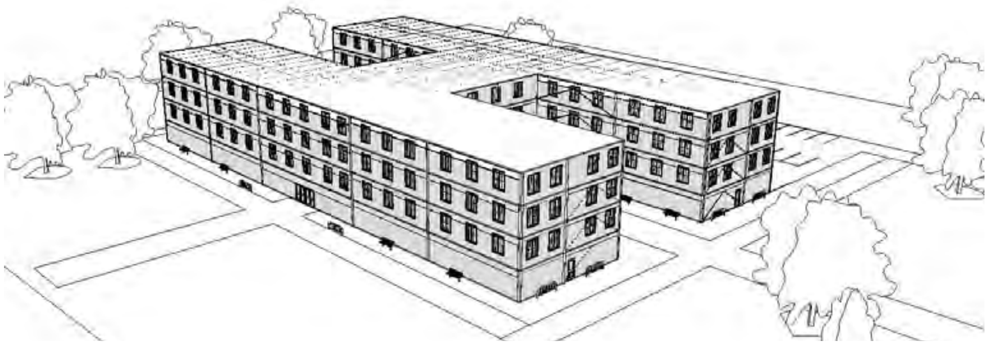
Sustainable WPI Residence Hall



A Major Qualifying Project Report
Submitted to the Faculty of the
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements for the
Degree of Bachelor of Science

by
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Report Submitted to:
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Abstract

The student population at Worcester Polytechnic Institute has outgrown the number of available beds on campus, forcing most upperclassmen to search for off campus apartments. This Major Qualifying Project explores this issue and proposes a design for a new suite-style residence hall to be constructed on the current site of Ellsworth Apartments. To accomplish this, the state building codes and local zoning laws were consulted to design floor and structural steel framing plans. Deliverables included a 3D AutoCAD Revit model with phasing, a Microsoft Project schedule, and a cost analysis. Additionally, sustainable alternatives were researched, analyzed, and ranked in order to develop a set of recommendations for which WPI should utilize in this new and future residence hall designs.

Authorship

Due to the nature of this project, the report was simultaneously written as the project work progressed. While each member of the team contributed to the overall writing and report edits as well as research into sustainable alternatives to building design, Heather and Tyler worked primarily on the structural design as Ava and Madelyn worked on the construction project management aspects including the 3D Revit Model and Microsoft Project Schedule. The following statements describe the work completed by each individual team member:

Tyler worked on the initial writing of the building design materials background as well as building design methods. For structural design, Tyler constructed the initial spreadsheet design that was used for all further calculations for the project. Those calculations were split amongst Tyler and Heather; they checked each other's calculations throughout the entire process. Tyler then contributed in the write up of all phases of the structural results. He then conducted sustainability research on the use and installation of green roofs.

Heather worked mostly on the project management background information, LEED certification, and solar power alternative research. Work was split up for structural design, and Tyler and Heather checked each other's calculations. Heather also led the cost analysis work using RSMeans. She worked with Madelyn to associate the cost estimate with the schedule. Heather wrote a large portion of the items that reflect the work she completed including the respective objectives for schedule, cost, and sustainability.

Ava worked on the initial interview process and gathering background information on WPI's current housing dilemma. She then focused efforts on the 3D model within AutoCAD Revit where she finished the structural framing and foundation plan Madelyn had started and created the final model, with materials, components, energy analysis, and project phasing. She also compiled and produced all of the model images and renderings for the poster and final report. She contributed to the report, writing on alternative material construction for sustainability, background of WPI housing, the design problem for the project, and project phasing, among other shared portions.

Madelyn worked primarily on the building code components of this project including the written portion in the background as well as developing the building program. Using AutoCAD Revit, she completed the floor layout design according to the constraints set by the Massachusetts State Building Code and added the proper beam sizes to the structural layout before passing the model back to Ava for its completion. She also helped in the structural design process to design footings, created the schedule in Microsoft Project, and conducted research on the application of greywater systems in residence halls.

Acknowledgements

Our team would like to thank…

- **Amy Beth Laythe and WPI Residential Services** for providing valuable insight into the housing situation at WPI.
- **Ronald O'Brian and WPI Facilities** for background information on what WPI typically looks for in their building architecture features and new construction.
- **Derrick Morse and Rugged Robotics** for expanding our understanding of innovations in the construction industry.
- **Professor Leonard Albano**, our MQP advisor, for supporting us throughout project development and completion.

Capstone Design Statement

The Accreditation Board for Engineering and Technology (ABET) requires that all accredited engineering programs include a capstone design experience. At Worcester Polytechnic Institute (WPI), this requirement is fulfilled through the Major Qualifying Project (MQP). The capstone design must address many of the following realistic constraints of a project: economic, environmental, sustainability, constructability, ethical, health and safety, social, and political. This MQP focuses on the design of structural elements of a residence hall on the WPI campus. The following is a description of how the project addressed each of the following constraints:

Economic: This project considered various construction project delivery methods in order to deliver the building design within the quickest timeline while also limiting additional costs.

Sustainability: This project investigated LEED certification as well as up-and-coming innovations within the construction industry that work to promote more environmentally stable practices in the pursuit of creating a healthier environment for all.

Constructability: Constructability is one of the most crucial factors for implementing this building design: Considerations regarding the target audience (first-year versus upperclassmen students), as well as room style, were taken into account. Similarly, the following factors were analyzed and considered:

- Site plan and floor plan for the building;
- Structural layout for the building design;
- Zoning, permitting, and regulations to determine the baseline minimum requirements for the design; and
- Construction schedule and cost feasibility for the project.

Ethical: The design for this project is compliant with the American Society of Civil Engineers (ASCE) Code of Ethics. For this project, the following ASCE canons were considered most applicable:

- *Canon 1* - Engineers shall hold paramount the safety, health and welfare of the public and shall strive to comply with the principles of sustainable development in the performance of their professional duties.
- *Canon 8* - Engineers shall, in all matters related to their profession, treat all persons fairly and encourage equitable participation without regard to gender or gender identity, race, national origin, ethnicity, religion, age, sexual orientation, disability, political affiliation, or family, marital, or economic status.

Health and Safety: Throughout this project, both local and state building codes such as the Worcester zoning laws and the *Massachusetts State Building Code* (780 CMR) are referenced. The use of these codes to develop a design ensures that the health and safety of the surrounding community and the future occupants of the building are addressed.

Social: This project considered the social constraints of site development by pursuing solutions with limited impact on the surrounding Worcester community and its residents

Professional Licensure Statement

Professional Engineer (PE) licensure is a standard of dedication, skill, and quality that is widely recognized. Only licensed engineers may prepare, sign, seal, and submit engineering plans and drawings to a public authority for final approval or to seal engineering work for public and private clients. The PE license is also a legal requirement for anyone who conducts work in the engineering field, therefore, it is held to the highest regard and something aspiring engineers work for years to obtain. Regardless of what path an engineer chooses, a successful career virtually requires PE licensure. The National Society of Professional Engineers (NSPE) is a professional organization whose mission is to "foster a world where the public can be confident that engineering decisions affecting their lives are made by qualified and ethically accountable professionals". The NSPE serves to champion, guide, advance, and unite professional engineers and foster professional advancement, unity, qualifications, and accountability.

To obtain licensure, an aspiring engineer must graduate from an approved undergraduate program (typically an ABET-accredited program as deemed by the corresponding state licensure board) and successfully complete the Fundamentals of Engineering (FE) exam. Only then may they move on to complete four years of qualifying engineering experience under the mentorship of a licensed professional engineer. Finally, the aspiring engineer may apply to determine their eligibility to take the Principles and Practice of Engineering exam within their state, which upon successful completion, will provide them with the licensure to practice as a professional engineer.

Besides being able to practice their discipline without supervision, a PE licensure is attractive for other reasons. Five of the most enticing reasons to get licensed include: prestige, career development, authority, flexibility, and money. PEs are respected and held in high regard by peers and colleagues in the engineering community. Employers seeking to fill engineering positions find potential job candidates with professional engineering licensure to be at the top of their list for their commitment to the profession as well as a perceived level of leadership and management skills that are above average. Additionally, only PEs can sign and seal engineering drawings, be in charge of a firm in private practice or serve as a qualified expert witness, and therefore have more options and flexibility when it comes to their career. They can pursue specialty paths within engineering, or establish their own business. It also allows engineers to go as far as their initiative and talent will take them. Finally, an enticing reason to get licensed, data shows that most PEs earn higher pay throughout their business careers due to their expanded opportunities.

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1. Introduction

In recent years, the availability of on campus housing at Worcester Polytechnic Institute (WPI) has been unable to keep up with the student demand. Incoming classes to the institution have grown exponentially since its founding, and the burden of finding a bed for new students falls on the shoulders of the Residential Services Office. Since on-campus housing is only guaranteed for first-year students, several residence halls have been constructed strictly to house them. The problem lies, however, with what happens when these beds are not enough to house the entire incoming class. As of the year 2010, almost all residence halls that were constructed specifically for upperclassmen living, now dedicate some, if not all, of their beds to first-year students. This leaves upperclassmen displaced and in a panic to find whatever housing is left in the area. While upperclassmen are made fully aware each year that their likelihood of obtaining on-campus housing is never guaranteed, the number of beds once dedicated to them continues to dwindle, with little action being taken to remediate the issue.

Previous efforts have been made to find students a space to live on campus. WPI expanded residential options in 2019 with the construction of Messenger Hall on top of the newest academic building, the WPI Innovation Studio, which added an additional 140 beds. The spread of the COVID-19 pandemic, however, forced WPI to completely rework their housing assignments in order to keep their residential students safe. This meant de-tripling most of the first-year housing and relocating those students to other residence halls. For that reason, multiple upperclassmen residence halls transitioned to housing first-year students, and WPI began using the WPI Townhouses, the Hampton Inn hotel, and housing formerly utilized by Becker College after it closed in 2021. Even with these new options for housing, the number of beds available for students are at full capacity. With the uncertainty of maintaining a lease with the Hampton Inn and the properties formerly known as Becker College, the Residential Services Office is left at a standstill for the future of housing assignments. The WPI campus needs a way to continue to provide first-years with housing without the need for these external properties while also maintaining a permanent space for upperclassmen to live.

The goal of this project was to propose a new residence hall option specifically designed for WPI's upperclassmen students. To accomplish this goal, a series of individual objectives were completed.

- Objective #1: Define the design problem
- Objective #2: Design a new residence hall
- Objective #3: Estimate construction schedule and costs
- Objective #4: Evaluate sustainability alternatives and industry advancements.

First, information regarding the current housing situation at WPI was gathered. This step was completed by conducting several interviews as well as research within both the Residential Services Office and the Facilities Office. With that information, a design for a new residence hall for WPI's campus was formulated. This design included site location, a floor plan, and structural member calculations.

Using the developed design, estimates of the construction schedule and costs were determined. To complete this, cost factors such as labor, materials, and time were considered. Sustainable design attributes that could be incorporated into a residence hall were also investigated. These alternatives were evaluated and compared against each other in order to determine which option for this particular residence hall could potentially be implemented to improve the cost of construction while also meeting the WPI communities' desire for a more sustainable campus.

At the end of this project, the following deliverables were produced:

- Structural steel design, as well as concrete slab and footing calculations;
- A proposed floor plan and multidimensional model;
- A complete project schedule generated by the Microsoft Project Software; and
- A list of recommendations as to how WPI can incorporate more sustainable alternatives into future building construction on campus.

2. Background

In this chapter, the idea that the demand for housing at Worcester Polytechnic Institute (WPI) continues to exceed the number of available beds is discussed. The first section opens a discussion on the potential for constructing a new residence hall through the use of structural steel or reinforced concrete design and the needed attention to building codes and zoning requirements. Additionally, the topic of project management is considered and insight is given as to how various project delivery methods can be used to facilitate new construction on campus. The benefits of Building Information Modeling will also be discussed as well as how new innovations in the construction industry can aid in cutting down the physical and environmental costs of construction.

2.1. Student Housing at WPI

Worcester Polytechnic Institute (WPI) was founded in 1824 with the purpose of creating an institution for men that unites the theory and practice of engineering. The campus, located on top of one of the seven hills in Worcester, Massachusetts, opened in 1868 with only two buildings, as the Worcester County Free Institute of Industrial Science.

Although the campus opened with only two buildings, it quickly expanded as more and more men sought engineering education in the late 1800s. However, it wasn't until 1926 that the campus opened its first residence hall, Sanford Riley Hall. It was built to house 115 men in 66 rooms, including a dining hall in the basement. The second residence hall, Morgan Hall, was built in 1958, to accommodate the rapidly growing campus size. Morgan was built to house 192 men in 8 single and 92 double rooms. Since then, the college has grown dramatically. WPI now has 13 residential buildings; however, with an increasing number of applicants each year (and a relatively constant acceptance rate) the institution can no longer house enough upperclassmen students seeking safety and comfort on campus and away from the public streets of Worcester.

The first few residence halls built for first-year students, Morgan Hall, Daniels Hall, and Stoddard Complex, were all designed for double rooms- now almost exclusively filled with forced triples. WPI only guarantees housing for first years, but the university has built several residence halls over the years designed specifically for upperclassmen. WPI broke ground on Ellsworth/ Fuller Apartments in 1972, and later in 1984, Founders Hall was built. As the fifth and sixth residence halls respectively, they were designed as upperclassman suite-style apartments, since the rest of the first-year classes had ample living space. This relief was short-lived- when the class of 1993 was rumored to be the largest class yet (at just over 700 students), WPI rushed to renovate an old apartment building to accommodate the first-year class without displacing any upperclassmen. This led to the opening of Institute Hall, housing 70 students at the time. Since then, WPI has increased the occupancy of nearly every residence hall in order to accommodate the incoming classes. Institute Hall expanded to house 90 first years, Morgan Hall expanded to 294, and the Stoddard Complexes now house 90 students in each of the three buildings.

The fact of the matter is, there is nowhere else to put the rapidly expanding first-year classes except to repurpose the spaces meant for upperclassmen. Due to this, it is rare that Juniors and Seniors live on campus. Previously mentioned Founders Hall, built to house 232 upperclassmen, has been overfilled to now house 286 students. Consequently, of those 286 beds, only one floor is currently housing upperclassmen. Messenger Hall, the newest residence hall built on top of the WPI Innovation studio in 2018, was also built for 140 upperclassmen. That was only the case for two years because in the academic year 2020-21 it housed some first-years and sophomores, and then in 2021-22, it changed to house first-years exclusively.

With each coming year, the first-year class grows, while the campus remains the same size. Not only does the limited housing capacity deny the university an additional source of revenue, but the housing process leaves upperclassman students displaced and without a plan B, forcing them to try and find off-campus housing within walking distance of the campus. In the past three years alone, the percentage of upperclassmen who request housing and are granted a bed has dropped from 85% to 75% (Laythe, 2021), but the demand hasn't changed. WPI cannot justify continually increasing class size without first housing its existing students.

2.2. Building Design Materials

In order to design the proposed building, the design team needed to specify the materials used to construct the project. Over time, the different materials used in the construction industry have varied. But modern construction methods used in the Northeastern United States utilize structural steel and reinforced concrete to complete building design. Both of these materials have properties that make them widely used within construction today. Each has a specific purpose within the design of a structure.

2.2.1. Structural Steel

Structural steel is widely used in modern building construction due to its high strength and ductility when loaded to capacity. Many steel elements are designed and fabricated off-site and then assembled in place to increase the speed and efficiency of the project. This method is known as prefabrication, which cuts down the number of laborers being used on the project and therefore decreases the overall cost of construction. With the use of prefabrication, the construction of typical low-rise buildings can be expedited compared to classic construction methods. This is especially helpful for organizations such as universities that are on a tight schedule given their academic calendars. Structural steel is the dominant material used in the Northeastern United States due to its ability to withstand variable weather conditions throughout the year. These elements are designed with the aid of the AISC Manual, Specification, and Commentary which provide calculation standards and governing equations for the design and construction of steel structures (AISC, 2017).

2.2.2. Reinforced Concrete

Concrete is a mixture of cement, water, and aggregates, such as sand or gravel. Concrete is a popular material used in construction because the specific mixture can be curated to support a specific compressive strength as calculated by the building's desired final load capacity. However, the tensile strength of concrete is low compared to its compressive strength. To offset this, steel is used to reinforce the concrete and provide support where its carrying capacity would otherwise be limited. By combining the two, reinforced concrete is a low-cost, weather, and fire-resistant material with good compressive strength for structural design. This combination allows for reinforced concrete to be used in an almost unlimited range of uses in the construction of a plethora of structures such as buildings, bridges, dams, and reservoirs (Darwin, 2021).

2.3. Design Constraints: Building Code and Zoning Regulations

Building codes are a collection of minimum requirements which are adopted by a town, city, county, or state to govern the construction and maintenance of new and existing buildings. Organizations such as the National Fire Protection Association (NFPA) and the International Code Council (ICC) develop these codes using data they have gathered from events such as fires, earthquakes, windstorms, and other extreme conditions. Every few years these organizations release new editions of their codes to keep up with modern standards for protecting buildings and their occupants. Building codes also work to ensure that the building has been designed and constructed to not only withstand these events but meet the standards of structural integrity, mechanical, electrical, and plumbing (MEP) safety, as well as to meet accessibility standards set forth by the Americans with Disabilities Act (ADA).

Zoning regulations establish regulations for the use of land by local governments in order to divide their town, city, or county into separate districts dedicated to residential, commercial, institutional, or industrial uses. This method of dividing up the local area makes it possible for city planners to manage orderly growth and change by controlling the desirable characteristics of each type of setting. Each zone is given a specific purpose and can also control how tall or wide a building can be constructed.

2.3.1. Governing Codes in Massachusetts

Various areas of the United States have formed their own committees which put forth a modified version of the building codes created by the NFPA and the ICC. The Commonwealth of Massachusetts adopted the ninth edition of the *Massachusetts State Building Code* (MSBC CMR 780) in late 2017. This edition draws upon many of the same codes featured in the 2015 editions of the codes published by the ICC including

- The *International Building Code* (IBC)
- *International Residential Code* (IRC)
- *International Existing Building Code* (IEBC)
- *International Mechanical Code* (IMC)
- *International Energy Conservation Code* (IECC)

- *International Swimming Pool and Spa Code* (ISPSC); and
- Portions of the *International Fire Code* (IFC).

The MSBC is separated into two distinct volumes: Base and Residential. The Residential volume regulates all one- and two-family structures and townhouses that are three stories or less. It also discusses any structures that may be considered an accessory to them. All structures not covered in the Residential volume, including the residence hall which will be designed for this project, are covered in the Base volume.

Massachusetts also has an Architectural Access Board (AAB) which develops and enforces building regulations designed to make public areas accessible, functional, and safe for use by those with disabilities. These regulations are collected and published as the 521 CMR. Currently, the Commonwealth of Massachusetts uses the sixth edition of the 521 CMR, published in 2006. Sections which this code covers include:

- Jurisdiction
- Space Allowance and Reach Ranges
- Building Types (retail establishments, transient lodging facilities, multiple dwellings, commercial buildings, educational facilities, medical care facilities, places of assembly, etc.)
- Accessible Routes
- Curb Cuts
- Walkways
- Parking and Passenger Loading Zones
- Ramps
- Room Type (kitchen, bathroom, storage, etc.)

While the design of a new residence hall on a college campus seems to be very specific in nature, these codes have been created to dictate such a case. Everything from occupancy classification, uses, building loadings, egress capacity, room sizing, and more can all be determined using these building codes and combined to create a program that will be looked back on and used as a consideration in each step of the building's design.

2.3.2. Zoning Regulations Around the WPI Campus

Across the City of Worcester, Massachusetts, the voluntary regulatory Zoning Board of Appeals (ZBA) has drawn distinct zoning districts which serve to dictate how the land in Worcester may be used. WPI's main campus is located within an institutional zone IN-S (Figure 1).

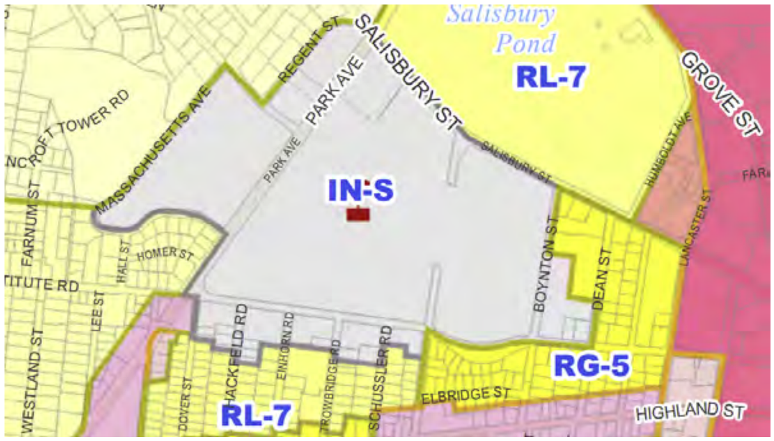


Figure 1: Worcester Polytechnic Institute's main campus shown on Worcester's zoning map

Within this zoning classification, the ZBA has defined permitted uses shown in Table 1.

Table 1: Examples of Permitted Uses of the Land Within an IN-S Zoning District

Use	Permitted
Residential	• Dormitory • Fraternity/Sorority/cooperative residence • Group Residence (general or limited) • Multi-family dwelling (low rise)
General	• Library/Museum (nonprofit) • Non-accessory residential parking • Non-residential parking facility (non-accessory) • Recreations/service facility (non-profit) • Schools (K-12, college, university, technical institute) non-profit • Schools (vocational, professional, other) profit
Business	• Food Service (excludes consumption/sale of alcoholic beverages)* • Research lab, w/o manufacturing abilities • Retail food sales* • Retails sales, including retail with incidental fabrication assembly

** indicates that a special permit is required*

Additionally, the ZBA has established permitted dimensions by district as shown in Table 2.

Table 2. Permitted Dimensions by District

District	Use	Lot		Yard Setbacks			Height		Floor to Area Ratio (Maximum)
		Area (minimum SP)	Frontage (minimum linear ft.)	Front	Side	Rear			
				Minimum depth (linear ft.)			Max in stories	Max in ft.	
IN-S	All	N/A	N/A	15	10	10	N/A	N/A	N/A

Looking at the permitted dimensions for an institutional zoning district shown in Table 2, it can be noted that other than the perimeter setbacks, there are not any significant restrictions set on how many stories a new building on the WPI campus can be or how much it can cover the lot it is constructed on.

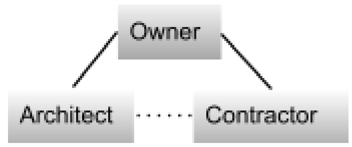
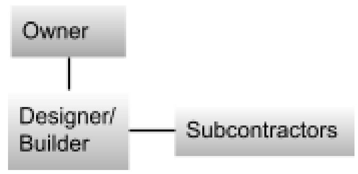
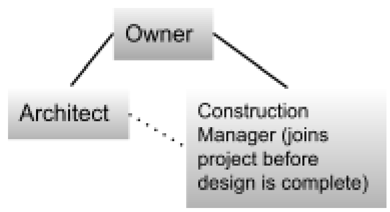
2.4. Project Management & Innovation in Construction

Many companies utilize project management techniques to better facilitate teamwork. A project management team facilitates the operations of a project in order to maximize productivity and efficiency. In construction project management, teams prioritize schedules, cost, quality, and customer satisfaction (Ribeiro et. al., 2013; Demirkesen et. al., 2017). In order to satisfy the many needs of the construction project, project management teams must integrate their priorities with labor and material resources to move the project along successfully. To accomplish such a complicated task, a project team must communicate effectively and adapt well to changes.

2.4.1. Management Based on Project Delivery Methods

The contractual arrangements, construction, and design responsibilities are dependent on the project delivery method used (Ohrn et. al., n.d.). Each project delivery method allows for a different project team setup and different levels of team integration (Mollaoglu-Korkmaz et. al., 2013). A select number of the common project delivery methods are listed in Table 3 along with typical uses for the listed methods (Gazder et. al., 2018; Mollaoglu-Korkmaz et. al., 2013). Design-bid-build (DBB) is a system in which the owner coordinates with separate entities for design and contracting. Design-Build (DB) is when the project is contracted to a single company to manage both design and construction. Both processes are highly recommended and common for clients of private organizations (Gazder et. al., 2018). Additionally, the Construction Manager at Risk (CM@R) delivery method may be valuable to a university project where a school has a strict budget for new campus facilities.

Table 3. Project Delivery Comparisons

Project Delivery Method	Projects	Project Team	Time of Project	Cost
Design-bid-build (DBB)	● Industrial ● Public		Extensive time for subcontractor bidding	Expensive
Design-Build (DB)	● Commercial ● Private ● Sustainable construction		Quick project delivery	Less Expensive
Construction Manager at Risk (CM@R)	● Sustainable construction		Time-efficient	Limits contractor to a guaranteed maximum price

The choice of project delivery method will alter the approach to scheduling the timeline of the project. After discussion with WPI Facilities representatives, it was determined that WPI typically utilizes a Guaranteed Maximum Price (GMP) contract with a CM@R project delivery method (WPI Facilities Office, 2021). Due to WPI preference, time efficiency, cost benefits, and sustainable priorities, CM@R is the project delivery method explored within this project for the new residence hall design and construction.

2.4.2. Scheduling Software and Project Costs

In order to evaluate scheduling, a project team can utilize software such as Primavera or Microsoft Project. This scheduling software allows for analysis of the critical path method, allowing for optimization of construction activities upon project commencement (Hawkins, 2007). Within Primavera and Microsoft Project, a scheduler can add information for the start/end date of the project, activities, activity durations, costs, locations, and work breakdown structures (Hawkins, 2007). Primavera can be difficult to navigate, is no longer being updated, and costs about $5000 per license (Hawkins, 2007). In contrast, Microsoft Project is much easier to use, has fast project setup times, is constantly updating software, and only costs $500 per license (Hawkins, 2007). Both software programs are commonly used by construction companies; however, Microsoft Project's ease of use and quick setup times far outweigh those of Primavera

(Hawkins, 2007). Therefore, Microsoft Project was used to create the construction project schedule for the new residence hall.

Companies are also likely to use software to visualize construction projects such as Building Information Modeling (BIM) and Revit (Demirkesen et. al., 2017). These tools can help to model a project in 3D (building), 4D (building+schedule), or 5D (building+schedule+cost). Layers of project cost, schedule, safety, and sustainability parameters can be compiled for the project using BIM software (Mesároš et. al., 2020). In the future, it could be possible that augmented or virtual reality modeling will be used to visualize construction projects (Mesároš et. al., 2020).

After scheduling, the cost is a top priority for project management. A project's cost comes from direct, indirect, and penalty costs. Direct costs include material and labor such as steel beams and a welder. Indirect costs include the salaries of the project management team, any company vehicles, and safety paperwork or drawings printed, etc. Penalty costs are the liquidated damages for the project. This includes any costs in delays or changes to design through change orders. If the schedule is delayed, the cost goes up (Ribeiro et. al., 2013). This is because the more days you spend on a project, the more hours each subcontractor and laborer work. To minimize cost, it is optimal to multitask within the schedule as best as possible by starting tasks before others are completed. The schedule and cost can be combined to display an S-curve of the total project cost over time. This curve is shaped like an S since costs often start out low, drastically increase towards the middle of the project, and level off towards project completion.

Typically each month the contractor or builder submits a requisition to the owner which will include the month's work cost plus an additional 10% markup, the average markup for profit percentage. The contractor will also hold a retainage which is a portion of the payment for the subcontractor to be paid when their job is complete. Throughout the project, the project management team may do evaluations on whether they are above or below on costs, behind or ahead on schedule, and cost variance which includes the cost to date and the cost to complete compared to the original budget.

2.4.3. Sustainability & Innovation

Sustainability is the practice of resource management where resources are consumed, but not overused so as to allow for use in future generations. The benchmarks for sustainability are different depending on what type of global sector is explored. In relation to construction projects, sustainability can be considered in the design, project management, and post-turn-over maintenance phases of the project's life-cycle.

To maintain sustainability throughout a project's construction phase, it is important to engage the stakeholders, most often the owners, in conversations about achieving sustainability goals in construction (Stanitsas et. al., 2021). After the project management team turns over the newly finished project, it is important that the owner still considers sustainability efforts after construction (Stanitsas et. al., 2021). The entire life cycle of the building can be evaluated to determine whether the materials that make up the building can be maintained for many years to come (Stanitsas et. al., 2021). Sustainability methods can be considered as renewable energy methods, green landscaping, and environmentally conscious materials, among others.

In addition to sustainability, the construction building process and procedures can continuously be improved. Building procedures are relatively the same from project to project due to the common goal of consistency in building quality. However, this results in processes that lack change or innovation. It is possible that systems for building walls or laying out Mechanical, Electrical, and Plumbing work can be altered to increase the efficiency and precision of a project. Technological advancements could help to automate some of the construction processes. It should be noted that these new processes may not be integrated easily as construction workers are often set in their ways. Despite this, it is valuable to explore the options available especially when it can help to shorten the time frame, lower cost, and improve the quality of the project.

3. Methodology

The goal of this project was to consider the housing problem faced by WPI and provide upperclassmen with a new housing option.

During the course of the design and research terms, a series of objectives to provide WPI upperclassmen with a new housing option were explored (Figure 2).

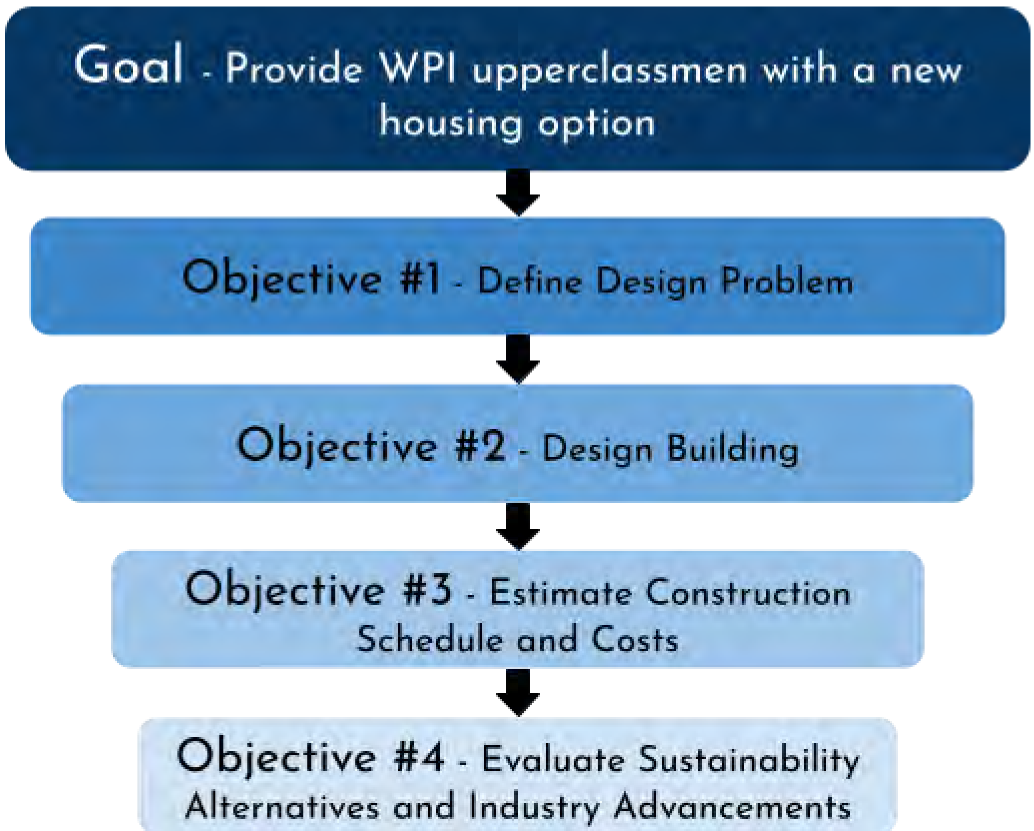


Figure 2: Flowchart depicting the progression of each of the project's objectives.

3.1. Objective #1: Define Design Problem

In order to design anything, the end-user and owner's needs and requests must be the first considerations. In the case of this project, the intended end-user was an upperclassman student at WPI who wished to continue to live on campus after their first year. To better understand the current status of WPI housing and which improvements can be accounted for in a new design, the following issues were considered: the number of students who are denied on-campus housing after they apply for it, the types of residence halls that are more attractive to upperclassmen, and the ideal group size for housing arrangements.

To begin the design process for a new residence hall, the history of WPI housing was researched through the collection of existing data provided by Residential Services. The data requested consisted of the number of beds available on campus for the 2020-2021 school year and any years prior, if available, as well as the number of applications for housing received by Residential Services. This information was used to highlight the current hypothesis that WPI's population has grown rapidly in the last several years and can no longer keep up with anticipated housing needs.

Once justification was made that the demand for on-campus housing will only continue to grow in the coming years, the focus was narrowed to current residential buildings on campus. More specifically, information was collected from Residential Services, Facilities, and the WPI Tech Bible regarding WPI's East, Faraday, and other residence halls. This information included which project delivery methods were used to construct these buildings, which class years they were initially intended to house versus which class years currently reside there, and what WPI's current thinking is behind what is desirable in a new residence hall such as location, size, dining options, etc.

Using this information, a suitable location was selected for constructing a new residence hall. Identifying the site enabled further research and created a list of constraints for the building design. The first constraint explored was those imposed by the Worcester Zoning Board of Appeals (ZBA). The city's *Zoning Ordinance* helped to determine the permitted land uses based on occupancy classification as well as the permitted dimensions including lot size, yard setbacks, maximum height in stories, and floor to area ratio. Following this, building codes such as those set in the base volume of the MSBC CMR 780, IBC 2015, NFPA 101, 527 CMR, and 521 CMR Section 8.00: TRANSIENT LODGING were consulted to determine:

- Building occupancy;
- Means of egress or escape;
- Egress size requirements (hallways, stairwells, etc.);
- Elevator lobby requirements;
- Room and suite sizes; and
- Accessibility requirements.

3.2. Objective #2: Design Building

Once the zoning and building code constraints were defined for the chosen location, along with the wants and needs of the WPI community, this information was compiled into a building program. This set of documents detailed information such as the number of stories, types of spaces, amenities, approximate unit sizes, and approximate allocations of area for the planned residence hall. Following this, the program was utilized as a guide to sketch out a proposed floor plan using Revit software which showed the sizing of the suites as well as the means of egress. After this was completed, structural steel framing was designed for the building structure.

To begin the structural design, concrete slabs that support the building were first designed. The IBC Fire Resistance Requirements were referenced as well as the ASD Composite slab and deck specifications in order to determine the proper total slab depth. Within these documents, the necessary fire-resistance rating as well as the required minimum thickness of the slab were found. From there the metal decking was designed to accommodate the largest unshored span given the requirements of the slab size.

To accomplish structural design, the building was divided into typical bays and framing schemes for suites, hallways, around the stairwells, elevators, and core of the building. For each area, design values were established for the gravity and lateral loads for each case. From there, the load case scenarios were calculated for the design of the structural system and its members according to the provisions of LRFD. For the floor framing, moments were calculated and wide-flange sections (W shapes) were used to size the respective beams and girders based on the strength provisions of the AISC Specification. Then, the beams and girders were checked for deflection based on standards set in the IBC. Given those new parameters, calculations were checked to ensure that the sizes selected were sufficient for the design. (AISC, 2016).

After the beams and girders were designed, the building's columns and lateral-load resisting system were designed. Initial column sizes were selected according to the AISC Specification for HSS Square columns. Column selection was completed based on factored loading acting on the tributary area supported by each column. Two types of columns were defined and designed: frame columns that are part of the lateral-load-resisting system and leaning (or gravity) columns that are not part of the lateral frames. The leaning columns were sized as pin-ended columns to support factored gravity loads.

To design the lateral-load-resisting system, bracing locations were selected for each floor in both the North/South and East/West directions. The story forces for wind and seismic loading were calculated separately according to *ASCE 7-10*. Seismic forces for the building were determined using R = 3. The larger of the two, seismic forces, was selected to define the story forces at each level. A truss analysis was completed for each bracing location to determine the axial loading on the bracing and any additional axial loading on the supporting columns due to seismic forces. Bracing sizes were selected based on AISC Specification Table 4-4 for square HSS columns.

In order to support the building's columns, typical footings were designed. Based on the previously determined design service loads on a given column, the required area and lateral dimensions of a square spread footing were determined, given the strength of the concrete and the allowable bearing pressure on the soil. The calculated footing size was rounded to the next highest even number. The thickness of the footing was determined by calculating and comparing the punching shear capacity of the concrete versus its one-way shear capacity. This process was used to design a typical interior, exterior, and corner footing for the proposed building. With the typical footing sizes determined, corresponding column base plates were designed in accordance with Section J8 of the AISC Specification and flexural methods available in the literature (McCormac and Csernak, 2018). As member sizes were selected during the process of calculations, they were updated in the 3-D Revit model framing design

3.3. Objective #3: Estimate Construction Schedule and Costs

Having selected Construction Manager at Risk (CM@R) as a project delivery method based on research and knowledge about the WPI community, a project schedule was created in Microsoft Project. General construction processes were added to the schedule under the UNIFORMAT II organization. Each of the scheduled items was added to the proper work breakdown structure for easy organization. Durations for each activity were estimated based on knowledge of previous projects and the general square footage of the building. Based on the schedule, a general set of phased construction was completed in Revit.

While the schedule was formatted, costs were calculated based on the labor and materials needed to complete the project within the designated time frame. Cost analysis was completed using data from RSMeans (Gordian, n.d.). Cost analysis included indirect and direct costs for construction processes. Two estimates, square footage and assembly, were calculated using RSMeans tools (Gordian, n.d.). Indirect costs of the general contractor included an additional 25% of total cost while the indirect cost for the architectural design was 7-9% of the total cost. The total building cost was estimated based on a guaranteed maximum price (GMP) structure for CM@R. A lazy S-curve was created based on benchmark activity costs and end dates, displaying total project cost over time.

3.4. Objective #4: Evaluate Sustainability Alternatives and Industry Advancements

While the preliminary schedule and project costs were being determined, sustainability and technology options were explored, such as LEED certification, sustainability alternatives, and technological advancements in the construction industry. Sustainability and technology alternatives included changes to materials, greywater reuse systems, greenhouses/gardens, solar panels, or automated construction tools. Alternatives were then formatted into a table based on cost, savings, benefits, downsides, maintenance, and schedule impact. Each category received a ranking from 1-4. A total score for each alternative was divided by total cost to display the utility value of each different practice. The selection of alternatives was then expressed as a set of recommendations to add to the design if the quality and sustainability benefits far outweighed the cost and schedule impacts.

4. Design Problem

To determine the best way to move forward with preliminary designs for the residence hall, a meeting was held with WPI Residential Services. This meeting allowed them to understand the demand and capacity issues that currently exist within WPI's campus residencies. Once the need for housing was established, focus was shifted to which design elements are of most use and interest to current students living on campus or with plans to live on campus in future years. This information was then cross-referenced with the relevant Massachusetts state building codes in order to compile a comprehensive building program. The program outlines all of the specific spaces and their intended uses, as well as what codes apply for those areas. In doing so, progression of the design calculations was possible.

4.1. WPI Community Needs

In order to gain a foundational understanding of the population on campus, a preliminary investigation into enrollment at WPI was conducted. The institution released a "Common Data Set", which included general information on the demographics and statistics of the first-year students and total undergraduates. Using these spreadsheets, the enrollment data from the fall semester of 2010 until the fall semester of 2020 was compiled to create graphs representing the number of first-year students enrolled (Figure 3) and the total undergraduate enrollment (Figure 4). These graphs clearly show that the number of students at WPI has been steadily increasing, and is therefore projected to continue increasing in the coming years unless changes are made in Admissions.

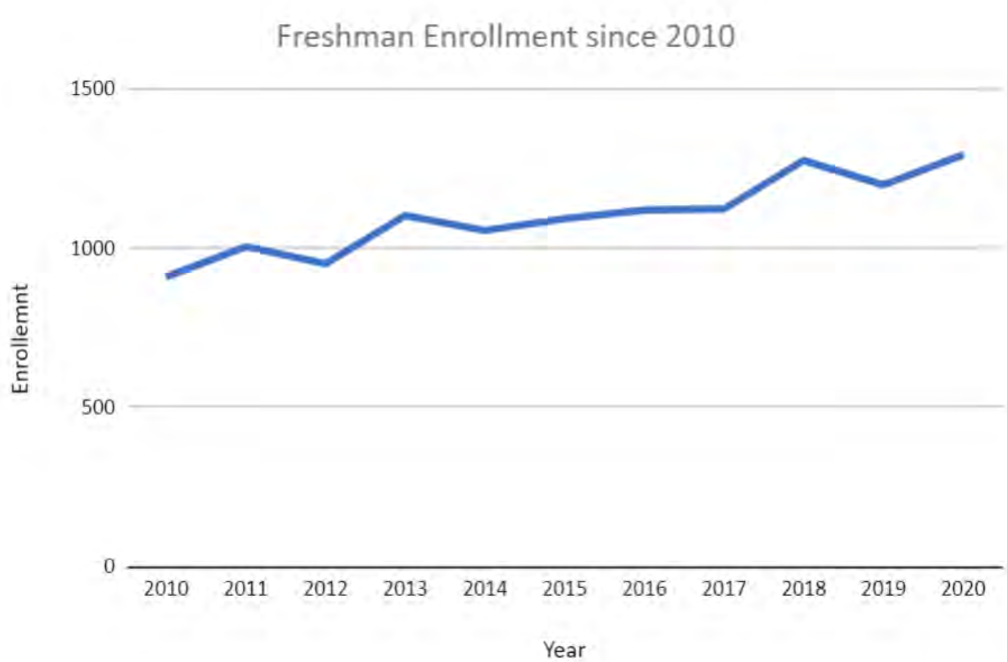


Figure 3: Freshman Enrollment 2010-2020

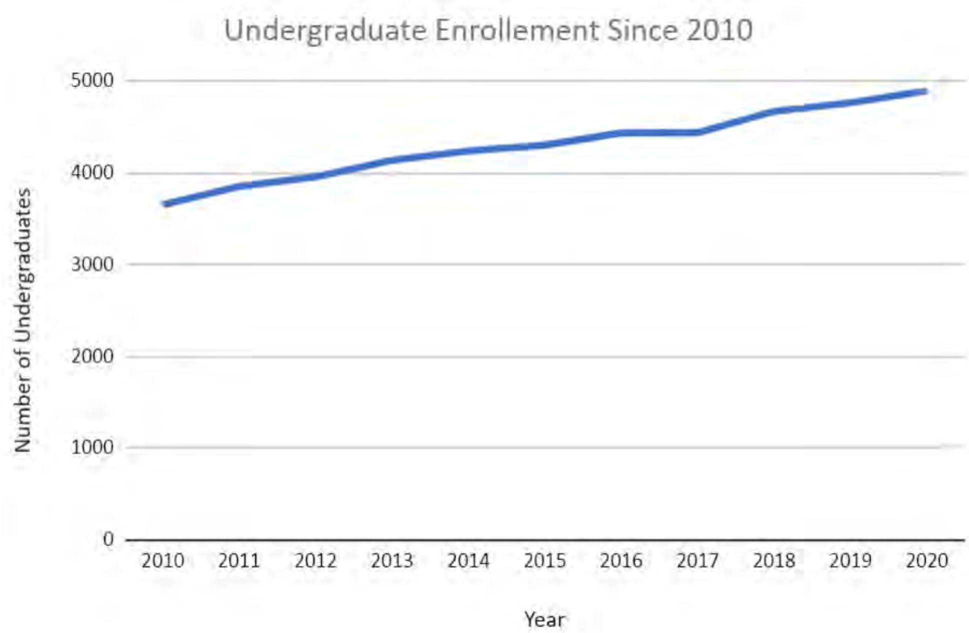


Figure 4: Undergraduate Enrollment 2010-2020

Once gaining confirmation that enrollment has increased in the last 10+ years, an interview was conducted with WPI Residential Services regarding the housing of these students. According to Senior Associate Director Amy Beth Laythe (Laythe, 2021), housing upperclassmen at WPI has become increasingly more challenging with the COVID-19 pandemic. After the campus shut down in March of 2020, the following school year was very different for residential services in order to ensure the students' safe return to campus. All residence halls with triple rooms -- Stoddard Complex, Morgan Hall, and Daniels Hall -- were de-tripled. The school signed a rental agreement with the nearby Hampton Inn Hotel and moved the displaced beds into the rooms there. This also caused the shift of freshmen moving into typically upperclassmen-only halls like Founders and Messenger. Most of these changes are still in place on campus today, and according to Ms. Laythe, will remain this way forever, regardless of the state of the pandemic. This change works because WPI continues to lease the Hilton, but where will those students live if the school is not granted a lease next year? Will more upperclassmen have to be displaced to account for another group of first-year students?

Another housing challenge presented by Residential Services was the housing selection application itself. On the application, one can apply as a single student, but the likelihood of getting a spot on-campus is far more likely within a group. However, assigning groups is almost impossible because of the differences in the available housing groups on campus. The suites within Founders Hall house 2, 4, 5, 6, or 8 people each; the Ellsworth and Fuller Apartments house groups of 5 or 7; and the remaining upperclassmen suites house groups of 4. If students apply as a group of 5, but only suites for 4 or 7 students are available, there is no simple option to change their initial application. A simple solution to this housing complication would be to ensure all upperclassmen suites are the same size, so there is far less confusion and difficulty when making groups for the application. For this reason, this project was based on a plan to demolish the existing Ellsworth Apartments and in their place construct a new residence hall with suites of 4 people each. This is beneficial in two-fold. The Ellsworth Apartments are currently part of the problem when going through housing as they have awkward group sizing, and are not space-efficient; however, they are close to the main campus and are in a prime location as they are within institutional zoning. The decision to provide four-person suites is in accordance with current housing in East and Faraday Halls. The new residence hall will also use space more efficiently, and provide more than 2.5 times the 93 beds lost with the demolition of Ellsworth Apartments.

4.2. Building Program

Upon the completion of a review of the building codes and zoning regulations applicable to the construction of a new residential building on campus, the following building program was developed. This program provides insight into decisions made regarding building size, egress capacity, number of suites and single rooms, as well as choices in accessory components to the proposed building.

Project
WPI Residence Hall

Project Address/Site
86 Institute Rd *Currently home to WPI's Ellsworth Apartments

Project Description
The project consists of the demolition of WPI's Ellsworth Apartments as well as the design and construction of a new dormitory that will contain approximately 249 beds.

Applicable Codes/Zoning Laws

Building	780 CMR - Massachusetts State Building Code 9th Edition [Amended version of 2015 International Building Code (IBC)]
Fire Code	527 CMR - Massachusetts Comprehensive Fire Safety Code [Amended version of 2015 Edition of NFPA 1]
Accessibility Regulations	521 CMR - Architectural Access Board (AAB) Rules and Regulations [6th ed.]
Zoning Laws	Worcester Zoning Laws

Use and Occupancy Groups

Description	**780 CMR Classification**	**Level(s)**
Dormitories, Apartment Units, Amenity Space <50 persons	Group R-2	GF-3

Accessory Occupancies

Description	**780 CMR Classification**	**Level(s)**
Lobby, Lounges, and Group Study Rooms	Group A-3	GF-3
Office	Group B	GF
Market	Group M	GF
Rooftop Garden	Group A	Roof

Allowable Building Height & Area
The building will be 4-stories above grade, 42 feet in height, and will have an approximate footprint of 24,939.67 square feet within the allowable building area of 33,422.5 square feet. The building will total 99,758.67 square feet.

Restrictions Set by Zoning Laws

Zoning District	IN-S
Relevant Permitted Uses	• Dormitory • Non-accessory residential parking • Food Service (with special permit) • Retail foods sales (with special permit)

Lot Setbacks/Max Stories

District	Use	Lot		Yard Setbacks			Height		Floor to Area Ratio (Maximum)
		Area (minimum SP)	Frontage (minimum linear ft.)	Front	Side	Rear			
				Minimum depth (linear ft.)			Max in stories	Max in ft.	
IN-S	All	NA	NA	15	10	10	NA	NA	NA

Living Spaces

Suites

Number of Suites	18 per floor	54 total
Number of ADA Suites	2 per floor *Minimum of 1 per Table 1107.6.1.1	6 total
Suite Size	General Suite	ADA Accessible
	42'x20'	20'x52'
Occupants Per Suite	Each suite will feature 2 single bedrooms and 1 double (a total of 4 beds per suite)	
Additional Suite Components	Each suite will also contain a bathroom with a sink, toilet, and shower, as well as kitchen, dining, and living room spaces.	

Rooms

# of RA/Single Rooms	3 per floor	9 total
# of ADA Rooms	All RA/Single Rooms are ADA compliant	
RA/Single Room Size	20'x20'	
Occupants Per Room	Each room will contain 1 bed	
Additional Room Components	RA/Single Rooms will be separate from suites and shall accommodate one bed, a small kitchen, and small living area	

Egress

Corridor	Minimum Size	Actual Size	
		Middle Corridor	Side Corridors
	3'8"	22'	7'6"
Stairways	Number of Staircases	Tread Size	Riser Height
	5	Min 10"	Max 7 ¾"
Elevators	Number of Elevators	Egress Considerations	
	2	Not to be considered as a form of egress	

Loading Used

Live Load (LL) *includes rooftop garden	100 psf
Live Load for Elevators (LL_{el})	150 psf
Dead Load (DL)	85 psf
Snow Load	35 psf

5. Structural Design

The structural design of the new residence hall was completed based on a series of eight framing schemes as shown below in Figure 5. Each scheme presents different sets of beam spacing and spans, girder spacings and spans, and column spacings. The same scheme layout is applicable for supporting levels one, two, three, and the roof while the ground floor level is supported by a slab-on-grade. Scheme layouts with exact measurements are listed in Appendix B along with example load cases for beams and girders in Appendix C. Each column is supported by a concrete footing and steel baseplate. Footing and base plate designs were prepared for three general cases: interior, exterior, or corner. The large scale structural Revit model is shown in Figure 6.

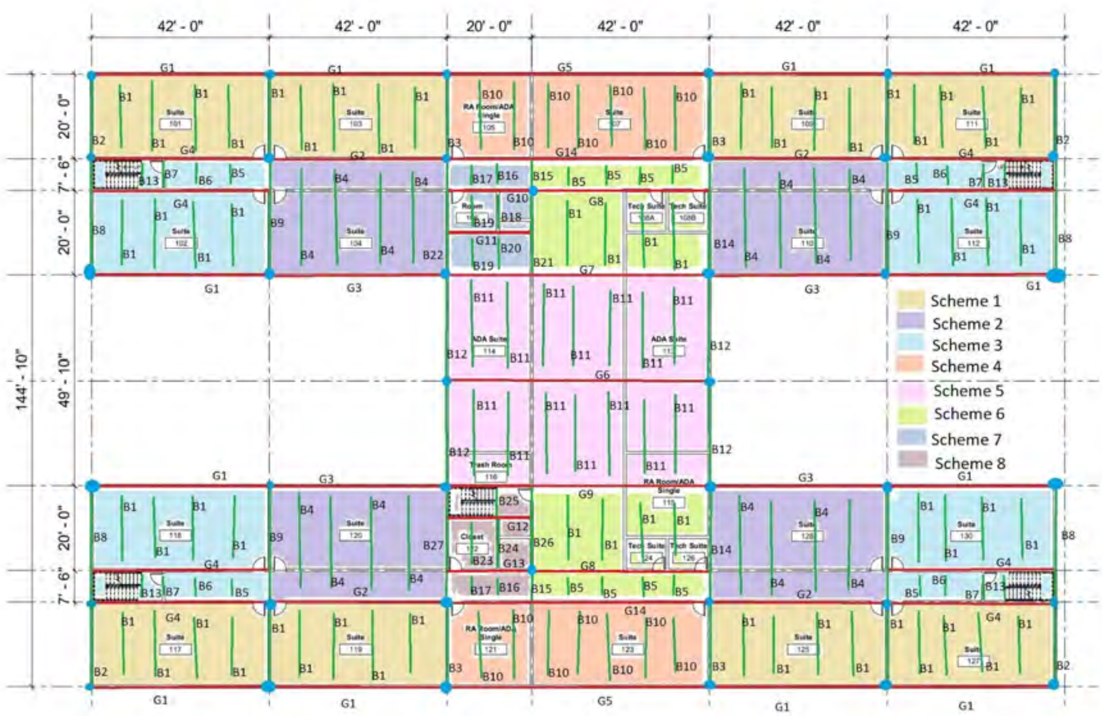


Figure 5: Basic Framing Scheme Layouts

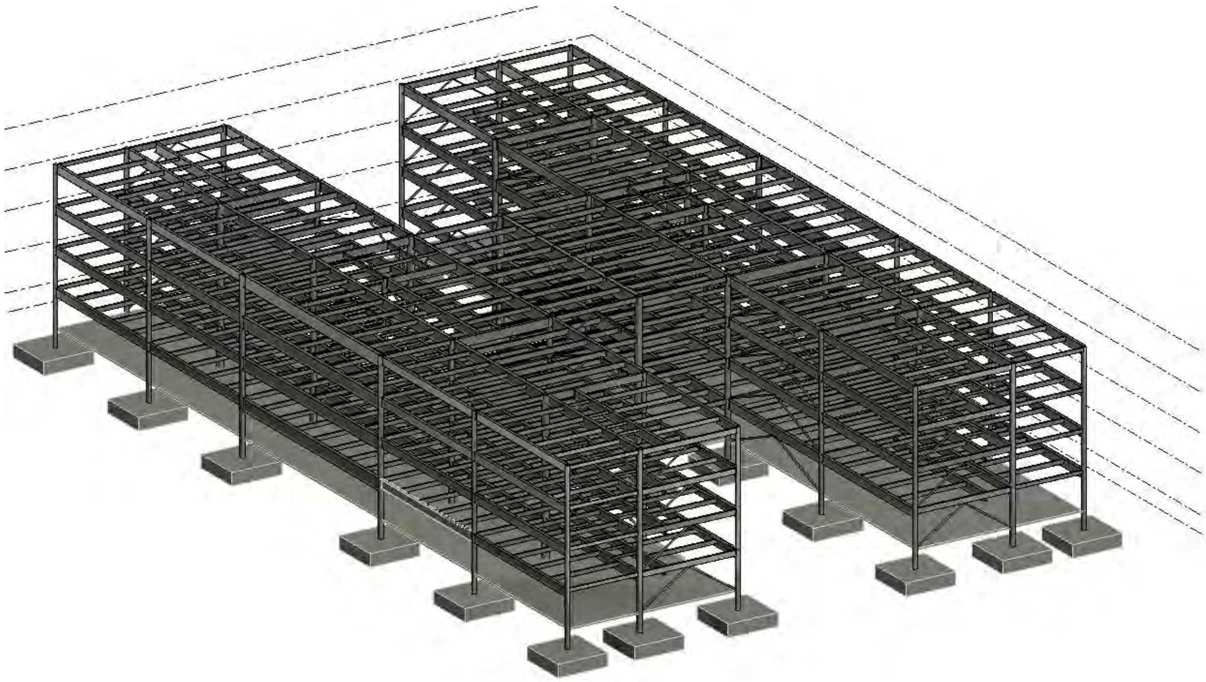


Figure 6: 3D Revit Structure

5.1. Slabs

In accordance with the IBC Fire Resistance requirements and the ASD Composite slab and deck specifications, the total slab depth was designed at 5 in. In order to achieve a fire-resistance rating of 1 hour using common Siliceous concrete, the slab was required to be a minimum of 3.4 in. per Figure 7.

TABLE 722.2.2.1 MINIMUM SLAB THICKNESS (inches)

CONCRETE TYPE	FIRE-RESISTANCE RATING (hours)				
	1	1 1/2	2	3	4
Siliceous	3.5	4.3	5	6.2	7
Carbonate	3.2	4	4.6	5.7	6.6
Sand-lightweight	2.7	3.3	3.8	4.6	5.4
Lightweight	2.5	3.1	3.6	4.4	5.1

For SI: 1 inch = 25.4 mm.

Figure 7: IBC Fire Resistance Slab Thickness (taken from IBC 2015)

A slab topping of 3.5 in results in a total composite slab depth of 5 in. as shown in Figure 8 from the ASD Specifications. The metal decking is designed to be 19 gauge in order to accommodate the building's largest unshored span of 8.4 ft (8 ft 4.8 in.). Gauge 19 metal decking satisfies the load requirements given in Figure 9 as it pertains to superimposed loading. A cut view of the slab is displayed in the Revit model (Figure 10).

Slab Depth Total	Slab Depth Topping	Deck Gage	Maximum Unshored Spans: Maximum Unshored Construction Clear Span 1	2	3	Composite Deck-Slab Properties: Concrete + Deck (psf)	Deflection $I_d = (I_{cr}+I_u)/2$ (in^4/ft)	Moment M_{no}/Ω (kip-ft/ft)	Shear V_{no}/Ω (kip/ft)
3½"	2"	22	6'-5"	7'-6"	7'-8"	32.2	2.64	1.84	2.01
		20	7'-9"	9'-1"	9'-2"	32.6	2.85	2.16	2.01
		19	8'-4"	9'-11"	10'-3"	32.9	3.03	2.47	2.01
		18	8'-9"	10'-7"	11'-0"	33.2	3.19	2.74	2.01
		16	9'-6"	11'-10"	11'-8"	33.9	3.52	3.30	2.01
5"	3½"	22	5'-7"	6'-7"	6'-8"	50.3	7.62	3.22	3.29
		20	6'-9"	7'-10"	7'-11"	50.7	8.18	3.83	3.29
		19	7'-3"	8'-8"	8'-10"	51.0	8.68	4.40	3.29
		18	7'-8"	9'-3"	9'-6"	51.3	9.12	4.90	3.29
		16	8'-4"	10'-4"	10'-4"	52.0	10.02	6.00	3.29
6"	4½"	22	5'-3"	6'-1"	6'-2"	62.4	13.11	4.24	4.27
		20	6'-3"	7'-3"	7'-5"	62.8	14.02	5.05	4.27
		19	6'-10"	8'-0"	8'-2"	63.1	14.85	5.81	4.27
		18	7'-2"	8'-7"	8'-10"	63.4	15.57	6.50	4.27
		16	7'-10"	9'-7"	9'-8"	64.1	17.06	7.98	4.27

Note:

1. Maximum unshored spans do not consider web-crippling. Required bearing should be determined based on specific span conditions.

Figure 8: ASD Specification for Metal Deck Gauges and Slab Depth (taken from Vulcraft, 2021 Product Data)

Superimposed Allowable Load, W_n/Ω, Limited by L/360 (psf) NWC (145 pcf), f'_c = 3000 psi

Total Slab Depth	Deck Gage	Span (ft-in.) 4'-0"	5'-0"	6'-0"	7'-0"	8'-0"	9'-0"	10'-0"	11'-0"	12'-0"
3½"	22	886	555	375	267	197	149	114	86	66
	20	974	659	448	320	237	170	124	93	72
	19	974	757	515	370	258	181	132	99	76
	18	974	772	574	406	272	191	139	104	80
	16	973	771	637	448	300	210	153	115	88
5"	22	1560	980	665	475	352	267	207	162	128
	20	1593	1174	800	574	427	327	255	202	161
	19	1592	1264	925	666	498	383	300	239	193
	18	1592	1263	1038	749	561	433	341	272	221
	16	1591	1263	1043	887	697	540	427	329	253
6"	22	2055	1292	878	629	467	355	276	217	172
	20	2074	1552	1058	761	568	435	341	270	217
	19	2073	1646	1228	885	663	510	401	321	259
	18	2073	1646	1361	997	749	578	456	366	297
	16	2072	1645	1360	1156	933	724	574	463	379

Notes:

1. For high loads long term concrete creep should be considered.
2. See Composite Deck-Slab Strength Web Based Solutions for alternate slabs or LRFD design.

Figure 9: ASD Specification for Allowable Load by Deck Gauge (taken fromVulcraft, 2021 Product Data)

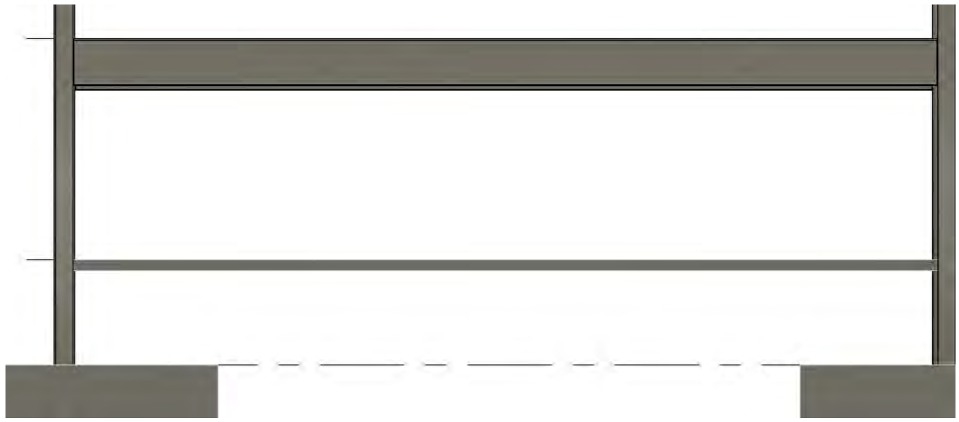


Figure 10: Sample Revit Drawing of Common Ground Floor Footing-Slab-Beam-Column System

5.2. Beams and Girders

The beams and girders defined in Figure 5 were designed given the load considerations in the building program and maximum lateral spacing according to the IBC and previously calculated slab design. Example hand calculations of beam and girder design can be seen in Appendix D. Following hand calculations, Excel tables were used to calculate the entire beam and girder system, and these Excel tables can be seen in Appendix E. After designing the beam for strength, deflections were checked. If the governing deflections failed, then a new beam was selected and checked again for strength and deflections. In Table 4 below, the progression of beam design is shown from initial member size according to strength, live load deflection, and dead/live load deflection, to the selected member size. A similar progression is displayed in Table 5 for girders. A structural Revit model of beams and girders can be seen in Figure 11.

Table 4. Beam Member Size Design Progression

Beam	Member Size for...			Selected Member Size
	Initial Strength Design	Live Load Deflection	Dead/Live Load Deflection	
B1	W14x22	W14x22	W14x22	W14x22
B2	W10x19	W12x19	W12x22	W12x22
B3	W12x22	W12x22	W14x22	W14x22
B4	W18x35	W18x35	W18x35	W18x35
B5	W8x10	W8x10	W8x10	W8x10
B6	W8x10	W8x10	W8x10	W8x10
B7	W8x10	W8x10	W8x10	W8x10
B8	W16x26	W16x26	W18x35	W18x35
B9	W24x68	W24x68	W24x68	W24x68
B10	W12x22	W12x22	W14x22	W14x22
B11	W16x26	W16x26	W16x31	W16x31
B12	W12x14	W12x14	W16x26	W16x26
B13	W8x10	W8x10	W8x10	W8x10
B14	W30x90	W30x90	W30x90	W30x90
B15	W8x10	W8x10	W8x10	W8x10
B16	W8x10	W8x10	W8x10	W8x10
B17	W8x10	W8x10	W8x10	W8x10
B18	W8x10	W8x10	W8x10	W8x10
B19	W8x10	W8x10	W8x10	W8x10
B20	W8x10	W8x10	W8x10	W8x10
B21	W21x48	W21x48	W21x48	W21x48
B22	W24x76	W24x76	W24x76	W24x76
B23	W8x10	W8x10	W10x12	W10x12
B24	W10x12	W10x12	W10x12	W10x12
B25	W8x10	W8x10	W8x10	W8x10
B26	W21x48	W21x48	W21x48	W21x48
B27	W24x62	W24x68	W24x68	W24x68

Table 5. Girder Member Size Design Progression

Girder	Member Size for...			Selected Member Size
	Initial Strength Design	**Live Load Deflection**	**Dead/Live Load Deflection**	
G1	W24x76	W24x76	W27x84	W27x84
G2	W30x116	W30x116	W33x118	W33x118
G3	W27x84	W27x84	W30x99	W30x99
G4	W24x84	W27X84	W30x90	W30x90
G5	W33x118	W33x130	W40x149	W40x149
G6	W33x130	W40x199	W44x230	W44x230
G7	W40x183	W40x199	W40x211	W40x211
G8	W24x84	W24x84	W30x90	W30x90
G9	W40x183	W40x199	W40x211	W40x211
G10	W16x26	W16x26	W16x26	W16x26
G11	W14x30	W14x30	W14x30	W14x30
G12	W14x34	W18x35	W18x35	W18x35
G13	W16x31	W16x31	W16x31	W16x31
G14	W33x130	W36x135	W40x149	W40x149

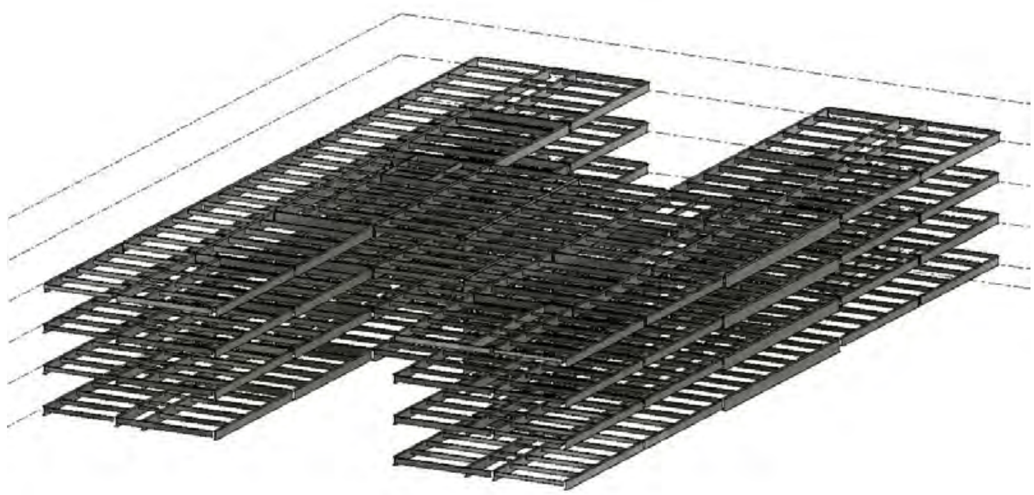


Figure 11: Revit Drawing of Completed Beam and Girder Design

5.3. Columns and Bracing

Upon the completion of the beam calculations, columns were determined next. First, columns were defined by their similarity in their tributary areas shown in Figure 12 below. Excel spreadsheet calculations were used to determine column sizes, and these calculations can be found in Appendix F. The factored loading on the roof level column was calculated given the tributary area the column supported, the predetermined load case that the beams and girders carried, and any exterior loading if the column was an exterior column. This process was then repeated for the story below it. An initial, square HSS column size was then found for the top two stories via Table 4-4 in the AISC Manual. The loading on the column was carried down to the two stories below it, and the subsequent initial sizing for the ground-level column was calculated, given its total loading. The width of the initial column was then checked against the flange widths of the supported beams or girders. The columns were then resized so that the width of the column was larger than the flange width of the incoming beam/girder. The summary of the final selected column sizes can be found below in Table 6.

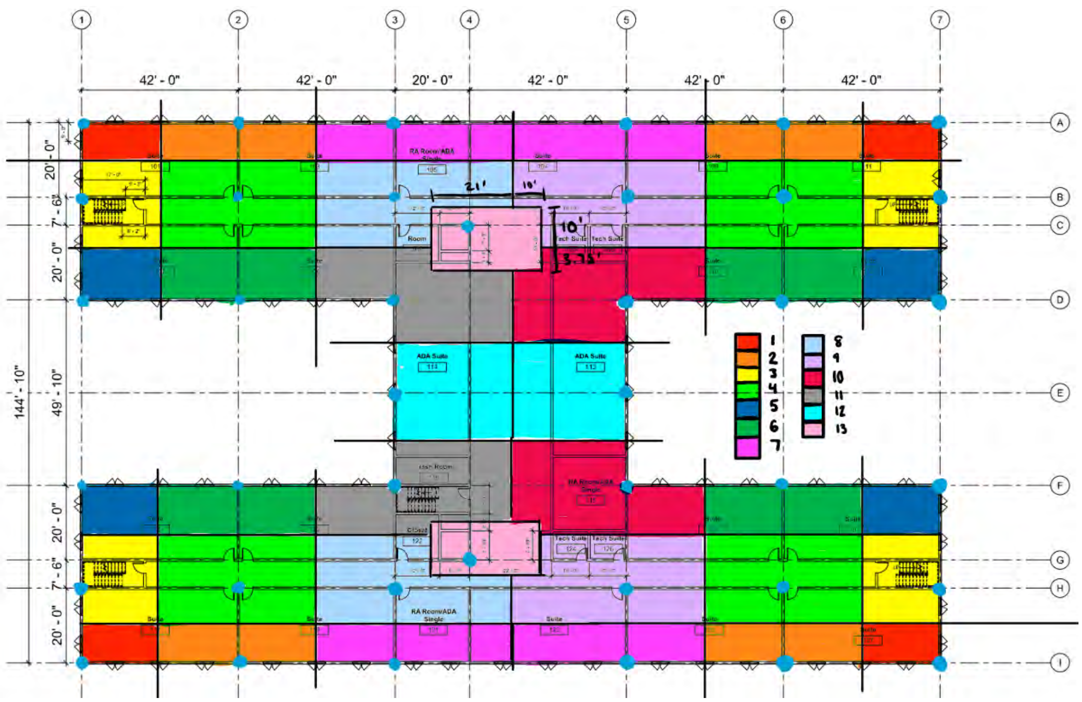


Figure 12: Column Tributary Area Layouts

Table 6: Column Sizes

Column #	Table 4-4 Initial Column Selection	Selected Columns
1	HSS6x6x1/2	HSS10x10x1/4
2	HSS8x8x5/8	HSS10x10x1/2
3	HSS8x8x5/8	HSS12x12x3/8
4	HSS16x16x1/2	HSS16x16x1/2
5	HSS6x6x5/8	HSS10x10x5/16
6	HSS9x9x5/8	HSS12x12x1/2
7	HSS10x10x1/2	HSS12x12x1/2
8	HSS14x14x5/8	HSS14x14x5/8
9	HSS14x14x5/8	HSS14x14x5/8
10	HSS14x14x5/8	HSS14x14x5/8
11	HSS16x16x1/2	HSS16x16x1/2
12	HSS14x14x1/2	HSS16x16x1/2
13	HSS8x8x5/8	HSS12x12x3/8

Bracing was then designed for the lateral-load resisting systems in two orthogonal directions. The seismic force conditions governed over wind. The calculated column story forces were then used to complete a truss analysis of the bracing locations shown in Figure 13. Based on the axial loading on the bracing, a square HSS section was selected via Table 4-4 in the AISC Manual. The final selected bracing sizes are shown in Table 7 with hand calculations in Appendix G and excel calculations shown in Appendix H. A cut of the column bracing system is shown in the Figure 14 Revit model.

Figure 13: Chevron Bracing Locations

Table 7. Chevron Bracing Sizes

	Level 1	**Level 2**	**Level 3**	**Roof**	**Selected Bracing Size**
N/S Bracing (interior)	HSS4x4x1/2	HSS4x4x3/8	HSS4x4x5/16	HSS3x3x3/8	HSS4x4x1/2
N/S Bracing (exterior)	HSS4x4x1/2	HSS4x4x3/8	HSS4x4x1/4	HSS3x3x3/8	HSS4x4x1/2
E/W Bracing	HSS4x4x5/16	HSS3-1/2x3-1/2x3/8	HSS3-1/2x3-1/2x5/16	HSS3x3x1/4	HSS4x4x5/16

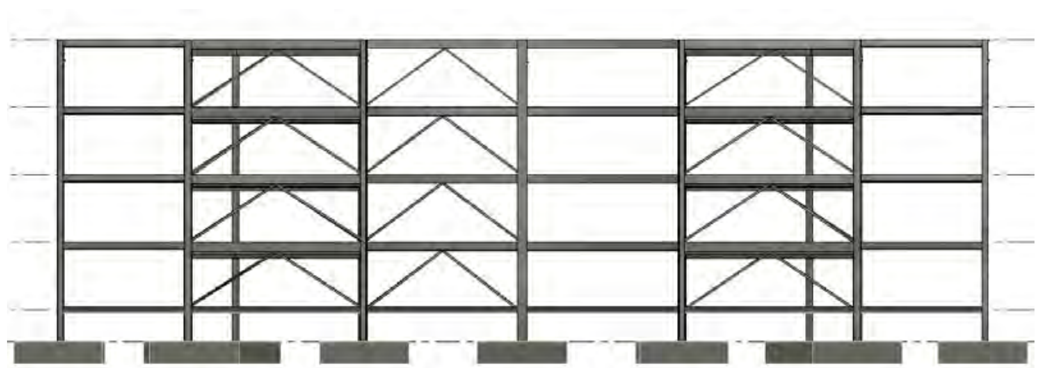


Figure 14: Revit Drawing of Full Bracing System

5.4. Footings

After designing columns, footings were designed based on the axial loading from columns, allowable bearing pressure in the soil, and both the two-way (punching) and one-way shear capacities of the concrete. The footings were designed as a combination of a concrete footing and a steel base plate. Three areas for footings were considered for design. The largest axial force for each case of interior, exterior, and corner column/footing locations were selected. This resulted in a maximum design for each based on column numbers 9, 10, and 5, respectively, shown in Figure 12 and Table 6. Calculations for the footings and base plates can be seen in Appendix I with simplified results in Table 8. An example Revit model of the completed footings is shown in Figure 15.

Table 8. Footing Design Results

Column Area	**Interior**	**Exterior**	**Corner**
Footing	14 ft x 14 ft x 34 in	14 ft x 14 ft x 35 in	8 ft x 8 ft x 22 in
Base Plate	2 in	2 in	1.25 in

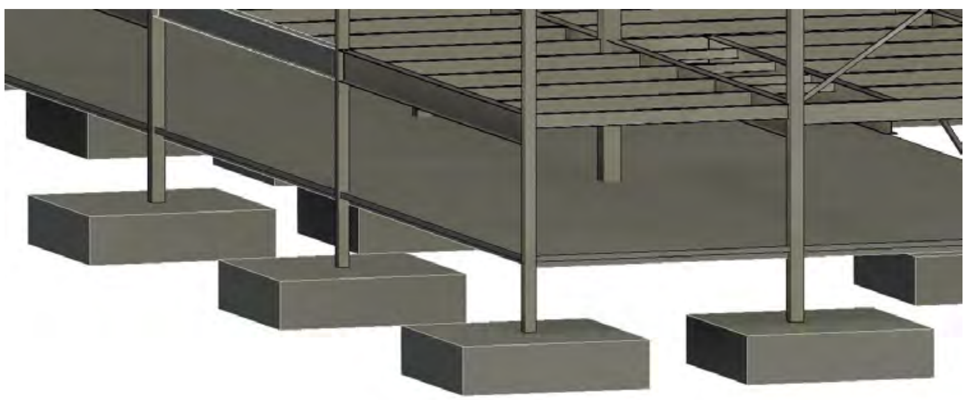


Figure 15: Revit Drawing of Completed Footing Design

6. Cost and Schedule

This section details an estimated cost and schedule for the new residence hall. Cost estimates were calculated using RSMeans and should be treated as rough estimates. The schedule was based on some experience in field construction and should also be taken as a rough estimate. It should be noted that the cost does not factor in the specifics of the schedule regarding labor over time.

6.1. Cost

An estimate of costs was completed using data from RSMeans (Gordian, n.d.). Two estimates were created based on the square foot estimator and the assembly cost estimator. The cost of each UNIFORMAT assembly number for each estimate is listed in Table 9. The square foot estimate totals around $23 million, and the assembly estimate totals about $27.5 million. This provides a baseline range for the estimated building cost since not all details were specifically designed during this project. Many quantities were estimated for both calculations based on general knowledge of the building such as client, intended use and square footage. The assembly cost may be a more accurate representation of total cost due to the process of selecting each item and it's quantities in comparison to the auto generated square footage estimate. A complete RSMeans report of the estimate tool outputs can be seen in Appendix J.

Table 9. Cost Estimate Results

UNIFORMAT Assembly Number	Section Total by Square Foot Estimate	Section Total by Assembly Estimate
A1010	$302,669.35	$ 301,393.77
A1030	$172,288.78	$ 178,817.43
A2010	$10,474.70	N/A
B1010	$1,601,652.42	$ 8,107,466.89
B1020	$319,336.79	$ 377,828.71
B2010	$1,469,939.05	$ 1,469,835.84
B2020	$905,452.01	$ 432,406.97
B2030	$48,040.42	$ 48,051.46
B3010	$225,622.91	$ 225,573.07
B3020	$15,543.21	N/A
C1010	$1,008,175.85	$ 804,160.80
C1020	$623,663.34	$ 734,832.92
C1030	$119,325.18	$ 65,059.83
C2010	$427,276.01	$ 425,946.47
C3010	$672,095.98	$ 672,465.67
C3020	$525,807.64	$ 551,328.96
C3030	$97,410.37	$ 97,364.78
D1010	$1,352,516.09	$ 418,472.00
D2010	$891,986.82	$ 794,622.45
D2020	$333,579.83	$ 333,321.75
D2040	$46,348.50	$ 46,343.47
D3010	$528,390.50	$ 528,722.70
D3030	$1,020,495.66	N/A
D4010	$347,547.44	$ 336,676.64
D4020	$89,932.24	$ 89,824.94
D4090	N/A	$ 250,671.60
D5010	$97,007.66	$ 96,992.46
D5020	$1,245,323.89	$ 1,245,986.00
D5030	$590,898.91	$ 593,248.66
E1010	N/A	$ 57,310.80
E1030	N/A	$ 81.12
E1090	$1,385,227.00	$ 214,778.37
E2010	N/A	$ 426,347.96
E2020	$78,436.63	$ 120,551.52
G1010	N/A	$ 12,998.24
G1030	N/A	$ 354,200.00
G2030	N/A	$ 3,502.00
G3010	N/A	$ 66,590.00
G3020	N/A	$ 6,690.00
G3030	N/A	$ 11,140.00
G3060	N/A	$ 18,580.00
G4010	N/A	$ 31,100.00
G4020	N/A	$ 16,379.40
SubTotal	$16,552,465.18	$ 20,567,665.65
Contractor Fees (General Conditions,Overhead,Profit) 25%	$4,138,116.30	$ 5,141,916.41
Architectural Fees 7-8.75%	$1,448,340.70	$ 1,799,670.74
Total Building Cost	**$22,138,922.18**	**$ 27,509,252.80**

6.2. Schedule

A schedule displaying the proposed timeline for the residence hall was completed using Microsoft Project. The basic timeline shown in Figure 16 shows that the project will begin with Building Design on July 5, 2022 with Close Out completing the project January 17, 2028. The schedule was created based on the UNIFORMAT groupings detailed in Appendix K. The durations and precedents were estimated from prior experience and general knowledge of the building such as client, intended use and square footage. These figures were then adjusted under the assumption of larger crew sizes completing the construction.

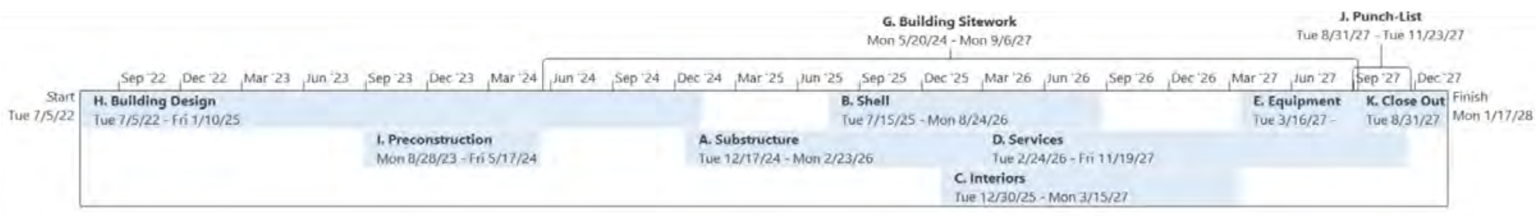


Figure 16: Timeline of the overall project schedule for the residence hall

After completion of the schedule and cost analysis, an S-curve was formulated with total cost over project timeline (Figure 17). The S curve demonstrates the different rates of increasing cost as the project continues. The rate of cost increase is slow when the project is initiated, increases significantly during major construction and levels off during project finishes and closeout. The dips in the graph reflect the automated curve of single UNIFORMAT benchmarks since labor rates were not considered.

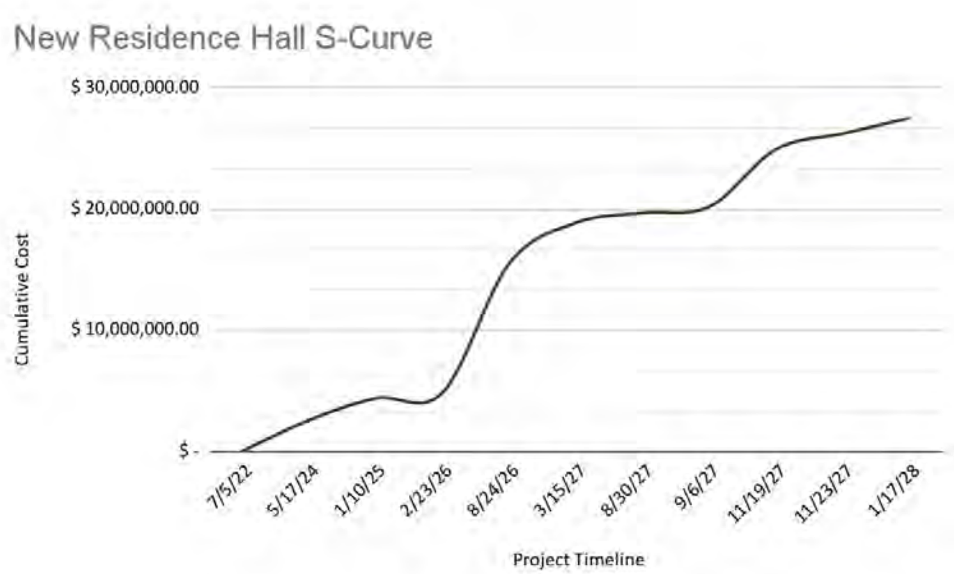


Figure 17: Lazy S-Curve

6.3. Phased Construction

Construction phasing is the process of developing a visual sequence of elements being constructed as they are completed on the task schedule. For this project, the phasing was completed using AutoCAD Revit, where each major portion of the project was given a phase and then a view was created corresponding to the appropriate phase. The sequence follows the project from start, Figure 18, to completion Figure 27, and all of the benchmark tasks in between. This helps to visualize the completion of the project, and a measurement of what the project will look like at certain points in the schedule.

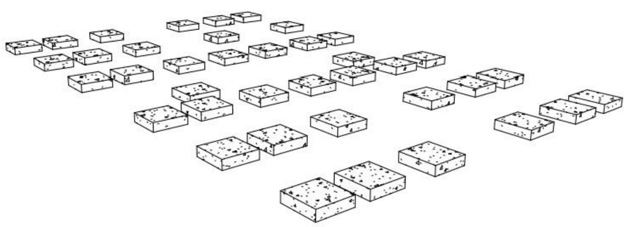


Figure 18: Phase 1- Footings

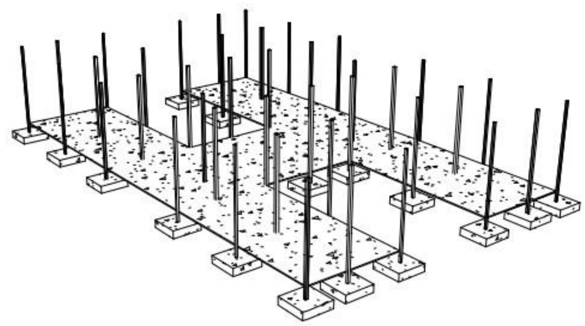


Figure 19: Phase 2- Columns and Foundation

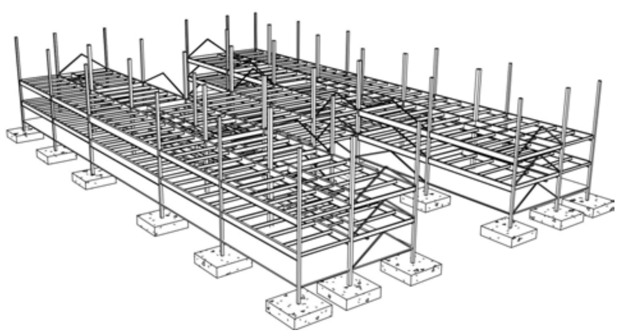


Figure 20: Phase 3- Framing Floor 1-2

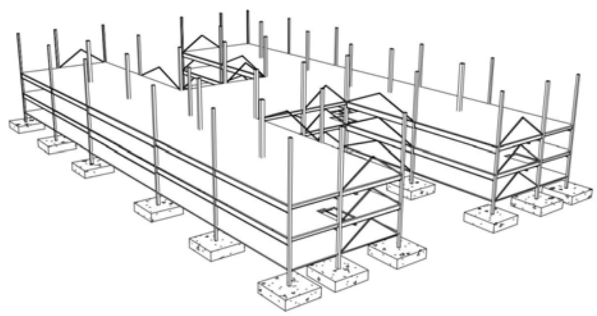


Figure 21: Phase 4- Slab Floor 1-2

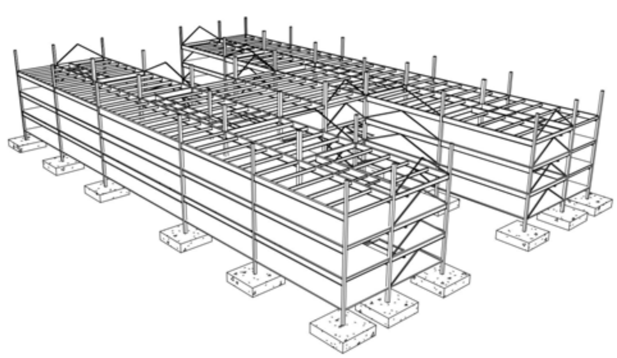


Figure 22: Phase 5- Framing Floor 3

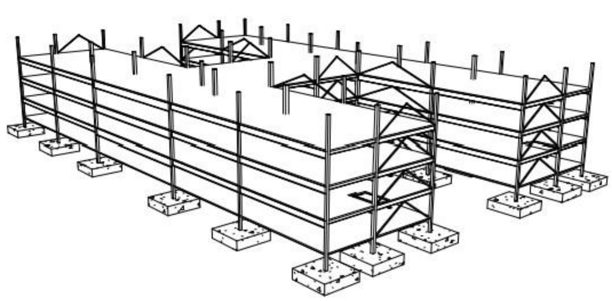


Figure 23: Phase 6- Slab Floor 3

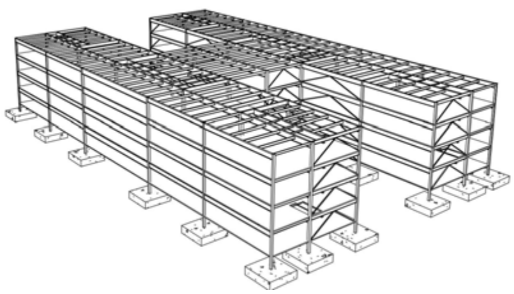


Figure 24: Phase 7- Framing Roof

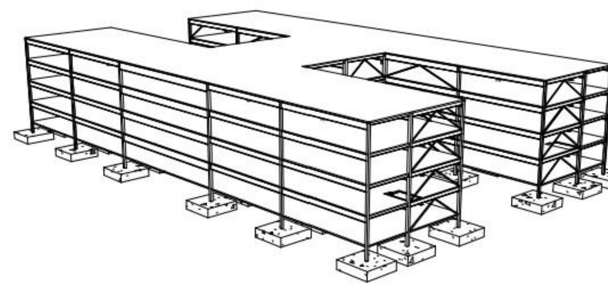


Figure 25: Phase 8- Roof Slab

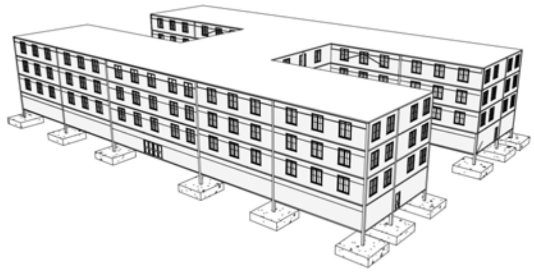


Figure 26: Phase 9- Architectural

Figure 27: Phase 10- Landscaping and Site Design

7. Sustainability Alternatives and Construction Technology

This section features the research conducted to provide context as to how LEED certification, solar power, greywater reuse systems, green roofs, Cross Laminated Timber and Smartglass are used in a broad sense as well as in dormitory buildings across the country. Case studies from colleges such as Tufts, Cornell, Emory, and University of Colorado Boulder were researched and used to provide context to the alternatives on a college campus. Additionally innovations in the construction industry, specifically the use of robotics, are explored.

7.1. Alternatives to Promoting Sustainability

7.1.1. LEED Certification

Building projects can work to achieve a status of sustainability through certification in a particular Leadership in Energy and Environmental Design (LEED) category (U.S. Green Building Council, 2021). In order to achieve a certain status, a serious amount of design and planning must be put into the project in order to ensure its energy efficiency and that environmentally conscious resources are used. The LEED Certification hopes to create a framework for green buildings by listing minimum energy efficiency requirements among other design considerations in the LEED credit library (U.S. Green Building Council, 2021). WPI currently has 5 buildings with LEED certification as follows (*Campus operations,* n.d.):

- Bartlett Center, 2006, LEED Certified
- East Hall, 2008, LEED Gold Certified
- Recreation Center, 2012, LEED Gold Certified
- Faraday Hall, 2013, LEED Silver Certified
- The Innovation Studio / Messenger Hall, 2018, LEED Gold Certified

7.1.2. Solar Power

Solar panels are made up of semiconductors that absorb light from the sun and convert it to electricity. Solar power has the ability to drastically push buildings to green energy solutions in an attempt to curb climate change. WPI has plans to install solar panels on its newly completed academic building, Unity Hall (WPI, 2022). A few other New England colleges have also added solar panels to campus buildings and residence halls. Tufts and Cornell have added solar panels to roofs of campus buildings in an attempt to minimize fossil fuel impact and fulfill sustainability initiatives (Friedlander, 2021; *Solar at tufts*, 2021).

7.1.3. Greywater Reuse Systems

As the world's water demand continues to rise, water conservation and efficiency measures have become increasingly important considerations when it comes to new building construction. Water conservation is the effort to decrease water consumption through fixtures such as low flow toilets. Water efficiency goes a step further as the idea that water conservation can be achieved through the reuse of water that is already available (Alvis, 2019). Typically, a building's water demands are met with potable water which runs through all fixtures including sinks, showers, toilets, etc. Not all fixtures, such as toilets, require the use of potable water which opens up the possibility for sustainable methods in providing sanitary water.

Greywater is the term used to refer to relatively clean waste water. It can come from washing machines, sinks, showers, bathtubs, and dish washers. Water collected from these fixtures and appliances can be transferred directly into an on-site greywater treatment system where it is pushed through a series of filters and treated with chemicals such as chlorine until it reaches a sanitary level. This greywater is then dyed and sent to a holding tank where it waits until it can be pumped into toilets for flushing (Alvis, 2019). Several colleges in the United States have utilized greywater reuse systems in their dormitories to provide water for their toilets. Eagle Hall (formerly known as Longstreet-Means Residence Hall) at Emory College installed their own greywater reuse system for an initial cost of $2,000,000. Their system collected an estimated 12,000 gallons of water each day from the sinks, showers, washers, and dishwashers of the dormitory. In just one year, the system conserved 4,000,000 gallons of potable water and collected triple the required water necessary for the dormitory's flushing needs. This led Emory College to pipe it off to be used as flushing water for two adjacent buildings (Alvis, 2019).

7.1.4. Green Roofs

A green roof is a permanent rooftop planting system for plants ranging from small flowers to moderate sized trees (US DOI, n.d.). There are two types of green roofs. The main difference between the two types, intensive and extensive, is that an intensive green roof requires its plantings to receive more concentrated and specialized maintenance, soil, and support in comparison to extensive systems. There is a rooftop garden on the roof of WPI's East Hall. Other colleges in the Northeastern United States, including the University of Hartford, Harvard University, and SUNY Cobleskill among others, have also constructed green roofs on top of campus buildings and residence halls (Recover Green Roofs, n.d.). Green roofs can reduce heating and cooling costs by absorbing and storing large amounts of heat when they are wet, thus reducing temperature fluctuations. As a result, the rate of flow of the heat through the roof is decreased when the roof is wet. The amount of energy needed to heat and cool the building is reduced as well as its respective cost.

7.1.5. Alternative Materials and Approaches

In structural system design, several performance and economic related factors are considered the most important and influential in the final design. These factors include schedule, cost, performance, durability, material availability, etc. However, very few of these factors consider sustainability measures or green engineering. The construction industry emits as high as 30% of the world's greenhouse gas emissions per year which receives very little attention in the design process (Nadoushani & Akbarnezhad, 2015). In reality, a small change to material choice or structural elements could impact the life cycle and carbon footprint of an entire building.

Some scientific advancements have begun to revolutionize the field of construction materials. One of the most notable is cross laminated timber (CLT). Cross-laminated timber is a large-scale, prefab, solid engineered wood panel consisting of layers of dried lumber boards, stacked and bonded, then pressed to create a solid panel that is lightweight but extremely strong, generating almost no on-site waste (Cross-Laminated Timber, 2018). The wood is made from sapling lumber which has low environmental impacts, due to its ability to be harvested sustainably. The use of this wood also reduces carbon emissions from the atmosphere since timber consumes carbon dioxide in photosynthesis (D'Amico, Pomponi, & Hart, 2020). The panels can be prefabricated off-site, and cut to the exact size, including window and door openings, and then shipped to site ready to be installed. The benefits of prefab reduce manpower efforts, as well as schedule and cost impacts that could take place with material delays or on-site prep errors.

Thermochromic window technology is another design alternative which has pioneered the way for energy-saving design through the use of new window glass science (Aburas et al., 2019). Commonly referred to as "Smartglass", users are able to control the amount of light admitted to the room by flipping a switch, which turns the glass from transparent to opaque. The glass has a thin film placed between two glass layers which contain particles that when electrified, align and prohibit light from passing through (Smartglass and Sustainable Living, 2021). This is a new innovative approach to green architecture which helps reduce the interior temperature and therefore better control the HVAC regulation. Researchers from 2009-2019 identified that thermochromic windows were reported to have the potential to save heating and cooling energy demand from 5 to almost 85% in comparison to plain glass (Aburas et al., 2019). In addition to saving energy, it decreases the admission of UV rays and has various applications for both residential and private construction.

7.2. Construction Technology: Robotics in Construction

When it comes to the latest technological innovations in the workforce, particularly robotics, few have been as resistant to integration as those in the construction industry. The current challenge faced by construction firms is that the shortage of subcontractor labor has been further exacerbated by the COVID-19 pandemic. In order to prevent any further delays in their project schedules, and to avoid an inevitable loss in profits, general contractors are on the hunt for creative solutions to labor shortage problems (Biggs, 2021). Derrick Morse, a WPI alumnus and Professional Engineer, is the co-founder of a company with its own take on approaching labor shortage issues.

Rugged Robotics, a Houston-based company Mr. Morse co-founded alongside former NASA engineer Logan Farrell, has developed the first in their series of construction robots: the "layout Roomba". Thanks to Consigli Construction, Rugged has had the opportunity to pilot and improve their robots which can now effectively draw blueprints on the concrete slabs of a building (Heater, 2021). Morse describes that the work these robots can accomplish is the "most appropriate application of robotics in construction," and are a necessary component in ensuring that project schedules do not fall victim to delays caused by human error. While every piece of MEP equipment should theoretically fit together as they are designed in BIM models, Morse states that this is not the reality superintendents are dealing with in the field (Morse, 2022). While it takes a subcontractor several weeks to use tape measures, chalk lines and total stations to draw out MEP and architectural layouts with mixed results, Rugged's robots are able to accurately draw layouts while also adding additional information such as trade names, hangar sizes, pipe elevations, system names, etc. in far less time than conventional methods. In adopting this technology on the job site, general contractors are opening up new doors by adding value through improved accuracy, repeatability, consistency, and speed (Morse, 2022).

7.3. Evaluation of Sustainability Alternatives and Advanced Technology

This section discusses the application of the previously mentioned sustainable alternatives and innovations in construction to the proposed WPI residence hall. A summary of each topic can be found in Appendix L.

7.3.1. LEED Certification

To provide a general estimate of LEED certification for the proposed residence hall design, the LEED scorecard was used to assign point values assumed to be feasible for WPI and the building design (*LEED scorecard*., 2021). Table 10 shows the score breakdown by category. A more detailed table of each point awarded can be found in Appendix M. Overall, the building has the possibility of achieving LEED Gold Status if WPI is willing to invest the time and money into the design and construction (U.S. Green Building Council, 2021). This status hinges on the ability to satisfy Indoor Environmental Quality and Energy and Atmosphere credits. Based on the square footage of the building and the type of construction, the estimated cost for LEED certification would be upwards of $11,000 (*Pricing tool: U.S. Green Building Council*., 2021). A breakdown of the total cost can be seen in Appendix M. This value does not include the additional costs to provide sustainably resourced materials, renewable energy, or environmental quality within the building. In order for WPI to maintain its sustainability initiative set by the Board of Trustees in 2007, it is required that the new building be at least LEED certified no matter the cost (*Campus operations,* n.d.). If WPI chooses to spend the money, the new residence hall design has the possibility of being LEED Gold. In order to achieve LEED certification, it may be necessary to implement the discussed alternatives, in turn increasing the cost of the new residence hall.

Table 10. LEED Credit Scorecard

LEED Category	Possible Points	Applied to Project	Percent of Possible Points
Location and Transportation	16	7	43.75%
Sustainable Sites	10	6	60.00%
Water Efficiency	11	8	72.73%
Energy and Atmosphere	33	19	57.58%
Materials and Resources	13	5	38.46%
Indoor Environmental Quality	16	15	93.75%
Integrative Process	1	1	100.00%
Regional Priority	4	4	100.00%
Total	**110**	**66**	**60.00%**

7.3.2. Solar Power

By installing solar panels on the roof of the new residence hall,WPI will save annually on their electric bill while also improving their use of renewable energy that will, in turn, benefit their green image (SF Magazine, 2021). Solar panels can be installed in the blue area presented in Figure 28.

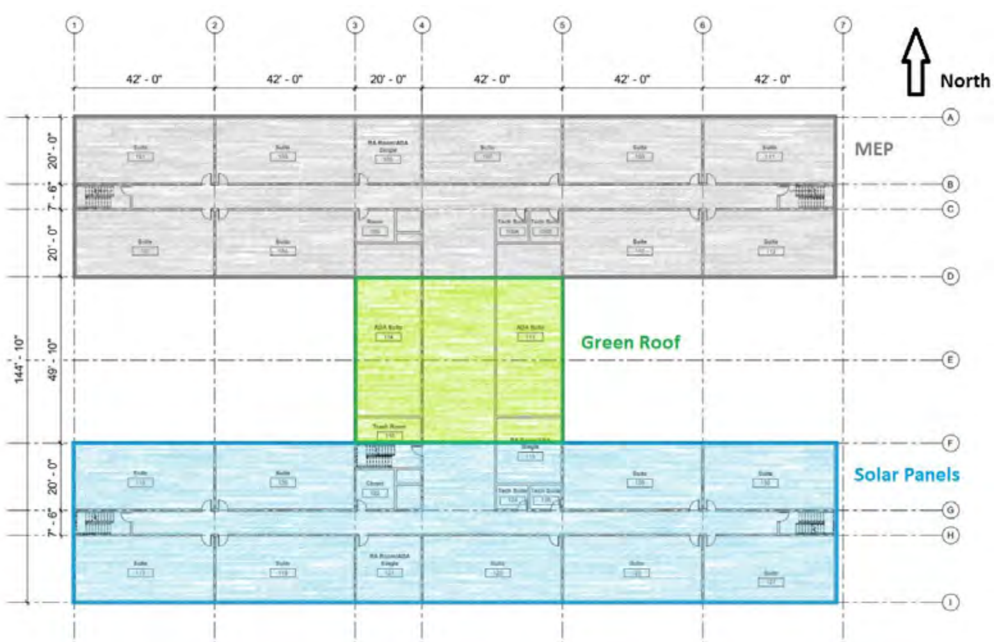


Figure 28: Sketch of Roof Locations for MEP Equipment, Green Roof, and Solar Panels

Installing a 100 kW system in the area presented will cost approximately \$300,000 and may save \$32,529 per year, which is only 7% of the estimated electric bill for the building (SunWatts, 2022; A1A Solar, 2022; Alternative Energy, LLC, 2021; MA Energy Ratings, 2022; *Large*

Offices, 2022). At this rate of savings, the return on investment is just over 9 years. The installation of solar panels will also make WPI slightly dependent on the weather; yet because the solar panel system would not be large enough to supply the whole building with energy, connection to the electrical grid will be required for supplemental electricity. Calculations for the total savings based on energy use of the project's approximate 100,000 sq, ft. can be seen in Appendix N.

In order to install solar panels, there will be a few schedule impacts. The installation site will need to be assessed before an engineer can design the system and apply for permits (Forme Solar, 2021). This initial process may take over 50 days depending on the size of the project (Forme Solar, 2021). Once approved, construction installation may take anywhere between 5 and 12 weeks (SunPower, 2020). After installation, the system must go through final commissioning before it can be used in practice for energy supply (SunPower, 2020). Maintaining solar panels is relatively simple as long as you have good warranty and insurance (Sendy, 2019). It is important to keep the panels free of dirt, debris, and, in Worcester, snow (Sendy, 2019). The facilities team at WPI could manage this upkeep, however, if a solar panel needs repair, it is best to hire a professional for an extra cost (Sendy, 2019).

7.3.3. Greywater Reuse Systems

If WPI were to go ahead with the installation of a greywater reuse system they would need to be aware of and prepared for the extensive maintenance it would require. At both Emory and U.C. Boulder, the greywater filtration systems posed a challenge when it came to the process of chlorination to get the water up to a sanitary condition. Due to the fluctuation of what is within water that comes from showers and sinks (soap, hair, etc.), maintenance workers would need to constantly keep an eye on and adjust the chlorination levels. This would frequently lead to over chlorination which, in turn, would break down the rubber components of their dormitory's toilet systems leading to leaky toilets (Alvis, 2019).

Using the initial costs of the greywater reuse systems installed at Emory College ($2,000,000) and University of Colorado Boulder ($1,000,000) along with the size of the residence halls they were installed in, an estimate of $1,750,000 was generated for the proposed WPI dormitory. This system, if installed, would save WPI around 3,000,000-4,000,000 gallons of potable water a year and save an estimated $14,000-$19,000 annually in water costs based on Worcester's current rate of $3.67 per hundred cubic feet of usage. Depending on the amount of water collected over the course of the year, it may also be possible for WPI, like Emory College, to pipe toilet flushing water over to the Stoddard Complex and Fuller Apartments. Choosing to use this system would require WPI to plan ahead for an increase in facilities workers' presence and work hours, informational training sessions for facilities workers to learn how to maintain proper chlorination levels, and have a budget set aside to maintain the filtration system as well as to replace any components of the toilets that may become damaged over time.

7.3.4. Green Roofs

The installation of a green roof will help WPI to reduce cooling costs by reducing the temperature of the roof's surface and the ambient air within the building. Because green roofs decrease the flow of heat through the roof when they are wet, they are able to reduce the energy needed for heat in the winter and air conditioning in the summer. The green roof of this size (Figure 28) would have a Net Present Value of $2.50 per square foot per year with an Internal Rate of Return of 5.0% (US General Services Administration, 2011). However, installing a green roof of the proposed size would cost around $60,000 to $90,000 (HomeAdvisor, 2021). Although the roof was designed to support the live load for a roof garden, additional structural support would be needed to ensure that the garden is fully operational. In order to maintain the green roof, a cost of $0.75 to $1.50 per square foot per year would need to be factored in as well (HomeAdvisor, 2021). There is also an additional cost associated with plant upkeep which can fluctuate depending on the types of plants used. WPI would see a return on investment of 220% on a green roof this size after 6.4 years (US General Services Administration, 2011). In terms of schedule impact for the construction of the building, it wouldn't have a major impact as installation can occur once initial roof construction is completed, while the interior of the building is being completed.

7.3.5. Alternative Materials and Approaches

For this project, CLT could be applied due to the long span wall and floor sections in the residence hall. The panels have possible widths up to 98 feet, and lengths up to 60 feet, making it a viable option for a larger building with a simple design. At the Rhode Island School of Design in Providence, RI, a six-story residence hall was constructed using CLT panels and steel framing (Natanzon, 2019). This was the first dorm built in New England using CLT paneling, and the results were very successful in terms of the project's budget, schedule and sustainability metrics. The entire superstructure was constructed in less than three weeks (Natanzon, 2019). The material is so lightweight that only a small crane is required to assemble the prefab pieces onsite, and since the plumbing penetrations were able to be fabricated prior to site, the panels significantly reduced shop drawing prep, review, and construction time compared to concrete systems. The material also reduced other construction efforts due to its inherent material properties, such as fire rating. The lumber contains an inherent fire rating due to a charring effect researched in the IBC, which means the material does not require fireproofing when used as a ceiling, saving the use of drywall while improving interior aesthetic. Other benefits include increased safety due to the paneling only requiring a chainsaw to cut, and site organization was simpler because the panels require fewer trucks to transport and stage prior to installment. The benefits of prefab reduce manpower efforts, as well as schedule and cost impacts that could take place with material delays or on-site prep errors.

Similarly, Smartglass is not only extremely user friendly, but it can give users a sense of control and ease when it comes to their comfort in a dorm. Instead of needing to get up and move around curtains, which is both tiresome and annoying, they could simply flip a switch and block dangerous, hot UV rays while staying in a comfortable climate. In Worcester, the climate is hot in the summer and extremely cold in the winter, and the new residence halls are equipped with air conditioning in common areas, and in some cases, the rooms. By using Smartglass, students can be more comfortable in their rooms by being able to moderate the climate without having to forfeit sunlight. This can also help the building's HVAC costs because the air-conditioned rooms will hold their temperature longer if the sun's rays are not able to heat the room up as quickly or as strongly with Smartglass (Aburas et al., 2019). This innovative technology can help WPI lower their energy footprint for their dorms, reduce their carbon emissions, and ensure that residents and staff are comfortable.

7.3.6. Construction Technology: Robotics in Construction

The school motto at WPI is *Lehr und Kunst*, or "theory and practice". This motto rings true not only in the work current students complete but in WPI's alumni as well. Derrick Morse and his team at Rugged Robotics have shown through their work that there are ways to integrate robotics into construction. This integration can help to fill the labor gap, as well as inspire younger generations to enter construction trades, speed up the layout and installation processes, and emphasize the importance of creating job opportunities that require a skilled workforce with technological knowledge. In making the choice of contractors for the proposed residence hall, WPI would greatly benefit from selecting one who utilizes technology such as that of Rugged Robotics. Not only would they gain savings of both cost and time, but there could also be the potential for MQP opportunities and faculty research. For example, Civil Engineering, Computer Science, as well as Robotics Engineering are among several majors who could work with companies such as Rugged Robotics to complete this project and gain the inspiration necessary to produce innovations in their future careers.

7.4. Selection of Alternatives

After researching each sustainability and construction alternative, categories in savings, benefits, downsides, maintenance, and schedule impact were scored on a ranking from 1-4, with 4 being the best (Table 11). A utility value was determined for each alternative based on the ratio of total score:cost, with a scale of 10^5. The highest ranked alternatives were Green Roof and Solar Panels at values of 111 and 43 with Alternative Construction (3), Greywater (4), and LEED (1) trailing behind. Robotics is non applicable in the utility value calculation due to missing cost information, but yields a relatively high total score based on improvements to schedule efficiency and accuracy which would likely reflect positively if implemented on a WPI project.

Based on the scores in Table 11, the new residence hall design should proceed with implementing a green roof and solar panels. Together these alternatives can aid in achieving sustainability standards for WPI. Despite LEED's low utility value, it is required to implement since all new WPI buildings must be at least LEED certified. The extremely low utility value for

LEED comes from the added cost of implementing the sustainability alternatives listed below to achieve a status in addition to the certification cost.

Table 11. Sustainability Alternative Scorecard

Sustainability/ Innovative Measure	Cost	Savings	Benefits	Downsides	Maintenance	Schedule Impact	Total score	Utility Value
LEED	$11,000.00	1	3	2	2	2	9	1.34
Rooftop Garden/Green Roof	$90,000	1	3	3	2	2	10	111.11
Solar Panels	$300,000.00	2	4	4	3	2	13	43.33
Greywater Reuse	$1,750,000	3	3	1	1	2	7	4.00
Alternative Construction	$4,586,200.00	3	4	4	3	4	15	3.27
Robotics	N/A	4	4	3	N/A	4	11	N/A*

8. Conclusions and Recommendations

The goal of this project was to propose a new residence hall option specifically designed for WPI's upperclassmen students.The objectives of this project were to define the design problem, design a building floor plan, estimate the construction schedule and cost, and evaluate sustainability alternatives and emerging construction technology. Upon identifying the issues in housing and capacity restraints on campus, a building program was compiled to define the parameters needed for the proposed residence hall. The building will be 4-stories above grade, 42 feet in height, and will have an approximate footprint of 24,939.67 square feet within the allowable buildable area of 33,422.5 square feet. The building will total 99,758.67 square feet. It was designed for suites of 4 people, in order to match the majority of other upperclassmen residence halls, and help facilitate a better housing selection process. The final design consists of 54 suites, 6 ADA suites, 9 ADA single rooms and a mixed-use ground floor at the discretion of the campus. After completion of the building program and floor plan, calculations were completed for all of the structural steel components of the building. Structural steel design included beams, girders, columns, and bracing. Additional concrete elements were designed for slabs and footings.The complete structural model can be seen in Figure 6.

Using the model, a cost estimate and project schedule were produced for the residence hall. The square foot estimate totals around $23 million, and the assembly estimate totals about $27.5 million. A proposed schedule of the entire timeline of the project was also produced. Microsoft Project was used to visualize the overall timeline of the project. The project will begin with Building Design on July 5, 2022 with Close Out completing January 17, 2028. To supplement the design, sustainability alternatives such as LEED certification, solar power, greywater reuse systems, green roofs, Cross Laminated Timber, Smartglass and robotics were researched. These alternatives and their applications were discussed to calculate a utility value, discerning which alternatives should be implemented into the design of the residence hall. The highest ranked alternatives were Green Roof and Solar Panels. These alternatives are recommended additions to the residence hall in order to satisfy WPI LEED certification requirements.

8.1. Recommendations

At the end of project completion, there is a select set of recommendations regarding improved detail in further developing this project. The Microsoft Project schedule could have included more detail about the project timeline. These details include the early start and early finish dates for each activity. It is recommended that more time goes into the research of durations for the schedule of activities to make the overall timeline more accurate. The WPI Facilities Department may be willing to provide previous project schedules to give a baseline of activity durations. With more detailed information about labor rates and schedule details, the S-curve would have a better representation of the project's 3D model.

With an improved construction schedule, the phases of construction can be presented and visualized in 4D modeling, which includes the 3D Revit model of the building and the additional timeline of construction. A Navisworks file integrating Revit, schedule, and cost, would provide a 5-Dimensional model to better represent the overall scope of this project.

To improve the overall model design, a design with more architectural details should be produced. A campus survey could be sent out asking for student input which could have aided in a more detailed design of the main floor. If a more detailed architectural plan is developed, a better Revit energy takeoff would have more value and purpose in determining the overall sustainability level of the building.

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Appendix A. - Proposal

Sustainable WPI Residence Hall

Proposal

A Major Qualifying Project Proposal
Submitted to the Faculty of the
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements for the
Degree of Bachelor of Science

by
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Date:
October 13th, 2021

Report Submitted to:
Professor Leonard Albano - Worcester Polytechnic Institute

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1. Introduction

In recent years, the availability of housing at Worcester Polytechnic Institute (WPI) has not been able to meet the student demand. The incoming classes have grown exponentially since the founding of the institution, and the burden of housing new students falls upon Residential Services. Since on-campus housing is guaranteed for first-year students, several residence halls have been built strictly for freshmen; however, the demand is quickly outgrowing the supply. As of 2010, almost all residence halls built specifically for upperclassmen, now dedicate some, if not all, of their beds to first-year students. What happens to the upperclassmen seeking that housing? They are left displaced with very few housing options. While upperclassmen are made fully aware that their likelihood of obtaining on-campus housing is never guaranteed, each year the number of beds once dedicated to them dwindles, with little action being taken to remediate the issue.

Previous efforts have been made to find students a space on campus to live in Campus expanded residential options in 2019 with the construction of Messenger Hall on top of the newest academic building, WPI Innovation Studio. This construction expanded housing to a total of 140 beds. However, the COVID-19 pandemic forced WPI to completely rework their rooming assignments in order to keep campus safe. This meant de-tripling most of the first-year housing and relocating those students to other dorms. For that reason, multiple upperclassmen dorms transitioned to housing first-year students, and WPI introduced the townhouses, the Hampton Inn hotel, and houses formerly utilized by Becker College after it closed in 2021. Even with these new areas, housing is still at capacity. The uncertainty of continuing to lease the hotel and old Becker properties leaves Residential Services at a standstill for future housing assignments. How can campus continue to provide housing for first-years without these properties, and without completely moving upperclassmen off campus permanently?

The goal of this project is to provide WPI's upperclassmen students with a new residence hall option. To accomplish this goal, we plan to complete a series of individual objectives.

- Objective #1: Define the design problem
- Objective #2: Design a new residence hall
- Objective #3: Estimate construction and schedule costs
- Objective #4: Evaluate sustainability alternatives and industry advancements.

First, we need to gather information on the current housing situation at WPI. This means conducting interviews and research both within the residential services office, as well as understanding campus enrollment trajectories for future classes. With that information, the team will work to design a new residence hall for WPI's campus. This design will include site location, a floor plan, and structural member calculations.

Based on that design our group will estimate the construction schedule and costs. We will do so by taking the calculated loads and then estimating the costs of the material. Additionally, we will create a construction schedule that will allow us to better estimate costs of labor and construction. The team will investigate sustainable design attributes which we could potentially include in our residence hall. These alternatives will be compared to find the best option for this particular residence to potentially implement within the design of the residence hall.

At the end of this project, we plan on providing the following deliverables:

- Structural steel design and concrete slab calculations;
- A basic floor plan and multidimensional model;
- A complete project schedule generated by the Microsoft Project Software; and
- A list of recommendations as to how WPI can incorporate more sustainable alternatives into future building construction on campus.

2. Background

In this chapter, we discuss the current problem faced by Worcester Polytechnic Institute (WPI) as the demand for housing continues to exceed the number of available beds. This section opens a discussion on the potential for a new residence hall to be constructed through the use of structural steel and reinforced concrete design and attention to building codes and zoning requirements. Additionally, the topic of project management is considered and insight is given as to how new construction on campus can be imagined through various project delivery methods, the use of Building Information Modeling (BIM), and how new innovations in the construction industry can aid in cutting down the physical and environmental costs of construction.

2.1. Student Housing at WPI

Worcester Polytechnic Institute (WPI) was founded in 1824 with the purpose of creating an institution for men that unites the theory and practice of engineering. The campus, located on top of one of the seven hills in Worcester, Massachusetts, opened in 1868 with only two buildings, as the Worcester County Free Institute of Industrial Science.

Although the campus opened with only two buildings, it quickly expanded as more and more men sought engineering education in the late 1800s. However, it wasn't until 1926 that the campus opened its first residence hall, Sanford Riley Hall. It was built to house 115 men in 66 rooms, including a dining hall in the basement. The second residence hall, Morgan Hall, was built in 1958, to accommodate the rapidly growing campus size. Morgan was built to house 192 men in 8 single and 92 double rooms. Morgan Hall was the last all-male residence hall on campus, and in 1999 females moved in after it was newly renovated, over 30 years after WPI became a co-ed institution. Since then, the college has grown dramatically. WPI now has 13 residential buildings; however, with an increasing number of applicants each year (and a relatively constant acceptance rate) the institution can no longer house upperclassmen students seeking safety and comfort on campus and away from the public streets of Worcester.

The first few residence halls built for first-year students, Morgan Hall, Daniels Hall, and Stoddard Complex, were all designed for double rooms- now almost exclusively filled with forced triples. WPI only guarantees housing for first years, but they have built several residence halls over the years designed specifically for upperclassmen. WPI broke ground on Ellsworth/Fuller Apartments in 1972, and later in 1984, Founders Hall was built. As the fifth and sixth residence halls respectively, they were designed as upperclassman suite-style apartments, since the rest of the first-year classes had ample living space. This relief was short-lived- when the class of 1993 was rumored to be the largest class yet (at just over 700 students), WPI rushed to renovate an old apartment building to accommodate the first-year class without displacing any upperclassmen. This led to the opening of Institute Hall, housing 70 students at the time. Since then, WPI has increased the occupancy of nearly every residence hall in order to accommodate the incoming classes. Institute Hall expanded to house 90 first years, Morgan Hall expanded to 294, and all three Stoddard Complexes now house 90 students each.

The fact of the matter is, there is nowhere else to put the rapidly expanding first-year classes except to infiltrate the spaces meant for upperclassmen. Due to this, it is rare that Juniors and Seniors live on campus. Previously mentioned Founders Hall, built to house 232 upperclassmen, has been overfilled to now house 286 students. Consequently, of those 286 beds, only one floor is currently housing upperclassmen. Messenger Hall, the newest residence hall built on top of the WPI Innovation studio in 2018, was also built for 140 upperclassmen. That was only true for two years because in the academic year 2020-21 it housed some first-years and sophomores, and then in 2021-22, it changed to housed first years exclusively. The list goes on- with an increasingly large demand for housing with too little-too late solutions. With each coming year, the first-year class grows exponentially, while the campus remains the same size. Not only does this result in a loss of revenue, but the housing process leaves upperclassman students displaced and without a plan B, forcing them to try and find off-campus housing within walking distance of the campus, months after leases are typically signed. In the past three years alone, the percentage of upperclassmen who request housing and are granted a bed has dropped from 85 to 75% (Laythe, 2021), but the demand hasn't changed. WPI cannot justify continually increasing class size without first housing its existing students.

2.2. Building Design Materials

In order to design the proposed building, the design team needs to specify the materials that will be used to construct the project. Over the course of time, the different materials used in the construction industry have varied. But modern construction methods used in the Northeastern United States utilize structural steel and reinforced concrete to complete the building design. Both of these materials have properties that make them widely used within construction today. Each has a specific purpose within the design of the structure.

2.2.1. Structural Steel

Structural steel is widely used in modern building construction due to its high strength and ductility when loaded to capacity. Many steel elements can be designed and fabricated off-site and then assembled in place to increase the speed and efficiency of the project. This method is known as prefabrication, which cuts down the number of laborers being used on the project and therefore decreases the overall cost of construction. With the use of prefabrication, the construction of typical low-rise buildings can be expedited compared to classic construction methods. This is especially helpful for organizations such as universities that are on a tight schedule given their academic calendars. Structural steel is the dominant material used in the Northeastern United States due to its ability to withstand variable weather conditions throughout the year. These elements are designed with the aid of the AISC Manual, Specification, and Commentary which provide calculation standards and governing equations for the design and construction of steel structures (AISC, 2017).

2.2.2. Reinforced Concrete

Concrete is a mixture of cement, water, and aggregates, such as sand or gravel. Concrete is a popular material used in construction because the specific mixture can be curated to support a specific compressive strength as calculated by the building's desired final load capacity. However, the tensile strength of concrete is low compared to its compressive strength. To offset this, steel is used to reinforce the concrete and provide support where its carrying capacity would otherwise be limited. By combining the two, reinforced concrete is a low-cost, weather, and fire-resistant material with good compressive strength for structural design. This combination allows for reinforced concrete to be used in an almost unlimited range of uses in the construction of a plethora of structures such as buildings, bridges, dams, and reservoirs (Darwin, 2021).

2.3. Design Constraints: Building Code and Zoning Regulations

Building codes are a collection of minimum requirements which are adopted by a town, city, county, or state to govern the construction and maintenance of new and existing buildings. Organizations such as the National Fire Protection Association (NFPA) and the International Code Council (ICC) develop these codes using data they have gathered from events such as fires, earthquakes, windstorms, and other extreme conditions. Every few years these organizations release new editions of their codes to keep up with modern standards for protecting buildings and their occupants. Building codes also work to ensure that the building has been designed and constructed to not only withstand these events but meet the standards of structural integrity, mechanical, electrical, and plumbing (MEP) safety, as well as to meet accessibility standards set forth by the Americans with Disabilities Act (ADA).

Zoning regulations establish regulations for the use of land by local governments in order to divide their town, city, or county into separate districts dedicated to residential, commercial, institutional, or industrial uses. This method of dividing up the local area makes it possible for city planners to manage orderly growth and change by controlling the desirable characteristics of each type of setting. Each zone is given a specific purpose and can also control how tall or wide a building can be constructed.

2.3.1. Governing Codes in Massachusetts

Various areas of the United States have formed their own committees which put forth a modified version of the building codes created by the NFPA and the ICC. The Commonwealth of Massachusetts adopted the ninth edition of the *Massachusetts State Building Code* (MSBC CMR 780) in late 2017. This edition draws upon many of the same codes featured in the 2015 editions of the codes published by the ICC including:

- The *International Building Code* (IBC)
- *International Residential Code* (IRC)
- *International Existing Building Code* (IEBC)
- *International Mechanical Code* (IMC)
- *International Energy Conservation Code* (IECC)
- *International Swimming Pool and Spa Code* (ISPSC); and

- Portions of the *International Fire Code* (IFC).

The MSBC is separated into two distinct volumes: Base and Residential. The Residential volume regulates all one- and two-family structures and townhouses that are three stories or less. It also discusses any structures that may be considered an accessory to them. All structures not covered in the Residential volume, including the dormitory which will be designed for this project, are covered in the Base volume.

Massachusetts also has an Architectural Access Board (AAB) which develops and enforces building regulations designed to make public areas accessible, functional, and safe for use by those with disabilities. These regulations are collected and published as the 521 CMR. Currently, the sixth edition of the 521 CMR, published in 2006, is in use by the Commonwealth of Massachusetts. Sections which this code covers include:

- Jurisdiction;
- Space Allowance and Reach Ranges
- Building Types (retail establishments, transient lodging facilities, multiple dwellings, commercial buildings, educational facilities, medical care facilities, places of assembly, etc.)
- Accessible Routes
- Curb Cuts
- Walkways
- Parking and Passenger Loading Zones
- Ramps
- Room Type (kitchen, bathroom, storage, etc.)

2.3.2. Zoning Regulations Around the WPI Campus

Across the city of Worcester, Massachusetts, the voluntary regulatory Zoning Board of Appeals (ZBA) has drawn distinct zoning districts which serve to dictate how the land in Worcester may be used. WPI's main campus is located within an institutional zone IN-S (Figure 1).

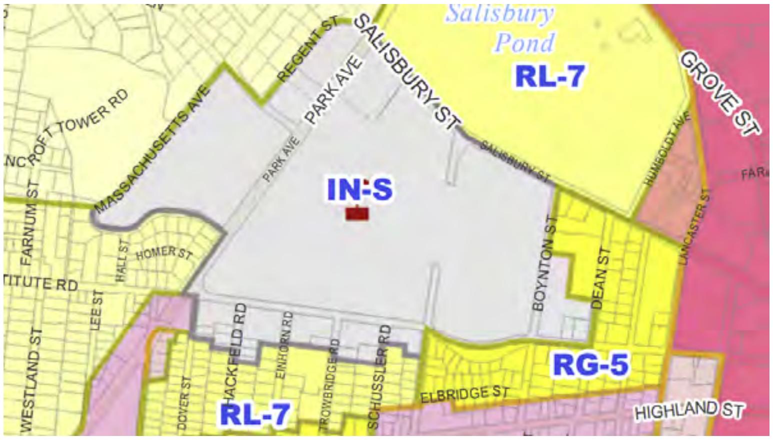


Figure 1: Worcester Polytechnic Institute's main campus shown on Worcester's zoning map

Within this zoning classification, the ZBA has defined permitted uses shown in Table 1.

Table 1: Examples of Permitted Uses of the Land Within an IN-S Zoning District

Use	Permitted
Residential	● Dormitory ● Fraternity/Sorority/cooperative residence ● Group Residence (general or limited) ● Multi-family dwelling (low rise)
General	● Library/Museum (nonprofit) ● Non-accessory residential parking ● Non-residential parking facility (non-accessory) ● Recreations/service facility (non-profit) ● Schools (K-12, college, university, technical institute) non-profit ● Schools (vocational, professional, other) profit
Business	● Food Service (excludes consumption/sale of alcoholic beverages)* ● Research lab, w/o manufacturing abilities ● Retail food sales* ● Retails sales, including retail with incidental fabrication assembly

** indicates that a special permit is required*

Additionally, the ZBA has established permitted dimensions by district as shown in Table 2.

Table 2. Permitted Dimensions by District

District	Use	Lot		Yard Setbacks			Height		Floor to Area Ratio (Maximum)
		Area (minimum SP)	Frontage (minimum linear ft.)	Front	Side	Rear			
				Minimum depth (linear ft.)			Max in stories	Max in ft.	
IN-S	All	N/A	N/A	15	10	10	N/A	N/A	N/A

Looking at the permitted dimensions for an institutional zoning district shown in the above table, it can be noted that other than the perimeter setbacks, there are not any significant restrictions set on how many stories a new building on the WPI campus can be or how much coverage it can have of the lot it is constructed on.

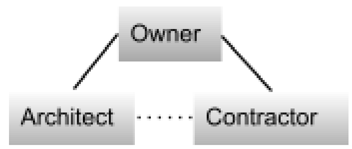
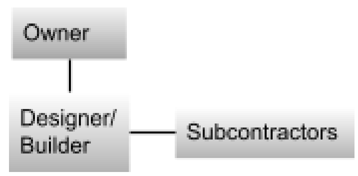
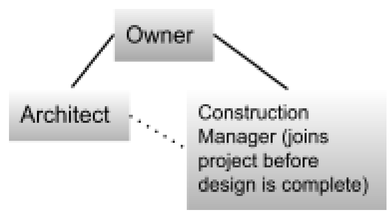
2.4. Project Management & Innovation in Construction

Many companies will utilize project management techniques to better facilitate teamwork. A project management team facilitates the operations of a project in order to maximize productivity and efficiency. In construction project management, teams prioritize schedules, cost, quality, and customer satisfaction (Ribeiro et. al., 2013; Demirkesen et. al., 2017). In order to satisfy the many needs of the construction project, project management teams must integrate their priorities with labor and material resources to move the project along successfully. To accomplish such a complicated task, a project team must communicate effectively and adapt well to changes.

2.4.1. Management Based on Project Delivery Methods

The organization and contractual arrangements, construction, and design responsibilities are dependent on the project delivery method used (Ohrn et. al., n.d.). Each project delivery method allows for a different project team setup and different levels of team integration (Mollaoglu-Korkmaz et. al., 2013). A select number of the common project delivery methods are listed in Table 3 along with typical uses for the select methods (Gazder et. al., 2018; Mollaoglu-Korkmaz et. al., 2013). Design-bid-build (DBB) is a system in which the owner coordinates with separate entities for design and contracting. Design-Build (DB) is when the project is contracted to a single company to manage both construction and design. Both processes are highly recommended and common for clients of private organizations (Gazder et. al., 2018). Additionally, the Construction Manager at Risk (CMR) delivery method may be valuable to a university project where a school has a strict budget or limit to their infrastructure spending.

Table 3. Project Delivery Comparisons

Project Delivery Method	**Projects**	**Project Team**	**Time of Project**	**Cost**
Design-bid-build (DBB)	● Industrial ● Public		Extensive time for subcontractor bidding	Expensive
Design-Build (DB)	● Commercial ● Private ● Sustainable construction		Quick project delivery	Less Expensive
Construction Manager at Risk (CMR)	● Sustainable construction		Time-efficient	Limits contractor to a guaranteed maximum price

The choice of project delivery method will alter the approach to scheduling the timeline of the project. The DB approach may prove valuable to a private university like WPI, where projects need to be completed prior to the start of the new academic year but without starting before the end of the previous year. After discussing with WPI Facilities representatives, it was determined that WPI typically utilizes a Guaranteed Maximum Price (GMP) contract with a CMR project delivery method (WPI Facilities Office, 2021). Due to WPI preference, time efficiency, cost benefits, and sustainable priorities, CMR will be the project delivery method our team explores within this project for the new residence hall design and construction.

2.4.2. Scheduling Software and Project Costs

In order to evaluate scheduling, a project team can utilize software such as Primavera or Microsoft Project. This scheduling software allows for analysis of the critical path method, allowing for optimization of construction activities upon project commencement (Hawkins, 2007). Within Primavera and Microsoft Project, a scheduler can add information for the start/end date of the project, activities, activity durations, costs, locations, and work breakdown structures (Hawkins, 2007). Primavera can be difficult to navigate, is no longer being updated, and costs about $5000 per license (Hawkins, 2007). Microsoft Project is much easier to use, has fast project setup times, is constantly updating software, and only costs $500 per license (Hawkins, 2007). Both software programs are commonly used by construction companies; however, Microsoft Project's ease of use and quick setup times far outweigh those of Primavera (Hawkins, 2007). Therefore, Microsoft Project will be used to create the construction project schedule for the new residence hall.

Companies are also likely to use software to visualize construction projects such as Building Information Modeling (BIM) and Revit (Demirkesen et. al., 2017). These tools can help to model a project in 3D (building), 4D (building+schedule), or 5D (building+schedule+cost). Layers of project cost, schedule, safety, and sustainability parameters can be evaluated for the project using BIM software (Mesároš et. al., 2020). In the future, it could be possible that augmented or virtual reality modeling will be used to visualize construction projects(Mesároš et. al., 2020).

After scheduling, the cost is a top priority for project management. If the schedule is delayed, the cost goes up (Ribeiro et. al., 2013). This is because the more days you spend on a project, the more hours each subcontractor and laborer work. These tradesmen are paid hourly, so it is important to use their time wisely. To minimize cost, it is optimal to multitask within the schedule as best as possible by starting tasks before others are completed. A project's cost comes from direct, indirect, and penalty costs. Direct costs include material and labor such as steel beams and a welder. Indirect costs include the salaries of the project management team, any company vehicles, and safety paperwork or drawings printed, etc. Penalty costs are the liquidated damages for the project. This includes any costs in delays or changes to design through change orders.

Typically each month the contractor or builder submits a requisition to the owner which will include the month's work cost plus an additional 10% markup, the average markup for profit percentage. The contractor will also hold a retainage which is a portion of the payment for the subcontractor to be paid when their job is complete. Throughout the project, the project management team may do evaluations on whether they are above or below on costs, behind or ahead on schedule, and cost variance which includes the cost to date and the cost to complete compared to the original budget.

2.4.3. Sustainability & Innovation

Sustainability is the practice of resource management where resources are used, but not overused so as to allow for use in future generations. The benchmarks for sustainability are different depending on what type of global sector you explore. In relation to construction projects, sustainability can be considered in the design, project management, and post-turn-over maintenance.

Projects can work to achieve a status of sustainability through certification in a particular Leadership in Energy and Environmental Design (LEED) category (U.S. Green Building Council, 2021). In order to achieve a certain status, a serious amount of design and planning must be put into the project in order to ensure its energy efficiency and environmentally conscious resource use. The LEED Certification hopes to create a framework of green building by listing minimum energy efficiency requirements among other design considerations in the

LEED credit library (U.S. Green Building Council, 2021). To maintain sustainability throughout a project's construction phase, it is important to engage the stakeholders, most often the owners, in conversations about achieving sustainability goals in construction (Stanitsas et. al., 2021). After the project management team turns over the newly finished project, it is important that the owner still considers sustainability efforts after construction (Stanitsas et. al., 2021). The entire life cycle of the building can be evaluated to determine whether the materials that make up the building can be sustained for many years to come (Stanitsas et. al., 2021).

In addition to sustainability, the construction building process and procedures can provide room for innovation. Building task procedures are relatively the same project to project due to the common goal of consistency in building quality. However, this results in processes that lack change or innovation. It is possible that systems of building walls or laying out Mechanical, Electrical, and Plumbing work can be altered to increase the efficiency and precision of a project. Technological advancements could help to automate some of the construction processes. It should be noted that these new processes may not be integrated easily as construction workers are often set in their ways. Despite this, it is valuable to explore the options available especially when it can help to shorten the time frame, lower cost, and improve quality.

3. Methodology

The goal of this project is to consider the current housing problem faced by WPI and provide upperclassmen with a new housing option.

During the course of our fourteen-week research and design terms, we plan to:

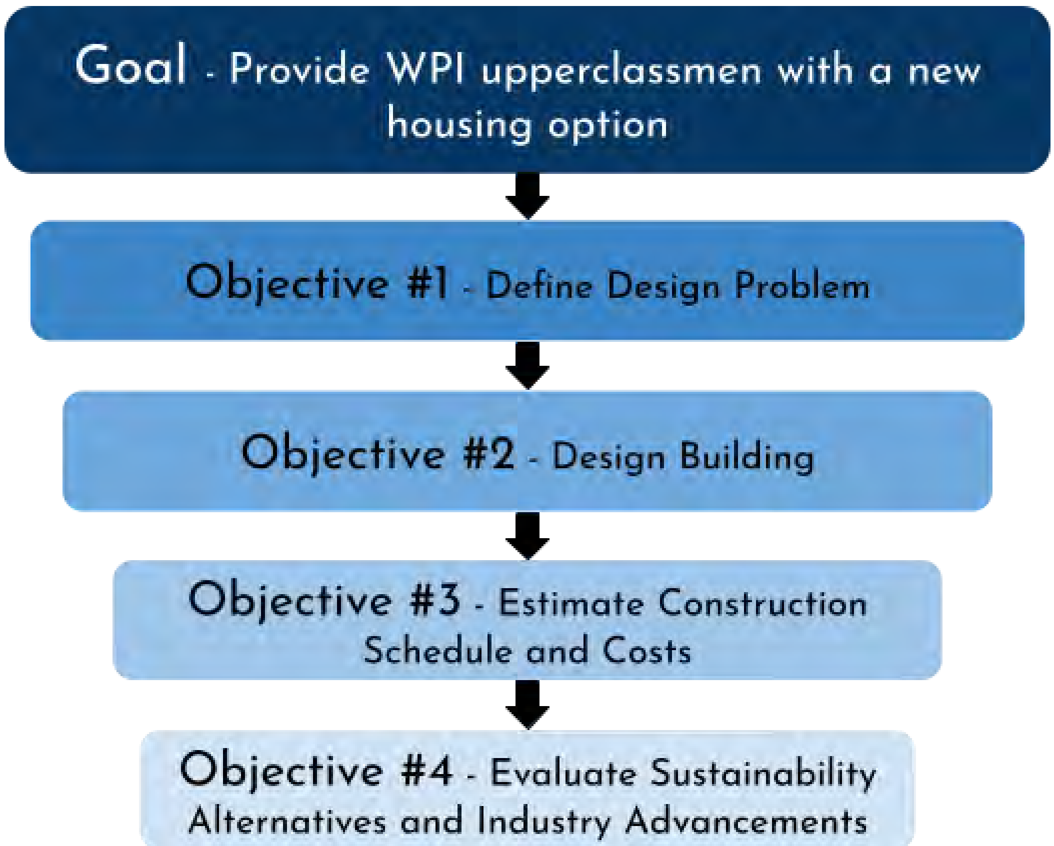


Figure 2: Flowchart depicting how the team will progress through each of the project's objectives

3.1.Objective #1: Define Design Problem

In order to design anything, the end-user and the owner must be the first considerations. For the case of this project, the intended end-user will be an upperclassman student at WPI who wishes to continue to live on campus after their first year. To better understand the current status of WPI housing and which improvements can be accounted for in a new design, our project team needs to understand and highlight underlying problems such as the: number of students who are denied on-campus housing after they apply for it, the types of residence halls that are more attractive to upperclassmen, and the ideal group size for housing arrangements.

To begin the design process for a new residence hall, the team will research the history of WPI housing by collecting existing data provided by Residential Services. The data requested will consist of the number of beds available on campus for the 2020-2021 school year and any years prior, if available, as well as the number of applications for housing received by Residential Services. This information will be used to highlight the current hypothesis that WPI's population has rapidly grown in the last several years and can no longer keep up with anticipated housing needs.

Once there is justification that the demand for on-campus housing will only continue to grow in the coming years, the team will narrow their focus to current residential buildings on campus. More specifically, the information collected from Residential Services, Facilities, and the WPI Tech Bible will be combined to gain a better understanding of WPI's residence halls such as which project delivery methods were used to construct them, which class years they were initially intended to house versus which class years currently reside there, and what WPI's current thinking is behind what is desirable in a new residence hall such as location, size, dining options, etc.

Using this information, our team will choose a suitable location for a new residence hall to be constructed. This will enable us to conduct further research and begin creating a list of constraints for our building design. The first constraint we will explore is those imposed by the Worcester Zoning Board of Appeals (ZBA). We will look into the zoning district where our proposed residential hall is located and use the city's *Zoning Ordinance* to determine the permitted land uses based on occupancy classification as well as the permitted dimensions including lot size, yard setbacks, maximum height in stories, and floor to area ratio. Following this, building codes such as those set in the base volume of the MSBC CMR 780, IBC 2015, NFPA 101, and 521 CMR Section 8.00: TRANSIENT LODGING will be researched to determine:

- Building occupancy;
- Means of egress or escape;
- Egress size requirements (hallways, stairwells, etc.);
- Elevator lobby requirements;
- Room and suite sizes; and
- Accessibility requirements.

3.2. Objective #2: Design Building

Once the zoning and building code constraints have been defined for our chosen location, along with the wants and needs of the WPI community, the team will compile this information into a program. This set of documents will detail information such as the number of stories, types of spaces, amenities, approximate unit sizes, and approximate allocations of area for the planned residence hall. Following this, the team will use the program as a guide to sketch out a rough floor plan for a residence hall using Revit software which will show the sizing of the suites as well as the means of egress. After this is complete, a structural layout of the building will be designed to support the floor plan and occupancy loads. To accomplish this, the team will look at particular areas of the structure for typical bay and framing around the stairwells, elevators, and core of the building. The team will also establish any gravity and lateral loads for each case.

From there, the load case scenarios are calculated for the respective member. Following the standards of LRFD design, the team will calculate moments, select the size of the respective beams and girders based on the AISC specification. Then, the team will check for deflection based on standards set in the IBC. Given those new parameters, calculations will be checked to ensure that the sizes selected are sufficient for design. This process should be repeated for the rest of the beams and girders in the system (AISC, 2016).

After the beams and girders are designed, the team will begin designing the building's columns. First, using the calculated girder sizes to determine axial forces (P_{nt}, P_{lt}), moments (M_{nt}, M_{lt}), and lateral sway. To determine if the column design is sufficient the team will use AISC equation H1-1a or H1-1b. The determining factor is that if P_r / P_c is greater than 0.2, then equation H1-1a be used. If AISC equation H1-1a is less than or equal to 1 then the design is sufficient. The team will follow these methods for any further column design work (AISC, 2017).

As member sizes are selected during the process of our calculations, member sizes will be updated in the 3-D Revit model framing design

3.3. Objective #3: Estimating Construction Schedule and Costs

Having selected CMR as a project delivery method based on research and knowledge about the WPI community, a project schedule can be formatted in Microsoft Project. General construction processes will be added to the schedule including, construction manager start date, procurement, concrete footing pours, steel install, slab pours, exterior walls, interior MEP and FP, interior walls, and furnishings. Each of the schedule items will be added to the proper work breakdown structure for easy organization. The schedule will also be inputted and formatted in Navisworks and combined with the Revit model to display the timeline of the building in 4-dimensional modeling which includes the 3D model of the building and the additional timeline of construction.

Upon completion of the schedule, costs will be calculated per labor and material needed to complete the project within the designated time frame. Cost analysis will include indirect and direct costs for construction processes. Cost can be added to the 4D model to create a 5D model with the addition of the lazy S-curve displaying total project cost over time.

3.4. Objective #4: Evaluate Sustainability Alternatives and Industry Advancements

While the preliminary schedule and project costs are being determined, sustainability and technology options can be explored. The team will research sustainable alternatives to design and LEED certification requirements. The team will also explore technological advancements in the construction industry. Sustainability and technology alternatives may include changes to materials, greenhouses/gardens, solar panels, or automated construction tools. Alternatives will be formatted into a ranking system from 1-5 to display the usefulness of each different practice. Alternatives will be evaluated on the impacts to cost, schedule, delivery methods, quality, and sustainability impact. A selection of alternatives may be recommended to add to the design if the quality and sustainability benefits far outweigh the cost and schedule impacts.

4. Deliverables

In designing a new residence hall for WPI upperclassmen, a selection of deliverables are presented. A major deliverable that this project will supply are the calculations for the design of the structural members for the building. To further illustrate the design, the team will complete a Revit model of the site to show the final design of the proposed building. A schedule and cost estimate for the building project will be presented to supplement the design and determine the overall feasibility of the project. The team will provide sustainability recommendations gathered through additional research on sustainable and technological alternatives for the residence hall. A final report will be developed to illustrate the methods used to produce the team's final results and recommendations. All of the information will then be consolidated in an organized and visually appealing manner in the form of a poster. The team will follow the schedule shown in Figure 3 with all of the tasks to be completed over the lifespan of the design project.

Figure 3: Gantt Chart of the team's proposed timeline for the project

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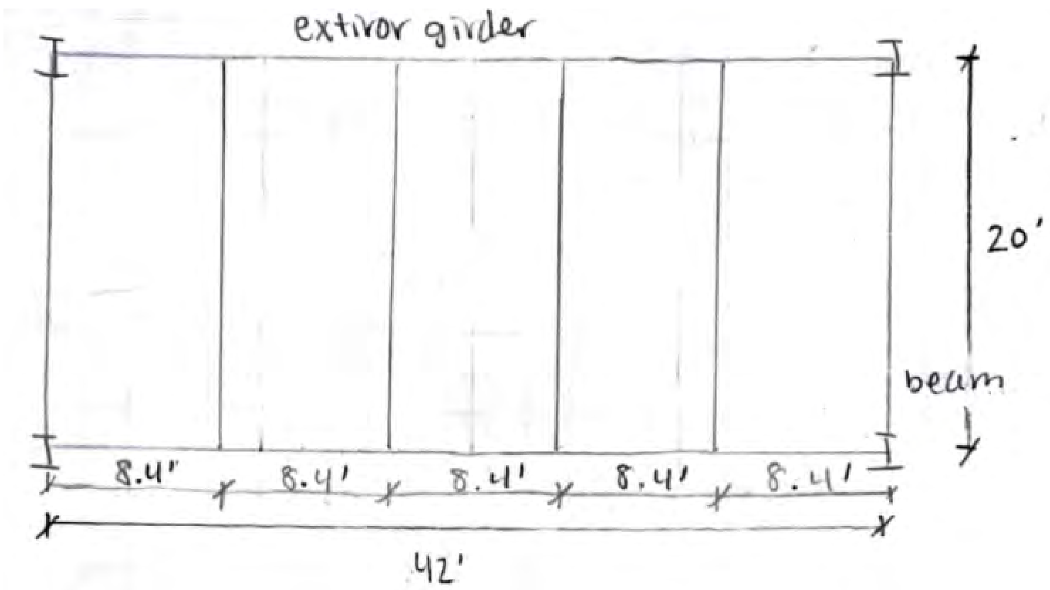
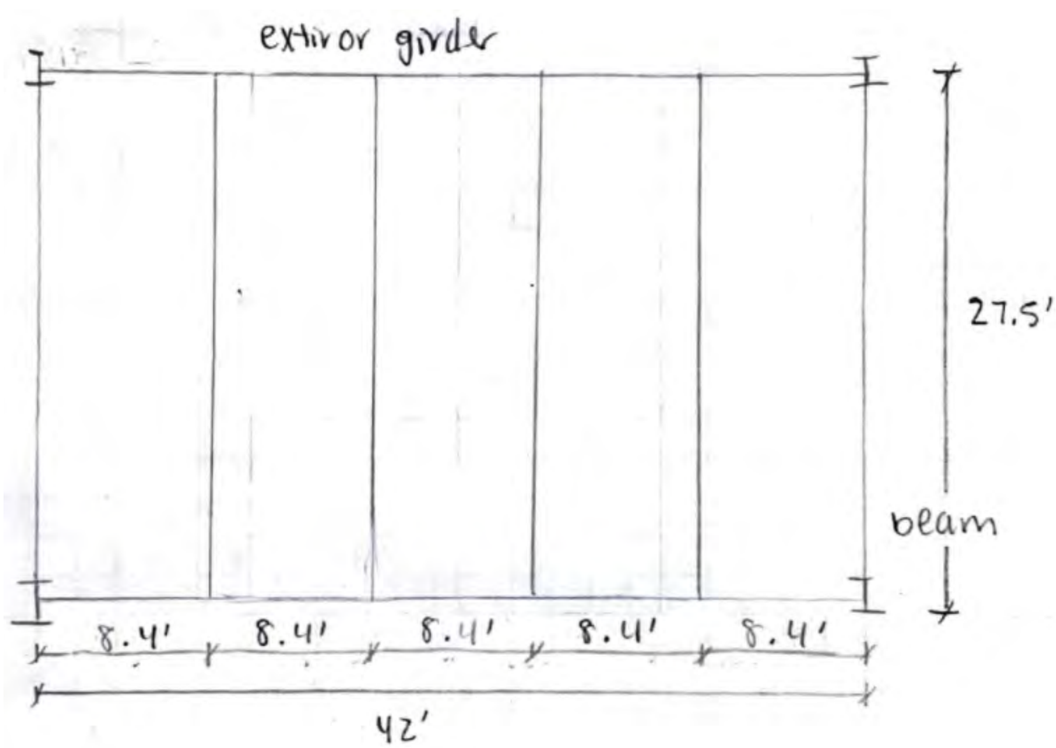
Appendix B. - Scheme Layouts

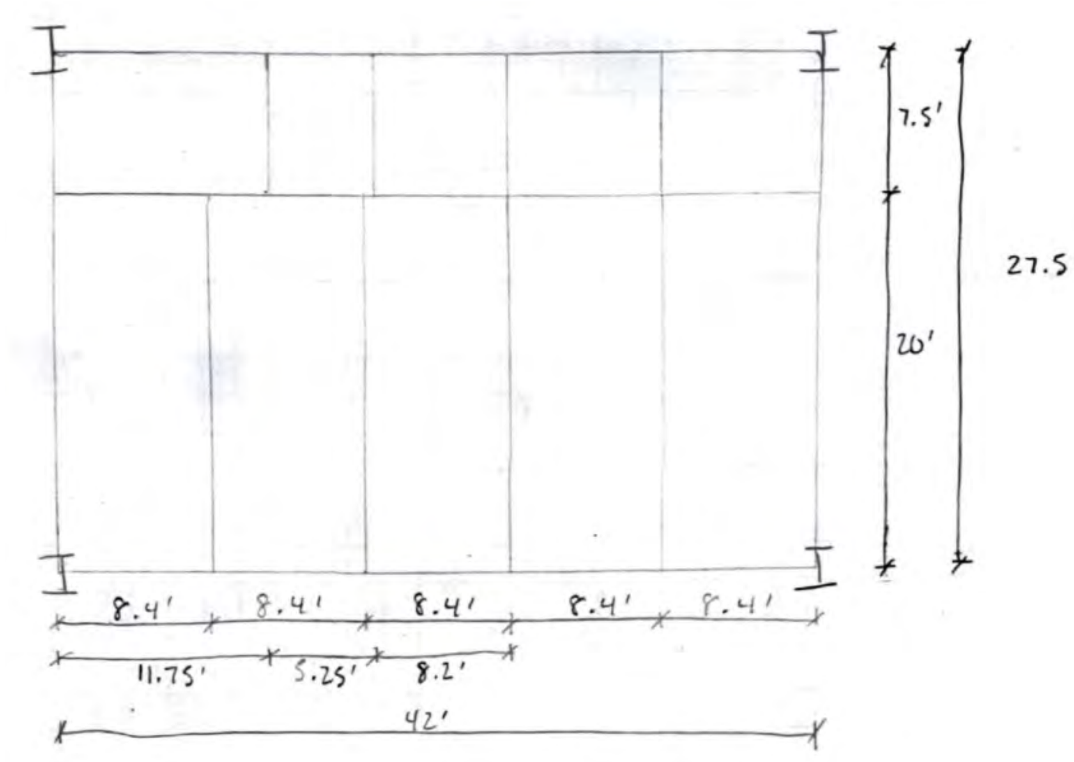
Scheme 1



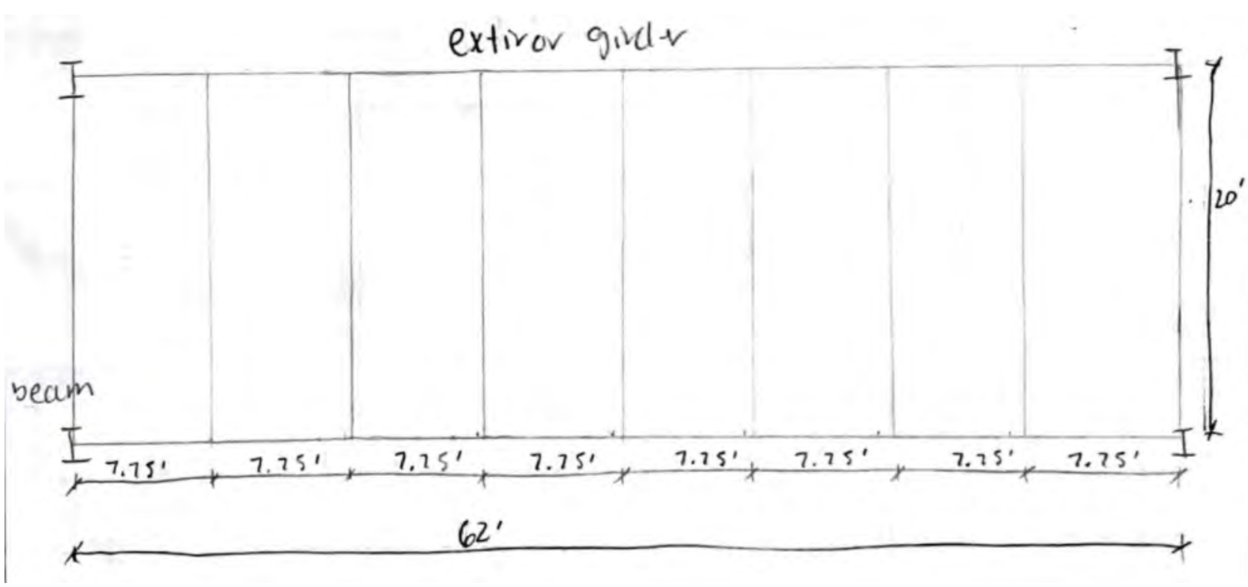
Scheme 2



Scheme 3



Scheme 4



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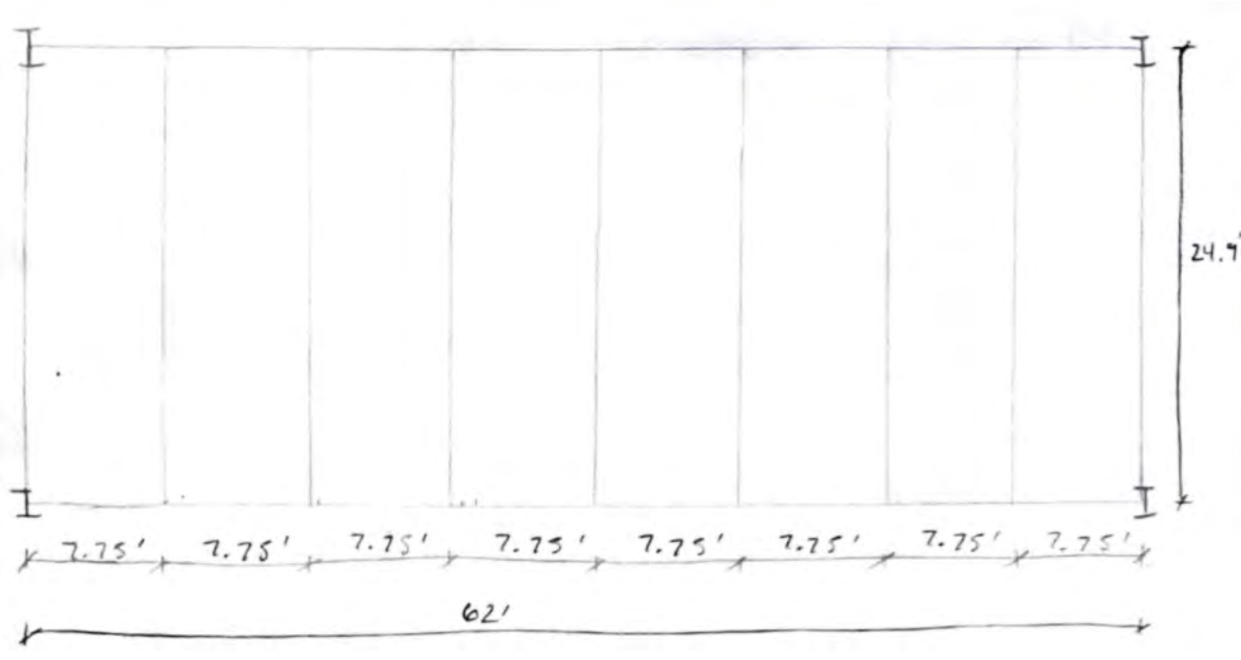

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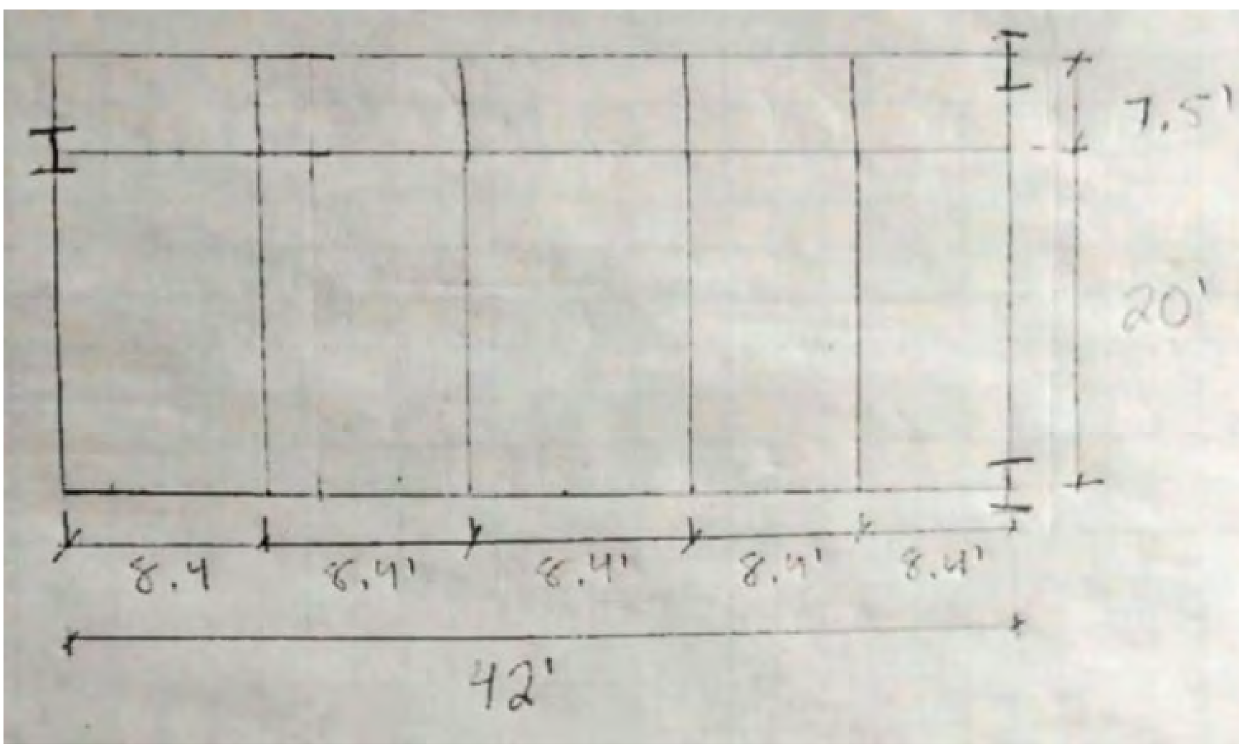

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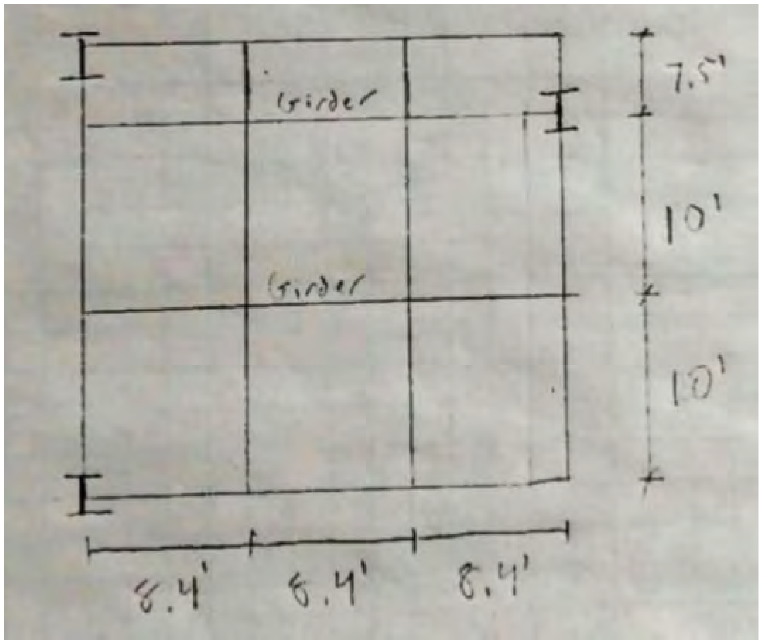
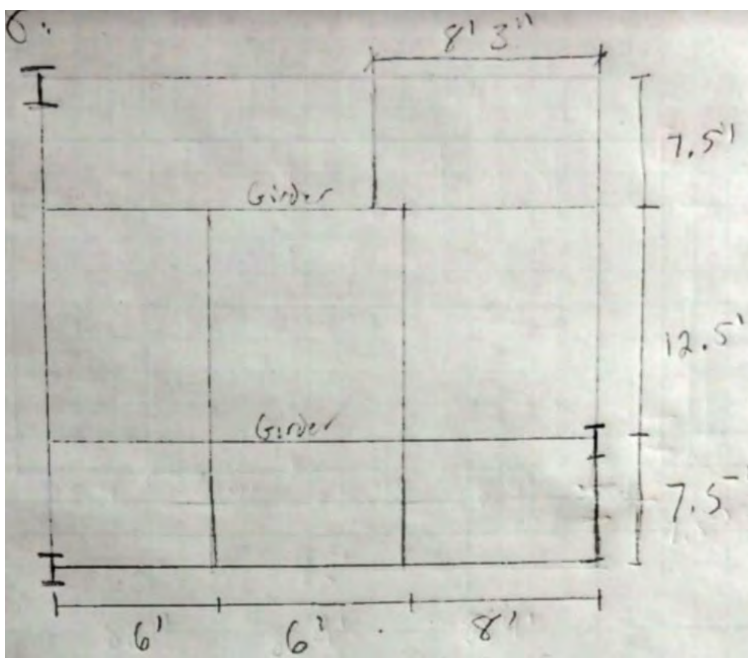


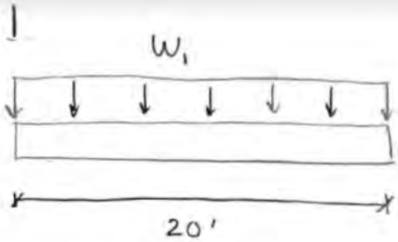
Scheme 8



Appendix C. - Example Load Cases for Beams and Girders

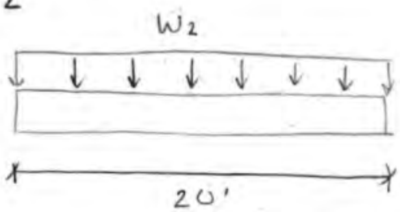
Example Load Cases for Beams (B1-B27)

B1



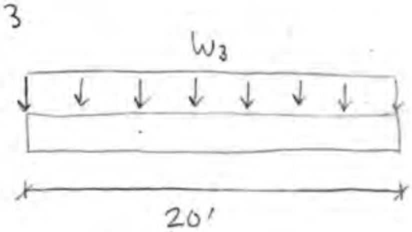
$$w_1 = 1.2D(8.4') + 1.6L(8.4')$$

B 2



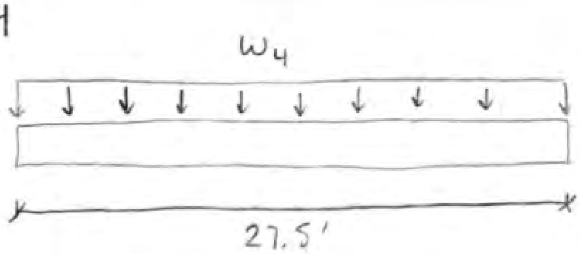
$$w_2 = 1.2D\left(\frac{8.4'}{2}\right) + 1.6L\left(\frac{8.4'}{2}\right) + 1.2\,(\text{Ext Deadload})$$

B 3



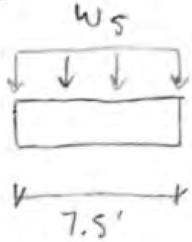
$$w_3 = 1.2D\left(\frac{8.4'}{2} + \frac{7.75'}{2}\right) + 1.6L\left(\frac{8.4'}{2} + \frac{7.75'}{2}\right)$$

B 4



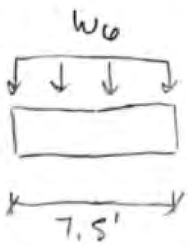
$$w_4 = 1.2D(8.4') + 1.6L(8.4')$$

B 5



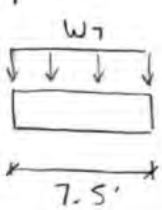
$$w_5 = 1.2D(8.4') + 1.6L(8.4')$$

B 6



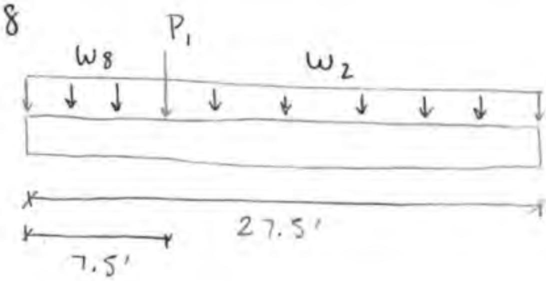
$$w_7 = 1.2D\left(\frac{8.4'}{2} + \frac{8.2'}{2}\right) + 1.6L\left(\frac{8.4'}{2} + \frac{8.2'}{2}\right)$$

B 7



$$w_7 = 1.2D\left(\frac{8.2'}{2} + \frac{5.25'}{2}\right) + 1.6L\left(\frac{8.2'}{2} + \frac{5.25'}{2}\right)$$

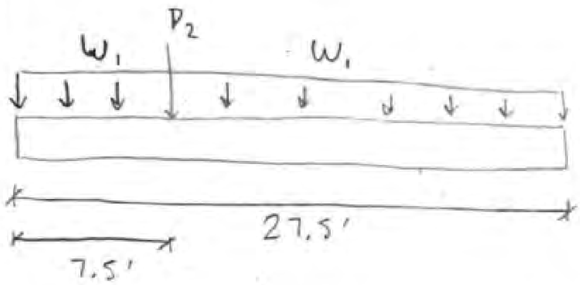
B 8



$$w_8 = 1.2D\left(\frac{11.75'}{2}\right) + 1.6L\left(\frac{11.75'}{2}\right) + 1.2(\text{Ext Dead loads})$$

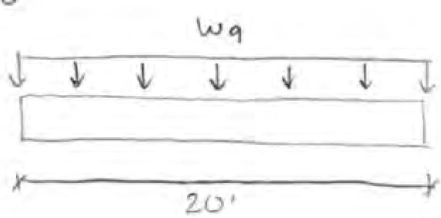
P_1 = G4 reaction

B9



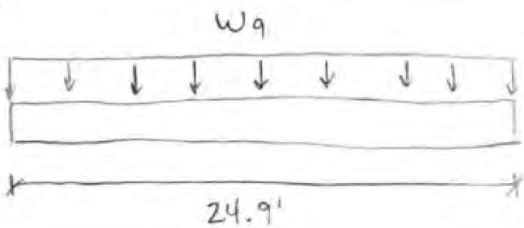
$P_2 =$ G4 reaction

B10

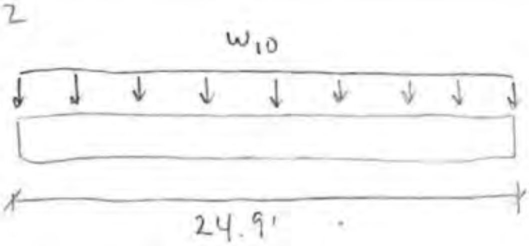


$w_9 = 1.2D(7.75') + 1.6L(7.75')$

B11

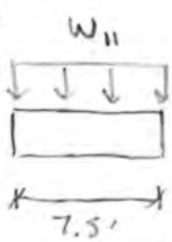


B12



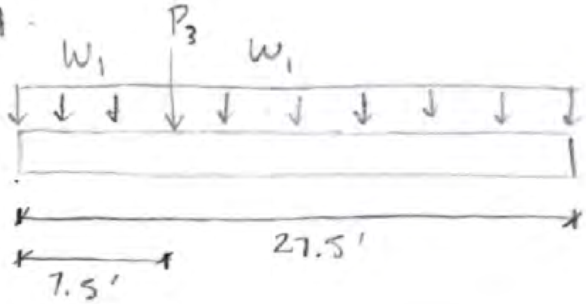
$w_{10} = 1.2D\left(\frac{7.75'}{2}\right) + 1.6L\left(\frac{7.75'}{2}\right)$
$+1.2(\text{Ext Deadload})$

B13



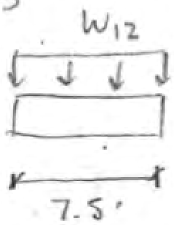
$w_{11} = 1.2D\left(\frac{5.25'}{2} + \frac{11.75'}{2}\right) + 1.6L\left(\frac{5.25'}{2} + \frac{11.75'}{2}\right)$

B14



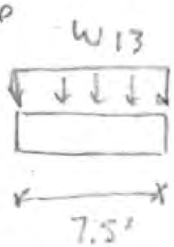
P_3 = G8 reaction

B15



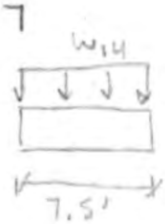
$$w_{12} = 1.2D\left(\frac{8.4'}{2} + \frac{8'}{2}\right) + 1.6L\left(\frac{8.4'}{2} + \frac{8'}{2}\right)$$

B16



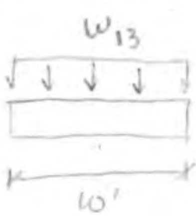
$$w_{13} = 1.2D\left(\frac{8'}{2} + \frac{6'}{2}\right) + 1.6L\left(\frac{8'}{2} + \frac{6'}{2}\right)$$

B17



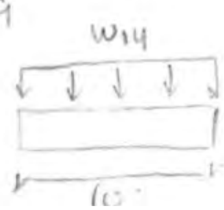
$$w_{14} = 1.2D(6') + 1.6L(6')$$

B18

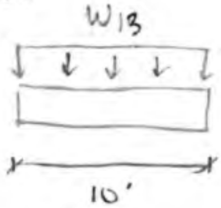


* live load = 150 psf

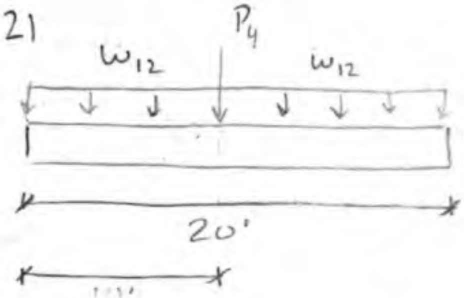
B19



B20



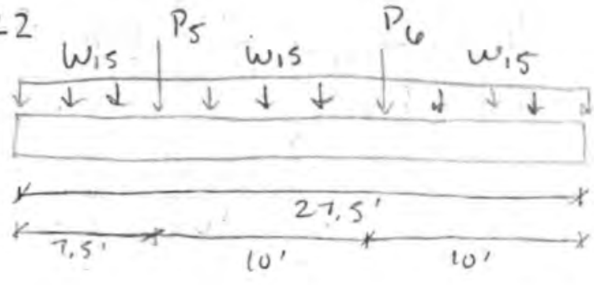
B21



P_4 = G11 reaction

* live load = 150psf

B22

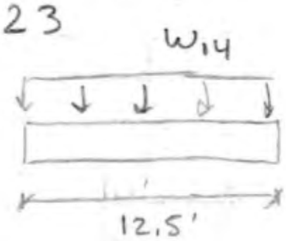


$$w_{15} = 1.2D\left(\frac{8.4'}{2} + \frac{6'}{2}\right) + 1.6L\left(\frac{8.4'}{2} + \frac{6'}{2}\right)$$

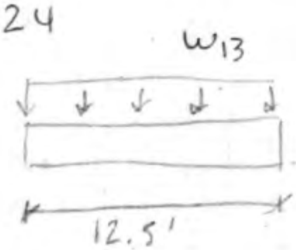
P_5 = G10 reaction

P_6 = G11 reaction

B 23

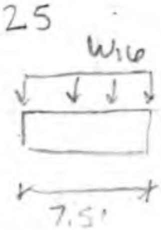


B 24



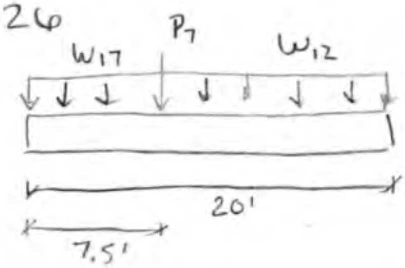
* live load = 180 psf

B 25



$$w_{16} = 1.2D\left(\frac{11.75'}{2} + \frac{8.25'}{2}\right) + 1.6L\left(\frac{11.75'}{2} + \frac{8.25'}{2}\right)$$

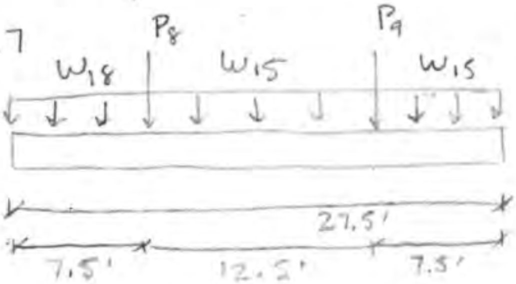
B 26



$$w_{17} = 1.2D\left(\frac{8.25'}{2} + \frac{8.4'}{2}\right) + 1.6L\left(\frac{8.25'}{2} + \frac{8.4'}{2}\right)$$

P_7 = G12 reaction

B 27



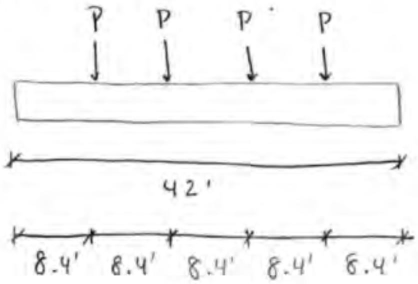
$$w_{18} = 1.2D\left(\frac{11.75'}{2} + \frac{8.4'}{2}\right) + 1.6L\left(\frac{11.75'}{2} + \frac{8.4'}{2}\right)$$

P_8 = G12 reaction

P_9 = G13 reaction

Example Load Cases for Girders (G1-G14)

G1



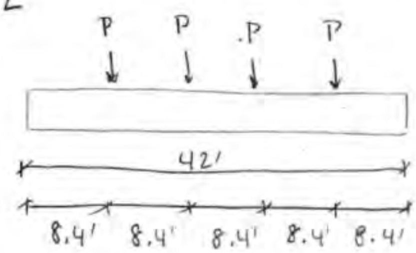
$P_L = L(8.4')(20'/2)$

$P_D = [D(8.4') + w_G + \text{Ext Dead load}]\left(\frac{20'}{2}\right)$

P = B_1 reaction

$M_u = \frac{8.4'P + 8.4'(2)P}{1000} + 1.2\left(\frac{\text{Ext Dead load}(L^2)}{8(1000)}\right)$

G2



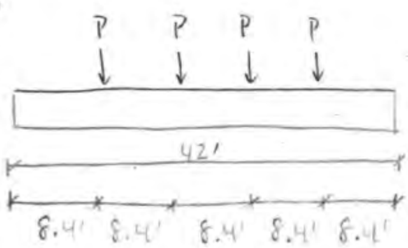
$P_L = L(8.4')\left(\frac{20'}{2} + \frac{27.5'}{2}\right)$

$P_D = [D(8.4') + w_g]\left(\frac{20'}{2} + \frac{27.5'}{2}\right)$

P = $B_1 + B_4$ reaction

$M_u = \frac{8.4'(P) + 8.4'(2)P}{1000}$

G3



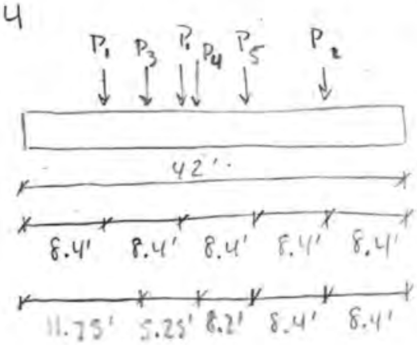
$P_L = L(8.4')(27.5'/2)$

$P_D = [D(8.4') + w_G + \text{Ext Dead load}]\left(\frac{27.5'}{2}\right)$

P = B_4 reaction

$M_u = \frac{8.4'P + 8.4'(2)P}{1000} + 1.2\left(\frac{\text{Ext Dead load}(L^2)}{8(1000)}\right)$

G4



$W_u = (1.2D + 1.6L)\left(\frac{20'}{2} + \frac{7.5'}{2}\right)$

- generalized beam setup

$P_1 = B_1$ reaction

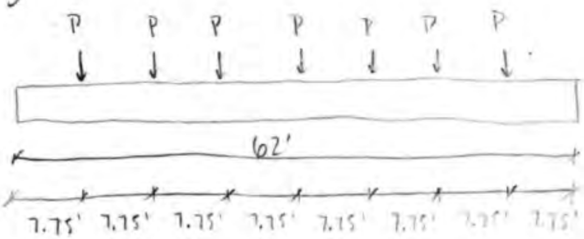
$P_4 = B_7$ reaction

$P_2 = B_1 + B_5$ reaction

$P_5 = B_1 + B_6$ reaction

$P_3 = B_{13}$ reaction

G5



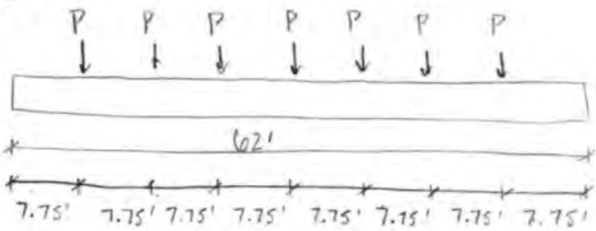
$P_L = L\,(7.75')\,(20'/2)$

$P_D = \left[D\,(7.75') + w_G + \text{Ext Dead load} \right] \left(\frac{20'}{2} \right)$

$P =$ B10 reaction

$$M_U = \frac{P(7.75') + P(7.75')(2) + P(7.75')(3) + P(7.75')(4/2)}{1000} + \frac{1.2\,(\text{Ext Dead load})\,L^2}{8\,(1000)}$$

G6



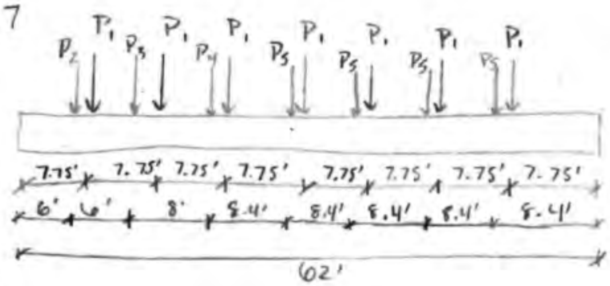
$P_L = L\,(7.75')(24.9')$

$P_D = \left[D\,(7.75') + w_G \right](24.9')$

$P =$ B11 reaction

$$M_U = \frac{P(7.75') + P(7.75')(2) + P(7.75')(3) + P(7.75')(4/2)}{1000}$$

G7



conservative design

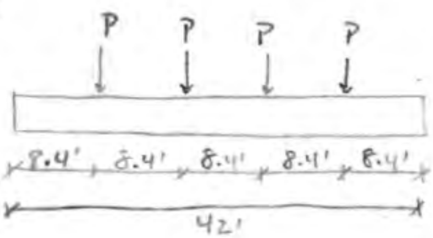
$$W_U = (1.2D + 1.6L)\left(\frac{20'}{2} + \frac{24.9'}{2} \right)$$

$P_1 =$ B11 reaction $\quad P_4 =$ B21 reaction

$P_2 =$ B19 reaction $\quad P_5 =$ B1 reaction

$P_3 =$ B20 reaction

G8



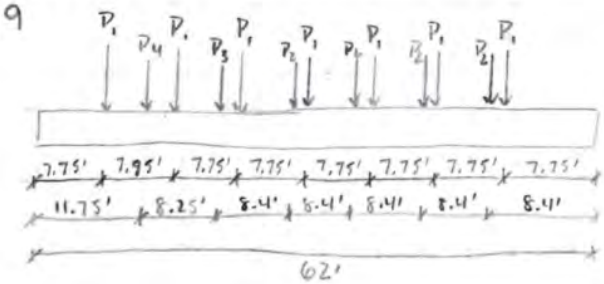
$P_L = L\,(8.4')\left(\frac{20'}{2} + \frac{7.5'}{2} \right)$

$P_D = \left[D\,(8.4') + w_G \right]\left(\frac{20'}{2} + \frac{7.5'}{2} \right)$

$P =$ B1 + B5 reaction

$$M_U = \frac{8.4'P + 8.4'P(2)}{1000}$$

G9



conservative design

$$W_u = (1.2D + 1.6L)\left(\frac{20'}{2} + \frac{24.9'}{2}\right)$$

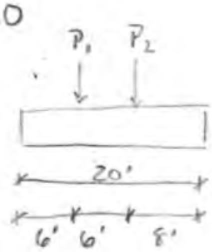
P_1 = B11 reaction

P_2 = B7 reaction

P_3 = B26 reaction

P_4 = B25 reaction

G10

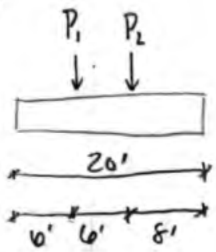


Δ_8 = AISC Table 3-23 case 8 @ P_1 only, P_2 only, P_1 only at center, P_2 only at center

P_1 = B17 + B19 reaction

P_2 = B16 + B18 reaction

G11

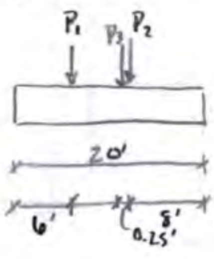


Δ_8 = to that for G10

P_1 = B19 (2) reaction

P_2 = B18 + B20 reaction

G12



Δ_8 = to that for G10

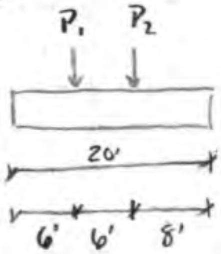
P_1 = B23 reaction

P_2 = B24 reaction

P_3 = B25 reaction

] assume located at same point

G13

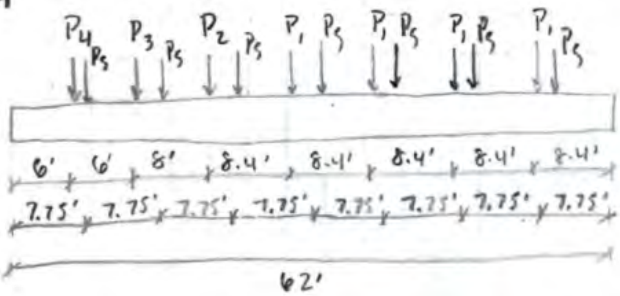


Δ_{ℓ} = to that for G10

P_1 = B23 + B17 reactions

P_2 = B24 + B16 reactions

G14



$W_u = (1.2D + 1.6L)\left(\frac{20'}{2} + \frac{7.5'}{2}\right)$

P_1 = B5 reaction

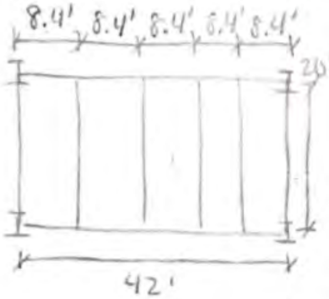
P_2 = B15 reaction

P_3 = B16 reaction

P_4 = B17 reaction

P_5 = B10 reaction

Appendix D. - Beam and Girder Hand Calculations (Scheme 1)



$LL = 100\,psf$

$DL = 75\,psf$] $85\,psf$

$DL = 10\,psf$

$F_y = 50\,ksi$

$\phi = 0.9 \qquad E = 29000\,ksi$

<u>Beam</u>

$$w_u = 1.2D + 1.6L = 1.2(85\,psf)(8.4') + 1.6(100\,psf)(8.4')$$
$$= 2200.8\ lb/ft$$

$$\Sigma M_{P_1} = 2200.8\,lb/ft\,(20')(20'/2) - P_2(20')$$
$$P_2 = P_1 = 22008\ lb$$

$$M_u = \frac{w_u L^2}{8} = \frac{2200.8\,lb/ft\,(20')^2}{8}\left|\frac{1k}{1000\,lb}\right. = 110.04\,'k$$

$$Z_x \geq \frac{M_u}{\phi F_y} = \frac{110.04\,'k}{0.9(50\,ksi)}\left|\frac{12\,in}{ft}\right. = 29.344\,in^3$$

trial beam: W14 x 22 $\quad Z_x = 33.2\,in^3 \quad I_x = 199$

$$w_u = 2200.8\ lb/ft + 1.2(22\,lb/ft) = 2227.2\ lb/ft$$

$$M_u = \frac{2227.2\,lb/ft\,(20')^2}{8}\left|\frac{1k}{1000\,lb}\right. = 111.36\,'k$$

$$Z_x \geq \frac{111.36\,'k}{0.9(50\,ksi)}\left|\frac{12\,in}{1\,ft}\right. = 29.696\,in^3 \leq 33.2\,in^3\ \checkmark$$

$$w_L = 100\,psf\,(8.4')\left|\frac{1k}{1000\,lb}\right. = 0.84\,k/ft$$

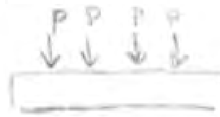
$$\Delta_L = \frac{5 w_L L^4}{384 E I_x} \leq \frac{L}{360} = \frac{20'}{360}\left|\frac{12\,in}{1\,ft}\right. = 0.667\,in$$

$$\Delta_L = \frac{5(0.84\,k/ft)(20')^4}{384(29000\,ksi)(199\,in^4)}\left|\frac{12^3\,in^3}{1\,ft^3}\right. = 0.524\,in \leq 0.667\,in\ \checkmark$$

$w_{D+L} = (85\,psf + 100\,psf)(8.4') \left| \frac{1k}{1000\,lb} \right. = 1.554\ k/ft$

$\Delta_{D+L} = \frac{5 w_{D+L} L^4}{384 E I_x} \leq L/240 = \frac{20'}{240} \left| \frac{12\,in}{1\,ft} \right. = 1\,in$

$\Delta_{D+L} = \frac{5(1.554\ k/ft)(20)^4}{384(29000\,ksi)(1199\,in^4)} \left| \frac{12^3 in^3}{1\,ft^3} \right. = 0.969\,in < 1\,in\ \checkmark$

External Girder  @ 8.4' Spacing

$M_u = 8.4'(P) + 8.4'(2)(P) = 25.2'P = 25.2'(22008\,lb)$
$= 554601.6'lb \left| \frac{1k}{1000\,lb} \right. = 554.6016'k$

$Z_x \geq \frac{554.6016'k}{0.9(50\,ksi)} \left| \frac{12\,in}{ft} \right. = 147.89\,in^3$

trial girder: W24x62 $Z_x = 153\,in^3$ $I_x = 1550\,in^4$
$w_u = 1.2(62\,lb/ft) = 74.4\,lb/ft$

$M_u = 554.6016'k + \frac{74.4\,lb/ft\,(42')^2}{8} \left| \frac{1k}{1000\,lb} \right. = 571.0068'k$

$Z_x \geq \frac{571.0068'k}{0.9(50\,ksi)} \left| \frac{12\,in}{1\,ft} \right. = 152.27\,in^3 < 153\,in^3\ \checkmark$

$w_L = 100\,psf\,(42'/5) = 840\ lb/ft$

$P_L = 840\,lb/ft\,(20'/2) = 8400\ lb$

$w_D = 85\,psf\,(42'/5) + 62\,lb/ft = 776\ lb/ft$

$P_{D+L} = 8400\,lb + 776\,lb/ft\,(20'/2) = 16160\ lb$

$\Delta_L = \frac{P_L(L/5)}{24EI}(3L^2 - 4(L/5)^2) + \frac{P_L(2L/5)}{24EI}(3L^2 - 4(2L/5)^2)$

$= \frac{P_L(L/5)}{24EI}\left(3L^2 - 4(L/5)^2 + 2(3L^2 - 4(2L/5)^2)\right)$

$= \frac{P_L(L/5)}{24EI}(3L^2 - 4(L/5)^2 + 6L^2 - 8(2L/5)^2)$

$$\Delta_L = \frac{P_L(L/5)}{24EI}\left(9L^2 - 4(L/5)^2 - 8(2L/5)^2\right) \leq \frac{L}{360} = \frac{42'}{360}\left|\frac{12\text{ in}}{\text{ft}}\right.$$

$$\Delta_L = \frac{8400\text{ lb}(42'/5)}{24(24000\text{ ksi})(1550\text{ in}^4)}\left(9(42')^2 - 4(42'/5)^2 - 8(2(42')/5)^2\right)$$

$$\Delta_L = 0.8722\,\frac{\text{lb ft ft}^2}{\text{ksi in}^4}\left|\frac{1\text{k}}{1000\text{ lb}}\right|\frac{12^3\text{ in}^3}{1\text{ ft}^3} = 1.51\text{ in} \leq 1.4\text{ in} \;\text{X}$$

$$\Delta_L = 1.51\text{ in}(1550\text{ in}^4) \leq 1.4\text{ in}\,(I_x)$$

$$1668.72\text{ in}^4 = I_x$$

new trial girder: W24 x 68 $\quad I_x = 1830\text{ in}^4 \quad Z_x = 177\text{ in}^3$

$$w_u = 1.2(68\text{ lb/ft}) = 81.6\text{ lb/ft}$$

$$M_u = 554.6016'\text{k} + \frac{81.6\text{ lb/ft}(42')^2}{8}\left|\frac{1\text{k}}{1000\text{ lb}}\right. = 572.5944'\text{k}$$

$$Z_x \geq \frac{572.5944'\text{k}}{0.9(50\text{ ksi})}\left|\frac{12\text{ in}}{\text{ft}}\right. = 152.69\text{ in}^3 \leq 177\text{ in}^3 \checkmark$$

$$w_D = 85\text{ psf}(42'/5) + 68\text{ lb/ft} = 782\text{ lb/ft}$$

$$P_{D+L} = 8400\text{ lb} + 782\text{ lb/ft}(20'/2) = 16220\text{ lb}$$

$$\Delta_L = \frac{8400\text{ lb}(42'/5)}{24(24000\text{ ksi})(1830\text{ in}^4)}\left(9(42')^2 - 4(42'/5)^2 - 8(2(42')/5)^2\right)$$

$$\Delta_L = 0.738\,\frac{\text{lb ft}^3}{\text{ksi in}^4}\left|\frac{1\text{k}}{1000\text{ lb}}\right|\frac{12^3\text{ in}^3}{\text{ft}^3} = 1.276\text{ in} < 1.4\text{ in} \checkmark$$

$$\Delta_{D+L} = \frac{16220\text{ lb}(42'/5)}{24(24000\text{ ksi})(1830\text{ in}^4)}\left(9(42')^2 - 4(42'/5)^2 - 8(2(42')/5)^2\right)$$

$$\Delta_{D+L} = 1.42\,\frac{\text{lb ft}^3}{\text{ksi in}^4}\left|\frac{12^3\text{ in}^3}{\text{ft}^3}\right|\frac{1\text{k}}{1000\text{ lb}} = 2.465\text{ in} \leq \frac{L}{240} = \frac{42'}{240}\left|\frac{12\text{ in}}{\text{ft}}\right. = 2.1\text{ in} \;\text{X}$$

$\Delta_{D+L} = 2.465\text{ in } (1830\text{ in}^4) \le 2.1\text{ in } I_x$

$2148\text{ in}^4 = I_x$

new trial girder: W27X84 $I_x = 2850\text{ in}^4$ $Z_x = 244\text{ in}^3$

$W_u = 1.2(84\text{ lb/ft}) = 100.8\text{ lb/ft}$

$M_u = 554.6016'^{k} + \frac{100.8\text{ lb/ft}(42')^2}{8} \left| \frac{1k}{1000\text{ lb}} \right. = 576.828'^{k}$

$Z_x \ge \frac{576.828'^{k}}{0.9(50\text{ ksi})} \left| \frac{12\text{ in}}{1\text{ ft}} \right. = 153.8208 \le 244\text{ in}^3$ ✓

$W_D = 85\text{ psf}(42'/5) + 84\text{ lb/ft} = 798\text{ lb/ft}$

$P_{D+L} = 8400\text{ lb} + 798\text{ lb/ft}(20'/2) = 16380\text{ lb}$

$\Delta_L = \frac{8400\text{ lb}(42'/5)}{24(29000\text{ ksi})(2850\text{ in}^4)} (9(42')^2 - 4(42'/5)^2 - 8(2(42'/5))^2) \left| \frac{k}{1000\text{ lb}} \right| \frac{12^3\text{ in}^3}{\text{ft}^3}$

$\Delta_L = 0.819\text{ in} < 1.4\text{ in}$ ✓

$\Delta_{D+L} = \frac{16380\text{ lb}(42'/5)}{24(29000\text{ ksi})(2850\text{ in}^4)} (9(42')^2 - 4(42'/5)^2 - 8(2(42'/5))^2)$

$\Delta_{D+L} = 0.925 \frac{\text{lb ft}^3}{\text{ksi in}^4} \left| \frac{1k}{1000\text{ lb}} \right| \frac{12^3\text{ in}^3}{\text{ft}^3} = 1.598\text{ in} < 2.1\text{ in}$ ✓

Appendix E. - Beam and Girder Excel Calculations

B1							
Initial Beam Design			**Trial Beam Check**			**Deflection Calcs**	
Dead Load (psf)	85		Beam unit weight (lb/ft)	22		wL (k/ft)	0.84
Live Load (psf)	100		Wu (lb/ft)	2227.2		ΔL (in)	0.524
Beam spacing (ft)	8.4		Length of beam (ft)	20		L/360 (in)	0.67
Wu (lb/ft)	2200.8		Mu (ft k)	111.36		Design Sufficient?	yes
Pu (lb)	22008		Φ	0.9			
Length of beam (ft)	20		Fy (ksi)	50		wD+L (k/ft)	1.55
Mu (ft k)	110.04		Zx (in^3)	29.696		ΔD+L (in)	0.969
Φ	0.9		Design Sufficient?	yes		L/240 (in)	1.00
Fy (ksi)	50					Design Sufficient?	yes
Zx (in^3)	29.344						
trial beam	W14x22						
trial Zx (in^3)	33.2						
E (ksi)	29000						
Ix (in^4)	199						

B2							
Initial Beam Design			**Trial Beam Check**			**Deflection Calcs**	
Floor height (ft)	10.5		Beam unit weight (lb/ft)	19		wL (k/ft)	0.42
4" Brick cladding (psf)	40		Wu (lb/ft)	1627.2		ΔL (in)	0.541
Exterior Deadload (lb/ft)	420		Length of beam (ft)	20		L/360 (in)	0.67
Dead Load (psf)	85		Mu (ft k)	81.36		Design Sufficient?	yes
Live Load (psf)	100		Φ	0.9			
Beam spacing (ft)	8.4		Fy (ksi)	50		wD+L (k/ft)	1.20
Wu (lb/ft)	1604.4		Zx (in^3)	21.696		ΔD+L (in)	1.543
Pu (lb)	16044		Design Sufficient?	no		L/240 (in)	1.00
Length of beam (ft)	20					Design Sufficient?	no
Mu (ft k)	80.22						
Φ	0.9						
Fy (ksi)	50						
Zx (in^3)	21.392						
trial beam	W10x19						
trial Zx (in^3)	21.6						
E (ksi)	29000						
Ix (in^4)	96.3						

B2 (continued)							
New Beam Design			**Trial Beam Check**			**Deflection Calcs**	
new trial beam	W12x19		Beam unit weight (lb/ft)	19		wL (k/ft)	0.42
new trial Zx (in^3) min	24.7		Wu (lb/ft)	1627.2		ΔL (in)	0.401
new Ix (in^4)	130		Length of beam (ft)	20		L/360 (in)	0.67
			Mu (ft k)	81.36		Design Sufficient?	yes
			Φ	0.9			
			Fy (ksi)	50		wD+L (k/ft)	1.20
			Zx (in^3)	21.696		ΔD+L (in)	1.143
			Design Sufficient?	yes		L/240 (in)	1.00
						Design Sufficient?	no
New Beam Design			**Trial Beam Check**			**Deflection Calcs**	
Ix (in^4) min	148.593103		Beam unit weight (lb/ft)	22		wL (k/ft)	0.42
new trial beam	W12x22		Wu (lb/ft)	1630.8		ΔL (in)	0.334
new trial Zx (in^3) min	29.3		Length of beam (ft)	20		L/360 (in)	0.67
new Ix (in^4)	156		Mu (ft k)	81.54		Design Sufficient?	yes
			Φ	0.9			
			Fy (ksi)	50		wD+L (k/ft)	1.20
			Zx (in^3)	21.744		ΔD+L (in)	0.953
			Design Sufficient?	yes		L/240 (in)	1.00
						Design Sufficient?	yes

B3							
Initial Beam Design			**Trial Beam Check**			**Deflection Calcs**	
Dead Load (psf)	85		Beam unit weight (lb/ft)	22		wL (k/ft)	0.8075
Live Load (psf)	100		Wu (lb/ft)	2142.05		ΔL (in)	0.643
Beam spacing (ft)	N/A		Length of beam (ft)	20		L/360 (in)	0.67
Wu (lb/ft)	2115.65		Mu (ft k)	107.1025		Design Sufficient?	yes
Pu (lb)	21156.5		Φ	0.9			
Length of beam (ft)	20		Fy (ksi)	50		wD+L (k/ft)	1.49
Mu (ft k)	105.7825		Zx (in^3)	28.5606666		ΔD+L (in)	1.189
Φ	0.9		Design Sufficient?	yes		L/240 (in)	1.00
Fy (ksi)	50					Design Sufficient?	no
Zx (in^3)	28.2086666						
trial beam	W12x22						
trial Zx (in^3)	29.3						
E (ksi)	29000						
Ix (in^4)	156						

B3 (continued)							
New Beam Design			**Trial Beam Check**			**Deflection Calcs**	
Ix (in^4) min	185.4465517		Beam unit weight (lb/ft)	22		wL (k/ft)	0.8075
new trial beam	W14x22		Wu (lb/ft)	2142.05		ΔL (in)	0.504
new trial Zx (in^3) min	33.2		Length of beam (ft)	20		L/360 (in)	0.67
new Ix (in^4)	199		Mu (ft k)	107.1025		Design Sufficient?	yes
			Φ	0.9			
			Fy (ksi)	50		wD+L (k/ft)	1.49
			Zx (in^3)	28.56066667		ΔD+L (in)	0.932
			Design Sufficient?	yes		L/240 (in)	1.00
						Design Sufficient?	yes

B4							
Initial Beam Design			**Trial Beam Check**			**Beam Deflection Calcs**	
Dead Load (psf)	85		Beam unit weight (lb/ft)	35		wL (k/ft)	0.84
Live Load (psf)	100		Wu (lb/ft)	2242.8		ΔL (in)	0.731
Beam spacing (ft)	8.4		Length of beam (ft)	27.5		L/360 (in) max	0.92
Wu (lb/ft)	2200.8		Mu (ft k)	212.0146875		Design Sufficient?	yes
Pu (lb)	30261		Φ	0.9			
Length of beam (ft)	27.5		Fy (ksi)	50		wD+L (k/ft)	1.55
Mu (ft k)	208.044375		Zx (in^3)	56.53725		ΔD+L (in)	1.352
Φ	0.9		Design Sufficient?	yes		L/240 (in) max	1.38
Fy (ksi)	50					Design Sufficient?	yes
Zx (in^3)	55.4785						
trial beam	W18x35						
trial Zx (in^3) min	66.5						
E (ksi)	29000						
Ix (in^4)	510						

B5							
Initial Beam Design			**Trial Beam Check**			**Deflection Calcs**	
Dead Load (psf)	85		Beam unit weight (lb/ft)	10		wL (k/ft)	0.84
Live Load (psf)	100		Wu (lb/ft)	2212.8		ΔL (in)	0.067
Beam spacing (ft)	8.4		Length of beam (ft)	7.5		L/360 (in)	0.25
Wu (lb/ft)	2200.8		Mu (ft k)	15.55875		Design Sufficient?	yes
Pu (lb)	8253		Φ	0.9			
Length of beam (ft)	7.5		Fy (ksi)	50		wD+L (k/ft)	1.55
Mu (ft k)	15.474375		Zx (in^3)	4.149		ΔD+L (in)	0.124
Φ	0.9		Design Sufficient?	yes		L/240 (in)	0.38
Fy (ksi)	50					Design Sufficient?	yes
Zx (in^3)	4.1265						
trial beam	W8x10						
trial Zx (in^3)	8.87						
E (ksi)	29000						
Ix (in^4)	30.8						

B6							
Initial Beam Design			**Trial Beam Check**			**Deflection Calcs**	
Dead Load (psf)	85		Beam unit weight (lb/ft)	10		wL (k/ft)	0.83
Live Load (psf)	100		Wu (lb/ft)	2186.6		ΔL (in)	0.066
Beam spacing (ft)	8.3		Length of beam (ft)	7.5		L/360 (in)	0.25
Wu (lb/ft)	2174.6		Mu (ft k)	15.37453125		Design Sufficient?	yes
Pu (lb)	8154.75		Φ	0.9			
Length of beam (ft)	7.5		Fy (ksi)	50		wD+L (k/ft)	1.54
Mu (ft k)	15.29015625		Zx (in^3)	4.099875		ΔD+L (in)	0.122
Φ	0.9		Design Sufficient?	yes		L/240 (in)	0.38
Fy (ksi)	50					Design Sufficient?	yes
Zx (in^3)	4.077375						
trial beam	W8x10						
trial Zx (in^3)	8.87						
E (ksi)	29000						
Ix (in^4)	30.8						

B7					
Initial Beam Design		**Trial Beam Check**		**Deflection Calcs**	
Dead Load (psf)	85	Beam unit weight (lb/ft)	10	wL (k/ft)	1.5474375
Live Load (psf)	100	Wu (lb/ft)	1980.275	ΔL (in)	0.123
Beam spacing (ft)	6.825	Length of beam (ft)	7.5	L/360 (in)	0.25
Wu (lb/ft)	1968.275	Mu (ft k)	13.92380859	Design Sufficient?	yes
Pu (lb)	7381.03125	Φ	0.9		
Length of beam (ft)	7.5	Fy (ksi)	50	wD+L (k/ft)	1.26
Mu (ft k)	13.83943359	Zx (in^3)	3.713015625	ΔD+L (in)	0.101
Φ	0.9	Design Sufficient?	yes	L/240 (in)	0.38
Fy (ksi)	50			Design Sufficient?	yes
Zx (in^3)	3.690515625				
trial beam	W8x10				
trial Zx (in^3)	8.87				
E (ksi)	29000				
Ix (in^4)	30.8				

B8					
Initial Beam Design		**Trial Beam Check**		**Deflection Calcs**	
Floor height (ft)	10.5	Beam unit weight (lb/ft)	26	wL (k/ft)	0.42
4" Brick cladding (psf)	40	Wu (lb/ft)	1635.6	ΔL (in)	0.619
Exterior Deadload (lb/ft)	420	Length of beam (ft)	27.5	L/360 (in)	0.92
Dead Load (psf)	85	Mu (ft k)	154.6153125	Design Sufficient?	yes
Live Load (psf)	100	Φ	0.9		
Beam spacing (ft)	8.4	Fy (ksi)	50	wD+L (k/ft)	1.20
Wu (lb/ft)	1604.4	Zx (in^3)	41.23075	ΔD+L (in)	1.765
Pu (lb)	22060.5	Design Sufficient?	yes	L/240 (in)	1.38
Length of beam (ft)	27.5			Design Sufficient?	no
Mu (ft k)	151.6659375				
Φ	0.9				
Fy (ksi)	50				
Zx (in^3)	40.44425				
trial beam	W16x26				
trial Zx (in^3)	44.2				
E (ksi)	29000				
Ix (in^4)	301				

B8 (continued)							
New Beam Design			**Trial Beam Check**			**Deflection Calcs**	
Min Ix (in^4)	386.2840248		Beam unit weight (lb/ft)	35		wL (k/ft)	0.42
new trial beam	W18x35		Wu (lb/ft)	1646.4		ΔL (in)	0.365
new trial Zx (in^3) min	66.5		Length of beam (ft)	27.5		L/360 (in)	0.92
new Ix (in^4)	510		Mu (ft k)	155.63625		Design Sufficient?	yes
			Φ	0.9			
			Fy (ksi)	50		wD+L (k/ft)	1.20
			Zx (in^3)	41.503		ΔD+L (in)	1.041
			Design Sufficient?	yes		L/240 (in)	1.38
						Design Sufficient?	yes

B9							
Initial Beam Design			**Trial Beam Check**			**Deflection Calcs**	
Dead Load (psf)	85		Beam unit weight (lb/ft)	68		wL (k/ft)	0.84
Live Load (psf)	100		Wu (lb/ft)	2282.4		ΔL (in)	0.460
Beam spacing (ft)	8.4		Length of beam (ft)	27.5		L/360 (in)	0.92
Wu (lb/ft)	2200.8		Mu (ft k)	628.408125		Design Sufficient?	yes
Pu (lb)	30261		Φ	0.9			
Length of beam (ft)	27.5		Fy (ksi)	50		wD+L (k/ft)	1.53
Mu (ft k)	620.694375		Zx (in^3)	167.5755		ΔD+L (in)	0.844
Φ	0.9		Design Sufficient?	yes		L/240 (in)	1.38
Fy (ksi)	50					Design Sufficient?	yes
Zx (in^3)	165.5185						
trial beam	W24x68						
trial Zx (in^3)	177						
E (ksi)	29000						
Ix (in^4)	1830						

B10							
Initial Beam Design			**Trial Beam Check**			**Deflection Calcs**	
Dead Load (psf)	85		Beam unit weight (lb/ft)	22		wL (k/ft)	0.775
Live Load (psf)	100		Wu (lb/ft)	2056.9		ΔL (in)	0.617
Beam spacing (ft)	7.75		Length of beam (ft)	20		L/360 (in)	0.67
Wu (lb/ft)	2030.5		Mu (ft k)	102.845		Design Sufficient?	yes
Pu (lb)	20305		Φ	0.9			
Length of beam (ft)	20		Fy (ksi)	50		wD+L (k/ft)	1.43
Mu (ft k)	101.525		Zx (in^3)	27.42533333		ΔD+L (in)	1.141
Φ	0.9		Design Sufficient?	yes		L/240 (in)	1.00
Fy (ksi)	50					Design Sufficient?	no
Zx (in^3)	27.07333333						
trial beam	W12x22						
trial Zx (in^3)	29.3						
E (ksi)	29000						
Ix (in^4)	156						
New Beam Design			**Trial Beam Check**			**Deflection Calcs**	
Ix (in^4) min	177.9827586		Beam unit weight (lb/ft)	22		wL (k/ft)	0.775
new trial beam	W14x22		Wu (lb/ft)	2056.9		ΔL (in)	0.483
new trial Zx (in^3) min	33.2		Length of beam (ft)	20		L/360 (in)	0.67
new Ix (in^4)	199		Mu (ft k)	102.845		Design Sufficient?	yes
			Φ	0.9			
			Fy (ksi)	50		wD+L (k/ft)	1.43
			Zx (in^3)	27.42533333		ΔD+L (in)	0.894
			Design Sufficient?	yes		L/240 (in)	1.00
						Design Sufficient?	yes

B11							
Initial Beam Design			**Trial Beam Check**			**Deflection Calcs**	
Dead Load (psf)	85		Beam unit weight (lb/ft)	26		wL (k/ft)	0.775
Live Load (psf)	100		Wu (lb/ft)	2061.7		ΔL (in)	0.768
Beam spacing (ft)	7.75		Length of beam (ft)	24.9		L/360 (in)	0.83
Wu (lb/ft)	2030.5		Mu (ft k)	159.78432 71		Design Sufficient?	yes
Pu (lb)	25279.725		Φ	0.9			
Length of beam (ft)	24.9		Fy (ksi)	50		wD+L (k/ft)	1.43
Mu (ft k)	157.36628 81		Zx (in^3)	42.609153 9		ΔD+L (in)	1.421
Φ	0.9		Design Sufficient?	yes		L/240 (in)	1.25
Fy (ksi)	50					Design Sufficient?	no
Zx (in^3)	41.964343 5						
trial beam	W16x26						
trial Zx (in^3)	44.2						
E (ksi)	29000						
Ix (in^4)	301						
New Beam Design			**Trial Beam Check**			**Deflection Calcs**	
Ix (in^4) min	343.46776 82		Beam unit weight (lb/ft)	31		wL (k/ft)	0.775
new trial beam	W16x31		Wu (lb/ft)	2067.7		ΔL (in)	0.616
new trial Zx (in^3) min	54		Length of beam (ft)	24.9		L/360 (in)	0.83
new Ix (in^4)	375		Mu (ft k)	160.24933 46		Design Sufficient?	yes
			Φ	0.9			
			Fy (ksi)	50		wD+L (k/ft)	1.43
			Zx (in^3)	42.733155 9		ΔD+L (in)	1.140
			Design Sufficient?	yes		L/240 (in)	1.25
						Design Sufficient?	yes

B12							
Initial Beam Design			**Trial Beam Check**			**Deflection Calcs**	
Floor height (ft)	10.5		Beam unit weight (lb/ft)	14		wL (k/ft)	0.3875
4" Brick cladding (psf)	40		Wu (lb/ft)	1536.05		ΔL (in)	0.581
Exterior Deadload (lb/ft)	420		Length of beam (ft)	24.9		L/360 (in)	0.83
Dead Load (psf)	85		Mu (ft k)	119.0457951		Design Sufficient?	yes
Live Load (psf)	100		Φ	0.9			
Beam spacing (ft)	7.75		Fy (ksi)	50		wD+L (k/ft)	1.14
Wu (lb/ft)	1519.25		Zx (in^3)	31.74554535		ΔD+L (in)	1.704
Pu (lb)	18914.6625		Design Sufficient?	yes		L/240 (in)	1.25
Length of beam (ft)	24.9					Design Sufficient?	no
Mu (ft k)	117.7437741						
Φ	0.9						
Fy (ksi)	50						
Zx (in^3)	31.39833975						
trial beam	W12x14						
trial Zx (in^3)	33.2						
E (ksi)	29000						
Ix (in^4)	199						
New Beam Design			**Trial Beam Check**			**Deflection Calcs**	
Ix (in^4) min	272.3486793		Beam unit weight (lb/ft)	26		wL (k/ft)	0.3875
new trial beam	W16x26		Wu (lb/ft)	1550.45		ΔL (in)	0.384
new trial Zx (in^3) min	44.2		Length of beam (ft)	24.9		L/360 (in)	0.83
new Ix (in^4)	301		Mu (ft k)	120.1618131		Design Sufficient?	yes
			Φ	0.9			
			Fy (ksi)	50		wD+L (k/ft)	1.14
			Zx (in^3)	32.04315015		ΔD+L (in)	1.126
			Design Sufficient?	yes		L/240 (in)	1.25
						Design Sufficient?	yes

B13

Initial Beam Design			Trial Beam Check			Deflection Calcs	
Dead Load (psf)	85		Beam unit weight (lb/ft)	10		wL (k/ft)	0.825
Live Load (psf)	100		Wu (lb/ft)	2166.95		ΔL (in)	0.066
Beam spacing (ft)	8.25		Length of beam (ft)	7.5		L/360 (in)	0.25
Wu (lb/ft)	2154.95		Mu (ft k)	15.23636719		Design Sufficient?	yes
Pu (lb)	8081.0625		Φ	0.9			
Length of beam (ft)	7.5		Fy (ksi)	50		wD+L (k/ft)	1.53
Mu (ft k)	15.15199219		Zx (in^3)	4.06303125		ΔD+L (in)	0.122
Φ	0.9		Design Sufficient?	yes		L/240 (in)	0.38
Fy (ksi)	50					Design Sufficient?	yes
Zx (in^3)	4.04053125						
trial beam	W8x10						
trial Zx (in^3)	8.87						
E (ksi)	29000						
Ix (in^4)	30.8						

B14

Initial Beam Design			Trial Beam Check			Deflection Calcs	
Dead Load (psf)	85		Beam unit weight (lb/ft)	90		wL (k/ft)	0.84
Live Load (psf)	100		Wu (lb/ft)	2308.8		ΔL (in)	0.337
Beam spacing (ft)	8.4		Length of beam (ft)	27.5		L/360 (in)	0.92
Wu (lb/ft)	2200.8		Mu (ft k)	961.02375		Design Sufficient?	yes
Pu (lb)	30261		Φ	0.9			
Length of beam (ft)	27.5		Fy (ksi)	50		wD+L (k/ft)	1.55
Mu (ft k)	950.814375		Zx (in^3)	256.273		ΔD+L (in)	0.494
Φ	0.9		Design Sufficient?	yes		L/240 (in)	1.38
Fy (ksi)	50					Design Sufficient?	yes
Zx (in^3)	253.5505						
trial beam	W30x90						
trial Zx (in^3)	283						
E (ksi)	29000						
Ix (in^4)	3610						

B15							
Initial Beam Design			**Trial Beam Check**			**Deflection Calcs**	
Dead Load (psf)	85		Beam unit weight (lb/ft)	10		wL (k/ft)	0.82
Live Load (psf)	100		Wu (lb/ft)	2160.4		ΔL (in)	0.065
Beam spacing (ft)	8.2		Length of beam (ft)	7.5		L/360 (in)	0.25
Wu (lb/ft)	2148.4		Mu (ft k)	15.1903125		Design Sufficient?	yes
Pu (lb)	8056.5		Φ	0.9		[redacted]	
Length of beam (ft)	7.5		Fy (ksi)	50		wD+L (k/ft)	1.52
Mu (ft k)	15.1059375		Zx (in^3)	4.05075		ΔD+L (in)	0.121
Φ	0.9		Design Sufficient?	yes		L/240 (in)	0.38
Fy (ksi)	50					Design Sufficient?	yes
Zx (in^3)	4.02825						
trial beam	W8x10						
trial Zx (in^3)	8.87						
E (ksi)	29000						
Ix (in^4)	30.8						

B16							
Initial Beam Design			**Trial Beam Check**			**Deflection Calcs**	
Dead Load (psf)	85		Beam unit weight (lb/ft)	10		wL (k/ft)	0.7
Live Load (psf)	100		Wu (lb/ft)	1846		ΔL (in)	0.056
Beam spacing (ft)	7		Length of beam (ft)	7.5		L/360 (in)	0.25
Wu (lb/ft)	1834		Mu (ft k)	12.9796875		Design Sufficient?	yes
Pu (lb)	6877.5		Φ	0.9		[redacted]	
Length of beam (ft)	7.5		Fy (ksi)	50		wD+L (k/ft)	1.30
Mu (ft k)	12.8953125		Zx (in^3)	3.46125		ΔD+L (in)	0.103
Φ	0.9		Design Sufficient?	yes		L/240 (in)	0.38
Fy (ksi)	50					Design Sufficient?	yes
Zx (in^3)	3.43875						
trial beam	W8x10						
trial Zx (in^3)	8.87						
E (ksi)	29000						
Ix (in^4)	30.8						
P End reaction live unfactored (lb)	2625						
P End reaction live/dead unfactored (lb)	4856.25						

B17							
Initial Beam Design			**Trial Beam Check**			**Deflection Calcs**	
Dead Load (psf)	85		Beam unit weight (lb/ft)	10		wL (k/ft)	0.6
Live Load (psf)	100		Wu (lb/ft)	1584		ΔL (in)	0.048
Beam spacing (ft)	6		Length of beam (ft)	7.5		L/360 (in)	0.25
Wu (lb/ft)	1572		Mu (ft k)	11.1375		Design Sufficient?	yes
Pu (lb)	5895		Φ	0.9			
Length of beam (ft)	7.5		Fy (ksi)	50		wD+L (k/ft)	1.11
Mu (ft k)	11.053125		Zx (in^3)	2.97		ΔD+L (in)	0.088
Φ	0.9		Design Sufficient?	yes		L/240 (in)	0.38
Fy (ksi)	50					Design Sufficient?	yes
Zx (in^3)	2.9475						
trial beam	W8x10						
trial Zx (in^3)	8.87						
E (ksi)	29000						
Ix (in^4)	30.8						
P End reaction live unfactored (lb)	2250						
P End reaction live/dead unfactored (lb)	4162.5						

B18							
Initial Beam Design			**Trial Beam Check**			**Deflection Calcs**	
Dead Load (psf)	85		Beam unit weight (lb/ft)	10		wL (k/ft)	1.05
Live Load (psf)	150		Wu (lb/ft)	2406		ΔL (in)	0.264
Beam spacing (ft)	7		Length of beam (ft)	10		L/360 (in)	0.33
Wu (lb/ft)	2394		Mu (ft k)	30.075		Design Sufficient?	yes
Pu (lb)	11970		Φ	0.9			
Length of beam (ft)	10		Fy (ksi)	50		wD+L (k/ft)	1.65
Mu (ft k)	29.925		Zx (in^3)	8.02		ΔD+L (in)	0.414
Φ	0.9		Design Sufficient?	yes		L/240 (in)	0.50
Fy (ksi)	50					Design Sufficient?	yes
Zx (in^3)	7.98						
trial beam	W8x10						
trial Zx (in^3)	8.87						
E (ksi)	29000						
Ix (in^4)	30.8						
P End reaction live unfactored (lb)	5250						
P End reaction live/dead unfactored (lb)	8225						

B19							
Initial Beam Design			**Trial Beam Check**			**Deflection Calcs**	
Dead Load (psf)	85		Beam unit weight (lb/ft)	10		wL (k/ft)	0.6
Live Load (psf)	100		Wu (lb/ft)	1584		ΔL (in)	0.151
Beam spacing (ft)	6		Length of beam (ft)	10		L/360 (in)	0.33
Wu (lb/ft)	1572		Mu (ft k)	19.8		Design Sufficient?	yes
Pu (lb)	7860		Φ	0.9			
Length of beam (ft)	10		Fy (ksi)	50		wD+L (k/ft)	1.11
Mu (ft k)	19.65		Zx (in^3)	5.28		ΔD+L (in)	0.280
Φ	0.9		Design Sufficient?	yes		L/240 (in)	0.50
Fy (ksi)	50					Design Sufficient?	yes
Zx (in^3)	5.24						
trial beam	W8x10						
trial Zx (in^3)	8.87						
E (ksi)	29000						
Ix (in^4)	30.8						
P End reaction live unfactored (lb)	3000						
P End reaction live/dead unfactored (lb)	5550						

B20							
Initial Beam Design			**Trial Beam Check**			**Deflection Calcs**	
Dead Load (psf)	85		Beam unit weight (lb/ft)	10		wL (k/ft)	0.7
Live Load (psf)	100		Wu (lb/ft)	1846		ΔL (in)	0.176
Beam spacing (ft)	7		Length of beam (ft)	10		L/360 (in)	0.33
Wu (lb/ft)	1834		Mu (ft k)	23.075		Design Sufficient?	yes
Pu (lb)	9170		Φ	0.9			
Length of beam (ft)	10		Fy (ksi)	50		wD+L (k/ft)	1.30
Mu (ft k)	22.925		Zx (in^3)	6.153333333		ΔD+L (in)	0.326
Φ	0.9		Design Sufficient?	yes		L/240 (in)	0.50
Fy (ksi)	50					Design Sufficient?	yes
Zx (in^3)	6.113333333						
trial beam	W8x10						
trial Zx (in^3)	8.87						
E (ksi)	29000						
Ix (in^4)	30.8						
P End reaction live unfactored (lb)	3500						
P End reaction live/dead unfactored (lb)	6475						

B21							
Initial Beam Design			**Trial Beam Check**			**Deflection Calcs**	
Dead Load (psf)	85		Beam unit weight (lb/ft)	48		wL (k/ft)	1.23
Live Load (psf)	150		Wu (lb/ft)	2862		ΔL (in)	0.388
Beam spacing (ft)	8.2		Length of beam (ft)	20		L/360 (in)	0.67
Wu (lb/ft)	2804.4		Mu (ft k)	401.1		Design Sufficient?	yes
Pu (lb)	28044		Φ	0.9			
Length of beam (ft)	20		Fy (ksi)	50		wD+L (k/ft)	1.93
Mu (ft k)	398.22		Zx (in^3)	106.96		ΔD+L (in)	0.619
Φ	0.9		Design Sufficient?	yes		L/240 (in)	1.00
Fy (ksi)	50					Design Sufficient?	yes
Zx (in^3)	106.192						
trial beam	W21x48						
trial Zx (in^3)	107						
E (ksi)	29000						
Ix (in^4)	959						

B22							
Interior Beam			**Trial Interior Beam Check**			**Interior Beam Deflection Calcs**	
Dead Load (psf)	85		Beam unit weight (lb/ft)	76		PL G11 (lb)	22700
Live Load (psf)	100		Length of beam(ft)	27.5		PL G10 (lb)	19950
Beam spacing (ft)	7.2		Mu (ft k)	723.545		ΔL @ x=7.5 G10 location (in)	0.3300
Wu (lb/ft)	1886.4		Φ	0.9		ΔL @ x=13.75 center (in)	0.4315
Pu (lb)	25938		Fy (ksi)	50		ΔL @ x=17.5 G11 location (in)	0.4492
Length of beam (ft)	27.5		Zx (in^3)	192.94533 33		Greatest ΔL (in)	0.4492
Mu (ft k)	714.92375		Design Sufficient?	yes		L/360 (in)	0.9167
Φ	0.9					Design Sufficient?	yes
Fy (ksi)	50						
Zx (in^3)	190.64633 33					P D+L G11 (lb)	37150
trial beam	W24x76					P D+L G10 (lb)	32594
trial Zx (in^3)	200					Δ D+L @ x=7.5 G10 location (in)	0.5397
E (ksi)	29000					Δ D+L @ x=13.75 center (in)	0.7057
Ix (in^4)	2100					Δ D+L @ x=17.5 G11 location (in)	0.7346
						Greatest Δ D+L (in)	0.7346
						L/240 (in)	1.3750
						Design Sufficient?	yes

B23							
Initial Beam Design			**Trial Beam Check**			**Deflection Calcs**	
Dead Load (psf)	85		Beam unit weight (lb/ft)	10		wL (k/ft)	0.6
Live Load (psf)	100		Wu (lb/ft)	1584		ΔL (in)	0.369
Beam spacing (ft)	6		Length of beam (ft)	12.5		L/360 (in)	0.42
Wu (lb/ft)	1572		Mu (ft k)	30.9375		Design Sufficient?	yes
Pu (lb)	9825		Φ	0.9			
Length of beam (ft)	12.5		Fy (ksi)	50		wD+L (k/ft)	1.11
Mu (ft k)	30.703125		Zx (in^3)	8.25		ΔD+L (in)	0.683
Φ	0.9		Design Sufficient?	yes		L/240 (in)	0.63
Fy (ksi)	50					Design Sufficient?	no
Zx (in^3)	8.1875						
trial beam	W8x10						
trial Zx (in^3)	8.87						
E (ksi)	29000		P End reaction live unfactored (lb)	3750			
Ix (in^4)	30.8		P End reaction live/dead unfactored (lb)	6937.5			
New Beam Design			**Trial Beam Check**			**Deflection Calcs**	
Ix (in^4) min	27.27640086		Beam unit weight (lb/ft)	12		wL (k/ft)	0.6
new trial beam	W10x12		Wu (lb/ft)	1586.4		ΔL (in)	0.211
new trial Zx (in^3) min	12.6		Length of beam (ft)	12.5		L/360 (in)	0.42
new Ix (in^4)	53.8		Mu (ft k)	30.984375		Design Sufficient?	yes
			Φ	0.9			
			Fy (ksi)	50		wD+L (k/ft)	1.11
			Zx (in^3)	8.2625		ΔD+L (in)	0.391
			Design Sufficient?	yes		L/240 (in)	0.63
						Design Sufficient?	yes

B24							
Initial Beam Design			**Trial Beam Check**			**Deflection Calcs**	
Dead Load (psf)	85		Beam unit weight (lb/ft)	12		wL (k/ft)	1.05
Live Load (psf)	150		Wu (lb/ft)	2408.4		ΔL (in)	0.370
Beam spacing (ft)	7		Length of beam (ft)	12.5		L/360 (in)	0.42
Wu (lb/ft)	2394		Mu (ft k)	47.0390625		Design Sufficient?	yes
Pu (lb)	14962.5		Φ	0.9			
Length of beam (ft)	12.5		Fy (ksi)	50		wD+L (k/ft)	1.65
Mu (ft k)	46.7578125		Zx (in^3)	12.54375		ΔD+L (in)	0.579
Φ	0.9		Design Sufficient?	yes		L/240 (in)	0.63
Fy (ksi)	50					Design Sufficient?	yes
Zx (in^3)	12.46875						
trial beam	W10x12						
trial Zx (in^3)	12.6						
E (ksi)	29000		P End reaction live unfactored (lb)	6562.5			
Ix (in^4)	53.8		P End reaction live/dead unfactored (lb)	10281.25			

B25							
Initial Beam Design			**Trial Beam Check**			**Deflection Calcs**	
Dead Load (psf)	85		Beam unit weight (lb/ft)	10		wL (k/ft)	1
Live Load (psf)	100		Wu (lb/ft)	2632		ΔL (in)	0.080
Beam spacing (ft)	10		Length of beam (ft)	7.5		L/360 (in)	0.25
Wu (lb/ft)	2620		Mu (ft k)	18.50625		Design Sufficient?	yes
Pu (lb)	9825		Φ	0.9			
Length of beam (ft)	7.5		Fy (ksi)	50		wD+L (k/ft)	1.85
Mu (ft k)	18.421875		Zx (in^3)	4.935		ΔD+L (in)	0.147
Φ	0.9		Design Sufficient?	yes		L/240 (in)	0.38
Fy (ksi)	50					Design Sufficient?	yes
Zx (in^3)	4.9125						
trial beam	W8x10						
trial Zx (in^3)	8.87						
E (ksi)	29000		P End reaction live unfactored (lb)	3750			
Ix (in^4)	30.8		P End reaction live/dead unfactored (lb)	6937.5			

B26							
Initial Beam Design			**Trial Beam Check**			**Deflection Calcs**	
Dead Load (psf)	85		Beam unit weight (lb/ft)	48		wL (k/ft)	1.24875
Live Load (psf)	150		Wu (lb/ft)	2904.75		ΔL (in)	0.365
Beam spacing (ft)	8.325	conservative	Length of beam (ft)	20		L/360 (in)	0.67
Wu (lb/ft)	2847.15		Mu (ft k)	389.08125		Design Sufficient?	yes
Pu (lb)	28471.5		Φ	0.9			
Length of beam (ft)	20		Fy (ksi)	50		wD+L (k/ft)	1.96
Mu (ft k)	386.20125		Zx (in^3)	103.755		ΔD+L (in)	0.580
Φ	0.9		Design Sufficient?	yes		L/240 (in)	1.00
Fy (ksi)	50					Design Sufficient?	yes
Zx (in^3)	102.987						
trial beam	W21x48						
trial Zx (in^3)	107						
E (ksi)	29000						
Ix (in^4)	959						

B27							
Initial Beam Design			**Trial Beam Check**			**Interior Beam Deflection Calcs**	
Dead Load (psf)	85		Beam unit weight (lb/ft)	62		PL G12 (lb)	21750.00
Live Load (psf)	100		Wu (lb/ft)	1960.8		PL G13 (lb)	22875
Beam spacing (ft)	7.2		Length of beam (ft)	27.5		ΔL @ x=7.5 G12 location (in)	0.4210
Wu (lb/ft)	1886.4		Mu (ft k)	634.6725313		ΔL @ x=13.75 center (in)	0.5478
Pu (lb)	25938		Φ	0.9		ΔL @ x=20 G13 location (in)	0.4679
Length of beam (ft)	27.5		Fy (ksi)	50		Greatest ΔL (in)	0.5478
Mu (ft k)	560.178		Zx (in^3)	169.2460083		L/360 (in)	0.9167
Φ	0.9		Design Sufficient?	no		Design Sufficient?	yes
Fy (ksi)	50						
Zx (in^3)	149.3808					P D+L G12 (lb)	35243.75
trial beam	W24x62					P D+L G13 (lb)	37325
trial Zx (in^3)	153					ΔL @ x=7.5 G12 location (in)	0.6844
E (ksi)	29000					ΔL @ x=13.75 center (in)	0.8909
Ix (in^4)	1550					ΔL @ x=20 G13 location (in)	0.7608
						Greatest Δ D+L (in)	0.8909
						L/240 (in)	1.3750
						Design Sufficient?	yes

B27 (continued)							
New Beam Design			**Trial Beam Check**			**Interior Beam Deflection Calcs**	
new trial beam	W24x68		Beam unit weight (lb/ft)	68		PL G12 (lb)	21750.00
new trial Zx (in^3) min	177		Wu (lb/ft)	1968		PL G13 (lb)	22875
new Ix (in^4)	1830		Length of beam (ft)	27.5		ΔL @ x=7.5 G12 location (in)	0.3566
			Mu (ft k)	641.8725313		ΔL @ x=13.75 center (in)	0.4640
			Φ	0.9		ΔL @ x=20 G13 location (in)	0.3963
			Fy (ksi)	50		Greatest ΔL (in)	0.4640
			Zx (in^3)	171.1660083		L/360 (in)	0.9167
			Design Sufficient?	yes		Design Sufficient?	yes
						P D+L G12 (lb)	35243.75
						P D+L G13 (lb)	37325
						ΔL @ x=7.5 G12 location (in)	0.5797
						ΔL @ x=13.75 center (in)	0.7546
						ΔL @ x=20 G13 location (in)	0.6444
						Greatest Δ D+L (in)	0.7546
						L/240 (in)	1.3750
						Design Sufficient?	yes

G1							
Exterior Girder			**Trial Exterior Girder Check**			**Exterior Girder Deflection Calcs**	
Floor height (ft)	10.5		Girder unit weight (lb/ft)	76		wL (lb/ft)	840
4" Brick cladding (psf)	40		Length of girder (ft)	42		PL (lb)	8400
Exterior Deadload (lb/ft)	420		Mu (ft k)	685.8432		ΔL (in)	1.11248497
Mu (ft k)	665.7336		Φ	0.9		L/360 (in)	1.4
Zx (in^3)	177.52896		Fy (ksi)	50		Design Sufficient?	yes
trial girder	W24x76		Zx (in^3)	182.89152			
trial Zx (in^3)	200		Design Sufficient?	yes		wD (lb/ft)	1210
Ix (in^4)	2100					P D+L unfactored (lb)	20500
						ΔD+L (in)	2.714993081
						L/240 (in)	2.1
						Design Sufficient?	no

G1 (continued)

New Girder Design			New Exterior Girder Check			Exterior Girder Deflection Calcs	
Ix (in^4) min	2714.993081		Girder unit weight (lb/ft)	84		wL (lb/ft)	840
new trial beam	W27x84		Length of girder (ft)	42		PL (lb)	8400
new trial Zx (in^3) min	244		Mu (ft k)	687.96		ΔL (in)	0.81972577
new Ix (in^4)	2850		Φ	0.9		L/360 (in)	1.4
			Fy (ksi)	50		Design Sufficient?	yes
			Zx (in^3)	183.456			
			Design Sufficient?	yes		wD (lb/ft)	1218
						P D+L unfactored (lb)	20580
						ΔD+L (in)	2.00832813
						L/240 (in)	2.1
						Design Sufficient?	yes

G2

Interior (Scheme 1-2) Girder			Trial Interior (Scheme 1-2) Girder Check			Interior (Scheme 1-2) Girder Deflection Calcs	
Mu (ft k)	1317.1788		Girder unit weight (lb/ft)	116		wL (lb/ft)	840
Zx (in^3)	351.24768		Length of girder (ft)	42		PL (lb)	19950
trial girder	W30x116		Mu (ft k)	1347.8724		ΔL (in)	1.1254602
trial Zx (in^3)	378		Φ	0.9		L/360 (in)	1.4
Ix (in^4)	4930		Fy (ksi)	50		Design Sufficient?	yes
			Zx (in^3)	359.43264			
			Design Sufficient?	yes		wD (lb/ft)	830
						P D+L unfactored (lb)	39662.5
						ΔD+L (in)	2.237522065
						L/240 (in)	2.1
						Design Sufficient?	no

New Girder Design			New Girder Check			Girder Deflection Calcs	
Ix (in^4) min	5252.849419		Girder unit weight (lb/ft)	118		wL (lb/ft)	840
new trial beam	W33x118		Length of girder (ft)	42		PL (lb)	19950
new trial Zx (in^3) min	415		Mu (ft k)	1348.4016		ΔL (in)	0.94042691
new Ix (in^4)	5900		Φ	0.9		L/360 (in)	1.4
			Fy (ksi)	50		Design Sufficient?	yes
			Zx (in^3)	359.57376			
			Design Sufficient?	yes		wD (lb/ft)	832
						P D+L unfactored (lb)	39710
						ΔD+L (in)	1.871897379
						L/240 (in)	2.1
						Design Sufficient?	yes

G3							
Exterior Girder			**Trial Exterior Girder Check**			**Exterior Girder Deflection Calcs**	
Floor height (ft)	10.5		Girder unit weight (lb/ft)	84		wL (lb/ft)	840
4" Brick cladding (psf)	40		Length of girder (ft)	42		PL (lb)	11550
Exterior Deadload (lb/ft)	420		Mu (ft k)	895.9356		ΔL (in)	1.12712293
Mu (ft k)	873.7092		Φ	0.9		L/360 (in)	1.4
Zx (in^3)	232.98912		Fy (ksi)	50		Design Sufficient?	yes
trial girder	W27x84		Zx (in^3)	238.91616			
trial Zx (in^3)	244		Design Sufficient?	yes		wD (lb/ft)	1218
Ix (in^4)	2850					P D+L unfactored (lb)	28297.5
						ΔD+L (in)	2.761451179
						L/240 (in)	2.1
						Design Sufficient?	no
New Girder Design			**New Exterior Girder Check**			**Exterior Girder Deflection Calcs**	
Ix (in^4) min	3747.683742		Girder unit weight (lb/ft)	99		wL (lb/ft)	840
new trial beam	W30x99		Length of girder (ft)	42		PL (lb)	11550
new trial Zx (in^3) min	312		Mu (ft k)	899.9046		ΔL (in)	0.80508781
new Ix (in^4)	3990		Φ	0.9		L/360 (in)	1.4
			Fy (ksi)	50		Design Sufficient?	yes
			Zx (in^3)	239.97456			
			Design Sufficient?	yes		wD (lb/ft)	1233
						P D+L unfactored (lb)	28503.75
						ΔD+L (in)	1.986841696
						L/240 (in)	2.1
						Design Sufficient?	yes

G4							
Trial Girder			**Trial Girder Check**			**Girder Deflection Calcs**	
Wu (lb/ft)	3602.5		Girder unit weight (lb/ft)	84		wL (k/ft)	1.375
Mu (ft k)	794.35125		Length of girder (ft)	42		ΔL (in)	1.400670668
Zx (in^3)	211.827		Mu (ft k)	816.57765		L/360 (in)	1.4
trial girder	W24x84		Φ	0.9		Design Sufficient?	no
trial Zx (in^3)	224		Fy (ksi)	50			
Ix (in^4)	2370		Zx (in^3)	217.75404		wD+L (k/ft)	2.54375
Pu End reaction (lb)	75652.5		Design Sufficient?	yes		ΔD+L (in)	2.591240735
P End reaction live unfactored (lb)	28875					L/240 (in)	2.1
P End reaction live/dead unfactored (lb)	53418.75					Design Sufficient?	no
New Girder			**Trial Girder Check**			**Girder Deflection Calcs**	
Min Ix (in^4)	2371.135345		Girder unit weight (lb/ft)	84		wL (k/ft)	1.375
trial girder	W27X84		Length of girder (ft)	42		ΔL (in)	1.16476824
trial Zx (in^3)	244		Mu (ft k)	816.57765		L/360 (in)	1.4
Ix (in^4)	2850		Φ	0.9		Design Sufficient?	yes
			Fy (ksi)	50			
			Zx (in^3)	217.75404		wD+L (k/ft)	2.54375
			Design Sufficient?	yes		ΔD+L (in)	2.154821243
						L/240 (in)	2.1
						Design Sufficient?	no
New Girder			**Trial Girder Check**			**Girder Deflection Calcs**	
Min Ix (in^4)	2924.400259		Girder unit weight (lb/ft)	90		wL (k/ft)	1.375
trial girder	W30x90		Length of girder (ft)	42		ΔL (in)	0.9195538733
trial Zx (in^3)	283		Mu (ft k)	818.16525		L/360 (in)	1.4
Ix (in^4)	3610		Φ	0.9		Design Sufficient?	yes
			Fy (ksi)	50			
			Zx (in^3)	218.1774		wD+L (k/ft)	2.54375
			Design Sufficient?	yes		ΔD+L (in)	1.701174666
						L/240 (in)	2.1
						Design Sufficient?	yes

G5							
Exterior Girder			**Trial Exterior Girder Check**			**Exterior Girder Deflection Calcs**	
Floor height (ft)	10.5		Girder unit weight (lb/ft)	118		wL (lb/ft)	775
4" Brick cladding (psf)	40		Length of girder (ft)	62		PL (lb)	7750
Exterior Deadload (lb/ft)	420		Mu (ft k)	1569.1208		ΔL (in)	1.91882943
Mu (ft k)	1501.082		Φ	0.9		L/360 (in)	2.066666667
Zx (in^3)	400.2885333		Fy (ksi)	50		Design Sufficient?	yes
trial girder	W33x118		Zx (in^3)	418.4322133			
trial Zx (in^3)	415		Design Sufficient?	no		wD (lb/ft)	1196.75
Ix (in^4)	5900					P D+L unfactored (lb)	19717.5
						ΔD+L (in)	4.88187346
						L/240 (in)	3.1
						Design Sufficient?	no
New Girder Design			**New Exterior Girder Check**			**Exterior Girder Deflection Calcs**	
new trial beam	W33x130		Girder unit weight (lb/ft)	130		wL (lb/ft)	775
new trial Zx (in^3) min	467		Length of girder (ft)	62		PL (lb)	7750
new Ix (in^4)	6710		Mu (ft k)	1576.04		ΔL (in)	1.68719726
			Φ	0.9		L/360 (in)	2.066666667
			Fy (ksi)	50		Design Sufficient?	yes
			Zx (in^3)	420.2773333			
			Design Sufficient?	yes		wD (lb/ft)	1208.75
						P D+L unfactored (lb)	19837.5
						ΔD+L (in)	4.31868074
						L/240 (in)	3.1
						Design Sufficient?	no
New Girder Design			**New Exterior Girder Check**			**Exterior Girder Deflection Calcs**	
Ix (in^4) min	9347.854112		Girder unit weight (lb/ft)	149		wL (lb/ft)	775
new trial beam	W40x149		Length of girder (ft)	62		PL (lb)	7750
new trial Zx (in^3) min	598		Mu (ft k)	1586.9954		ΔL (in)	1.15521364
new Ix (in^4)	9800		Φ	0.9		L/360 (in)	2.066666667
			Fy (ksi)	50		Design Sufficient?	yes
			Zx (in^3)	423.1987733			
			Design Sufficient?	yes		wD (lb/ft)	1227.75
						P D+L unfactored (lb)	20027.5
						ΔD+L (in)	2.98529563
						L/240 (in)	3.1
						Design Sufficient?	yes

G6							
Interioir Girder			**Trial Interior Girder Check**			**Interior Girder Deflection Calcs**	
Mu (ft k)	1567.34295		Girder unit weight (lb/ft)	130		wL (lb/ft)	775
Zx (in^3)	417.95812		Length of girder (ft)	62		PL (lb)	19297.5
trial girder	W33x130		Mu (ft k)	1642.30095		ΔL (in)	4.20112119
trial Zx (in^3)	467		Φ	0.9		L/360 (in)	2.066666667
Ix (in^4)	6710		Fy (ksi)	50		Design Sufficient?	no
			Zx (in^3)	437.94692			
			Design Sufficient?	yes		wD (lb/ft)	788.75
						P D+L unfactored (lb)	38937.375
						ΔD+L (in)	8.47677839
						L/240 (in)	3.1
						Design Sufficient?	no
New Girder Design			**New Interior Girder Check**			**Interior Girder Deflection Calcs**	
Ix (in^4) min	13640.09185		Girder unit weight (lb/ft)	199		wL (lb/ft)	775
new trial beam	W40x199		Length of girder (ft)	62		PL (lb)	19297.5
new trial Zx (in^3) min	869		Mu (ft k)	1682.08635		ΔL (in)	1.89191431
new Ix (in^4)	14900		Φ	0.9		L/360 (in)	2.066666667
			Fy (ksi)	50		Design Sufficient?	yes
			Zx (in^3)	448.55636			
			Design Sufficient?	yes		wD (lb/ft)	857.75
						P D+L unfactored (lb)	40655.475
						ΔD+L (in)	3.98583624
						L/240 (in)	3.1
						Design Sufficient?	no
New Girder Design			**New Interior Girder Check**			**Interior Girder Deflection Calcs**	
Ix (in^4) min	19157.72901		Girder unit weight (lb/ft)	230		wL (lb/ft)	775
new trial beam	W44x230		Length of girder (ft)	62		PL (lb)	19297.5
new trial Zx (in^3) min	1100		Mu (ft k)	1699.96095		ΔL (in)	1.35526554
new Ix (in^4)	20800		Φ	0.9		L/360 (in)	2.066666667
			Fy (ksi)	50		Design Sufficient?	yes
			Zx (in^3)	453.32292			
			Design Sufficient?	yes		wD (lb/ft)	888.75
						P D+L unfactored (lb)	41427.375
						ΔD+L (in)	2.90944908
						L/240 (in)	3.1
						Design Sufficient?	yes

G7=G9							
Interioir Girder			**Trial Interior Girder Check**			**Interior Girder Deflection Calcs**	
Wu (lb/ft)	5881.9	note conservative design	Girder unit weight (lb/ft)	183		wL (k/ft)	2.245
Mu (ft k)	2826.25295		Length of girder (ft)	62		ΔL (in)	1.949816281
Zx (in^3)	753.6674533		Mu (ft k)	2931.77075		L/360 (in)	2.066666667
trial girder	W40x183		Φ	0.9		Design Sufficient?	yes
trial Zx (in^3)	774		Fy (ksi)	50			
Ix (in^4)	13200		Zx (in^3)	781.8055333		wD+L (k/ft)	4.15325
Pu End reaction (lb)	182338.9		Design Sufficient?	no		ΔD+L (in)	3.607160119
						L/240 (in)	3.1
						Design Sufficient?	no
New Girder Design			**New Interior Girder Check**			**Interior Girder Deflection Calcs**	
trial girder	W40x199		Girder unit weight (lb/ft)	199		wL (k/ft)	2.245
trial Zx (in^3)	869		Length of girder (ft)	62		ΔL (in)	1.72735402
Ix (in^4)	14900		Mu (ft k)	2940.99635		L/360 (in)	2.066666667
			Φ	0.9		Design Sufficient?	yes
			Fy (ksi)	50			
			Zx (in^3)	784.2656933		wD+L (k/ft)	4.15325
			Design Sufficient?	yes		ΔD+L (in)	3.195604938
						L/240 (in)	3.1
						Design Sufficient?	no
New Girder Design			**New Interior Girder Check**			**Interior Girder Deflection Calcs**	
Min Ix (in^4)	15359.52051		Girder unit weight (lb/ft)	211		wL (k/ft)	2.245
trial girder	W40x211		Length of girder (ft)	62		ΔL (in)	1.660488703
trial Zx (in^3)	906		Mu (ft k)	2947.91555		L/360 (in)	2.066666667
Ix (in^4)	15500		Φ	0.9		Design Sufficient?	yes
			Fy (ksi)	50			
			Zx (in^3)	786.1108133		wD+L (k/ft)	4.15325
			Design Sufficient?	yes		ΔD+L (in)	3.071904101
						L/240 (in)	3.1
						Design Sufficient?	yes

G8					
Interior Girder		**Trial Interior Girder Check**		**Interior Girder Deflection Calcs**	
Mu (ft k)	762.5772	Girder unit weight (lb/ft)	84	wL (lb/ft)	840
Zx (in^3)	203.35392	Length of girder (ft)	42	PL (lb)	11550
trial girder	W24x84	Mu (ft k)	784.8036	ΔL (in)	1.355400992
trial Zx (in^3)	224	Φ	0.9	L/360 (in)	1.4
Ix (in^4)	2370	Fy (ksi)	50	Design Sufficient?	yes
Wu (lb/ft)	3602.5	Zx (in^3)	209.28096		
P1 (lb)	22008	Design Sufficient?	yes	wD (lb/ft)	798
P2 (lb)	8253			P D+L unfactored (lb)	22522.5
Pu End reaction (lb)	136174.5			ΔD+L (in)	2.643031934
P B1 live unfactored end reaction (lb)	8400			L/240 (in)	2.1
P B1 live/dead unfactored end reaction (lb)	15540			Design Sufficient?	no
P B5 live unfactored end reaction (lb)	3150				
P B5 live/dead unfactored end reaction (lb)	5827.5				
P End reaction live unfactored (lb)	51975				
P End reaction live/dead unfactored (lb)	67278.75	**New Girder Check**		**Interior Girder Deflection Calcs**	
		Girder unit weight (lb/ft)	90	wL (lb/ft)	840
New Girder Design		Length of girder (ft)	42	PL (lb)	11550
Ix (in^4) min	2982.850326	Mu (ft k)	786.3912	ΔL (in)	0.8898338922
new trial beam	W30x90	Φ	0.9	L/360 (in)	1.4
new trial Zx (in^3) min	283	Fy (ksi)	50	Design Sufficient?	yes
new Ix (in^4)	3610	Zx (in^3)	209.70432		
		Design Sufficient?	yes	wD (lb/ft)	804
				P D+L unfactored (lb)	22605
				ΔD+L (in)	1.741532046
				L/240 (in)	2.1
				Design Sufficient?	yes

G10							
Interior Girder			**Trial Interior Girder Check**			**Interior Girder Deflection Calcs**	
Mu (ft k)	150.78		Girder unit weight (lb/ft)	26		PL B16,18 (lb)	7875
Zx (in^3)	40.208		Length of girder (ft)	20		PL B17,19 (lb)	5250
trial girder	W16x26		Mu (ft k)	152.34		ΔL @ x=6 B17,19 location (in)	0.3093
trial Zx (in^3)	44.2		Φ	0.9		ΔL @ x=10 center (in)	0.3825
Ix (in^4)	301		Fy (ksi)	50		ΔL @ x=12 B16,18 location (in)	0.3642
Wu (lb/ft)	2992.5		Zx (in^3)	40.624		Greatest ΔL (in)	0.3825
Pu End reaction left (lb)	47092.5		Design Sufficient?	yes		L/360 (in)	0.6667
P End reaction left live unfactored (lb)	19950					Design Sufficient?	yes
P End reaction left live/dead unfactored (lb)	32593.75						
						P D+L B16,18 (lb)	13081.25
						P D+L B17,19 (lb)	9713
						Δ D+L @ x=6 B17,19 location (in)	0.5369
						Δ D+L @ x=10 center (in)	0.6612
						Δ D+L @ x=12 B16,18 location (in)	0.6285
						Greatest Δ D+L (in)	0.6612
						L/240 (in)	1.0000
						Design Sufficient?	yes

G11							
Interior Girder			**Trial Interior Girder Check**			**Interior Girder Deflection Calcs**	
Mu (ft k)	169.12		Girder unit weight (lb/ft)	30		PL B20,18 (lb)	8750
Zx (in^3)	45.09866667		Length of girder (ft)	20		PL B19,19 (lb)	6000
trial girder	W14x30		Mu (ft k)	170.92		ΔL @ x=6 B19,19 location (in)	0.3595
trial Zx (in^3)	47.3		Φ	0.9		ΔL @ x=10 center (in)	0.4441
Ix (in^4)	291		Fy (ksi)	50		ΔL @ x=12 B20,18 location (in)	0.4226
Wu (lb/ft)	3420		Zx (in^3)	45.57866667		Greatest ΔL (in)	0.4441
Pu End reaction right (lb)	51600		Design Sufficient?	yes		L/360 (in)	0.6667
P Unfactored live end reaction right (lb)	22050					Design Sufficient?	yes
P Unfactored live/dead end reaction right (lb)	35650						
P End reaction left live unfactored (lb)	22700					P D+L B20,18 (lb)	14700
P End reaction left live/dead unfactored (lb)	37150					P D+L B19,19 (lb)	11100
Pu End reaction left (lb)	53660					Δ D+L @ x=6 B17,19 location (in)	0.6285
						Δ D+L @ x=10 center (in)	0.7736
						Δ D+L @ x=12 B16,18 location (in)	0.7351
						Greatest Δ D+L (in)	0.7736
						L/240 (in)	1.0000
						Design Sufficient?	yes

G12							
Interior Girder			**Trial Interior Girder Check**			**Interior Girder Deflection Calcs**	
Mu (ft k)	204.496875	conservative	Girder unit weight (lb/ft)	34		PL B24,25 (lb)	10312.5000
Zx (in^3)	54.5325		Length of girder (ft)	20		PL B23 (lb)	3750.0000
trial girder	W14x34		Mu (ft k)	206.536875		ΔL @ x=6 B23 location (in)	0.2942
trial Zx (in^3)	54.6		Φ	0.9		ΔL @ x=10 center (in)	0.3711
Ix (in^4)	340		Fy (ksi)	50		ΔL @ x=12 B24,25location (in)	0.3565
Wu (lb/ft)	3420		Zx (in^3)	55.0765		Greatest ΔL (in)	0.3711
Pu End reaction right (lb)	52020		Design Sufficient?	no		L/360 (in)	0.6667
P Unfactored live end reaction right (lb)	22312.5					Design Sufficient?	yes
P Unfactored live/dead end reaction right (lb)	35912.5						
P End reaction left live unfactored (lb)	21750					P D+L B24,25 (lb)	14031.25
P End reaction left live/dead unfactored (lb)	35243.75					P D+L B23 (lb)	6938
						Δ D+L @ x=6 B23 location (in)	0.4381
						Δ D+L @ x=10 center (in)	0.5474
						Δ D+L @ x=12 B24,25location (in)	0.5236
						Greatest Δ D+L (in)	0.5474
						L/240 (in)	1.0000
						Design Sufficient?	yes
New Girder Design			**Trial Interior Girder Check**			**Interior Girder Deflection Calcs**	
new trial beam	W18x35		Girder unit weight (lb/ft)	35		PL B24,25 (lb)	10312.5000
new trial Zx (in^3) min	66.5		Length of girder (ft)	20		PL B23 (lb)	3750.0000
new Ix (in^4)	510		Mu (ft k)	206.596875		ΔL @ x=6 B23 location (in)	0.1961
			Φ	0.9		ΔL @ x=10 center (in)	0.2474
			Fy (ksi)	50		ΔL @ x=12 B24,25location (in)	0.2376
			Zx (in^3)	55.0925		Greatest ΔL (in)	0.2474
			Design Sufficient?	yes		L/360 (in)	0.6667
						Design Sufficient?	yes
						P D+L B24,25 (lb)	14031.25
						P D+L B23 (lb)	6938
						Δ D+L @ x=6 B23 location (in)	0.2920
						Δ D+L @ x=10 center (in)	0.3649
						Δ D+L @ x=12 B24,25location (in)	0.3491
						Greatest Δ D+L (in)	0.3649
						L/240 (in)	1.0000
						Design Sufficient?	yes

G13							
Interior Girder			**Trial Interior Girder Check**			**Interior Girder Deflection Calcs**	
Mu (ft k)	180.18	conservative	Girder unit weight (lb/ft)	31		PL B16,24 (lb)	9187.50
Zx (in^3)	48.048		Length of girder (ft)	20		PL B17,23 (lb)	6000
trial girder	W16x31		Mu (ft k)	182.04		ΔL @ x=6 B17,23 location (in)	0.2873
trial Zx (in^3)	54		Φ	0.9		ΔL @ x=10 center (in)	0.3555
Ix (in^4)	375		Fy (ksi)	50		ΔL @ x=12 B16,24 location (in)	0.3386
Wu (lb/ft)	3420		Zx (in^3)	48.544		Greatest ΔL (in)	0.3555
Pu End reaction left (lb)	50913.9		Design Sufficient?	yes		L/360 (in)	0.6667
P End reaction left live unfactored (lb)	22875					Design Sufficient?	yes
P End reaction left live/dead unfactored (lb)	37325						
						P D+L B16,24 (lb)	15137.5
						P D+L B17,23 (lb)	11100
						Δ D+L @ x=6 B17,23 location (in)	0.4961
						Δ D+L @ x=10 center (in)	0.6112
						Δ D+L @ x=12 B16,24 location (in)	0.5811
						Greatest Δ D+L (in)	0.6112
						L/240 (in)	1.0000
						Design Sufficient?	yes

G14							
Interior Girder			**Trial Interior Girder Check**			**Interior Girder Deflection Calcs**	
Wu (lb/ft)	3602.5		Girder unit weight (lb/ft)	130		wL (k/ft)	1.375
Mu (ft k)	1731.00125		Length of girder (ft)	62		ΔL (in)	2.349262012
Zx (in^3)	461.6003333		Mu (ft k)	1805.95925		L/360 (in)	2.066666667
trial girder	W33x130		Φ	0.9		Design Sufficient?	no
trial Zx (in^3)	467		Fy (ksi)	50			
Ix (in^4)	6710		Zx (in^3)	481.5891333		wD+L (k/ft)	2.54375
Pu End reaction (lb)	111677.5		Design Sufficient?	no		ΔD+L (in)	4.346134723
						L/240 (in)	3.1
						Design Sufficient?	no
New Girder Design			**New Interior Girder Check**			**Interior Girder Deflection Calcs**	
trial girder	W36x135		Girder unit weight (lb/ft)	135		wL (k/ft)	1.375
trial Zx (in^3)	509		Length of girder (ft)	62		ΔL (in)	2.020967706
Ix (in^4)	7800		Mu (ft k)	1808.84225		L/360 (in)	2.066666667
			Φ	0.9		Design Sufficient?	yes
			Fy (ksi)	50			
			Zx (in^3)	482.3579333		wD+L (k/ft)	2.54375
			Design Sufficient?	yes		ΔD+L (in)	3.738790255
						L/240 (in)	3.1
						Design Sufficient?	no
New Girder Design			**New Interior Girder Check**			**Interior Girder Deflection Calcs**	
Min Ix (in^4)	9407.278707		Girder unit weight (lb/ft)	149		wL (k/ft)	1.375
trial girder	W40x149		Length of girder (ft)	62		ΔL (in)	1.608525317
trial Zx (in^3)	598		Mu (ft k)	1816.91465		L/360 (in)	2.066666667
Ix (in^4)	9800		Φ	0.9		Design Sufficient?	yes
			Fy (ksi)	50			
			Zx (in^3)	484.5105733		wD+L (k/ft)	2.54375
			Design Sufficient?	yes		ΔD+L (in)	2.975771836
						L/240 (in)	3.1
						Design Sufficient?	yes

Appendix F. - Column Excel Calculations

Roof

Column #	Tributary Area (ft^2)	Dead Load (psf)	Live Load (psf)	4" Brick Cladding (psf)	Length of Wall (ft)	Story Height (ft)	Exterior Dead Load (lb)	qu (psf)	Pu (k)	DL (k)	LL (k)	P (k)
1	210.00	85	100	40	31	5.25	6510	262	63	[redacted]	[redacted]	[redacted]
2	420.00	85	100	40	42	5.25	8820	262	121	[redacted]	[redacted]	[redacted]
3	498.75	85	100	40	23.75	5.25	4988	262	137	[redacted]	[redacted]	[redacted]
4	997.50	85	100	[redacted]	[redacted]	[redacted]	[redacted]	262	261	[redacted]	[redacted]	[redacted]
5	288.75	85	100	40	34.75	5.25	7298	262	84	31.84125	36.1725	68.01375
6	577.50	85	100	40	42	5.25	8820	262	162	[redacted]	[redacted]	[redacted]
7	520.00	85	100	40	52	5.25	10920	262	149	[redacted]	[redacted]	[redacted]
8	1025.00	85	100	[redacted]	[redacted]	[redacted]	[redacted]	262	269	[redacted]	[redacted]	[redacted]
9	1135.00	85	100	[redacted]	[redacted]	[redacted]	[redacted]	262	297	96.475	113.5	209.975
10	1063.71	85	100	40	33.46	5.25	7026	262	287	97.44123	113.39682	210.838063
11	1022.46	85	100	40	33.46	5.25	7026	262	276	[redacted]	[redacted]	[redacted]
12	772.41	85	100	40	24.92	5.25	5233	262	209	[redacted]	[redacted]	[redacted]
13	426.25	85	150	[redacted]	[redacted]	[redacted]	[redacted]	342	146	[redacted]	[redacted]	[redacted]

Level 3

Column #	Tributary Area (ft^2)	Dead Load (psf)	Live Load (psf)	4" Brick Cladding (psf)	Length of Wall (ft)	Story Height (ft)	Exterior Dead Load (lb)	q_u (psf)	Pu (k)	DL (k)	LL (k)	P total (k)	Pu total (k)	Table 4-4 Initial Column Selection	Larger than incoming beams b_f	Max b_f of input beams/columns	New Column Selection
1	210.00	85	100	40	31	10.5	13020	262	71				133	HSS4.5x4.5x5/16	no	10	HSS10x10x3/16
2	420.00	85	100	40	42	10.5	17640	262	131				252	HSS6x6x3/8	no	10	HSS10x10x1/4
3	498.75	85	100	40	23.75	10.5	9975	262	143				279	HSS6x6x1/2	no	10.4	HSS12x12x1/4
4	997.50	85	100					262	261				523	HSS8x8x5/8	yes	11.5	HSS12x12x3/8
5	288.75	85	100	40	34.75	10.5	14595	262	93	39.13875	43.47	150.6225	178	HSS4.5x4.5x3/8	no	10	HSS10x10x3/16
6	577.50	85	100	40	42	10.5	17640	262	172				334	HSS6x6x5/8	no	10.5	HSS12x12x1/4
7	520.00	85	100	40	52	10.5	21840	262	162				312	HSS6x6x1/2	no	11.8	HSS12x12x1/4
8	1025.00	85	100					262	269				537	HSS8x8x5/8	yes	11.8	HSS12x12x3/8
9	1135.00	85	100					262	297	96.475	113.5	419.95	595	HSS8x8x5/8	yes	11.8	HSS12x12x3/8
10	1063.71	85	100	40	33.46	10.5	14052	262	296	104.467	120.423	435.729	583	HSS8x8x5/8	yes	11.8	HSS12x12x3/8
11	1022.46	85	100	40	33.46	10.5	14052	262	285				561	HSS8x8x5/8	yes	11.8	HSS12x12x3/8
12	772.41	85	100	40	24.92	10.5	10465	262	215				424	HSS7x7x5/8	no	15.8	HSS16x16x5/16
13	426.25	85	150					342	146				292	HSS6x6x1/2	no	10.4	HSS12x12x1/4

<u>Level 2</u>

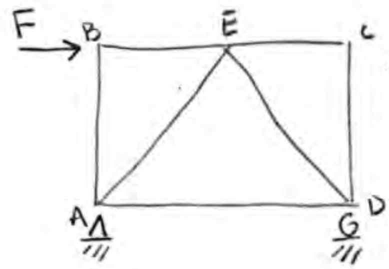
Column #	Tributary Area (ft^2)	Dead Load (psf)	Live Load (psf)	4" Brick Cladding (psf)	Length of Wall (ft)	Story Height (ft)	Exterior Dead Load (lb)	qu (psf)	Pu (k)	DL (k)	LL (k)	P total (k)	Pu total (k)
1	210.00	85	100	40	31	10.5	13020	262	71				204
2	420.00	85	100	40	42	10.5	17640	262	131				383
3	498.75	85	100	40	23.75	10.5	9975	262	143				422
4	997.50	85	100					262	261				784
5	288.75	85	100	40	34.75	10.5	14595	262	93	39.1387	43.47	233.231	271
6	577.50	85	100	40	42	10.5	17640	262	172				507
7	520.00	85	100	40	52	10.5	21840	262	162				474
8	1025.00	85	100					262	269				806
9	1135.00	85	100					262	297	96.475	113.5	629.925	892
10	1063.71	85	100	40	33.46	10.5	14052	262	296	104.467	120.423	660.619	878
11	1022.46	85	100	40	33.46	10.5	14052	262	285				846
12	772.41	85	100	40	24.92	10.5	10465	262	215				639
13	426.25	85	150					342	146				437

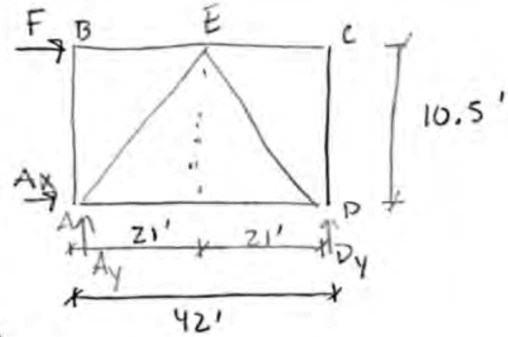
Level 1

Column #	Tributary Area (ft^2)	Dead Load (psf)	Live Load (psf)	4" Brick Cladding (psf)	Length of Wall (ft)	Story Height (ft)	Exterior Dead Load (lb)	qu (psf)	Pu (k)	DL (k)	DL sum	LL (k)	LL sum	P total (k)	Pu total (k)	Table 4-4 Initial Column Selection	Larger than incoming beams b_f	Max b_f of input beams/columns	New Column Selection	Level 3 Column Selection	Selected Columns
1	210.00	85	100	40	31	10.5	13020	262	71						275	HSS6x6x1/2	no	10	HSS10x10x1/4	HSS10x10x3/16	HSS10x10x1/4
2	420.00	85	100	40	42	10.5	17640	262	131						514	HSS8x8x5/8	no	10	HSS10x10x1/2	HSS10x10x1/4	HSS10x10x1/2
3	498.75	85	100	40	23.75	10.5	9975	262	143						565	HSS8x8x5/8	no	10.4	HSS12x12x3/8	HSS12x12x1/4	HSS12x12x3/8
4	997.50	85	100					262	261						1045	HSS16x16x1/2	yes	11.5	HSS16x16x1/2	HSS12x12x3/8	HSS16x16x1/2
5	288.75	85	100	40	34.75	10.5	14595	262	93	39.13875	*149.2575*	43.47	*166.5825*	315.84	364	HSS6x6x5/8	no	10	HSS10x10x5/16	HSS10x10x3/16	HSS10x10x5/16
6	577.50	85	100	40	42	10.5	17640	262	172						679	HSS9x9x5/8	no	10.5	HSS12x12x1/2	HSS12x12x1/4	HSS12x12x1/2
7	520.00	85	100	40	52	10.5	21840	262	162						637	HSS10x10x1/2	no	11.8	HSS12x12x1/2	HSS12x12x1/4	HSS12x12x1/2
8	1025.00	85	100					262	269						1074	HSS14x14x5/8	yes	11.8	HSS14x14x5/8	HSS12x12x3/8	HSS14x14x5/8
9	1135.00	85	100					262	297	96.475	*385.9*	113.5	*454*	839.9	1189	HSS14x14x5/8	yes	11.8	HSS14x14x5/8	HSS12x12x3/8	HSS14x14x5/8
10	1063.71	85	100	40	33.46	10.5	14052	262	296	104.4674887	*410.844*	120.423075	*474.666*	885.510	1174	HSS14x14x5/8	yes	11.8	HSS14x14x5/8	HSS12x12x3/8	HSS14x14x5/8
11	1022.46	85	100	40	33.46	10.5	14052	262	285						1131	HSS16x16x1/2	yes	11.8	HSS16x16x1/2	HSS12x12x3/8	HSS16x16x1/2
12	772.41	85	100	40	24.92	10.5	10465	262	215						853	HSS14x14x1/2	no	15.8	HSS16x16x1/2	HSS16x16x5/16	HSS16x16x1/2
13	426.25	85	150					342	146						583	HSS8x8x5/8	no	10.4	HSS12x12x3/8	HSS12x12x1/4	HSS12x12x3/8

Appendix G. - Bracing Truss Hand Calculations

12/10/2021 | E/W Truss analysis | bracing





$$\Sigma M_A = 0 = F(10.5') - D_y(42')$$

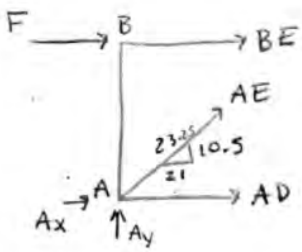
$$D_y = \frac{F(10.5')}{42'}$$

$$\Sigma F_x = 0 = F + A_x$$

$$A_x = -F$$

$$\Sigma F_y = 0 = A_y + D_y$$

$$A_y = -D_y$$



$$\Sigma M_A = 0 = F(10.5) + BE(10.5)$$

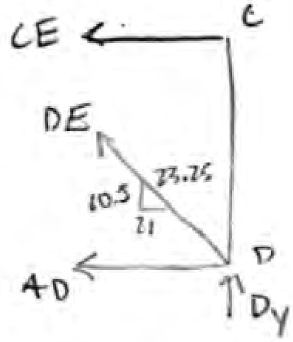
$$BE = -F$$

$$\Sigma F_y = 0 = \frac{10.5}{23.25}(AE) + A_y$$

$$AE = -A_y\left(\frac{23.25}{10.5}\right)$$

$$\Sigma F_x = 0 = F + BE + A_x + AD + \frac{21}{23.25} AE$$

$$AD = -F - BE - A_x - \frac{21}{23.25} AE$$

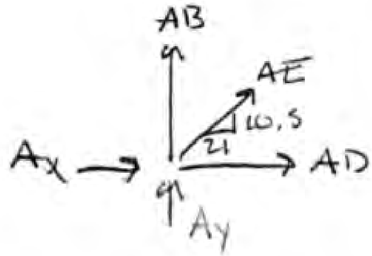


$$\Sigma F_y = 0 = D_y + \frac{10.5}{23.25} DE$$

$$DE = -D_y \left(\frac{23.25}{10.5}\right) \quad \star$$

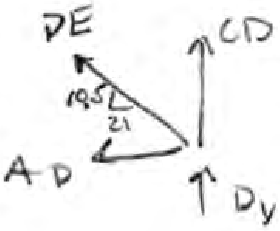
$$\Sigma F_x = 0 = -CE - AD - \frac{21}{23.25} DE$$

$$CE = -AD - \frac{21}{23.25} DE$$



$$\Sigma F_y = 0 = AB + \frac{10.5}{23.25} AE + A_y$$

$$AB = \frac{-10.5}{23.25} AE - A_y \quad \star$$



$$\Sigma F_y = 0 = CD + D_y + \frac{10.5}{23.25} DE$$

$$CD = -D_y - \frac{10.5}{23.25} DE \quad \star$$

Appendix H. - Bracing Excel Calculations

North - South Bracing

First Level			Second Level			Third Level			Roof	
Fx (k)	70.44		Fx (k)	143.7		Fx (k)	218.06		Fx (k)	287.68
Torsion (T) (ft-k)	810.06		Torsion (T) (ft-k)	1652.55		Torsion (T) (ft-k)	2507.69		Torsion (T) (ft-k)	3308.32
Interior Seismic Force (k)	12.66		Center Seismic Force (k)	25.82		Center Seismic Force (k)	39.18		Center Seismic Force (k)	51.69
Dy (k)	5.34		Dy (k)	10.89		Dy (k)	16.52		Dy (k)	21.80
Ay (k)	-5.34		Ay (k)	-10.89		Ay (k)	-16.52		Ay (k)	-21.80
Ax (k)	-12.66		Ax (k)	-25.82		Ax (k)	-39.18		Ax (k)	-51.69
BE (k)	-12.66		BE (k)	-25.82		BE (k)	-39.18		BE (k)	-51.69
AE (k)	**8.28**		**AE (k)**	**16.90**		**AE (k)**	**25.65**		**AE (k)**	**33.83**
			AD (k)	12.91		AD (k)	19.59		AD (k)	25.84
DE (k)	**-8.28**		**DE (k)**	**-16.90**		**DE (k)**	**-25.65**		**DE (k)**	**-33.83**
CE (k)	6.33		CE (k)	0.00		CE (k)	0.00		CE (k)	0.00
AB (k)	**0.00**		**AB (k)**	**0.00**		**AB (k)**	**0.00**		**AB (k)**	**0.00**
CD (k)	**0.00**		**CD (k)**	**0.00**		**CD (k)**	**0.00**		**CD (k)**	**0.00**
Bracing Selection	HSS2x2x 3/16		Bracing Selection	HSS2-1/4x2-1/4x1/4		Bracing Selection	HSS2-1/2x2-1/2x5/16		Bracing Selection	HSS3x3 x1/4
Exterior Seismic Force (k)	13.40		Edge Seismic Force (k)	23.97		Edge Seismic Force (k)	36.37		Edge Seismic Force (k)	47.97
Dy (k)	5.11		Dy (k)	9.15		Dy (k)	13.89		Dy (k)	18.32
Ay (k)	-5.11		Ay (k)	-9.15		Ay (k)	-13.89		Ay (k)	-18.32
Ax (k)	-13.40		Ax (k)	-23.97		Ax (k)	-36.37		Ax (k)	-47.97
BE (k)	-13.40		BE (k)	-23.97		BE (k)	-36.37		BE (k)	-47.97
AE (k)	**8.43**		**AE (k)**	**15.08**		**AE (k)**	**22.88**		**AE (k)**	**30.18**
			AD (k)	11.99		AD (k)	18.18		AD (k)	23.99
DE (k)	**-8.43**		**DE (k)**	**-15.08**		**DE (k)**	**-22.88**		**DE (k)**	**-30.18**
CE (k)	6.70		CE (k)	0.00		CE (k)	0.00		CE (k)	0.00
AB (k)	**0.00**		**AB (k)**	**0.00**		**AB (k)**	**0.00**		**AB (k)**	**0.00**
CD (k)	**0.00**		**CD (k)**	**0.00**		**CD (k)**	**0.00**		**CD (k)**	**0.00**
Bracing Selection	HSS2x2x 3/16		Bracing Selection	HSS2-1/2x2-1/2x3/16		Bracing Selection	HSS2-1/2x2-1/2x5/16		Bracing Selection	HSS3x3 x3/16

East - West Bracing

First Level			Second Level			Third Level			Roof	
Fx (k)	70.44		Fx (k)	143.7		Fx (k)	218.06		Fx (k)	287.68
Torsion (T) (ft-k)	510.10		Torsion (T) (ft-k)	1040.63		Torsion (T) (ft-k)	1579.12		Torsion (T) (ft-k)	2083.28
Seismic Force (k)	17.61		Center Seismic Force (k)	35.93		Center Seismic Force (k)	54.52		Center Seismic Force (k)	71.92
Dy (k)	4.40		Dy (k)	8.98		Dy (k)	13.63		Dy (k)	17.98
Ay (k)	-4.40		Ay (k)	-8.98		Ay (k)	-13.63		Ay (k)	-17.98
Ax (k)	-17.61		Ax (k)	-35.93		Ax (k)	-54.52		Ax (k)	-71.92
BE (k)	-17.61		BE (k)	-35.93		BE (k)	-54.52		BE (k)	-71.92
AE (k)	**9.75**		**AE (k)**	**19.89**		**AE (k)**	**30.18**		**AE (k)**	**39.81**
			AD (k)	17.96		AD (k)	27.26		AD (k)	35.96
DE (k)	**-9.75**		**DE (k)**	**-19.89**		**DE (k)**	**-30.18**		**DE (k)**	**-39.81**
CE (k)	8.81		CE (k)	0.00		CE (k)	0.00		CE (k)	0.00
AB (k)	**0.00**		**AB (k)**	**0.00**		**AB (k)**	**0.00**		**AB (k)**	**0.00**
CD (k)	**0.00**		**CD (k)**	**0.00**		**CD (k)**	**0.00**		**CD (k)**	**0.00**
AE Table Size	HSS2x2x1/4		AE Table Size	HSS2-1/2x2-1/2x3/16		AE Table Size	HSS3x3x3/16		AE Table Size	**HSS3x3x1/4**
DE Table Size	HSS2x2x1/4		DE Table Size	HSS2-1/2x2-1/2x3/16		DE Table Size	HSS3x3x3/16		DE Table Size	**HSS3x3x1/4**

Appendix I. - Footing Excel Calculations

Interior

Base Plate Directly on Interior Footing		Column Number	9	
Base plate Fy (ksi)	36			
Column Fy (ksi)	50			
f'c (ksi)	5			
Footing width (ft)	**14**			
Footing Length (ft)	**14**			
column d (in)	14			
column bf (in)	14			
phi(c)	0.65			
P (k)	839.9		w	12.32956202
A2 (in^2)	28224			
A1 (in^2)	152.0			
sqrt(a2/a1)	2	Note that the area of the supporting concrete is for greater than the base plate area, such that sqrt(a2/a1) =2		
Base Plate Sizing				
delta (in)	1.050			
N (in)	13.38	14		
B (in)	11.36			
Bearing strength				
phi(c)*Pp	1082.9	must be larger than Pu		
Required base plate thickness				
m	0.35			
n	1.4			
n'	3.5			
l	3.5			
t reqd	1.80	**2**		

Column Footing Design - Interior (9)					
Given:	f'c	5	ksi		
	fy	50	ksi		
	PDL	385.9	k		
	PLL	454	k		
	qa	5	k/ft^2	assumed	
	a	14	in	NEED TO USE COLUMN SIZING	
1. Find qe					
	qa	5			
	qsoil+concrete	0.625	=(0.125k/ft^3)(5ft)	=(0.125k/ft^3)(5ft)	both numbers assumed
	qe	4.375	k/ft^2		
2. Find Areq					
	Areq	191.9771429	ft^2		
	b	13.85558165	ft		
	selected b	14	ft		
3. Find qu					
	qu	6.06877551	k/ft^2		
4. Find "d" req for shear					
	Pu	1189.48		=1.2DL+1.6LL	
	Vu	1189.48-0.0421((14+d)^2)		=Pu-((a+d)^2)qu	
Calculate punching shear strength					
	ΦVc	0.75*4*(sqrt(5000)/1000)(4d(14+d))		=Φ*4*(sqrt(f'c))(4(a+d))d	
	d	29.8	inches		
	d	30	inches		
5. Check for beam shear					
	ρ	0.003			
	vc	0.1414213562			
	ΦVc	534.5727266	k		
	Vu	332.7711905	k		
6. Calc for h					
	h	34	inches		

Exterior

Base Plate Directly on Exterior Footing		Column Number	10	
Base plate Fy (ksi)	36			
Column Fy (ksi)	50			
f'c (ksi)	5		2 tons/sqft	
Footing width (ft)	**14**			
Footing Length (ft)	**14**			
column d (in)	14			
column bf (in)	14			
phi(c)	0.65			
P (k)	885.51		w	12.65990929
A2 (in^2)	28224			
A1 (in^2)	160.3			
sqrt(a2/a1)	2	Note that the area of the supporting concrete is for greater than the base plate area, such that sqrt(a2/a1) =2		
Base Plate Sizing				
delta (in)	1.050			
N (in)	13.71	14		
B (in)	11.69			
Bearing strength				
phi(c)*Pp	1082.9	must be larger than Pu		
Required base plate thickness				
m	0.35			
n	1.4			
n'	3.5			
l	3.5			
t reqd	1.85	**2**		

Column Footing Design - Exterior (10)					
Given:	f'c	5	ksi		
	fy	50	ksi		
	PDL	410.8	k		
	PLL	474.67	k		
	qa	5	k/ft^2	assumed	
	a	14	in	NEED TO USE COLUMN SIZING	
1. Find qe					
	qa	5			
	qsoil+concrete	0.625	=(0.125k/ft^3)(5ft)	=(0.125k/ft^3)(5ft)	both numbers assumed
	qe	4.375	k/ft^2		
2. Find Areq					
	Areq	202.3931429	ft^2		
	b	14.2264944	ft		
	selected b	15	ft		
3. Find qu					
	qu	5.566364444	k/ft^2		
4. Find "d" req for shear					
	Pu	1252.432		=1.2DL+1.6LL	
	Vu	1252.43-0.0387((14+d)^2)		=Pu-((a+d)^2)qu	
Calculate punching shear strength					
	ΦVc	0.75*4*(sqrt(5000)/1000)(4d(14+d))		=Φ*4*(sqrt(f'c))(4(a+d))d	
	d	30.86	inches		
	d	31	inches		
5. Check for beam shear					
	ρ	0.003			
	vc	0.1414213562			
	ΦVc	591.8483759	k		
	Vu	361.8136889	k		
6. Calc for h					
	h	35	inches		

Corner

Base Plate Directly on Corner Footing		Column Number	5	
Base plate Fy (ksi)	36			
Column Fy (ksi)	50			
f'c (ksi)	5			
Footing width (ft)	**8**			
Footing Length (ft)	**8**			
column d (in)	10			
column bf (in)	10			
phi(c)	0.65			
P (k)	315.84		w	7.560794327
A2 (in^2)	9216			
A1 (in^2)	57.2			
sqrt(a2/a1)	2	Note that the area of the supporting concrete is for greater than the base plate area, such that sqrt(a2/a1) =2		
Base Plate Sizing				
delta (in)	0.750			
N (in)	8.31	9		
B (in)	6.88			
Bearing strength				
phi(c)*Pp	447.5	must be larger than Pu		
Required base plate thickness				
m	-0.25			
n	0.5			
n'	2.5			
l	2.5			
t reqd	1.23	**1.25**		

Column Footing Design - Corner (5)				
Given:	f'c	5	ksi	
	fy	50	ksi	
	P_{DL}	149.26	k	
	P_{LL}	166.58	k	
	q_a	5	k/ft^2	assumed
	a	10	in	NEED TO USE COLUMN SIZING
1. Find q_e				
	q_a	5		
	$q_{soil+concrete}$	0.625	=(0.125k/ft^3)(5ft)	=(0.125k/ft^3)(5ft)
	q_e	4.375	k/ft^2	
2. Find Areq				
	Areq	72.192	ft^2	
	b	8.49658755	ft	
	selected b	9	ft	
3. Find q_u				
	q_u	5.501728395	k/ft^2	
4. Find "d" req for shear				
	Pu	445.64		=1.2DL+1.6LL
	Vu	445.64-0.0382((10+d)^2)		=Pu-((a+d)^2)qu
Calculate punching shear strength				
	ΦVc	0.75*4*(sqrt(5000)/1000)(4d(10+d))		=Φ*4*(sqrt(f'c))(4(a+d))d
	d	17.7	inches	
	d	18	inches	
5. Check for beam shear				
	ρ	0.003		
	vc	0.1414213562		
	ΦVc	206.1923374	k	
	Vu	127.9151852	k	
6. Calc for h				
	h	22	inches	

Appendix J. Building Cost Estimate

RSMeans Square Foot Estimate - Output

Square Foot Cost Estimate Report Date: **2/3/2022**

Estimate Name:	**MQP**
Building Type:	**College, Dormitory, 4-8 Story with Brick Veneer / Rigid Steel**
Location:	**WORCESTER, MA**
Story Count:	**4**
Story Height (L.F.):	**10.50**
Floor Area (S.F.):	**99759**
Labor Type:	**STD**
Basement Included:	**No**
Data Release:	**Year 2022**
Cost Per Square Foot:	**$221.92**
Building Cost:	**$22,138,922.18**

Costs are derived from a building model with basic components. Scope differences and market conditions can cause costs to vary significantly.

		Quantity	% of Total	Cost Per S.F.	Cost
A	**Substructure**		**2.93%**	**$4.87**	**$485,432.83**
A1010	**Standard Foundations**			**$3.03**	**$302,669.35**
A10101051560	**Foundation wall, CIP, 4' wall height, direct chute, .148 CY/LF, 7.2 PLF, 12" thick**	1411.8		**$1.56**	**$155,227.41**
A10101103100	**Strip footing, concrete, reinforced, load 14.8 KLF, soil bearing capacity 6 KSF, 12" deep x 32" wide**	1086		**$0.66**	**$65,366.34**
A10102107700	**Spread footings, 3000 PSI concrete, load 200K, soil bearing capacity 6 KSF, 6' - 0" square x 20" deep**	75.11		**$0.82**	**$82,075.60**
A1030	**Slab on Grade**			**$1.73**	**$172,288.78**
A10301202240	**Slab on grade, 4" thick, non industrial, reinforced**	24939.75		**$1.73**	**$172,288.78**
A2010	**Basement Excavation**			**$0.11**	**$10,474.70**
A20101106911	**Excavate and fill, 100,000 SF, 4' deep, sand, gravel, or common earth, on site storage**	24939.75		**$0.11**	**$10,474.70**
B	**Shell**		**27.70%**	**$45.97**	**$4,585,586.81**
B1010	**Floor Construction**			**$16.06**	**$1,601,652.42**
B10102481720	**Floor, concrete, slab form, open web bar joist @ 2' OC, on W beam and wall, 25'x25' bay, 23" deep, 40 PSF superimposed load, 84 PSF total load**	74819.25		**$12.11**	**$1,207,687.44**

B10102481730	Floor, concrete, slab form, open web bar joist @ 2' OC, on W beam and wall, 25'x25' bay, 23" deep, 40 PSF superimposed load, 84 PSF total load, for columns add	74819.25		$0.51	$51,057.40
B10107203700	Fireproofing, gypsum board, fire rated, 2 layer, 1" thick, 14" steel column, 3 hour rating, 22 PLF	6255.36		$3.44	$342,907.58
B1020	Roof Construction			$3.20	$319,336.79
B10201123300	Roof, steel joists, beams, 1.5" 22 ga metal deck, on columns, 25'x25' bay, 20" deep, 40 PSF superimposed load, 60 PSF total load	24939.75		$2.64	$263,833.87
B10201123400	Roof, steel joists, beams, 1.5" 22 ga metal deck, on columns, 25'x25' bay, 20" deep, 40 PSF superimposed load, 60 PSF total load, add for column	24939.75		$0.56	$55,502.92
B2010	Exterior Walls			$14.73	$1,469,939.05
B20101305050	Brick veneer wall, standard face, 16 ga x 6" LB @ 16" metal stud back-up, running bond	38227.2		$14.73	$1,469,939.05
B2020	Exterior Windows			$9.08	$905,452.01
B20201066650	Windows, aluminum, sliding, standard glass, 5' x 3'	637.12		$9.08	$905,452.01
B2030	Exterior Doors			$0.48	$48,040.42
B20301106350	Door, aluminum & glass, without transom, narrow stile, double door, hardware, 6'-0" x 7'-0" opening	2.35		$0.17	$16,481.13
B20301106600	Door, aluminum & glass, without transom, non-standard, hardware, 3'-0" x 7'-0" opening	7.04		$0.32	$31,559.29
B3010	Roof Coverings			$2.26	$225,622.91
B30101203400	Roofing, single ply membrane, EPDM, 60 mils, loosely laid, stone ballast	24939.75		$0.51	$50,623.95
B30103202700	Insulation, rigid, roof deck, extruded polystyrene, 40 PSI compressive strength, 4" thick, R20	24939.75		$1.13	$112,278.76
B30104201400	Roof edges, aluminum, duranodic, .050" thick, 6" face	1086		$0.39	$38,450.92
B30104300040	Flashing, aluminum, no backing sides, .019"	1086		$0.12	$11,993.95
B30106305100	Gravel stop, aluminum, extruded, 4", mill finish, .050" thick	1086		$0.12	$12,275.33
B3020	Roof Openings			$0.16	$15,543.21
B30202100300	Roof hatch, with curb, 1" fiberglass insulation, 2'-6" x 3'-0", galvanized steel, 165 lbs	4.69		$0.07	$7,009.47
B30202102100	Smoke hatch, unlabeled, galvanized, 2'-6" x 3', not incl hand winch operator	4.69		$0.09	$8,533.74
C	Interiors		20.99%	$34.82	$3,473,754.37
C1010	Partitions			$10.11	$1,008,175.85
C10101049000	Concrete block (CMU) partition, light weight, hollow, 6" thick, no finish, foamed in insulation	11084.33		$1.61	$160,578.18
C10101265425	Metal partition, 5/8"fire rated gypsum board face, no base,3 -5/8" @ 24" OC framing, same opposite face, sound attenuation insulation	99759		$7.67	$765,297.18

C10101280700	Gypsum board, 1 face only, exterior sheathing, fire resistant, 5/8"	38227.2		$0.47	$46,868.08
C10101280960	Add for the following: taping and finishing	38227.2		$0.36	$35,432.41
C1020	Interior Doors			$6.25	$623,663.34
C10201022600	Door, single leaf, kd steel frame, hollow metal, commercial quality, flush, 3'-0" x 7'-0" x 1-3/8"	415.66		$6.25	$623,663.34
C1030	Fittings			$1.20	$119,325.18
C10301100400	Toilet partitions, cubicles, ceiling hung, painted metal	88.02		$0.82	$81,990.46
C10307100170	Bathroom accessories, stainless steel, mirror, framed, with shelf, 72" x 24"	88.02		$0.37	$37,334.72
C2010	Stair Construction			$4.28	$427,276.01
C20101100760	Stairs, steel, pan tread for conc in-fill, picket rail,20 risers w/ landing	23.47		$4.28	$427,276.01
C3010	Wall Finishes			$6.74	$672,095.98
C30102300140	Painting, interior on plaster and drywall, walls & ceilings, roller work, primer & 2 coats	155180.6 7		$1.72	$171,916.90
C30102300140	Painting, interior on plaster and drywall, walls & ceilings, roller work, primer & 2 coats	38227.2		$0.42	$42,350.00
C30102300320	Painting, masonry or concrete, latex, brushwork, primer & 2 coats	22168.67		$0.54	$54,368.21
C30102301940	Ceramic tile, thin set, 4-1/4" x 4-1/4"	44337.33		$4.04	$403,460.87
C3020	Floor Finishes			$5.27	$525,807.64
C30204100060	Carpet tile, nylon, fusion bonded, 18" x 18" or 24" x 24", 24 oz	79807.2		$3.93	$392,453.50
C30204101600	Vinyl, composition tile, maximum	9975.9		$0.28	$27,692.40
C30204101720	Tile, ceramic natural clay	9975.9		$1.06	$105,661.74
C3030	Ceiling Finishes			$0.98	$97,410.37
C30302106000	Acoustic ceilings, 3/4" fiberglass board, 24" x 48" tile, tee grid, suspended support	9975.9		$0.98	$97,410.37
D	Services		39.54%	$65.60	$6,544,027.54
D1010	Elevators and Lifts			$13.56	$1,352,516.09
D10101109350	Traction, geared passenger, 4000 lb, 6 floors, 12' story height, 2 car group, 200 FPM	4.69		$13.56	$1,352,516.09
D2010	Plumbing Fixtures			$8.94	$891,986.82
D20101102080	Water closet, vitreous china, bowl only with flush valve, wall hung	88.02		$3.66	$365,285.18
D20103102160	Lavatory w/trim, wall hung, vitreous china, 18" x 15"	88.02		$1.90	$189,875.85
D20104202200	Laundry sink w/trim, stainless steel, countertop, 22" x 17" single compartment	14.08		$0.14	$14,428.38
D20104404380	Service sink w/trim, vitreous china, wall hung 22" x 20"	7.04		$0.40	$39,921.79
D20107101840	Shower, stall, fiberglass 1 piece, three walls, 36" square	109.15		$2.30	$229,939.54

D20108201920	Water cooler, electric, wall hung, wheelchair type, 7.5 GPH	19.95	$0.53	$52,536.08
D2020	Domestic Water Distribution		$3.34	$333,579.83
D20202402100	Electric water heater, commercial, 100 < F rise, 300 gal, 180 KW 738 GPH	3.87	$3.34	$333,579.83
D2040	Rain Water Drainage		$0.46	$46,348.50
D20402102040	Roof drain, DWV PVC, 4" diam, diam, 10' high	6	$0.11	$10,589.49
D20402102080	Roof drain, DWV PVC, 4" diam, for each additional foot add	803.64	$0.36	$35,759.01
D3010	Energy Supply		$5.30	$528,390.50
D30105202040	Commercial building heating system, fin tube radiation, forced hot water, 100,000 SF, 1mil CF, total 3 floors	99759	$5.30	$528,390.50
D3030	Cooling Generating Systems		$10.23	$1,020,495.66
D30301103280	Packaged chiller, air cooled, with fan coil unit, medical centers, 40,000 SF, 93.33 ton	99759	$10.23	$1,020,495.66
D4010	Sprinklers		$3.48	$347,547.44
D40104100620	Wet pipe sprinkler systems, steel, light hazard, 1 floor, 10,000 SF	16959.03	$0.71	$70,838.21
D40104100740	Wet pipe sprinkler systems, steel, light hazard, each additional floor, 10,000 SF	82799.97	$2.66	$265,470.78
D40104108940	Standard High Rise Accessory Package 8 story	0.88	$0.11	$11,238.45
D4020	Standpipes		$0.90	$89,932.24
D40203301580	Dry standpipe risers, class III, steel, black, sch 40, 6" diam pipe, 1 floor	1.41	$0.21	$20,852.42
D40203301600	Dry standpipe risers, class III, steel, black, sch 40, 6" diam pipe, additional floors	7.04	$0.35	$35,171.56
D40204103550	Fire pump, electric, with controller, 4" pump, 30 HP, 500 GPM	1.17	$0.34	$33,908.26
D5010	Electrical Service/Distribution		$0.97	$97,007.66
D50101301400	Underground service installation, includes excavation, backfill, and compaction, 100' length, 4' depth, 3 phase, 4 wire, 277/480 volts, 800 A	1.25	$0.50	$49,405.50
D50102300400	Feeder installation 600 V, including RGS conduit and XHHW wire, 800 A	100	$0.24	$23,613.20
D50102400280	Switchgear installation, incl switchboard, panels & circuit breaker, 120/208 V, 3 phase, 800 A	1.2	$0.24	$23,988.96
D5020	Lighting and Branch Wiring		$12.48	$1,245,323.89
D50201100720	Receptacles incl plate, box, conduit, wire, 20 per 1000 SF,2.4 W per SF, with transformer	74819.25	$4.83	$481,707.28
D50201300360	Wall switches, 5.0 per 1000 SF	69831.3	$1.08	$107,570.93
D50201350200	Miscellaneous power, to .5 watts	99759	$0.18	$18,307.77
D50201400280	Central air conditioning power, 4 watts	99759	$0.77	$77,177.55

D50201452080	Motor installation, three phase, 460 V, 15 HP motor size	2		$0.06	$5,574.92
D50201550440	Motor feeder systems, three phase, feed to 200 V 5 HP, 230 V 7.5 HP, 460 V 15 HP, 575 V 20 HP	200		$0.03	$2,741.56
D50202100500	Fluorescent fixtures recess mounted in ceiling, 0.8 watt per SF, 20 FC, 5 fixtures @32 watt per 1000 SF	149638.5		$5.54	$552,243.88
D5030	Communications and Security			$5.92	$590,898.91
D50303101020	Telephone wiring for offices & laboratories, 8 jacks/MSF	74819.25		$1.97	$196,286.81
D50309100452	Communication and alarm systems, fire detection, addressable, 25 detectors, includes outlets, boxes, conduit and wire	1.41		$0.34	$34,227.01
D50309100462	Fire alarm command center, addressable with voice, excl. wire & conduit	1.17		$0.17	$16,518.21
D50309100640	Communication and alarm systems, includes outlets, boxes, conduit and wire, intercom systems, 100 stations	1.29		$2.38	$237,071.28
D50309101000	Communication and alarm systems, includes outlets, boxes, conduit and wire, master TV antenna systems, 30 outlets	2.23		$1.07	$106,795.60
D50309200110	Internet wiring, 8 data/voice outlets per 1000 S.F.	1		$0.00	$0.00
E	Equipment & Furnishings		8.84%	$14.67	$1,463,663.63
E1090	Other Equipment			$13.89	$1,385,227.00
E1090D1010140130 0	2.00-Traction geared elevators, passenger, 2000 lb, 5 floors, 200 FPM	2		$4.03	$401,544.00
E109028461127520 0	400.00-Detection system, heat detector, smoke detector, ceiling type, excl. wires & conduit	400		$1.15	$115,192.00
E109012564310800 0	246.00-Dormitory furniture, rule of thumb: total cost of furniture, minimum	246		$7.00	$698,443.20
E109011301325050 0	20.00-Laundry equipment, dryers, gas-fired residential, 16 lb capacity, average	20		$0.27	$27,378.00
E109011441310690 0	66.00-Range, commercial kitchen equipment, restaurant type, 6 burners & 1 standard oven, 36" wide	66		$1.07	$107,078.40
E109026521310050 0	20.00-Emergency lighting units, lead battery operated, twin sealed beam light, 25 W, 6 V each	20		$0.07	$7,199.40
E109011301324500 0	20.00-Laundry equipment, washer, residential, 4 cycle, average	20		$0.28	$28,392.00
E2020	Moveable Furnishings			$0.79	$78,436.63
E20202200240	Furnishings, dormitory furniture, dressing unit, built-in, deluxe	88.02		$0.79	$78,436.63
F	Special Construction		0.00%	$0.00	$0.00
G	Building Sitework		0.00%	$0.00	$0.00

SubTotal	100%	$165.92	$16,552,465.18
Contractor Fees (General Conditions,Overhead,Profit)	25.0 %	$41.48	$4,138,116.30

Architectural Fees	**7.0 %**	**$14.52**	**$1,448,340.70**
User Fees	**0.0 %**	**$0.00**	**$0.00**
Total Building Cost		**$221.92**	**$22,138,922.18**

RSMeans Assembly Cost Estimate - Output

MQP									
Assembly Cost Estimate		**Worcester**	**Massachusetts**	01609			Data Release: Year 2022		
Quantity	**Assembly Number**	**Description**	**Unit**	**Material O&P**	**Installation O&P**	**Total O&P**	**Ext. Material O&P**	**Ext. Installation O&P**	**Ext. Total O&P**
1411.8	A10101051560	Foundation wall, CIP, 4' wall height, direct chute, .148 CY/LF, 7.2 PLF, 12" thick	L.F.	$ 30.75	$ 78.77	$ 109.52	$ 43,412.85	$ 111,207.49	$ 154,620.34
1086	A10101103100	Strip footing, concrete, reinforced, load 14.8 KLF, soil bearing capacity 6 KSF, 12" deep x 32" wide	L.F.	$ 24.19	$ 35.56	$ 59.75	$ 26,270.34	$ 38,618.16	$ 64,888.50
75.11	A10102107700	Spread footings, 3000 PSI concrete, load 200K, soil bearing capacity 6 KSF, 6' - 0" square x 20" deep	Ea.	$ 438.70	$ 651.50	$ 1,090.20	$ 32,950.76	$ 48,934.17	$ 81,884.93
24939.67	A10301204460	Slab on grade, 6" thick, non industrial, non reinforced	S.F.	$ 3.32	$ 3.85	$ 7.17	$ 82,799.70	$ 96,017.73	$ 178,817.43
	B1010208	Steel Columns and Bracing	V.L.F						$ 385,142.91
		cost/vertical linear foot	linear foot/column or bracing	number of columns	total cost				
		$ 118.93	21	80	$ 199,802.40				
		bracing east west	23.25	32	$ 88,483.92				
		bracing int. north south	16.3	16	$ 31,016.94				
		bracing ext. north south	17.3	32	$ 65,839.65				
				total cost	$ 385,142.91				
	B1010241	W Shape Beams and Girders	S.F.						$ 3,958,923.22

		cost/sq ft	sq ft of one floor	Cost steel beams and girders					
		$ 39.69	24939.67	$ 3,958,923.22					
20160	B10102542400	Floor, composite metal deck, 5" slab, 30'x30' bay, 35" total depth, 125 PSF superimposed load, 182 PSF total load	S.F.	$ 28.50	$ 14.28	$ 42.78	$ 574,560.00	$ 287,884.80	$ 862,444.80
27720	B10102544000	Floor, composite metal deck, 5" slab, 35'x35' bay, 41" total depth, 125 PSF superimposed load, 184 PSF total load	S.F.	$ 30.43	$ 15.33	$ 45.76	$ 843,519.60	$ 424,947.60	$ 1,268,467.20
26939	B10102544400	Floor, composite metal deck, 5" slab, 35'x40' bay, 41" total depth, 125 PSF superimposed load, 184 PSF total load	S.F.	$ 31.88	$ 15.99	$ 47.87	$ 858,815.32	$ 430,754.61	$ 1,289,569.93
6255.36	B10107203700	Fireproofing, gypsum board, fire rated, 2 layer, 1" thick, 14" steel column, 3 hour rating, 22 PLF	V.L.F.	$ 8.65	$ 46.17	$ 54.82	$ 54,108.86	$ 288,809.97	$ 342,918.83
6720	B10201124500	Roof, steel joists, beams, 1.5" 22 ga metal deck, on columns, 30'x30' bay, 28" deep, 40 PSF superimposed load, 62 PSF total load	S.F.	$ 9.37	$ 2.81	$ 12.18	$ 62,966.40	$ 18,883.20	$ 81,849.60
6720	B10201124600	Roof, steel joists, beams, 1.5" 22 ga metal deck, on columns, 30'x30' bay, 28" deep, 40 PSF superimposed load, 62 PSF total load, add for column	S.F.	$ 1.44	$ 0.39	$ 1.83	$ 9,676.80	$ 2,620.80	$ 12,297.60
18219.75	B10201125700	Roof, steel joists, beams, 1.5" 22 ga metal deck, on columns, 35'x35' bay, 28" deep, 40 PSF superimposed load, 62 PSF total load	S.F.	$ 10.67	$ 3.16	$ 13.83	$ 194,404.73	$ 57,574.41	$ 251,979.14
18219.75	B10201125800	Roof, steel joists, beams, 1.5" 22 ga metal deck, on columns, 35'x35' bay, 28" deep, 40 PSF superimposed load, 62 PSF total load, add for column	S.F.	$ 1.36	$ 0.38	$ 1.74	$ 24,778.86	$ 6,923.51	$ 31,702.37
38227.2	B20101305050	Brick veneer wall, standard face, 16 ga x 6" LB @ 16" metal stud back-up, running bond	S.F.	$ 10.37	$ 28.08	$ 38.45	$ 396,416.06	$ 1,073,419.78	$ 1,469,835.84
637.12	B20201066400	Windows, aluminum, double hung, insul. glass, 3'-0" x 4'-0"	Ea.	$ 480.18	$ 198.51	$ 678.69	$ 305,932.28	$ 126,474.69	$ 432,406.97

2.35	B20301106350	Door, aluminum & glass, without transom, narrow stile, double door, hardware, 6'-0" x 7'-0" opening	Opng.	$ 4,507.35	$ 2,514.05	$ 7,021.40	$ 10,592.27	$ 5,908.02	$ 16,500.29
7.04	B20301106600	Door, aluminum & glass, without transom, non-standard, hardware, 3'-0" x 7'-0" opening	Opng.	$ 3,012.45	$ 1,469.25	$ 4,481.70	$ 21,207.65	$ 10,343.52	$ 31,551.17
24939.75	B30101203400	Roofing, single ply membrane, EPDM, 60 mils, loosely laid, stone ballast	S.F.	$ 1.32	$ 0.71	$ 2.03	$ 32,920.47	$ 17,707.22	$ 50,627.69
24939.75	B30103202700	Insulation, rigid, roof deck, extruded polystyrene, 40 PSI compressive strength, 4" thick, R20	S.F.	$ 3.69	$ 0.81	$ 4.50	$ 92,027.68	$ 20,201.20	$ 112,228.88
1086	B30104201400	Roof edges, aluminum, duranodic, .050" thick, 6" face	L.F.	$ 20.50	$ 14.90	$ 35.40	$ 22,263.00	$ 16,181.40	$ 38,444.40
1086	B30104300040	Flashing, aluminum, no backing sides, .019"	S.F.	$ 5.89	$ 5.15	$ 11.04	$ 6,396.54	$ 5,592.90	$ 11,989.44
1086	B30106305200	Gravel stop, aluminum, extruded, 4", duranodic, .050" thick	L.F.	$ 4.81	$ 6.50	$ 11.31	$ 5,223.66	$ 7,059.00	$ 12,282.66
11084.33	C10101045500	Concrete block (CMU) partition, light weight, hollow, 6" thick, no finish	S.F.	$ 2.13	$ 10.05	$ 12.18	$ 23,609.62	$ 111,397.52	$ 135,007.14
99759	C10101265450	Metal partition, 5/8"fire rated gypsum board face, no base layer, 3-5/8" @ 24", 5/8" regular gypsum board opposite face, no insulation	S.F.	$ 1.22	$ 4.66	$ 5.88	$ 121,705.98	$ 464,876.94	$ 586,582.92
38227.2	C10101280700	Gypsum board, 1 face only, exterior sheathing, fire resistant, 5/8"	S.F.	$ 0.36	$ 0.87	$ 1.23	$ 13,761.79	$ 33,257.66	$ 47,019.45
38227.2	C10101280960	Add for the following: taping and finishing	S.F.	$ 0.06	$ 0.87	$ 0.93	$ 2,293.63	$ 33,257.66	$ 35,551.29
415.66	C10201022600	Door, single leaf, kd steel frame, hollow metal, commercial quality, flush, 3'-0" x 7'-0" x 1-3/8"	Opng.	$ 1,158.00	$ 342.41	$ 1,500.41	$ 481,334.28	$ 142,326.14	$ 623,660.42
415.66	C10203100100	Hinges, full mortise, low frequency, steel base, 4-1/2" x 4-1/2", USP	Ea.	$ 1.82	$ -	$ 1.82	$ 756.50	$ -	$ 756.50
400	C10203100400	Locksets, heavy duty cylindrical, keyed, single cylinder function	Ea.	$ 189.14	$ 86.90	$ 276.04	$ 75,656.00	$ 34,760.00	$ 110,416.00
69	C10307100110	Bathroom accessories, stainless steel, curtain rod, 5' long, 1-1/2" diameter	Ea.	$ 19.78	$ 66.80	$ 86.58	$ 1,364.82	$ 4,609.20	$ 5,974.02
15	C10307100140	Bathroom accessories, stainless steel, grab bar, 1-1/4" diameter, 12" long	Ea.	$ 30.40	$ 36.32	$ 66.72	$ 456.00	$ 544.80	$ 1,000.80

15	C10307100150	Bathroom accessories, stainless steel, grab bar, 1-1/2" diameter, 36" long	Ea.	$ 37.15	$ 43.45	$ 80.60	$ 557.25	$ 651.75	$ 1,209.00
69	C10307100160	Bathroom accessories, stainless steel, mirror, framed, with shelf, 18" x 24"	Ea.	$ 103.26	$ 43.45	$ 146.71	$ 7,124.94	$ 2,998.05	$ 10,122.99
69	C10307100210	Bathroom accessories, stainless steel, towel bar, 30" long	Ea.	$ 61.28	$ 41.50	$ 102.78	$ 4,228.32	$ 2,863.50	$ 7,091.82
69	C10308300115	Cabinets, residential, base, hardwood, 1 top drawer & 1 door below x 24" W	Ea.	$ 496.98	$ 77.82	$ 574.80	$ 34,291.62	$ 5,369.58	$ 39,661.20
23.47	C20101100760	Stairs, steel, pan tread for conc in-fill, picket rail,20 risers w/ landing	Flight	$ 14,571.50	$ 3,577.05	$ 18,148.55	$ 341,993.11	$ 83,953.36	$ 425,946.47
193407.87	C30102300140	Painting, interior on plaster and drywall, walls & ceilings, roller work, primer & 2 coats	S.F.	$ 0.14	$ 0.97	$ 1.11	$ 27,077.10	$ 187,605.63	$ 214,682.73
22168.67	C30102300320	Painting, masonry or concrete, latex, brushwork, primer & 2 coats	S.F.	$ 0.26	$ 2.19	$ 2.45	$ 5,763.85	$ 48,549.39	$ 54,313.24
44337.33	C30102301940	Ceramic tile, thin set, 4-1/4" x 4-1/4"	S.F.	$ 1.45	$ 7.65	$ 9.10	$ 64,289.13	$ 339,180.57	$ 403,469.70
79807.2	C30204100060	Carpet tile, nylon, fusion bonded, 18" x 18" or 24" x 24", 24 oz	S.F.	$ 3.80	$ 1.12	$ 4.92	$ 303,267.36	$ 89,384.06	$ 392,651.42
9975.9	C30204101600	Vinyl, composition tile, maximum	S.F.	$ 1.17	$ 1.61	$ 2.78	$ 11,671.80	$ 16,061.20	$ 27,733.00
9975.9	C30204101720	Tile, ceramic natural clay	S.F.	$ 2.62	$ 7.98	$ 10.60	$ 26,136.86	$ 79,607.68	$ 105,744.54
4000	C30206000065	Resilient base, 1/8" vinyl corner, 2-1/2" H, straight or cove, std. colors	L.F.	$ 3.74	$ 2.56	$ 6.30	$ 14,960.00	$ 10,240.00	$ 25,200.00
9975.9	C30302106000	Acoustic ceilings, 3/4" fiberglass board, 24" x 48" tile, tee grid, suspended support	S.F.	$ 7.09	$ 2.67	$ 9.76	$ 70,729.13	$ 26,635.65	$ 97,364.78
2	D10101402500	Traction geared elevators, passenger, 4000 lb, 5 floors, 200 FPM	Ea.	$ 149,500.00	$ 59,736.00	$ 209,236.00	$ 299,000.00	$ 119,472.00	$ 418,472.00
69	D20101102080	Water closet, vitreous china, bowl only with flush valve, wall hung	Ea.	$ 3,127.90	$ 1,022.00	$ 4,149.90	$ 215,825.10	$ 70,518.00	$ 286,343.10
69	D20104101720	Kitchen sink w/trim, countertop, PE on CI, 24" x 21", single bowl	Ea.	$ 1,059.45	$ 991.34	$ 2,050.79	$ 73,102.05	$ 68,402.46	$ 141,504.51
7.04	D20104404380	Service sink w/trim, vitreous china, wall hung 22" x 20"	Ea.	$ 4,187.35	$ 1,481.90	$ 5,669.25	$ 29,478.94	$ 10,432.58	$ 39,911.52
54	D20107101840	Shower, stall, fiberglass 1 piece, three walls, 36" square	Ea.	$ 1,084.68	$ 1,022.00	$ 2,106.68	$ 58,572.72	$ 55,188.00	$ 113,760.72
15	D20107102100	Shower, handicap with fixed and handheld heat, control valves,grab bar & seat	Ea.	$ 6,003.55	$ 4,701.20	$ 10,704.75	$ 90,053.25	$ 70,518.00	$ 160,571.25

19.95	D20108201920	Water cooler, electric, wall hung, wheelchair type, 7.5 GPH	Ea.	$ 1,866.65	$ 766.50	$ 2,633.15	$ 37,239.67	$ 15,291.68	$ 52,531.35
3.87	D20202402100	Electric water heater, commercial, 100 F rise, 300 gal, 180 KW 738 GPH	Ea.	$ 83,242.50	$ 2,887.15	$ 86,129.65	$ 322,148.48	$ 11,173.27	$ 333,321.75
6	D20402102040	Roof drain, DWV PVC, 4" diam, diam, 10' high	Ea.	$ 640.72	$ 1,124.20	$ 1,764.92	$ 3,844.32	$ 6,745.20	$ 10,589.52
803.64	D20402102080	Roof drain, DWV PVC, 4" diam, for each additional foot add	Ea.	$ 12.81	$ 31.68	$ 44.49	$ 10,294.63	$ 25,459.32	$ 35,753.95
99759	D30105202040	Commercial building heating system, fin tube radiation, forced hot water, 100,000 SF, 1mil CF, total 3 floors	S.F.	$ 2.17	$ 3.13	$ 5.30	$ 216,477.03	$ 312,245.67	$ 528,722.70
16959.03	D40104100620	Wet pipe sprinkler systems, steel, light hazard, 1 floor, 10,000 SF	S.F.	$ 1.82	$ 2.36	$ 4.18	$ 30,865.43	$ 40,023.31	$ 70,888.74
82799.97	D40104100740	Wet pipe sprinkler systems, steel, light hazard, each additional floor, 10,000 SF	S.F.	$ 1.02	$ 2.19	$ 3.21	$ 84,455.97	$ 181,331.93	$ 265,787.90
1.41	D40203301580	Dry standpipe risers, class III, steel, black, sch 40, 6" diam pipe, 1 floor	Floor	$ 8,929.65	$ 5,854.35	$ 14,784.00	$ 12,590.81	$ 8,254.63	$ 20,845.44
7.04	D40203301600	Dry standpipe risers, class III, steel, black, sch 40, 6" diam pipe, additional floors	Floor	$ 3,001.78	$ 1,994.85	$ 4,996.63	$ 21,132.53	$ 14,043.74	$ 35,176.27
1.17	D40204103550	Fire pump, electric, with controller, 4" pump, 30 HP, 500 GPM	Ea.	$ 24,216.00	$ 4,675.65	$ 28,891.65	$ 28,332.72	$ 5,470.51	$ 33,803.23
300	D40909100040	Detectors with brackets, fixed temperature heat detector	Ea.	$ 45.91	$ 114.46	$ 160.37	$ 13,773.00	$ 34,338.00	$ 48,111.00
100	D40909100280	Extinguisher agent, 75 lb carbon dioxide cylinder	Ea.	$ 1,690.08	$ 255.50	$ 1,945.58	$ 169,008.00	$ 25,550.00	$ 194,558.00
20	D40909100550	Manual pull station	Ea.	$ 100.90	$ 142.06	$ 242.96	$ 2,018.00	$ 2,841.20	$ 4,859.20
20	D40909100740	Bell signaling device	Ea.	$ 56.50	$ 100.67	$ 157.17	$ 1,130.00	$ 2,013.40	$ 3,143.40
1.25	D50101301400	Underground service installation, includes excavation, backfill, and compaction, 100' length, 4' depth, 3 phase, 4 wire, 277/480 volts, 800 A	Ea.	$ 25,802.80	$ 13,709.60	$ 39,512.40	$ 32,253.50	$ 17,137.00	$ 49,390.50
100	D50102300400	Feeder installation 600 V, including RGS conduit and XHHW wire, 800 A	L.F.	$ 123.49	$ 112.64	$ 236.13	$ 12,349.00	$ 11,264.00	$ 23,613.00
1.2	D50102400280	Switchgear installation, incl switchboard, panels & circuit breaker, 120/208 V, 3 phase, 800 A	Ea.	$ 15,562.00	$ 4,428.80	$ 19,990.80	$ 18,674.40	$ 5,314.56	$ 23,988.96
74819.25	D50201100720	Receptacles incl plate, box, conduit, wire, 20 per 1000	S.F.	$ 1.68	$ 4.76	$ 6.44	$ 125,696.34	$ 356,139.63	$ 481,835.97

		SF,2.4 W per SF, with transformer							
69831.3	D50201300360	Wall switches, 5.0 per 1000 SF	S.F.	$ 0.29	$ 1.25	$ 1.54	$ 20,251.08	$ 87,289.13	$ 107,540.21
99759	D50201350200	Miscellaneous power, to .5 watts	S.F.	$ 0.04	$ 0.14	$ 0.18	$ 3,990.36	$ 13,966.26	$ 17,956.62
99579	D50201400280	Central air conditioning power, 4 watts	S.F.	$ 0.23	$ 0.54	$ 0.77	$ 22,903.17	$ 53,772.66	$ 76,675.83
2	D50201452080	Motor installation, three phase, 460 V, 15 HP motor size	Ea.	$ 918.66	$ 1,868.80	$ 2,787.46	$ 1,837.32	$ 3,737.60	$ 5,574.92
200	D50201550440	Motor feeder systems, three phase, feed to 200 V 5 HP, 230 V 7.5 HP, 460 V 15 HP, 575 V 20 HP	L.F.	$ 3.26	$ 10.44	$ 13.70	$ 652.00	$ 2,088.00	$ 2,740.00
149638.5	D50202100500	Fluorescent fixtures recess mounted in ceiling, 0.8 watt per SF, 20 FC, 5 fixtures @32 watt per 1000 SF	S.F.	$ 1.34	$ 2.36	$ 3.70	$ 200,515.59	$ 353,146.86	$ 553,662.45
74819.25	D50303101020	Telephone wiring for offices & laboratories, 8 jacks/MSF	S.F.	$ 0.41	$ 2.21	$ 2.62	$ 30,675.89	$ 165,350.54	$ 196,026.43
1.41	D50309100452	Communication and alarm systems, fire detection, addressable, 25 detectors, includes outlets, boxes, conduit and wire	Ea.	$ 9,864.30	$ 14,438.40	$ 24,302.70	$ 13,908.66	$ 20,358.14	$ 34,266.80
1.17	D50309100462	Fire alarm command center, addressable with voice, excl. wire & conduit	Ea.	$ 11,847.20	$ 2,227.20	$ 14,074.40	$ 13,861.22	$ 2,605.82	$ 16,467.04
1.29	D50309100640	Communication and alarm systems, includes outlets, boxes, conduit and wire, intercom systems, 100 stations	Ea.	$ 85,842.00	$ 97,792.00	$ 183,634.00	$ 110,736.18	$ 126,151.68	$ 236,887.86
2.23	D50309101000	Communication and alarm systems, includes outlets, boxes, conduit and wire, master TV antenna systems, 30 outlets	Ea.	$ 16,967.60	$ 30,924.80	$ 47,892.40	$ 37,837.75	$ 68,962.30	$ 106,800.05
1	D50309200110	Internet wiring, 8 data/voice outlets per 1000 S.F.	M.S.F.	$ 522.08	$ 2,278.40	$ 2,800.48	$ 522.08	$ 2,278.40	$ 2,800.48
20	E10106100100	Architectural equipment, laundry equipment dryers, gas fired, residential, 16 lb capacity	Ea.	$ 1,075.00	$ 332.77	$ 1,407.77	$ 21,500.00	$ 6,655.40	$ 28,155.40
20	E10106100160	Architectural equipment, laundry equipment, washers, residential, 4 cycle	Ea.	$ 1,125.00	$ 332.77	$ 1,457.77	$ 22,500.00	$ 6,655.40	$ 29,155.40
1	E10303100110	Architectural equipment, dock bumpers, rubber blocks, 4-1/2" thick, 10" high , 14" long	Ea.	$ 50.00	$ 31.12	$ 81.12	$ 50.00	$ 31.12	$ 81.12
69	E10904100110	Architectural equipment, appliances, range, cook top, 4 burner, economy	Ea.	$ 325.00	$ 156.81	$ 481.81	$ 22,425.00	$ 10,819.89	$ 33,244.89

69	E10904100220	Architectural equipment, appliances, refrigerator, no frost, 21 to 29 CF, deluxe	Ea.	$ 2,200.00	$ 430.92	$ 2,630.92	$ 151,800.00	$ 29,733.48	$ 181,533.48
637.12	E20103100120	Furnishings, blinds, exterior, aluminum, louvered, 1'-4" wide x 6'-8" long	Ea.	$ 580.00	$ 89.18	$ 669.18	$ 369,529.60	$ 56,818.36	$ 426,347.96
249	E20202200210	Furnishings, dormitory furniture, desk top (built-in), laminated plastic, 24"deep, economy	L.F.	$ 59.50	$ 32.32	$ 91.82	$ 14,815.50	$ 8,047.68	$ 22,863.18
249	E20202200230	Furnishings, dormitory furniture, dressing unit, built-in, economy	L.F.	$ 229.00	$ 134.06	$ 363.06	$ 57,021.00	$ 33,380.94	$ 90,401.94
69	E20202200330	Furnishings, cabinets, hospital, countertop, laminated plastic, no backsplash	L.F.	$ 65.50	$ 40.10	$ 105.60	$ 4,519.50	$ 2,766.90	$ 7,286.40
0.77	G10101201100	Remove trees & stumps up to 12 inches in diameter by cut and chip and haulaway stumps	Acre	$ -	$ 12,063.73	$ 12,063.73	$ -	$ 9,289.07	$ 9,289.07
0.77	G10101202000	Remove brush by saw, 4' tall, 10 mile haul cycle	Acre	$ -	$ 4,817.10	$ 4,817.10	$ -	$ 3,709.17	$ 3,709.17
20000	G10301201400	Excavate common earth, 1/2 CY backhoe, two 12 CY dump trucks, 4 mile round trip	C.Y.	$ -	$ 17.71	$ 17.71	$ -	$ 354,200.00	$ 354,200.00
100	G20301201620	Concrete sidewalk, 4" thick, 4" gravel base, 5' wide	L.F.	$ 15.68	$ 19.34	$ 35.02	$ 1,568.00	$ 1,934.00	$ 3,502.00
1000	G30101102130	Water distribution piping, ductile iron class 250, mechanical joint, 4" diameter, excludes excavation and backfill	L.F.	$ 55.38	$ 11.21	$ 66.59	$ 55,380.00	$ 11,210.00	$ 66,590.00
1000	G30201102130	Drainage and sewage piping, 4" diameter, plain, PVC, excavation and backfill excluded	L.F.	$ 2.15	$ 4.54	$ 6.69	$ 2,150.00	$ 4,540.00	$ 6,690.00
1000	G30306101050	Small Surface Retention, Rain Garden	C.F.	$ 8.06	$ 3.08	$ 11.14	$ 8,060.00	$ 3,080.00	$ 11,140.00
1000	G30601102070	Gas service piping, 1-1/4" diameter, polyethylene, SDR-10, excavation and backfill excluded	L.F.	$ 3.17	$ 4.50	$ 7.67	$ 3,170.00	$ 4,500.00	$ 7,670.00
1000	G30601121000	Gasline, 60 psi coils, compression coupling @ 100', 1/2" diameter, SDR 11, 2' deep, including excavation, backfill, bedding & compaction	L.F.	$ 1.76	$ 9.15	$ 10.91	$ 1,760.00	$ 9,150.00	$ 10,910.00
1000	G40103201016	Underground electrical duct, 2" dia. Schedule 40 PVC, 6' deep, include excavate CE, backfill, concrete, compaction	L.F.	$ 9.57	$ 21.53	$ 31.10	$ 9,570.00	$ 21,530.00	$ 31,100.00
6	G40202100200	Light pole, aluminum, 20' high, 1 arm bracket	Ea.	$ 1,395.45	$ 1,334.45	$ 2,729.90	$ 8,372.70	$ 8,006.70	$ 16,379.40

						Sub Total	$ 8,454,471.41	$ 7,769,128.11	$ 20,567,665.65
								GC Markup 25%	$ 5,141,916.41
								Arch Markup 8.75%	$ 1,799,670.74
								Total	**$ 27,509,252.80**

Appendix K. Work Breakdown Structure

Worcester Polytechnic Institute - Civil & Environmental Engineering Department			
MQP New Residence Hall			
Level One	**Level Two**	**Level Three**	**Duration**
Major Group Elements	Group Elements	Individual Elements	
A. SUBSTRUCTURE			
6	A10 Foundations	A1010 Standard Footings	100
7		A1030 Slab on Grade	40
B. SHELL			
8	B10 Superstructure	B1010 Floor Construction	120
9		B1020 Roof Construction	24
10	B20 Exterior Closure	B2010 Exterior Walls	120
11		B2020 Exterior Windows and Exterior Doors	50
12	B30 Roofing	B3010 Roof Coverage	60
C. INTERIORS			
13	C10 Interior Construction	C1010 Partitions	150
14		C1020 Interior Doors	25
15		C1030 Specialties	25
16	C20 Staircases	C2010 Stair Construction	75
17		C2020 Stair Finishes	40
18	C30 Interior Finishes	C3010 Wall Finishes	100
19		C3020 Floor Finishes	40
20		C3030 Ceiling Finishes	115
D. SERVICES			
21	D10 Conveying Systems	D1010 Elevators	94
22	D20 Plumbing		374
23	D30 HVAC		324
24	D40 Fire Protection		118
25	D50 Electrical		300
E. EQUIPMENT & FURNISHINGS			
26	E10 Equipment		50
27	E20 Furnishings		120
G. BUILDING SITEWORK			
28	G10 Site Prep	G1010 Site Clearing	22
29		G1020 Site Demolition & Relocations	33
30		1030 Site Earthwork	64
31		1040 Hazardous Waste Remediation	32
32	G20 Site Improvements	2030 Pedestrian Paving	41
33		2050 Landscaping	42
34		Exterior Finishes, Plantation & Grading	60
35	G30 Site Civil/ Mechanical Utilities	3010 Water Supply & Distribution Systems	30
36		3020 Sanitary Sewer System	50
37		3030 Storm Sewer Systems	30
38		3060 Fuel Distribution	30
39	G40 Site Electrical Utilities	4010 Electrical Distribution	20
40		4020 Exterior Lighting	25
41		4030 Exterior Communication & Security	20
42		4040 Other Electrical Utilities	10

H BUILDING DESIGN			
1			659
I PRECONSTRUCTION			MAKE CMR
2			190
J PUNCH-LIST			
43			61
K CLOSE-OUT			
44			100

Appendix L. Sustainability Summary Table

Sustainability/ Innovative Measure	Cost	Savings	Is it legal in MA?	Permit required	Benefits	Downsides	Maintenance	Schedule Impact
LEED	$11,000 for certification only	none	yes	no	● Drives sustainability goals ● Fulfills sustainability initiative requirements	● WPI willing to pay whatever it costs to achieve a label	Many aspects for points require continued monitoring and assessment	Possible added lead times on materials, additional time for final assessment
Rooftop Garden/Green Roof	$60-90k for install	ROI	yes	yes	● can absorb and store large amounts of heat when they are wet, so they are able to reduce temperature fluctuations. ● able to reduce the energy needed for heat in the winter and air conditioning in the summer.	● Additional structural support needed compared to standard roofs ● ROI time is about 6 years for a green roof of the proposed size	$0.75 to $1.50 per square foot, plus small amount for plant upkeep depending on type of plant	
Solar Panels	$300,000 for 100 kW system	$32,529.60/yr (7% of estimated electric bill for the building)	yes	yes	● Can save some money overall ● renewable energy ● improve green image ● no noise	Dependent on weather	● Get good warranty and insurance ● keep panels free of dirt and snow ● when needed hire a professional for repair	Can take over 50 days to asses the site, engineer the system, get permits approved, and final commissioning About 5-12 weeks for install
Greywater Reuse	Est. $1,500,000-$2,000,000	Around 3,000,000-4,000,000 gallons of water a year Est. $14,716-$19,623 (calculated using Worcester water rate of $3.67/hundred cubic feet of usage)	Yes	potentially	● Money is saved on water utility bill ● Helps to conserve water/reduce consumption of potable water ● It is possible to exceed the amount of water collected necessary for one building and it can then be pumped into other buildings (i.e. an educational building that does not have showers or washing machines.	● Water needs to be chlorinated to a certain level to be sanitary and constantly monitored ● Chlorine can break down the rubber components of toilet systems ● If water stagnant in the tanks for too long it gives off a bothersome smell ● Might take longer than the system's lifespan to pay off	Operation may require staff to come in several times a week to monitor the system. Staff need to be well trained to understand any issues that may occur with the chlorination of the water.	Added times to piping and plumbing installation. Pipes leading to and from the filtration tank in the basement/lowest level will need to be installed as well as traditional piping systems. *it is a requirement that traditional piping leading to and from toilet water is installed as a backup
CLT	Hard to estimate but costs $42-46/sf	none	yes		● Can reduce the schedule of the project ● Saves money on potential on-site errors or mistakes ● Helps reduce carbon emission in the atmosphere	● More expensive than concrete or steel ● Code restrictions on building height ● Electrical and plumbing costs may	Requires preservation in moist and tropical climates to protect the wood against deterioration and decay	Would likely speed-up the schedule if implemented because it would replace any concrete curing time and all panels with window and door openings would be pre-cut

					• Naturally fire resistant	increase due to lack of wall cavities		Could have long lead times if impacted by shortage of timber
Smart glass	$50-150 per sf	n/a	yes	no	• Easy to use • Provides control to the user at the switch of a flip • Can help regulate the internal climate • Saves money on HVAC	• High cost • Difficult installation • High electrical consumption • Not widely used	Cleaned just like a regular glass window. It could potentially be destroyed by humidity or heat, so regular checks of the silicon gel. Regular checks of the film and transformer is needed to ensure the mechanics still work	Lead time is 2-3 weeks and the delivery can be 5-10 days.
Robotics	N/A	Time and money spent during construction	yes	no	• Speeds up the process of layout • Prevents human error during layout - lines are drawn accurately the first time and contain more information than typically seen • Subcontractors are free to learn other aspects of their trade • Potential for WPI MQP's to work with companies such as Rugged Robotics and learn more about the innovative process	• This technology is still very new and not yet widespread • The construction industry is known for showing resistance to innovations in technology on the job site • Some laborers may view these robots as their replacements/taking away their work	N/A	Considerable reduction in layout times during construction.

Appendix M. LEED Estimates

Credit Scorecard

LEED Category	Subcategory	Pre-req	Possible Points	Applied to project	notes
Location and Transportation	Sensitive Land Protection		1	1	
Location and Transportation	High priority Site and Equitable Development		2	0	
Location and Transportation	Surrounding Density and Diverse Uses		5	4	
Location and Transportation	Access to Quality Transit		5	0	
Location and Transportation	Bicycle Facilities		1	1	as long as we provide storage for 13 bikes
Location and Transportation	Reduced Parking Footprint		1	1	
Location and Transportation	Electric Vehicles		1	0	
Sustainable Sites	Construction Activity Pollution Prevention	y			create and implement erosion/sedimentation control plan
Sustainable Sites	Site Assessment		1	1	include how this influenced design
Sustainable Sites	Protect or Restore Habitat		2	0	
Sustainable Sites	Open Space		1	1	
Sustainable Sites	Rainwater Management		3	3	retain increase in runoff
Sustainable Sites	Heat Island Reduction		2	0	
Sustainable Sites	Light Pollution Reduction		1	1	
Water Efficiency	Outdoor Water Use Reduction	y			ensure no irrigation required
Water Efficiency	Indoor Water Use Reduction	y			reduce water by 20% from baseline
Water Efficiency	Building-Level Water Metering	y			instal permanent water meters
Water Efficiency	Outdoor Water Use Reduction		2	2	
Water Efficiency	Indoor Water Use Reduction		6	3	
Water Efficiency	Optimize Process Water Use		2	2	minimum 30% recycled alternative water
Water Efficiency	Water Metering		1	1	install permanent water metering
Energy and Atmosphere	Fundamental Commissioning and Verification	y			
Energy and Atmosphere	Minimum Energy Performance	y			
Energy and Atmosphere	Building-Level Energy Metering	y			

Energy and Atmosphere	Fundamental Refrigerant Management	y			
Energy and Atmosphere	Enhanced Commissioning		6	3	
Energy and Atmosphere	Optimize Energy Performance		18	9	
Energy and Atmosphere	Advanced Energy Metering		1	1	
Energy and Atmosphere	Grid Harmonization		2	2	
Energy and Atmosphere	Renewable Energy		5	3	
Energy and Atmosphere	Enhanced Refrigerant Management		1	1	
Materials and Resources	Storage and Collection of Recyclables	y			safe disposal in disposal areas
Materials and Resources	Building Life-Cycle Impact Reduction		5	1	conduct life cycle assessment
Materials and Resources	Environmental Product Declarations		2	1	
Materials and Resources	Sourcing of Raw Materials		2	1	
Materials and Resources	Material Ingredients		2	1	
Materials and Resources	Construction and Demolition Waste Management		2	1	
Indoor Environmental Quality	Minimum Indoor Air Quality Performance	y			
Indoor Environmental Quality	Environmental Tobacco Smoke Control	y			
Indoor Environmental Quality	Enhanced Indoor Air Quality Strategies		2	2	
Indoor Environmental Quality	Low -Emitting Materials		3	3	
Indoor Environmental Quality	Construction Indoor Air Quality Management Plan		1	1	
Indoor Environmental Quality	Indoor Air Quality Assessment		2	2	
Indoor Environmental Quality	Thermal Comfort		1	1	
Indoor Environmental Quality	Interior Lighting		2	2	
Indoor Environmental Quality	Daylight		3	2	
Indoor Environmental Quality	Quality Views		1	1	

Indoor Environmental Quality	Acoustic Performance		1	1	
Integrative Process	Integrative Process		1	1	analyze two
Innovation	Innovation		5	0	
Innovation	LEED Accredited Professional		1	1	LEED accredited professional on project team
Regional Priority	Regional Priority Specific Credits		4	4	
		sum	110	**66**	
				LEED Gold	

Certification Cost Estimate

LEED

Price Estimate

Estimate On: 19 Jan 2022, 11:31:06 am

Product	LEED
State	Massachusetts
Country	United States
Currency	USD - United States Dollar

Project Type: Campus Project **Rating System:** LEED v4 BD+C: New Construction Request: 1

Item	Timeline							
	Precert + Combined		Combined		Precert + Split		Split	
	Member*	Non Member	Member*	Non Member	Member*	Non Member	Member*	Non Member
Registration	$ 1,200.00	$ 1,500.00	$ 1,200.00	$ 1,500.00	$ 1,200.00	$ 1,500.00	$ 1,200.00	$ 1,500.00
Precertification Preliminary Review	$ 3,200.00	$ 4,000.00	–	–	$ 3,200.00	$ 4,000.00	–	–
MQP - 99,758,670 sq ft								
|— Design and Construction Preliminary Review	$ 4,549.00	$ 5,426.87	$ 4,549.00	$ 5,426.87	–	–	–	–
|— Design Preliminary Review	–	–	–	–	$ 3,750.93	$ 4,389.38	$ 3,750.93	$ 4,389.38
|— Construction Preliminary Review	–	–	–	–	$ 1,276.91	$ 1,436.52	$ 1,276.91	$ 1,436.52
Total	**$ 8,949.00**	**$ 10,926.87**	**$ 5,749.00**	**$ 6,926.87**	**$ 9,427.84**	**$ 11,325.90**	**$ 6,227.84**	**$ 7,325.90**

Pricing includes the 20% discount on certification fees for campus project.

*USGBC Silver level and higher. For additional information on USGBC membership please visit www.usgbc.org.

NOTE:

- All estimates are based on the Gross Floor Area (visit https://www.usgbc.org/help/what-gross-floor-area) provided. As these inputs change, the price will vary accordingly. Please note that prices are subject to change.
- To register, please visit LEED Online at www.leedonline.com.
- LEED, or Leadership in Energy & Environmental Design, is a green building certification program that recognizes best-in-class strategies and practices. The Green Business Certification Inc. (GBCI) administers the LEED certification program, performing third-party technical reviews and verification of registered projects to determine if they have met the standards set forth by the LEED system.

Appendix N. Solar Panel Calculations

solar area = (42'(5) + 20')(20'(2) + 7.5')

= 10,925 ft^2

Commercial solar panel unit: 78in x 39in

$= 78\text{in}(39\text{in}) = 3042\ \text{in}^2 \left|\ \frac{1\ \text{ft}^2}{12^2\ \text{in}^2}\right. = 21.125\ \text{ft}^2$

Use 70% of solar area for panels

$0.7(10925\ \text{ft}^2) \left|\ \frac{\text{panel}}{21.125\ \text{ft}^2}\right. = 362.012$ panels

362 panels

$0.7(10925\ \text{ft}^2) = 7647.5\ \text{ft}^2$ for use

- 100kW solar power system
- $300,000
- needs 6,500 ft^2 space
- 12000 kWh/month
- assume 5 sun hours/day, panels face south
- 20 $\frac{\text{kWh}}{\text{sq ft}}$ each year   - 22.59 ¢/kWh

New Res hall

$99758.67\ \text{sq ft} \left|\ \frac{20\ \text{kWh}}{\text{sq ft year}}\right. = 1995173.4\ \frac{\text{kWh}}{\text{yr}}$

need $1995173.4\ \frac{\text{kWh}}{\text{yr}} \left|\ \frac{22.59¢}{\text{kWh}}\right. \left|\ \frac{1\$}{100¢}\right. = \$450,709.67/\text{yr}$

solar $12000\ \frac{\text{kWh}}{\text{month}} \left|\ \frac{22.59¢}{\text{kWh}}\right. \left|\ \frac{1\$}{100¢}\right. \left|\ \frac{12\ \text{mon}}{1\ \text{yr}}\right. =$ save $32,529.6/yr

only 7% of bill

$\frac{\$300,000\ \text{install}}{\$32,529.6\ \text{save/yr}} = 9.22$ yrs to pay off