite Floor Slabs	3-inch concrete slab 2.5-inch metal decking	
Columns	W14x99	
1^{st} Floor Beams	W16x40 W18x55 W21x55 W21x57 W21x101	W24x68 W24x84 W24x117 W27x102
2^{nd} Floor Beams	W16x40 W18x55 W18x71 W21x55	W21x101 W24x68 W24x84 W27x102
3^{rd} Floor Beams	W16x40 W18x71 W21x55 W21x101	W24x68 W24x84 W24x117 W27x102
Roof Beams	W16x40 W18x71 W21x55 W21x101	W24x84 W24x117 W27x102
Composite Roof Slab	3-inch concrete slab 2.5-inch metal decking	

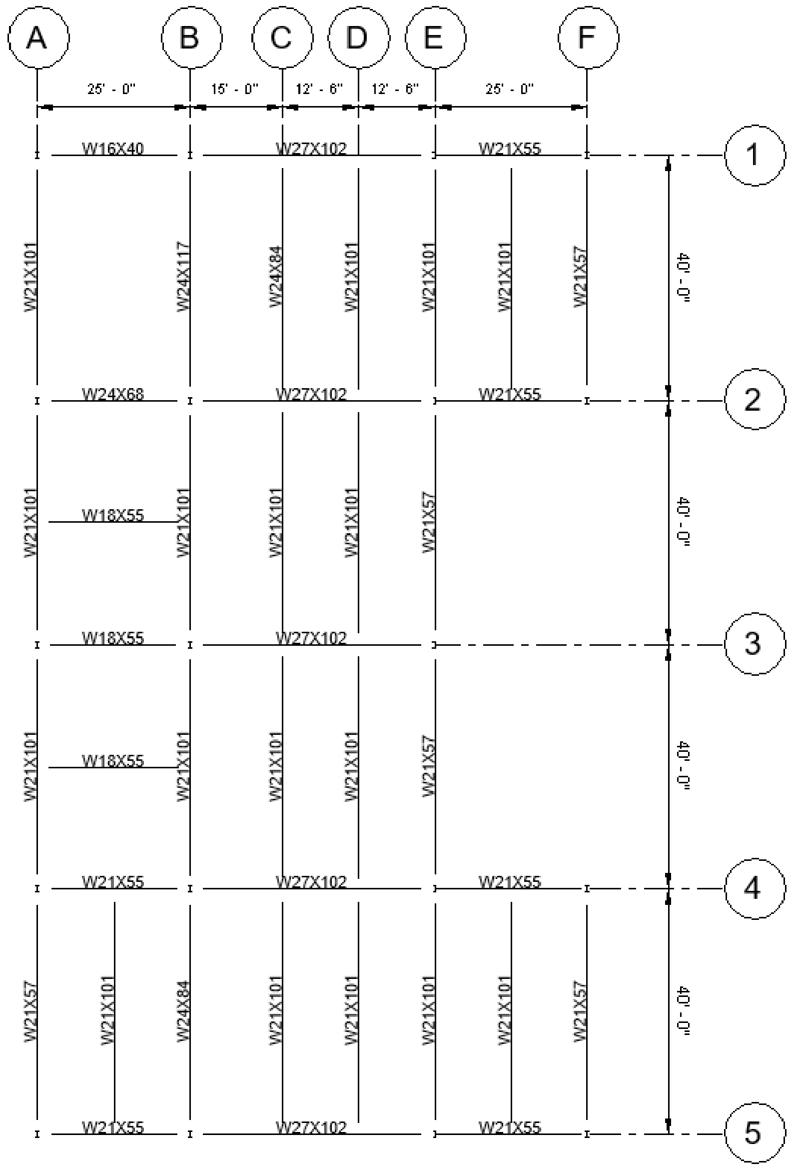


Figure 9: Steel Column and Beam Layout

4.2.3 Reinforced Concrete Design

The structural design of a reinforced concrete alternative for the new Kaven Hall building began with adjusting the layout. The I-Shape layout selected had a surplus of open space throughout the building. The original column grid being implemented in the steel design would not work in the concrete design because of the large spans between columns. The new concrete column grid is seen in layout uses 51 columns opposed to the steel grid which has 19 columns. Although there are more columns than the structural steel option, the design takes advantage of smaller columns, beams, and slab sizes. A full list of columns, beams, and slabs can be seen in Table 10 and the corresponding locations can be seen in the column grid in Figure 10. Figure 11 shows the layout of beams and T-beams for the floor while in Figure 11 the typical cross section of a T-beam is shown.

The T-beams run along the length of the building and make up the slab. The T-beam floor system reduces the number of beams needed because they act as the beam in the direction that they are constructed. The tops of the T-beams are also part of the slab and the supporting beams are flush. All columns were designed based on required strength needed to support factored design loads, including the weight of the floor system and beams. The slenderness ratio imposed minimum dimensions on the columns. Although the minimum column dimensions may be considered counterproductive towards the more columns, smaller size philosophy, the trade-off was to avoid consideration of column slenderness concerns to reduce design time. The column grid was designed to be as repeatable as possible for ease of construction. Specifying consistent sizes for the continuous beams and columns provides formwork economy for constructing the floor. The formwork for this process is universal and can be reused throughout the construction process, which will save time and money.

Table 10: Concrete building components

Component	Location	Size(in)	Steel Area (in^2)
Basement Column	B-(1-9), E-(1-9)	16x16	5 - #3
Basement Column	A,C,D,F-(1-9)	16x16	4 - #3
1st Floor Column	B-(1-9), E-(1-9)	16x16	4 - #3
1st Floor Column	A,C,D,F-(1-9)	16x16	3 - #3
2nd Floor Column	A,B,C,D,E,F-(1-9)	16x16	3 - #3
3rd Floor Column	A,B,C,D,E,F-(1-9)	16x16	3 - #3
Beam A	EF-(1-9) and AB-(1-9)	18x12	3 - #10
Beam B	BC,CD,DE-(1-9)	14x8	2 - #9
Slab on Grade	Basement	5	N/A
General Floor	First floor to third floor	24x18 T beam	6 - #10

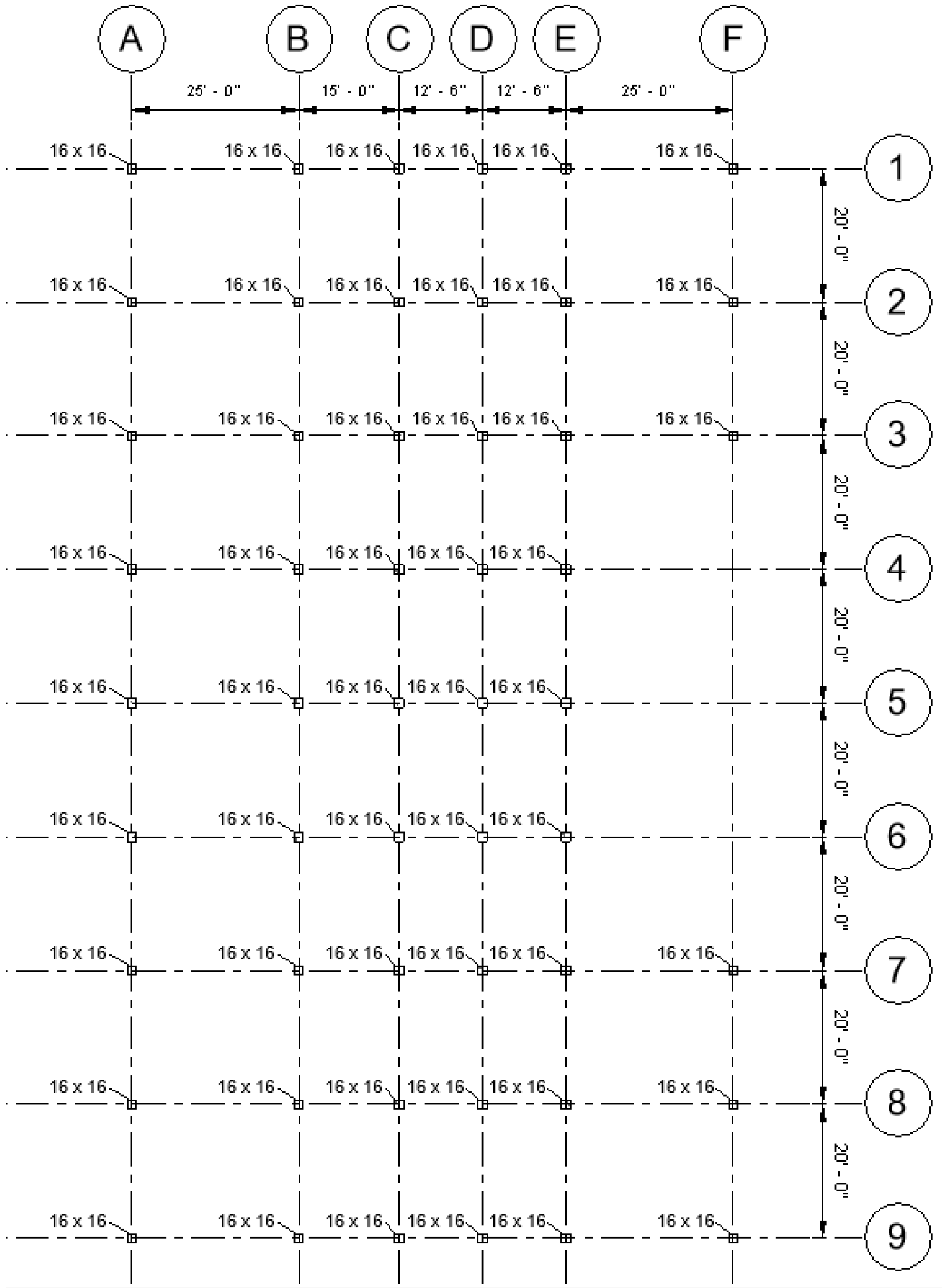


Figure 10: Concrete column layout

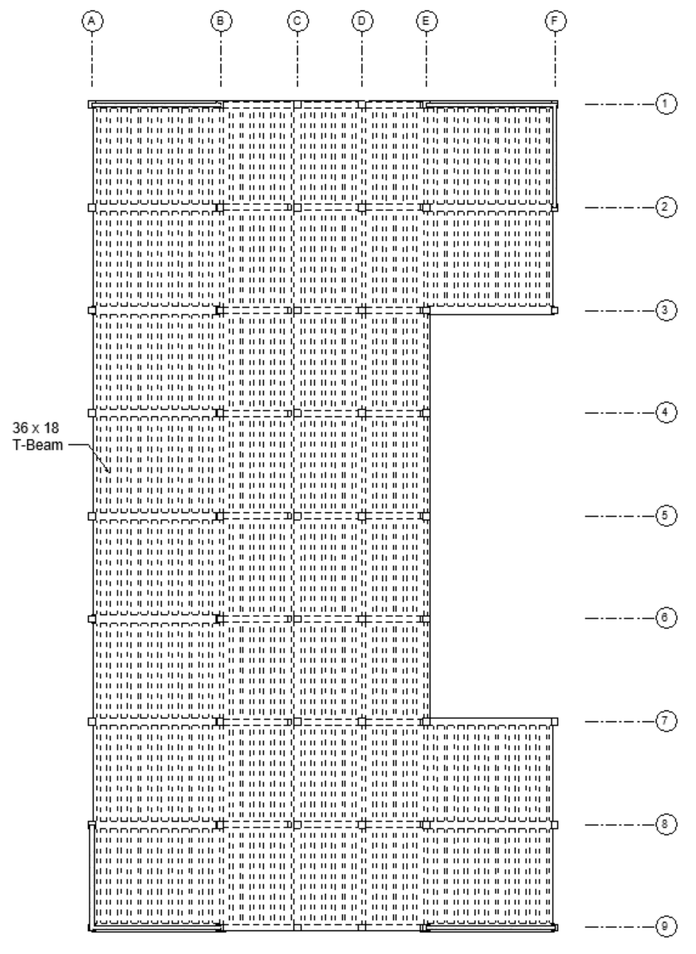


Figure 11: Concrete Beam Layout

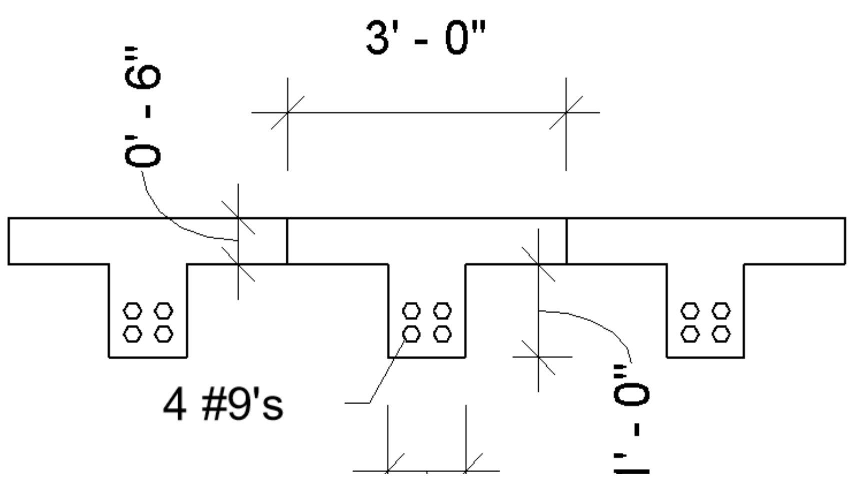


Figure 12: T-beam Cross Section

4.2.4 Design for Lateral Loads

Lateral loads were addressed in both the structural steel and reinforced concrete designs to add additional support. Design parameters for lateral loads can be seen in Table 11 below. In the steel design, an X bracing system was used on each floor to control deflection from the wind loading since that is the governing load combination. This is because of the little to no seismic activity in the New England area. Bracing was set up to use light weight members in tension that did not require supporting any load in compression. This made solving for the size of these members straight forward because it made the system determinate. When sizing members, the radius of gyration was the governing component in this design which was determined by using L/r <300, as prescribed by chapter D 1 "slenderness limits" (Specifications, 2016). A table can be seen below showing the size of members used and their spans.

Table 11: Lateral Load Design Parameters

Basic Parameters	
Risk Category	III
Basic Wind Speed, V	100 mph
Wind Directionality Factor, K_d	0.85
Exposure Category	B
Topographic Factor, K_{zt}	1.00
Gust Wind Factor, G	0.836
Enclosure Classification	Enclosed
Internal Pressure Coefficient, GC_{pi}	+/- 0.18
Terrain Exposure Constant, α	7.0
Terrain Exposure Constant, z_g	1,200 ft

Table 12: Lateral Bracing for Steel Construction

Member Size	**Span (feet)**
WT4 x 17.5	43
WT2.5 x 8	28

In the reinforced concrete design option, shear walls were used to resist wind loads. Minimum design requirements from the American Concrete Institute (ACI) governed the design of this wall. The wall design was governed in three ways: the minimum wall thickness had to be greater than 7.5 inches, the wall had to be greater than 1/25 times the unsupported distance which is roughly 10" thick, and the minimum amount of rebar required for a wall is .002, which is used to limit cracking from shrinkage and temperature. The resulting wall that is used in 6 locations in the building is 56' tall x 20' wide x 10" thick.

4.2.5 Slab on Grade and Foundation Design

The design for both buildings contains a spread footing under every column with a frost wall around the border of the building. A 5-inch slab-on-grade was defined for the basement floor. This design was based on guidelines given by the Portland Cement Association (Packard, 1976) which uses the compressive strength of concrete of 4 ksi, the flexural strength of 569 psi, and the subgrade factor K of 100 pci. These three values were then used to compute a slab thickness of 5 inches with 760 psf allowable load (Packard, 1976). Copies of original blueprints were reviewed in the Gordon Library's Curation, Preservation, and Archives. Foundation notes stated the soil bearing capacity was 3 tons psf, which was used in calculating the size of the footings. The frost wall is used as a retaining wall to hold back the exterior grading and will give a border for the slab on grade.

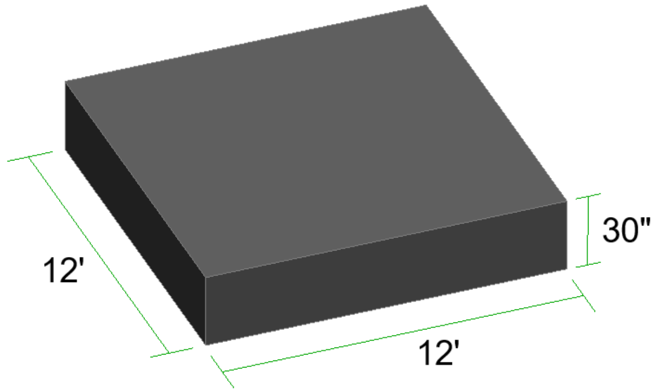


Figure 13: Typical Footing for Structural Steel Frame

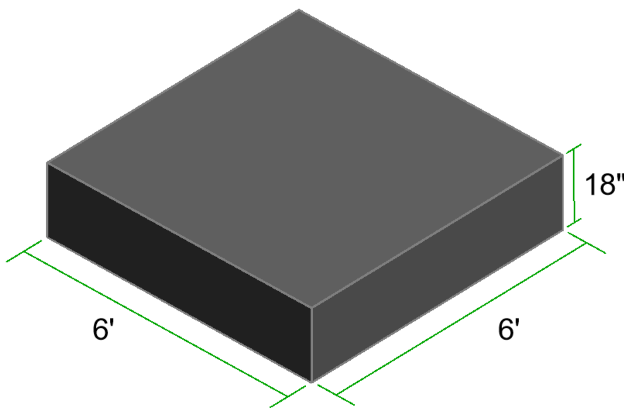


Figure 14: Typical Footing for Structural Concrete Frame

4.3 Objective 3 Results

4.3.1 Cost Estimate

The cost estimate for both the structural steel and reinforced concrete construction was completed using Revit's material takeoff feature, Microsoft Excel, and the *2019 Building Construction Costs with RSMeans data* textbook (Mewis, 2019). Using the Uniformat classification to organize the cost estimation, the costs per square foot of the substructure, shell, interiors, services, equipment and furnishings, special construction, and building site work for both concrete and steel were calculated (Charette, 2019).

For both the reinforced concrete and structural steel designs, many of the sections of cost estimation including: demolition costs, site work, equipment and furnishings, and interior work were all the same. On the other hand, framing, floor and roof construction, foundation design, and several utility services separated the cost between the steel and concrete options. These key differences can be seen in Table 13.

Table 13: Cost Estimate Overview

	Steel		Concrete	
	Cost/sq ft	Total Cost	Cost/sq ft	Total Cost
Framing	$12.35	$612,600	$26.12	$1,295,600
Floor/Roof Construction	$7.59	$180,400	$16.41	$813,900
Utilities	$35.90	$1,780,600	$39.50	$1,958,700
Foundation Design	$1.61	$79,900	$0.85	$42,200
Total Cost of Building	$189.40	**$7,850,200**	$214.82	**$9,307,000**

The driving influence behind the cost differences in the structural steel versus concrete frame was the ability of the steel framing to span longer distances. This allowed for fewer columns, simple concrete flooring with metal decking instead of the T-beam design used for the concrete frame, and easier access for utilities. The full cost estimation can be seen in Appendix K.

4.3.2 Schedule

The schedule for the steel construction framing plan was created using Primavera. The activity list includes 64 unique activities ranging from preparing the site through building commissioning and WPI moving into the completed facility. The tasks were arranged in the order needed to be completed. Some tasks were able to be completed simultaneously, but other tasks need to be completed before certain tasks can begin. For example, the construction crew cannot place the third-floor slab until the third-floor steel framing and metal decking has been erected. Alternatively, once the frame of the building is completed large amounts of utility work can be done at the same time. These trends are identified in the schedule by long lines of single tasks and big blocks of multiple tasks.

The completed schedule will take approximately one year and nine months. This entails from the first day of site prep to the last day of WPI moving back into the building. The start date was selected to be the first day of WPI's spring break, March 1st, 2018. This start date implies that all of the contents in Kaven Hall have already been removed, most likely over the winter break. This project will end on December 30th, 2020. All of the project milestones are shown in Figure 12. This takes advantage of WPI's term breaks and summers resulting in the least amount of displacement of faculty as possible.

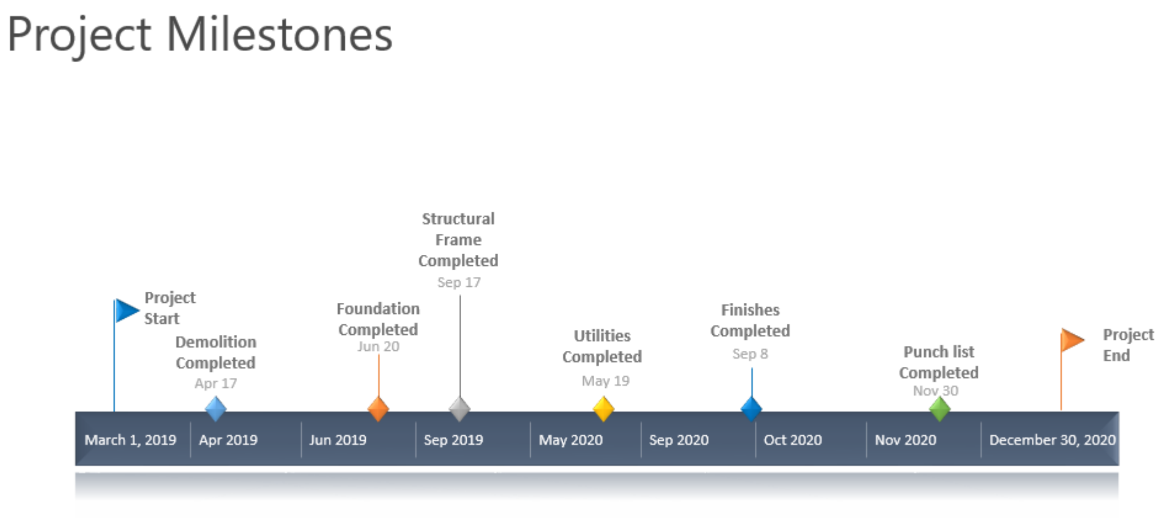


Figure 12: Project Milestones

5.0 Conclusions and Recommendations

All in all, the goals of the project were met and a design for Kaven Hall was developed. The gravity and lateral loads were calculated and used to size the structural components for the frames. The structural models for both steel and concrete were put into Revit to create a 3D model of the structure. The structural model for steel is seen below in Figure 13 and the model for concrete is seen in Figure 14. Using these models, the amount of material was calculated and used in the cost estimate, which was then compared to decide the best option. The tasks needed to complete the most cost-effective building were compiled into a schedule to construct the new building. The recommended method of construction for the new structural frame is structural steel. Steel allows larger spaces because it can span larger distances, thus accommodating the new layout. The steel had a much lower cost than the concrete option, partly because there were much less columns and footings.

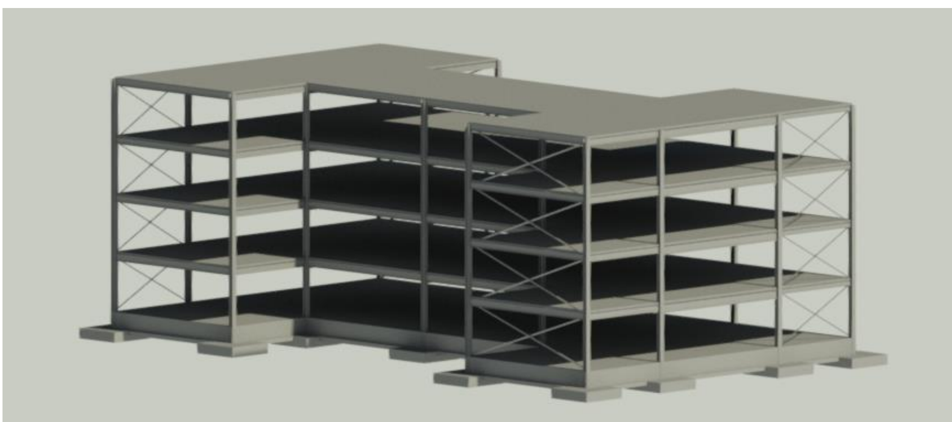


Figure 13: Steel Frame Structural Model

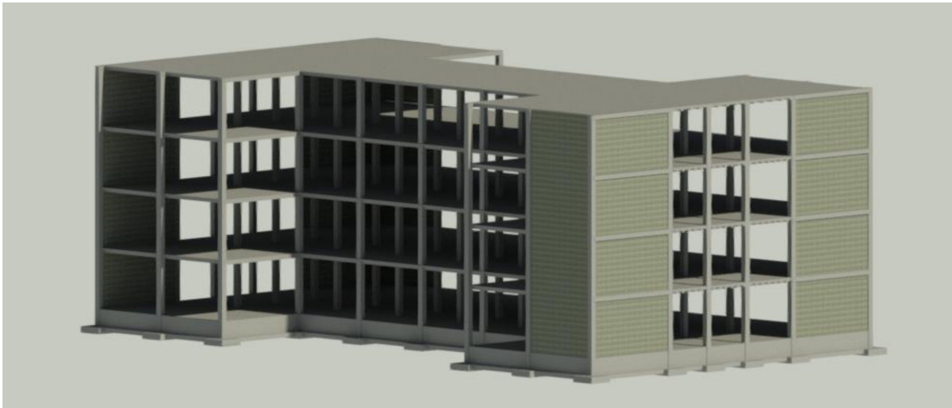


Figure 14: Concrete Frame Structural Model

At the completion of this project the team feels with more time many aspects of this project could be further analyzed. The structural system was designed neglecting the design of the angles, welds, or bolts for each individual connection. Also, for the concrete option the reinforcement developmental length and bends going into abutting members was neglected. This would need to be designed for both structures to further complete the design. Another aspect of the project that could be further investigated is the elevator shaft and footing designs. While the footings were designed to resist the loads of the buildings additional or larger footings may be required depending on the size of the elevator. The design now reflects the location of the shaft along with members sized appropriately for an opening.

Another area that could be altered for a more efficient design would be the floor plan layout. Specifically, for the concrete design, integrating the column layout was difficult because of the restricted span lengths of the T-beams. Also, looking into different roof options to top the building could reduce water run-off or electricity costs. Thoughts of a green roof or solar panel roof were discussed based on those features, but the idea was not pursued.

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Appendix A: Project Proposal

WPI Replacement to Kaven Hall: Structural Design

Major Qualifying Project Proposal

Presented by:

Laurence Cafaro, Nicholas Day, James Loring, & Eric Schroeder

Presented to:

Professor Leonard Albano and the Worcester Polytechnic Institute Civil Engineering Department

2018-2019

Abstract

Kaven Hall has housed the Civil and Environmental Engineering Department for over 60 years. Growing class sizes and an increase in the need for meeting spaces demand a new CEE building. A new building will be designed to comfortably accommodate this growing demand for space and provide the CEE students with a state-of-the-art facility. The scope of this project includes design of structural steel and concrete members, a functional floor plan to maximize space, project schedule, and a cost analysis.

Capstone Design Statement

To successfully complete the requirements produced by the Accreditation Board for Engineering and Technology (ABET) for the Capstone Design Project, numerous realistic constraints must be thoroughly evaluated during the design Process. This project will address constructability, environmental, sustainability, social, economic, health and safety, and ethics. Each of these constraints are described below.

Constructability:

Constructability is a very important consideration to be aware of throughout the design process. If the design is presented that is impossible to construct, then there is a loss in materials and time to redesign the structure. That is why our team will be working effortlessly to make this building easily buildable. Standard beams and columns will be used for easy of construction and affordability.

Environmental:

When working with an old building, such as Kaven Hall there are a lot of environmental issues to be concerned with. One of the big things to be concerned with are the building materials that are used such as things like lead paint, asbestos titles or insulations are some of the common things that should be monitored as the old building is torn down. This will effect demo costs if some materials need to be abated. Water runoff off will not be impacted drastically in this design since the new building foot print will not be much bigger than the existing layout. Runoff will still need to be considered throughout the building process and handled appropriately with erosion control and other temporary measures called for on the plans. There are also some very old trees in the front of the building, these will need to be evaluated for their safety to see if they can remain. If they don't remain new trees will be planted.

Sustainability:

Sustainably has been a growing topic over the last 20 years and for WPI as a growing Campus in an urban area. WPI needs a building that will be durable and last another 60 plus years with minimal maintenance. Some research will be done on using sustainable materials or sustainably sourced materials. Another way that we can encompass sustainability in our design is producing the most efficient design limiting the unnecessary resources used.

Social:

A building on any campus must be socially accepted by its users for it to be efficiently used. The proposed design will be more user friendly for everyone. This starts with the professors who will have class rooms that adequately meet their needs. The building will be more accessible for all students with ADA Compliant rooms and this significant addition of an elevator. The facilities staff will enjoy working in this building as it will be tied into the loading dock already present at the base of Fuller Labs with easy access to the elevator to facilitate the distribution of paper goods and cleaning product and for easy removal of trash and recyclables.

Economic:

Economic analysis of the proposed building will focus mainly the structural components and there will be an estimated allowance for other elements of the building to understand the total cost of the project. Cost is an important consideration since it will be funded by WPI, and the board of trustees will want the most economical design that will meet their needs. This cost estimate will be compared to other construction options that WPI has evaluated for Kaven Hall.

Health and Safety:

Health and safety need to be considered for the duration of the project, especially in the construction period. The United States Department of Labor states that in 2016 that there were more than 14 deaths a day (United, 2018). Accident rates can be reduced by having more systems pre-fabricated by contractors at their warehouse. Long term safety factors that will be evaluated will be snow load, occupancy load and fire restrictions to name a few. To do this we will be using the Massachusetts Building Code (780 CMR), International Building Code (IBC 2015), and The American Society of Civil Engineers Standards (ASCE-10) to make sure we meet all safety requirements.

Ethics:

When it comes to ethics, proper decisions must always be made based on building codes, OSHA regulations, and morality. This will ensure that Kaven Hall is designed and built ethically and complies with all the required provisions. Understanding the appropriate licensure requirements for structural design will give us, the design team, insight and moral/ethical values when it comes to executing this project. Provisions and regulations must always be followed and should never be abused, even if there may be any potential loopholes. Building quality and the safety of the occupants are the most important concerns when it comes to designing and constructing a new building.

Licensure Statement

In the world of civil engineering obtaining licensure is the mark of being a professional and is the standard in todays' society. Only a licensed engineer may prepare, sign, seal, and submit engineering work and drawings to a public authority for approval and for public and private clients. Professional Engineers (PEs) are also responsible for the work of others in the engineering field, making sure that they follow high ethical standards of practice. Obtaining licensure is necessary for engineers who are aspiring to hold upper-level management positions in a civil engineering firm.

Obtaining licensure is a major milestone in the career of any engineer and is very rewarding. However, there is a level of difficulty that is involved with it, and it does take a significant amount of time to fulfill all the requirements necessary. To obtain licensure, aspiring engineers must first graduate from a four-year university engineering program accredited by EAC/ABET. Following graduation, engineers must take and pass the Fundamentals of Engineering Exam (FE). This is a 6-hour long exam that consists of 110 multiple choice questions that cover the basics learned throughout an engineer's college career. Topics include mathematics, statics, structural analysis, chemistry, and surveying just to name a few. Once the FE Exam is passed, aspiring engineers will now be recognized as an Engineer-In-Training (EIT). EIT's must then complete four years of work experience under the supervision of a Professional Engineer. Once four years are completed, an EIT can then register for the Principles and Practice Engineering Exam (PE). This exam lasts 8-hours and consists of 80 multiple choice questions. The PE exam is based on the particular discipline of civil engineering an individual practices in and which state they want to be licensed in. Each state has a different set of standards and qualifications. Aspiring engineers may also register and take the Structural Engineering Exam also known as the "SE". This exam is a 16-hour long test that tests for the competency in the field of structural engineering. This exam is designed for engineers who practice in jurisdictions that license structural engineers separately from other professional engineers. This 16-hour exam uses separate gravity and lateral components to test one's ability to safely design buildings or bridges, especially in areas of high seismicity and high wind.

In the practicing world of civil engineering it is necessary for an engineer to obtain the appropriate licensure in his/her discipline. Through the numerous amounts of structural calculations and designs a licensed engineer works to ensure the safety of those who interact and occupy a building or structure.

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1.0 Introduction

Kaven Hall is located on the corner of Salisbury Street and Boynton Street and is home to the Civil and Environmental Engineering Department at Worcester Polytechnic Institiute (WPI). It was built in 1954, and named after a graduate of the 1865 class, Moses Kaven a generous benefactor for WPI. Kaven Hall's exterior was built out of Brick and Limestone creating a sturdy exoskeleton. The floor plan of the building accommodates many different class sizes and faculty offices. Over the sixty plus years that Kaven Hall has provided for the WPI community, it is approaching time for a new facility. Kaven Hall is getting small for the growing class sizes that WPI has, and it is also limiting to the fact it does not have an elevator.

Our project will be a complete redesign of Kaven Hall to meet building code, fit typical class sizes at WPI, and be welcoming to the end users within the Civil and Environmental Engineering department. The proposed building that our team will be designing over the next two terms is a four story I-shaped building. This building will include multiple 70-student class rooms, 25-student class rooms, tech suites, offices, testing laboratories, and computer labs. We will be designing both steel and concrete frames to be compared for constructability, economics and scheduling. Other aspects of our project will include the survey of existing conditions, scheduling, cost estimates, and foundation design.

2.0 Background

This project is intended to provide a complete redesign of Kaven Hall by designing both steel and concrete frames that will be compared for constructability, economics and scheduling. The most constructible, cost effective and efficient design will then be identified and selected. The ultimate goal of this design is to provide students and professors with the necessary amenities and space needed to further their education and research in Civil Engineering and beyond. By developing this new design, Kaven Hall, will finally be able to accommodate the larger classes of sixty-plus students for the CE 2000 level classes, and be able to efficiently perform class labs and research in the new laboratory on the bottom floor of the building. In order to properly deliver this project, certain background knowledge and understanding is required. This background section provides an overview of the necessary information regarding the numerous factors that must be taken into consideration in the design of a new Kaven Hall. Information regarding the current status of the project site, the regulatory provisions and design parameters to deliver a safe and constructible project, and the properties of the materials used can be found in this section.

2.1 Existing Conditions

Kaven Hall sits at the corner of Boynton Street and Salisbury Street housing the Civil and Environmental Engineering Department. This building was completed in 1954 and was a completely Civil Engineering building and over the 60 years that it has serviced WPI it has had a couple of major renovations which has changed the configuration of rooms and how space was utilized. The original blue prints are in the WPI archives, so the initial design and layout is well documented. The building was designed in the shape of a C for Civil engineering and it has three floors in service with an attic space. The basement floor is approximately at grade level and has not changed in use over the years: it has been an area for lab testing for various classes. On the other two floors of the building there were three individual dedicated rooms for sophomores, juniors, and seniors. In these rooms, each student in the department would have their own desk and they could leave work at school, so it wouldn't need to be transported to and from school. Throughout the other two floors there were class rooms, coat rooms, offices, and other special dedicated rooms. One feature that was common on campus at this time was one library for each department so Kaven Hall had a library for civil reference books.

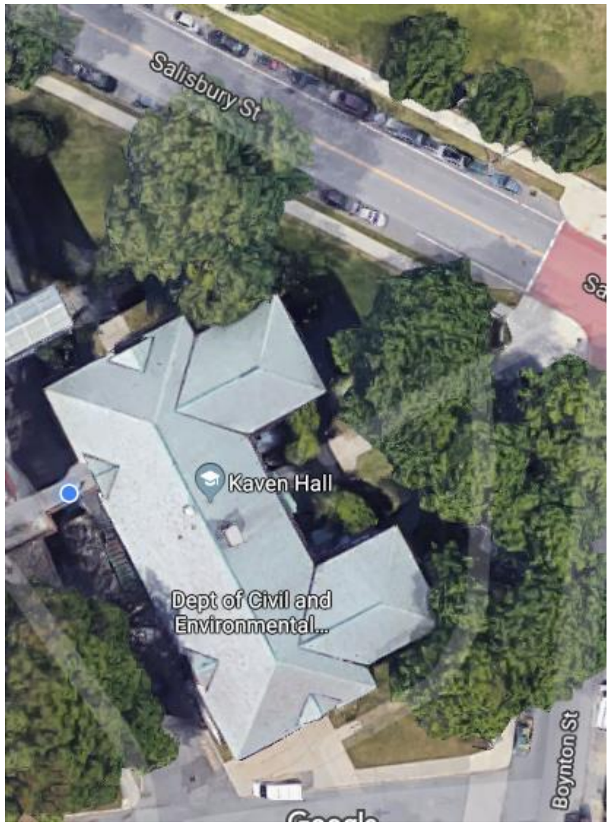

Figure 15: Kaven Hall Google Maps View

2.2 Construction Materials

Over thousands of years of construction history, some of the building materials have changed drastically, and some have stood the test of time and are still used today. When designing a building it is crucial that the best materials are selected to make the final outcome a resilient building that will last for the end users with as little maintenance as possible.

2.2.1 Concrete

Concrete is a composite material that is formed from a hydration reaction, which reaches its rated strength at 28 days. Concrete normally is made with Portland cement, aggregate, water and admixtures as needed to produce the desired material properties and quality. Concrete is used in most cases because of its workability and versatility on a job with such a high strength once cured.

Reinforced concrete consists of reinforcing bars, rebar for short, embedded in concrete. The rebar is generally made of steel with nobbles or ridges that anchor firmly into the concrete, in order to avoid slipping. There are many techniques used to reinforce concrete, but one technique consists of tying rebar together with wire to form a cage, which the wet concrete is then placed on and hardens over. The concrete and rebar combine to resist compressive, tensile, and shear forces. The rebar is able to increase the compression capacity of the reinforced concrete while also absorbing the majority of the tensile and shear forces.

The use of reinforcement increases compression capacity, enhances ductility, and reduces long-term deflections of concrete elements. It also increases the flexural capacity of beams. Another technique for reinforcing concrete uses stirrups, ties, and hoops to provide lateral reinforcement, which resists principle stresses resulting from shear. This technique provides confinement to column beams and joints in highly stressed areas of compression zones, which is especially important in structures located in high seismic risk zones because it improves their strength and ductility.

Steel is the common choice for reinforcement because it expands and contracts in the heat and cold roughly as much as concrete. This reduces the likelihood of the steel cracking the concrete due to varying temperatures. However, if the concrete cracks and water is able to penetrate the reinforced concrete structure, it can rust the steel rebar. This process ruins the durability of concrete structures, and it is difficult to detect and repair. Deterioration due to rusting can begin in as little as 10 years and has resulted in shorter life spans of 50-100 years in reinforced concrete structures (Keulemans).

2.2.2 Steel

Steel is a very common material used for constructing high occupancy buildings since it can carry very high compressive and tensile forces. Steel is used over other materials due to its speed of construction with the use of bolts or welds. Smaller, easily transportable beams and columns can come together on-site to produce a strong lightweight building frame. These beams and columns are typical w-section style beams, which can carry high tension and compressive forces in a lighter, more compact shape.

Steel Structures tend to have longer spans between columns than concrete structures. Normally, buildings that have steel structures allow for more flexibility and can be divided up with metal stud and gypsum boards more easily. When compared to concrete, steel has more available open space due to the reduced number of columns which allows for the space to be easily repurposed. Steel structures also produce generally more variability in design since they can generally implement large overhangs and glass faced wall more easily.

One of the properties that makes steel a great structural framing component is its ductility. With the increased ductility, steel greatly reduces the effective seismic loads that must be accounted for compared to the effective seismic loads that a rigid concrete frame will have to carry. This will allow for a smaller members to be chosen, reducing cost of the project and making the self-weight of the frame lower.

2.3 Design Tools

There are many engineering tools that can be utilized in the design process for a particular structure or building. Autodesk Revit, RAM Structural System, Microsoft Excel, and Tekla's TEDDs are some of the software we will be using in this MQP to perform calculations, structural analysis, and ultimately the redesign of Kaven Hall.

2.3.1 Revit

Autodesk Revit is a 3D modeling software typically used for creating structural and architectural models of buildings or structures. The software allows a design to be created in 2D as well as a 3D representation. This software is great for adding architectural and structural members for a particular structure. For example, the selection of beam and column sizes can be implemented within the software to give an actual representation of the building frame.

2.3.2 RAM Structural System

RAM Structural System is a structural analysis software provided by Bentley that allows users to create computer models of the structural members they have designed. For example, a steel framing system for a particular building design can be implemented in RAM. Loads and load factors must then be applied to the structure in both the vertical and horizontal directions to simulate the various load combinations that must be considered for design based on the specific building codes governing local construction. Once the loads and loading combinations are implemented, this software has the ability to size all the structural members to the most optimal, cost-effective, and lightest structural design. The software is also capable of analyzing the effects of the loads on the given structure by determining moment, shear, and deflection values. RAM has made itself very convenient for structural engineers by providing printable reports for each individual component of the building's shell (ie: an exterior beam) along with the entire structural frame.

2.3.3 Microsoft Excel and Tekla's TEDDs

Hand-calculations can become repetitive when designing multiple components of a building with numerous loads and loading combinations. Microsoft Excel software provides the ability to create spreadsheets capable of performing the necessary calculations for multiple iterations of similar member types. The software makes use of data and formulas to output the necessary design values. The sheets can be repeated, increasing the speed and efficiency of the design process. Microsoft Excel can be very helpful when trying to calculate the snow and wind loading on a specific part of the building through the easy development and implementation of the design equations in Excel.

Just like Microsoft Excel, TEDDs is another software that can be used to complete numerous repetitive calculations and can be actually linked back to Excel. Created by Tekla, TEDDs is a fast and easy software to learn, and is widely used in the field by structural engineers. TEDDs has the ability to perform 2-D structural frame analysis, generate loads and loading combinations, and determine properties for sections.

2.4 Design Parameters

When it comes to designing any structure or building, safety and constructability are the ultimate underlying responsibilities of any engineer. It is extremely important and a requirement for a building project to comply with all national, state, and local rules and regulations to ensure a safe design and building practice. In Massachusetts, all current and future buildings must be in compliance with provisions of Minimum Design Loads for Buildings and Other Structures (ASCE 7-10), the International Building Code (IBC 2015), the Americans with Disabilities Act (ADA) and the Massachusetts State Building Code (780 CMR).

Table 14: Design Parameters

Provision	**Use**
Minimum Design Loads for Buildings and Other Structures (ASCE 7-10)	Snow Loads Wind Loads Seismic Loading Floor and Roof Live Load
International Building Code (IBC 2015)	General building heights and area Foundation Inspections General structural design Occupancy requirements Quality control of materials
Americans with Disabilities Act (ADA)	Hall way widths Door widths Elevator requirements Ramp slopes
Massachusetts State Building Code (780 CMR)	Adopts IBC and ASCE 7 by reference, as well as provides certain provisions unique to Massachusetts

In order to successfully redesign Kaven Hall the project has been separated into phases. Completing these phases in a specific timeframe will keep the project on schedule and will help to limit errors and omissions that would undermine the quality of work. Table 2 lists the phases of the project and the tasks associated with each phase. Figure 2 illustrates the project schedule and outlines the critical path in completing the report.

Table 15: Methods & Deliverables Breakdown

Phase	Activity
1. Existing Conditions	Site Evaluation.
	Faculty Interviews.
	Site Survey.
2. Floor Plan Layout	Faculty Interviews.
	Locate Construction Restraints in Building Code.
	Organize necessary elements within a feasible budget.
3. Building Design	Foundation Design.
	Concrete Frame Design.
	Steel Frame Design.
4. Design Analysis	Compare cost of steel vs concrete design.
	Compare estimated time of completion of steel vs concrete design.
	Compare spaces available to information from interview.
5. Schedule Estimate	Demolition of existing building
	New Construction
6. Cost Estimate	Final Design

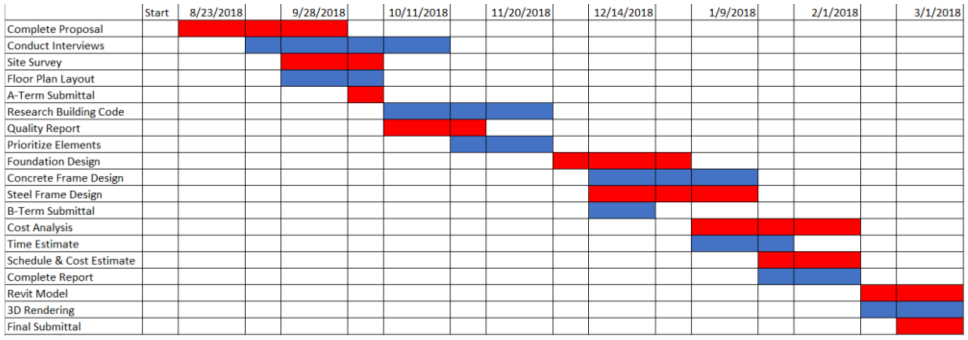

Figure 16: MQP Methods and Deliverables Schedule

3.1 Existing Conditions

The first phase in any design process is to evaluate the site beforehand. The building will be analyzed for key features that need to be retained in the new design. The building performs many different functions, thus, documenting them is important to the final design. To further understand these functions, interviews with a variety of professors within the civil engineering department will be held. It is imperative to the design to address concerns of those occupying the space on a daily basis.

An interview will be conducted with the academic scheduler, Cathy Battelle. This interview will provide us with the occupancy and types of academic spaces needed. With this information we can develop a list of necessities for the new design.

According to the original drawings there are no records documenting the site boundaries and elevations. To complete the site evaluation a survey will be conducted on the topography of the site. With this being said, a series of data points will be collected around Kaven Hall to enable an accurate foundation design.

3.2 Floor Plan Layout

The floor plan layout will incorporate all the ideas gathered in phase one. After all the wants and needs have been received, the building codes need to be taken into consideration. Parameters such as emergency exits, capacities, and ADA compliancy need to be taken into consideration. The current building code is the International Build Code 2015, but there are also criteria in the Massachusetts State Building Code that will be used in this design. The last part of this process is to organize all of the elements of the design within a reasonable amount of space and for a feasible amount of money. With the combination of the building code and the desires of faculty, there will need to be a prioritization of elements. Multiple layouts will be proposed and evaluated to identify the one that fits the best.

3.3 Building Design

After the floor plan layout is completed, the structural design of the new building will begin. This design will be based off today's building codes and will be as cost-effective as possible; while still adhering to the wishes of the university.

3.3.1 Foundation Design

When designing a foundation of any building, a soil analysis must first be executed. For this design of Kaven Hall, the original 1952 test results will be used. Ideally, foundations tend to be composed of reinforced concrete and typical components will be calculated/repeated throughout the design. Extra components will be designed only for special cases forced by the layout. Important focuses of design in this section are:

- Typical / Special Spread Footings
- Typical / Foundation Walls
- Typical / Continuous Footings

3.3.2 Frame Design

The next step involves two structural systems for the rest of the building. The first design will continue to utilize concrete for the building superstructure. This design will benefit from the great compressive strength of concrete but will have to accommodate scheduling challenges due to New England's climate. The second design will use steel as the primary structural frame. This alternative will benefit due to steel's adaptability and faster construction rates. As for the foundation, building components will be designed and adopted repetitively throughout most of the frame. Important focuses of the structural design are:

- Typical / Special Beams
- Typical / Special Girders
- Typical / Special Columns
- Roof System

3.4 Design Analysis

After the designs are completed, they will be compared based on their layout capabilities, scheduling, and cost. The estimated time to complete these designs is important because this is an academic building. Based on the previous construction of academic buildings on campus this project should be implemented as a design-build with a "fast-track" schedule. This will allow WPI to plan accordingly to the time implications of the demolition and construction of the new building. The time as mentioned before will be incorporated into the cost, which is the most important thing for the owner. This will be evaluated on worker days and cost overhead per day. The amount of material and time required for installation will be estimated for both designs. Material takeoffs will be used and formulated in an Excel spreadsheet. This cost analysis will be the leading factor for identifying which design alternative will be selected.

4.0 Deliverables

At the completion of this project our team will provide a structural design of our proposed Kaven Hall. Along with this will include analysis of the structural members, foundation, project schedule, cost analysis and a model of the proposed building. Our project will be summarized in a final report which will include our calculations, design consideration, and constraints.

Table 16: Deliverables Responsibilities

Deliverable	Primary Author(s)	Assistant Author(s)
Proposal	All	All
Foundation	James	Larry
Building Structure	Larry	James
Cost Analysis	Eric	Nick
3D Model	James	Nick
Final Report	All	All
Background	Larry	Nick
Methodology	Eric	Nick
Report Editing	All	All
Paper Formatting	Nick	All
Poster Design	Nick	Larry

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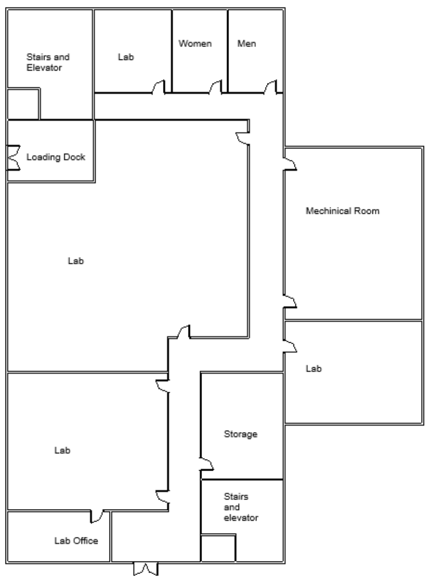
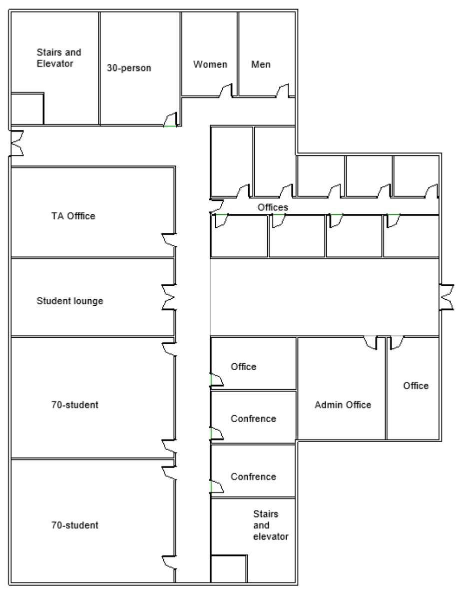
Appendix B: Alternative Layouts

T-Shape

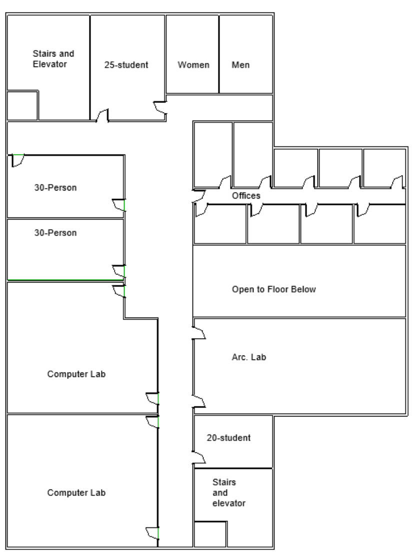
Basement



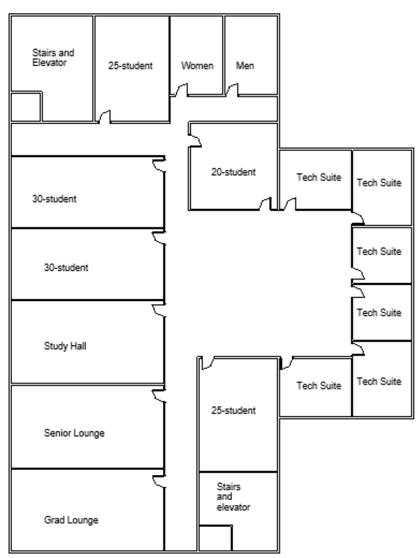
First Floor



Second Floor

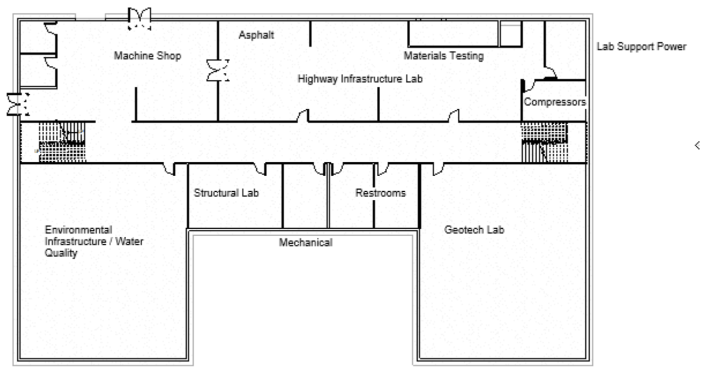


Third Floor



C-Shape

Basement



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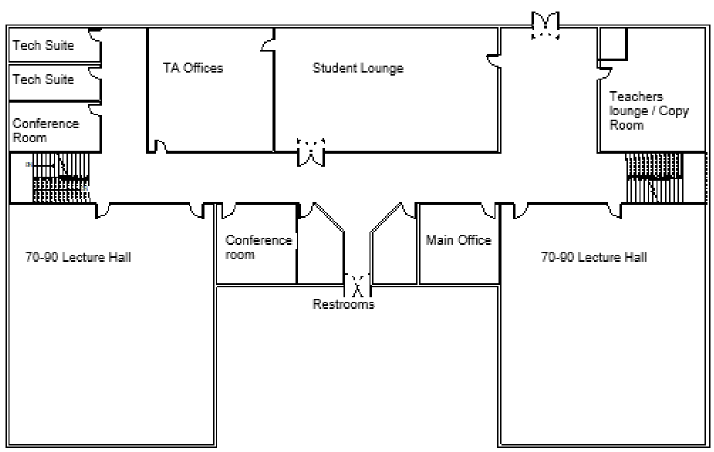

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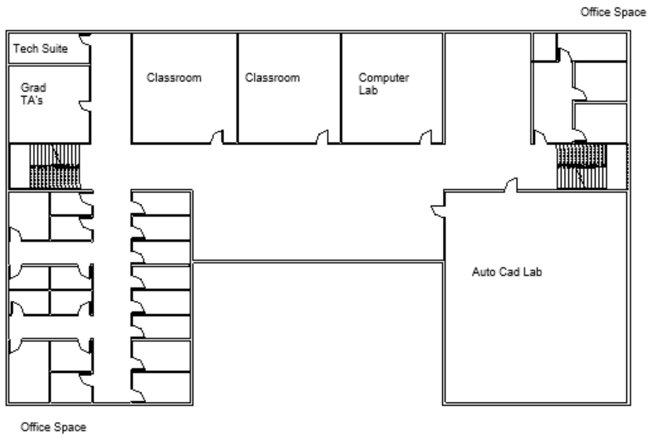
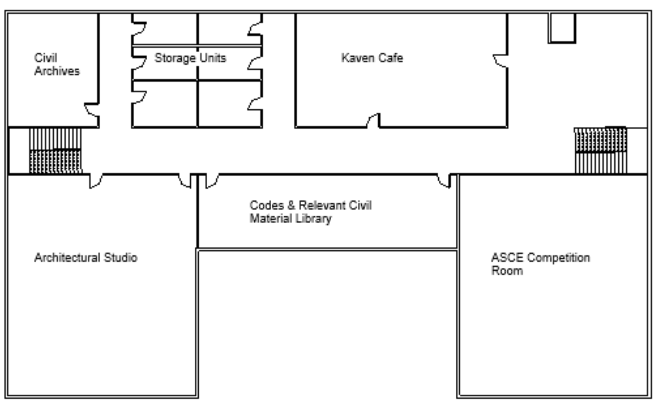
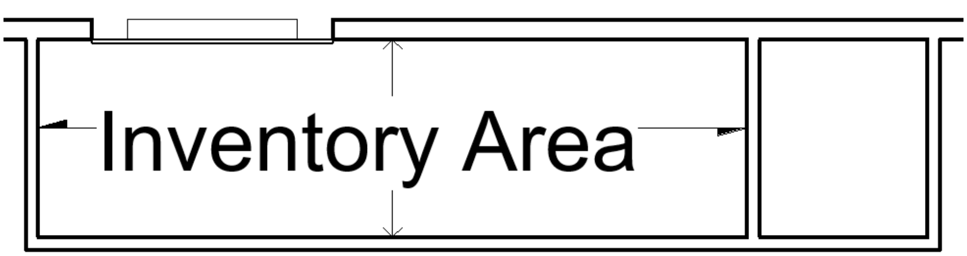


Third Floor

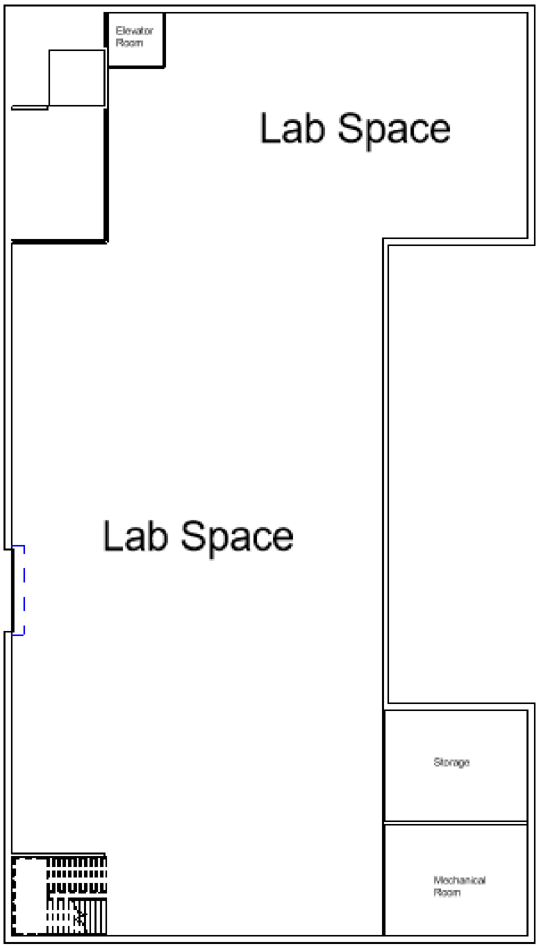


Mezzanine

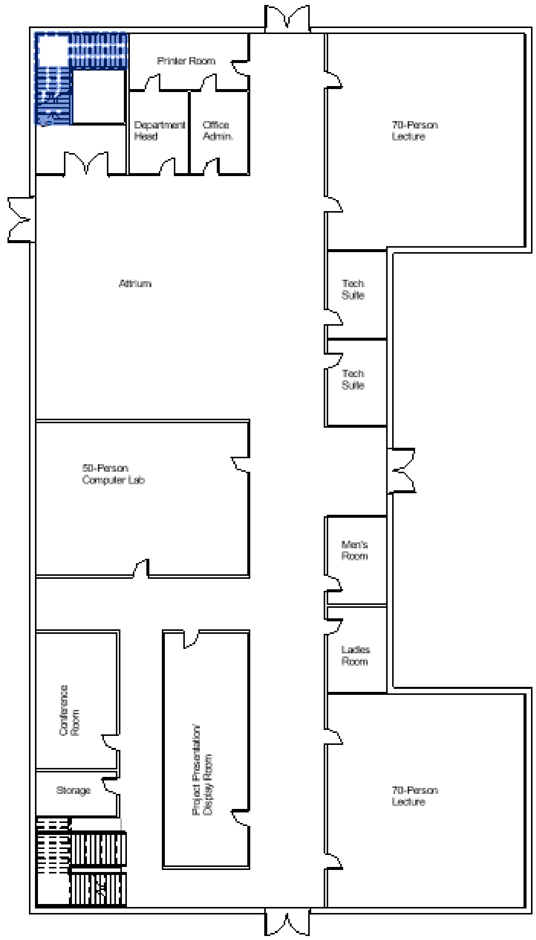


I-Shape

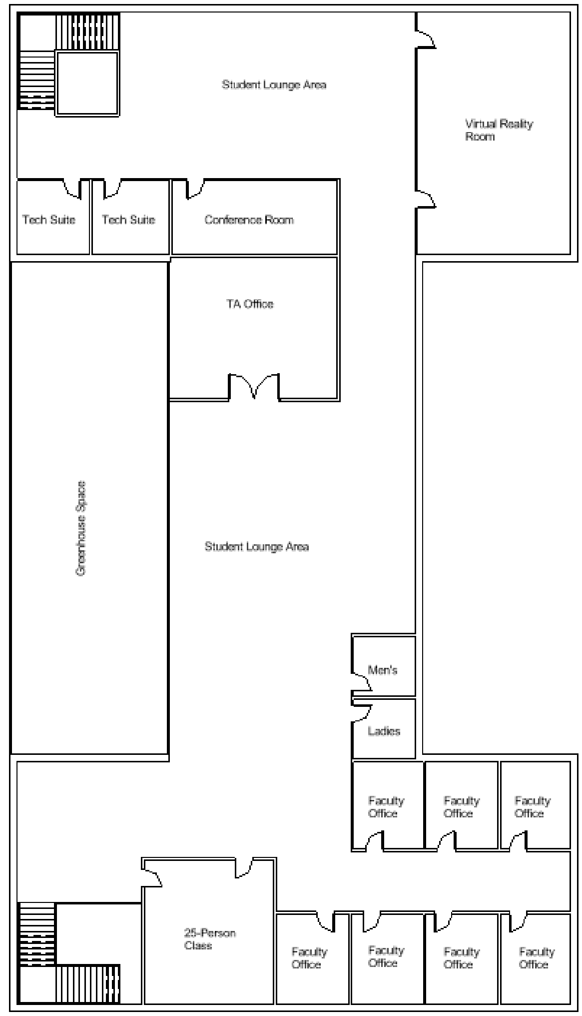
Basement



First Floor



Second Floor **Third Floor**



Appendix C: Survey Questions

Student Survey

1. What is your major?
2. What is your year of graduation?
3. Do you think that Kaven Hall's basement lab space is conducive to work flow?
4. Are Kaven Hall's computer labs adequate in space?
5. Would you prefer large classrooms such as (KH116) or smaller classrooms such as (KH115)?
6. Do you use the Student Lounge as a workplace?
7. Do you think the Student Lounge is a comfortable working environment?
8. Have you had a hard time finding faculty offices in Kaven Hall?
9. Do you prefer to work and meet, in public or private areas? (Lounge vs Tech Suite)
10. How likely would you visit a small cafe located in Kaven Hall?
11. What is your favorite aspect of Kaven Hall?
12. What do you dislike most about Kaven Hall?
13. What do you think is missing from Kaven Hall?

Faculty Survey

1. Do you primarily work in Kaven Hall?
2. Do you think that Kaven Hall's basement lab space is conducive to work flow?
3. Are Kaven Hall's computer labs adequate in space?
4. Would you prefer large classrooms such as (KH116) or smaller classrooms such as (KH115)?
5. If you have an office in Kaven Hall, do you like the location relative to the spaces in the building?
6. How likely would you visit a small cafe located in Kaven Hall?
7. What is your favorite aspect of Kaven Hall?
8. What do you dislike most about Kaven Hall?
9. What do you think is missing from Kaven Hall?
10. Any other comments?

Appendix D: Snow Load

2018 MQP | Snow Loading | 1

Risk Category: III   flat roof

Ground Snow Load (p_g) : 55 psf

$p_f = 0.7 C_e C_t I_s p_g$

(sec. 26.7)

$C_e = 0.9$; fully exposed roof, terrain category B

$C_t = 1.0$; thermal factor

$I_s = 1.10$; importance factor (table 1.5-2)

$p_f = (0.7)(0.9)(1.0)(1.10)(55) =$ **38.115 psf**

Snow Drift @ patio

windward drift = 2.85 ft   leeward drift = 3.8 ft

l_u = 80 ft lower roof length

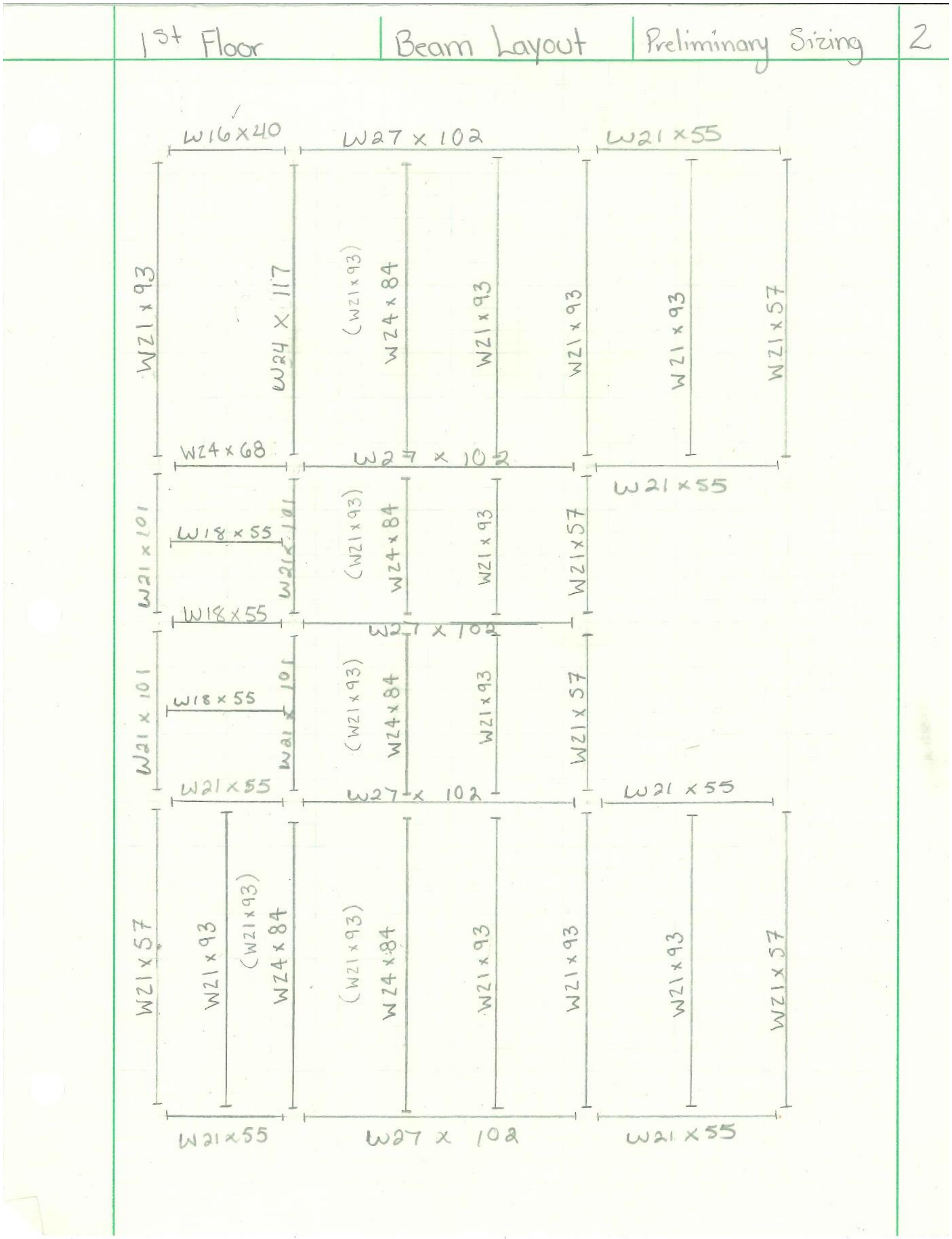
h_d = 3.8 ft (fig 7-9) → * 0.75 = 2.85 ft

Snow surcharge $p_d = h_d \gamma$

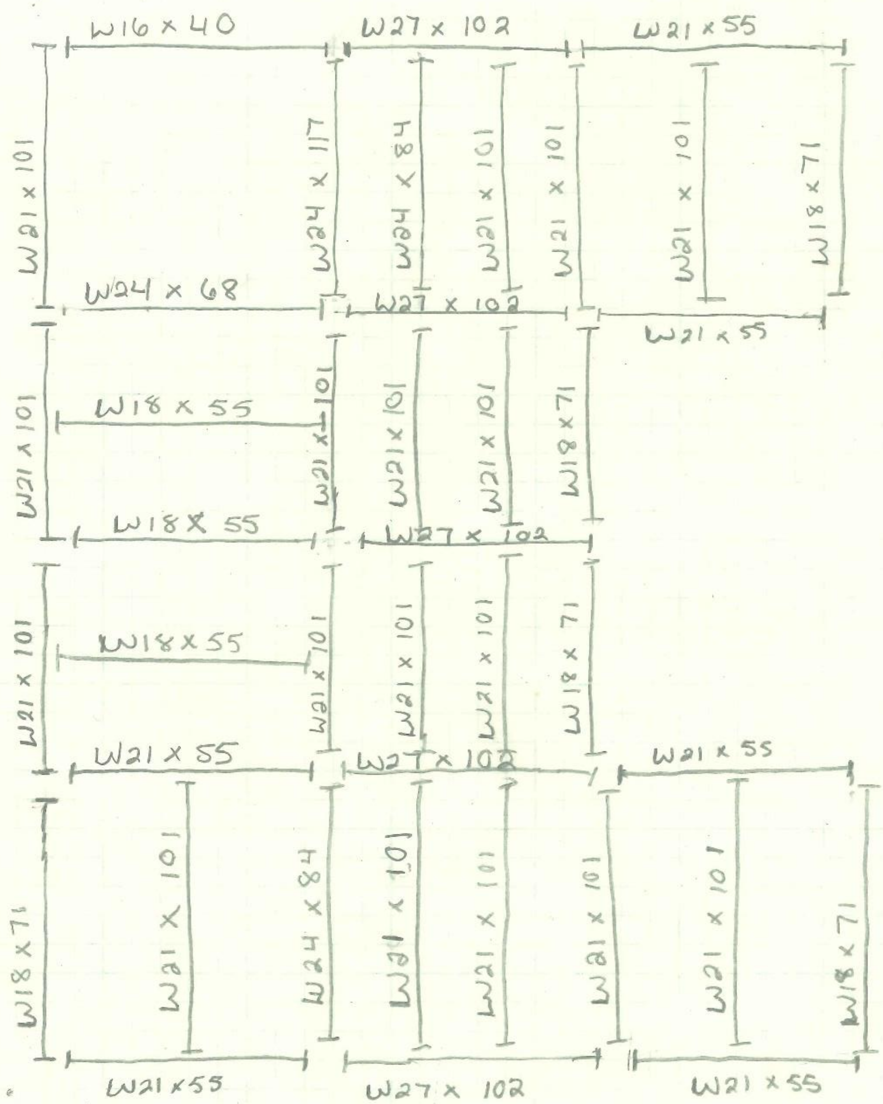
$\gamma = 0.13 p_g + 14 \rightarrow (0.13)(55 psf) + 14 = 21.5 psf$

$p_d = (3.8 ft)(21.15) =$ **80.37 psf**

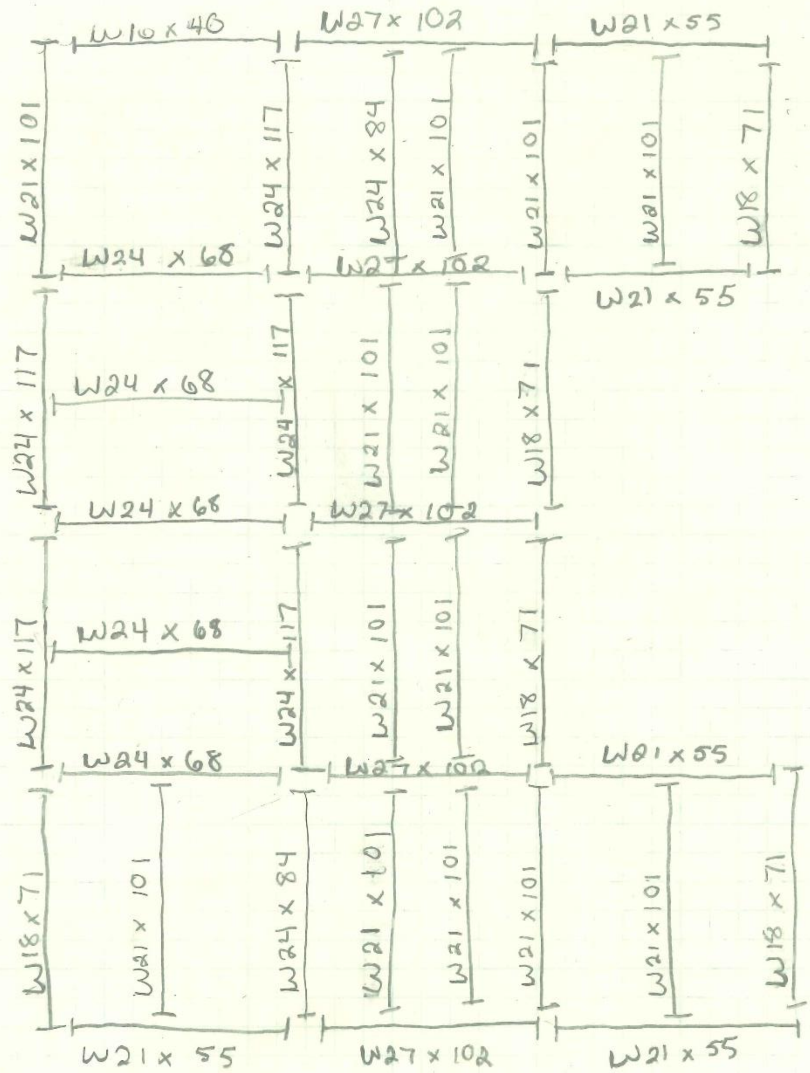
Appendix E: Gravity Load Steel



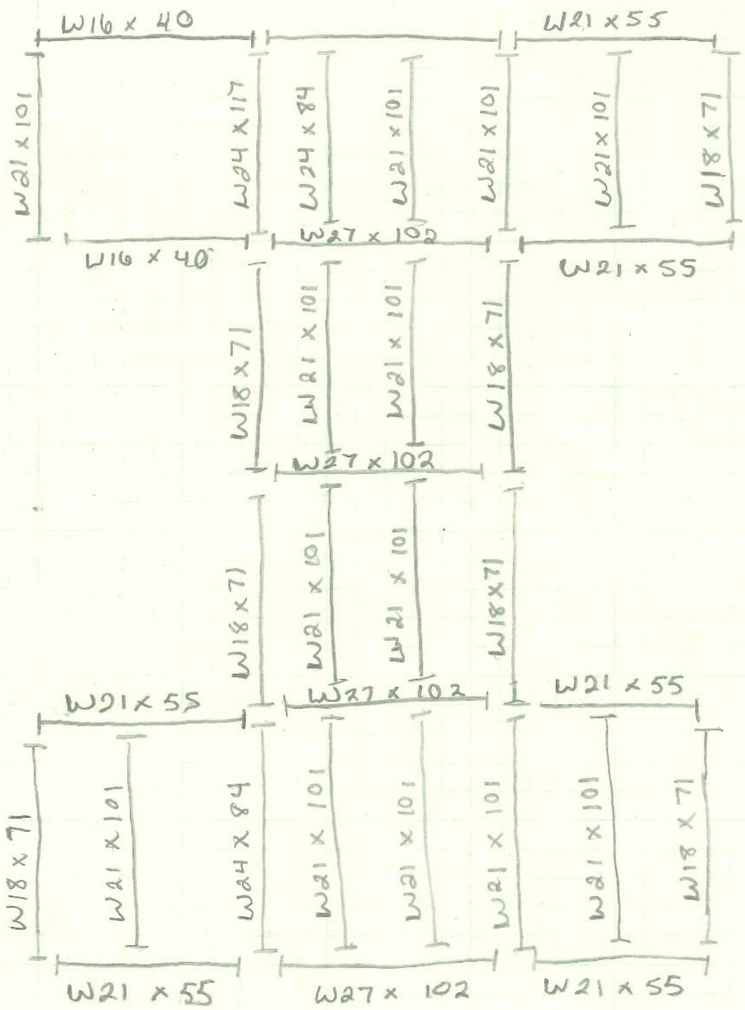
2nd floor | Beam Layout | Preliminary Sizing | 3



3rd floor | Beam Layout | Preliminary Sizing | 4



Roof | Beam Layout | Preliminary Sizing | 5

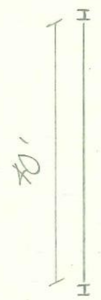


* Snow load of 38.115 psf

* Service LL of 20 psf

Location :

4.5" concrete slab w/ 3" metal decking



tributary width = 6.25 ft

Spacing = 12.5 ft

Design for Construction

DL for Metal Decking → 3psf × 6.25' = 18.75 lb/ft

LL for weight of concrete → 72 × 6.25' × 1.1 = 495 lb/ft

LL for construction → 25psf × 6.25' = 156.25 lb/ft

Load Combinations

$1.4D \rightarrow 1.4(18.75) = 26.25$ lb/ft

$1.2D + 1.6L \rightarrow 1.2(18.75) + 1.6(495 + 156.25) = 1064.5$ lb/ft

$M_u = \frac{1}{8} wL^2 \rightarrow \frac{1}{8}\left(\frac{1064.5}{1000}\right)(40^2) = 212.9$ ft-kips

$$Z_x = \frac{M_u}{\phi f_y} = \frac{212.9 \times 12''}{0.9(50ksi)} = 56.77 \text{ in}^3$$

$66.5in^3 > 56.77in^3$ ✓ $\phi M_n = 249$ ft-kips

$M_u \leq \phi M_n \rightarrow 212.9 \leq 249$ ✓

Try W18 × 35

$$\Delta = \frac{5 w_u L^4}{384 EI} = \frac{5(0.549)(40^4)(1728in^3)}{384(29{,}000)(510in^4)} = 2.137 \times$$

Design For Occupancy

DL for Metal Decking	3psf × 6.25' = 18.75 lb/ft
DL for CMEP	10psf × 6.25' = 62.5 lb/ft
Concrete	72psf × 6.25' = 450 lb/ft
Service Load	100psf × 6.25' = 625 lb/ft
Steel = 35 lb/ft	

Load Combinations

$1.4D \rightarrow 1.4(18.75 + 62.5 + 450 + 35) = 792.75$ lb/ft

$1.2D + 1.6L \rightarrow 1.2(18.75 + 62.5 + 450 + 35) + 1.6(625)$

$= 1{,}679.5\ ^{lb}/_{ft}$

$M_u = \frac{1}{8} wL^2 \rightarrow \frac{1}{8}(1.6795\ k\text{-}ft)(40^2) = 335.9'^{K}$

$$Z_x = \frac{M_u}{\phi f_y} \rightarrow \frac{335.9 \times 12'}{0.9\ (50)} = 89.57\ in^3$$

$66.5 in^3 \leq 89.57 in^3 \rightarrow$ <u>FAILS</u>

Try W21 x 44 $\quad Z_x = 95.4 in^3 \quad \phi M_n = 358$

$$\Delta = \frac{5 w_u L^4}{384\ EI} = \frac{5(0.57525)(40^4)(1728 in^3)}{384(29{,}000)(843)} = 1.35'' \quad X$$

Required $I_x \rightarrow 843 \times 1.35/1 = 1138.05 in^4$

Try W21 x 57

$$\Delta = \frac{5 w_u L^4}{384\ EI} \rightarrow \frac{5(0.58825)(40^4)(1728 in^3)}{384(29{,}000)(1170)} = 0.999\ ✓$$

FLB : $\frac{b_f}{2t_f} \leq 0.38\sqrt{E/f_y} \qquad 5.04 \leq 9.2$ ✓

WLB : $\frac{h}{t_w} \leq 3.76\sqrt{E/f_y} \qquad 46.3 \leq 90.5$ ✓

B_E $\quad \frac{1}{2}$ spacing $= \frac{1}{2}(6.25' \times 12'') = 37.5''$ (USE)

$\quad \frac{1}{8}$ span $= \frac{1}{8}(40' \times 12'') = 60''$

C = T

$0.85 f'_c\, a\, b_E = A_s f_y$

$0.85(4ksi)\, a\,(37.5'') = 16.7 in^2(50 ksi) \rightarrow a = 6.55 in$

$a = 6.55 in \leq 7.5''$ ✓

$Y_1 = 0,\ Y_2 = t_s - a/2 \rightarrow 7.5'' - 6.55''/2 = 4.225 in$

$C_c = 0.85 f'_c\, a\, B_E \rightarrow 0.85(4)(6.55'')(37.5'') = 835.125$ kips

$C_c = \Sigma Q_n \rightarrow 835.125$ kips

$V_n = T = A_s f_y \rightarrow (16.7 in^2)(50 ksi) = 835$ kips

# of Studs $\rightarrow N = \frac{V_n}{Q_n}$

$$Q_n = 0.5\, A_{sc} \sqrt{f'_c E_c} \le R_g R_p A_{sc} f_u$$

$$A_{sc} = \frac{\pi \delta^2}{4} = \frac{\pi (3/4")^2}{4} \rightarrow 0.4418 \text{ in}^2$$

$$Q_n = 0.5 (0.4418) \sqrt{4(3625)} \le (1)(0.6)(0.4418)(65)$$

$$Q_n = 26.60 \le 17.23 \text{ k/stud}$$

$$\# \text{ of studs} = \frac{835}{17.23} \rightarrow 48.46 \text{ studs}$$

Spacing

$$L = \frac{40' \times 12}{48} = 10"$$

Location: row 4, column line A - B Second Floor

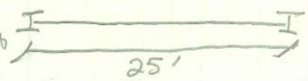
4.5' concrete slab with 3" metal steel decking

Design for Construction

DL for metal decking 3psf * 12.5' = 37.5 lb/ft

LL for concrete 72 * 12.5 * 1.1 = 990 lb/ft tributary width: 12.5'

LL for construction 25psf * 12.5' = 312.5 lb/ft



Load Combinations

① $1.4D \rightarrow 1.4(37.5) = 52.5\ \text{lb/ft}$

② $1.2D + 1.6L \rightarrow 1.2(37.5) + 1.6(990 + 312.5) = 2129\ \text{lb/ft}$

$M_u = \frac{1}{8}(2.129)(25)^2 = 166.328\ \text{kip-ft}$

$Z_x = \frac{M_u}{\phi f_y} = \frac{166.328 * 12''}{0.9(50)} = 44.35\ \text{in}^3$

*** try W14 x 30 $\phi M_n = 177 > 166.328$ ✓

$Z_x = 47.3\ \text{in}^3 > 44.35$ ✓

$$\Delta = \frac{(5)(1.0575)(25)^4(1728)}{384(29{,}000)(291)} = 1.10\ \text{in} < 1'' \times$$

Required I_x

$291\left(\frac{1.10}{1}\right) = 320\ \text{in}^4$

*** try W14 x 34

$$\Delta = \frac{(5)(1.0615)(25)^4(1728)}{384(29{,}000)(340)} = 0.946\ \text{in} < 1'' \checkmark$$

Design for occupancy

DL for metal decking	3psf * 12.5′ = 37.5 lb/ft
DL for CMEP	10psf * 12.5′ = 125 lb/ft
Concrete	72 * 12.5′ = 900 lb/ft
service load	100psf * 12.5′ = 1250 lb/ft
Steel	34 lb/ft

Load Combinations

$1.4D \rightarrow 1.4(37.5 + 125 + 900 + 34) = 1535.1 \text{ lb/ft}$

$1.2D + 1.6L \rightarrow 1.2(37.5 + 125 + 900 + 34) + 1.6(1250) = 3315.8 \text{ lb/ft}$

$M_u = \frac{1}{8}(3.3158)(25)^2 = 259.047 \text{ k-ft}$

$Z_x = \frac{M_u}{\phi f_y} = \frac{259.047 * 12''}{(0.9)(50)} = 69.08 \text{ in}^3$

*** try W16 × 40 $\phi M_n = 274 > 259$ ✓
$Z_x = 73.0 > 69.08$ ✓

$\Delta = \frac{5(1.1025)(25)^4(1728)}{384(29{,}000)(518)} = 0.64 < 1''$ ✓

$FLB = 6.93 < 9.20$ ✓

$WLB = 46.5 < 90.5$ ✓

B_E $\frac{1}{2}$ spacing $= \frac{1}{2}(40 * 12) = 240''$

$\frac{1}{8}$ span $= \frac{1}{8}(25 * 12) = 37.5''$

$C = T$

$0.85 f'_c \, a B_E = A_s f_y$

$0.85(4)a(37.5) = (11.8)(50)$ $a = 4.627$ in

$Y_1 = 0$ $Y_2 = t_s - a/2 \longrightarrow 7.5'' - 4.627/2 = 5.1865$ in

$V_h = T = A_s f_y = 590$ kips

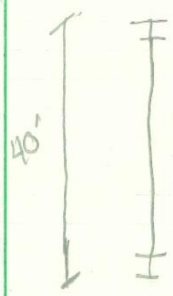
# of studs

$$\frac{590\text{ k}}{17.23\text{ k/stud}} = 34.24, \quad 34 \text{ studs}$$

spacing

$$\frac{25' * 12''}{34} = 8.82, \quad 9''$$

Location row 2.5-3 column line A Second floor



4.5" concrete with 3" metal steel deck

tributary width = 12.5 ft

Spacing = 25 ft

Design for construction

DL metal decking 3psf * 12.5' = 37.5 lb/ft

LL for concrete 72 * 12.5' * 1.1 = 990 lb/ft

LL for construction 25psf * 12.5' = 312.5 lb/ft

DL of steel beam 55 lb/ft

Load Combinations

$1.4D \longrightarrow 1.4(37.5 + 55) = 129.5 \text{ lb/ft}$

$1.2D + 1.6L \longrightarrow 1.2(37.5 + 55) + 1.6(990 + 312.5) = 2195 \text{ lb/ft}$

$M_u = 1/8\, w L^2 + \frac{PL}{4}$

$M_u = 1/8(2.195)(40)^2 + (2.195)(40)/4 = 441.195 \text{ k-ft}$

$Z_x = \frac{441.195 * 12''}{(0.9)(50)} = 117.65 \text{ in}^3$

*** try W21 x 55 $\phi M_n = 473 > 441.195$ ✓

$Z_x = 126 \text{ in}^3 > 117.65$ ✓

$\Delta = \frac{(5)(1.1375)(40)^4(1728)}{384(29{,}000)(1140)} = 1.98'' < 1''$ X

Required I_x

$1140\left(\frac{1.98}{1}\right) = 2257.2 \text{ in}^4$

*** try W21 × 101 $Z_x = 253 \text{ in}^3$

$\phi M_n = 949$ k-ft

$$\Delta = \frac{5(1.183)(40)^4(1728)}{384(29{,}000)(2420)} = 0.97 \text{ in} < 1'' \checkmark$$

Design for occupancy

DL metal decking 3 psf * 12.5' = 37.5 lb/ft

DL CMEP 10 psf * 12.5' = 125 lb/ft

concrete 72 * 12.5' = 900 lb/ft

service Load 100psf * 12.5' = 1250 lb/ft

Steel 55 lb/ft

Load Combination

$1.4D \longrightarrow 1.4(37.5 + 125 + 900 + 55) = 1564.5$ lb/ft

$1.2D + 1.6L \longrightarrow 1.2(37.5 + 125 + 900 + 55) + 1.6(1250) = 3341$ lb/ft

$$M_u = \frac{1}{8}(3.341)(40)^2 + \frac{(3.341)(40)}{4} = 701.61 \text{ k-ft}$$

$$Z_x = \frac{M_u}{\phi f_y} \longrightarrow \frac{701.61 * 12''}{0.9(50)} = 187.096 \text{ in}^3$$

W21 × 101

$\phi M_n = 949 > 701.61 \checkmark$

$Z_x = 253 \text{ in}^3 > 187.096 \checkmark$

$$\Delta = \frac{5(1.2185)(40)^4(1728)}{384(29{,}000)(2420)} = 1.0 < 1'' \text{ max} \checkmark$$

FLB = 7.68 < 9.20 ✓

WLB = 37.5 < 90.5 ✓

B_E 1/2 spacing

$$\frac{1}{2}(25' * 12") = 150"$$

1/8 span

$$\frac{1}{8}(40' * 12") = 60"$$

$C = T$

$0.85 f'_c \, a \, B_E = A_s f_y$

$0.85(4) a (60") = (29.8)(50)$ $a = 7.30$ in

$Y_1 = 0$ $Y_2 = t_s - a/2 \longrightarrow 7.5" - 7.30/2 = 3.85$ in

$V_h = T = A_s f_y = (29.8)(50) = 1490$ kip

\# of studs

$$\frac{1490k}{17.23k/stud} = 86.47, \text{ 86 studs}$$

Spacing

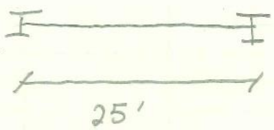
$$\frac{40' * 12"}{86} = 5.58 \text{ in}, 6"$$

min = 4.5"

max = 36"

Location: row 4, column line E-F second floor

4.5" concrete slab with 3" metal steel decking



tributary width = 20 ft

spacing = 40 ft

Design for construction

DL for metal decking 3 psf * 20' = 60 lb/ft

LL for concrete 72 * 20' * 1.1 = 1584 lb/ft

LL for construction 25 psf * 20' = 500 lb/ft

DL of steel beam 93 lb/ft

Load Combinations

① 1.4D → 1.4(60 + 93) = 214.2 lb/ft

② 1.2D + 1.6L → 1.2(60 + 93) + 1.6(1584 + 500) = 3518 ft/lb

$$M_u = \frac{1}{8}(3.518)(25)^2 + (3.518)(25)/(4) = 324.676 \text{ k-ft}$$

$$Z_x = \frac{M_u}{\phi f_y} = \frac{324.676 * 12''}{0.9(50)} = 86.58 \text{ in}^3$$

*** try W21 x 44 $\phi M_n = 358$ k-ft > 324.676 ✓

$$\Delta = \frac{(5)(1.781)(25)^4(1728)}{384(29{,}000)(843)} = 0.64 \text{ in} < 1'' \checkmark$$

Design for Occupancy

DL for metal decking	3 psf * 20' = 60 lb/ft
DL for CMEP	10 psf * 20' = 200 lb/ft
concrete	72 * 20' = 1440 lb/ft
service load	100 psf * 20' = 2000 lb/ft
Steel	44 lb/ft
DL of beam	93 lb/ft

Load Combinations

$1.4D \rightarrow 1.4(60 + 200 + 1440 + 44 + 93) = 2571.8 \text{ lb/ft}$

$1.2D + 1.6L \rightarrow 1.2(60 + 200 + 1440 + 44 + 93) + 1.6(2000) =$

5404.4 lb/ft

$M_u = \frac{1}{8}(5.404)(25)^2 + (5.404)(25)/(4) = 455.96 \text{ k-ft}$

$Z_x = \frac{M_u}{\phi f_y} = \frac{455.96 * 12''}{(0.9)(50)} = 121.589 \text{ in}^3$

$121.589 \text{ in}^3 > 95.4 \text{ in}^3$ ✗

*** try W21 x 55

$\phi M_n = 473 \text{ K-ft}$ ✓

$Z_x = 126 \text{ in}^3 > 121.59$ ✓

$\Delta = \frac{5(1.848)(25)^4(1728)}{384(29{,}000)(1140)} = 0.49 \text{ in} < 1''$ ✓

FLB $= 7.87 < 9.2$ ✓

WLB $= 50 < 90.5$ ✓

B_E

$\frac{1}{2}$ spacing $= \frac{1}{2}(40' \times 12'') = 240''$

$\frac{1}{8}$ span $= \frac{1}{8}(25' * 12'') = 37.5''$

* use 37.5''

$C = T$

$0.85 f'_c \, a \, B_E = A_s f_y$

$0.85(4)(a)(37.5) = (16.2)(50) \rightarrow a = 6.35 \text{ in} < 7.5$ ✓

$Y_1 = 0, \; Y_2 = t_s - a/2 \rightarrow 7.5 - 6.35/2 = 4.325 \text{ in}$

$V_n = T = A_s f_y \rightarrow (16.2)(50) = 810 \text{ kips}$

\# of studs = $\frac{810^k}{17.23^k/\text{stud}}$ = 47.01, 47 studs

Spacing

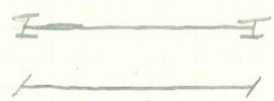
$L = \frac{25' * 12''}{47} = 6.38''$ or $6''$

min 6d = 4.5

max sts = 60'' ≤ 36'' upper bound

Location: row 4, column line B-E, second floor

4.5" concrete slab with 3" metal steel decking



tributary width = 20 ft

spacing = 40 ft

Design for Construction

DL for metal decking: 3 psf * 20' = 60 lb/ft

LL for concrete: 72 * 20' * 1.1 = 1584 lb/ft

LL for construction: 25 psf * 20' = 500 lb/ft

DL for steel beams: 84 lb/ft, 93 lb/ft

Load Combinations

$1.4D \longrightarrow 1.4(60+84+93) = 331.8\ lb/ft$

$1.2D + 1.6L \longrightarrow 1.2(60+84+93) + 1.6(1584+500) = 3618.8\ lb/ft$

$$M_u = \frac{1}{8}(3.6188)(40)^2 + \frac{(81.5625)(15)}{1000} + \frac{(95.4375)(12.5)}{1000}$$

$M_u = 726.176$ kip-ft

$$Z_x = \frac{M_u}{\phi f_y} = \frac{726.176 * 12''}{(0.9)(50)} = 193.647\ in^3$$

$$\Delta = \frac{5(1.897)(40)^4(1728)}{384(29{,}000)(2100)} = 1.794\ in < 1'' \times$$

*** try W24 x 76

$\phi M_n = 750$ k-ft > 726.176 ✓

$200\ in^3 > 193.647\ in^3$ ✓

Required I_x

$$2100\left(\frac{1.794}{1}\right) = 3767.4\ in^4$$

*** try W24 x 131

$$\Delta = \frac{5(1.952)(40)^4(1728)}{384(29{,}000)(4020)} = 0.96\text{ in} < 1'' \checkmark$$

Design for occupancy

DL for metal decking	3psf * 20' = 60 lb/ft
DL for CMEP	10 psf * 20' = 200 lb/ft
concrete	72 * 20' = 1440 lb/ft
service load	100psf * 20' = 2000 lb/ft
steel	131 lb/ft
DL of Beams	84 lb/ft , 93 lb/ft

$1.4D \longrightarrow 1.4(60 + 200 + 1440 + 131 + 84 + 93) = 2811.6\text{ lb/ft}$

$1.2D + 1.6L \longrightarrow 1.2(60 + 200 + 1440 + 131 + 84 + 93) + 1.6(2000) = 5609.6\text{ lb/ft}$

$$M_u = \frac{1}{8}(5.6096)(40)^2 + \frac{(81.5625)(15)}{1000} + \frac{(95.4375)(12.5)}{1000}$$

$M_u = 1124.34$ k-ft

$$Z_x = \frac{M_u}{\phi f_y} = \frac{1124.34 * 12}{(0.9)(50)} = 299.824\text{ in}^3$$

*** try W27 x 102

$\phi M_n = 1140$ k-ft $> M_u = 1124.34$ ✓

$Z_x = 305\text{ in}^3 > 299.824$ ✓

$$\Delta = \frac{5(1.979)(40)^4(1728)}{384(29{,}000)(3620)} = 1.0 \leq 1''\text{max} \checkmark$$

FLB = 6.03 < 9.20 ✓

WLB = 47.1 < 90.5 ✓

B_E : 1/2 spacing = 1/2 (40' * 12") = 240"

1/8 span = 1/8 (40' * 12") = 60" *use 60"

C = T

$0.85 f'_c\, a\, B_E = A_s f_y$

$0.85(4)(a)(60) = (30)(50)$ a = 7.35 < 7.5 ✓

$Y_1 = 0$, $Y_2 = t_s - a/2 \rightarrow 7.5 - 7.35/2 = 3.825$ in

$V_n = T = A_s f_y = (30)(50) = 1500$ kips

# of studs

$\# = \frac{1500}{17.23} = 87$ studs

Spacing

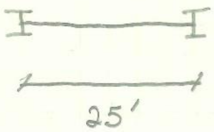
$L = \frac{40' * 12"}{87} = 5.51"$ or 6"

min 6d = 4.5"

max $8t_s$ = 60" ≤ 36" upper bound

Location : row 2.5 - 3 , column line A - B second floor

4.5" concrete slab with 3" metal steel decking



tributary width = 20 ft

spacing = 20 ft

Design for construction

DL for metal decking 3psf * 20' = 60 lb/ft

LL for weight of concrete 72 * 20' * 1.1 = 1584 lb/ft

LL for construction 25 psf * 20' * = 500 lb/ft

Load Combinations

① 1.4D → 1.4 (60) = 84 lb/ft

② 1.2D + 1.6L → 1.2(60) + 1.6 (1584 + 500) = 3406.4 lb/ft

$M_u = \frac{1}{8} wL^2 = (\frac{1}{8})(3.4064)(25')^2 = 238$ ft-kips

$Z_x = \frac{M_u}{\phi f_y} = \frac{238 * 12''}{0.9 (50)} = 63.46 \text{ in}^3$

*** try W16 × 36 $M_u = 238 \leq 240$ K ✓

$\Delta = \frac{5 W_u L^4}{384 EI} = \frac{(5)(1.680)(25)^4 (1728)}{384 (29{,}000)(448 \text{ in}^4)}$

$\Delta = 1.132$ in $\leq \frac{L}{360} \leq 1''$ max

Required I_x

$448 \text{ in}^4 \left(\frac{1.132}{1}\right) = 507.136 \text{ in}^4$

* try W16 × 40

$$\Delta = \frac{(5)(1.684)(25)^4(1728)}{384(29,000)(518 \text{ in}^4)} = 0.98 \text{ in} \leq 1'' \text{max} \checkmark$$

Design for occupancy

DL for metal decking 3psf * 20' = 60 lb/ft

DL for CMEP 10psf * 20' = 200 lb/ft

concrete 72 * 20' = 1440 lb/ft

service load 100psf * 20' = 2000 lb/ft

Steel 40 lb/ft

Load Combinations

$1.4D \longrightarrow 1.4(60 + 200 + 1440 + 40) = 2436$ lb/ft

$1.2D + 1.6L \longrightarrow 1.2(60 + 200 + 1440 + 40) + 1.6(2000) =$ 5288 lb/ft

$M_u = \frac{1}{8} wL^2 \longrightarrow (\frac{1}{8})(5.288)(25)^2 = 413.125$ kip-ft

$$Z_x = \frac{M_u}{\phi f_y} = \frac{413.125 * 12''}{0.9(50)} = 110.167 \text{in}^3$$

$73.0 \text{in}^3 > 110.167 \text{in}^3$ ✗

*** try W18 × 55

$\phi M_n = 420 \geq 413.125$ k-ft ✓

$Z_x = 112 \text{in}^3 \geq 110.167$ in ✓

$$\Delta = \frac{5(1.755)(25)^4(1728)}{384(29,000)(890 \text{in}^4)} = 0.597 \text{ in} \leq 1'' \checkmark$$

FLB : $\frac{b_f}{2t_f} = 5.98 < 9.20$ ✓

WLB : $\frac{h}{t_w} = 41.1 < 90.5$ ✓

B_E

$\frac{1}{2}$ spacing $= \frac{1}{2}(20' * 12'') = 120''$

$\frac{1}{8}$ span $= \frac{1}{8}(25' * 12'') = 37.5''$

* use 37.5''

$C = T$

$0.85 f'_c\, a\, b_E = A_s f_y$

$0.85(4\text{ksi})\, a\, (37.5) = (16.2)(50) \rightarrow a = 6.35\text{ in} \leq 7.5$ ✓

$Y_1 = 0\ ,\ Y_2 = t_s - a/2 \rightarrow 7.5'' - 6.35''/2 = 4.325\text{in}$

$C_c = 0.85 f'_c\, a\, B_E \rightarrow (0.85)(4)(6.35)(37.5) = 809.625$ kips

$CC = \Sigma Q_n = 810$ kips

$V_h = T = A_s f_y = (16.2\text{in}^2)(50\text{ksi}) = 810$ kips

# of studs $\rightarrow N = \frac{V_h}{Q_n}$

$Q_n = 26.60 \leq 17.23^k/\text{stud}$

# of studs $= \frac{810^k}{17.23^k/\text{stud}} = 47.01$, 47 studs

Spacing

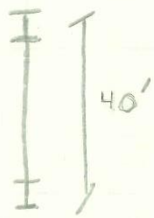
$L = \frac{25' * 12}{47} = 6.38'' \Rightarrow 6''$

$\min = 6d = 4.5''$

$\max = 8t_s = 60'' \leq 36''$ upper bound

Location: row 3-4, column line d   second floor

4.5" concrete slab with 3" metal steel decking



tributary width = 12.5 ft

spacing = 12.5 ft

Design for construction

DL for metal decking 3 psf * 12.5' = 37.5 lb/ft

LL for weight of concrete 72 * 12.5' * 1.1 = 901.1 lb/ft

LL for construction 25 psf * 12.5' = 312.1 lb/ft

Load Combinations

① $1.4D \rightarrow 1.4(37.5) = 52.5$ lb/ft

② $1.2D + 1.6L \rightarrow 1.2(37.5) + 1.6(312.1 + 901.1) = 1986.12$ lb/ft

$M_u = \frac{1}{8} wL^2 = \left(\frac{1}{8}\right)\left(\frac{1986.2}{1000}\right)(40)^2 \rightarrow 397.24$ ft-kips

$Z_x = \frac{M_u}{\phi f_y} = \frac{397.24 * 12''}{0.9 * 50 \text{ ksi}} = 105.867 \text{ in}^3$

** try W21x50 $M_u \leq \phi M_n \rightarrow 397.24k < 413 k$

$\Delta = \frac{5 w_u L^4}{384 EI} = \frac{(5)(0.9886)(40)^4 * 1728}{384(29{,}000 \text{ ksi})(984 \text{ in}^4)} = 1.995 \text{ in}$

$1.995 \leq \frac{L}{360} \leq 1''$ max ✗

Required I_x

$984\left(\frac{1.995}{1}\right) = 1963.08 \text{ in}^4$

*try W21 x 93

$$\Delta = \frac{5(1.0316)(40')(1728)}{384(29{,}000)(2070\,in^4)} = 0.000015\text{ in}$$

$0.000015'' \leq 1''max$ ✓

Design for Occupancy

DL for metal decking 3 psf * 12.5' = 37.5 lb/ft

DL for CMEP 10 psf * 12.5' = 125 lb/ft

concrete 72 psf * 12.5' = 900 lb/ft

Service load 100psf * 12.5' = 1250 lb/ft

Steel 93 lb/ft

Load Combinations

$1.4D \rightarrow 1.4(37.5 + 125 + 900 + 93) = 1617.7$ lb/ft

$1.2D + 1.6L \rightarrow 1.2(37.5 + 125 + 900 + 93) + 1.6(1250) = 3386.6$ lb/ft

$M_u = \frac{1}{8}wL^2 \rightarrow \frac{1}{8}(3.3866\,k\text{-}ft)(40')^2 = 677.32$ ft-kips

$$Z_x = \frac{M_u}{\phi f_y} = \frac{677.32 * 12''}{0.9 * 50\,ksi} = 180.619\,in^3$$

$221.0\,in^3 \geq 180.619\,in^3$ ✓

FLB: $\frac{b_f}{2t_f} \leq 0.38\sqrt{E/f_y}$

$4.53 \leq 9.2$ ✓

WLB: $\frac{h}{t_w} \leq 3.76\sqrt{E/f_y}$

$32.3 \leq 90.5$ ✓

B_E

$\frac{1}{2}$ spacing $= \frac{1}{2}(12.5' * 12'') = 75''$

$\frac{1}{8}$ span $= \frac{1}{8}(40' * 12'') = 60''$

* use 60''

$C = T$

$0.85 f'c \; a \; b_E = A_s f_y$

$0.85(4ksi)\,a\,(60'') = (27.3in^2)(50ksi) \rightarrow a = 6.69$ in

$a = 6.69in \leq 7.5in$ ✓

$Y_1 = 0$, $Y_2 = t_s - a/2 \longrightarrow 7.5'' - \frac{6.69''}{2} = 4.155$ in

$C_c = 0.85 f'c \; a \; B_E \rightarrow 0.85(4ksi)(6.69in)(60'') = 1364.76$ kips

$C_c = \Sigma Q_n \longrightarrow 1364.76$ kips

$V_h = T = A_s f_y \longrightarrow (27.3in^2)(50ksi) = 1365$ Kips

\# of studs $\longrightarrow N = \frac{V_h}{Q_n}$

$Q_n = 0.5 \, A_{sc} \sqrt{f'c \, E_c} \leq R_g R_p \, A_{sc} \, f_u$

$A_{sc} = \frac{\pi d^2}{4} = \frac{\pi (3/4'')^2}{4} \longrightarrow 0.4418 \, in^2$

$Q_n = 0.5\,(0.4418)\sqrt{4(3625)} \leq (1)(0.6)(0.4418)(65)$

$Q_n = 26.60 \leq 17.23^k/stud$

\# of studs $= \frac{1365}{17.23} \longrightarrow 79.22$, 79 studs

Spacing

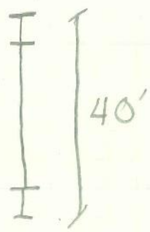
$$L = \frac{40' * 12''}{79} = 6''$$

$min = 6d = 6(0.75'') = 4.5''$

$max = 8t_s = 8(7.5'') = 60'' \leq 36''$ upper bound

Location: row 3-4, column line C   Second floor

4.5' concrete slab width   3" metal steel decking



tributary width = 13.75'

Spacing = 13.75'

Design for construction

DL for metal decking   3psf * 13.75' = 41.25 lb/ft

LL for weight of concrete   72 * 13.75' * 1.1 = 1089 lb/ft

LL for construction   25psf * 13.75' = 343.75 lb/ft

Load Combinations

① $1.4D \longrightarrow 1.4(41.25) = 57.75\ \text{lb/ft}$

② $1.2D + 1.6L \longrightarrow 1.2(41.25) + 1.6(1089. + 343.75) = 2341.9\ \text{lb/ft}$

$$M_u = \tfrac{1}{8} wL^2 \longrightarrow \tfrac{1}{8}(2.3419)(40)^2 = 468.38\ \text{ft-kips}$$

$$Z_x = \frac{M_u}{\phi f_y} \longrightarrow \frac{468.38 * 12''}{0.9(50)} = 124.9\ \text{in}^3$$

*** try W24 x 55 $M_u \le \phi M_n \rightarrow 468.38 < 503\text{k}$

$$\Delta = \frac{5 w_u L^4}{384EI} = \frac{(5)(1.18525)(40)^4(1728)}{384(29{,}000\text{ksi})(1350\text{ in}^4)} = 1.74\text{ in}$$

Required I_x $1.74\text{ in} \le \frac{L}{360} \le 1''\text{max}$ X

$$1350\left(\frac{1.74}{1}\right) = 2349\text{ in}^4$$

* try W24 x 84

$$\Delta = \frac{(5)(1.21425)(40)^4(1728)}{384(29{,}000\text{ksi})(2370)} = 1.0\ \checkmark$$

Design for occupancy

DL for metal decking 3 psf * 13.75' = 41.25 lb/ft

DL for CMEP 10psf * 13.75' = 137.5 lb/ft

concrete 72 psf * 13.75' = 990 lb/ft

service load 100psf * 13.75 = 1375 lb/ft

Steel 84 lb/ft

Load Combinations

1.4D ⟶ 1.4(41.25 + 137.5 + 990 + 84) =

1.2D + 1.6L ⟶ 1.2(41.25 + 137.5 + 990 + 84) + 1.6(1375) = 3703 lb/ft

$M_u = 1/8\, wL^2 \rightarrow 1/8(3.703)(40)^2 = 740.6$ ft-kip

$$Z_x = \frac{M_u}{\phi f_y} = \frac{740.6 * 12''}{0.9(50)} = 197.49\ in^3$$

$224\ in^3 > 197.49\ in^3$

FLB:

$$\frac{b_f}{2t_f} = 5.86 < 9.2\ ✓$$

WLB: $\frac{h}{t_w} = 45.9 < 90.5$ ✓

B_E 1/2 spacing = 1/2(13.75' * 12") = 82.5"

1/8 span = 1/8(40' * 12") = 60"

* use 60"

C = T $0.85f'_c\, a\, B_E = A_s f_y$

$0.85(4)(a)(60'') = (24.7'')(50) \rightarrow a = 6.05$ in

$a = 6.05 \leq 7.5''$ ✓

$y_1 = 0$, $y_2 = t - a/2 \rightarrow 7.5'' - 6.05/2 = 4.475$ in

$C_c = 0.85f'_c \, a \, B_E \rightarrow 0.85(4)(6.05)(60) = 1234.2$ kips

$C_c = \Sigma Q_n \rightarrow 1234.2$ K

$V_h = T = A_s f_y \rightarrow (24.7)(50) = 1235$ kips

# of studs $\rightarrow N = \frac{V_h}{Q_n}$

$Q_n = 0.5 A_{sc}\sqrt{f'_c E_c} \rightarrow 26.60 \leq 17.23^k$/stud

* upper bound *

# of studs $= \frac{1235}{17.23} = 71.62$, 71 studs

spacing $L = \frac{40' * 12''}{71} = 6.76$ in, so 6''

min 6d $\rightarrow 4.5''$

max 8ts $\rightarrow 60'' \leq 36''$ upper boud

Alternative Option for W24 x 84

Location 3,4 Column Line C – 2nd Floor

Design for Occupancy

- Same loads as W24 x 84

Load Combinations

$1.4D \rightarrow 1.4(41.25 + 137.5 + 990 + 84) =$

$1.2D + 1.6L \rightarrow 1.2(41.25 + 137.5 + 990 + 84) + 1.6(1375) = 3703\ lb/ft$

$M_u = 1/8\ WL^2 \rightarrow 1/8(3.703)(40^2) = 740.6\ ft\text{-}kip$

$Z_x = \frac{M_u}{\Phi f_y} = \frac{740.6 \times 12''}{0.9(50)} = 197.49\ in^3$

Try 21 x 93 $\quad 221\ in^3 > 197.4$

FLB: $\frac{b_f}{2t_f} = 4.53 < 9.2$

WLB: $\frac{h}{t_w} = 32.3 < 90.5$

B_E $\quad 1/2$ spacing $= 1/2(13.75' \times 12'') = 82.5''$

$1/8$ span $= 1/8(40' \times 12'') = 60''$

* use 60"

$C = T \quad 0.85 f'_c\, a\, B_E = A_s f_y$

$0.85(4)(a)(60) = 27.3(50) \qquad a = 6.69$

$a = 6.69'' \leq 7.5''$ ✓

$Y_1 = 0,\ Y_2 = t - a/2 \rightarrow 7.5'' - 6.69''/2 = 4.155\ in$

$C_c = 0.85 f'_c\, a\, B_E \rightarrow 0.85(4)(6.69)(60) = 1364.76\ k$

$C_c = \Sigma Q_n \rightarrow 1364.76\ k$

$V_h = T = A_s f_y \rightarrow (27.3)(50) = 1365\ k$

\# of Studs $= N = V_h / Q_n$

$$Q_n = 0.5\, A_{sc} \sqrt{f'_c\, E_c}$$

$$A_{sc} = \frac{\pi d^2}{4} = \frac{\pi (3/4")^2}{4} = 0.4418\, in^2$$

$$Q_n = 0.5(0.4418)\sqrt{(4)(3625)} \le (1)(0.6)(0.4418)(65)$$

$$Q_n = 26.60 \le 17.23^k/stud$$

$$\# \text{ of studs} = \frac{1365}{17.23} \longrightarrow 79 \text{ studs}$$

Deflection $\Delta = \frac{5 W_u L^4}{384\, EI} = \frac{5(1.22325)(40^4)}{384(29{,}000)(2070 in^4)}$

$$= 0.0007 \le 1 \checkmark$$

Second floor

Location : row 3-4 column line B

* try W24 x 76 , fails
* try W24 x 117 , passes

Beam Cambering

- will use a 3/4 in camber on all beams greater than a 25 ft span

W21 x 57 ⇝ $\Delta = 0.999$ in

can use W21 x 44 $\Delta = 1.35$ in $- 0.75$ in $= 0.60$ in ✓

* based on analyzing previous deflections, only 5 beams can be cambered on the first floor

Steel column design

- computations done in microsoft excel
- columns made all the same size to ease manufacturing

size of columns: W14 x 99

other column sizes that work: W10 x 112
W12 x 106

Appendix F: Gravity Load Concrete

MQP | Concrete design | 1

38.115 PSF

design of a simply supported one way slab L=2

Normal weight aggregate Concrete =15

LL = 100 PSF $f'c = 5KSI$ $f_y = 60 KSI$

Try $h = L/20 = \frac{20' \cdot 12''}{20} = 12''$

$W_{DL} = \gamma \cdot H = 150 \, lbs/ft^3 \cdot 12'' \times \frac{1'}{12''} = 150 \, \frac{lbs}{ft^2}$

$W_u = 1.2(150) + 1.6(100) = 340$ PSF

M_u @ first = 0

M_u @ middle $= \frac{wL^2}{8} = \frac{340 \cdot 20^2}{8} = 17{,}000$ lbs Ft/ft or 17 Kipft/ft

M_u @ end $\frac{wL^2}{24} = \frac{340 \cdot 20^2}{24} = 5.67$ Kipft

ρ_{max} and ρ @ .005

$\rho_{max} = .85 \cdot B_1 \cdot \frac{f'c}{f_y} \left(\frac{\varepsilon_u}{\varepsilon_u + .004} \right) = .85 \cdot .84875 \cdot \frac{5KSI}{60KSI} \cdot \frac{.003}{.007} = .025765$

$B_1 = .85 - .005 \frac{(5000-4000)}{4000} = .84875$

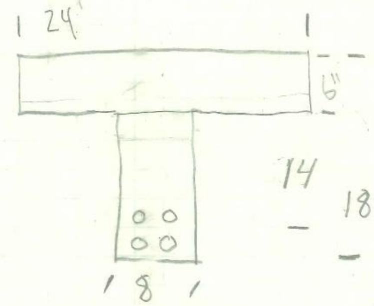
$\rho @ .005 = .85 \cdot .84875 \cdot \frac{5}{60} \left(\frac{.003}{.008} \right) = .022544$

assume $\rho_{.005} = .022544$ $\phi = .9$ $M_u = \phi \rho f_y b d^2 \left(1 - .59 \rho \frac{f_y}{f'c}\right)$

$17 \text{ Kip ft} \times 12'' = .9 \cdot .022544 \cdot 60KSI \cdot 12 d^2 \left(1 - .59 \cdot .022544 \cdot \frac{60}{5}\right)$

$204 = 1.217376 d^2 (.84038848)$

$d^2 = 199.4$ $d = 14.12''$ too Big redesign.



LL = 100 PSF

$DL = \gamma \cdot h = 150 \frac{lbs}{ft^3} \times .5' = 75 lbs/ft^2$

+

$DL = \gamma \cdot h = 150 \frac{lbs}{ft^3} \cdot \frac{1ft^2}{144''} \times 8 \times \frac{12}{2} = 50$

DL = 125 lbs/ft

$W_u = 1.2(125) + 1.6(100) = 310$ PSF

Mu @ first = 0

M @ Middle = $\frac{wL^2}{8} = \frac{310 \cdot 20^2}{8} = 15{,}500$ lbs ft/ft

M @ End = $\frac{wL^2}{24} = \frac{310 \cdot 20^2}{24} = 5{,}166$ lbs·ft/ft

use 15.5 Kip ft/ft × 20' = 310 Kip ft × 12" = **3720 Kip In**

$M_u = \phi A_s f_y (d - a/2)$

$3720 = .9 \cdot A_s 60 (14 - a/2)$ $A_s = 6.26 \text{ in}^2$

C = T

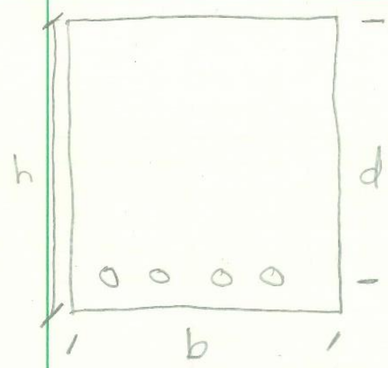
$.85 f'c\, a b = A_s f_y$ $.85 \cdot 4 \cdot a \cdot 24 = 6.26 \cdot 60$

$a = 4.6''$

$c = \frac{a}{B_1} = \frac{4.6}{.85} = 5.42$

$\varepsilon_T = \varepsilon_u \left(\frac{d-c}{c}\right) = .003\left(\frac{14-5.42}{14}\right) = .06475$

$A_s = 6.26$ **3 #14's = 6.75 in²** ✓



D-E 8 $L = 12.5'$

$f_y = 60$ KSI $f'c = 5$ KSI

live load = $20' \times 100$ PSF = 2 Kips/ft

Dead load = $20' \times 62.5$ PSF = 1.25 Kips/ft

$h = \frac{L}{10} = \frac{12.5' \times 12''}{10} = 15''$ go with 18''

Self weight = $\gamma\, h \cdot b = 150\ \text{lbs/ft}^3 \cdot \frac{18''}{12} \cdot \frac{12''}{12''}$ $b = \frac{d}{1.5} = \frac{18}{1.5} = 12''$

Self weight = 225 lbs/ft → .225 Kips/ft

$W_u = 1.2\,W_D + 1.6\,W_L$

$W_u = 1.2(.225 + 1.25) + 1.6(2) = 4.97$ Kip/ft

M_u @ end $\frac{wL^2}{24} = \frac{4.97\ \text{Kip/ft} \cdot 12.5^2}{24} = 32.35$ Kipft

M_u @ Midde $\frac{wL^2}{12}$ $\frac{4.97 \cdot 12.5^2}{12} = \underline{64.71\ \text{Kipft}}$

$\beta_1 = .85 - .05\left(\frac{f'c - 4000}{1000}\right) = .85 - .05\left(\frac{5000-4000}{1000}\right) = .8$

$M_n = \phi \rho f_y bd^2 \left(1 - .59\rho \frac{f_y}{f'c}\right) = .9 \cdot .02125 \cdot 60\, bd^2 \left(1 - .59 \cdot .02125 \cdot \frac{60}{5}\right)$

$\rho_{max} = .85\,\beta_1 \frac{f'c}{f_y} \cdot \frac{\varepsilon_u}{\varepsilon_u + \varepsilon_t} = .85 \cdot .8 \cdot \frac{5000}{60{,}000} \cdot \frac{.003}{.003 + .005} = .02125$

$M_n = M_u$

$M_n = .9748\, bd^2 = 64.71\ \text{Kip ft} \times 12''$

$.9748\, b(1.5b)^2 = 776.56$ Kip In

$2.1933 \cdot b^3 = 776.56$ $b^3 = 354.06$ $b = 7.07''$

$d = 10.611''$

go with 8'' X 12''

Beam Continued

$W_{self} = 150 \times \frac{8}{12} \times \frac{12}{12} = 100 \rightarrow .1$ Kips

New $W_u = 1.2(.1 + 1.25) + 1.6(2) = 4.82$ Kip/ft

$M_u = \frac{1}{12} 4.82 \cdot 12.5^2 = 62.76$ Kip ft $\times 12 = 753.12$ KipIn

$753.12 = 2193 \cdot b^3$ $b = 7''$ $d = 10.5$

8x12 ✓ passes.

$M_u = \phi \rho f_y bd^2 (1 - .59 \rho f_y/f'c)$

$753.12 = .9 \cdot \rho \cdot 60 \cdot 8 \cdot 12^2 (1 - .59 \rho \, 60/5)$

$753.12 = 62208\rho - 440432.64\rho^2$

$440{,}432\rho^2 - 62{,}208\rho + 753.12$ $\rho = .127$ or $\underline{.013}$

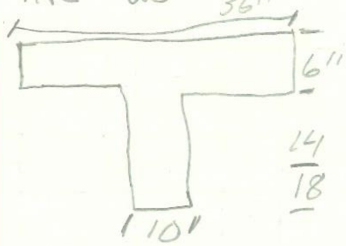
$\rho = \frac{A_s}{Bd}$ $A_s = \rho Bd = .0133 \times 8 \times 12 = \underline{1.2768 \text{ in}^2} = A_s$

Steel selection 3 #6 Bars 1.32 in^2

Roof Slab | | | 5

Snow 80.37 PSF

live 20



$L = 20'$

$DL = \gamma \cdot h = 150 \times .5' = 75 \text{lbs/ft}^2$

+

$DL = \gamma \cdot h = 150 \cdot \frac{1ft^2}{144} 10 \times 12 / 3' = 41.66$

$DL = 41.66 + 75 = 116.66$

$W_u = 1.2D + 1.6L + .5S$

$W_u = 1.2(116.66) + 1.6(20) + .5(80.37)$

$W_u = 212.185$ PSF

$M_u = 0$

$M_u = \frac{wl^2}{8} \quad \frac{212.2 \cdot 20^2}{8} = 10,609.25$ lb-ft/ft

$M_u = \frac{wl^2}{24} = \frac{212.2 \cdot 20^2}{24} = 3536.41$ lb-ft/ft

use 10.61 Kip ft/ft $\times 20' = 212.185 \times 12 = \underline{2546.22 \text{ Kip In}}$

$M_u = \phi A_s f_y (d - a/2) \quad 2546.22 = .9 A_s \cdot 60(14 - a/2)$

$A_s = 4.28$

$.85 \cdot f'c \cdot a \cdot b = A_s f_y$

$.85 \cdot 4 \cdot a \cdot 36 = 4.28 \cdot 60 \quad a = 2.10$ ✓

$c = \frac{a}{\beta_1} \quad \frac{2.10}{.85} = 2.47$

$\varepsilon_T = \varepsilon_u \left(\frac{d-c}{c}\right) = .003\left(\frac{14 - 2.47}{2.47}\right) = \frac{.014}{.002}$

$A_s = 4.28$

Slenderness ACI Code 6.2.5

$\frac{K l_w}{r} \leq 34 + 12 \, M_1/M_2$ and ≤ 40

To be Conservative $\frac{K l_w}{r} \leq 34$

$K = 1$ $l_w = 13' \times 12'' = 156$ $r = .3h$ for rectangular Beams

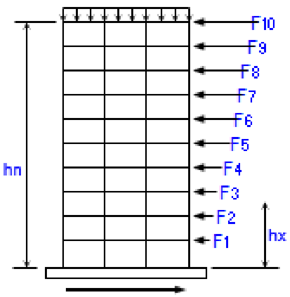
$\frac{K l_w}{r} \leq 34$ $\frac{1 \cdot 156}{.3 \cdot h} \leq 34$ $h \geq 15.29''$

go with 16"x16" for Constructability

Appendix G: Seismic Load

Input Data:

Risk Category =	III	IBC 2012, Table 1604.5, page 336
Importance Factor, I =	1.25	ASCE 7-10 Table 1.5-2, page 5
Soil Site Class =	B	ASCE 7-10 Table 20.3-1, page 204
Location Zip Code =	1609	
Spectral Accel., SS =	0.240	ASCE 7-10 Figures 22-1 to 22-11
Spectral Accel., S1 =	0.067	ASCE 7-10 Figures 22-1 to 22-11
Long. Trans. Period, TL =	12.000	sec. ASCE 7 Fig's. 22-12 to 22-18
Structure Height, hn =	56.000	ft.
Actual Calc. Period, Tc =	0.000	sec. from independent analysis
Seismic Resist. System =	B1	Steel eccentrically braced frames (ASCE 7-10 Table 12.2-1)



V = Cs*W = Σ(Fi) = 70.46 kips

Seismic Base Shear

(Regular Bldg. Configurations Only)

Structure Weight Distribution:

No. of Seismic Levels = 1

Seismic Level x	Height, hx (ft.)	Weight, Wx (kips)
1	14.000	6200.00

Seismic Shear Vertical Distribution:

Distribution Exponent, k = 1.06 k = 1 for T<=0.5 sec., k = 2 for T>=2.5 sec.

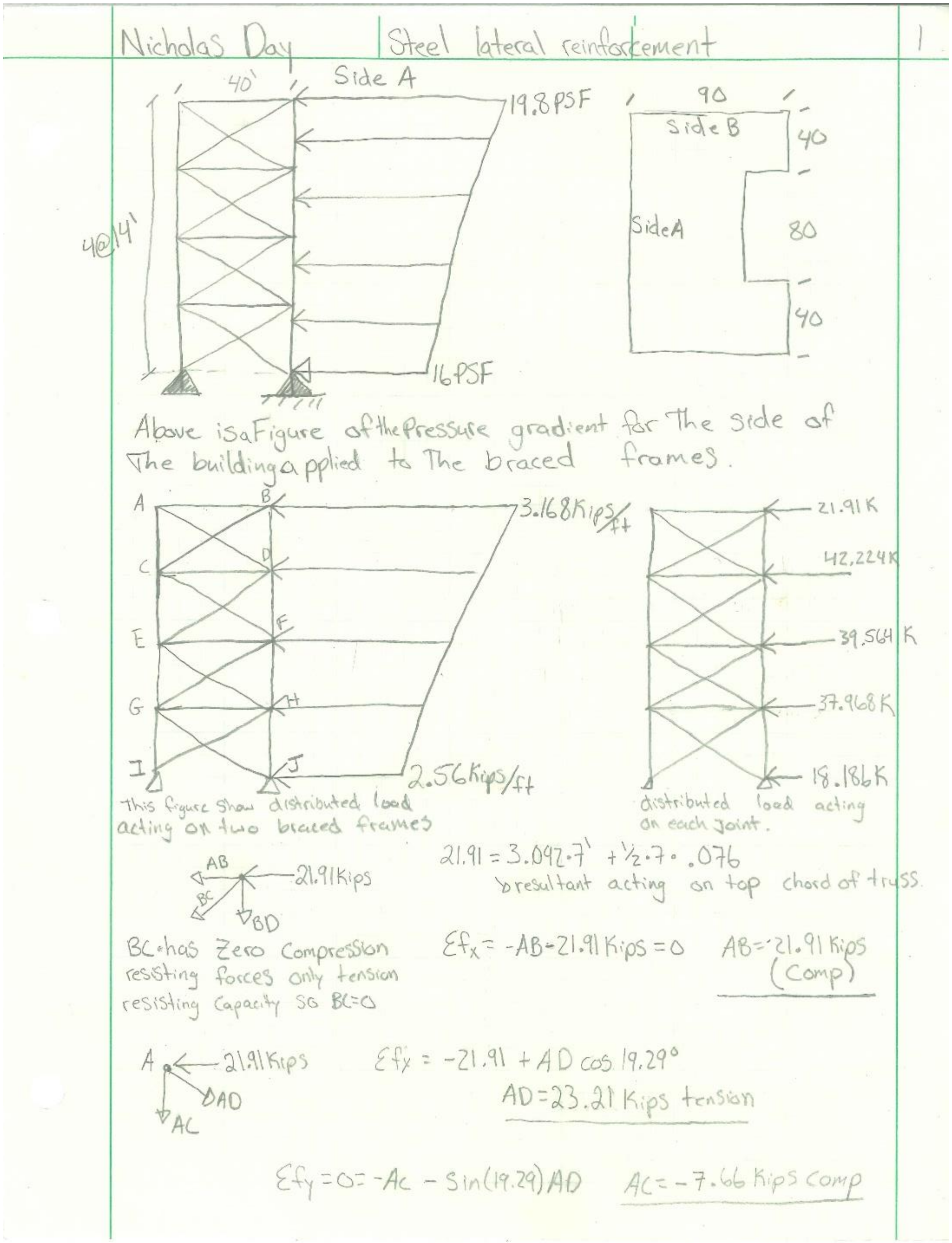
k = (2-1)*(T-0.5)/(2.5-0.5)+1, for 0.5 sec. < T < 2.5 sec.

Lateral Force at Any Level: Fx = Cvx*V, ASCE 7-10 Section 12.8.3, Eqn. 12.8-11, page 91

Vertical Distribution Factor: Cvx = Wx*hx^k/(ΣWi*hi^k), ASCE 7-10 Eqn. 12.8-12, page 91

Seismic Level x	Weight, Wx (kips)	hx^k (ft.)	Wx*h^k (ft-kips)	Cvx (%)	Shear, Fx (kips)	Σ Story Shears
1	6200.00	16.275	100907.9	1.000	70.46	70.46
Σ =	6200.00		100907.9	1.000	70.46	

Appendix H: Lateral Load Steel



Nicholas Day | Steel lateral reinforcement | 1

Side A

40'

4@14'

19.8PSF

16PSF

90

Side B

40

80

Side A

40

Above is a Figure of the Pressure gradient for the side of The building applied to The braced frames.

A B C D E F G H I J

3.168Kips/ft

2.56Kips/ft

This figure show distributed load acting on two braced frames

21.91K

42.224K

39.564K

37.968K

18.186K

distributed load acting on each joint.

21.91 = 3.092·7' + ½·7·.076

resultant acting on top chord of truss.

AB

21.91Kips

BC

BD

BC has Zero Compression resisting forces only tension resisting Capacity so BC=0

Σfx = -AB-21.91 Kips = 0   AB=-21.91 Kips (Comp)

A ← 21.91Kips

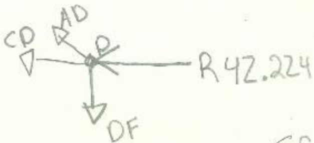
AD

AC

Σfx = -21.91 + AD cos 19.29°

AD=23.21 Kips tension

Σfy=0=-Ac - Sin(19.29)AD   Ac=-7.66 Kips Comp



$R = 2.94 \cdot 14 + \frac{1}{2} \cdot 14 \cdot (.152)$

$R = 42.224$ Kips

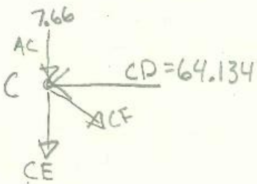
$\Sigma f_x = -AD\cos 19.29 - 42.224 - CD = 0$

$\Sigma f_y = 0 = \sin(19.29) AD - DF$

$-23.21 \cdot \cos 19.29 - 42.224 = CD$

DF = 7.66 Kips tension

CD = -64.134 Kip Comp

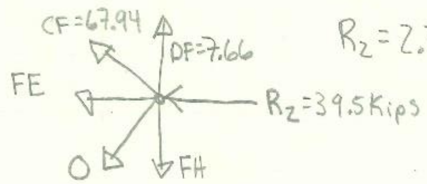


$\Sigma f_x = -64.134 + CF \cdot \cos(19.29) = 0$

$CF = \frac{+64.134}{\cos(19.29)} =$ 67.94 Kips T = CF

$\Sigma f_y = -7.66 - CE - 67.94 \sin(19.29) = 0$

$CE = -7.66 - 22.44 = -30.1$ Kips C = CE



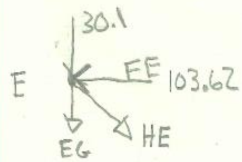
$R_2 = 2.788 \cdot 14 + \frac{1}{2} \cdot 14 \cdot .152 = 39.564$

$\Sigma f_x = 0 = -39.5 - 67.94\cos(19.29) - FE$

Fe = -103.62 Kips comp

$\Sigma f_y = 0 = 67.94 \cdot \sin(19.29 + 7.66 - FH$

FH = 30.1 Kips T

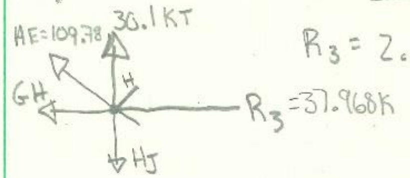


$\Sigma f_x = -103.62 + \cos(19.29) HE = 0$

HE = 109.78 T

$\Sigma f_y = 0 = -30.1 - 109.78 \cdot \sin(19.29) - EG$

EG = 66.36 K Comp



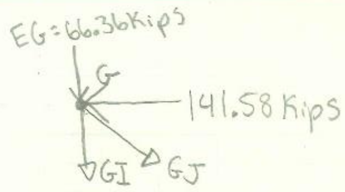
$R_3 = 2.636 \cdot 14 + \frac{1}{2} \cdot 14 \cdot .152 = 37.968$ Kips

$\Sigma f_x = -37.968 - 109.78 \cdot \cos(19.29) - GH = 0$

GH = - 141.58 COMP

$\Sigma f_y = 30.1 + 109.78 \cdot \sin(19.29) - HJ$

HJ = 66.36K Tension



$$\Sigma f_x = -141.58 + \cos(19.29) \cdot GJ$$

$$\underline{GJ = 150.00 \text{ Kips T}}$$

$$\Sigma f_y = -66.36 - 150.00 \cdot \sin(19.29) - GI$$

$$\underline{GI = 115.91K \text{ C}}$$

Max tension Member is 150 Kips T
This is distributed over two Braced frames
so tension = 75 Kips
Brace is $\sqrt{14^2 + 40^2} = 42.37'$

$\frac{L}{r} < 300$ for tension

Counterbrace | Steel Design | 4

$\frac{L}{r} < 300 \longrightarrow \frac{43ft * 12in}{300} = 1.72\,in$

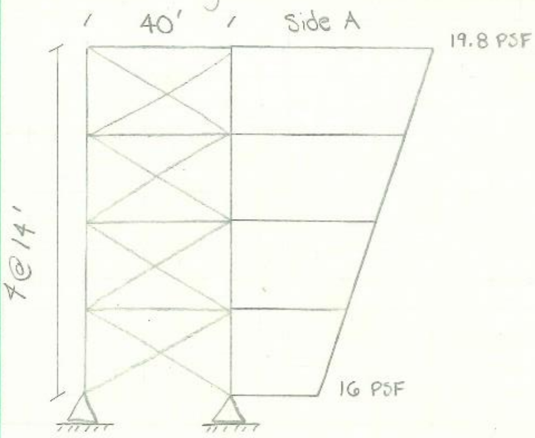
* must carry 75 kips

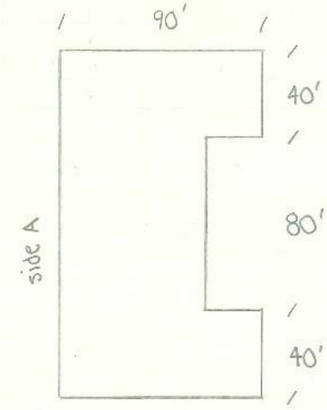
$(50ksi)(A) = \frac{75k}{0.9} \longrightarrow A = 1.67 in^2$

Use WT4 x 17.5

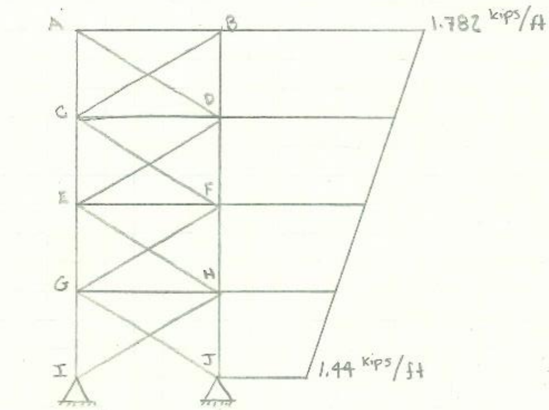
$A = 5.14 in^2 > 1.67 in$ ✓

$R_y = 2.03 in > 1.72 in$ ✓

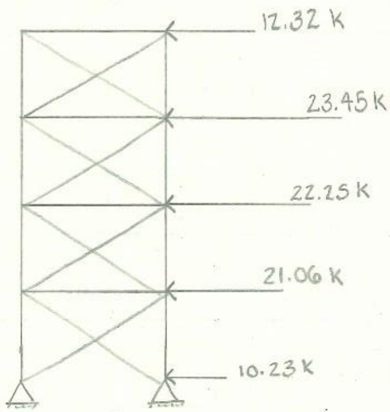




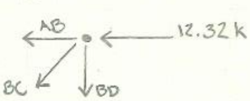
→ Above is a figure of the pressure gradient for the side of the building applied to the braced frames.



→ This figure shows distributed load acting on two braced frames

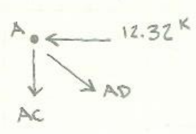


→ Distributed load acting on each joint



BC has zero compression resisting forces only tension resisting capacity so BC = 0

$\Sigma F_x = -AB - 12.32^K = 0$ $AB = -12.32^K$ (comp.)

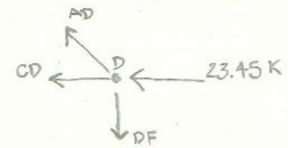


$\Sigma F_x = -12.32^K + AD \cos 19.29°$

$AD = 13.05\,K$ (Tension)

$\Sigma F_y = -AC - \sin(19.29)(AD)$

$AC = -4.31\,K$ (comp.)

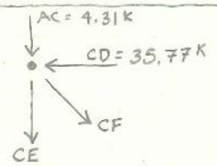


$\Sigma F_x = -AD\cos 19.29 - 23.45 - CD = 0$

$-13.05 \cos 19.29 - 23.45 = CD$

$CD = -35.77^K$ (comp.)

$\Sigma F_y = 0 = \sin(19.29)\,AD - DF \qquad DF = 4.31^K$ (Tens.)

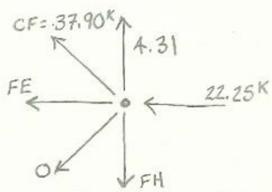


$\Sigma F_x = -35.77 + CF\cos(19.29) = 0$

$CF = 37.90^K$ (Tens.)

$\Sigma F_y = -4.31 - CE - 37.90\sin(19.29) = 0$

$CE = -16.83^K$ (comp.)

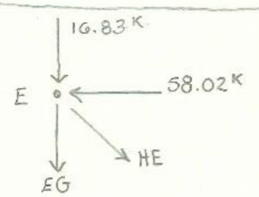


$\Sigma F_x = 0 = -22.25 - 37.90\cos(19.29) - FE$

$FE = -58.02^K$ (comp.)

$\Sigma F_y = 0 = 37.90\sin(19.29) + 4.31 - FH$

$FH = 16.83^K$ (Tens.)

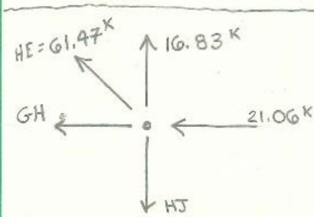


$\Sigma F_x = 0 = -58.02^K + \cos(19.29)\,HE$

$HE = 61.47^K$ (Tens.)

$\Sigma F_y = 0 = -16.83 - 61.47\sin(19.29) - EG$

$EG = -37.14^K$ (comp.)

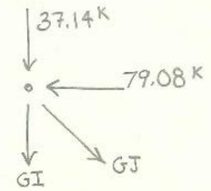


$\Sigma F_x = 0 = -21.06 - 61.47\cos(19.29) - GH$

$GH = -79.08^K$ (comp.)

$\Sigma F_y = 0 = 16.83 + 61.47\sin(19.29) - HJ$

$HJ = 37.14^K$ (Tens.)



$\Sigma F_x = 0 = -79.08 + GJ\cos(19.29)$

$GJ = 83.78^K$ (Tens.)

$\Sigma F_y = 0 = -37.14 - 83.78(\sin(19.29)) - GI$

$GI = -64.82^K$ (comp.)

→ Max tension member is 83.78^K (Tension). This is distributed over two frames so tension = 41.89^K

$$(50\ \text{ksi})(A) = \frac{41.89^K}{0.9} \rightarrow A = 0.93\ \text{in}^2$$

$$\frac{L}{r} < 300 \longrightarrow \frac{28\text{ft} * 12\text{in}}{300} = R_y = 1.12\text{in}$$

Use WT2.5 x 8

$A = 2.35\ \text{in}^2 > 0.93\ \text{in}^2$ ✓

$R_y = 1.26\ \text{in} > 1.12\ \text{in}$ ✓

Steel lateral	load check		8

lateral loads aply an extra 115.91 K To the columns In The braced frame.

A W14X99 column can hold 1130 Kips

Taken from footing design

One column = 99 lbs/ft x3 x 14' long = 4158 lbs

Concrete = 68.75 lb/ft² x 20' x 32.5' = 44,687.5 lbs

Beams and girders = 11,610 lbs

live load = 100PSF x 3 x 32.5x20 = 195 Kips

Dead = 4158 + (4 x 44,687) + (4x 11,610) = 229.34 Kips

Snow = 38 PSF x 40 x32.5 = 49.4 K

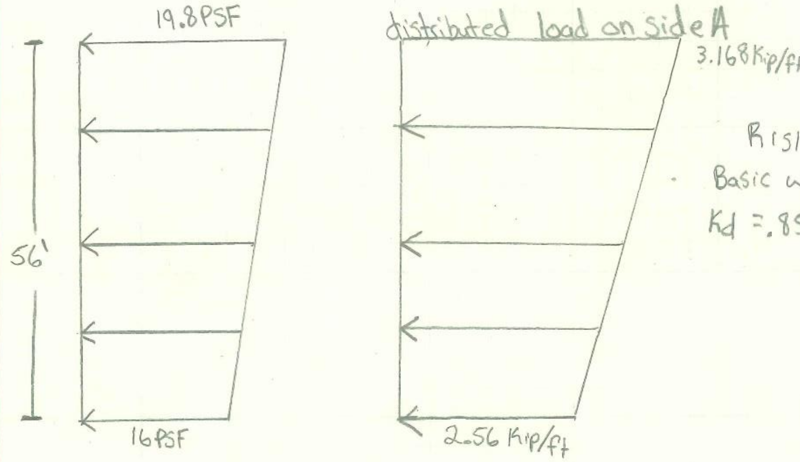
Biggest load Combination = 1.2D + 1.6W + L + .5S

1.2·229.34 + 1.6(115.91) + 195 + .5(49.4 = 680.3 Kips

680.3 Kips ≤ 1130 Kips So lateral forces do not effect The Size of The Columns.

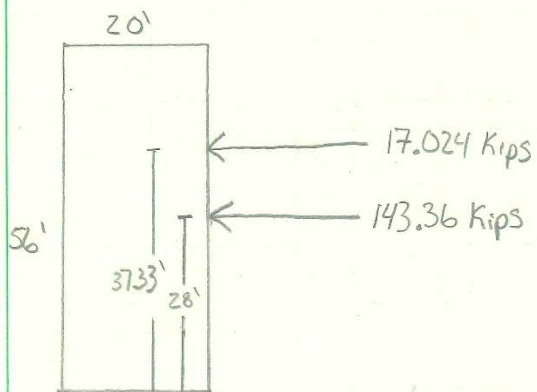
Appendix I: Lateral Load Concrete

Concrete Shear wall | 1



Risk category III
Basic wind speed 100mph
Kd = .85 Exposure B

Total force = 160.384 Kips



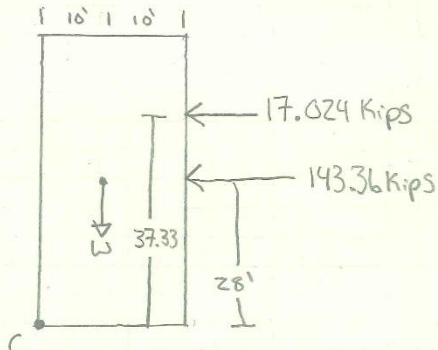
ACI-318 limits Plain Concrete Wall to min thickness of 7 ½"

It also states Wall thickness > $\frac{1}{25}$ · unsupported length

So Wall thickness > $\frac{1}{25} \cdot 20' \times 12'' = 9.6''$ So go with 10" thick wall. 4 shear walls will be use to resist force

$$4 \cdot \phi V_c = 4 \cdot \left(.75 \cdot 2 \cdot \frac{\sqrt{3000}}{1000} \cdot 20' \times 12'' \cdot 10''\right) \geq 160.384\,\text{Kips}$$

788.72 Kips ≥ 160.384 Kips shear in Concrete alone passes.



This wind force will be distributed to 4 identical Shear walls

$W = 56' \times 20' \times \frac{10''}{12''} \times 150\ PCF = \underline{140\ Kips}$

$\Sigma M_c = 10 \cdot 140 - \frac{28 \cdot 143.36}{4} - \frac{37.33 \cdot 17.024}{4}$

$\Sigma M_c = 237.6 > 0$

Wall will Not over turn

Check Compressive Strength of Concrete

$f'c = 3000\ PSI \qquad \frac{Mc}{I} + \frac{P}{a} \le .6f'c$

$M = \frac{28 \cdot 143.36}{4} + \frac{37.33 \cdot 17.024}{4} = \underline{1162.39\ Kip\,ft} \qquad \underline{C = 10'}$

$I = \frac{1}{12} b h^3 = \frac{1}{12} \cdot 10 \cdot (20 \cdot 12)^3 = 11{,}520{,}000\ in^4$

$P = \text{weight} = 140\ Kips \qquad a = 10'' \times (20' \times 12'') = 2400\ in^2$

$\frac{1162.39 \times 12'' \times 1000 \times 10' \times 12''}{11{,}520{,}000\ in^4} + \frac{140{,}000}{2400} =$

$145.29 + 58.33 = 203.63$

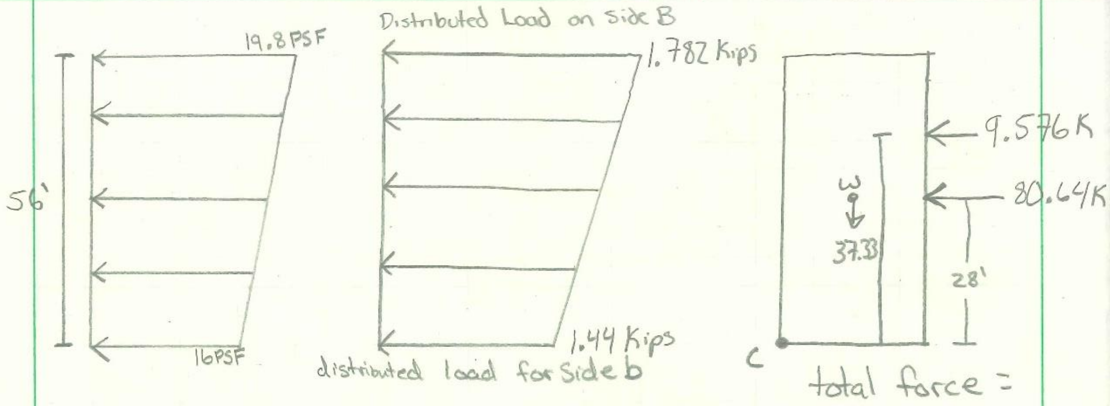
$203.63 \le .6(3000) = 1800\ PSI$ ✓ Compression Strength passes.

Tensile Strength $= .07 f'c = 210\ PSI$

Tensile force in Concrete $= \frac{Mc}{I} - P/a = 145.29 - 58.33 = 86.96$

$86.96 < 210\ PSI$ Tensile capacity passes ✓

Need to go with $20' \times 56' \times 10''$ wall.



Same minimal wall thick as side A = 10"

Weight = 56' X 20' X 10"/12" X 150 PCF = 140 Kips = w

$\Sigma m_c = 10 \cdot 140 - \frac{80.64 \cdot 28'}{2} - \frac{9.57 \cdot 37.33}{2} = 92.41$ Kipft

Wall will Not over turn ✓

Shear check

$2\phi V_c = 2\left(.75 \cdot 2 \frac{\sqrt{3000}}{100} \cdot 20' \times 12'' \times 10''\right) \geq 90.216$ Kips

394 ≥ 90.216K ✓ Passes shear check

Check Compressive Strength of Concrete

$f'c = 3000$ PSI $\quad \frac{Mc}{I} + \frac{P}{a} \leq .6 f'c$

$M = \frac{80.64 \cdot 28}{2} + \frac{9.57 \cdot 37.33}{2} = 1307.58$ Kipft $\quad C = 10'$

I = Same as Side A = 11,520,000 weight = 140K a = 2400 in²

$\frac{1307.58 \times 12'' \times 1000 \times 10' \times 12''}{11{,}520{,}000 \text{ in}^4} + \frac{140{,}000}{2400} =$

163.44 + 58.33 = 221.77 PSI ≤ .6f'c = 1800 PSI ✓

Tensile strength = .07 f'c = .07 · 3000 = 210 PSI

Tensile force in Concrete = $\frac{Mc}{I} - \frac{P}{a}$ = 163.44 − 58.33 = 105.11 < 210 PSI

Tensile capacity passes go with 20' X 56' X 10"

Appendix J: Footing Design

Footing design 1

3tons/sqft → 6000lbs/sqft

16"X16" Column $f'c = 4000$ PSI $f_y = 60$ KSI

assume 125 PCF for Soil and Concrete

footing 3' Below grade

$q_e = q_a - q_{soil} \Rightarrow q_e = 6000\ \text{lbs/SF} - 3\times125 = 5625\ \text{lbs/SF}$

Live load = 100PSF x3X(20X20) = 120,000 lbs → 120 Kips

Dead load = $125\times3 + 225\times20\times3 + 4\left(\frac{16\times16}{144}\times150\right) = 27{,}741$ lbs → 27.7 Kips

Snow load = 38psf * 20 * 20 = 15.2kips

$A_{req} = \frac{D+L}{q_e} = \frac{27.7+120+15.2}{5.625} = 28.96\ ft^2$ $b = 5.38' \rightarrow 5.5'$

$q_u = \frac{1.2\cdot27.7 + 1.6(120)}{5.5'^2} = 7.45\ K/ft^2$

$V_c = .75\cdot4\cdot\frac{\sqrt{4000}}{1000}\left(4(16+d)d\right)$

$V_c = .759\left((16+d)d\right)$

$V_u = q_u(\text{big}A - \text{Small}A) = 7.45\left(5.5^2 - \frac{(16+d)^2}{12^2}\right)$

$V_u = 225.36 - .05(16+d)^2$

$.759\left((16+d)d\right) = 225.36 - .05(16+d)^2$

$.759d^2 + 12.14d = 225.36 - .05(256 + 32d + d^2)$

$.759d^2 + 12.14d = 212.56 - 1.6d - .05d^2$

$.809d^2 + 13.74d - 212.56 = 0$ $d = 9.8'' \rightarrow 10''$

$\phi V_c = \phi\cdot2\cdot\sqrt{f'c}\cdot b\cdot d = .75\cdot2\cdot\frac{\sqrt{4000}}{1000}\times5.5\cdot10'' = 5.22$ Kips

$V_u\text{Beam} = 7.45\left(\frac{5.5 - \frac{16}{12}}{2} - \frac{10''}{12}\right) = 9.3125$ Kips $\phi V_c \geq V_u$

This fails Need to Scale up to 6'X6' and 18" thick

Footing design 2

$\phi V_c = \phi 2 \sqrt{f'c} \cdot b \cdot d = .75 \cdot 2 \frac{\sqrt{4000}}{1000} \times 6' \times 18'' = 10.24$ Kips

$V_{u\,Beam} = 7.45\left(\left(\frac{6 - \frac{16}{12}}{2}\right) - \frac{18}{12}\right) = 6.20$ Kips

$\phi V_c > V_u$ ✓ Concrete Column spread footings

6'x6'x18"

foundation Steel design W14x99

One column = 99 lbs/ft x 14ft x 4 = 5,544 lbs

Concrete $\frac{5.5''}{12''}$ x 150PCF = 68.75 lbs/ft² x 32.5'x40' = 89,375 lbs

Beam and girder (117 lbs/ft x 40) + (101x40) + $\left(\frac{102 \times 40}{2}\right)$ + $\left(\frac{68 \times 25}{2}\right)$ =

(4680) + (4040) + (2040) + (850) = 11,610 lbs

live load = 100 PSF x 3 x (32.5'x40') = 390,000 lbs

Dead = 5544 lbs + (4x 89,375) + (4x 11,610) = 409,464

Snow = 38 psf * 40 * 40 = 60.8 kips

$A_{req} = \frac{D+L+S}{q_e} = \frac{409.5 + 390 + 60.8}{5.625} = 152 ft^2$ $b = 12.36' \rightarrow b = 12'$

$q_u = \frac{1.2(409.5) + 1.6(390)}{12^2} = 7.74\ K/ft^2$

$V_c = .75 \cdot 4 \cdot \frac{\sqrt{4000}}{1000}\left(4(15+d)d\right) = .759((15+d)d)$

$V_u = 7.74\left(12^2 - \left(\frac{(15+d)^2}{12^2}\right)\right) = 1114.5 - .05(15+d)^2$

Footing design

3

Steel frame foundation continued

$11.39d + .759d^2 = 1114.5 - 112.5 - .05d^2 - 1.5d$

$9.89d + .809d^2 - 1012 = 0 \qquad d = 29.7'' \rightarrow 30''$

$\phi V_c = .75 \cdot 2 \cdot \frac{\sqrt{4000}}{1000} \times 12' \times 30'' = 34.15$

$V_u = 7.74\left(\frac{12 - \frac{15}{12}}{2} - \frac{30}{12}\right) = 22.25$

$\phi V_c > V_u$
So
foundation design
Pass

using $12' \times 12' \times 30''$

Appendix K: Material Takeoffs

Steel Building Material Takeoff					
Floor Material Takeoff					
Family and Type	Material: Area	Material: Volume	Material: Name	Count	
Floor: 5" Slab on Grade	12400 SF	191.36 CY	Concrete, Cast-in-Place gray	1	
Floor: 3" Concrete Depth w/ 2.5" Metal Deck	12400 SF	114.81 CY	Concrete, Cast-in-Place gray	3	
Floor: 3" Concrete Depth w/ 2.5" Metal Deck	12400 SF	95.68 CY	Metal Deck	3	
Floor: 3" Concrete Depth w/ 2.5" Metal Deck	10400 SF	96.30 CY	Concrete, Cast-in-Place gray	1	
Floor: 3" Concrete Depth w/ 2.5" Metal Deck	10400 SF	80.25 CY	Metal Deck	1	

Column Material Takeoff					
Family and Type	Material: Area	Material: Volume	Material: Name	Length	Count
W-Wide Flange-Column: W14X99	126 SF	3.79 CF	Steel ASTM A992	18' - 0"	19
W-Wide Flange-Column: W14X99	98 SF	2.95 CF	Steel ASTM A992	14' - 0"	56

Framing Material Takeoff					
Family and Type	Material: Area	Material: Volume	Material: Name	Length	Count
W-Wide Flange: W16X40	115 SF	1.98 CF	Steel ASTM A992	25' - 0"	5
W-Wide Flange: W18X55	127 SF	2.71 CF	Steel ASTM A992	25' - 0"	6
W-Wide Flange: W18X71	211 SF	5.69 CF	Steel ASTM A992	40' - 0"	17
W-Wide Flange: W21X101	289 SF	8.14 CF	Steel ASTM A992	40' - 0"	30
W-Wide Flange: W21X55	144 SF	2.69 CF	Steel ASTM A992	25' - 0"	23
W-Wide Flange: W21X57	215 SF	4.55 CF	Steel ASTM A992	40' - 0"	5
W-Wide Flange: W24X117	314 SF	9.38 CF	Steel ASTM A992	40' - 0"	8
W-Wide Flange: W24X68	160 SF	3.38 CF	Steel ASTM A992	25' - 0"	7
W-Wide Flange: W24X84	264 SF	6.78 CF	Steel ASTM A992	40' - 0"	8
W-Wide Flange: W27X102	296 SF	8.18 CF	Steel ASTM A992	40' - 0"	20
WT-Structural Tee: WT2.5X8	32 SF	0.43 CF	Steel ASTM A992	28' - 5"	16
WT-Structural Tee: WT4X17.5	81 SF	1.5 CF	Steel ASTM A992	43'	16

Wall Material Takeoff					
Family and Type	Material: Area	Material: Volume	Material: Name	Count	
Basic Wall: Foundation - 12" Concrete	364 SF	13.48 CY	Concrete, Cast-in-Place gray	1	
Basic Wall: Foundation - 12" Concrete	160 SF	5.93 CY	Concrete, Cast-in-Place gray	2	
Basic Wall: Foundation - 12" Concrete	100 SF	3.7 CY	Concrete, Cast-in-Place gray	2	
Basic Wall: Foundation - 12" Concrete	320 SF	11.85 CY	Concrete, Cast-in-Place gray	1	
Basic Wall: Foundation - 12" Concrete	360 SF	13.33 CY	Concrete, Cast-in-Place gray	1	
Basic Wall: Foundation - 12" Concrete	636 SF	23.56 CY	Concrete, Cast-in-Place gray	1	

Foundation Material Takeoff					
Family and Type	Material: Area	Material: Volume	Material: Name	Count	
Footing-Rectangular: 12' x 12' x 30"	408 SF	13.33 CY	Concrete, Cast-in-Place gray	19	
Wall Foundation: Bearing Footing - 36" x 12"	920 SF	12.44 CY	Concrete, Cast-in-Place gray	8	

Concrete Building Material Takeoff				
Floor Material Takeoff				
Family and Type	Material: Area	Material: Volume	Material: Name	Count
Floor: 5" Slab on Grade	12400 SF	5166.67 CF	Concrete, Cast-in-Place gray	1
Column Material Takeoff				
Family and Type	Material: Area	Material: Volume	Material: Name	Count
Concrete-Rectangular-Column: 16 x 16	17545 SF	170.26 CY	Concrete, Cast-in-Place gray	201
Framing Material Takeoff				
Family and Type	Material: Area	Material: Volume	Material: Name	Count
Concrete-Rectangular Beam: 14 x 8	4800 SF	958.25 CF	Concrete, Cast-in-Place gray	108
Concrete-Rectangular Beam: 18 x 12	7125 SF	1651.74 CF	Concrete, Cast-in-Place gray	57
Pan Joist With Ledges: 24 x 18 - T-Beam	107765 SF	19482.39 CF	Concrete, Cast-in-Place gray	171
Pan Joist With Ledges: 36 x 18 - T-Beam 2	26971 SF	5124.66 CF	Concrete, Cast-in-Place gray	46
Foundation Material Takeoff				
Family and Type	Material: Area	Material: Volume	Material: Name	Count
Footing-Rectangular: 6' x 6' x 18"	5508 SF	2754 CF	Concrete, Cast-in-Place gray	51
Wall Foundation: Bearing Footing - 36" x 12"	3224 SF	1146 CF	Concrete, Cast-in-Place gray	8
Wall Material Takeoff				
Family and Type	Material: Area	Material: Volume	Material: Name	Count
Basic Wall: Foundation - 12" Concrete	2200 SF	2200 CF	Concrete, Cast-in-Place gray	8
Basic Wall: Concrete Shear Wall	7840 SF	6533.34 CF	Concrete, Cast-in-Place gray	6

Appendix L: Cost Estimate

Building Cost Estimate	Steel		Concrete	
	$/SQFT	Total $	$/SQFT	Total $
A. Substructure				
Standard Foundations	$ 0.49	$ 24,304.00	$ 0.49	$ 24,304.00
Special Foundations	$ 1.61	$ 79,856.00	$ 0.85	$ 42,160.00
Slab on Grade	$ 5.92	$ 73,408.00	$ 5.92	$ 73,408.00
Basement Excavations	$ 0.18	$ 99.00	$ 0.18	$ 99.00
B. Shell				
Framing	$ 12.35	$ 612,560.00	$ 26.12	$ 1,295,552.00
Floor Construction	$ 2.32	$ 115,072.00	$ 13.13	$ 651,248.00
Roof Construction	$ 5.27	$ 65,348.00	$ 3.28	$ 162,688.00
Exterior Windows	$ 3.32	$ 164,672.00	$ 3.32	$ 164,672.00
Exterior Doors	$ 2.80	$ 138,880.00	$ 2.80	$ 138,880.00
Roof Coverings	$ 6.91	$ 85,684.00	$ 6.91	$ 85,684.00
Exterior Walls	$ 7.54	$ 93,496.00	$ 7.54	$ 93,496.00
C. Interiors				
Interior Doors	$ 1.80	$ 89,280.00	$ 1.80	$ 89,280.00
Fittings	$ 0.05	$ 2,480.00	$ 0.05	$ 2,480.00
Stair Construction	$ 4.40	$ 218,240.00	$ 4.40	$ 218,240.00
Wall Finishes	$ 5.92	$ 293,632.00	$ 5.92	$ 293,632.00
Floor Finishes	$ 6.76	$ 335,296.00	$ 6.76	$ 335,296.00
Ceiling Finishes	$ 7.69	$ 381,424.00	$ 7.69	$ 381,424.00
D. Services				
Elevator	$ 2.52	$ 124,992.00	$ 2.52	$ 124,992.00
Plumbing Fixtures	$ 33.54	$ 1,663,584.00	$ 33.54	$ 1,663,584.00
Domestic Water Distribution	$ 1.69	$ 83,824.00	$ 1.69	$ 83,824.00
Rain Water Drainage	$ 0.91	$ 11,284.00	$ 0.91	$ 11,284.00
Distribution Systems	$ 0.89	$ 44,144.00	$ 0.89	$ 44,144.00
Terminal & Package Units	$ 20.40	$ 1,011,840.00	$ 20.40	$ 1,011,840.00
Sprinklers	$ 2.97	$ 147,312.00	$ 3.27	$ 162,043.20
Standpipes	$ 0.37	$ 18,352.00	$ 0.41	$ 20,187.20
Electrical Service/ Distribution	$ 1.39	$ 68,944.00	$ 1.53	$ 75,838.40
Lighting/ Branch Wiring	$ 26.88	$ 1,333,248.00	$ 29.57	$ 1,466,572.80
Communications & Security	$ 3.49	$ 173,104.00	$ 3.84	$ 190,414.40
Other Electrical Systems	$ 0.80	$ 39,680.00	$ 0.88	$ 43,648.00
E. Equipment & Furnishings				
Institutional Equipment	$ 1.57	$ 77,872.00	$ 1.57	$ 77,872.00
Moveable Furnishings	$ 0.16	$ 7,936.00	$ 0.16	$ 7,936.00
F. Special Construction				
Demolition	5.2	257920	5.2	257920
E.Building Sitework				
Fencing	$ 8.45	$ 9,295.00	$ 8.45	$ 9,295.00
Erosion Control	$ 2.84	$ 3,124.00	$ 2.84	$ 3,124.00
Total Cost	**Steel**		**Concrete**	
	$/SQFT	Total $	$/SQFT	Total $
	$ 189.40	$ 7,850,186.00	$ 214.82	$ 9,307,062.00

Appendix M: Schedule Activity List

Activity Name
START PROJECT
Erect Fence/Prep Site/Erosion Control
Relocate Utilities
Backfill/Restore Grade
Excavate for Foundation Wall
Excavation for Spread Footings
Backfill Int. Fnd. Walls & U/G Duct
Form/Place/Strip Spread Footings
Form/Place/Strip Foundation Walls
Concrete Curing
Dampproof & Insulate Foundation
Fabricate & Deliver Steel
Erect Basement Steel
Erect First Floor Steel
Erect Second Floor Steel
Erect Third Floor Steel
Install First Floor Deck/Studs
Install Second Floor Deck/Studs
Install Third Floor Deck/Studs
Install Roof Metal Decking
Prep/Pour Main Slab on Grade
Prep/Pour First Floor Slab on Deck
Prep/Pour Second Floor Slab on Deck
Prep/Pour Third Floor Slab on Deck
Install Roof Decking
Install Slate Shingles
Install Precast Supports / Adjust
Install Windows
Exterior Walls Insulation Panels
Install First, Second, Third Floor Brick - E/W/N/S
Install Stairs/Areaway Grates
Install Stair Rails
Install Doors & Hardware
Install Drywall
Paint - Finish
Install Wood Paneling
Install Elevator
Install & Complete Flooring
Paint - Prime
Install HVAC Duct/Piping
Install Electrical
Install Plumbing
Install Telecommunications

Install Fire Protection
Mechanical Finishes
Fab. & Del. Auditorium Seating
Ext. Lights W/E Entrances
Install Signage Building
Owner Furniture
Exterior Finishes, Plantation & Grading
Landscaping & Brick Paving
Place Exterior Concrete Sidewalks
Place Exterior Site Concrete
Test & Balance Building - Bldg
Punchlist - 1st flr
Punchlist - 2nd flr
Punchlist- 3rd flr
Final Clean - 1st flr
Final Clean - 2nd flr
Final Clean - 3rd flr
Commissioning Building
Flush Building
Substantial Completion Cert. of Occup.
WPI Move - in
Building Dedication
END PROJECT