Design for a Performing Arts Center for Worcester Polytechnic Institute

A Major Qualifying Project Proposal submitted to the
Faculty of 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

This project focused on the significant elements of structural design for a Performing Arts Center (PAC) at Worcester Polytechnic Institute. The PAC was proposed to provide more space for students in the music and theater programs, including practice rooms, classrooms, storage rooms, and an improved auditorium. The critical need for these spaces was determined via interviews and surveys with students, faculty, and staff. This information was used to create an architectural program from which floor layouts were designed. From these layouts, an architectural Revit model was developed alongside a structural frame design. The project also featured a construction schedule, cost estimate, and considerations for sustainability and acoustics to deliver a comprehensive proposed building.

Capstone Design Statement

Worcester Polytechnic Institute (WPI) requires that the Civil, Environmental, and Architectural Engineering Department prepare students for engineering practice through design projects to meet ABET (Accreditation Board for Engineering and Technology) standards and capstone design, in particular. The Major Qualifying Project (MQP) is completed towards the end of a student's undergraduate career and brings together the different disciplines and information learned to address a technical issue in the field. This MQP focused on designing a new Performing Arts Center for WPI to address the needs of students and faculty concerning space and acoustics for performances. The following realistic constraints were considered in this design project.

Economic

While designing the Performing Arts Center, the team performed a cost estimate for construction activities which included total material costs, labor costs, and project overhead costs. Cost considerations were reviewed, such as direct costs related to design, project management, and construction work. The costs of any additional components that have been added to increase sustainability advantages in the building were considered as well.

Social

The new Performing Arts Center will benefit students in theater, choral, and musical instrument groups. The building includes more practice rooms, rehearsal spaces, classrooms, and other spaces that will foster more community engagement with different organizations. This project also considered site selection. With that, Gateway Park, (specifically the Salisbury Square area) was chosen as the project location due to access to a larger building area and more space for parking. Sound and general height compatibility with surrounding structures were also considered for this project.

Ethical

The team followed the design guidelines of the American Society of Civil Engineers Code of Ethics to provide a sufficient design for the new Performance Art Center building. The construction and the chosen lot in Gateway were considered as well in terms of how the building fits in that specific area in Worcester.

Health and Safety

Zoning regulations from the City of Worcester were implemented at the beginning of the project. The team also followed requirements within the Massachusetts State Building Code to collect information on load capacities for spaces and the provisions of the American Institute of Steel Construction (AISC) to develop the structural steel design. The American Society of Civil

Engineers Code of Ethics was used to ensure the overall aim of the building. These sections in the Code of Ethics were considered:

- 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..”

Constructability

Considerations to promote ease of construction included (but are not limited to) the use of standard section sizes for structural members and a repetitive structural layout with consistent dimensions and material properties. A construction schedule was completed in Microsoft Projects and estimates of direct and indirect costs were prepared using information found in the RSMeans Online catalog.

Sustainability

This project includes an assessment for LEED certification as well as ways the Performing Arts Center can be more sustainable for students and faculty over the years such as integrating solar energy, implementing LED lighting, and more.

Professional Licensure Statement

Individual states require that engineers in their respective fields are held to a standard of knowledge and experience by having the necessary licensing to complete projects in certain industries. This license ensures quality work in projects nationally and promotes best practices and understanding in the long run. The National Council of Examiners for Engineering and Surveying (NCEES) supports the implementation of state law by providing the licensing exams and serving as a clearinghouse for information and records.

There are multiple steps involved in obtaining a professional license that requires time, effort, and experience inside and outside formal education. First, one must graduate from an approved undergraduate program that was certified by the Accreditation Board for Engineering and Technology (ABET). Next, one must successfully complete their Fundamentals of Engineering (FE) exam, which can be taken as early as a student's senior year before graduation, or after getting a bachelor's degree. Individuals obtain an Engineer in Training (EIT) certification and work in the industry for four years under a licensed Professional Engineer (PE). With four years of experience, one then applies to determine their eligibility to take the Professional Engineering exam in their state.

Obtaining a PE license can be beneficial for multiple reasons including career development, increase in earnings, flexibility, and leadership. A PE license is required to sign and approve drawings, and PEs hold authority in engineering firms. They have more options in their careers as well and are able to start their own businesses. Moreover, PEs must be professional in the workplace and uphold standards set by the National Society of Professional Engineers (NSPE) Code of Ethics. The NSPE fosters a community of growth, accountability, and knowledge for engineers; its goal is to provide a safe environment in multiple industries.

In this project, a PE would need to approve the structural steel designs and the way loads and moments were addressed before final submission or before fabrication in other real-world projects. Due to the importance of accurate and safe construction for the health and welfare of society, it is essential for more civil and structural engineers to obtain their PE license. In this line of work, the more PEs a firm has, the more opportunities they have to grow and take on new projects. Data shows that licensed engineers have a higher salary in their careers as well.

1. Introduction

At WPI, students are more than engineers. WPI has prioritized well-roundedness in its students for over 50 years through the development of a Humanities and Arts (HUA) requirement. Many options are available to students to fulfill their HUA project including language, history, and performing arts. Hundreds of students choose to further participate in performing arts at WPI through one of the over twenty-five clubs on the campus focused on performing arts.

With the importance of performing arts on campus, it is astonishing that WPI does not have an adequate facility. WPI's Alden Hall has been the official home of performing arts on campus for almost thirty years, but the facility is inadequate in the most important aspects of a Performing Arts Center - performing and group rehearsal space, practice rooms, and storage.

As WPI continues to admit more students, the situation in Alden Memorial is getting worse. Many ensembles are now reaching over 100 students but with only one space on campus capable of holding rehearsals with groups that size, what are groups to do? Groups have taken to rehearsing in the basement of Sanford Riley, a dormitory on campus, and even the Campus Center. On an individual level, students looking to practice have two choices: occupy one of the few practice rooms or occupy an entire classroom. With over 1,800 students in music ensembles on campus, the lack of individual practice space is unacceptable.

Storage in Alden Memorial is an even larger issue; every space in Alden is occupied to the maximum capacity. As dedicated storage space runs out, groups are forced to use hallways, classrooms, or facility spaces to store equipment. This limits the ability to use spaces for their designed purpose and poses many accessibility issues to everyone in the building.

Even with renovation, Alden Memorial is an inadequate facility. The space is simply too small for the current and growing size of WPI.

The student team designed a new Performing Arts Center for the WPI community. The project was defined in terms of the following six objectives:

1. Identify the needs of WPI for a Performing Arts Center
2. Design the layout and floor plans for a new Performing Arts Center
3. Create a Structural Design
4. Create a Construction Schedule and Cost Estimate
5. Conduct Sustainability and Acoustic Analyses on the proposed design
6. Develop a 3D model of the proposed design

First, the team established the necessary spaces and attributes for a Performing Arts Center. The team designed the layout and floor plans incorporating these necessary spaces and created a corresponding structural design. The group then developed a project schedule for the building and derived a cost estimate. Sustainability and acoustic analyses were conducted to supplement the structural design. Finally, the team developed a 3D model of the design incorporating the proposed site and architectural layout as well as the structural design.

The team submitted the following deliverables at the end of the project:

- A basic layout and 3D Model by Autodesk Revit,

- A structural design including member sizes for beams, girders, columns, and other primary structural elements and their appropriate materials,
- A project schedule and cost estimate, and
- Recommendations for sustainability and acoustic designs.

2. Background

2.1. Introduction

In this section, guiding information for each stage of the project is discussed. To establish the contents of a new Performing Arts Center, WPI's history in the performing arts and the current and past uses of the school's facilities were researched. It was important to create a building that accurately reflects WPI's needs for both arts and sciences. The team also spent considerable time discussing the selection of the building location and the regulations associated with that location. Structural steel design and materials were discussed to determine the best processes to establish the building's structural design. Finally, the computer tools used in the project and how they assisted the team are described.

2.2. WPI and the Status of its Existing Performing Arts Centers

As a STEM-focused school, performing arts may not be seen as the top priority at WPI. Still, hundreds of WPI students chose to participate in performing arts. There are over 25 performance groups and clubs which are incredibly taxing on WPI's current limited rehearsal areas which include Alden Memorial, Riley Commons in the basement of Sanford Riley Hall, and WPI's Little Theater. In addition, a partnership started about ten years ago in which the First Baptist Church (FBC) agreed to allow WPI music groups to use their spaces when they are not in use by the church. As a result, all WPI choir activities and resources exist in the FBC including rehearsals, storage of concert attire, and their music library. As well, despite theater groups performing in Alden Memorial, most of their storage was spread out in other buildings around campus and even off-campus facilities. Clearly, WPI's current Performing Arts Center, Alden Memorial Auditorium, does not have the necessary space for WPI's performing arts.

Alden Memorial was first opened in 1940 and was used to host lectures, performances, and other events, not to serve as a Performing Arts Center. In 1992, after 52 years of service as an auditorium for lectures and performances, WPI completely renovated the building to transform it into a center for performing arts (Alden, 2022). The Great Hall was left nearly untouched by this renovation despite it being the largest performing space at WPI with, unfortunately, poor acoustics. The basement of Alden features one large recital hall (Spaulding Hall), one smaller rehearsal space (Perrault Chamber Room), two private practice rooms, a music technology lab, a computer lab, and one music classroom. A "sub-basement" located below the basement, is used for storing lighting and sound equipment, a wood shop for set building, and a maintenance area. These spaces are not adequate for the size of WPI's student body. For example, private practice rooms are essential to the development of student talent, and the two designated spaces are not enough for the hundreds of students in WPI's performing arts. Storage is also important to ensure students have access to the performing arts. In the basement, three instrument closets are available for all students to store their instruments. Offices are also important to keep professors in touch with students. There are only a few offices in Alden, which has forced professors to share offices or move their offices to other buildings. The Director of Choral Activities and Coordinator of Music Ensembles, Joshua Rohde, has his office in the FBC.

Alden Hall also has numerous accessibility concerns. There is only one set of public bathrooms in the building, which is located below the main floor. Alden also only has one elevator that is placed inconveniently at the back of the building. There is no proper lobby area for people to converse prior to an event causing attendees to often wait outside the building for events to begin. In conclusion, Alden Hall has been struggling to uphold the demand of the current student body and staff alike, causing a compromise in the quality of their experiences; WPI is in desperate need of a new purpose-built Performing Arts Center.

2.3. Building Site and Zoning Regulations

Determination of the building site of the Performing Arts Center (PAC) was based on meeting three parameters - building site area, location, and constructability. The site area was seen as the largest restriction to the overall design of the facility since it limits the maximum dimensions of the building. The location of the PAC was also an important factor to consider since many students do not have cars or bicycles which would make the PAC inconvenient if it was built far from campus. Constructability was another focus as the team aimed to lower the chance of complications arising during the planning and construction processes. This included analyzing the building site level and viewing the Worcester City Zoning Ordinance to ensure the assigned zoning district coincides with the proposed building's use case. If the initial building site did not match the required use case, then additional actions were considered.

According to the Worcester Zoning Ordinance, WPI's Campus and Facilities all currently lie in an IN-S district, designated for Institutional/Educational uses, which allows the construction of a PAC. Gateway Park is in a BG-6.0 zone, which is designated for general business applications and also allows for the construction of a PAC.

If the PAC were to be constructed in a zoning district where it is not permitted, a zoning district change may be requested to have it re-zoned. This process involves filing an application to the Worcester Zoning Board of Appeals, followed by hearings in front of the Board and a final vote by the Board on whether to approve the application. In other specific cases, some zones do allow for the construction of a PAC but only if a special permit has been obtained. A special permit can be issued by a special permit granting authority, once an application for the permit has been completed followed by a hearing with the special permit granting authority.

There are restrictions set on how close the building can be to the property line, known as setbacks. For a new building constructed in an IN-S zone, the front of the building must be a minimum of 15 ft away from the property lines and the sides and rear of the building must be a minimum of 10 ft away. These restrictions impacted the final design of the structure and reduced the allowable space for the structure to be built. A BG-6.0 zone has no required setbacks. Consideration was also given to the context of the area. This inherently limited the height potential of the final structure design so that it wouldn't seem out of place in the area.

2.4. Building Code and Sustainable Development

There are criteria that must be followed for the new facility to adhere to the 780 CMR Massachusetts State Building Code. Applicable standards from the 780 CMR, including 527 CMR (fire protection), 310 & 314 CMR (environmental protection), and 780 CMR section 13.00 (energy efficiency), were referenced. Careful consideration of the environmental protection codes would be critical in maintaining WPI's pledge in 2007 to require all new buildings to achieve LEED Certificates. Building codes also apply to components such as elevators (524 CMR: Elevators). Designing the structure by following the appropriate codes is important for the safety of the occupants as well as the area around it. The *International Building Code* (IBC) was referenced in tandem with the *Massachusetts State Building Code* (MSBC); however, in instances where the two codes contradict each other, the MSBC overrules the IBC code.

2.5. Structural Design and Materials

For WPI's new Performing Arts Center, A992 steel was used as the reference material in the structural frame. ASTM A992 steel is the preferred material choice for W-shapes, the most common section used in structural framing due to the significant strength in major-axis bending (Tavarez, 2018). A992 steel is commonly used for its high yield strength of 50 ksi (F_y = 50 ksi) and ultimate strength of 65 ksi (F_u = 65 ksi). However, there are materials with nearly identical strengths like ASTM A572 Grade 50 steel (F_y = 50 ksi, F_u = 65 ksi), and even materials that exceed those strengths, such as ASTM A572 Grade 65 steel (F_y = 65 ksi, F_u = 80 ksi) (Tavarez, 2018). A992 has taken over as the standard in rolled-shape production over the previous standard of A572 Grade 50 due to some major advancements in serviceability, ductility, and corrosion resistance. A992 has an increase in weldability compared to A572 Grade 50, and its high corrosion resistance was critical for long-standing applications that could be exposed to weather (American Institute of Steel Construction, 2021; Infra-Metals Co., 2023). A992 and other high-strength, low-alloy steels are chosen for structural framing over carbon steels like A36 steel due to their increased strength, wear resistance, and long-term durability due to the inclusion of other alloys in addition to carbon (Anjoran, 2018). The use of high-strength steel in structural framing allows the creation of a structure that is strong and lightweight in comparison to other building techniques like concrete construction.

Concrete is less expensive to produce than steel and is much stronger in compressive applications, like column footings, rather than in tensile applications like beams. Concrete emits less CO_2 per ton than steel, with approximately 0.9 metric tons of CO_2 emitted per metric ton of concrete versus 1.85 metric tons of CO_2 emitted per metric ton of new steel (non-recycled). (Kamczyc, 2021; EPA 2019). However, the steel industry is using more recycled steel scrap in its production to help cut down CO_2 emissions. According to the American Institute of Steel Construction, "structural steel produced in the United States contains 93% recycled steel scrap", and around 98% of structural steel is recycled without any loss in material properties (American Institute of Steel Construction, 2023). By using recycled steel in manufacturing, CO_2 emissions can be reduced by 1.5 metric tons per metric ton of steel, which results in an 80% reduction in CO_2 emissions. (Kamczyc, 2021).

In adherence with WPI's LEED Certification pledge, the use of recycled steel rather than concrete would be beneficial. Thus, it was decided to use only steel for the superstructure design of the building, excluding the foundations. That way it was still possible to construct the facility to withstand the loads for its use case while also adhering to LEED Certification requirements.

2.6. Computer-Based Tools

Modern engineering practices rely on the use of technology to complete tasks faster and more efficiently. Websites and software are used to complete many tasks in design, from calculations to 3D modeling to scheduling. In previous academic experiences, the team created calculators for the design of structural members in both Microsoft Excel and Google Sheets, two extremely powerful spreadsheet tools. These tools were used for a majority of the structural calculations for standard beams, girders, and columns, and for the tabulation of the final sizes for these items. The extensive calculation and customization options in Google Sheets allowed the team to create easy-to-read tables. Google Sheets was also used to help generate a cost estimate for the project by inputting average construction rates and costs and multiplying them by the quantities applicable to the building. Another powerful tool utilized was Bluebeam Revu, a standard in PDF editing for civil engineers, architects, and contractors. The numerous annotation and scaling options available in the software are optimal for reviewing contract drawings and construction plans, and for marking up architectural renderings. Bluebeam was used to create a detailed layout of the structural frame including bay numbers, beam and girder lengths, and column locations.

A variety of design software programs were used to assist in the modeling of the building. Autodesk Revit is an industry standard in architectural and structural modeling of buildings and excels in interoperability with various model types. Revit is capable of producing complex Building Information Models that take input from architects, structural engineers, MEP designers, and civil engineers, and create construction schedules and 4D phasing plans. For this project, the team used Revit to create the architectural floor plan and structural framing plan.

Certain parts of the structural design required advanced structural analysis that could not be completed manually; RISA-3D was used to solve these problems. RISA-3D is a structural analysis software that uses finite element analyses alongside building codes and design specifications to assist in the design of systems. While the program cannot generate a design, it can provide reaction and internal forces as well as deflections to assist in the selection or design of structural sections. This software was ideal for testing out structural ideas in an isolated environment without having to analyze the entire building system at once.

The last program used was Rhinoceros 3D (Rhino), which models small and large objects visually. Rhino is a 3D computer-aided design application software that can simulate and calculate reverberation time and clarity of sound through the use of a plug-in called Pachyderm Acoustics. Pachyderm can be downloaded and accessed through a tool in Rhino titled

“Grasshopper.” According to applications for Rhino and Grasshopper, Pachyderm contains “algorithms which can be used to predict noise, visualize sound propagation, and critically listen to designed spaces.” (Arty, 2021). By assigning certain objects and spaces with dimensions in meters, Pachyderm can simulate sound vectors and sound particles based on the number of bounces.

3. Methodology

3.1. Introduction

The goal of this project was to design a new Performing Arts Center for WPI that meets the needs and desires of students, faculty, and staff. A flowchart of the project's steps taken to reach this goal is shown below in Figure 1. The schedule to complete these objectives can be found in Appendix B.

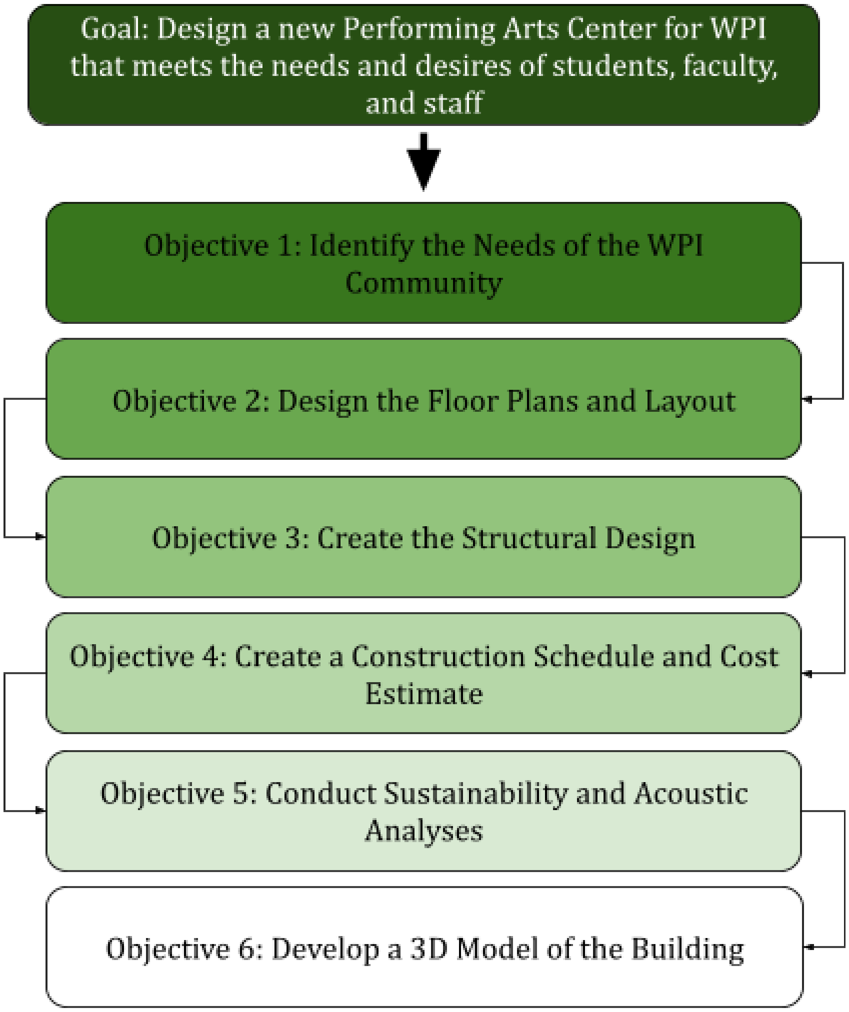


Figure 1: Flowchart Depicting the Progression of the Project Objectives

3.2. Identify the Needs of the WPI Community

3.2.1. Evaluate Alden Hall and Other Performing Arts Centers

First, the team toured Alden Hall, investigating the layout and current operation of the building. The original renovation schematics of Alden Hall from 1992 were reviewed as a reference for typical room sizes in a Performing Arts Center. The current occupancies of spaces in Alden Hall were identified and used to estimate the room sizes in the new buildings based on the desired occupancies.

3.2.2. Creating and Conducting Surveys and Interviews

The team collected feedback and opinions directly from members of the WPI community on whether or not a new performing arts center is needed. An online survey created via Google Forms was distributed to WPI students in the humanities and arts community, which asked students their thoughts on Alden Hall, as well as what inclusions the team should make in the PAC which would most benefit their specific group(s). Questions on this survey aimed to probe interest in the type of auditorium space (i.e, either a classic proscenium-style stage or a more open-concept recital hall; see *Figures 2* and *3* below). The survey also asked the respondents for their thoughts on the inclusion of other rooms typically found in Performing Arts Centers, such as rehearsal halls, storage, and practice rooms, as well as more versatile spaces such as a lobby, box office, study spaces, and classrooms. An open response section allowed students to include any additional thoughts they had on the subject as well. The prompts in the survey are provided in Appendix C.

Figures 2 & 3: Mechanics Hall, Worcester, MA, an Acoustically-Focused Concert Hall (left, Concerts & Performances, n.d.) and the Auditorium Building, Chicago, IL, a Traditional Proscenium Stage (right, Encyclopedia Britannica, n.d.)

Additionally, faculty and staff in the humanities and arts community were interviewed to obtain their opinions on WPI's current assets and the features they would want to see in a new Performing Arts Center. Interview questions were similar to those asked in the student survey, but with a focus on the individual's professional experiences in the performing arts. All interviewees were asked for consent to record the interview and quote their responses in the report as necessary. The questions asked in the interviews are available in Appendix C. The major takeaways from each interview were tabulated and reviewed as well as the most common responses to questions in the survey. These data were used to create an architectural program for the building, defining the desired spaces as well as floor plan organization and room sizes.

3.3. Design the Floor Plans and Layout

After creating an architectural program, the team began to locate potential building sites that would fit that program. The top two candidates, both of which were already owned by WPI, were an approximately 40,000-square-foot lot behind WPI's Ellsworth Apartments (referred to as the Erskine Lot) and a significantly larger 65,000-square-foot lot near WPI's Gateway Garage. The two locations are shown below in Figures 4 and 5 as aerial images from Google Maps (MassGIS et al., 2023).

Figures 4 & 5: Erskine Lot behind Ellsworth Apartments at WPI (left), and Property near WPI's Gateway Park (right)

The lot near Gateway Park is considered a "building-ready pad", meaning the site has been appropriately prepared with utility extensions and soil surveys. This was more desirable than the Erskine Lot, which is currently used as storage and has a considerable slope that would require more excavation. The 65,000 square feet at the Gateway site would serve as more than enough area for the intended use. Zoning would not be an issue for either plot, as the current zone in each area allows for this type of construction, as mentioned in Section 2.3. The Gateway plot is a significant walk away from WPI's main campus, but WPI's largest parking garage is within close proximity. With all of these factors, the plot at Gateway Park was selected as the location of the new building.

Hand drawings of potential building layouts were created by each team member (see Appendix D), then compared to help develop the initial design. A scaled functional layout of the building was drawn on engineering paper as seen in Appendix E. The table of required room sizes compared to Alden Hall, which was prepared in the previous objective, was used to fit the desired spaces into the building.

Table 1 - Building Program (below) details the applicable zoning regulations, use and occupancy groups, and accessory occupancies. The square footage of each room was presented alongside the applicable loadings as well.

Table 1: Building Program

After reviewing the building codes and zoning regulations applicable to constructing a new Performing Arts Center on WPI Campus, the following building program was developed. The program provides detailed information regarding building size, egress capacity, number of offices, practice rooms, and auditorium design.

Project
WPI Performing Arts Center

Project Address/Site
51 Prescott St, Worcester, MA 01605

Project Description
The project will feature the construction of a new Performing Arts Center in Gateway for the WPI Campus.

Table 1.1: Applicable Codes/Zoning Laws

Building	780 CMR - Massachusetts State Building Code 9th Edition
Fire Code	527 CMR - Massachusetts Comprehensive Fire Safety Code
Accessibility Regulations	521 CMR - Architectural Access Board (AAB) Rules and Regulations
Zoning Laws	Worcester Zoning Laws

Table 1.2: Use and Occupancy Groups

Description	**780 CMR Classification**	**Level(s)**
(Main) Auditorium/Theater Space	Group A-1	1-4

Table 1.3: Accessory Occupancies

Description	780 CMR Classification	Level(s)
Lobby, Gallery, Lounges	Group A-3	1-4
Cafe	Group A-2	4
Offices	Group B	2-3
Dance Room	Group A-3	4
Storage Spaces	Group S-1	1-5

Allowable Building Height & Area

The building will be 5-stories above grade with the first four floors having dimensions of 215’ x 215’, and the fifth floor having a dimension of 215’ x 170’. Floors 1-4 are 15 feet high, and the fifth floor is 24 feet high. The total height of the building is 84 feet.

Table 1.4: Restrictions Set by Zoning Laws

Zoning District	BG-6.0
Relevant Permitted Uses	● Business, General ● Residential, non-residential ● No-accessory parking was required ● No height limitation ● Has parking subarea in Downtown ● no rear yard setback was required

Table 1.5: Lot Setbacks/Max Stories

District	Use	Lot	Yard Setbacks	Height	Floor to Area Ratio (Maximum)
BG-6.0	Residential, Non-residential	Area = 5000, no minimum SF Frontage = 40 per du4, no min linear ft	10 ft for minimum depth (linear ft.) for REAR	N/A	6 to 1

Table 1.6: Rooms

Space	**Floor(s)**	**Occupancy**	**Square Footage**
Auditorium	1,2		
Stage		120	1059
Seating		1600	5600
Wings		N/A	400
Dressing- Rooms		10	220
Backstage		10	405
Lobby	1	1600	2438.4
Gallery	1	1600	2438.4
Costume Shop	1	20	500
Green Room	1	20	1000
Woodshop	1	10	2000
Class	2,3,4	50	1500
Recording Studio	2,3	10	1000
Offices	2,3	1	175
Conference Room	2,3	15	450
Art Maker Space	2,3	50	2000
Lobby 2	2,3	1600	2400
Student Lounge	4	20	600
Dance Room	4	100	2800

Table 1.6: Rooms (Continued)

Space	Floor(s)	Occupancy	Square Footage
Rehearsal Rooms			
Choir	4	50	1200
Orchestra	5	50	1500
Band	5	50	1200
Practice Rooms	4,5	2	60
Blackbox Theatre	4		
Floor		30	1200
Seating		100	1500
Booth		2	100
Storage	2,3,4,5		
Instrument Lockers		250	1250
Piano Closet		3	300
LNL		10	1000
Chairs/Risers		1	500
Music Library		5	500
Bathrooms	B-5		
Public		2	700
Backstage		4	200

Table 1.7: Egress

Corridor	Size	
	4’0”	
Stairways	Number of Staircases	Sqft/person
	5	200
Elevators	Number of elevators	Sqft/person
	3	Freight - 200 Public - 100

Table 1.8: Loading Used

Live Load (LL)	Mostly used = 100 psf (varies)
Live Load for Elevators, Stage, and Fly Space (LL)	150 psf
Live Load for Auditorium Seating Areas	60 psf
Dead Load (DL)	85 psf
Snow Load	40 psf

3.4. Create the Structural Design

Using the floor plan layout as a guide, the structural layout of beams, girders, and columns was drawn onto the Revit floor plans using Bluebeam Revu. The first-floor structural plan can be seen below in Figure 6 as a sample, and all other floors can be seen in Appendix G. Columns were placed in the same grid location on each floor to create simple load paths. After establishing the structural bays and placing the columns (black circles) on the plans, girders were placed between columns (blue lines). Beams were placed (brown lines) with a typical ten-foot spacing, and high-load areas were given five-foot spacing. Spreadsheets with floor numbers and bay dimensions were created to tabulate the layout. Figure 7 below presents a flowchart that defines the structural scheme plan.

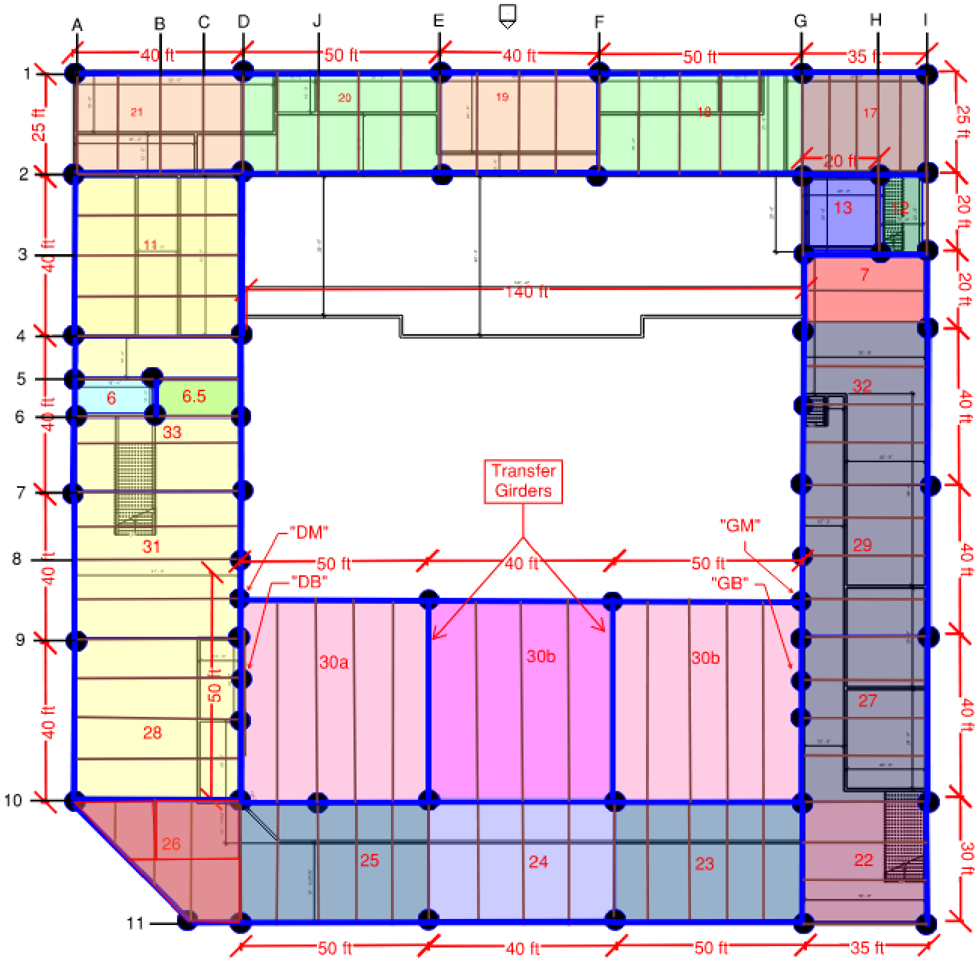


Figure 6: First-floor Layout of Beams, Girders, and Columns in Bluebeam Revu

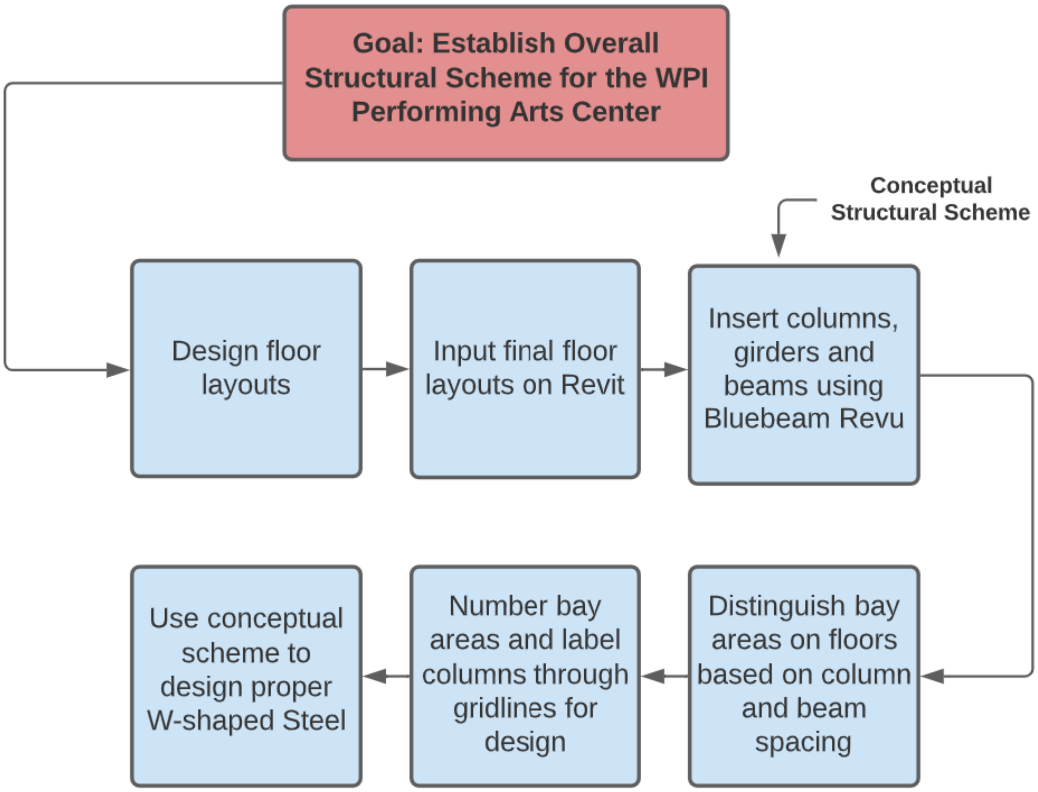


Figure 7: Flowchart establishing the Building Structural Scheme

With the structural layout drawings completed, the structural design began. Each bay was organized by girder and beam length and sorted into a girder scheme and a beam scheme based on similar parameters. Figure 8 below shows the steps taken to design each individual member. The use of beam and girder schemes allowed the design of one member to be used for multiple bays. Spreadsheets were developed that aided in the sizing of the beams, girders, and columns.

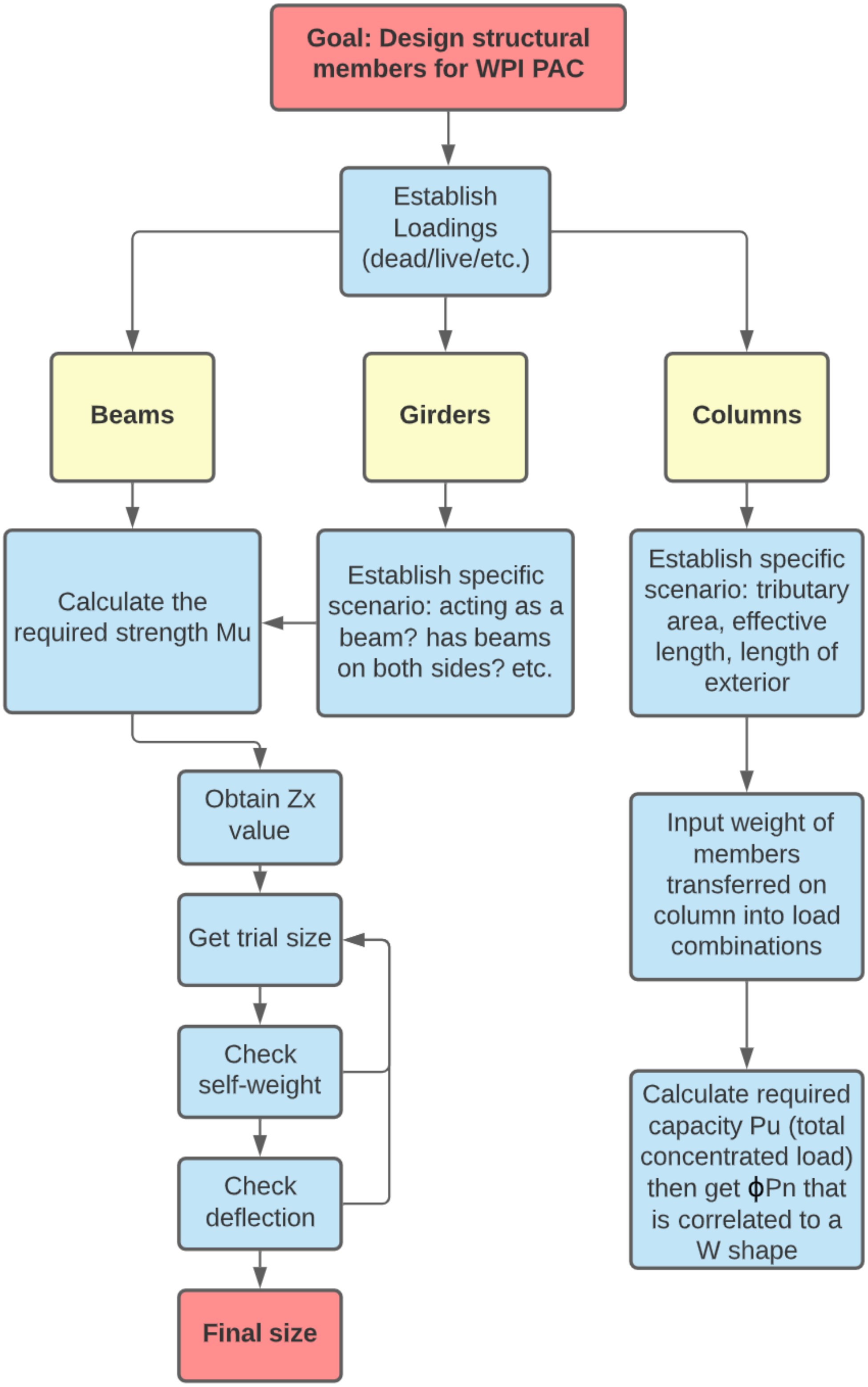


Figure 8: Flowchart for designing Structural Beams, Girders, and Columns

3.4.1. Beams

Structural designs went through three phases, following the load path: (1) beams, (2) girders, and (3) columns. Beams carry the dead and live loads associated with a given floor, including floor slab dead loads, superimposed dead loads (mechanical, electrical, and plumbing systems (MEP), and partitions) and use case live loads. Typical loadings are shown in Table 2.

Beam lengths for each bay were tabulated in an Excel spreadsheet, then categorized into schemes of similar members, i.e., cases where the variable design factors remained the same. To be part of a scheme (such as scheme 1 - refer to Appendix H), a member would need to support the same loadings, have the same span length, and have the same beam spacing within a bay. Some schemes were labeled as “atypical”, meaning that the beam designs are part of a unique bay that appears once within the building.

Table 2: Typical Floor Loading Categories and Values

Load Item	Load Category	Loading, pounds per square foot (psf)
Standard Classrooms, Offices, Hallways, Rehearsal Spaces	Live Load (LL)	100
Auditorium Seating Areas	Live Load (LL)	60
Stage and Fly Space	Live Load (LL)	150
Concrete Floor Slab on Metal Decking (5” total thickness)	Dead Load (DL)	75
MEP Systems	Dead Load (DL)	10
Roof and Snow Load	Roof Live Load (RLL) and Snow Load (S)	40

The structural steel beams were designed according to the Load and Resistance Factor Design (LRFD) provisions of the AISC Specification, which was developed into a spreadsheet design aid. The governing load combination established by ASCE 7-10 was typically 1.2DL+1.6LL, which was used alongside tributary widths to calculate the distributed load *Wu* in pounds per foot (plf). The distributed load and simple support conditions were used to calculate the maximum moment *Mu* and plastic section modulus *Zx*. The equations for *Mu* and *Zx* are below:

$$Mu = \frac{WuL^2}{8}; Zx = \frac{Mu}{\phi Fy} * 12\ \frac{in}{ft}$$

In the *Zx* equation, ϕ is the factor of safety, 0.9, and Fy is the yield strength of A992 steel, equal to 50 ksi. Refer to Appendix I to view a detailed hand calculation of a sample beam design. After an initial member size was selected, live load and combined live and dead load deflections were checked. Deflections were calculated using the basic distributed load deflection equation shown below:

$$\Delta = \frac{5WL^4}{384EI}$$

In this equation, *W* is the uniform load in pounds per foot on the beam due to either the live load or the combined live and dead load. *L* represents the length of the beam, *E* is the elastic modulus of steel (29000 ksi), and *I* is the moment of inertia of the beam (in inches^4). The live load deflection value (ΔLL) must be less than or equal to 1” or L/360, and the combined live and dead load deflection value (ΔD+LL) to L/240 in order for the selected beam design to remain adequate. Refer again to Appendix I to see deflection calculations for the sample beam designs.

3.4.2. Girders

Girders are responsible for supporting the weight of the beams in a bay, so the size and weight of the supported beams must be known before designing girders. The loading of each specific girder depends on the supported beam’s length, spacing, and the total number of interior purlins. Some girders carried both floor weight and individual beams and needed a modified M_u equation. Refer to Figures 9, 10, 11, and 12 below to see a variety of possible girder loading scenarios. These could be combined in any manner depending on the situation. Refer to Appendix I for a sample girder design that includes both interior purlins and facade weight, which follows LRFD provisions in the AISC Specification as well.

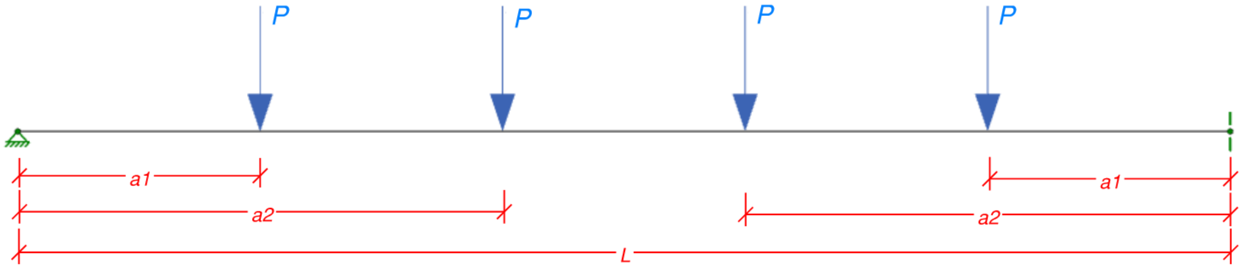


Figure 9: Sample Girder Scheme with Four Interior Purlins of Load P Equal Distances ‘a’ Apart

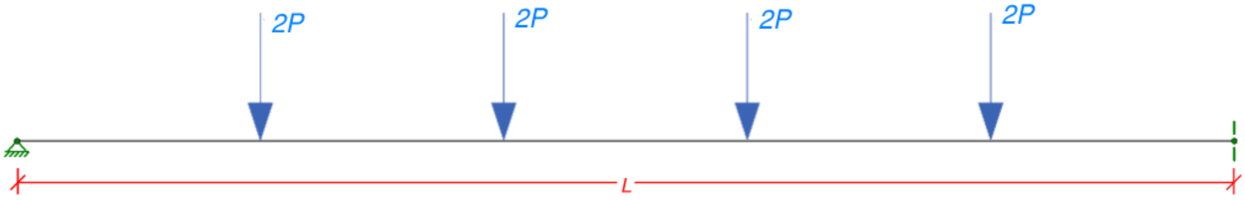


Figure 10: Sample Girder Scheme with Four Interior Purlins of Load 2P, which Indicates Purlins Sitting on Girder from Both Sides

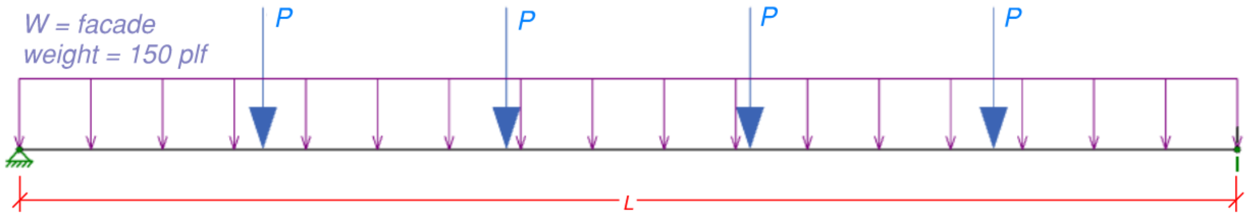


Figure 11: Sample Exterior Girder Scheme with Four Interior Purlins of Load P and a Distributed Facade Weight of 150 pounds per foot (plf)

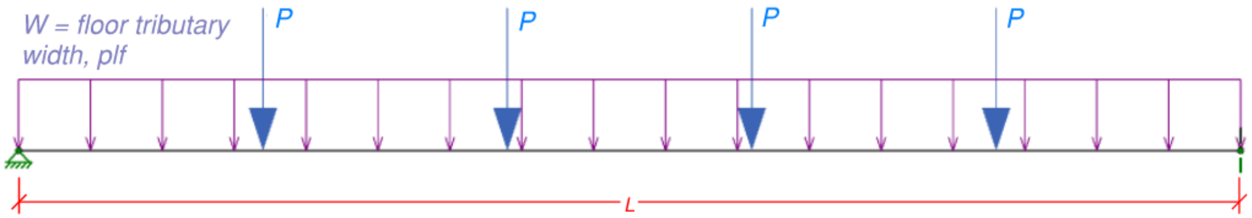


Figure 12: Sample Girder Scheme with Four Interior Purlins of Load P and a Distributed Weight from Supporting Floor Area Like a Beam on One Side

After selecting the trial girder size based on its plastic section modulus, deflections were checked using the principle of superposition. The equation for the deflection at midspan for members with multiple point loads, from the AISC Steel Manual Table 3-23, is given as

$$\Delta_{max} = \frac{Pa}{24EI}(3l^2 - 4a^2).$$

Here, *a* is the distance of a point load *P* from each end support (see Figure 9 above), *l* is the length of the member, and *I* is the major-axis moment of inertia. In Figure 9, *a1* and *a2* refer to the principle of superposition and indicate multiple uses of the equation above depending on the number of interior purlins. This equation was combined with deflection equations for single point loads at the center and uniform loads to determine the ultimate deflection on girders for live load and combined live and dead load applications. Refer again to Appendix I to see a deflection check for a girder.

3.4.3. Columns

Once the weights of the members on a column are determined, the column can be designed. To determine the ultimate point load on a column, *Pu,* in pounds, several pieces of information are needed. First, the loadings within the tributary area around the column must be known based on the floor plan layout created previously. The effective length *L'c* of the column must also be known, which was assumed equal to the floor height. For the first five levels in this building, $L'c = 15ft$, and on the 5th floor, to account for the elevated ceilings of the band and orchestra rooms, $L'c = 24ft$.

The most important part of a column design was the determination of the tributary area on the column. This value helps to calculate the portion of the floor loads that will be transferred to a specific column - it depends on the applicable loadings and the sizes of the bays adjacent to the column. A sample calculation for a tributary area is shown in Appendix L. To aid in the determination of the tributary area, a spreadsheet detailing each column on each floor and the bay sizes each column supports was created. A formula took the area of each bay, divided it by four, and then tallied up all the bays applicable to that column. Similarly, diagrams showing the tributary areas for each column were created as a visual aid. The diagram for the 4th floor is shown below in Figure 13 as an example.

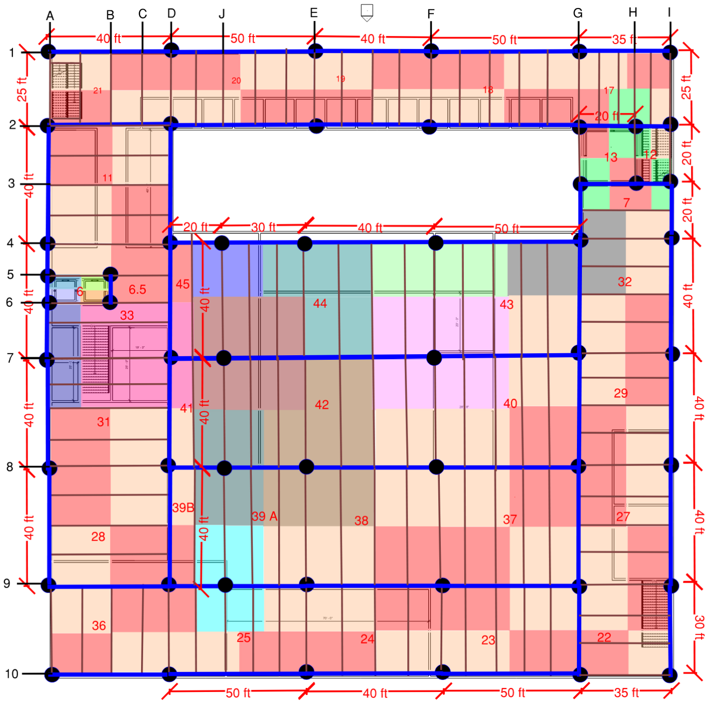


Figure 13: Tributary Area Plan for the Fourth Floor. Each Shaded Box represents the Area Supported by the Column within it.

Once tributary areas for each column were determined, the required column size was determined using LRFD provisions of the AISC Specification. The governing ASCE 7-10 load combination, 1.2D+1.6L+0.5S, was used to determine the ultimate load, *Pu*. AISC Steel Manual Table 4-1a was referenced to select a column size based on the effective length and allowable nominal load $\Phi_C Pn$. Refer again to Appendix L to see a sample column design. Simultaneous design spreadsheets were created to ensure the proper transfer of loads through the building. Refer to Appendix G for diagrams indicating column location. In those diagrams, column A1 refers to the column in line with grid label A at the top and grid label 1 along the left side (see Figure 13 above as a reference for this labeling tactic as well).

3.4.4. Column Base Plates and Footings

One of the last requirements to finalize the PAC involved designing the foundation of the building- individual column footings. To start, the team needed to complete a base plate design needed for the column footing. The required base plate and footing areas were determined so the length and width of the base plate could be calculated. Lastly, the team calculated the thickness of the plate and labeled the plate design under the appropriate nomenclature. The order in which the calculations were completed for the base plate is shown in Figure 14 below. All calculations pertaining to the column base plate were completed using a spreadsheet using equations found in the 5th Edition Structural Steel Design by McCormac & Csernak, which can be found under Appendix N.

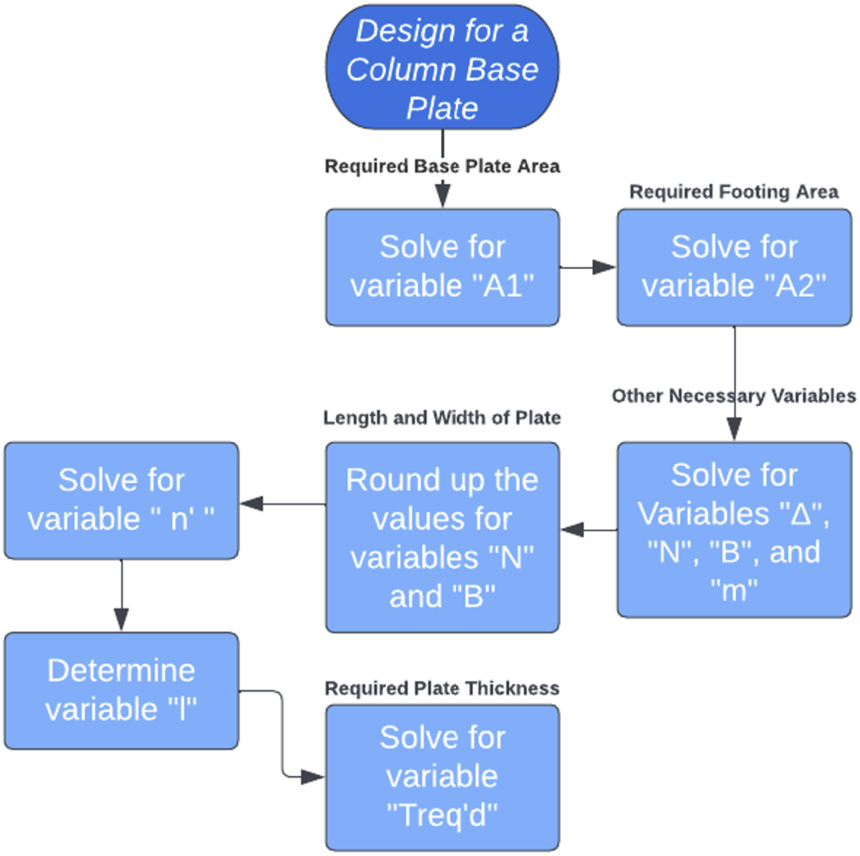


Figure 14: Flowchart explaining the Variables needed to solve for the Column Base Plate

Once the column base plate design was completed, the column footing design was determined. The team started out by calculating the allowable bearing pressure on the soil (Qe) and the required column footing area (Areq'd). Next, the team solved for the uniform load due to the total column load (Qu) using LRFD provisions to determine the total shear (Vu) that needs to be supported by the reinforced concrete footing system. ϕVc was calculated next and compared to Vc to determine if steel was required for added shear strength. Since the design required steel to be added to the footing, Vu was calculated a second time, leading to the calculation of the overall footing thickness. The ultimate moment was calculated next following the updated ultimate shear calculation. The ultimate moment helps to determine the required area of steel needed in the footing, by allowing the team to calculate the reinforcement factor (ρ). Once the area of steel was calculated, the team found the required rebar diameter as well as the number of bars needed at the effective depth of the footing. The order in which the calculations were completed for the column footing is shown in Figure 15 below. All calculations related to the column footing design are located in Appendix O.

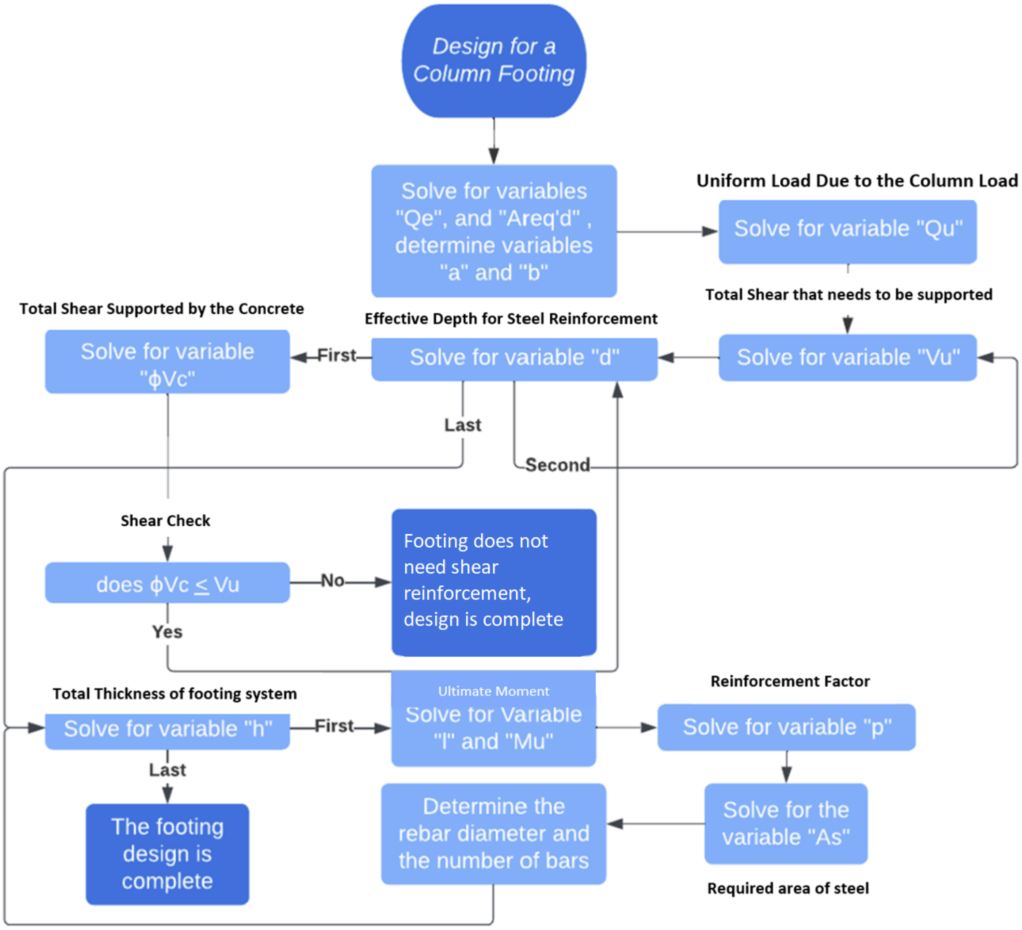


Figure 15: Flowchart explaining the Variables needed to solve the First Footing Design

The second approach investigated shear reinforcement design by incorporating wide flange sections in place of rebar. The purpose of this was so that the team can have multiple designs to choose from when finalizing the building design, as well as the benefit of making the footing more compact by choosing the footing dimensions prior to performing other calculations. The team then calculated the total shear that needs to be supported by the concrete followed by a shear check with the total shear calculated in the previous design. This led to the calculation of ϕVc_{Steel} which represents the total shear needed to be supported by the steel alone. After that, the team managed to determine the required area of steel. The AISC 15th Edition Steel Construction Manual was used to find the wide flange sizes as well as the number of members required for the footing. This process was repeated a second time for a footing area of a slightly larger size so that the team had two designs to compare. Finally, the team picked one of the three footing designs based on which option requires the least amount of materials. The order in which the calculations were completed for the column footing (with wide flange sections) is shown in Figure 16 below. All calculations related to the column footing design are located in Appendix O.

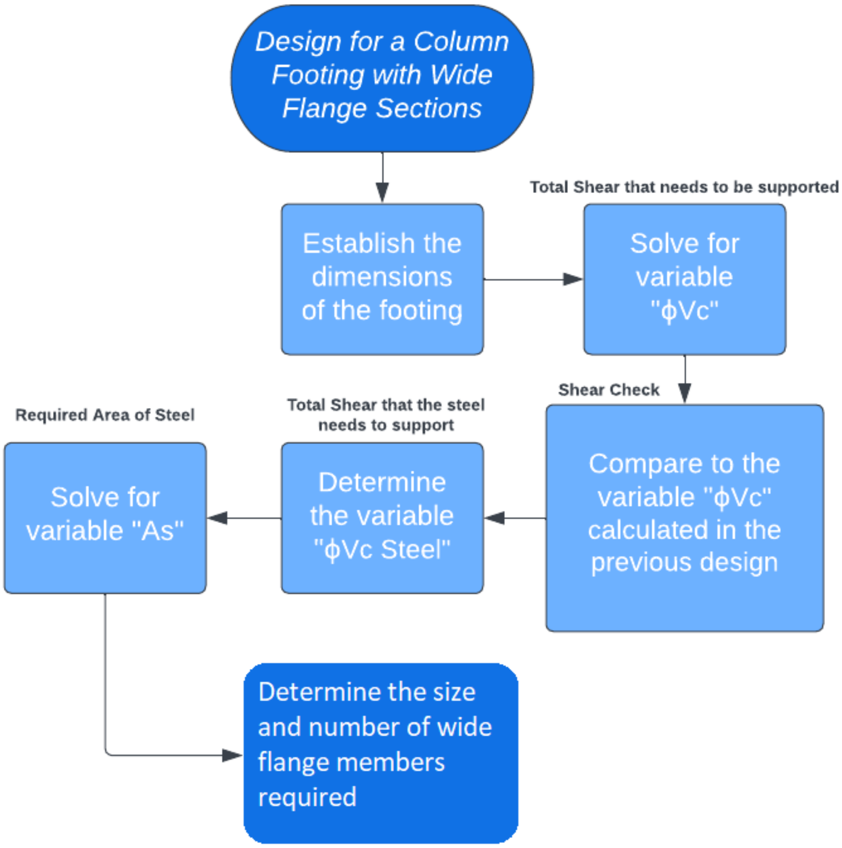


Figure 16: Flowchart explaining the Variables needed for the Footing Design involving Wide Flange Section Steel Reinforcement

3.4.5. Long-Span Moment Frames and Double-Web Girders

Due to the nature of auditorium design, long spans were required to support the ceiling. The addition of occupied levels above the auditorium ceiling meant that additional columns would carry large, concentrated forces onto the center of the girders creating transfer girders. Typically, in auditorium or stadium design, a truss system would be used to support this ceiling. Unfortunately, a truss could not be placed inside the auditorium due to sightline obstruction for balcony seating. A truss also couldn’t be placed above the auditorium ceiling because it would conflict with the usable spaces on the overlying floor. To combat this, the team researched a variety of solutions to support the ceiling and the overlying floors without using an obtrusive truss system.

Built-up girders and double-web sections were explored as feasible solutions. The long 140-foot-spans were susceptible to significant deflections which were countered by substantial member stiffness. In the distributed load deflection equation, the limiting factor is the major axis moment of inertia (I_X) for a given section. Thus, different W-shape sections were selected until the deflections were within the allowable limits (L/360 for live load, and L/240 for combined live and dead load).

For some members, the team utilized both double-web sections and camber. Double-web sections are created by connecting the flanges of two members (side-by-side) via welds or connection plates. This increases the overall major-axis moment of inertia, which are added together for the two sections, and significantly decreases deflection. Similarly, a mechanical process known as cambering can be done to install positive deflection in a member before loading.

Cambering, which is typically applied in ¼" increments, was used to decrease the net deflection - if a member was expected to deflect 6", but a 2.5" camber was applied at the location of maximum deflection, the net deflection will be 3.5". This was often a more cost-effective option rather than upsizing a member. This tactic only works for members carrying a distributed load and cannot be used for transfer girders that are subjected to concentrated forces.

The team utilized RISA-3D as a design aid for testing out solutions to the long-span transfer girders. RISA-3D allows for the easy change of member sizes in a structure, and its advanced analysis results allowed the team to change member sizes until they not only supported the required loads but also were within allowable deflection limits. To design these frames, the team determined the distributed load on each girder and the concentrated forces from the columns above the frame. These loads were added to the RISA-3D model and member sizes were modified until the maximum deflections in the long-span girders (140 feet) were within the allowable limits. Built-up sections were explored as the solution to this issue. Built-up sections involve designing a custom I-shaped section with two flanges plates welded to a web; this customization allowed the team to design members that had larger major-axis moments of inertia than even the largest W-shape sections.

Due to the indeterminate nature of the frames, the columns that would support these frames would be subjected to combined axial and bending forces rather than pure axial compression. According to the AISC Specification for Structural Steel Building, there are limits on the combined axial and flexural forces a member can sustain based on the shape properties. For this project, Equation H1-1a was used based on the following provision:

$$When\ \frac{P_r}{P_c} \geq 0.2,\ \frac{P_r}{P_c} + \frac{8}{9}\left(\frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}}\right) \leq 1.0$$

The required axial force P_r and the required major-axis bending moment M_{rx} was analyzed with the available axial capacity P_c and available major-axis bending moment capacity M_{cx}. Based on the static boundary conditions for this design, M_{ry} was zero. This equation must be less than or equal to 1.0 for the member to be sufficient.

3.5. Create a Construction Schedule and Cost Estimate

3.5.1. Delivery Method

Before beginning the cost estimation and construction schedule development process, the recommended delivery method for the project was established. There were a variety of possible delivery methods, but Design-Bid-Build, Design-Build, and Construction Manager@Risk were the most popular. The team factored WPI's resources and financial needs into this decision.

3.5.2. Cost Estimate

The team began by looking at recent WPI construction projects to get an estimate for appropriate prices per square foot. The RSMeans Online system was used to generate cost estimates for the auditorium space; the rest of the building was estimated as college classroom space. The RSMeans estimates were limited in their scope and needed to be fleshed out to suit the project. A project-specific Excel spreadsheet was created to mimic the RSMeans cost estimator. The values were updated using raw data from RSMeans. These construction estimates included labor costs as well as indirect costs, contractor costs, and architectural fees. Inflation markups of 36% (U.S. Department of Labor) were taken into consideration as well in order to adjust the RSMeans Data Online values which were from 2011.

3.5.3. Project Schedule

Data from previous experiences was referenced and adjusted to the designed PAC. This data was scaled to this project based on the difference in perimeter, square footage, and footprint. Some data did not need to be altered as it was consistent across all construction. Lead times for specific equipment and materials were researched and addressed within the pre-construction phase. This general work and scaling were done in Excel and then transferred to Microsoft Projects for final editing.

3.6. Conduct Sustainability and Acoustic Analyses

A sustainability analysis was conducted by considering ways in which Performing Arts Centers can be more energy and material efficient. A LEED scorecard was used to address design and construction strategies to make the project more sustainable through lighting, energy, water systems, and more. In practice, different score ranges on the LEED scorecard earn projects different levels of certification from simply certified to platinum.

Acoustic analysis was evaluated based on a Rhinoceros 3D model with calculations done through a plug-in called Pachyderm Acoustics. Pachyderm can calculate reverberation time and sound clarity in a designated space based on materials in the space and their sound absorption rates.

3.7. Develop a 3D Model

Once the final sizes for beams, girders, and columns were determined, they were placed into the Revit model to show the superstructure of the building.

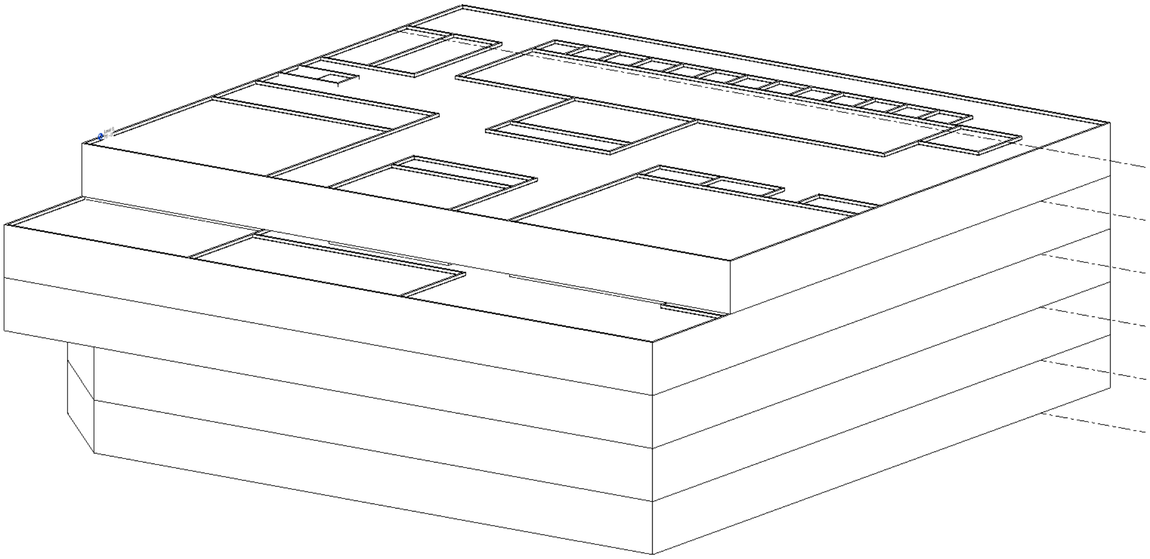


Figure 17: Preliminary Revit Model

The Revit model was updated during the design process to include any changes made to the initial architectural and structural layouts. With that, the general floor schemes were finalized, which includes five floors and a basement. Once the Revit superstructure was completed, visual enhancements to the exterior and interior were made to present the model in greater detail.

4. Results

4.1. Introduction

Through background research, interviews, and surveys, the team identified the needs of WPI for a Performing Arts Center. Layouts of the various rooms were established in the building's floor plan, which was translated to Revit to develop the 3D model. A structural framing plan was designed and modeled in Revit. A proposed project schedule and cost estimate for the construction was generated, followed by acoustic and sustainability analyses.

4.2. Identify the Needs of the WPI Community

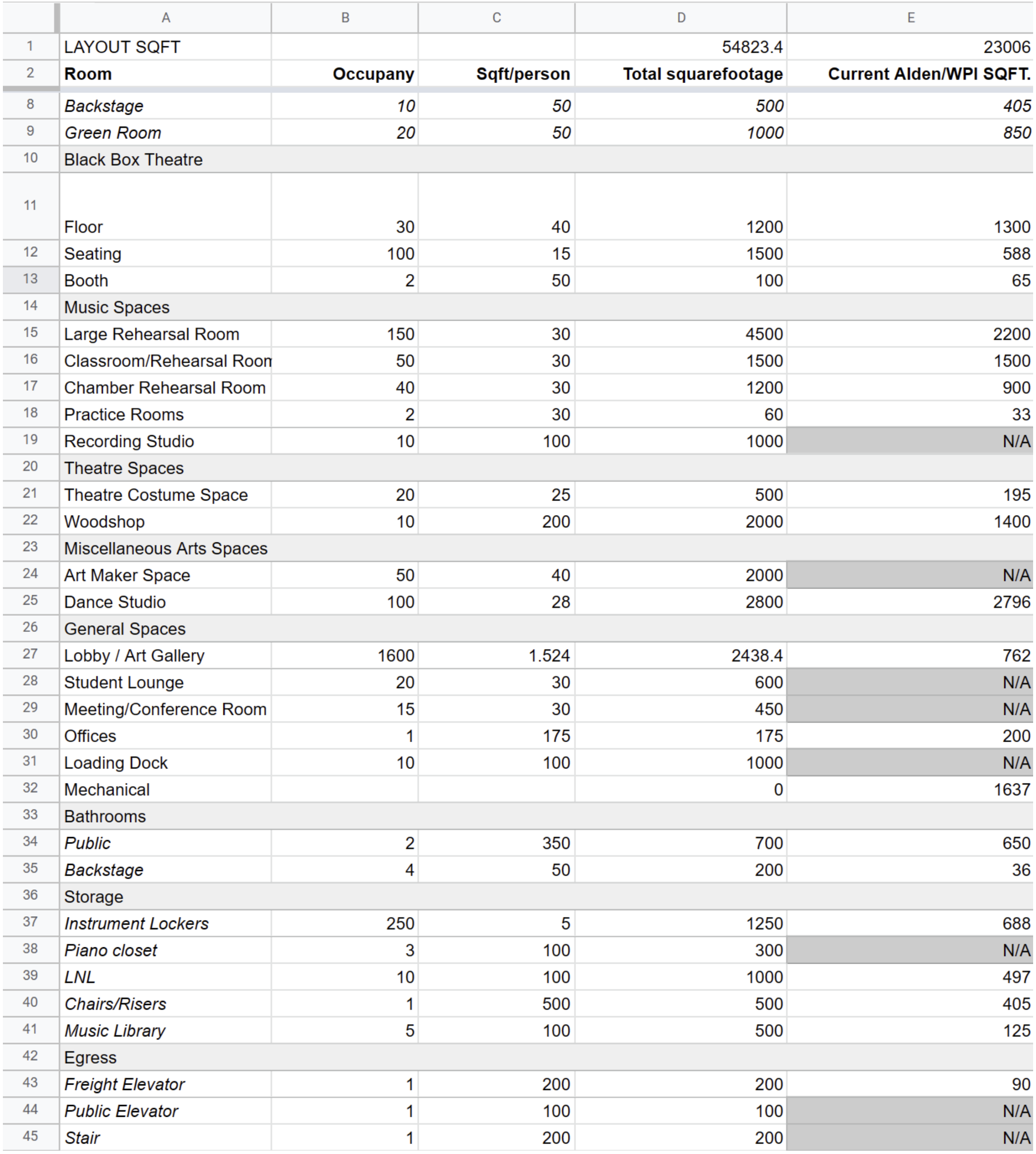
It was apparent that a new performance facility was needed on campus - input from members of the WPI community confirmed this and helped guide the designs of the included interior spaces. The survey was sent to twenty student organizations ranging from 10 or fewer members to over 100, which included music ensembles, theater and dance groups, art and design clubs, and comedy groups. Seventy responses were obtained with an overwhelming majority (92.9%) stating that WPI needs a new performing arts facility. Open response questions yielded important considerations, such as the inclusion of a woodworking shop, wide hallways for transportation of large instruments and theater set pieces, and a stage accessible via an external loading dock.

The team also chose to interview students, faculty, and staff in the WPI humanities and arts community to gain their knowledge and opinion on this issue. Table 3 below details the names and positions of the individuals interviewed, as well as the key takeaways from these interviews.

After completion of the interviews and analysis of the survey responses, an architectural program for the proposed facility was created to understand the scope of the project visually. The floor plan drawings of Alden Memorial and the Little Theater were referenced to gain more perspective on a typical interior layout. A list of square footage values for each space in the new facility was created and compared to the current Alden square footage values as a reference (See *Figure 18* below).

Table 3: Interviewees and Key Interview Takeaways

Individual	Position at WPI	Key Takeaways
Dr. Kathryn Moncrief	Professor and Head of the Department of Humanities and Arts	● WPI’s available Arts spaces for the number of interested students (1800 students) are not sufficient ● Most departments on campus have collaborative spaces for their students, but Arts do not. These students deserve this space for their own well-being.
William Batelle	Director of Events	● Must consider the importance of available parking relative to site ● New performance venue should seat at least double the capacity of Alden Hall (500 seats)
Joshua Rohde	Director of Choral Activities and Coordinator of Music Ensembles	● Importance of multi-use spaces cannot be overlooked
Laura Eckelman	Associate Professor of Theater, Department for Humanities and Arts	● Theater spaces need unique additions that could be easily overlooked, such as a kitchen
Patrick Crowe	Instructor/Lecturer - Arts, Communications, and Humanities	● Current performance spaces are not adequate for the scale of WPI performances ● Little Theater (black box) was not initially intended for theater and thus was not correctly equipped
Benjamin Antupit	Student and Vice President of WPI Lens and Lights club	● Ideal performance spaces have dedicated equipment with proper connections and rigging built-in ● Fly space above the stage should be large enough to allow for storage of lighting above stage



	A	B	C	D	E
1	LAYOUT SQFT			54823.4	23006
2	**Room**	**Occupany**	**Sqft/person**	**Total squarefootage**	**Current Alden/WPI SQFT.**
8	*Backstage*	*10*	*50*	*500*	*405*
9	*Green Room*	*20*	*50*	*1000*	*850*
10	Black Box Theatre				
11	Floor	30	40	1200	1300
12	Seating	100	15	1500	588
13	Booth	2	50	100	65
14	Music Spaces				
15	Large Rehearsal Room	150	30	4500	2200
16	Classroom/Rehearsal Roon	50	30	1500	1500
17	Chamber Rehearsal Room	40	30	1200	900
18	Practice Rooms	2	30	60	33
19	Recording Studio	10	100	1000	N/A
20	Theatre Spaces				
21	Theatre Costume Space	20	25	500	195
22	Woodshop	10	200	2000	1400
23	Miscellaneous Arts Spaces				
24	Art Maker Space	50	40	2000	N/A
25	Dance Studio	100	28	2800	2796
26	General Spaces				
27	Lobby / Art Gallery	1600	1.524	2438.4	762
28	Student Lounge	20	30	600	N/A
29	Meeting/Conference Room	15	30	450	N/A
30	Offices	1	175	175	200
31	Loading Dock	10	100	1000	N/A
32	Mechanical			0	1637
33	Bathrooms				
34	*Public*	2	350	700	650
35	*Backstage*	4	50	200	36
36	Storage				
37	*Instrument Lockers*	250	5	1250	688
38	*Piano closet*	3	100	300	N/A
39	*LNL*	10	100	1000	497
40	*Chairs/Risers*	1	500	500	405
41	*Music Library*	5	100	500	125
42	Egress				
43	*Freight Elevator*	1	200	200	90
44	*Public Elevator*	1	100	100	N/A
45	*Stair*	1	200	200	N/A

Figure 18: Occupancy and Square Footage of Desired Spaces

4.3. Design the Floor Plans and Layout

After gathering the square footage of the spaces, the team put together hand-drawn and digital sketches to visualize the building layout (Appendices 5 and 6). A set of floor designs were agreed upon and converted to a Revit model (see Section 4.7). Figure 19 shows each space included in the building along with its occupancy and square footage (See Appendix F for full final layouts). The proposed PAC includes a proscenium stage, fly space, rehearsal spaces, dedicated storage spaces, classrooms, an orchestral pit, practice rooms, a woodshop, and an art gallery integrated with the lobby.

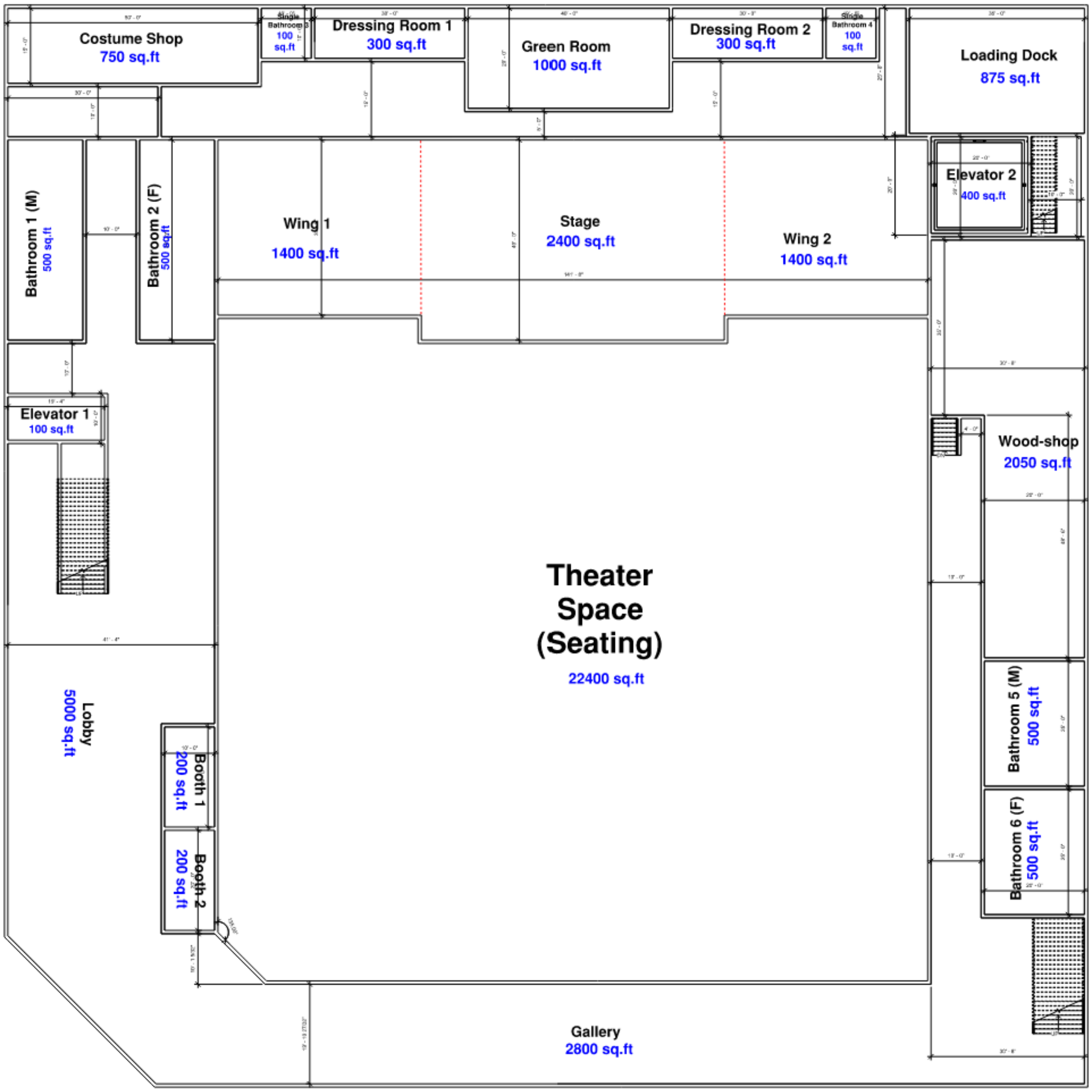


Figure 19: First Floor Layout with Room Labels and Square Footage

4.4. Create the Structural Design

All structural members were designed, including all standard schemes and special cases that required additional work. A live load of 100 pounds per square foot (psf) was sufficient for most rooms, and some atypical areas required different loads based on the use, as seen in Table 4. Refer again to Appendix G for the structural layouts, which are referenced in the final member results.

Table 4: Live Loads for Selected Spaces

Element	Type	Loads
Typical Floor	LL	100 psf
Stage	LL	150 psf
Rehearsal Rooms	LL	150 psf
Balcony/Mezzanine	LL	60 psf

4.4.1. Beams and Girders

Using the Excel spreadsheets to aid in calculating the beam and girder sizes, the appropriate member sizes for each bay were determined. The results of the member sizes are tabulated on Excel spreadsheets located in Appendix H. Refer as well to Appendix I for a sample calculation of both a beam and a girder, and to Appendix J for beam and girder design samples using the developed spreadsheets. Refer to Appendix S for finalized framing layouts of beams and girders.

4.4.2. Columns

Spreadsheets were created to aid the design in the design of columns in a similar way to beams and girders. Adequate member sizes were determined for each column in the building, and columns that required special attention or related designs were solved individually. Once each member was designed, it was tabulated into a different spreadsheet along with the ultimate axial compressive load in that column from the weight above it. Refer to Appendix K for all finalized column sizes, Appendix L for a sample hand-calculated column design, and Appendix M for column design samples that detail the full functionality of the developed spreadsheets.

4.4.3. Column Base Plates and Footings

A base plate was designed for column E2 using the LRFD method, which was implemented in an Excel spreadsheet. After tabulating the necessary LRFD equations and variables, the final base-plate design for the column was a PL4.5 x 30 x 2ft 6in, meaning that the plate has a 4.5” thickness, and a 30” width and length. Refer to Appendix N for the plate design spreadsheet. A total of three column footing designs for column E2 were created. The first footing used a design similar to a reinforced concrete design, which yielded a large required concrete footing area to transfer shear. The second and third designs required a much smaller footing size due to the use of wide flange members as shear reinforcement in place of rebar. Based on the three designs, it was decided that the second design (the 12’ x 12’ footing) was the best option. The second footing design was the most “compact” design since it has smaller dimensions; which aids in keeping the concrete costs down. Refer to Appendix O for sample calculations of the three column footing designs.

4.4.4. Long-Span Moment Frames and Double-Web Girders

To create the long-span support systems, the team decided to offset some of the weight on the original transfer girders by adding a new girder halfway between each transfer girder. Figure 20 below is a portion of the structural layout of the 3rd Floor ceiling supporting the 4th-floor area. The girders in rows 4, 7, and 9 are transfer girders and support columns from above, while the girders in rows 6, 8, and 9.5 only carry distributed loads from beams.

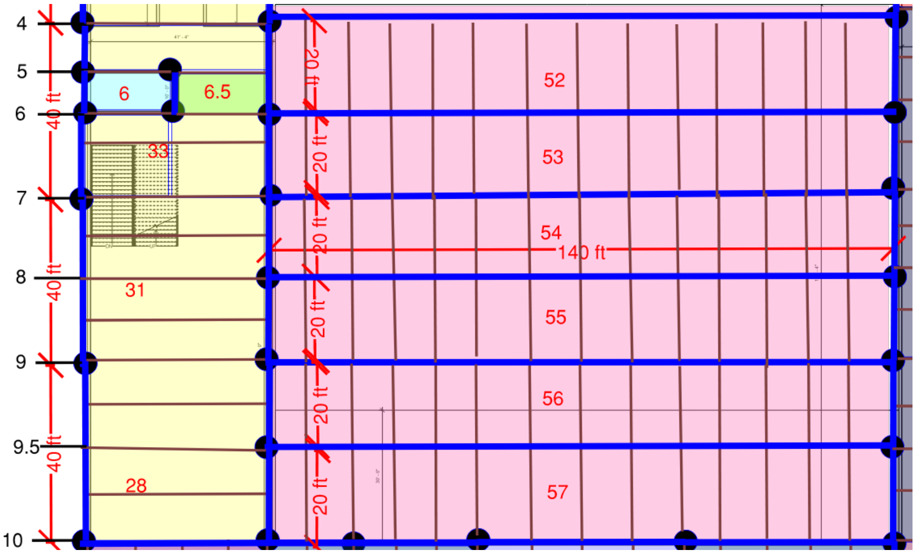


Figure 20: Section of the 3rd-floor ceiling. The pink area represents the area over the auditorium. The blue members are girders, and the brown members are beams.

To design the girders in rows 6, 8, and 9.5, the same process used for most of the girders was followed, with a few modifications. The final section for all three members features a double web section of two W36x723 members welded together at the flange with 8” of camber instilled over the member’s 140-foot length for a net deflection of 0.289”. See Figure 21 for detailed section properties, and Appendix P for the calculations.

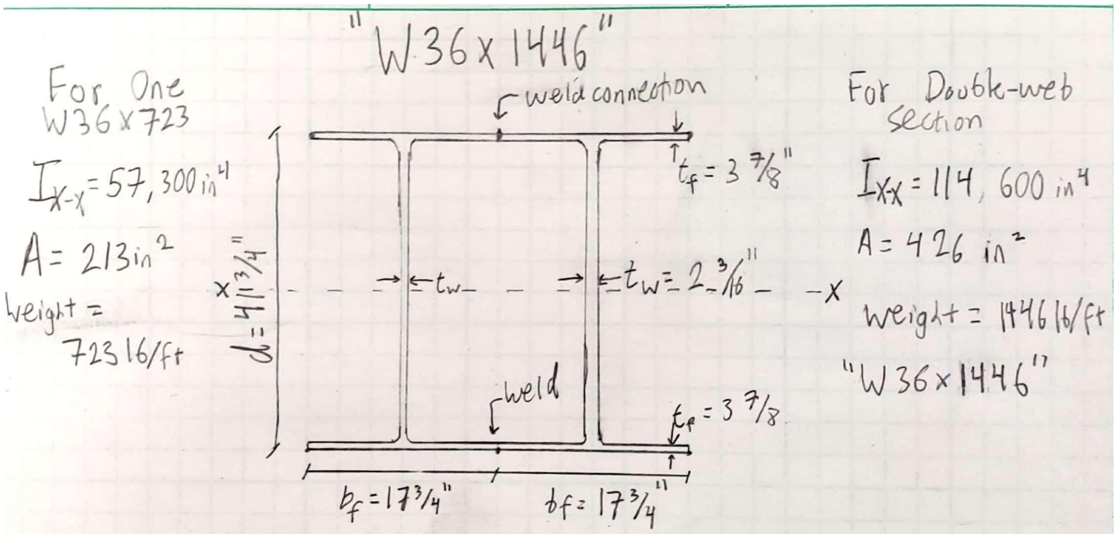


Figure 21: Detail and Section Properties for the W36x1446 Long-Span Girder

To design the transfer girders in rows 4, 7, and 9, the team defined moment-resisting frames that spanned two floors. These frames included two 140-foot continuous girders with columns throughout at their necessary locations with HSS bracing hidden in walls to provide lateral stability and reduce deflection. The member sizes were established using RISA-3D. Figure 22 shows the final frame for row 4, and Table 5 details the member sizes and functions.

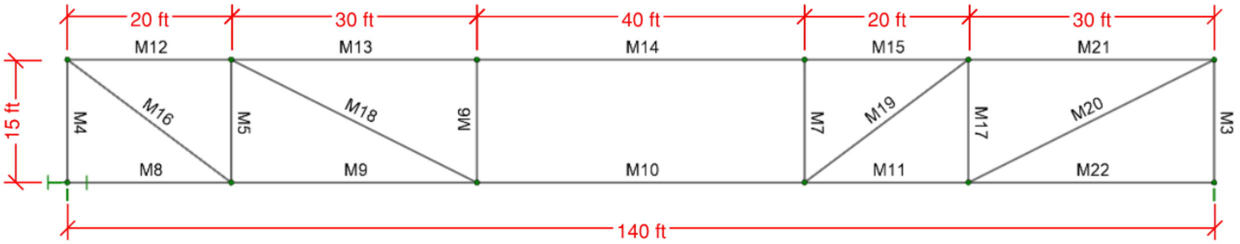
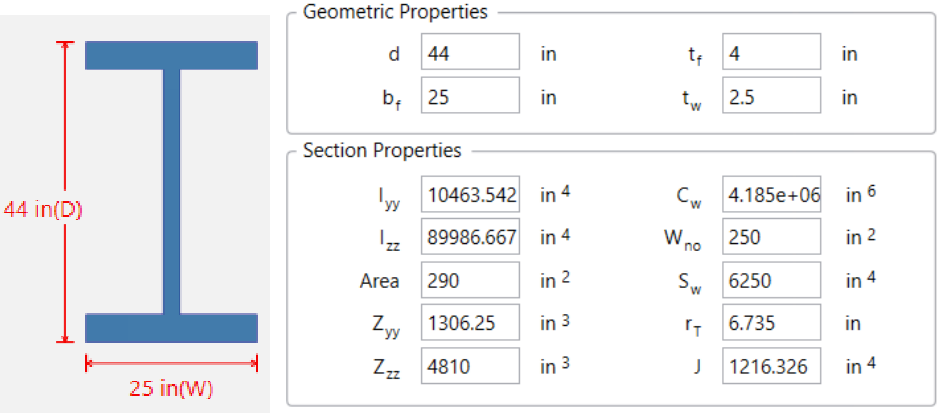


Figure 22: Moment-resisting Frame Design for Row 4 Across the Auditorium

Table 5: Row 4 Frame Member Sizes based on Labels in Figure 22

Member Type	Applicable Labels from Figure 22	Selected Sections	Member Wt. (lb/ft) for A992 steel
Long-Span Girder	M8, M9, M10, M11, M12, M13, M14, M15, M21, M22	Built-up Section 1 (See Figures 23 and 24 below for detail)	987.9
Column	M3, M4, M5, M6, M7, M17	W40X593	593
Lateral Brace	M16, M18, M19, M20	HSS24X12X12	171.16



Geometric Properties

d	44	in	t_f	4	in
b_f	25	in	t_w	2.5	in

Section Properties

I_{yy}	10463.542	in^4	C_w	4.185e+06	in^6
I_{zz}	89986.667	in^4	W_{no}	250	in^2
Area	290	in^2	S_w	6250	in^4
Z_{yy}	1306.25	in^3	r_T	6.735	in
Z_{zz}	4810	in^3	J	1216.326	in^4

Figures 23 and 24: Detail for 140-foot Girder in the Row 4 Frame

See Appendix Q for additional information regarding the row 4 frame including a model with loadings visible and a deflected model. Note that the deflections are magnified to visually confirm that the frames are following the expected structural behavior. Similar information for the frames in rows 7 and 9 is included in Appendix Q as well.

The final step in designing the frames was to add columns to the RISA-3D model that extended to the foundation. RISA-3D analysis granted the ability to see the axial and flexural forces in the column at the ground level, to be used in Equation H1-1a from the AISC Specification. Figure 25 shows the row 4 frame with columns added; the final sizes of these columns can be seen in Appendix K alongside the other column sizes. The pinned connections at the base of the lowest columns rendered the system indeterminate. The resulting reactions included combined axial and bending forces that had to be checked.

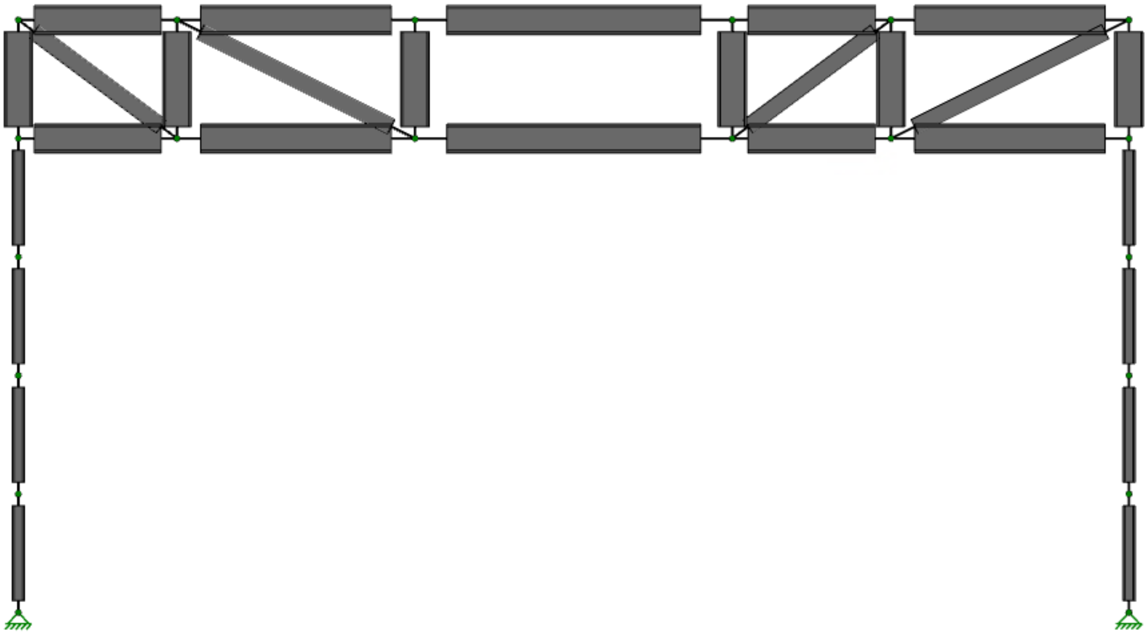
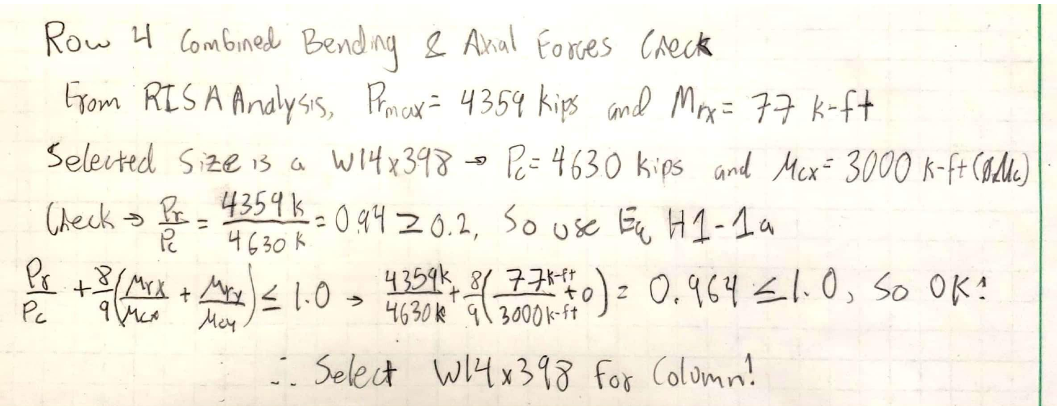


Figure 25: Row 4 Frame with Supporting Columns to the Basement Level. The Final Column size was a W14x398, and each was 15 feet tall (Lc=15 feet)

Appendix R includes figures of rows 7 and 9 frames with their respective columns. Below, in Figure 26, is a hand calculation using AISC Specification Equation H1-1a in the combined axial and bending check. These calculations for the frames in rows 7 and 9 are in Appendix R with the frame/column figures.



Row 4 Combined Bending & Axial Forces Check

From RISA Analysis, $P_{rmax} = 4359$ kips and $M_{rx} = 77$ k-ft

Selected Size is a W14x398 → $P_c = 4630$ kips and $M_{cx} = 3000$ k-ft ($\phi_b M_c$)

Check → $\frac{P_r}{P_c} = \frac{4359k}{4630k} = 0.94 \geq 0.2$, So use Eq H1-1a

$$\frac{P_r}{P_c} + \frac{8}{9}\left(\frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}}\right) \leq 1.0 \rightarrow \frac{4359k}{4630k} + \frac{8}{9}\left(\frac{77^{k\text{-}ft}}{3000^{k\text{-}ft}} + 0\right) = 0.964 \leq 1.0, \text{ So OK!}$$

∴ Select W14x398 For Column!

Figure 26: Combined Axial and Bending check for a Basement-level Column in Row 4

4.5. Create a Construction Schedule and Cost Estimate

The team decided to go with a Design-Build project delivery method for the project. With the specialty equipment and steel sections needed for the building's auditorium, it was necessary that fabrication begins on these items before construction commences.

The final cost estimate for the proposed building was $92 million. The breakdowns for the various sectors of the building can be found in Table 6, and the expanded costs can be found in Appendix T.

Table 6: Summary of Cost Estimation

Building Sector	% of Total Cost	Cost per SQFT	Cost
Substructure	3.59%	$8.45	$1,768,063
Shell	27.34%	$64.28	$13,471,019
Interiors	20.45%	$48.13	$10,076,624
Services	32.82%	$77.26	$16,173,943
Equipment & Furnishing	15.80%	$37.18	$7,783,937
Building Sitework	1.98%	$4.66	$975,375
SubTotal			$49,273,585
Fees (Contractor/Architectural)	37.00%	$87.08	$18,231,226
Total Building Cost		$322.45	$67,504,811
2023 Building Cost		$438.53	$91,806,543

Construction of the PAC, including design and pre-construction, was estimated to take roughly five years. Figure 27 presents the breakdown of this time into separate phases - design, pre-construction, and various construction phases. The data used to create this schedule can be found in Appendix U. Design and bidding were estimated to take almost two years of that time, from August 2023 to July 2025.

The beginning of the project was tested several times to ensure that excavation would finish before winter and the building would be sealed before the winter of the following year. Exterior work needed overtime work to be completed within a reasonable deadline. This was done by adding a second shift to the project for that duration, decreasing the time by one-third. Given the customized steel sections required, steel fabrication was planned to begin during pre-construction and end as soon as the foundation was finished. Overall, construction of the Performing Arts Center would begin in July 2025 with a handover to WPI in August 2028.

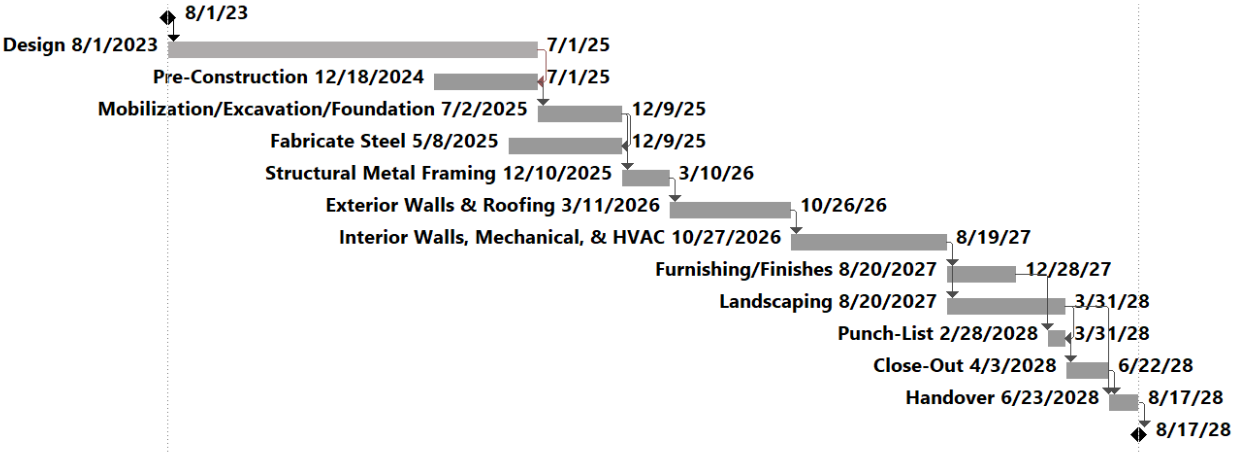


Figure 27: Project Schedule for proposed Performing Arts Center

4.6. Conduct Sustainability Analyses

This section discusses multiple sustainable development strategies that can be integrated into the design and construction of the Performing Arts Center (PAC).

4.6.1. LEED Certification

LEED (Leadership in Energy and Environmental Design) is a commonly used building rating system that aims to lower building costs, improve efficiency, lower carbon emissions, and create healthier environments for the public. The LEED system is part of a larger initiative to address climate change in projects for the urban environment by reducing the number of harmful effects caused by construction and design. To evaluate how environmentally-conscious the project would be, a LEED scorecard was used to track points that are assigned to specific certain categories. These categories include location and transportation, sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, integrative process, and innovation. Achieving different totals or percentages of points corresponds to certain certificates awarded to the overall project. However, a significant amount of planning and design must be integrated to make the building or program healthier for the environment and to achieve higher status certificates. Table 7 presents the number of points required for each LEED Certificate. According to WPI Campus Operations in the Office of Sustainability, five campus buildings have achieved LEED certifications:

- 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

Table 7: LEED Certification Categories

Point Range	LEED Certificate
40-49 Points	LEED Certification
50-59 Points	LEED Silver Certification
60-79 Points	LEED Gold Certification
80+ Points	LEED Platinum Certification

4.6.2. Solar Power

Solar panels can be impactful in making a project self-sustaining. They are typically made from silicon, which is a semiconductor and can generate electricity through the photovoltaic effect of sunlight. Sunlight is absorbed to generate an electric current, and the current is captured by wires and converted into usable energy. Using solar panels on a larger scale project such as the PAC would lead to significant energy and cost savings. Moreover, the

United States Government has incentive programs to provide money for solar power developments that can help lower energy costs.

4.6.3. LED lighting

In theaters, lighting fixture wattages usually range from 500 to 1000 watts, and in film applications, fixture wattages usually range from 1000 to 5000 watts (Bill Williams, n.d). Moreover, stage and studio lamps can range from 300-2000 watts depending on the purpose. Light Emitting Diodes (LEDs) emit light when an electric current runs through them. Compared to standard fluorescent and incandescent lighting, LEDs have a longer lifespan, are more energy-efficient, release no heat or UV emissions, have low voltage operations, and have more design flexibility. An LED lasts 10 times longer than an incandescent bulb and uses less energy for the same amount of light, leading to lower carbon emissions (Sitelogic, 2023). Auditoriums and performance centers have a significant number of lighting fixtures; the use of LEDs would be a sustainable long-term solution.

4.6.4. Greywater Reuse Systems

Greywater is a category of wastewater sourced from bathing, laundry, washing dishes, and runoff. Most applicable to this building would be the collection of rainwater runoff on the roof as well as the laundry and sink facilities. Greywater is collected in a surge tank and then discharged to a treatment facility. Sanitization treatments may include filtering, settlement of solids, separation, anaerobic or aerobic digestion, and chemical disinfection (certified under NSF350 C.) This certification includes 26 weeks of continuous testing and maintenance to make sure water is safe for residential and commercial buildings (Ecovie, 2022). However, it is more sustainable long-term to reuse that water, especially considering the lack of available clean water in some locations. Treated greywater can be reused in multiple ways, including toilet flushing, irrigation, car washing, cooling tower makeup, green roofs, and other minor ways that can make a lasting impact. Recycling greywater for irrigation by piping directly outside, for example, can keep it out of the sewer system, which can reduce the chance of polluting local water bodies.

4.6.5. Alternative Sustainability Approaches

Sustainability in theater design is important, especially with changing props, scenery, costumes, and more. The *Theatre Green Book,* which collaborates with multiple organizations such as Theatres Trust, Stage Sight, and EcoStage, outlines multiple ways theaters and auditoriums can be more sustainable through their three online books titled *Sustainable Productions, Sustainable Buildings,* and *Sustainable Operations*. In their second volume, sustainable design strategies include replacing fossil fuels with low-carbon energy sources, integrating wind power through turbines, air and ground source heat pumps, rainwater, landscape planting, integrating draught lobbies, revolving doors, and condensing boilers for heating. However, continued sustainability in the Performing Arts Center relies on the healthy operational practices of students and faculty. These practices include minimizing the amount of material a set requires, reuse of materials and furniture such as doors, flats, and furniture, and costume sharing and reuse. Based on the first volume of the book, sets and scenery are a substantial part of a theater’s footprint; as an example, The Royal Court Theatre uses 30,000 kg of steel, timber, and boards a year, accounting for 30% of its carbon footprint in 2020.

4.6.6. Evaluation of Sustainability in the Performing Arts Center

According to the U.S. Green Building Council (LEED scorecard, n.d), certain sustainable options can be implemented in the project to gain more points based on standard credit requirements. Concepts to integrate to make the Performing Arts Center more sustainable can be found in Table 8. A potential distribution of LEED Certification points is shown in Table 9. Some sustainable design alternatives, as addressed in Table 8 were proposed to be included in the overall design and cost estimate of the project.

Table 8: LEED Concepts of Implementation

LEED Category	**Concepts for Implementation**
Location and Transportation	● PAC location near WPI Gateway garage for easy access to events ● Integrate WPI shuttle services, provide bike storage, improve sidewalk near site
Sustainable Sites	● Control soil erosion, waterway sedimentation ● Land area considers unique topographic features and slope stability risks (does not need substantial work regarding cut/fill process) ● Provide outdoor spaces ● Rainwater capture on flat roof, use of parking spaces under cover
Water Efficiency	● Reduce irrigation and use of energy star appliances ● Install water meters, include impermeable pavement ● Reduce indoor water use, include washing machines for costumes with required IP units
Energy and Atmosphere	● Meet owner's project requirements for energy and environmental quality, meet standard for reducing greenhouse gas emissions ● Use existing building-level energy meters ● Reuse existing HVAC&R equipment, integrate on-site renewable energy generation
Materials and Resources	● Reuse existing building resources through use of life-cycle assessment ● Use products sourced from at least five different manufacturers, use products that have a compliant material ingredient optimization ● Reduce construction waste
Indoor Environmental Quality	● Meet requirements of ASHRAE Standard, provide outdoor air monitors for ventilation systems ● Provide direct exhaust airflow measurement device ● Interior space has materials that meet low-emitting requirements ● Meet thermal comfort requirements based on ASHRAE Standard (air temperature and humidity can be adjusted in spaces) ● Use LED lighting, provide multi-level lighting for 90% of spaces, integrate lighting with glare control ● Theater space has efficient acoustic performance (reverberation time of sound is ideal with the use of paneling)
Integrative Process	● Conduct early analysis of the relationships between energy-related systems and water-related systems ● Project addresses site selection process, social equity, along with health & well-being in the design phase and the construction phase
Innovation	● Integrate strategies to help improve environmental health and equity, design, construction, and operations
Regional Priority	● PAC is located in a site that addresses the overall environment and the public (minimum of four credits)

Table 9: LEED Credit Scorecard

LEED Category	**Possible Points**	**Applied to Project**	**Percent of Possible Points**
Location and Transportation	16	6	37.5%
Sustainable Sites	10	4	40%
Water Efficiency	11	8	80%
Energy and Atmosphere	33	16	48%
Materials and Resources	13	6	46%
Indoor Environmental Quality	16	14	87.5%
Integrative Process	1	1	100%
Innovation	6	6	100%
Regional Priority	4	4	100%
Total	**110**	**65**	**59%**

This proposed facility has the potential for a Silver or Gold LEED certification based on the 59% possible point percentage. However, that is only attainable if WPI chose to spend the money and effort to include sustainable development strategies in the building. With that, the use of solar panels can save on the school's electric bill and they can be installed in the area highlighted in Figure 28. Moreover, because this building would not be residential, the reuse of greywater for toilet flushing and irrigation can benefit the overall environment in Gateway Park. The most important strategy that could be integrated into the operation of the facility would be the reuse and recycling of materials needed for production shows. Instead of buying new boards, wood paneling, and furniture, an investment in durable and reusable set materials can impact the amount of money spent on theater and musical theater events as well.

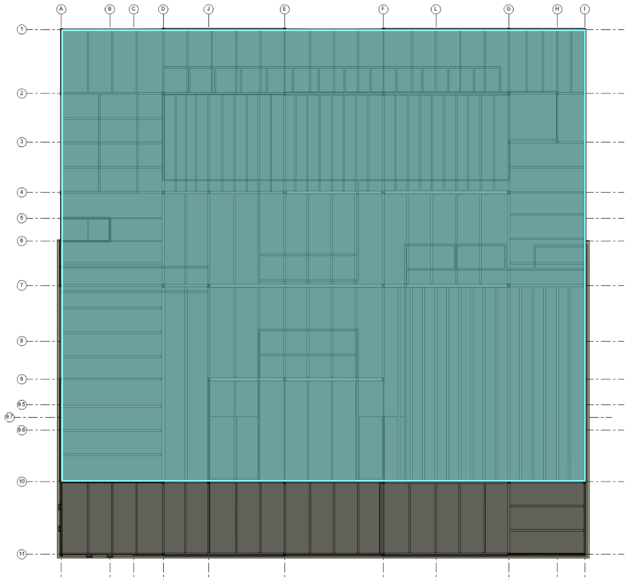


Figure 28: Location of Solar Panels on Roof

4.7. Conduct Acoustic Analysis

Acoustics is an integral part of auditorium design to understand how sound moves from a sound source to the receiver. Determining a closed space's ability to reflect sound waves to produce distinct hearing is crucial, which ties in with sound reverberations, rays, and frequencies (Larson Davis, n.d). Reverberation is the continuation of sound as it bounces off surfaces and back to a person's ear; this is different from an echo which is a sound reflection. Sound waves are measured in decibels (dbs), and the reverberation time is the total time a sound takes to reduce by 60db (or to fade away after bouncing off a surface). Theater spaces have an ideal reverberation time of 1.8 and 2.2 seconds (Nebraska Acoustics Group, n.d). Overall, acoustics can be improved by using materials that affect the absorption and diffusion of sound to help reduce flat-surface reflections or echoes.

Acoustic analysis was conducted using Rhinoceros 6 (Rhino) along with other plug-ins necessary to show sound vector rays and the motion of sound particles. First, a general layout of the auditorium was modeled in Rhino. A point near the stage area was chosen to represent the source of a sound, as seen in Figure 29. To visualize vector rays using Pachyderm, multiple inputs were required. Inputs included - a sound source (like a speaker), a room (the auditorium), a direction away from the sound source, a terminating surface, and the number of bounces. The first model showed how sound would move if the setting was changed from 1 bounce to 2 bounces, which is shown in Table 10. A second model was created to obtain reverberation times. This model also included a general layout similar to the first model but was divided into layers and integrated acoustic paneling on the ceiling and walls (see Figure 30.) In that second model, all the layers were assigned different materials from the software that have different absorption coefficients (at different frequencies). In the material properties, the ceiling, walls, and acoustic panels were chosen to have 95% sound absorption. Sound will get absorbed by the walls and ceiling instead of bouncing off surfaces as it did previously when no materials were assigned to surfaces.

An emitter was created near the stage area and a receiver near the mezzanine to calculate the reverberation time. These calculations were performed by Pachyderm when different components were selected and connected to each other as inputs and outputs. These components included the room, the source of sounds, the number of rays, and the Energy Time Curve (ETC), which uses absorption percentages to calculate reverberation.

For the layout with acoustic panels (blue components on walls and ceilings), the reverberation time (RT) for low frequencies ranged from 1.31 seconds to 1.41 seconds, and for high frequencies, they were from 1.59 to 1.51 seconds (see Figure 31). After deleting the absorption panels and repeating the calculations without them, the reverberation time increased from 1.98 to 3.2 seconds (see Figure 32), which was expected since the paneling helps decrease reverberation time. Ideally, reverberation time for theaters is between 1.0 and 1.3 seconds, so the design with acoustic paneling was preferred. It is worth noting that this model assumes both mezzanine and balcony have wood finishes due to minimal options presented in Rhino, so when the seating material is considered, the reverberation time would be much more improved.

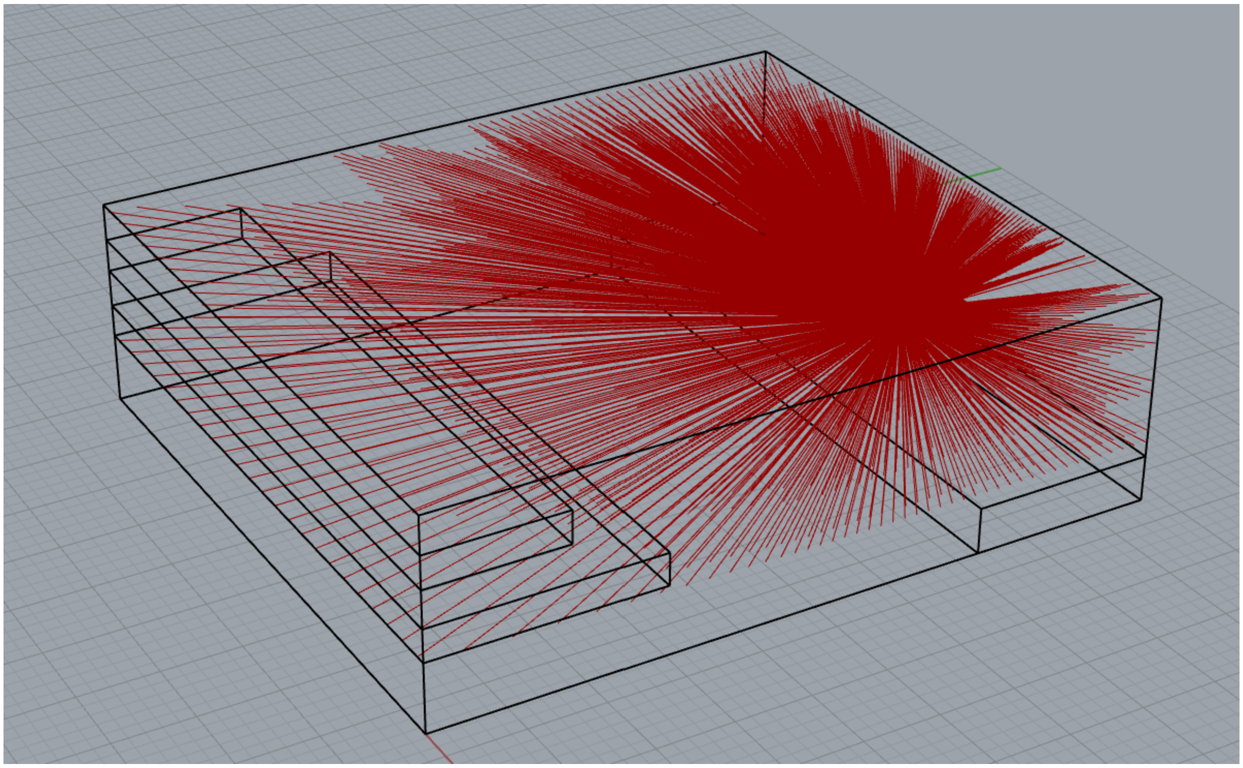


Figure 29: Sound Vector Rays from Source

Table 10: Visual of Sound Particles Moving Over Time due to One or Two Bounces

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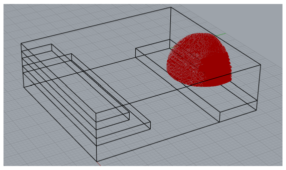
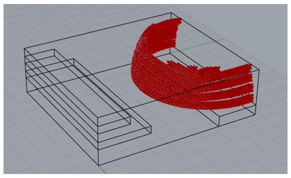
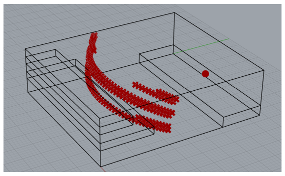
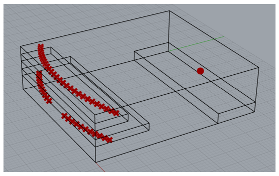
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr><td colspan="4">2 bounces</td></tr>
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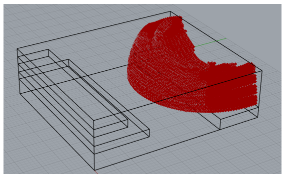
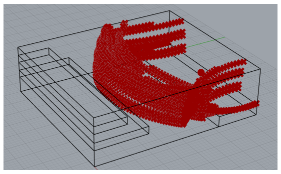
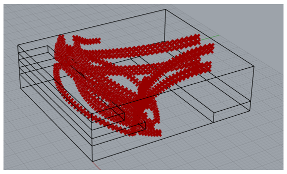
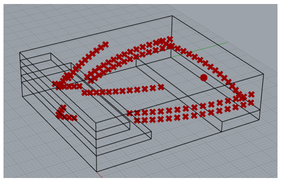
<td></td>
<td></td>
<td></td>
<td></td>
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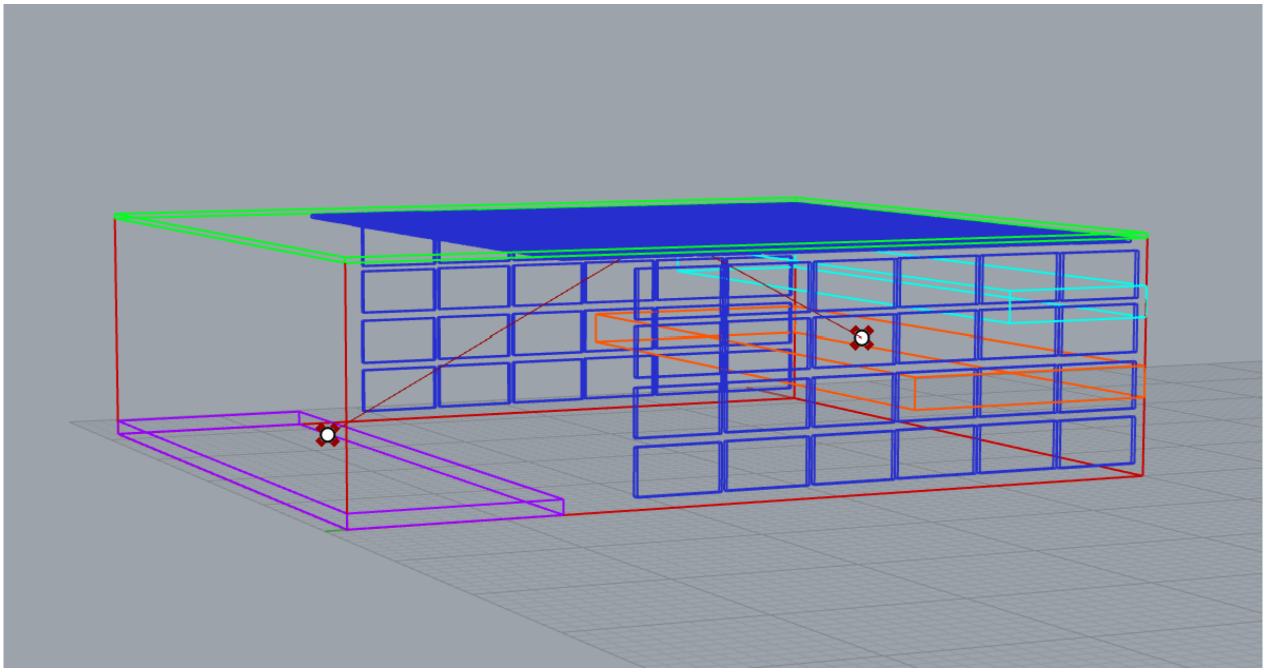
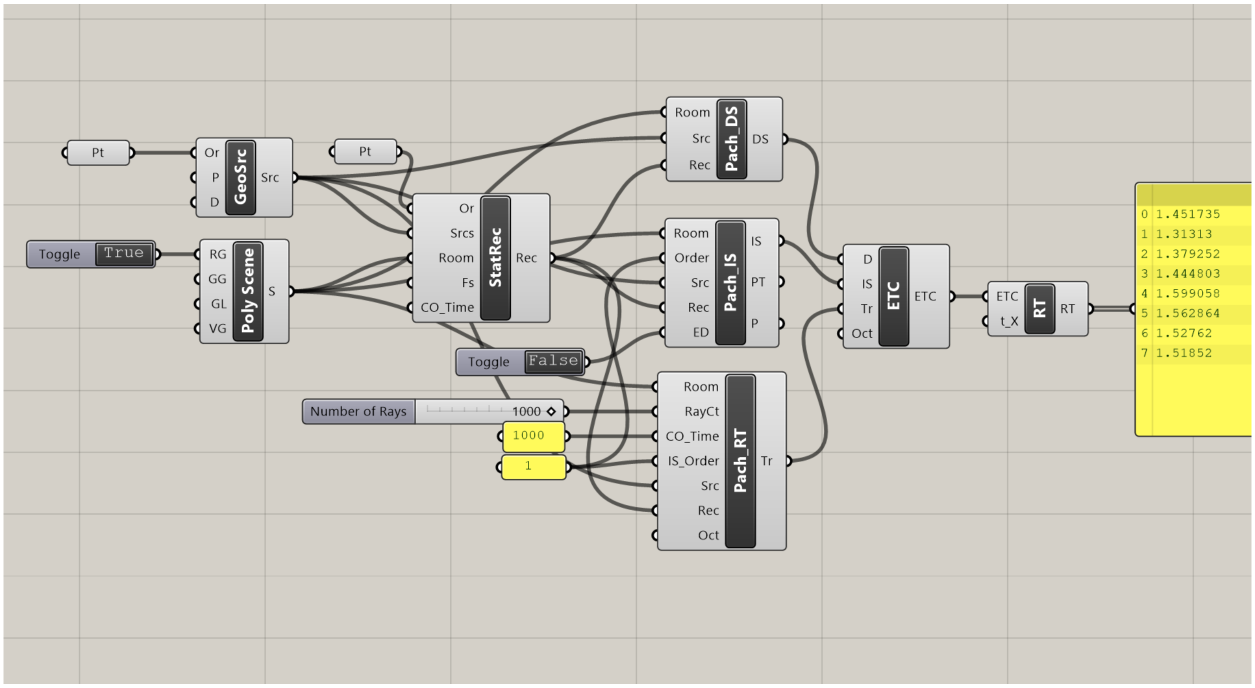
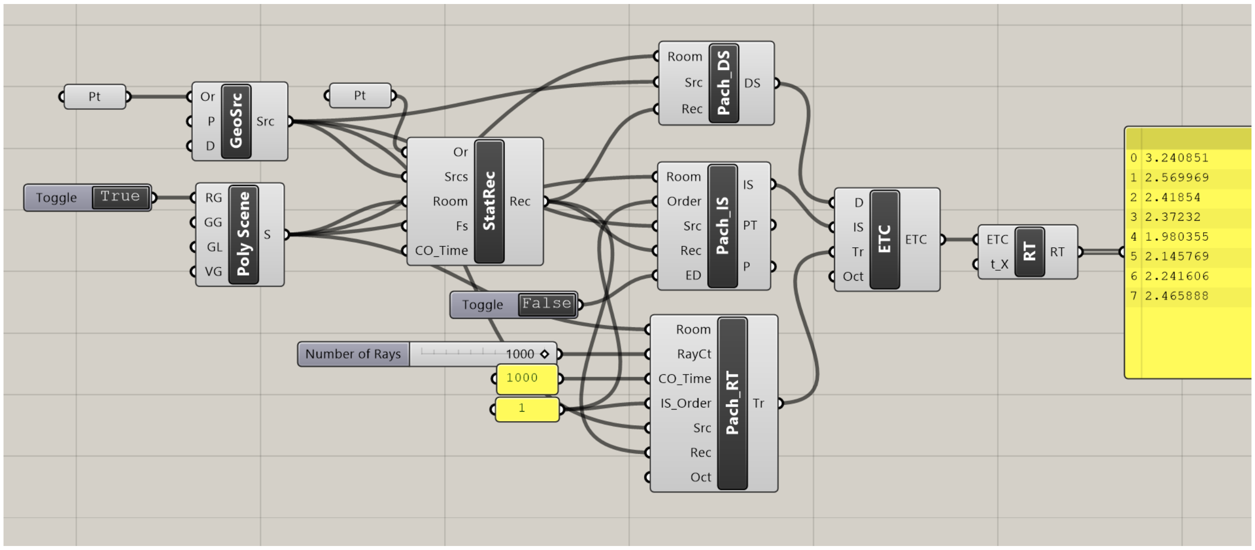


Figure 30: Second Rhino Model with Materials Assigned to each Major Layer



```
0 1.451735
1 1.31313
2 1.379252
3 1.444803
4 1.599058
5 1.562864
6 1.52762
7 1.51852
```

Figure 31: Reverberation Time with Acoustic Panels using Pachyderm Acoustics



```
0 3.240851
1 2.569969
2 2.41854
3 2.37232
4 1.980355
5 2.145769
6 2.241606
7 2.465888
```

Figure 32: Reverberation Time without Acoustic Panels using Pachyderm Acoustics

4.8. Develop a 3D Model

The team used Revit to develop a model of the overall architectural and structural layout of the building. The architectural layout displayed the exterior wall finishes and some of the site components which can be seen in Figure 33. The structural layout portrayed the different column sizes and locations along with girders and beam systems which can also be seen in Figure 34. Footings were also integrated into the structural layout as calculated above. Phases were assigned to each of the main construction components and renderings of the exterior and interior layout of the building were taken for visualization. Elevations of the Performing Arts Center and other project renderings can be found in Appendix V.

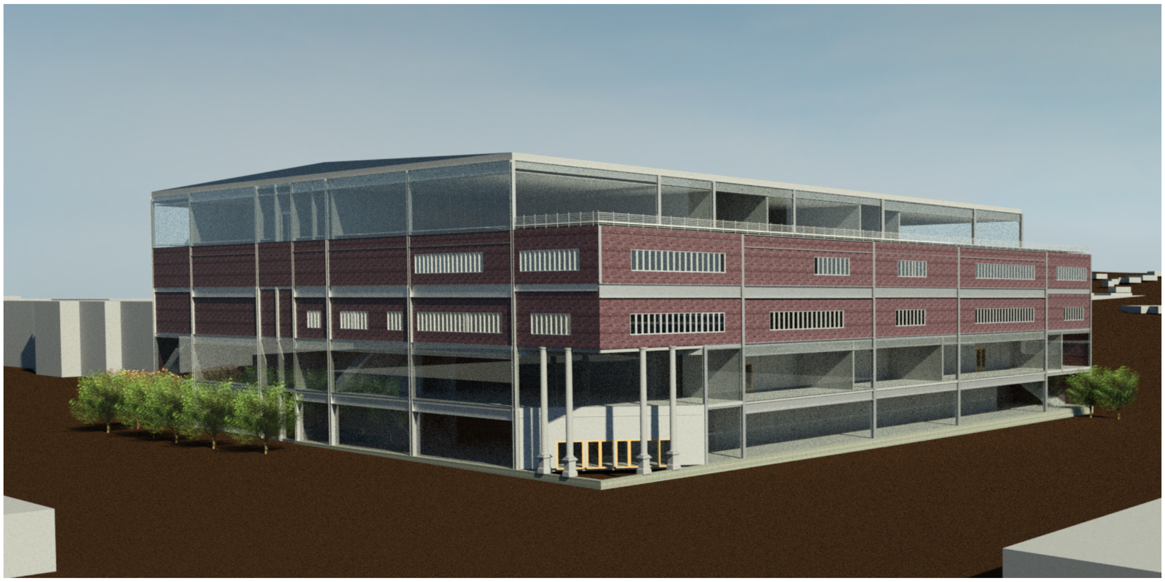


Figure 33: Architectural Exterior Rendering

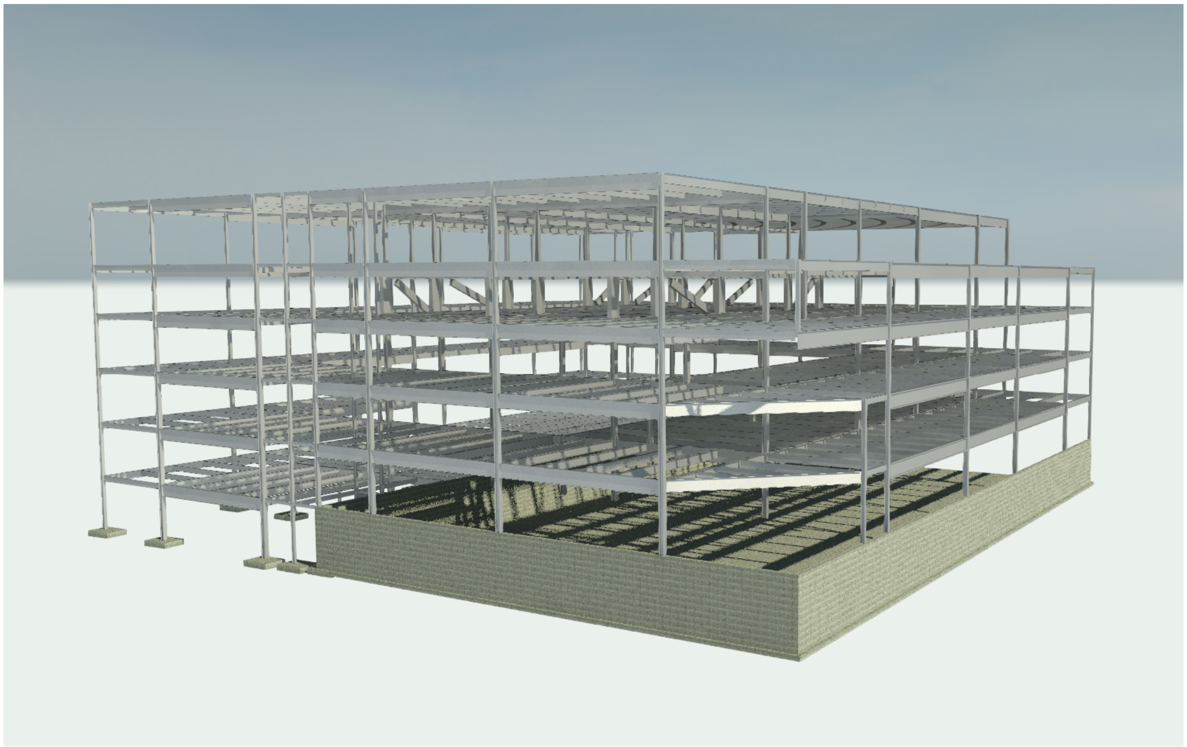


Figure 34: Structural Frame Rendering

5. Conclusion

The completed design for the proposed Performing Arts Center is roughly 209,000 sq ft including a 2200 fixed-seat auditorium, a black box theater, three large rehearsal rooms, two chamber rehearsal rooms, 16 offices, 27 practice rooms, a dance studio, five classrooms, a cafe, a recording studio, an art space, and a workshop. This project was estimated to take five years from the start of design to handover to WPI and cost $92 million. The design included several unique structural elements such as custom built-up sections, long-span moment-resisting frames with combined axial and bending forces, and double-web girders. The team delivered a 3D Revit model of the building and a complete structural design, cost estimate, and project schedule. The proposed Performing Arts Center also had several recommendations for sustainable and acoustic designs to improve its performance.

There are opportunities for further development of this project by future teams. It is recommended to complete an architectural engineering design to accompany the building, including facades, interiors, HVAC systems, and layout optimization. The auditorium interior could be evaluated at a higher level, including the slope of the main floor, soundproofing, and lighting rigs. Throughout the facility, egress, fire protection, and accessibility could be considered according to building codes, with the building layout adjusted as necessary. Integration of a more in-depth architectural plan with the structural design may have improved the feasibility of the layout. For example, some floors have different bay areas and layouts than other floors, which made the structural design more complex. Similarly, two additional floors were placed over the auditorium space, which produced large transverse loads on long-span members and required unique structural design techniques to overcome those challenges. Reevaluating the layout of the building to take occupied spaces off the ceiling of the auditorium would be desirable.

Additional structural considerations could include concrete or mass timber designs as a comparison to the cost and feasibility of steel. To further complete the structural design, lateral bracing for wind and seismic loadings should be considered as well as connection and bolt designs. An advanced structural design could include the further integration of camber, checks for lateral-torsional buckling, and the inclusion of web and bearing stiffeners.

Another potential exploration could include the integration of Building Information Modeling (BIM). BIM utilizes 4D phase modeling to optimize the cooperation of design and construction disciplines. This BIM model would include the Revit model, the cost estimate, and the time of each phase. A popular software program for this type of modeling is Navisworks, which allows the combination of 3D models with cost and time data to create phasing plans and construction animations.

This project provided a base for WPI's new Performing Arts Center. It was important to prioritize the feedback of the WPI community in the design, and the team was able to produce a building that meets their desires. The structural design, project schedule, cost estimation, and various analyses could be used as tools to develop a complete facility. The team hopes to see the design expanded in future projects.

6. References

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7. Appendices

7.1. Appendix Table of Contents

Appendix A: Proposal

Proposal Table of Contents

Abstract

This project will focus on the significant elements of structural design to create a performing arts center for Worcester Polytechnic Institute. Due to available space issues on campus, this new building should provide more rooms for students in the music and theater departments which may include more practice rooms, classrooms, storage rooms and more. Moreover, the new PAC will include fixed seating in the main auditorium space and better acoustics for cast members and audiences. The need for these crucial spaces will be taken from interviews with faculty and surveys from students. Based on a proper list of necessities, general floor layouts will be designed. From these layouts, a Revit model will be made along with a structural design with structural steel and concrete which will include calculations and drawings. Nevertheless, the project will take into account a construction schedule and cost estimate as well as considerations for sustainability and acoustics to address this civil project in a cohesive way.

Capstone Design Statement

Worcester Polytechnic Institute (WPI) necessitates that the Civil, Environmental, and Architectural Engineering Department prepare students for engineering practice through design projects to meet ABET (Accreditation Board for Engineering and Technology) standards. The Major Qualifying Project (MQP) towards the end of a student's undergraduate career brings together the different disciplines and information learned to address a technical issue in the field. This MQP focused on designing a new Performance Art Center for the WPI main campus to address the needs of students and faculty concerning space and acoustics for performances. The following realistic constraints were considered in this auditorium design project.

Economic

While designing the auditorium layout, the team will perform a cost estimate for construction activities which will include total material cost, labor cost, and total project overhead cost. With that, we will take into account direct costs related to design, project management, and construction work. We will also consider the cost of any liquidated damages that might be charged to the contractor assuming general values and costs through assumptions and investigations from past projects.

Social

The new Performance Art Center will have social implications on the WPI campus since it will benefit students who are in theater or play musical instruments. The auditorium will include more practice rooms, rehearsal spaces, classrooms, and other spaces that will foster more community engagement with different organizations. With that, the building might be constructed in an area that was mostly residential, so the team will take into account the scope of the project along with the height ordinance and sound compatibility with surrounding structures.

Political

Since one of the potential sites of construction was in a residential zone near campus, the team will consider the process of rezoning part of the space for the Performance Art Center. This will include applying to petition for rezoning, communicating with the zoning board regarding an appeal of zoning, attending public hearings, and having a plan for legislative decision. An appeal for decisions can also be considered through contact with the city council or county commission.

Ethical

The team will follow the design guidelines of the American Society of Civil Engineers Code of Ethics to provide a sufficient design for the new Performance Art Center building. We will also consider how the construction and sounds from future shows will affect neighboring residential areas.

Health and Safety

The team will follow guidelines and codes from the American Concrete Institute (ACI), the American Institute of Steel Construction (AISC), and the American Society of Civil Engineers Code of Ethics to govern proper loading and design techniques. With that, the team will look into the International Building Code (IBC) chapters 9 and 10 for general fire protection and life safety systems and means of egress, and the Massachusetts State Building Code for information on safety and protection which can be found in chapters 9, 10 and 33 in the code.

Constructability

The team will consider site layout, building zones and ordinances, the necessary materials needed for the structural and interior design of the auditor,ium and work breakdown structure using Masterformat editions of important building requirements. Considerations to promote ease of construction will include (but are not limited to) the use of standard section sizes for structural members and a repetitive structural layout with consistent dimensions as well as consistent material properties. We will also consider scheduling on Primavera and look into overall cost estimates of direct and indirect costs of the project.

1. Introduction

Here at WPI, we are more than engineers. WPI has prioritized well-roundedness in its students for over 50 years through the development of a Humanities and Arts (HUA) requirement. Many options are available to students to fulfill their HUA project including English, language, and performing arts. Hundreds of students choose to further participate in performing arts at WPI through one of the over 25 clubs on WPI campus focused on performing arts or music ensembles.

With the importance of performing arts on campus, it was astonishing that WPI does not have an adequate facility. WPI's Alden Hall has been the official home of performing arts on campus for almost 30 years, but it was an inadequate facility. Alden Memorial Auditorium was lacking in the most important aspects of a performing arts building- performing and rehearsal space, practice rooms, and storage.

As WPI continues to admit more students, the situation in Alden Memorial was getting worse. Many ensembles are now breaching over 100 students but with only one space on campus capable of holding rehearsals with groups that size, what are groups to do? Groups have taken to rehearsing in the basement of Sanford Riley, a dormitory on campus, and even the Campus Center. On an individual level, students looking to practice have two choices- occupy one of the two practice rooms or occupy an entire classroom. With over 1,800 students in music ensembles on campus, the lack of individual practice space was unacceptable.

Storage in Alden Memorial was an even larger issue. Every space in Alden was being occupied to the maximum capacity. As dedicated storage space runs out, groups are forced to use hallways, classrooms, or facility spaces to store equipment. This not only limits the ability to use spaces for their designed purpose but poses many accessibility issues to everyone in the building.

Even with renovation, Alden Memorial was an inadequate facility. The space was simply too small for the current and growing size of WPI.

Our team will be designing a new performing arts building for the WPI campus. We have broken our project into the following six objectives:

1. Identify the needs of WPI for a performing arts building
2. Design the layout and floor plans for a new performing arts building
3. Create a Structural Design
4. Create a Construction Schedule and Cost Estimate
5. Conduct Sustainability and Acoustical Analyses on our design
6. Develop a 3D model of our design

First, we will need to establish the necessary spaces and attributes for a performing arts building. We will design the layout and floor plans incorporating these necessary spaces and create a corresponding structural design. The group will then develop a project schedule for this building and derive a cost estimate. Sustainability and acoustical analyses will be conducted to supplement our structural design. Finally, we will develop a 3D model of our design incorporating the proposed site and architectural layout as well as structural design.

We will present the following deliverables at the end of our project:

1. A Structural Design including member sizes for beams, girders, columns, and other structural elements and their applicable materials,
2. A basic layout and 3D Model by Autodesk Revit,
3. A project schedule by Primavera 6 and cost estimate,
4. Recommendations for sustainability and acoustical.

2. Background

This chapter will discuss the current status of WPI's arts and performance facilities and the problems that exist with them. To address this concern, materials with the specified physical properties will be selected which properly address these concerns. The constraints associated with the design, such as zoning and building codes, LEED certification, and cost, will be discussed as well.

2.1. Design Problem

Worcester Polytechnic Institute (WPI) was an engineering institution founded in 1865 to provide students with a technological education encompassing both theory and practice. Though WPI provides an engineering education first, the institution also provides opportunities in other fields like the humanities and arts, social sciences, economics and business, and athletics. WPI continues to produce well-rounded individuals in part due to the implementation of the WPI Plan in 1970. This plan was a bold experiment to incorporate learning through applications in the form of projects, one of which was a project in the Humanities and Arts (HUA), entitled the HUA Capstone. Students are given the opportunity to pick a discipline within the HUA department and complete a project in the field in addition to their technical studies. Many students choose to do theirs in music, theater, and art.

While the WPI Plan was installed in 1970, WPI hasn't simply dabbled in music performance and education since its conception- students have been performing at WPI long before that. The growth of the performing arts at WPI continued when the university's first and only performance space was built in 1940 - Alden Memorial Auditorium. This building features a main hall with a large proscenium stage and an open, flat space that has been used as a multi-use space since it was built. Anything from musical theater to career fairs to lectures has been held in this space for over 80 years. Yet it wasn't until 1992 that Alden Hall was officially deemed WPI's performing arts building. In that year, Alden Hall was completely renovated to modernize all floors of the building, particularly the basement. That space features one large recital hall (Spaulding Hall), one smaller rehearsal space (Perrault), two private practice rooms, a music technology lab, a computer lab, and one music classroom. Storage was limited in the basement, which was the main hub for most music students - three instrument closets are available for all players to store their instruments. Finally, a "sub-basement" below the basement was used for storing lighting and sound equipment as well as a maintenance area.

Musically inclined students are usually quite excited to come to WPI - there are over 25 music groups on campus for students to get involved with. However, as the number of ensembles grow, more space was required for their rehearsals and performances. Incoming class sizes at WPI are on the rise and as a result, ensembles that do not have a cap on the number of members in the group continue to grow and eventually outgrow the few spaces on campus sufficient to hold them. Some of the largest groups on campus (Concert Band, Orchestra, Marching Band, and Festival Choir) have a limited number of spaces available to them on campus due to the sheer size of the group. Those spaces include the Alden Memorial Great Hall, the Odeum in the Rubin Campus Center, Riley Commons in the basement of Sanford Riley Hall, and Gordon Hall in the neighboring First Baptist Church (FBC). Other groups, like theater clubs, have only two options for their performances - the Alden Great Hall and the Little Theater under Sanford Riley Hall. All other music ensembles usually have their concerts in the Great Hall as well, which, due to the poor acoustics in the space, was not ideal for music performances. A cappella groups often try to hold shows in the Great Hall as well. Due to the large open floor space, it was also a popular place for banquets and dances as well as career and project fairs. As a result of the incredibly high demand, it was very difficult to book this room since so many different groups need to access it. Simply put, this one building, which has been the home to WPI performing arts for over 80 years, has not been able to adapt to the growing student population and volume of clubs.

A partnership started in which the FBC agreed to allow WPI music groups to use their spaces when they are not in use by the church. As a result, all WPI choir activities happen in the FBC including rehearsals, storage of concert attire, and their music library. The Director of Choral Activities and Coordinator of Music Ensembles, Joshua Rohde, has his office in the FBC as well. The program truly had no chance of surviving in Alden Hall given the space restrictions and thus had to move out. They aren’t the only club to do this either - despite theater groups performing in Alden Hall, most of their storage was spread out in other buildings around campus and even off-campus in some cases. WPI was also the only school in the country with the capability of showing 70mm movie film, which used to take place through the Alden Hall projector booth. Those projectors have since been moved to another building as well, and the booth has since been repurposed into a closet. Similarly, not all music professors have their offices in Alden Hall, the building in which their department was based. Of that available office space, some professors are still required to share offices, and they are not easily accessible by students. Continuing on, private practice rooms are essential for student growth - Alden Hall only has two for the hundreds of students on campus.

The issue boils down to simply not having enough space to hold the ever-growing size of the WPI music programs and facilities. The issues extend past available space as well. The only public bathroom in the building was below the main floor of the building, and a large portion of the building was not ADA-compliant. There was only one elevator, which was located at the back of the building away from the main entrance. There was no proper lobby for people to arrive and mingle prior to performances. No art spaces exist anywhere on campus for those interested in pottery, painting, and the like. There are multiple student art groups on campus that would utilize these spaces, including some academic classes, which currently use a separate room that was not fitted for this application. Furthermore, art and design students do not have a space to display their work such as a gallery. The problems with the available space extend deeper than the lack of an auditorium - thus, a new multi-use building for WPI arts and performance was needed.

2.2. Materials & Structure

For the structural framing of the building, the team will use concrete and steel for beams and columns. With that, we will be basing our design on standard ASTM A992 with a minimum yield strength of 50 ksi for wide-flange. Structural steel I-beams will be efficient because they have a high strength-to-weight ratio, so they can withstand high stresses. Moreover, they are resistant to aging, and they can be modified easily with other new structural additions in the process. For large spans such as the auditorium on which the team will be planning on creating, trusses with angles and beams such as wide-flange will be analyzed.

Our team will also investigate different types of construction, composite and non-composite construction. The benefits of composite construction were that there was typically: a lower cost for the structural frame (thus reducing foundation costs as well), lighter weight beams and girders, reduced column loads, increased span lengths are possible, and stiffer floors for better vibrational performance. The two construction methods are shored and unshored construction. In shored construction, shoring is used to help the structural steel sustain their self-weight plus the weight of the wet concrete, after the concrete dries, the shores are removed. In unshored construction, shoring was not used, so the steel members must be larger in size to accommodate their self-weight and the additional weight of the wet concrete. Non-composite construction tends to be more expensive than composite construction. Since the concrete slabs are not a structural part of the building, only the steel beams are meant to carry the entire building load thus leading to the use of larger-sized members. The only benefit of non-composite construction was that it takes less time to complete allowable stress calculations since the concrete slabs are not an integral part of the building structure, making it more simple to design. Other than that, the team will also incorporate concrete beams and columns in our structure due to its strength and durability. Depending on the span size, large spans will require a bar size #8 for analysis while other smaller spans will need a #5 bar size.

For the interior of the auditorium, certain acoustical finishes and furnishings should be used and they need to be hard, sound-reflective materials. According to designer David McCandless, plaster was a traditional material for ceilings and walls in concert halls. This was because it can be used on the side walls and ceilings in shapes to help diffuse reflections throughout the room, enhance reverberance, and give a sense of sound development. Interiors also include surfaces repeated to allow precasting. This casting was usually done with fiberglass-reinforced gypsum (FRG). Wood paneling can be used in the process, but it was important to note where that wood was placed around the auditorium place itself.

2.3. Constraints

With this project, there are some constraints that need to be acknowledged. Area zoning, site/building constraints, building codes and guidelines, and total cost all need to be acknowledged in order for the performing art center (PAC) to be built without any setbacks.

One concern with our project was facing potential zoning issues with the building grounds. According to the Worcester Zoning Ordinance, WPI's Campus and Facilities all lie on the same zone with the designation of IN-S. An IN-S zone designation was typically given to areas reserved for Institutional/Educational uses. This zone type allows for the construction of PACs, however not all zone types allow this. Much of the Worcester area falls under an R (residential) type zone which prohibits the construction of a PAC. In the instance that you wish to construct a building that was prohibited in your zoning region, you must have the land rezoned to a zone type such as: IN-S, BG, ML, MG, which allows the construction of a PAC. This process involves having to file an application to the Zoning Board of Appeals, followed by hearings in front of the board committee where they vote on whether to approve the zone expansion or not.

Assuming that zone changes are performed, according to the Worcester Zoning Ordinance, there are also restrictions set on how close the building can be to the property line. For a new building constructed in an IN-S zone, the front of the building must be a minimum of 15ft away from the property lines and the sides and rear of the building must be a minimum of 10ft away from the property lines. Additionally, there was a governing equation reserved for substantially irregular lots that must be calculated for the building lot and if it surpasses a certain value, then the lot was considered irregular and must be redesigned. These restrictions will impact the final design of the structure since these requirements will reduce the allowable space for the structure to be built. Consideration must also be given to the surrounding structures near the area which are mainly 2-story buildings. This inherently limits the height potential of the final structure design so that it wouldn't seem out of place in the area.

On the topic of restrictions, there are building codes that must be followed in order for the building to adhere to the 780 CMR Massachusetts State Building Code. It was required for us to follow the other regulations found in 780 CMR that apply to the structure itself such as 527 CMR which covers fire protection, 310 & 314 CMR both cover environmental protection, and 780 CMR section 13.00 which mentions energy efficiency. Building codes also apply to building additions such as elevators, which were reflected in 524 CMR: Elevators. Building our structure by following the appropriate guidelines was important for the safety of the occupants using the building as well as the residential area around it. The *International Building Code* (IBC) should also be used in tandem with the *Massachusetts State Building Code* (MSBC). The IBC focuses on the same restrictions covered in the MSBC, however, in the instance where the two codes contradict each other, the MSBC overrules the IBC code.

Since 2007, WPI has taken steps in making each of its new buildings constructed have a minimum of LEED certification. There are five buildings currently LEED certified on WPI's campus, and our goal was to also make this new building follow LEED certification requirements as well. In order to keep this pledge, environmental protection guidelines that we plan to look into are energy efficiency, air/water pollution, waste management, and other guidelines mentioned in LEED v4.

Lastly, the cost will play a big factor in determining whether the PAC is viable for WPI to construct. Steel member design and different methods of concrete construction will be analyzed in reference to the *American Institute of Steel Construction* (AISC), and *American Concrete Institute* (ACI) standards. Material cost for the interior of the building needs to be considered as well. Some factors mentioned earlier such as LEED certification and rezoning the building lot also have their own costs aside from the construction of the building. A final cost analysis will be conducted.

3. Methodology

The goal of this project was to design a new building that fits the requirements and needs set forth by the WPI humanities and arts community. During the course of two, 7-week terms, we plan to:

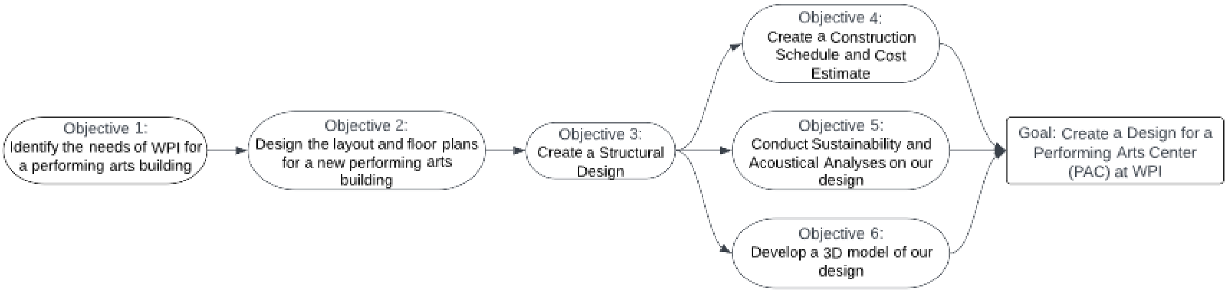


Figure 1: Methodology Diagram of Objectives and Goal

3.1. Identify the needs of WPI for a Performing Arts Building

To begin our project, we will need to establish the specific needs WPI has for a performing arts Building. We will aim to create a summary of the required details of the performing arts building. These will include specific spaces needed and how the spaces should interact as well as the required amenities and size of each space.

We will conduct several interviews with WPI Faculty and Staff as well as share an input form with students involved in the arts on campus. We will analyze the data from the student input form and interviews to create a comprehensive list of necessary attributes to incorporate into our design. This comprehensive list will be the basis of our program for our project.

Before we begin the layout or structural design for our building, we will need to choose a location for our building. Through analysis on Google Maps and QGIS, we will establish possible areas for development. We will compare the lot sizes of WPI's Alden Hall and similar performing arts buildings to find plots near WPI campus with appropriate size. Our group will visit the proposed locations to assess the viability of the locations before we begin our design.

3.2. Design the layout and floor plans for a new Performing Arts Building

Following the feedback received from WPI faculty in the music and theater department as well as inputs from students, the team will make a structured list of important rooms and facilities needed for the WPI campus. These include more rehearsal spaces, practice rooms, dressing rooms, classrooms, and storage spaces among other options. Nonetheless, the team will also look at some examples of other college theater spaces for overall layout ideas. Team members will draw the basic layout of the building with the necessary amount of space, and use Revit to start modeling the architecture of the auditorium. Site design will consist of importing data from QGIS into AutoCAD and then importing that into the Revit model in which the architectural design will be placed. The site design will also be based on zoning regulations and frontage. The team will start with exterior layouts, work on interior walls and spaces while adding necessary elements to the theater space. The Revit model layout will be ongoing until the end of the project, and changes and updates to it will be made along the process.

3.3. Create a Structural Design for this Building

It was important to look at multiple sources of structural materials when designing a building. This building will feature a structural steel design as the focus for the main superstructure, and concrete features will be used for comparison purposes. Select members will be evaluated for both steel and concrete design for efficiency and cost analysis purposes, as well as needed spaces. Reinforced and prestressed concrete design methods will be considered for the aforementioned selected members.

3.3.1. Structural Steel

Using the LRFD approach in accordance with ASCE 7-16 and the *AISC 15th Edition Steel Manual*, the team will investigate the load combinations needed for the design of steel members so that the PAC can be constructed safely. Different governing equations will help us in determining the typical design loads which include live loads, dead loads, and wind loads. We will also consider the required allowable snow loads since WPI was located in Worcester, Massachusetts where there was a high expectancy of yearly snowfall. Since our building was expected to seat many people at once, occupancy load requirements also need to be considered as well. The *International Building Code* (IBC, 2017) along with the ASCE 7-10 standard provides us with the occupant loads by listing the required floor area needed per occupant as well as the minimum allowable loads required for the performing arts centers to support. We will also take a look at using composite vs. non-composite construction techniques.

After deciding on whether composite or non-composite construction was suitable for this project, we must evaluate the allowable forces for the structural design. The allowable forces for all steel members need to be calculated in ordinance to governing equations found in the ASCE 7-16 and AISC 15th Edition Handbook. The deflection, compression, and buckling conditions of all steel members need to be addressed. Since the beams are bolted onto the columns, metal plating and bolt designs also need to be calculated. Different framing connections need to be evaluated, either simple or moment connections. Lastly, we plan to look into different bracing strategies for the structural frame to combat seismic forces. The AISC 15th Edition Handbook also contains the allowable stresses allowed for all member, bolt, and plate sizes, making it an important tool for selecting the appropriate sizes for our design.

3.3.2. Structural Concrete

The team will evaluate which portions of the structure may be most viable to be constructed from concrete versus structural steel. Factors to be considered in this step will include function, span length, constructability, and compatibility with nearby features. Additionally, multiple designs will be generated using prestressed concrete sections versus reinforced concrete sections, which will allow for comparisons of viability in the overall structure. These comparisons will be made against the use of structural steel as well.

For the design of reinforced concrete elements, the design will follow the applicable sections of the American Concrete Institute (ACI) 318 Building code. For the design of reinforced concrete beams and girders, the applicable moments and loads will be calculated to allow for the determination of the cracking and ultimate moments of a selected section, which can then be adjusted to combat those moments. Deflections will be checked against the ACI code as well to ensure they are within the allowable limits. Based on the moments and geometry of the selected sections, the required reinforcement and its spacing will be determined as well to complete the design. Reinforced concrete may also be used in the design of other features such as foundations, retaining walls, and columns as necessary for means of comparison. A similar process will be followed which allows for the determination of the applied loadings and pressures of these elements, and then for adequate geometry and reinforcement design.

In certain cases, prestressed concrete members will be considered due to their efficient ability to cover large spans. In the planned auditorium space, which will require a large roof without columns, prestressed members may be a better alternative to structural steel due to its constructability. Thus, prestressed concrete beams will be calculated according to the *Prestressed Concrete Institute (PCI) Design Handbook*. The moments and loadings calculated for each member will be used to determine the required geometry of the prestressed member, which will be chosen from a set of standard precast sections established in the *PCI Design Handbook*. Within those members, the number of prestressed tendons required will be calculated as well as the maximum eccentricity allowed within the beam. Similar to the reinforced concrete members, this design will be compared to the structural steel design to determine the best option.

3.4. Create a Construction Schedule and Cost Estimate

Our cost analysis and proposed project schedule will be developed together following our structural design. We will begin by identifying known costs and creating a basic construction schedule using national databases such as RS Means. Materials costs of concrete and steel can be identified through our structural design and known costs. Materials to be used in the interior design will need to be estimated based on our design. We will further develop our construction schedule by comparing our project to similar projects and developing duration times for more complex activities.

From this construction schedule, we will estimate labor costs based on listed activity durations and subcontractor costs. These labor costs will be added to material costs from our design. Other costs to be added may include indirect costs such as contingency, bonds, and markup. We will organize and estimate our costs in a thorough budgeting sheet using appropriate calculations and researched numbers. Other than that, we will investigate past projects to include an assumption on costs of liquidated damages that might be charged to the contractor.

3.5. Conduct Sustainability and Acoustic Analyses on our design

3.5.1. Sustainability

WPI has prioritized LEED certification in its buildings for the last 15 years. We will research the requirements for LEED v4 certification and various sustainability alternatives to incorporate into our design. These sustainability alternatives may include alternative materials, a green roof, or a variety of energy sources. These options will be included as possible add-ons in our schedule and cost estimate as well as organized in our recommendations.

3.5.2. Acoustics

Typical acoustic analysis of rooms relies on various ASTM standards. With that, sound absorption and sound absorption coefficients by reverberation room method can be found in ASTM C423, while measurement of airborne sound attenuation between rooms in buildings can be found in ASTM E336. However, for this project, the team will focus on interior designs in our performing arts building. This would include adding more insulation such as gypsum board to the space, filling in wall cavities with fiberglass or mineral wool, and including proper wall sealing and door gaskets to prevent sound bleed. Moreover, the team will consider sound absorptive insulation for suspended ceiling systems, reduce sound transmission with insulation, reduce HVAC noise with acoustical boards, and use concave or convex insulation. Nevertheless, an acoustil analysis may be a late B-term or early C-term research project in which design strategies along with surface finishes may be investigated through our cost estimate analysis as the project continues.

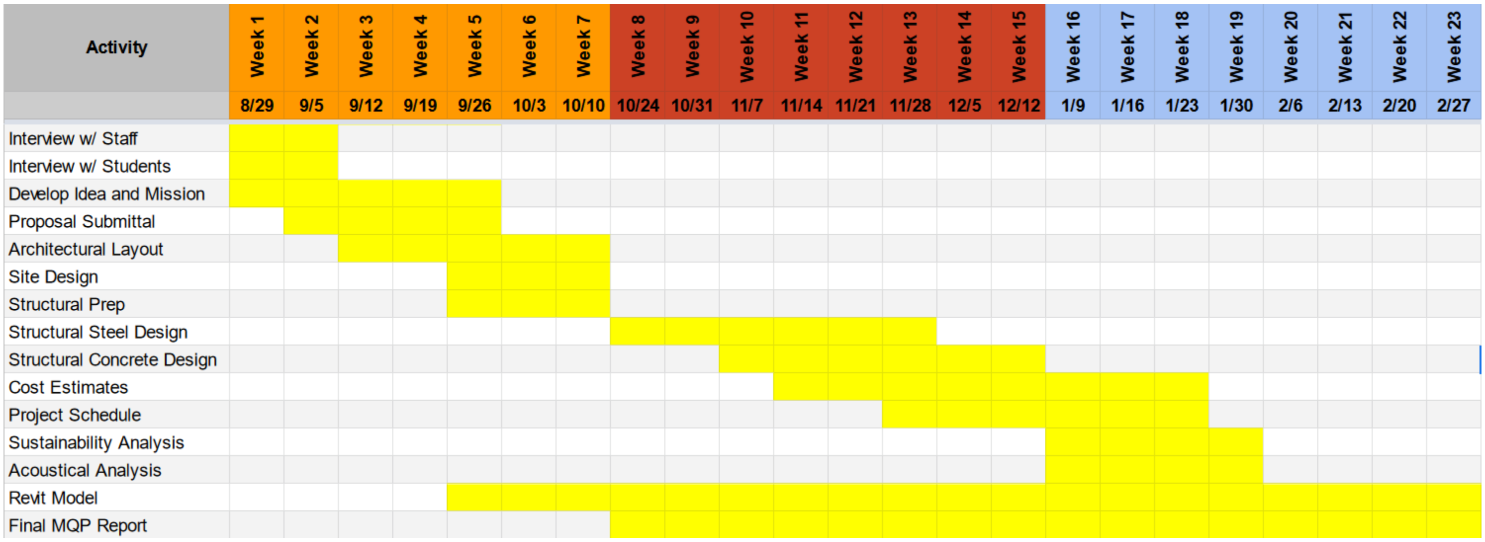
3.6. Develop a 3D model of our design

We plan to make multiple 2-D and 3-D of what the final design may look like by using Autodesk Revit CAD software. We chose Revit as our design software because it has an intuitive layout allowing us to fully take advantage of its capabilities when it comes to making sketches and rendering large structures. Revit also has the capability to add the topography of the building site by downloading GIS data of the area, importing that file and making adjustments in Autocad 3D, then importing the file a second time into Revit. Adding a topographical surface onto our Revit drawings adds more realism since it displays the true elevation changes of the building site.

4. Deliverables

Towards the end of this project experience, the team will have a proposed layout of the performance art building which will include a site design, and an architectural and structural model from Revit. We will have spreadsheets with calculations of our structural steel design and supplemental materials featuring alternate designs in prestressed and reinforced concrete. The team will also incorporate sustainability analysis such as potential LEED credits and points and acoustical analysis from ASTM standards. Along with the crucial materials we will use, we will perform a general cost analysis on labor and material costs and an overall construction schedule on Primavera.

5. Project Schedule



Activity	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13	Week 14	Week 15	Week 16	Week 17	Week 18	Week 19	Week 20	Week 21	Week 22	Week 23
	8/29	9/5	9/12	9/19	9/26	10/3	10/10	10/24	10/31	11/7	11/14	11/21	11/28	12/5	12/12	1/9	1/16	1/23	1/30	2/6	2/13	2/20	2/27
Interview w/ Staff	🟨	🟨																					
Interview w/ Students	🟨	🟨																					
Develop Idea and Mission	🟨	🟨	🟨	🟨	🟨																		
Proposal Submittal		🟨	🟨	🟨	🟨																		
Architectural Layout			🟨	🟨	🟨	🟨	🟨																
Site Design					🟨	🟨	🟨																
Structural Prep					🟨	🟨	🟨																
Structural Steel Design								🟨	🟨	🟨	🟨	🟨	🟨										
Structural Concrete Design										🟨	🟨	🟨	🟨	🟨	🟨								
Cost Estimates											🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨					
Project Schedule													🟨	🟨	🟨	🟨	🟨	🟨					
Sustainability Analysis																🟨	🟨	🟨	🟨				
Acoustical Analysis																🟨	🟨	🟨	🟨				
Revit Model					🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Final MQP Report								🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨

Figure 2: Project Schedule

6. Conclusions

At the conclusion of our project, we will present a comprehensive layout and structural design of a performing arts building for WPI campus along with a complete Revit model of the building. We will also present a project schedule and cost estimate along with sustainability and acoustical analyses for the proposed building. These deliverables are to be used as a recommendation to the Institution for the development of a new performing arts building.

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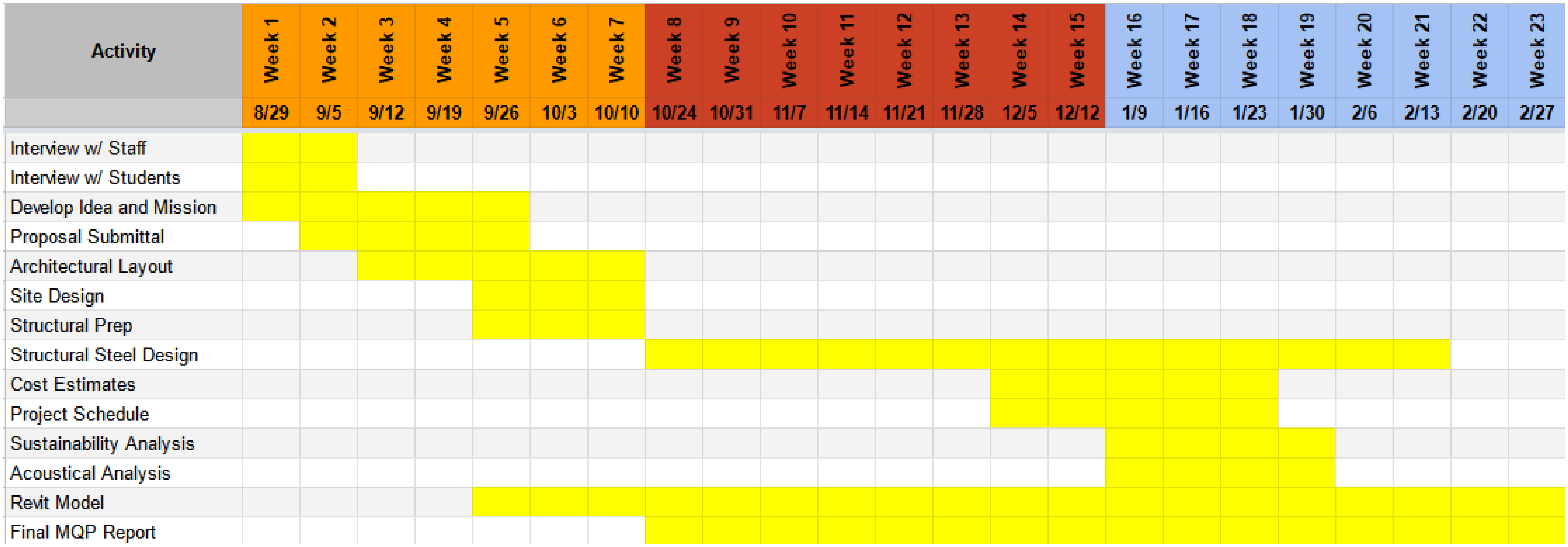
Appendix B: Project Schedule



Activity	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13	Week 14	Week 15	Week 16	Week 17	Week 18	Week 19	Week 20	Week 21	Week 22	Week 23
	8/29	9/5	9/12	9/19	9/26	10/3	10/10	10/24	10/31	11/7	11/14	11/21	11/28	12/5	12/12	1/9	1/16	1/23	1/30	2/6	2/13	2/20	2/27
Interview w/ Staff	🟨	🟨																					
Interview w/ Students	🟨	🟨																					
Develop Idea and Mission	🟨	🟨	🟨	🟨	🟨																		
Proposal Submittal		🟨	🟨	🟨	🟨																		
Architectural Layout			🟨	🟨	🟨	🟨	🟨																
Site Design					🟨	🟨	🟨																
Structural Prep					🟨	🟨	🟨																
Structural Steel Design								🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨		
Cost Estimates														🟨	🟨	🟨	🟨	🟨					
Project Schedule														🟨	🟨	🟨	🟨	🟨					
Sustainability Analysis																🟨	🟨	🟨	🟨				
Acoustical Analysis																🟨	🟨	🟨	🟨				
Revit Model					🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Final MQP Report								🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨

Figure B.1: Project Schedule

Appendix C: Interview and Survey Questions

Interview Questions

[Interviewee’s name],

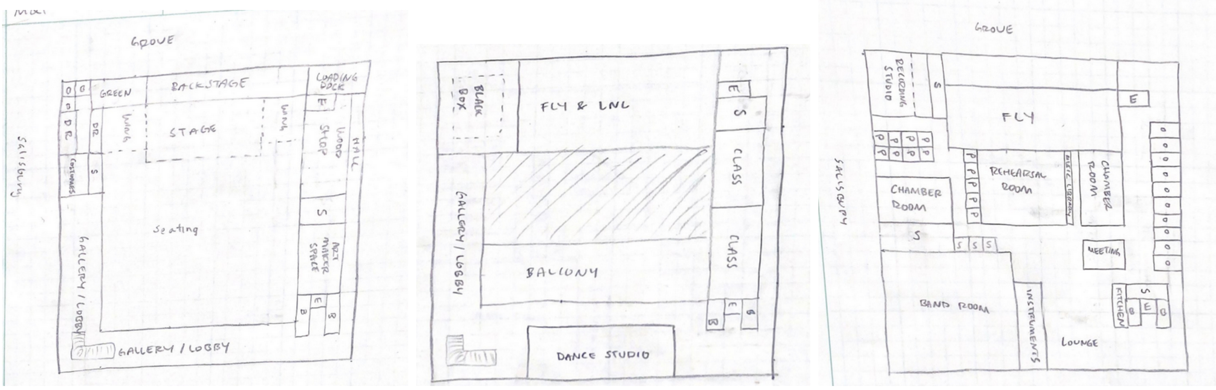
1. Please state your name and position at WPI.
2. What organizations/ensembles do you oversee?
3. What do you think are the major problems with WPI’s current Performing Arts space?
4. Our design will include a traditional auditorium space, in a concert hall and/or theater style. What style of location do you think would benefit WPI the most?
5. What types of rooms (excluding an auditorium space) do you think would benefit this new building the most? Examples could include practice rooms, dressing rooms, storage closets, rehearsal spaces, etc.
6. Is there anything else you think would be beneficial to have in a new PAC?
7. In your experience, did any performing arts center have a unique feature you thought was especially beneficial? Were there any features you especially disliked?
8. What do you view as short-term and long-term solutions to the problem? (Event’s office only)

Survey Questions

1. What organization(s) are you a part of?
2. If you are an instrumentalist, what instrument(s) do you play?
3. Do you think WPI needs another arts building?
4. Our design will include a traditional auditorium space - what style of location do you think would benefit WPI the most? For example, view the concert hall and stage set-ups in the following 2 images. Note that it was possible to do both.
5. If your organization doesn't already use a location like an auditorium (i.e. a comedy or art group), do you think your club would explore using the space? If so, what for?
6. What types of rooms (excluding an auditorium space) do you think would benefit this new building the most? Examples could include practice rooms, dressing rooms, storage closets, rehearsal spaces, art gallery, etc.
7. Is there anything else you think would be beneficial to have in a new arts building? Things could include a box office, refreshments, classrooms, or anything else!
8. If you are comfortable with our group potentially reaching out to you about your response, please provide your name and WPI email below.

Appendix D: Preliminary Layout Drawings

Conceptual Design 1



Figures D.1, D.2, and D.3: Conceptual Design #1 featuring Hand Drawn Floor Plans for the 1st-3rd Floors

Conceptual Design 2

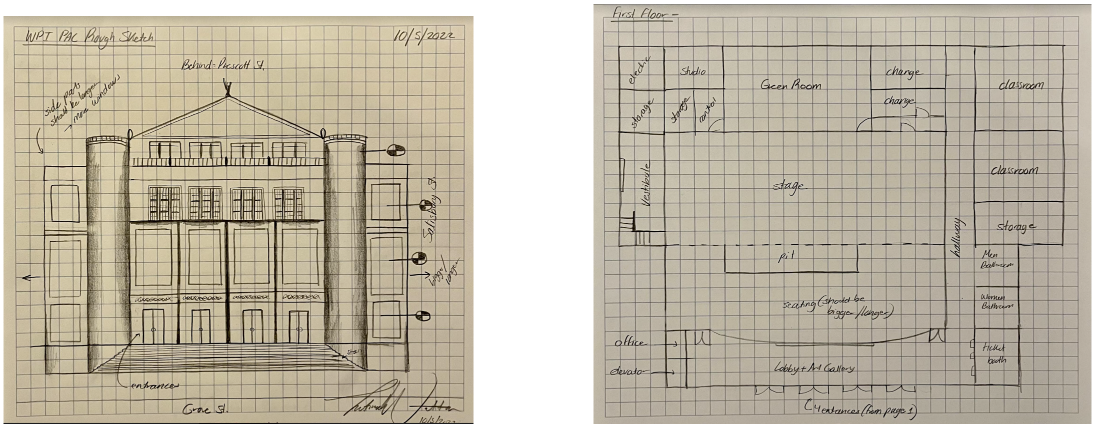
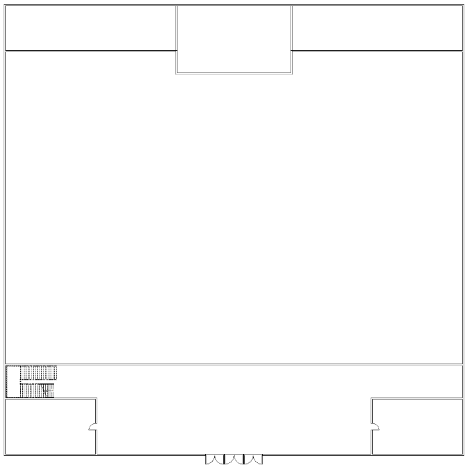


Figure D.4 and D.5: Conceptual Design #2 featuring a Hand-Drawn Exterior and First Floor view

Conceptual Design 3



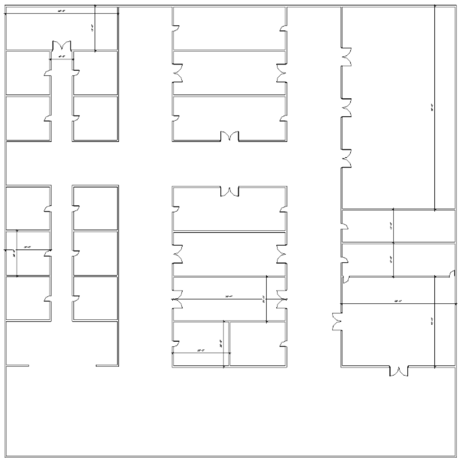
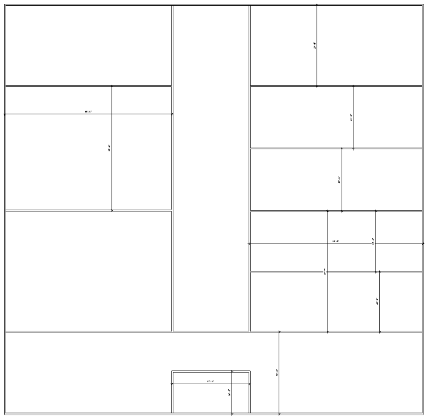


Figure D.6 (left): First Floor on Revit (3rd design) Auditorium, Stage, and 2 Bathrooms Shown.
Figure D.7 (right): Second Floor on Revit - 10 Offices, 2 Conference Rooms, 1 Black Box Theater, 1 Large Rehearsal Room, 2 Bathrooms, 1 Instrument Storage Closet, 1 Costume Storage Space, 5 Classrooms



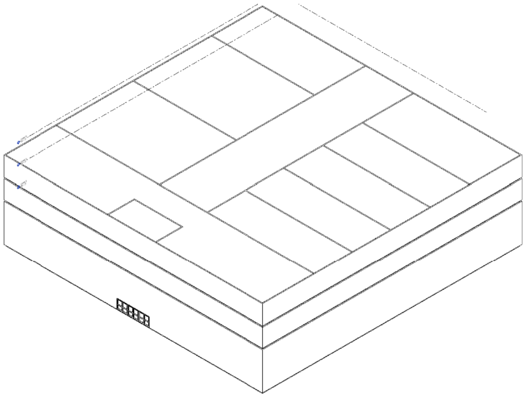


Figure D.8 (left): Third floor on Revit (3rd Design) - 1 Workshop, 1 Large Storage Space, 1 Recording Studio, 1 Art Maker space, 1 Lighting and Sound Equipment Storage Space, 1 Music Library, 1 Bathroom.
Figure D.9 (right): 3D View of Conceptual PAC in Revit

Conceptual Design 4

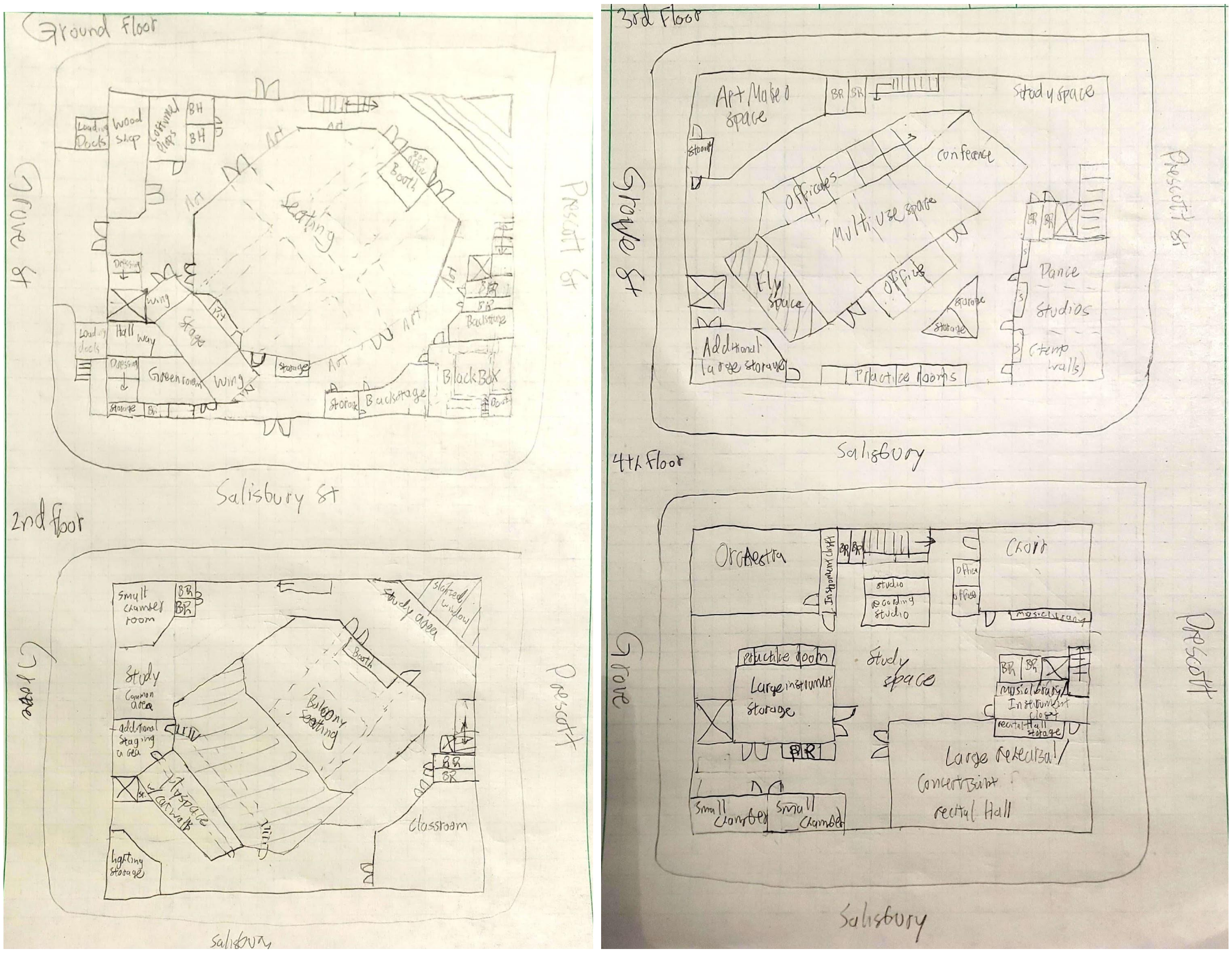


Figure D.10 & D.11: Design #4 featuring Hand-Drawn Floor Plans from the 1st to 4th Floor

Appendix E: Scaled Initial Floor Plan Layouts

In these drawings, some abbreviations are used, as below:

- "B" = Bathroom
- "DR" = Dressing Room"
- "E" = Elevator
- "LD" = Loading Dock
- "O" = Office
- "P" = Practice Room
- "S" = Storage

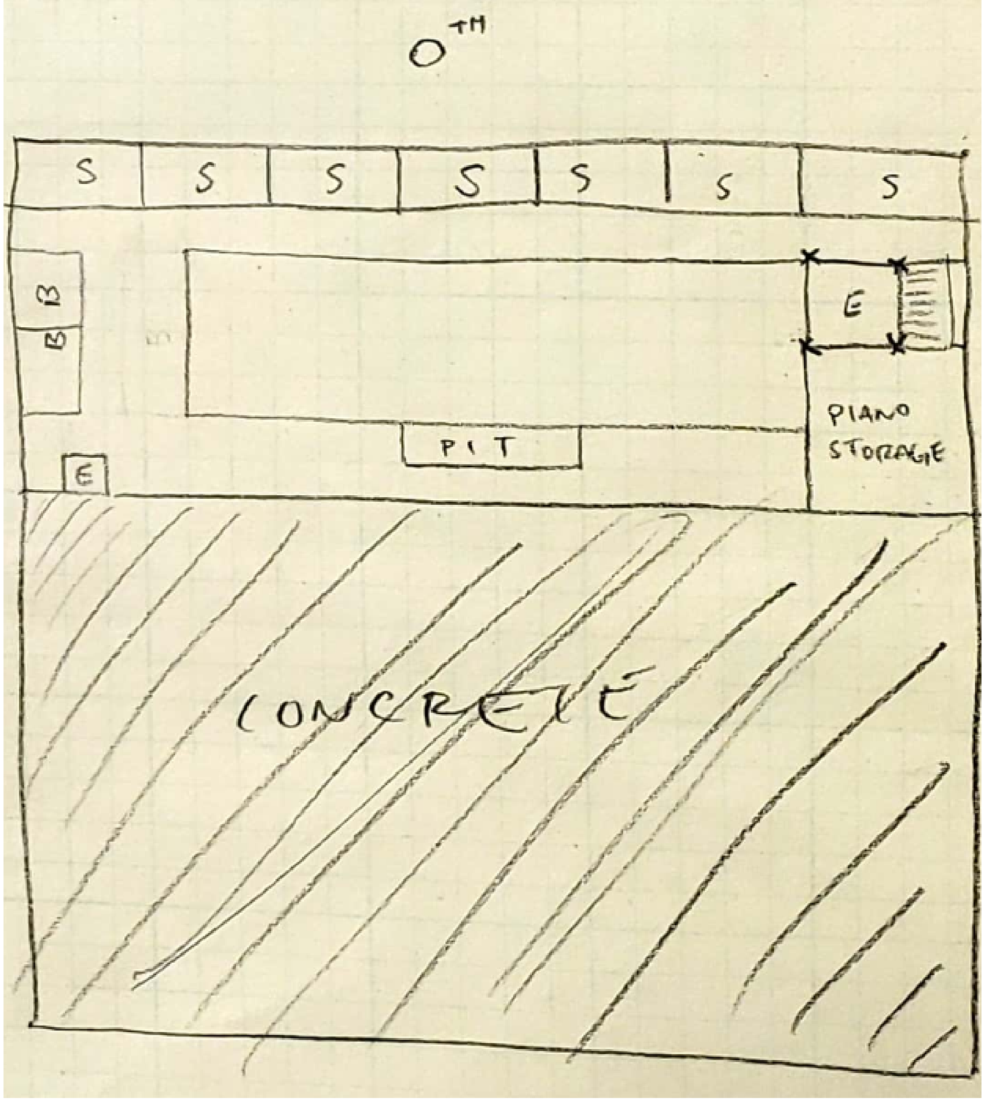


Figure E.1: Hand-drawn, Scaled Layout for the Basement (0th Floor). Each grid space = 10'.

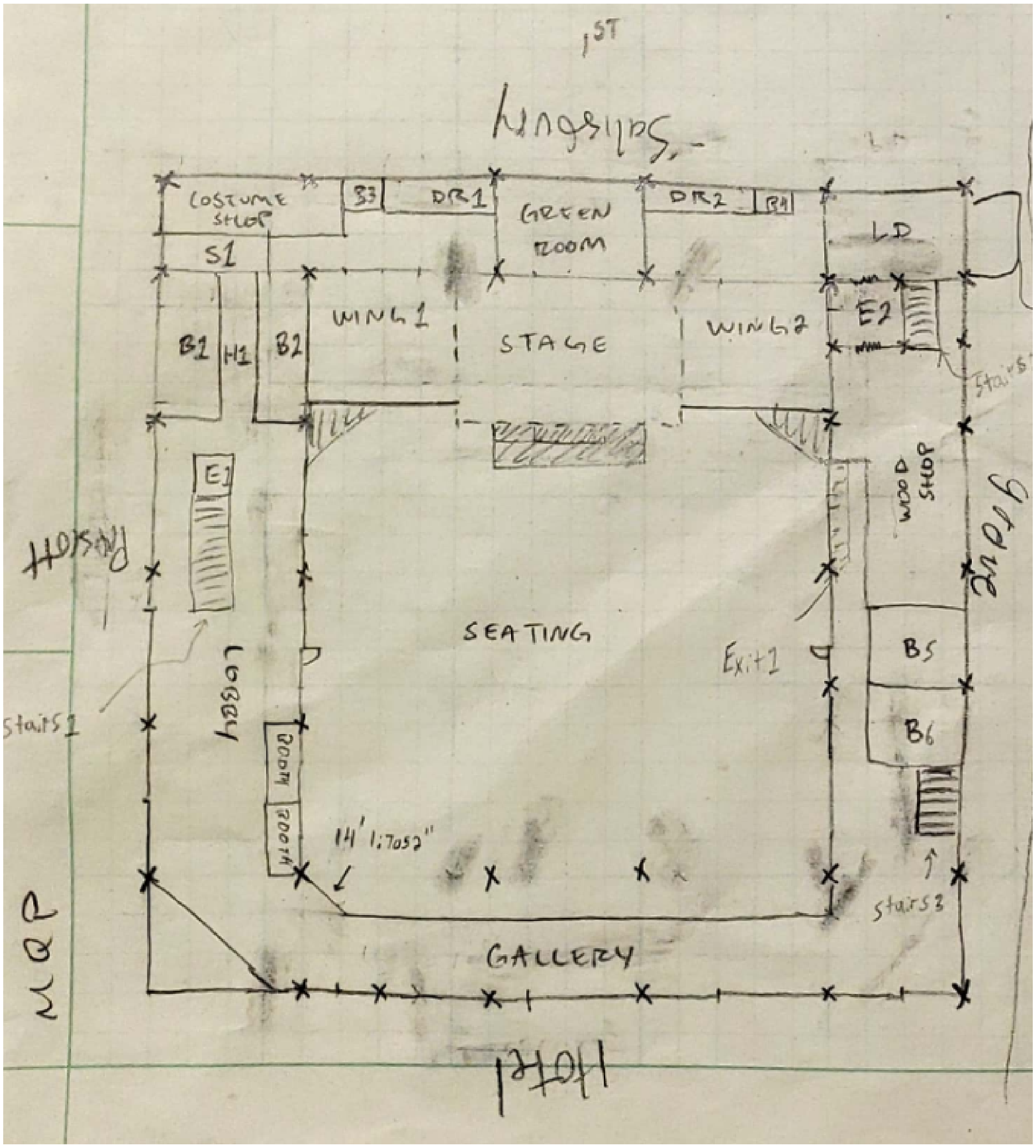


Figure E.2: Hand-drawn, Scaled Layout for Floor 1. Each grid space = 10'.

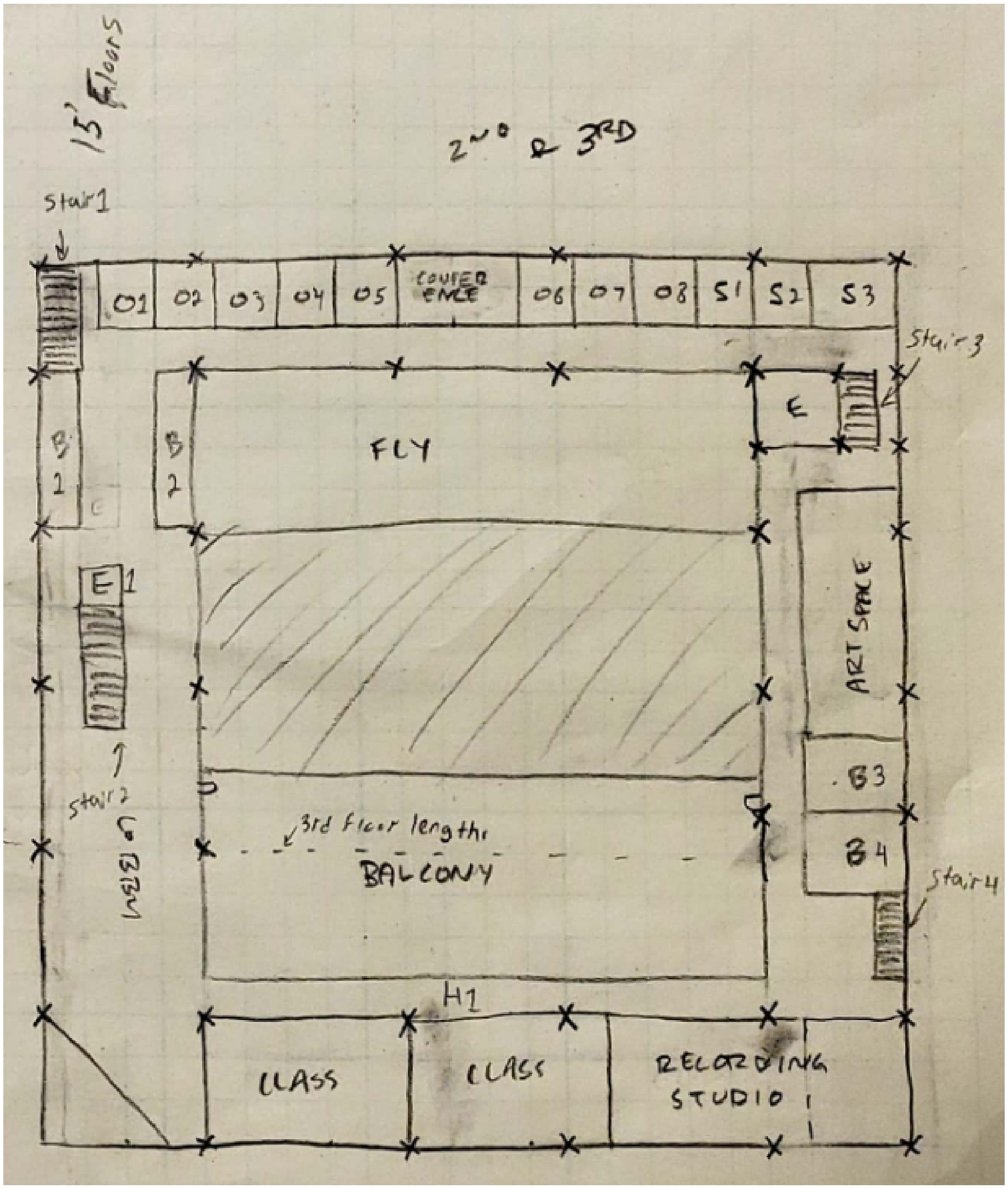


Figure E.3: Hand-drawn, Scaled Layout for Floors 2 and 3. Each grid space = 10'.

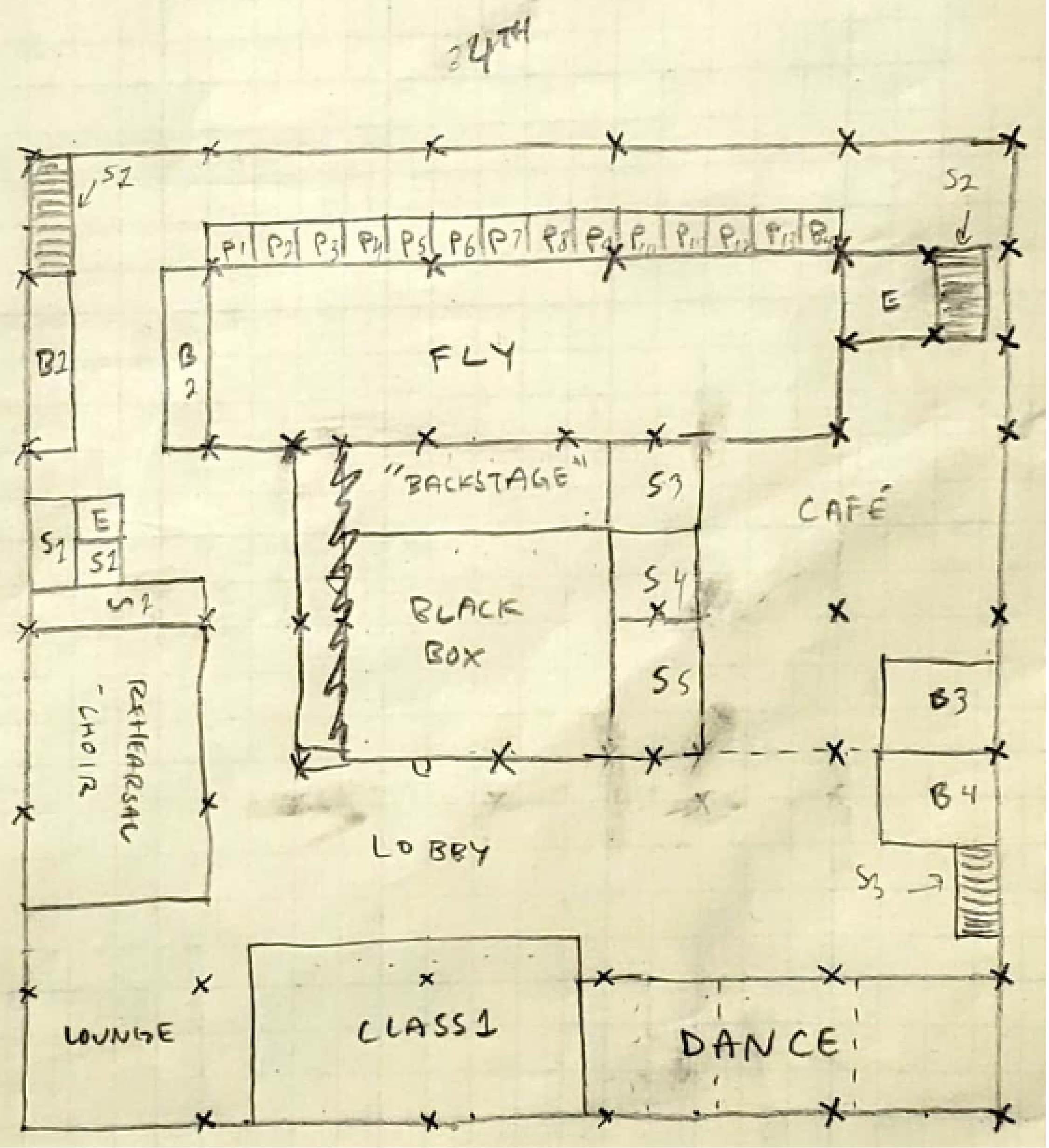


Figure E.4: Hand-drawn, Scaled Layout for Floor 4. Each grid space = 10'.

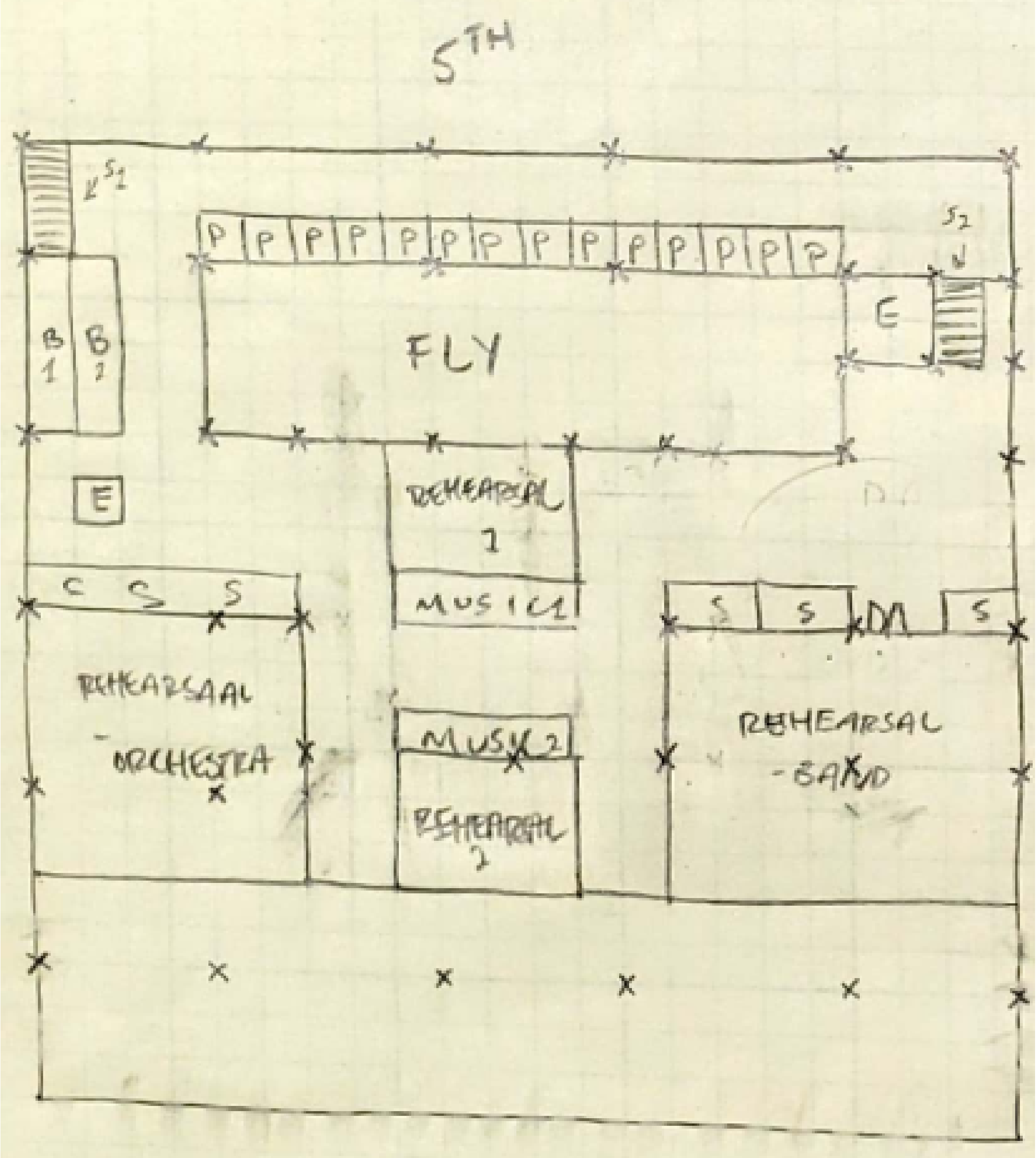


Figure E.5: Hand-drawn, Scaled Layout for Floor 5. Each grid space = 10'.

Appendix F: Final Layout on Revit

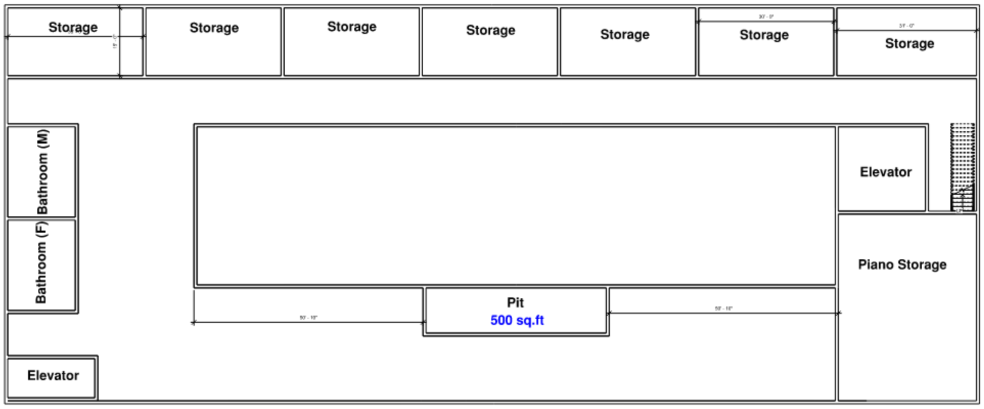


Figure F.1: Basement Floor Layout

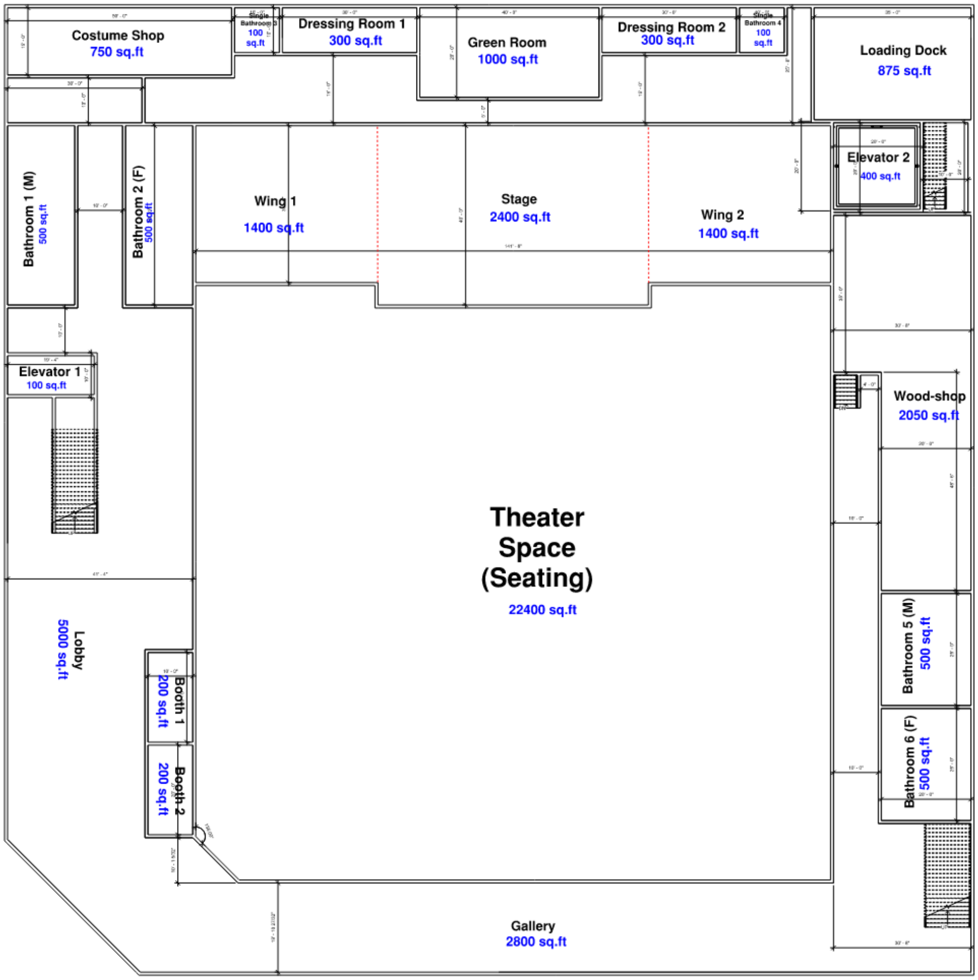


Figure F.2: First Floor Layout

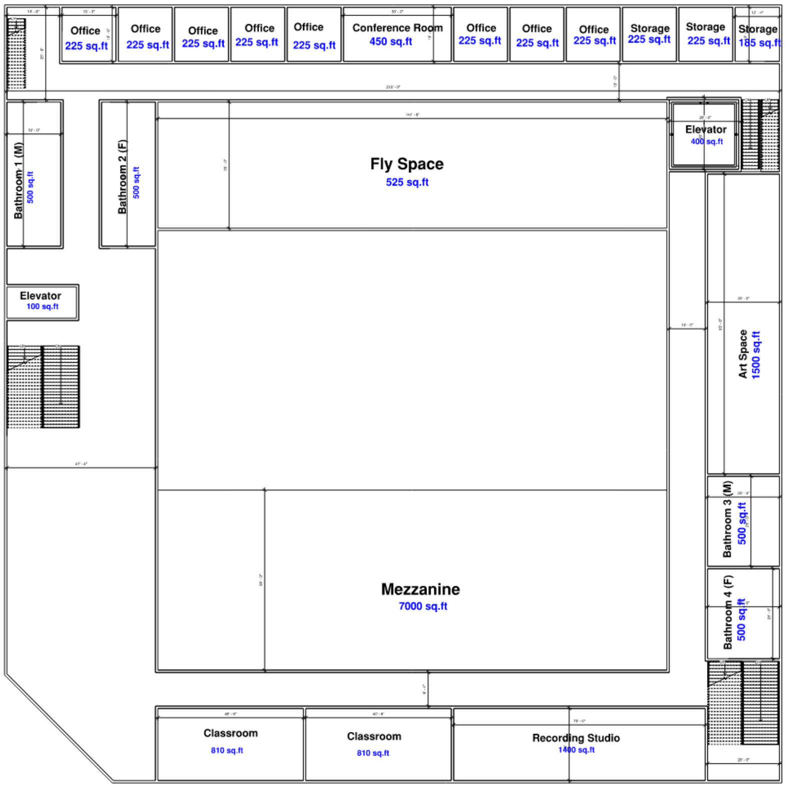


Figure F.3: Second Floor Layout

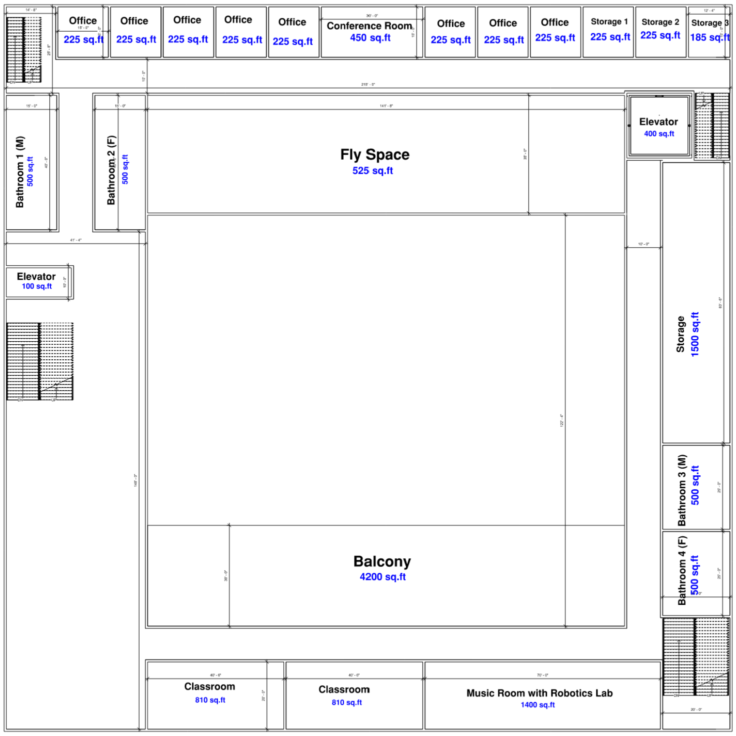


Figure F.4: Third Floor Layout

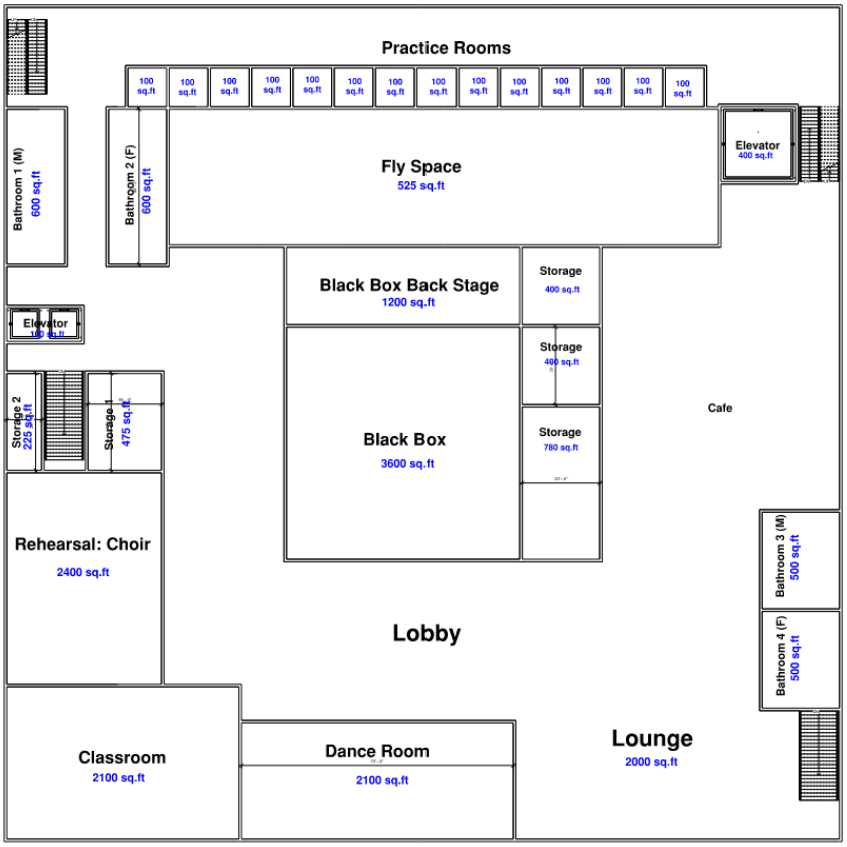


Figure F.5: Fourth Floor Layout

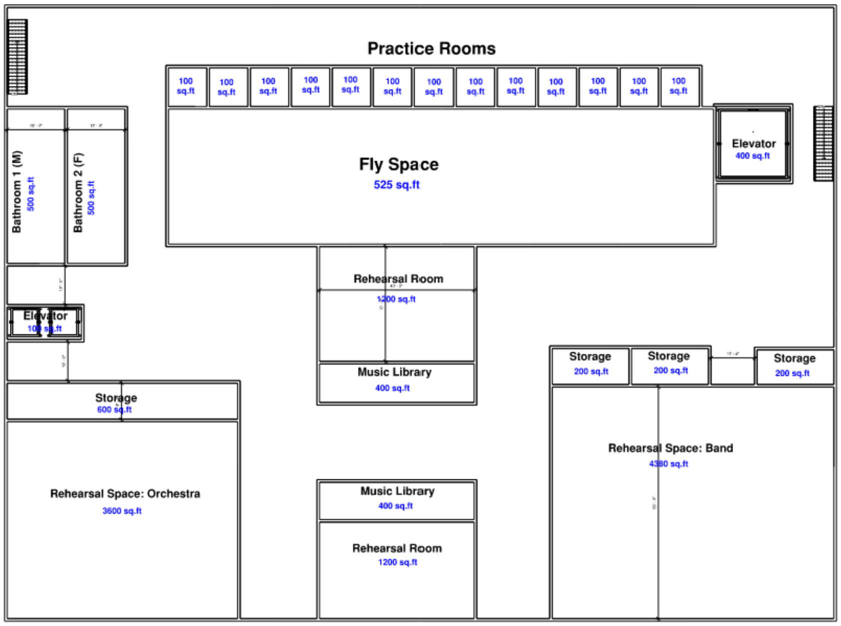
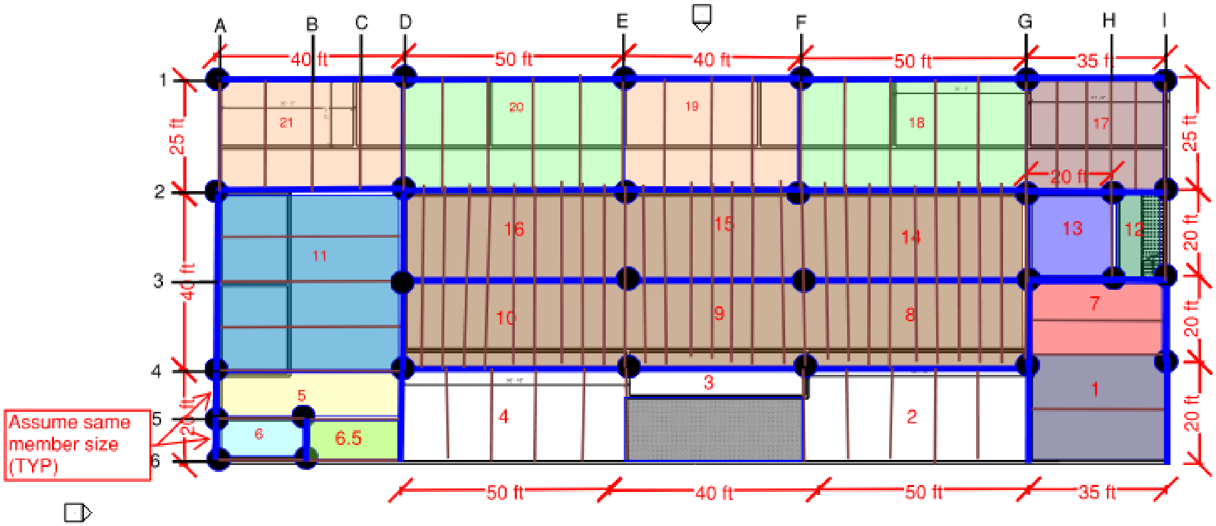


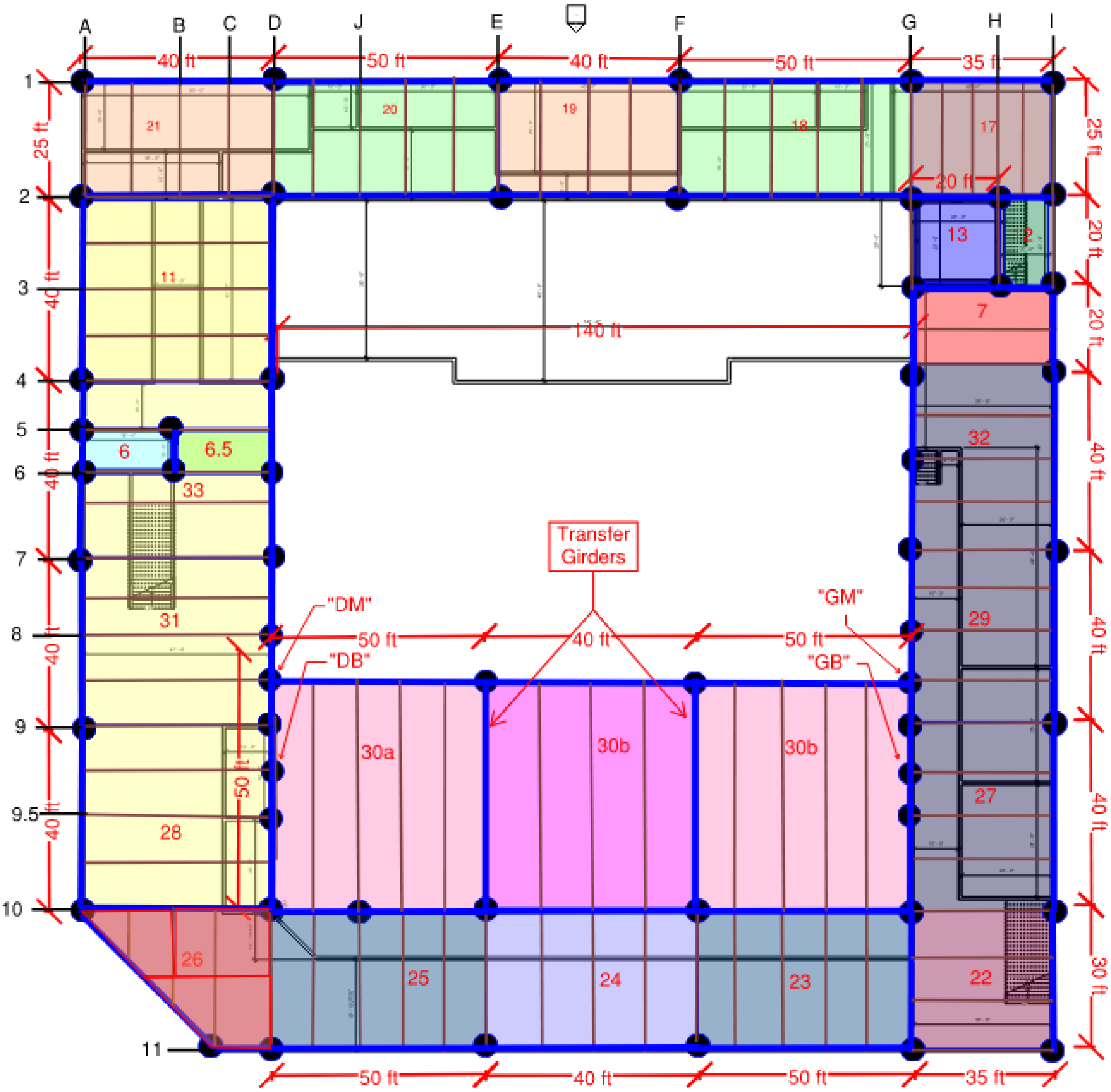
Figure F.6: Fifth Floor Layout

Appendix G: Bluebeam Revu Markups



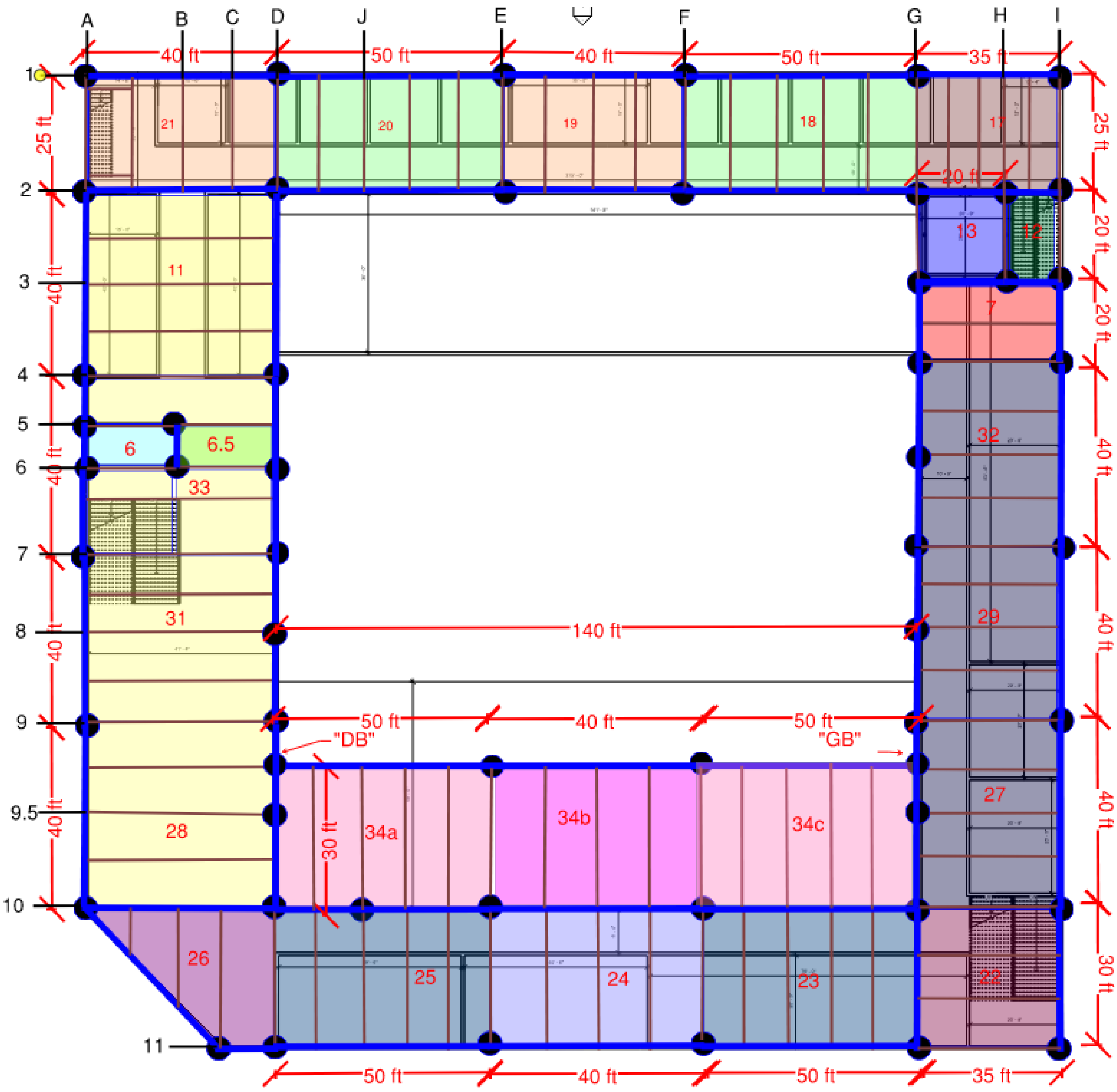
PAC Basement

Figure G.1: Bluebeam Markup of Beams, Girders, and Columns for the Basement Floor Plan



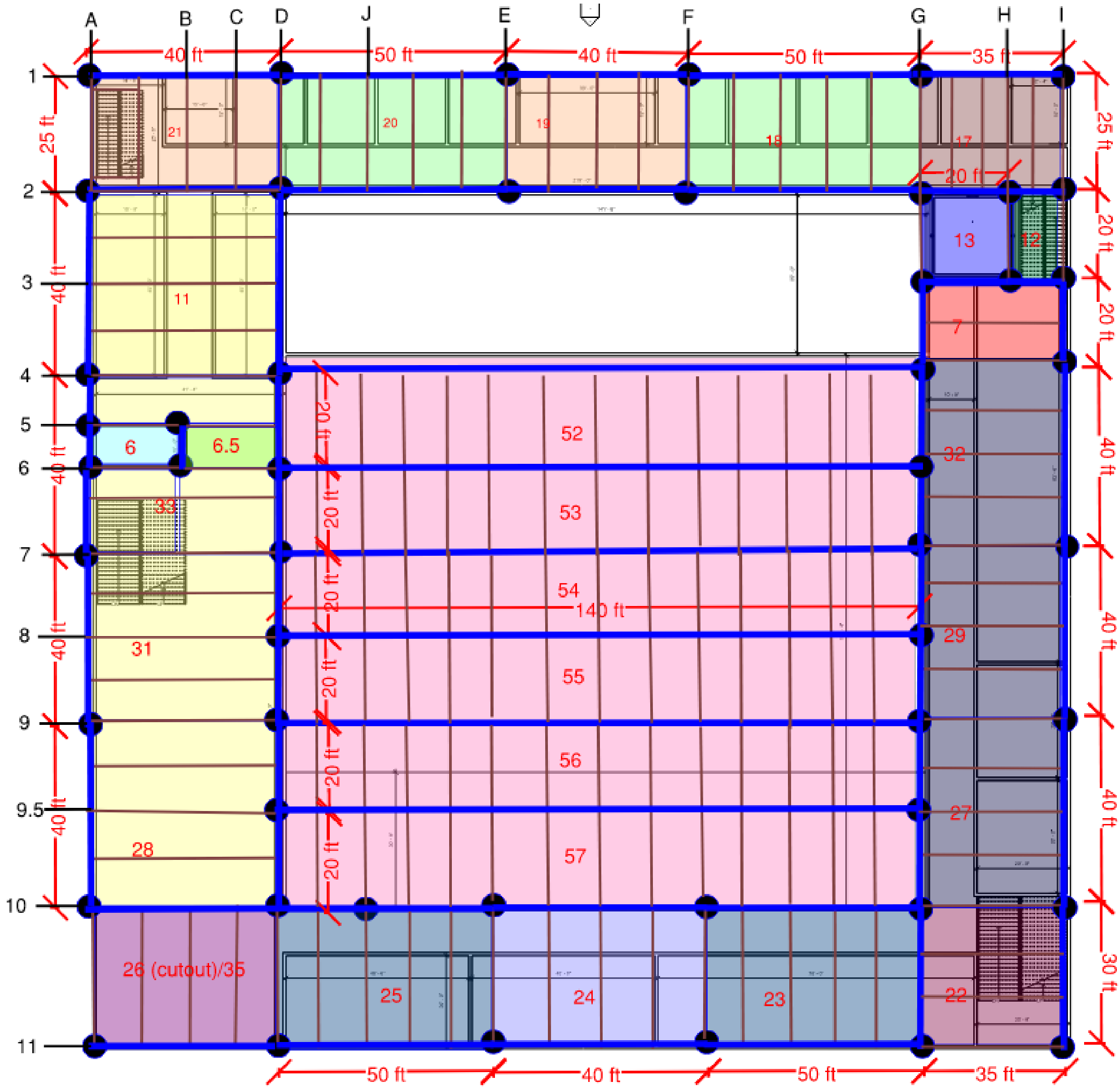
PAC Floor 1

Figure G.2: Bluebeam Markup of Beams, Girders, and Columns for the First Floor Plan. Some Annotations in Bay 26 are included for Column Tributary Areas.



PAC Floor 2

Figure G.3: Bluebeam Markup of Beams, Girders, and Columns for the 2nd Floor Plan.



PAC Floor 3

Figure G.4: Bluebeam Markup of Beams, Girders, and Columns for the 3rd Floor Plan.

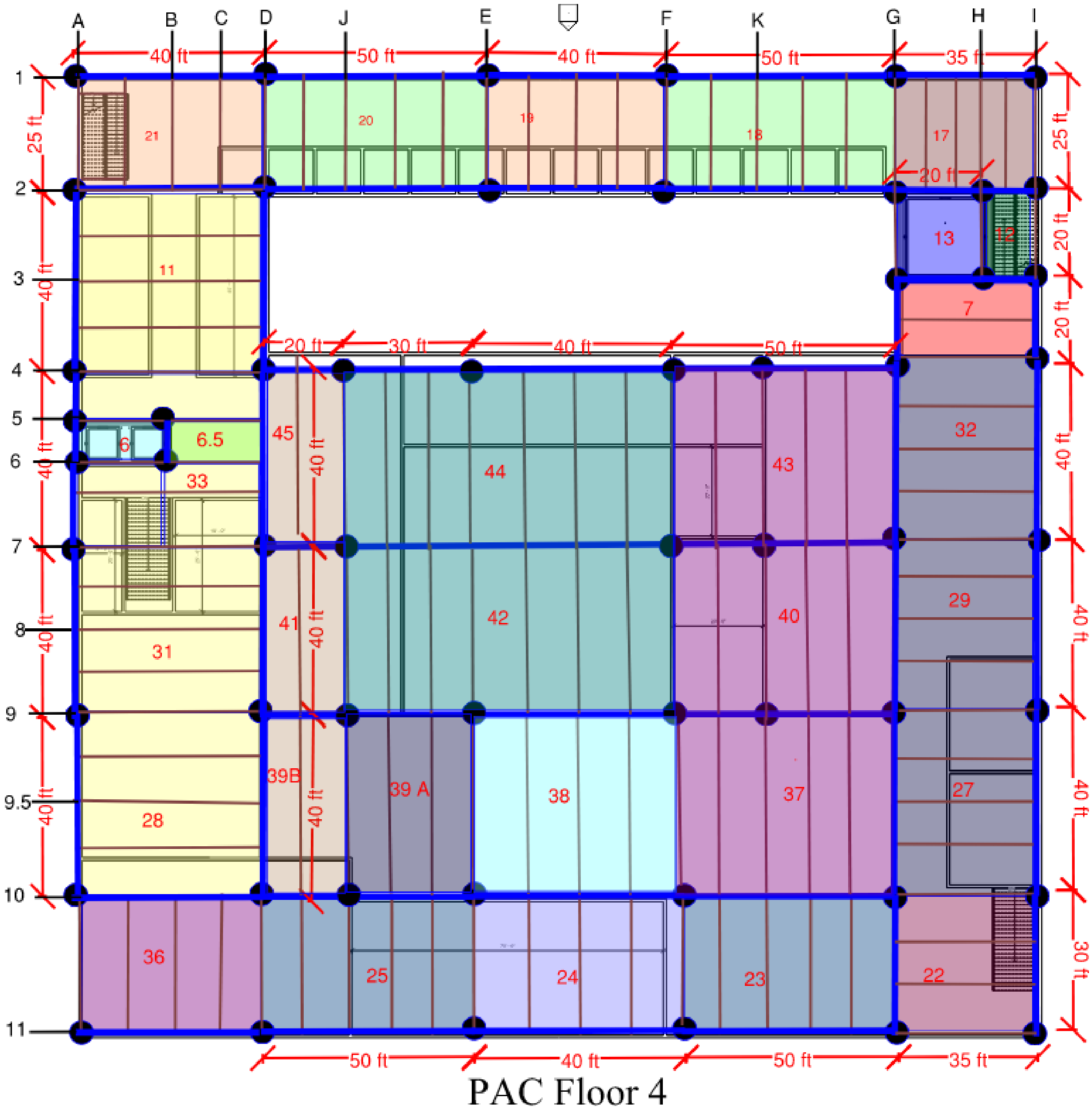
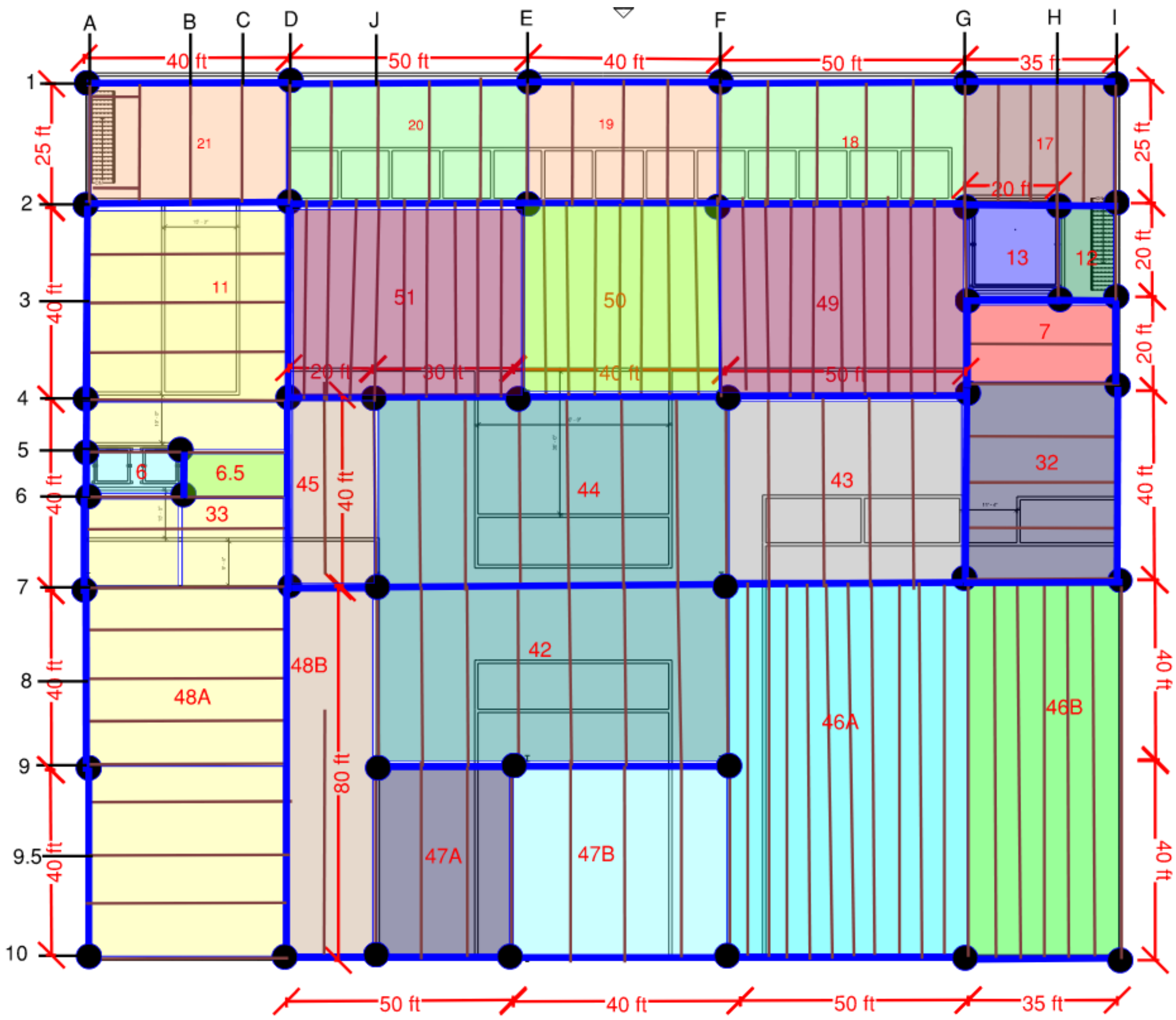


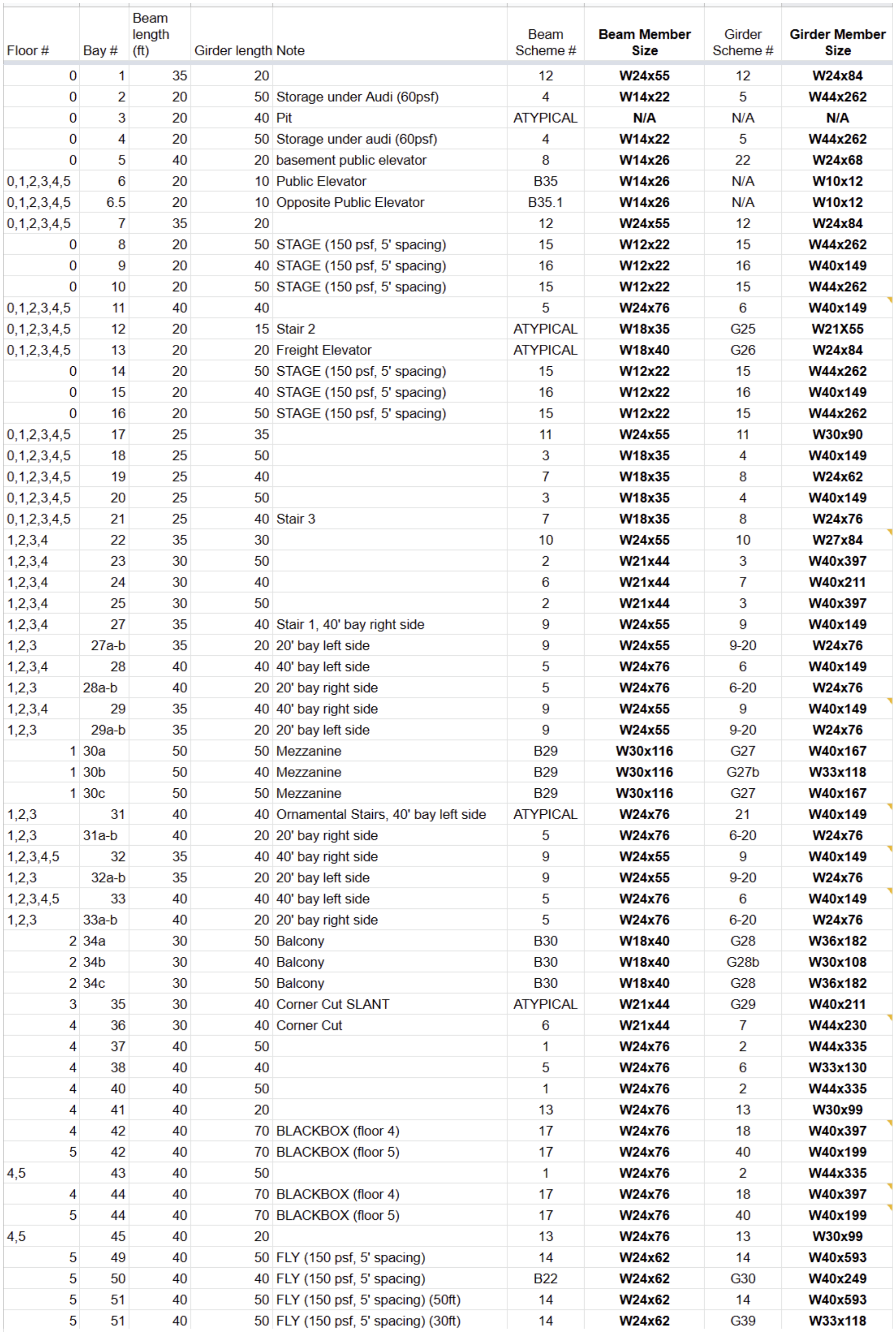
Figure G.5: Bluebeam Markup of Beams, Girders, and Columns for the 4th Floor Plan.



PAC Floor 5

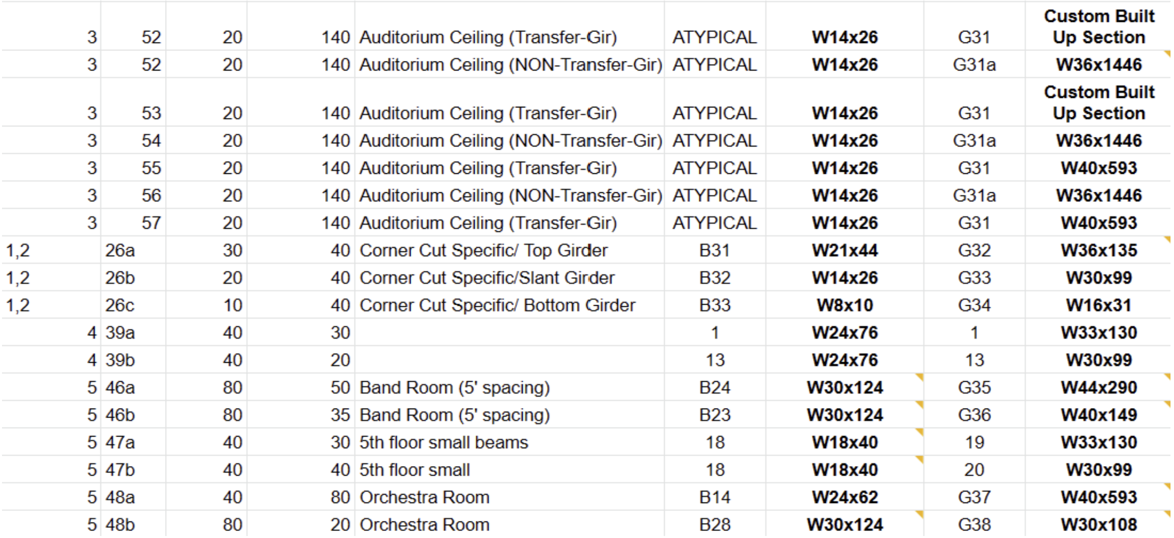
Figure G.6: Bluebeam Markup of Beams, Girders, and Columns for the 5th Floor Plan.

Appendix H: Beam and Girder Calculation Results



Floor #	Bay #	Beam length (ft)	Girder length	Note	Beam Scheme #	**Beam Member Size**	Girder Scheme #	**Girder Member Size**
0	1	35	20		12	**W24x55**	12	**W24x84**
0	2	20	50	Storage under Audi (60psf)	4	**W14x22**	5	**W44x262**
0	3	20	40	Pit	ATYPICAL	**N/A**	N/A	**N/A**
0	4	20	50	Storage under audi (60psf)	4	**W14x22**	5	**W44x262**
0	5	40	20	basement public elevator	8	**W14x26**	22	**W24x68**
0,1,2,3,4,5	6	20	10	Public Elevator	B35	**W14x26**	N/A	**W10x12**
0,1,2,3,4,5	6.5	20	10	Opposite Public Elevator	B35.1	**W14x26**	N/A	**W10x12**
0,1,2,3,4,5	7	35	20		12	**W24x55**	12	**W24x84**
0	8	20	50	STAGE (150 psf, 5' spacing)	15	**W12x22**	15	**W44x262**
0	9	20	40	STAGE (150 psf, 5' spacing)	16	**W12x22**	16	**W40x149**
0	10	20	50	STAGE (150 psf, 5' spacing)	15	**W12x22**	15	**W44x262**
0,1,2,3,4,5	11	40	40		5	**W24x76**	6	**W40x149**
0,1,2,3,4,5	12	20	15	Stair 2	ATYPICAL	**W18x35**	G25	**W21X55**
0,1,2,3,4,5	13	20	20	Freight Elevator	ATYPICAL	**W18x40**	G26	**W24x84**
0	14	20	50	STAGE (150 psf, 5' spacing)	15	**W12x22**	15	**W44x262**
0	15	20	40	STAGE (150 psf, 5' spacing)	16	**W12x22**	16	**W40x149**
0	16	20	50	STAGE (150 psf, 5' spacing)	15	**W12x22**	15	**W44x262**
0,1,2,3,4,5	17	25	35		11	**W24x55**	11	**W30x90**
0,1,2,3,4,5	18	25	50		3	**W18x35**	4	**W40x149**
0,1,2,3,4,5	19	25	40		7	**W18x35**	8	**W24x62**
0,1,2,3,4,5	20	25	50		3	**W18x35**	4	**W40x149**
0,1,2,3,4,5	21	25	40	Stair 3	7	**W18x35**	8	**W24x76**
1,2,3,4	22	35	30		10	**W24x55**	10	**W27x84**
1,2,3,4	23	30	50		2	**W21x44**	3	**W40x397**
1,2,3,4	24	30	40		6	**W21x44**	7	**W40x211**
1,2,3,4	25	30	50		2	**W21x44**	3	**W40x397**
1,2,3,4	27	35	40	Stair 1, 40' bay right side	9	**W24x55**	9	**W40x149**
1,2,3	27a-b	35	20	20' bay left side	9	**W24x55**	9-20	**W24x76**
1,2,3,4	28	40	40	40' bay left side	5	**W24x76**	6	**W40x149**
1,2,3	28a-b	40	20	20' bay right side	5	**W24x76**	6-20	**W24x76**
1,2,3,4	29	35	40	40' bay right side	9	**W24x55**	9	**W40x149**
1,2,3	29a-b	35	20	20' bay left side	9	**W24x55**	9-20	**W24x76**
1	30a	50	50	Mezzanine	B29	**W30x116**	G27	**W40x167**
1	30b	50	40	Mezzanine	B29	**W30x116**	G27b	**W33x118**
1	30c	50	50	Mezzanine	B29	**W30x116**	G27	**W40x167**
1,2,3	31	40	40	Ornamental Stairs, 40' bay left side	ATYPICAL	**W24x76**	21	**W40x149**
1,2,3	31a-b	40	20	20' bay right side	5	**W24x76**	6-20	**W24x76**
1,2,3,4,5	32	35	40	40' bay right side	9	**W24x55**	9	**W40x149**
1,2,3	32a-b	35	20	20' bay left side	9	**W24x55**	9-20	**W24x76**
1,2,3,4,5	33	40	40	40' bay left side	5	**W24x76**	6	**W40x149**
1,2,3	33a-b	40	20	20' bay right side	5	**W24x76**	6-20	**W24x76**
2	34a	30	50	Balcony	B30	**W18x40**	G28	**W36x182**
2	34b	30	40	Balcony	B30	**W18x40**	G28b	**W30x108**
2	34c	30	50	Balcony	B30	**W18x40**	G28	**W36x182**
3	35	30	40	Corner Cut SLANT	ATYPICAL	**W21x44**	G29	**W40x211**
4	36	30	40	Corner Cut	6	**W21x44**	7	**W44x230**
4	37	40	50		1	**W24x76**	2	**W44x335**
4	38	40	40		5	**W24x76**	6	**W33x130**
4	40	40	50		1	**W24x76**	2	**W44x335**
4	41	40	20		13	**W24x76**	13	**W30x99**
4	42	40	70	BLACKBOX (floor 4)	17	**W24x76**	18	**W40x397**
5	42	40	70	BLACKBOX (floor 5)	17	**W24x76**	40	**W40x199**
4,5	43	40	50		1	**W24x76**	2	**W44x335**
4	44	40	70	BLACKBOX (floor 4)	17	**W24x76**	18	**W40x397**
5	44	40	70	BLACKBOX (floor 5)	17	**W24x76**	40	**W40x199**
4,5	45	40	20		13	**W24x76**	13	**W30x99**
5	49	40	50	FLY (150 psf, 5' spacing)	14	**W24x62**	14	**W40x593**
5	50	40	40	FLY (150 psf, 5' spacing)	B22	**W24x62**	G30	**W40x249**
5	51	40	50	FLY (150 psf, 5' spacing) (50ft)	14	**W24x62**	14	**W40x593**
5	51	40	50	FLY (150 psf, 5' spacing) (30ft)	14	**W24x62**	G39	**W33x118**

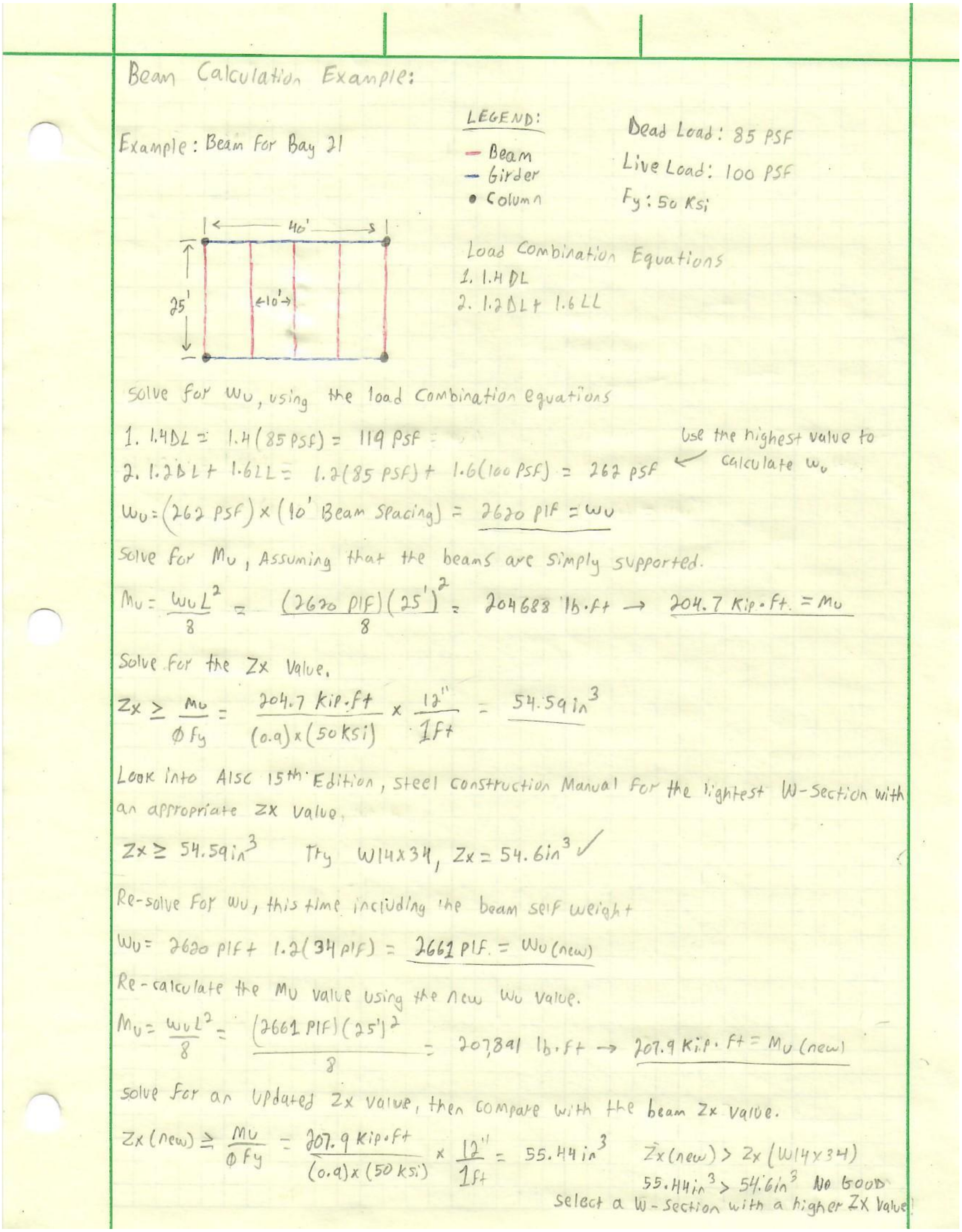
Figure H.1: Spreadsheet showing the Final Beam and Girder Calculation Results ***(in bold)***



3	52	20	140	Auditorium Ceiling (Transfer-Gir)	ATYPICAL	**W14x26**	G31	**Custom Built Up Section**
3	52	20	140	Auditorium Ceiling (NON-Transfer-Gir)	ATYPICAL	**W14x26**	G31a	**W36x1446**
3	53	20	140	Auditorium Ceiling (Transfer-Gir)	ATYPICAL	**W14x26**	G31	**Custom Built Up Section**
3	54	20	140	Auditorium Ceiling (NON-Transfer-Gir)	ATYPICAL	**W14x26**	G31a	**W36x1446**
3	55	20	140	Auditorium Ceiling (Transfer-Gir)	ATYPICAL	**W14x26**	G31	**W40x593**
3	56	20	140	Auditorium Ceiling (NON-Transfer-Gir)	ATYPICAL	**W14x26**	G31a	**W36x1446**
3	57	20	140	Auditorium Ceiling (Transfer-Gir)	ATYPICAL	**W14x26**	G31	**W40x593**
1,2	26a	30	40	Corner Cut Specific/ Top Girder	B31	**W21x44**	G32	**W36x135**
1,2	26b	20	40	Corner Cut Specific/Slant Girder	B32	**W14x26**	G33	**W30x99**
1,2	26c	10	40	Corner Cut Specific/ Bottom Girder	B33	**W8x10**	G34	**W16x31**
4	39a	40	30		1	**W24x76**	1	**W33x130**
4	39b	40	20		13	**W24x76**	13	**W30x99**
5	46a	80	50	Band Room (5' spacing)	B24	**W30x124**	G35	**W44x290**
5	46b	80	35	Band Room (5' spacing)	B23	**W30x124**	G36	**W40x149**
5	47a	40	30	5th floor small beams	18	**W18x40**	19	**W33x130**
5	47b	40	40	5th floor small	18	**W18x40**	20	**W30x99**
5	48a	40	80	Orchestra Room	B14	**W24x62**	G37	**W40x593**
5	48b	80	20	Orchestra Room	B28	**W30x124**	G38	**W30x108**

Figure H.2: Spreadsheet showing the Final Beam and Girder Calculation Results Continued ***(in bold)***

Appendix I: Beam and Girder Sample Hand Calculations



Beam Calculation Example:

Example: Beam For Bay 21

LEGEND:
— Beam
— Girder
● Column

Dead Load: 85 PSF
Live Load: 100 PSF
F_y: 50 Ksi

Load Combination Equations
1. 1.4 DL
2. 1.2DL + 1.6 LL

Solve for w_u, using the load combination equations

1. $1.4DL = 1.4(85\ PSF) = 119\ PSF$
2. $1.2DL + 1.6LL = 1.2(85\ PSF) + 1.6(100\ PSF) = 262\ PSF$

Use the highest value to calculate w_u

$W_u = (262\ PSF) \times (10'\ \text{Beam Spacing}) = \underline{2620\ plf = W_u}$

Solve for M_u, Assuming that the beams are simply supported.

$$M_u = \frac{W_u L^2}{8} = \frac{(2620\ plf)(25')^2}{8} = 204688\ lb \cdot ft \rightarrow \underline{204.7\ Kip \cdot ft = M_u}$$

Solve for the Zx Value.

$$Z_x \geq \frac{M_u}{\phi F_y} = \frac{204.7\ kip \cdot ft}{(0.9) \times (50\ ksi)} \times \frac{12''}{1ft} = \underline{54.59\ in^3}$$

Look into AISC 15th Edition, steel construction Manual for the lightest W-Section with an appropriate Zx value.

$Z_x \geq 54.59\ in^3$ Try W14x34, $Z_x = 54.6\ in^3$ ✓

Re-solve for w_u, this time including the beam self weight

$W_u = 2620\ plf + 1.2(34\ plf) = \underline{2661\ plf = W_u(new)}$

Re-calculate the M_u value using the new W_u value.

$$M_u = \frac{W_u L^2}{8} = \frac{(2661\ plf)(25')^2}{8} = 207{,}891\ lb \cdot ft \rightarrow \underline{207.9\ Kip \cdot ft = M_u(new)}$$

Solve for an updated Zx value, then compare with the beam Zx value.

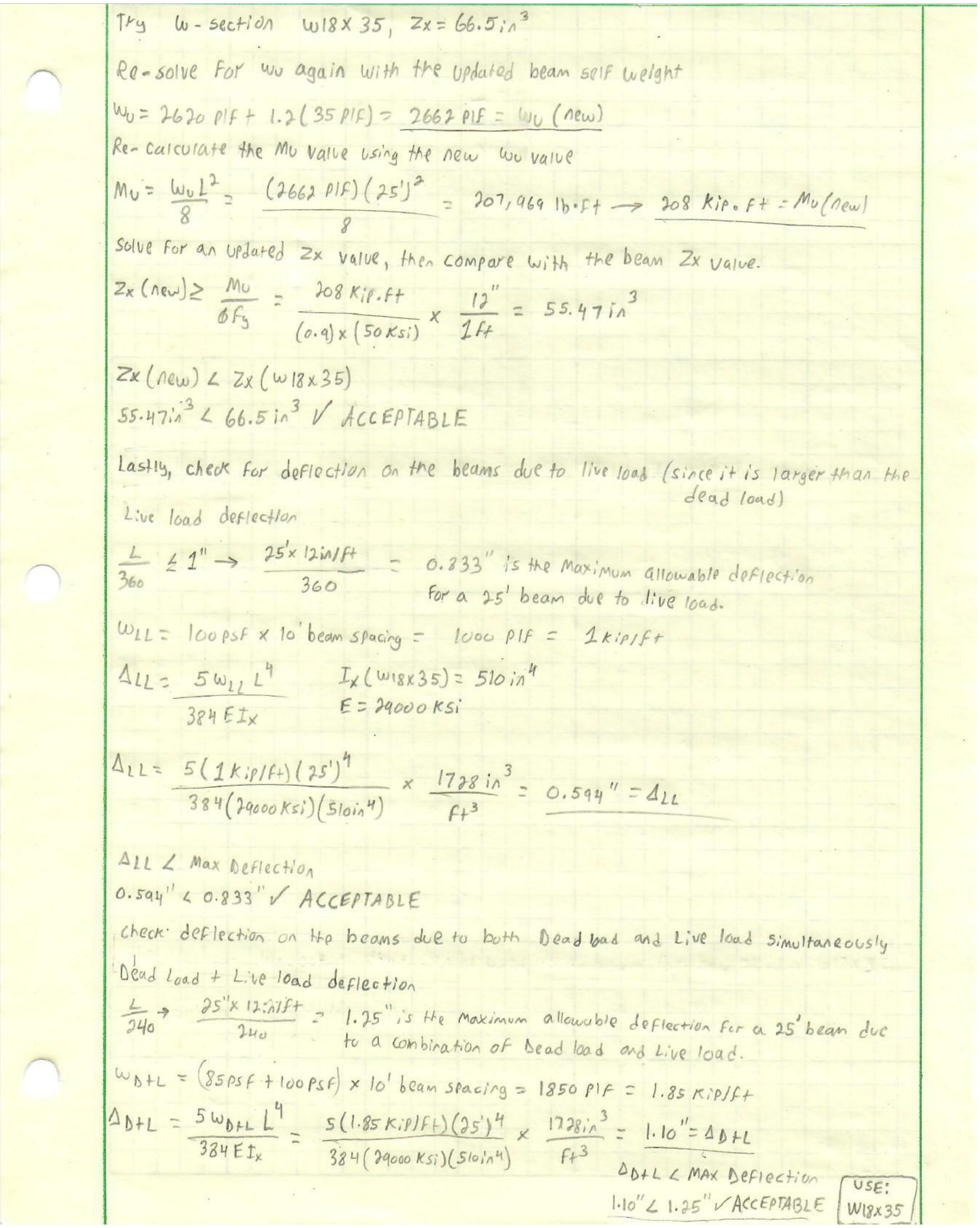
$$Z_x(new) \geq \frac{M_u}{\phi F_y} = \frac{207.9\ kip \cdot ft}{(0.9) \times (50\ ksi)} \times \frac{12''}{1ft} = 55.44\ in^3$$

$Z_x(new) > Z_x$ (W14x34)

$55.44\ in^3 > 54.6\ in^3$ No Good

Select a W-Section with a higher ZX Value!

Figure I.1: Beam Sample Calculation Page 1. Continued in Figure I.2.



Try W-section W18X35, $Z_x = 66.5 \text{ in}^3$

Re-solve for w_u again with the updated beam self weight

$w_u = 2620 \text{ plf} + 1.2(35 \text{ plf}) = \underline{2662 \text{ plf} = w_u \text{ (new)}}$

Re-calculate the M_u value using the new w_u value

$$M_u = \frac{w_u L^2}{8} = \frac{(2662 \text{ plf})(25')^2}{8} = 207{,}969 \text{ lb}\cdot\text{ft} \rightarrow \underline{208 \text{ kip}\cdot\text{ft} = M_u \text{(new)}}$$

Solve for an updated Z_x value, then compare with the beam Z_x value.

$$Z_x \text{(new)} \geq \frac{M_u}{\phi F_y} = \frac{208 \text{ kip}\cdot\text{ft}}{(0.9) \times (50 \text{ ksi})} \times \frac{12''}{1 \text{ ft}} = 55.47 \text{ in}^3$$

$Z_x \text{(new)} < Z_x \text{(W18x35)}$

$55.47 \text{ in}^3 < 66.5 \text{ in}^3$ ✓ ACCEPTABLE

Lastly, check for deflection on the beams due to live load (since it is larger than the dead load)

Live load deflection

$\frac{L}{360} \leq 1'' \rightarrow \frac{25' \times 12 \text{ in/ft}}{360} = 0.833''$ is the maximum allowable deflection for a 25' beam due to live load.

$w_{LL} = 100 \text{ psf} \times 10' \text{ beam spacing} = 1000 \text{ plf} = 1 \text{ kip/ft}$

$\Delta_{LL} = \frac{5 w_{LL} L^4}{384 E I_x}$ $\quad I_x \text{(W18x35)} = 510 \text{ in}^4$

$E = 29000 \text{ ksi}$

$$\Delta_{LL} = \frac{5(1 \text{ kip/ft})(25')^4}{384(29000 \text{ ksi})(510 \text{ in}^4)} \times \frac{1728 \text{ in}^3}{\text{ft}^3} = \underline{0.594'' = \Delta_{LL}}$$

$\Delta_{LL} <$ Max Deflection

$0.594'' < 0.833''$ ✓ ACCEPTABLE

Check deflection on the beams due to both Dead load and Live load simultaneously

Dead Load + Live load deflection

$\frac{L}{240} \rightarrow \frac{25'' \times 12 \text{ in/ft}}{240} = 1.25''$ is the maximum allowable deflection for a 25' beam due to a combination of Dead load and Live load.

$w_{D+L} = (85 \text{ psf} + 100 \text{ psf}) \times 10' \text{ beam spacing} = 1850 \text{ plf} = 1.85 \text{ kip/ft}$

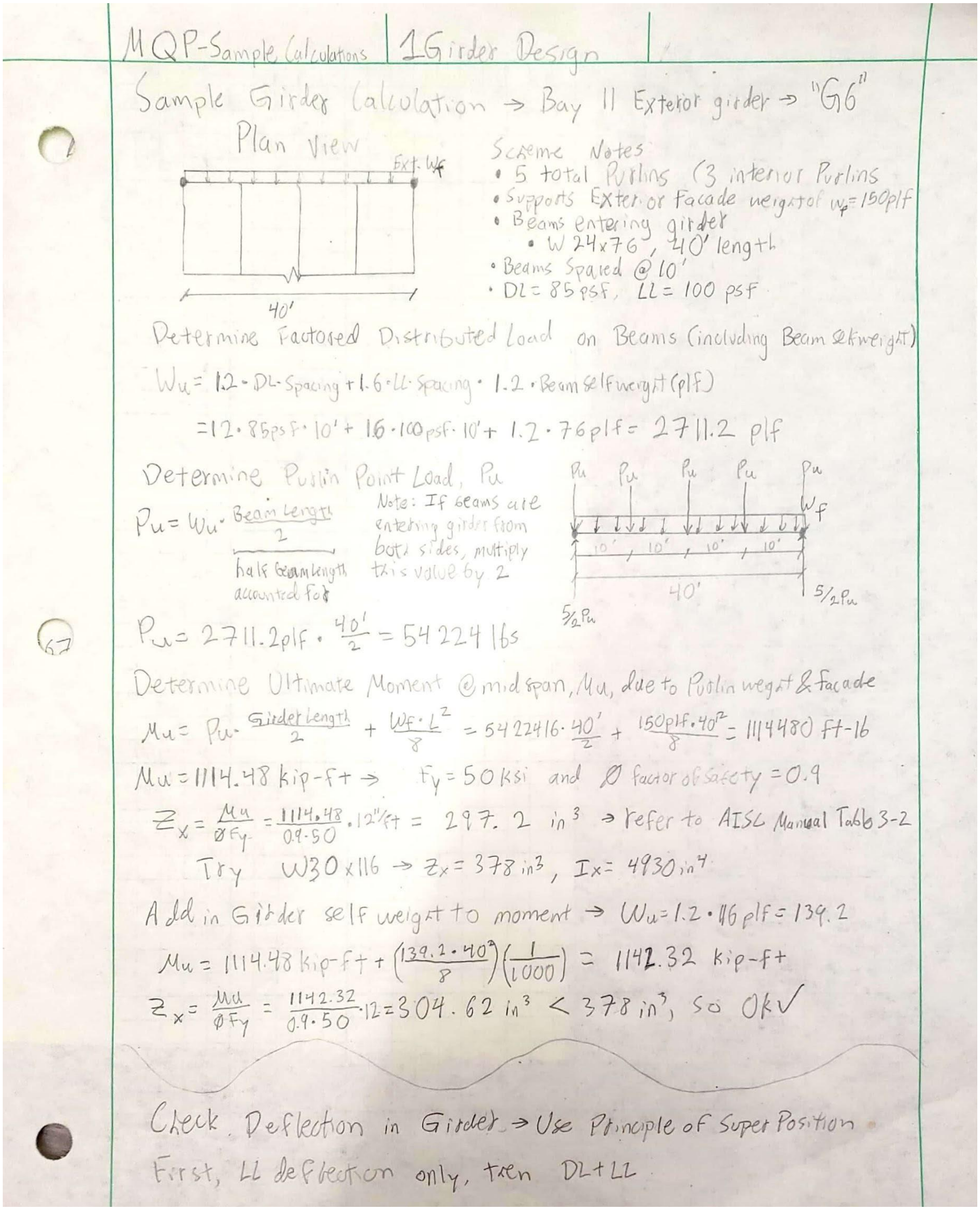
$$\Delta_{D+L} = \frac{5 w_{D+L} L^4}{384 E I_x} = \frac{5(1.85 \text{ kip/ft})(25')^4}{384(29000 \text{ ksi})(510 \text{ in}^4)} \times \frac{1728 \text{ in}^3}{\text{ft}^3} = \underline{1.10'' = \Delta_{D+L}}$$

$\Delta_{D+L} <$ Max Deflection

$1.10'' < 1.25''$ ✓ ACCEPTABLE

$\boxed{\text{USE: W18x35}}$

Figure I.2: Beam Sample Calculation Page 2



MQP-Sample Calculations | 1Girder Design

Sample Girder Calculation → Bay 11 Exterior girder → "G6"

Plan View

Scheme Notes
- 5 total Purlins (3 interior Purlins
- Supports Exterior Facade weight of $w_f = 150plf$
- Beams entering girder
  - W24x76, 40' length
- Beams Spaced @ 10'
- DL = 85 psf, LL = 100 psf

Determine Factored Distributed Load on Beams (including Beam selfweight)

$W_u = 1.2 \cdot DL \cdot Spacing + 1.6 \cdot LL \cdot Spacing \cdot 1.2 \cdot Beam\ selfweight\ (plf)$

$= 12 \cdot 85psf \cdot 10' + 16 \cdot 100psf \cdot 10' + 1.2 \cdot 76plf = 2711.2\ plf$

Determine Purlin Point Load, Pu

$P_u = W_u \cdot \underbrace{\frac{Beam\ Length}{2}}_{\text{half beam length accounted for}}$

Note: If beams are entering girder from both sides, multiply this value by 2

$P_u = 2711.2plf \cdot \frac{40'}{2} = 54224\ lbs$

Determine Ultimate Moment @ midspan, Mu, due to Purlin weight & facade

$M_u = P_u \cdot \frac{Girder\ Length}{2} + \frac{W_f \cdot L^2}{8} = 54224lb \cdot \frac{40'}{2} + \frac{150plf \cdot 40'^2}{8} = 1114480\ ft\text{-}lb$

$M_u = 1114.48\ kip\text{-}ft$ → $F_y = 50 ksi$ and Ø factor of safety = 0.9

$Z_x = \frac{M_u}{\phi F_y} = \frac{1114.48}{0.9 \cdot 50} \cdot 12''/ft = 297.2\ in^3$ → refer to AISC Manual Table 3-2

Try W30x116 → $Z_x = 378\ in^3$, $I_x = 4930\ in^4$

Add in Girder self weight to moment → $W_u = 1.2 \cdot 116\ plf = 139.2$

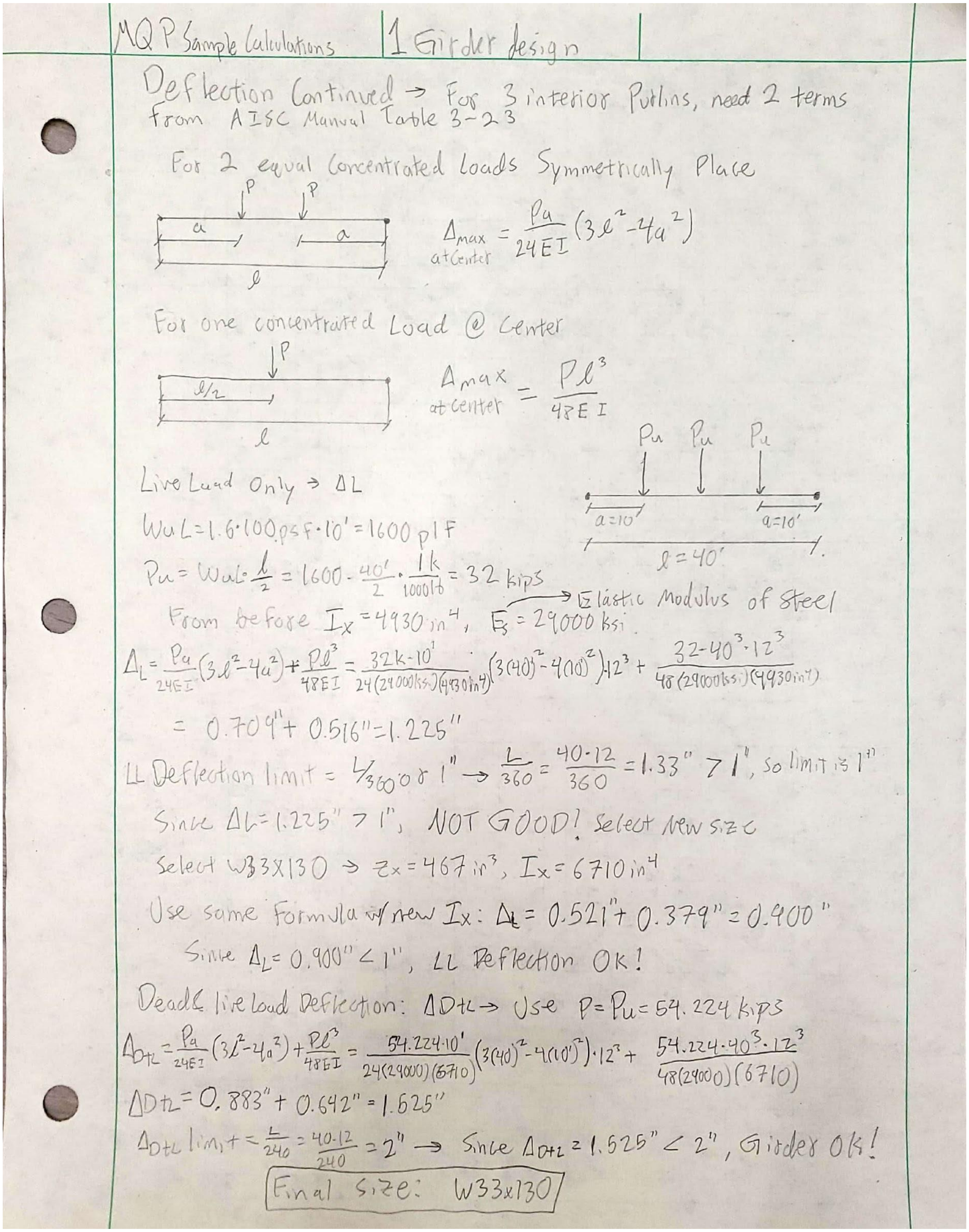
$M_u = 1114.48\ kip\text{-}ft + \left(\frac{139.2 \cdot 40^2}{8}\right)\left(\frac{1}{1000}\right) = 1142.32\ kip\text{-}ft$

$Z_x = \frac{M_u}{\phi F_y} = \frac{1142.32}{0.9 \cdot 50} \cdot 12 = 304.62\ in^3 < 378\ in^3$, so Ok ✓

Check Deflection in Girder → Use Principle of Super Position

First, LL deflection only, then DL+LL

Figure I.3: Girder Sample Calculation Page 1. Continued in Figure I.4.



MQP Sample Calculations | 1 Girder design

Deflection Continued → For 3 interior Purlins, need 2 terms from AISC Manual Table 3-23

For 2 equal Concentrated Loads Symmetrically Place

Δ_{max} at Center $= \frac{Pa}{24EI}(3l^2-4a^2)$

For one concentrated Load @ Center

Δ_{max} at center $= \frac{Pl^3}{48EI}$

Live Load Only → ΔL

$W_{uL} = 1.6 \cdot 100\text{psf} \cdot 10' = 1600$ plf

$P_u = W_{uL} \cdot \frac{l}{2} = 1600 \cdot \frac{40'}{2} \cdot \frac{1k}{1000lb} = 32$ kips

From before $I_x = 4930 \text{ in}^4$, $E_s = 29000$ ksi → Elastic Modulus of Steel

$\Delta_L = \frac{Pa}{24EI}(3l^2-4a^2) + \frac{Pl^3}{48EI} = \frac{32k \cdot 10'}{24(29000ksi)(4930in^4)}(3(40)^2-4(10)^2) \cdot 12^3 + \frac{32 \cdot 40^3 \cdot 12^3}{48(29000ksi)(4930in^4)}$

$= 0.709'' + 0.516'' = 1.225''$

LL Deflection limit $= L/360$ or $1'' \rightarrow \frac{L}{360} = \frac{40 \cdot 12}{360} = 1.33'' > 1''$, so limit is $1''$

Since $\Delta_L = 1.225'' > 1''$, NOT GOOD! Select New size

Select W33X130 → $Z_x = 467 \text{ in}^3$, $I_x = 6710 \text{ in}^4$

Use same Formula w/ new I_x: $\Delta_L = 0.521'' + 0.379'' = 0.900''$

Since $\Delta_L = 0.900'' < 1''$, LL Deflection OK!

Dead & live Load Deflection: Δ_{D+L} → Use $P = P_u = 54.224$ kips

$\Delta_{D+L} = \frac{Pa}{24EI}(3l^2-4a^2) + \frac{Pl^3}{48EI} = \frac{54.224 \cdot 10'}{24(29000)(6710)}(3(40)^2-4(10')^2) \cdot 12^3 + \frac{54.224 \cdot 40^3 \cdot 12^3}{48(29000)(6710)}$

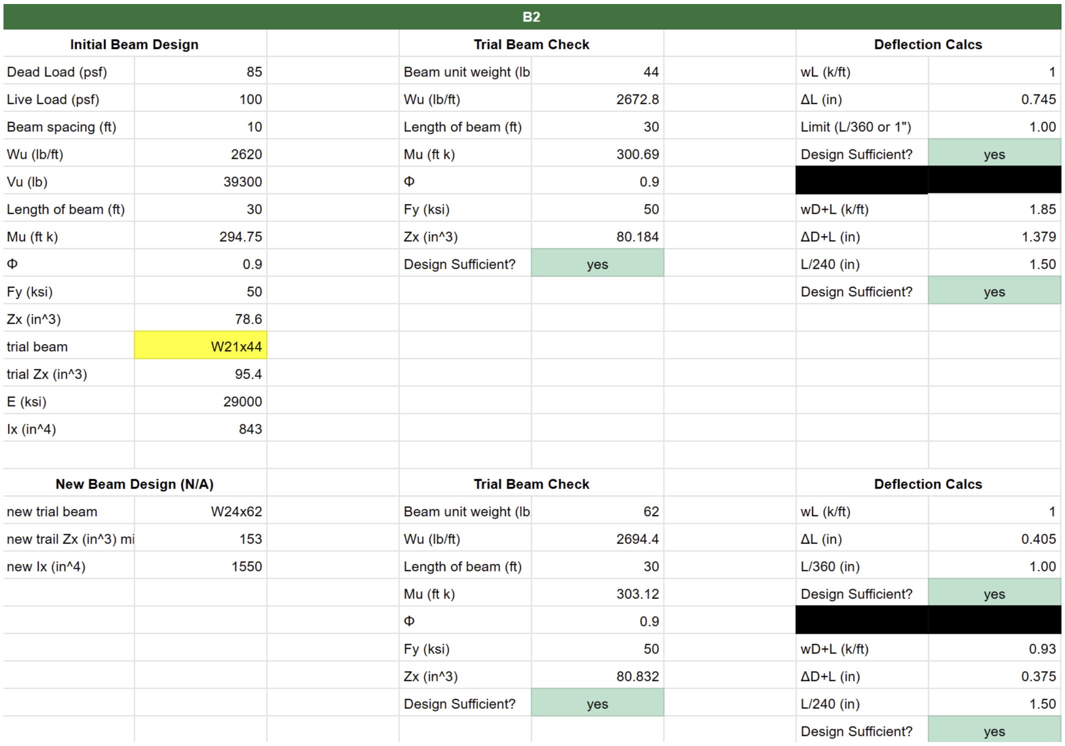
$\Delta_{D+L} = 0.883'' + 0.642'' = 1.625''$

Δ_{D+L} limit $= \frac{L}{240} = \frac{40 \cdot 12}{240} = 2'' \rightarrow$ Since $\Delta_{D+L} = 1.525'' < 2''$, Girder OK!

$\boxed{\text{Final size: W33x130}}$

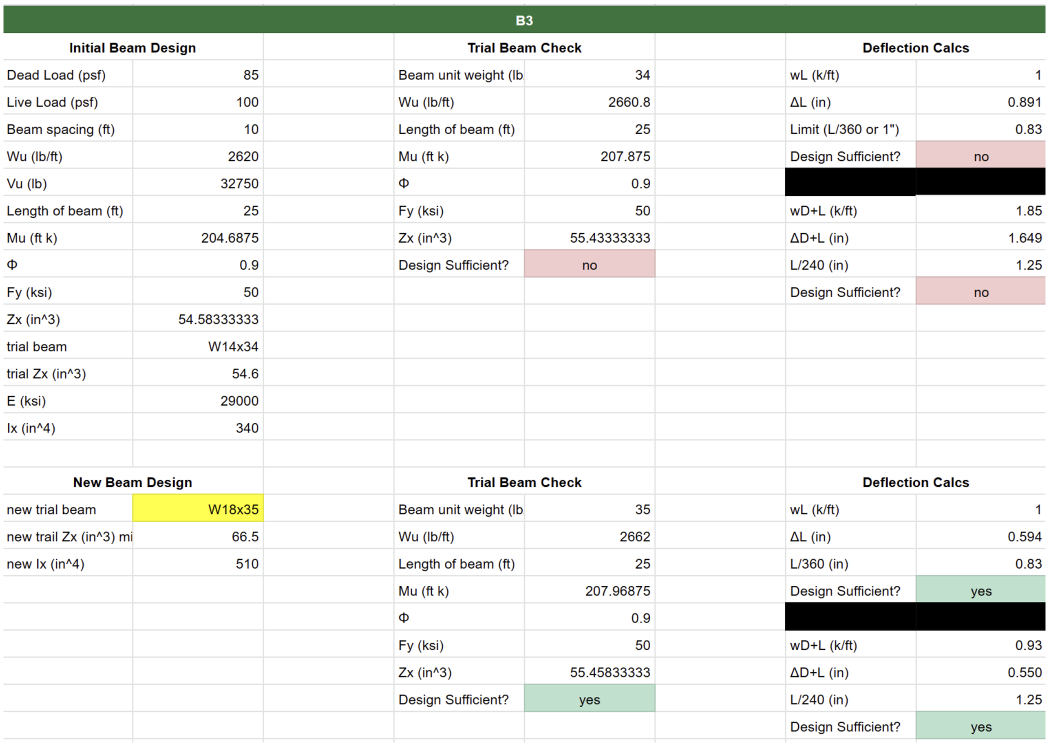
Figure I.4: Sample Girder Hand Calculation Page 2

Appendix J: Beam and Girder Design Spreadsheet Samples



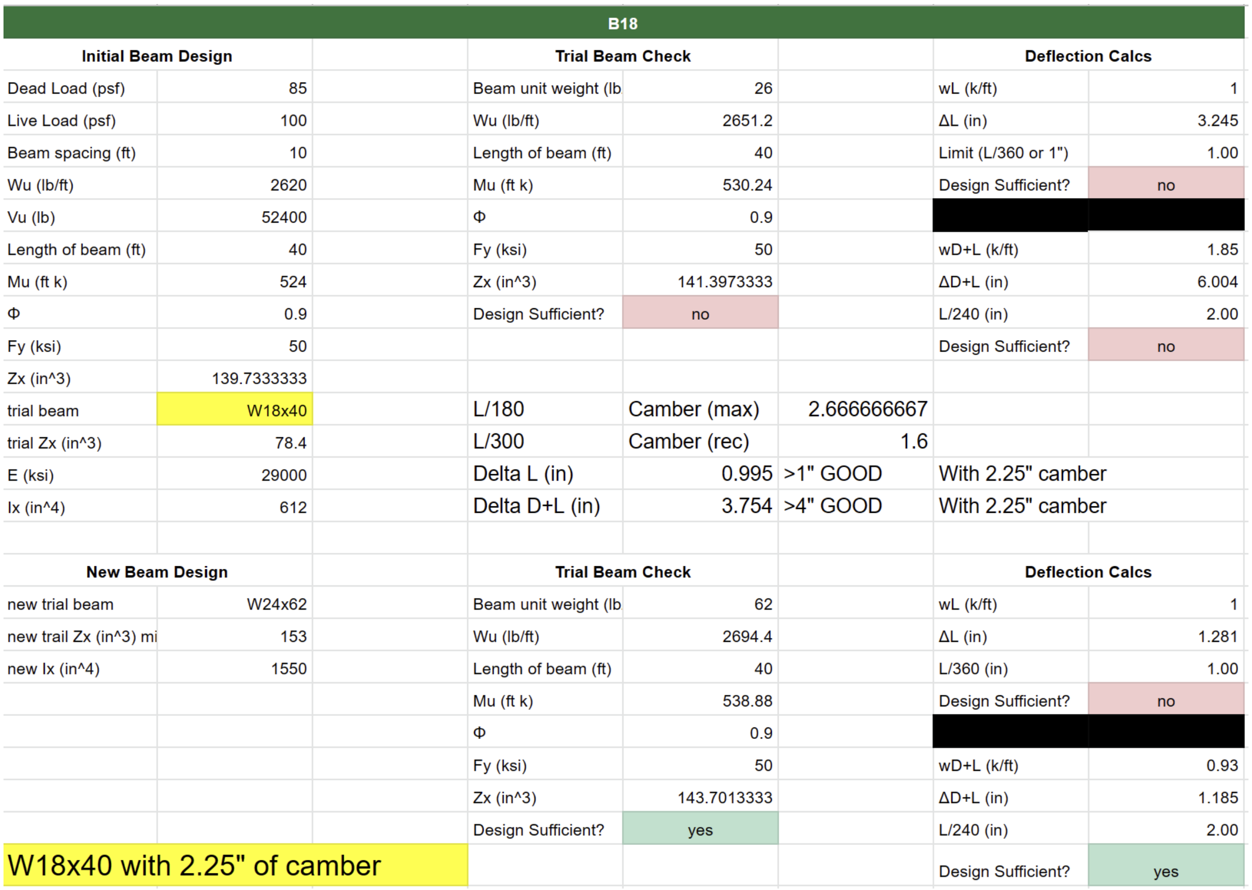
B2					
Initial Beam Design		**Trial Beam Check**		**Deflection Calcs**	
Dead Load (psf)	85	Beam unit weight (lb	44	wL (k/ft)	1
Live Load (psf)	100	Wu (lb/ft)	2672.8	ΔL (in)	0.745
Beam spacing (ft)	10	Length of beam (ft)	30	Limit (L/360 or 1")	1.00
Wu (lb/ft)	2620	Mu (ft k)	300.69	Design Sufficient?	yes
Vu (lb)	39300	Φ	0.9		
Length of beam (ft)	30	Fy (ksi)	50	wD+L (k/ft)	1.85
Mu (ft k)	294.75	Zx (in^3)	80.184	ΔD+L (in)	1.379
Φ	0.9	Design Sufficient?	yes	L/240 (in)	1.50
Fy (ksi)	50			Design Sufficient?	yes
Zx (in^3)	78.6				
trial beam	W21x44				
trial Zx (in^3)	95.4				
E (ksi)	29000				
Ix (in^4)	843				
New Beam Design (N/A)		**Trial Beam Check**		**Deflection Calcs**	
new trial beam	W24x62	Beam unit weight (lb	62	wL (k/ft)	1
new trail Zx (in^3) mi	153	Wu (lb/ft)	2694.4	ΔL (in)	0.405
new Ix (in^4)	1550	Length of beam (ft)	30	L/360 (in)	1.00
		Mu (ft k)	303.12	Design Sufficient?	yes
		Φ	0.9		
		Fy (ksi)	50	wD+L (k/ft)	0.93
		Zx (in^3)	80.832	ΔD+L (in)	0.375
		Design Sufficient?	yes	L/240 (in)	1.50
				Design Sufficient?	yes

Figure J.1: Beam design for beam scheme "B2". The Final Member Size is Highlighted Yellow.



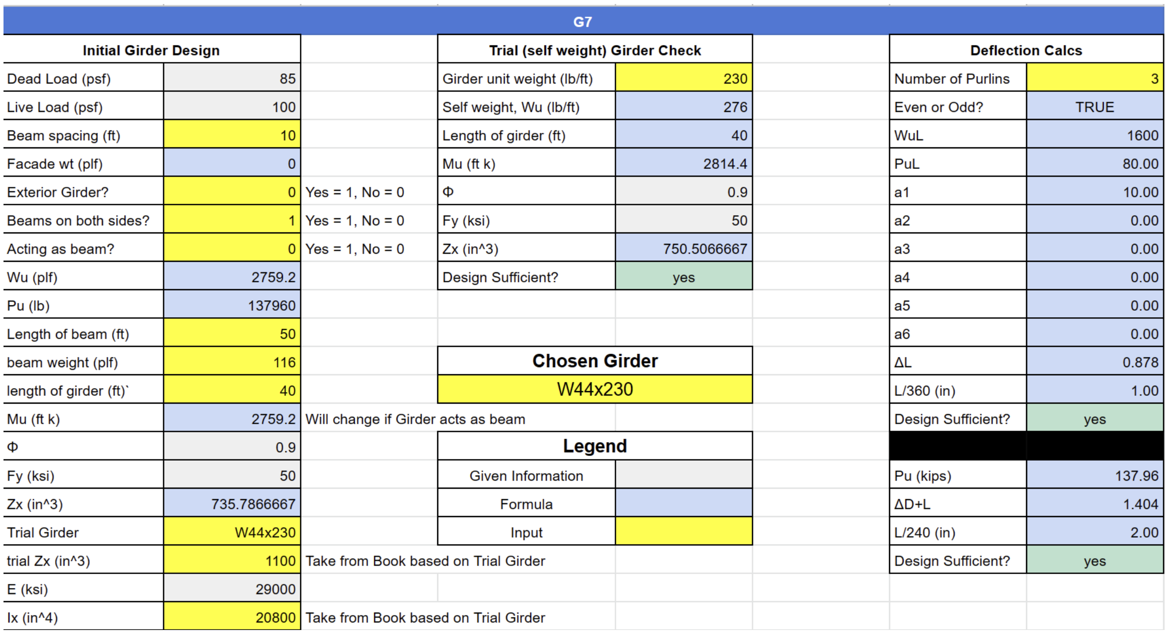
B3					
Initial Beam Design		**Trial Beam Check**		**Deflection Calcs**	
Dead Load (psf)	85	Beam unit weight (lb	34	wL (k/ft)	1
Live Load (psf)	100	Wu (lb/ft)	2660.8	ΔL (in)	0.891
Beam spacing (ft)	10	Length of beam (ft)	25	Limit (L/360 or 1")	0.83
Wu (lb/ft)	2620	Mu (ft k)	207.875	Design Sufficient?	no
Vu (lb)	32750	Φ	0.9		
Length of beam (ft)	25	Fy (ksi)	50	wD+L (k/ft)	1.85
Mu (ft k)	204.6875	Zx (in^3)	55.43333333	ΔD+L (in)	1.649
Φ	0.9	Design Sufficient?	no	L/240 (in)	1.25
Fy (ksi)	50			Design Sufficient?	no
Zx (in^3)	54.58333333				
trial beam	W14x34				
trial Zx (in^3)	54.6				
E (ksi)	29000				
Ix (in^4)	340				
New Beam Design		**Trial Beam Check**		**Deflection Calcs**	
new trial beam	W18x35	Beam unit weight (lb	35	wL (k/ft)	1
new trail Zx (in^3) mi	66.5	Wu (lb/ft)	2662	ΔL (in)	0.594
new Ix (in^4)	510	Length of beam (ft)	25	L/360 (in)	0.83
		Mu (ft k)	207.96875	Design Sufficient?	yes
		Φ	0.9		
		Fy (ksi)	50	wD+L (k/ft)	0.93
		Zx (in^3)	55.45833333	ΔD+L (in)	0.550
		Design Sufficient?	yes	L/240 (in)	1.25
				Design Sufficient?	yes

Figure J.2: Beam design for beam scheme "B3" with the Trial Beam Check. The Final Member Size is Highlighted Yellow.



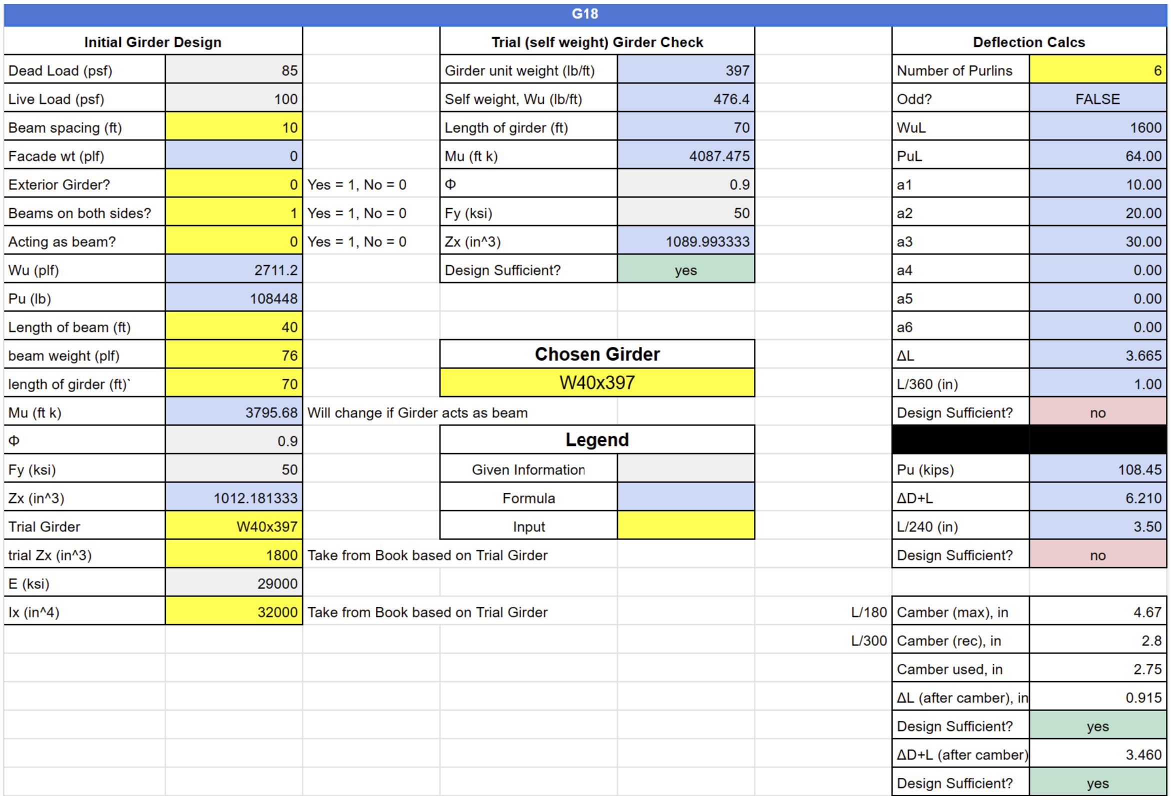
B18							
Initial Beam Design			**Trial Beam Check**			**Deflection Calcs**	
Dead Load (psf)	85		Beam unit weight (lb	26		wL (k/ft)	1
Live Load (psf)	100		Wu (lb/ft)	2651.2		ΔL (in)	3.245
Beam spacing (ft)	10		Length of beam (ft)	40		Limit (L/360 or 1")	1.00
Wu (lb/ft)	2620		Mu (ft k)	530.24		Design Sufficient?	no
Vu (lb)	52400		Φ	0.9			
Length of beam (ft)	40		Fy (ksi)	50		wD+L (k/ft)	1.85
Mu (ft k)	524		Zx (in^3)	141.3973333		ΔD+L (in)	6.004
Φ	0.9		Design Sufficient?	no		L/240 (in)	2.00
Fy (ksi)	50					Design Sufficient?	no
Zx (in^3)	139.7333333						
trial beam	W18x40		L/180	Camber (max)	2.666666667		
trial Zx (in^3)	78.4		L/300	Camber (rec)	1.6		
E (ksi)	29000		Delta L (in)	0.995	>1" GOOD	With 2.25" camber	
Ix (in^4)	612		Delta D+L (in)	3.754	>4" GOOD	With 2.25" camber	
New Beam Design			**Trial Beam Check**			**Deflection Calcs**	
new trial beam	W24x62		Beam unit weight (lb	62		wL (k/ft)	1
new trail Zx (in^3) mi	153		Wu (lb/ft)	2694.4		ΔL (in)	1.281
new Ix (in^4)	1550		Length of beam (ft)	40		L/360 (in)	1.00
			Mu (ft k)	538.88		Design Sufficient?	no
			Φ	0.9			
			Fy (ksi)	50		wD+L (k/ft)	0.93
			Zx (in^3)	143.7013333		ΔD+L (in)	1.185
			Design Sufficient?	yes		L/240 (in)	2.00
W18x40 with 2.25" of camber						Design Sufficient?	yes

Figure J.3: Beam design for beam scheme "B18". Camber Deflection is considered to Reduce Deflection without Upsizing the Beam. The Final Member Size is Highlighted Yellow.



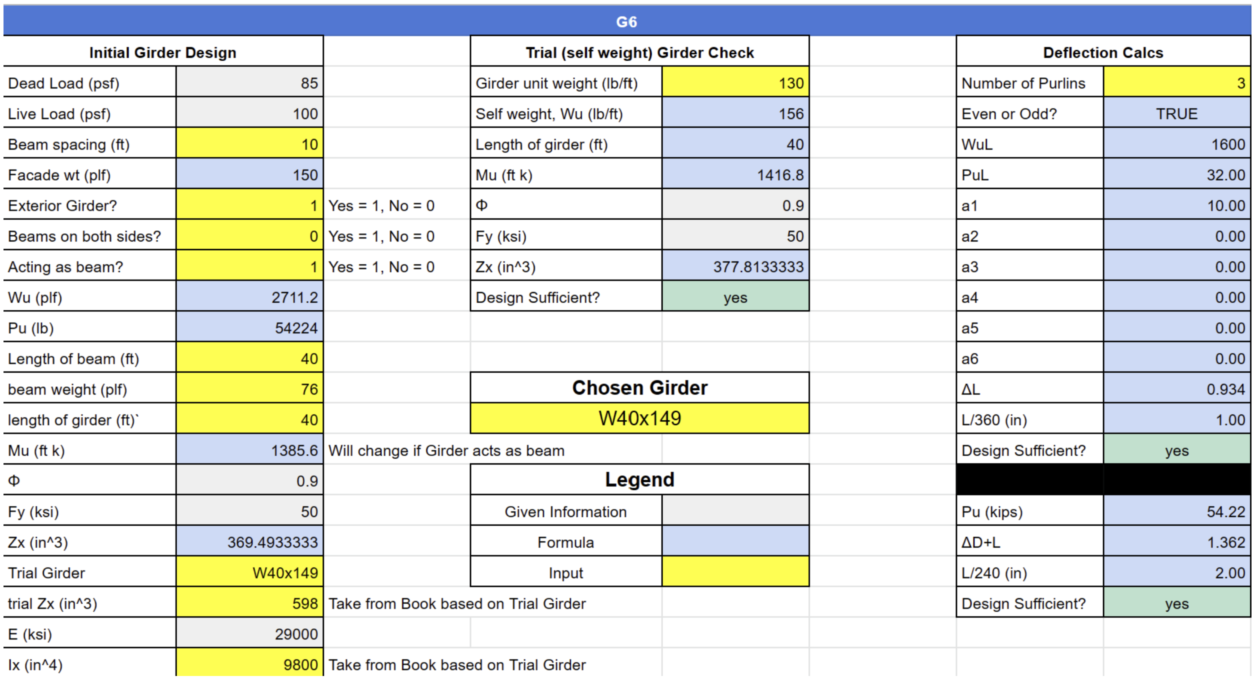
G7							
Initial Girder Design			**Trial (self weight) Girder Check**			**Deflection Calcs**	
Dead Load (psf)	85		Girder unit weight (lb/ft)	230		Number of Purlins	3
Live Load (psf)	100		Self weight, Wu (lb/ft)	276		Even or Odd?	TRUE
Beam spacing (ft)	10		Length of girder (ft)	40		WuL	1600
Facade wt (plf)	0		Mu (ft k)	2814.4		PuL	80.00
Exterior Girder?	0	Yes = 1, No = 0	Φ	0.9		a1	10.00
Beams on both sides?	1	Yes = 1, No = 0	Fy (ksi)	50		a2	0.00
Acting as beam?	0	Yes = 1, No = 0	Zx (in^3)	750.5066667		a3	0.00
Wu (plf)	2759.2		Design Sufficient?	yes		a4	0.00
Pu (lb)	137960					a5	0.00
Length of beam (ft)	50					a6	0.00
beam weight (plf)	116		**Chosen Girder**			ΔL	0.878
length of girder (ft)`	40		W44x230			L/360 (in)	1.00
Mu (ft k)	2759.2	Will change if Girder acts as beam				Design Sufficient?	yes
Φ	0.9		**Legend**				
Fy (ksi)	50		Given Information	⬜		Pu (kips)	137.96
Zx (in^3)	735.7866667		Formula	🟦		ΔD+L	1.404
Trial Girder	W44x230		Input	🟨		L/240 (in)	2.00
trial Zx (in^3)	1100	Take from Book based on Trial Girder				Design Sufficient?	yes
E (ksi)	29000						
Ix (in^4)	20800	Take from Book based on Trial Girder					

Figure J.4: Girder design for Girder Scheme "7".



G18							
Initial Girder Design			**Trial (self weight) Girder Check**			**Deflection Calcs**	
Dead Load (psf)	85		Girder unit weight (lb/ft)	397		Number of Purlins	6
Live Load (psf)	100		Self weight, Wu (lb/ft)	476.4		Odd?	FALSE
Beam spacing (ft)	10		Length of girder (ft)	70		WuL	1600
Facade wt (plf)	0		Mu (ft k)	4087.475		PuL	64.00
Exterior Girder?	0	Yes = 1, No = 0	Φ	0.9		a1	10.00
Beams on both sides?	1	Yes = 1, No = 0	Fy (ksi)	50		a2	20.00
Acting as beam?	0	Yes = 1, No = 0	Zx (in^3)	1089.993333		a3	30.00
Wu (plf)	2711.2		Design Sufficient?	yes		a4	0.00
Pu (lb)	108448					a5	0.00
Length of beam (ft)	40					a6	0.00
beam weight (plf)	76		**Chosen Girder**			ΔL	3.665
length of girder (ft)`	70		W40x397			L/360 (in)	1.00
Mu (ft k)	3795.68	Will change if Girder acts as beam				Design Sufficient?	no
Φ	0.9		**Legend**				
Fy (ksi)	50		Given Information	⬜		Pu (kips)	108.45
Zx (in^3)	1012.181333		Formula	🟦		ΔD+L	6.210
Trial Girder	W40x397		Input	🟨		L/240 (in)	3.50
trial Zx (in^3)	1800	Take from Book based on Trial Girder				Design Sufficient?	no
E (ksi)	29000						
Ix (in^4)	32000	Take from Book based on Trial Girder			L/180	Camber (max), in	4.67
					L/300	Camber (rec), in	2.8
						Camber used, in	2.75
						ΔL (after camber), in	0.915
						Design Sufficient?	yes
						ΔD+L (after camber)	3.460
						Design Sufficient?	yes

Figure J.5: Girder design for girder scheme "18". Camber is considered to aid with deflection without upsizing the member. The Final Member Size is Highlighted Yellow and Tabulated under the "Chosen Girder" Box.



G6						
Initial Girder Design			**Trial (self weight) Girder Check**		**Deflection Calcs**	
Dead Load (psf)	85		Girder unit weight (lb/ft)	130	Number of Purlins	3
Live Load (psf)	100		Self weight, Wu (lb/ft)	156	Even or Odd?	TRUE
Beam spacing (ft)	10		Length of girder (ft)	40	WuL	1600
Facade wt (plf)	150		Mu (ft k)	1416.8	PuL	32.00
Exterior Girder?	1	Yes = 1, No = 0	Φ	0.9	a1	10.00
Beams on both sides?	0	Yes = 1, No = 0	Fy (ksi)	50	a2	0.00
Acting as beam?	1	Yes = 1, No = 0	Zx (in^3)	377.8133333	a3	0.00
Wu (plf)	2711.2		Design Sufficient?	yes	a4	0.00
Pu (lb)	54224				a5	0.00
Length of beam (ft)	40				a6	0.00
beam weight (plf)	76		**Chosen Girder**		ΔL	0.934
length of girder (ft)`	40		W40x149		L/360 (in)	1.00
Mu (ft k)	1385.6	Will change if Girder acts as beam			Design Sufficient?	yes
Φ	0.9		**Legend**			
Fy (ksi)	50		Given Information	⬜	Pu (kips)	54.22
Zx (in^3)	369.4933333		Formula	🟦	ΔD+L	1.362
Trial Girder	W40x149		Input	🟨	L/240 (in)	2.00
trial Zx (in^3)	598	Take from Book based on Trial Girder			Design Sufficient?	yes
E (ksi)	29000					
Ix (in^4)	9800	Take from Book based on Trial Girder				

Figure J.6: Girder design for girder scheme "6". Note the Girder is also acting as a Beam in this scenario, as shown by the presence of Facade Weight. The Final Member Size is Highlighted Yellow and tabulated under the "Chosen Girder" Box.

Appendix K: Column Calculation Results

Table K.1: Tabulated Column Calculation Results for Floor 0

Column						Row					
	A	B	C	D	E	F	G	H	I	J	K
1	W10x100			W12x190	W12x190	W12x190	W12x190		W10x88		
2	W12x230			W14x370	W12x305	W12x305	W12x336	W10x68	W10x112		
3	W12x279			W10x45	W12x65	W12x65	W12x136	W10x68	W10x100		
4	W10x33			W14x398	W10x49	W10x49	W14x398		W12x190		
5	W10x112	W10x33									
6	W10x33	W10x33									
7											
8											
9											
10											
11											

Table K.2: Tabulated Column Calculation Results for Floor 1

Column						Row					
	A	B	C	D	E	F	G	H	I	J	K
1	W10x88			W12x170	W12x170	W12x170	W12x170		W10x77		
2	W12x190			W12x336	W12x252	W12x252	W12x230	W10x60	W10x100		
3							W10x88	W10x60	W10x88		
4	W12x230			W14x398			W14x398		W12x170		
5	W10x33	W10x33									
6	W10x88	W10x33		W10x100			W10x100				
7	W12x252			W14x370			W14x370		W12x230		
8				W10x100	HSS16x0.625	HSS16x0.625	W10x100				
9	W12x252			W14x193			W14x193		W12x170		
10	W12x210			W14x370	W14x311		W14x500			W12x279	
11			W10x60	W10x100	W12x170		W12x152				

Table K.3: Additional First Floor Columns (Refer to Appendix G for Location)

Name	D9.5	DM(mezzanine)	DB(balcony)	G9.5	GM(mezzanine)	GB(balcony)
Size	W10x100	W10x49	W10x60	W10x100	W10x60	W10x54

Table K.4: Tabulated Column Calculation Results for Floor 2

Column						Row					
	A	B	C	D	E	F	G	H	I	J	K
1	W10x68			W12x136	W12x136	W12x136	W12x136		W10x60		
2	W12x152			W12x279	W12x210	W12x210	W12x190	W10x49	W10x77		
3							W10x77	W10x49	W10x68		
4	W12x190			W14x398			W14x398		W12x136		
5	W10x33	W10x33									
6	W10x77	W10x33		W10x100			W10x100				
7	W12x210			W14x370			W14x370		W12x190		
8				W10x100	HSS10x0.5	HSS10x0.5	W10x100				
9	W12x190			W14x193			W14x193		W12x136		
10				W12x305	W14x243	W12x336	W14x398			W12x210	
11			W10x60	W10x77	W12x136	W12x136	W12x120				

Table K.5: Additional Second Floor Columns (Refer to Appendix G for Location)

Name	D9.5	DB(balcony)	G9.5	GB(balcony)
Size	W10x100	W10x60	W10x100	W10x54

Table K.6: Tabulated Column Calculation Results for Floor 3

Column						Row					
	A	B	C	D	E	F	G	H	I	J	K
1	W10x49			W10x112	W12x106	W12x106	W12x96		W10x49		
2	W12x120			W12x230	W12x190	W12x190	W12x170	W10x49	W10x60		
3							W10x60	W10x49	W10x54		
4	W12x152			W14x398			W14x398		W10x112		
5	W10x33	W10x33									
6	W10x54	W10x33		W10x100			W10x100				
7	W12x152			W14x370			W14x370		W12x152		
8				W10x100			W10x100				
9	W12x152			W14x193			W14x193		W10x100		
10	W12x120			W12x230	W12x170	W12x252	W14x342		W12x136	W12x170	
11				W10x54	W10x100	W10x100	W12x87		W10x45		

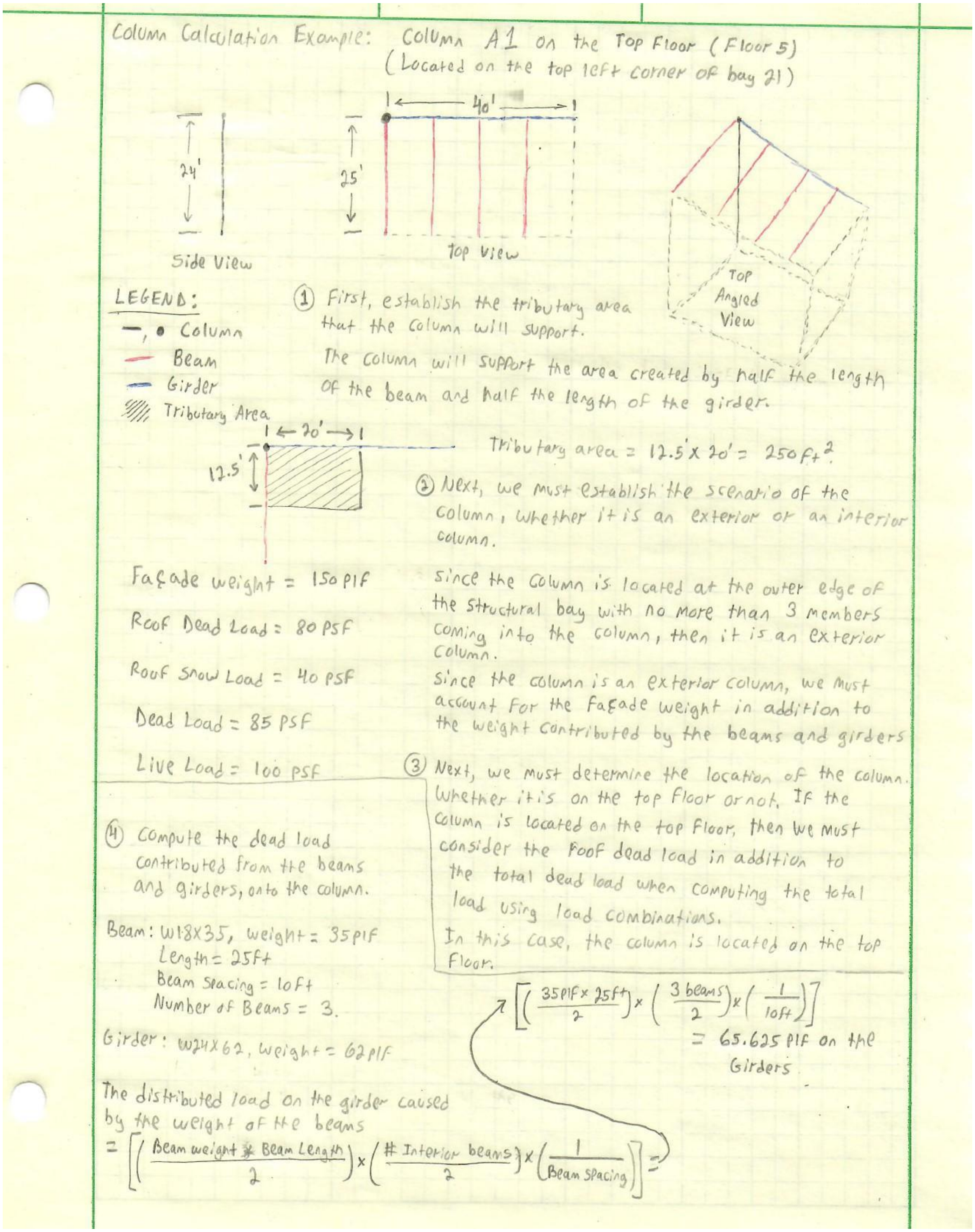
Table K.7: Tabulated Column Calculation Results for Floor 4

Column						Row					
	A	B	C	D	E	F	G	H	I	J	K
1	W10x49			W10x77	W12x72	W12x72	W12x72		W10x49		
2	W10x100			W12x190	W12x170	W12x170	W12x136	W10x49	W10x49		
3							W10x49	W10x49	W10x49		
4	W10x112			W40x593	W40x593	W40x593	W40x593		W10x77	W40x593	W40x593
5	W10x33	W10x33									
6	W10x49	W10x33									
7	W12x106			W40x593		W40x593	W40x593		W12x120	W40x593	W40x593
8											
9	W10x112			W40x297	W40x297	W40x297	W40x297		W10x54	W40x297	W40x297
10	W10x100			W12x120	W12x120	W12x230	W12x279		W12x96	W12x106	
11	W10x33			W10x39	W10x54	W10x54	W12x53		W10x45		

Table K.8: Tabulated Column Calculation Results for Floor 5

Column						Row					
	A	B	C	D	E	F	G	H	I	J	K
1	W10x49			W10x77	W12x72	W12x72	W12x72		W10x49		
2	W10x88			W12x170	W12x170	W12x170	W12x136	W10x49	W10x49		
3							W10x49	W10x49	W10x49		
4	W10x100			W12x152	W12x230	W12x210	W12x170		W10x77	W12x65	
5	W10x33	W10x33									
6	W10x49	W10x33									
7	W10x112			W12x170		W14x211	W14x257		W12x120	W14x176	
8											
9	W10x112				W12x120	W12x65	W40x297			W14x90	
10	W10x49			W12x87	W12x72	W12x190	W12x252		W12x87	W12x79	
11											

Appendix L: Column Sample Hand Calculation



Column Calculation Example: Column A1 on the Top Floor (Floor 5)
(Located on the top left corner of bay 21)

LEGEND:
- —, ● Column
- — Beam
- — Girder
- ▨ Tributary Area

① First, establish the tributary area that the column will support.
The column will support the area created by half the length of the beam and half the length of the girder.

Tributary area = 12.5' x 20' = 250 ft².

② Next, we must establish the scenario of the column, whether it is an exterior or an interior column.

Since the column is located at the outer edge of the structural bay with no more than 3 members coming into the column, then it is an exterior column.
Since the column is an exterior column, we must account for the façade weight in addition to the weight contributed by the beams and girders

Façade weight = 150 plf

Roof Dead Load = 80 PSF

Roof Snow Load = 40 PSF

Dead Load = 85 PSF

Live Load = 100 PSF

③ Next, we must determine the location of the column. Whether it's on the top floor or not. If the column is located on the top floor, then we must consider the roof dead load in addition to the total dead load when computing the total load using load combinations.
In this case, the column is located on the top floor.

④ Compute the dead load contributed from the beams and girders, onto the column.

Beam: W18X35, weight = 35plf
Length = 25ft
Beam spacing = 10ft
Number of Beams = 3.

Girder: W24X62, weight = 62plf

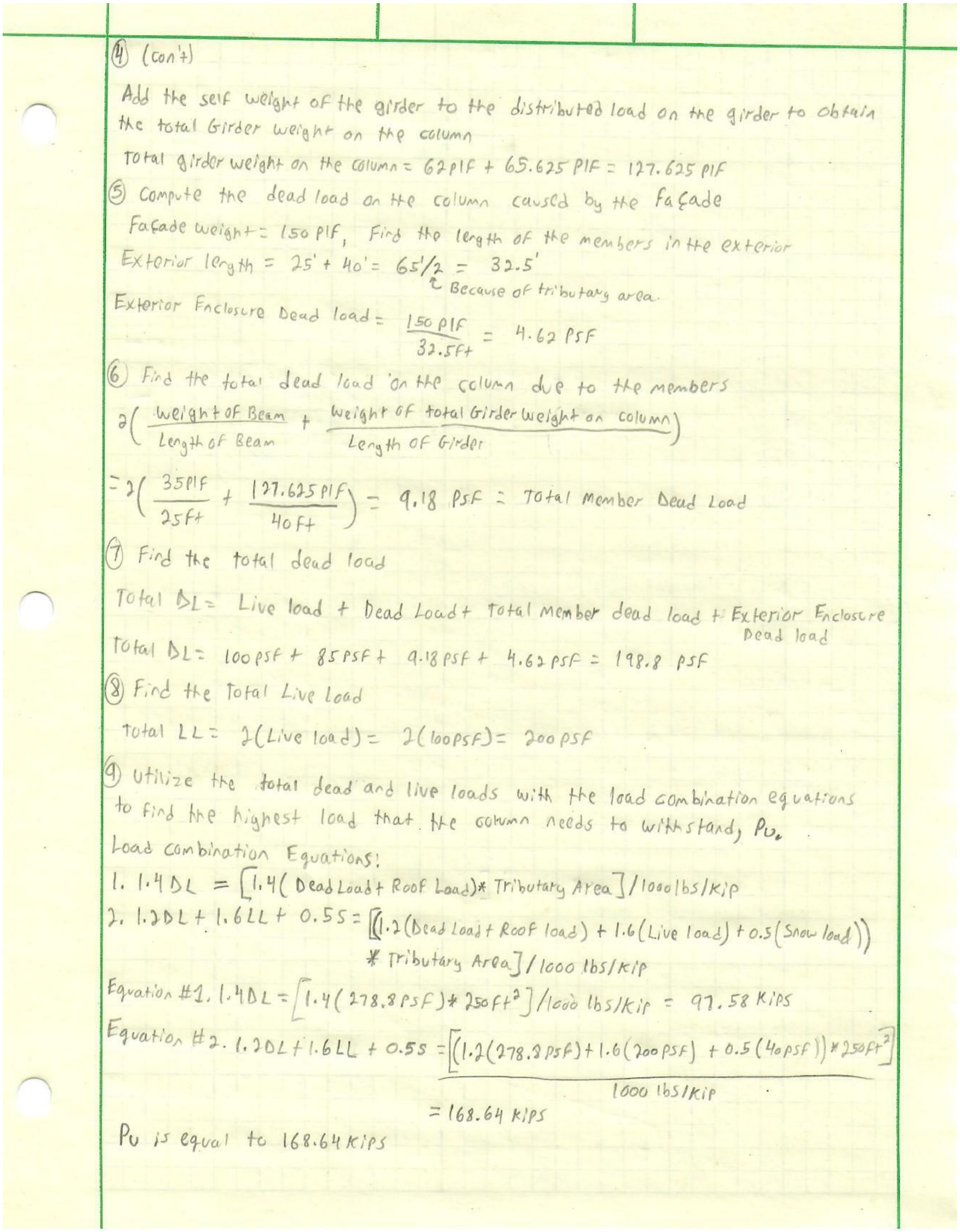
The distributed load on the girder caused by the weight of the beams

$$= \left[\left(\frac{\text{Beam weight} * \text{Beam Length}}{2}\right) \times \left(\frac{\#\text{ Interior beams}}{2}\right) \times \left(\frac{1}{\text{Beam Spacing}}\right)\right] =$$

$$\left[\left(\frac{35\text{plf} \times 25\text{ft}}{2}\right) \times \left(\frac{3\text{ beams}}{2}\right) \times \left(\frac{1}{10\text{ft}}\right)\right]$$

= 65.625 plf on the Girders

Figure L.1: Column Sample Calculation Page 1. Continued in Figures L.2 and L.3.



④ (con't)

Add the self weight of the girder to the distributed load on the girder to obtain the total Girder weight on the column

Total girder weight on the column = 62 plf + 65.625 plf = 127.625 plf

⑤ Compute the dead load on the column caused by the Façade

Façade weight = 150 plf, Find the length of the members in the exterior

Exterior length = 25' + 40' = 65'/2 = 32.5'

Because of tributary area.

Exterior Enclosure Dead load = $\frac{150\ \text{plf}}{32.5\ \text{ft}}$ = 4.62 psf

⑥ Find the total dead load on the column due to the members

$$2\left(\frac{\text{Weight of Beam}}{\text{Length of Beam}} + \frac{\text{Weight of total Girder Weight on column}}{\text{Length of Girder}}\right)$$

$$= 2\left(\frac{35\ \text{plf}}{25\ \text{ft}} + \frac{127.625\ \text{plf}}{40\ \text{ft}}\right) = 9.18\ \text{psf} = \text{Total Member Dead Load}$$

⑦ Find the total dead load

Total DL = Live load + Dead Load + total member dead load + Exterior Enclosure Dead load

Total DL = 100 psf + 85 psf + 9.18 psf + 4.62 psf = 198.8 psf

⑧ Find the Total Live Load

Total LL = 2(Live load) = 2(100 psf) = 200 psf

⑨ Utilize the total dead and live loads with the load combination equations to find the highest load that the column needs to withstand, Pu.

Load combination Equations:

1. 1.4DL = [1.4(Dead Load + Roof Load) * Tributary Area] / 1000 lbs/kip

2. 1.2DL + 1.6LL + 0.5S = [(1.2(Dead Load + Roof load) + 1.6(Live load) + 0.5(Snow load)) * Tributary Area] / 1000 lbs/kip

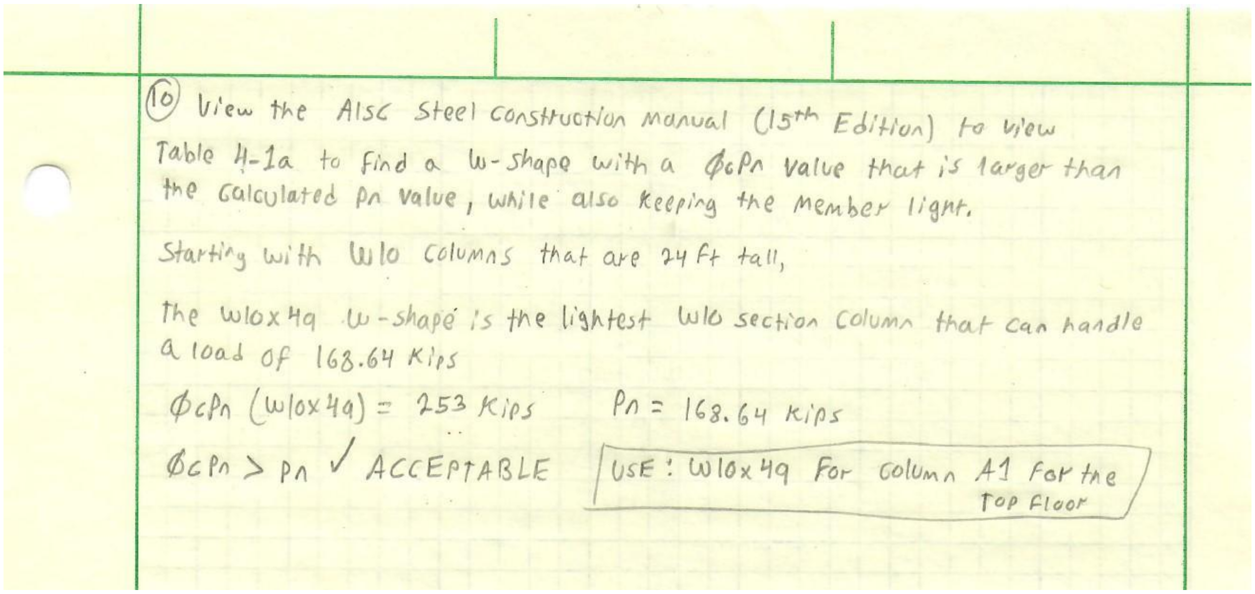
Equation #1. 1.4DL = [1.4(278.8 psf) * 250 ft^2] / 1000 lbs/kip = 97.58 kips

Equation #2. 1.2DL + 1.6LL + 0.5S = $\frac{[(1.2(278.8\ \text{psf}) + 1.6(200\ \text{psf}) + 0.5(40\ \text{psf})) * 250\ \text{ft}^2]}{1000\ \text{lbs/kip}}$

= 168.64 kips

Pu is equal to 168.64 kips

Figure L.2: Column Sample Calculation Page 2. Concluded in Figure L.3.



⑩ View the AISC Steel construction manual (15th Edition) to view Table 4-1a to find a W-shape with a $\phi_c P_n$ value that is larger than the calculated P_n value, while also keeping the member light.

Starting with W10 columns that are 24 ft tall,

The W10x49 W-shape is the lightest W10 section column that can handle a load of 168.64 Kips

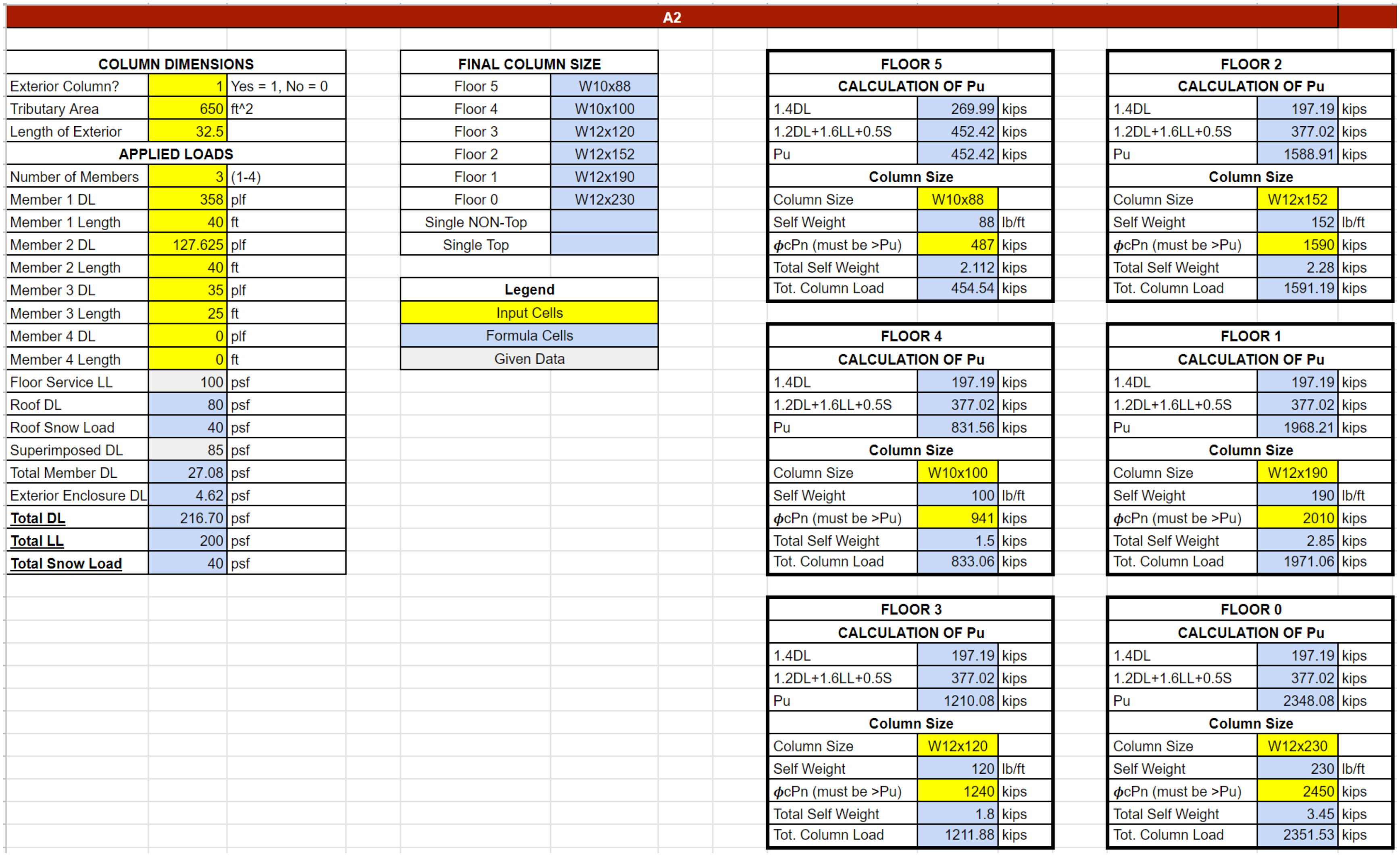
$\phi_c P_n$ (W10x49) = 253 Kips P_n = 168.64 Kips

$\phi_c P_n > P_n$ ✓ ACCEPTABLE

$\boxed{\text{USE: W10x49 For column A1 For the Top Floor}}$

Figure L.3: Column Sample Calculation Page 3

Appendix M: Column Design Spreadsheet Samples



A2

COLUMN DIMENSIONS		
Exterior Column?	1	Yes = 1, No = 0
Tributary Area	650	ft^2
Length of Exterior	32.5	
APPLIED LOADS		
Number of Members	3	(1-4)
Member 1 DL	358	plf
Member 1 Length	40	ft
Member 2 DL	127.625	plf
Member 2 Length	40	ft
Member 3 DL	35	plf
Member 3 Length	25	ft
Member 4 DL	0	plf
Member 4 Length	0	ft
Floor Service LL	100	psf
Roof DL	80	psf
Roof Snow Load	40	psf
Superimposed DL	85	psf
Total Member DL	27.08	psf
Exterior Enclosure DL	4.62	psf
Total DL	216.70	psf
Total LL	200	psf
Total Snow Load	40	psf

FINAL COLUMN SIZE	
Floor 5	W10x88
Floor 4	W10x100
Floor 3	W12x120
Floor 2	W12x152
Floor 1	W12x190
Floor 0	W12x230
Single NON-Top	
Single Top	

Legend
Input Cells
Formula Cells
Given Data

FLOOR 5		
CALCULATION OF Pu		
1.4DL	269.99	kips
1.2DL+1.6LL+0.5S	452.42	kips
Pu	452.42	kips
Column Size		
Column Size	W10x88	
Self Weight	88	lb/ft
ϕcPn (must be >Pu)	487	kips
Total Self Weight	2.112	kips
Tot. Column Load	454.54	kips

FLOOR 2		
CALCULATION OF Pu		
1.4DL	197.19	kips
1.2DL+1.6LL+0.5S	377.02	kips
Pu	1588.91	kips
Column Size		
Column Size	W12x152	
Self Weight	152	lb/ft
ϕcPn (must be >Pu)	1590	kips
Total Self Weight	2.28	kips
Tot. Column Load	1591.19	kips

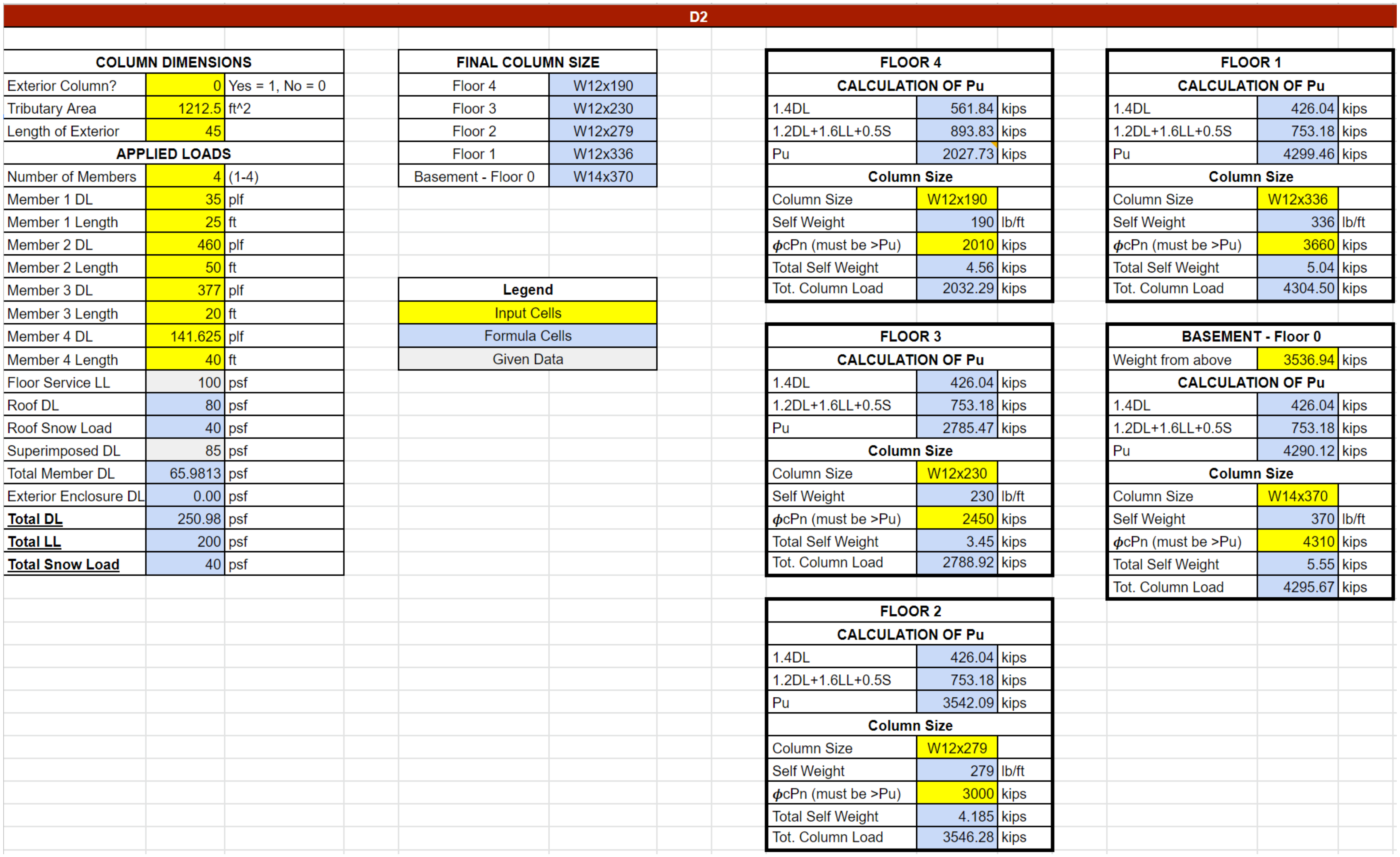
FLOOR 4		
CALCULATION OF Pu		
1.4DL	197.19	kips
1.2DL+1.6LL+0.5S	377.02	kips
Pu	831.56	kips
Column Size		
Column Size	W10x100	
Self Weight	100	lb/ft
ϕcPn (must be >Pu)	941	kips
Total Self Weight	1.5	kips
Tot. Column Load	833.06	kips

FLOOR 1		
CALCULATION OF Pu		
1.4DL	197.19	kips
1.2DL+1.6LL+0.5S	377.02	kips
Pu	1968.21	kips
Column Size		
Column Size	W12x190	
Self Weight	190	lb/ft
ϕcPn (must be >Pu)	2010	kips
Total Self Weight	2.85	kips
Tot. Column Load	1971.06	kips

FLOOR 3		
CALCULATION OF Pu		
1.4DL	197.19	kips
1.2DL+1.6LL+0.5S	377.02	kips
Pu	1210.08	kips
Column Size		
Column Size	W12x120	
Self Weight	120	lb/ft
ϕcPn (must be >Pu)	1240	kips
Total Self Weight	1.8	kips
Tot. Column Load	1211.88	kips

FLOOR 0		
CALCULATION OF Pu		
1.4DL	197.19	kips
1.2DL+1.6LL+0.5S	377.02	kips
Pu	2348.08	kips
Column Size		
Column Size	W12x230	
Self Weight	230	lb/ft
ϕcPn (must be >Pu)	2450	kips
Total Self Weight	3.45	kips
Tot. Column Load	2351.53	kips

Figure M.1: Column Design Spreadsheet for Column A2 Through Whole Building. Left Shows the Tributary Area, Exterior Length, Length of Each Member on it and their Weight, and Total Loads in PSF. Right shows Ultimate Load Pu *based on Tributary Area and Factored Loading, and Selected Column Size. Total Column Load Field is Added to Column Below it for Transfer of Loads.*



D2

COLUMN DIMENSIONS		
Exterior Column?	0	Yes = 1, No = 0
Tributary Area	1212.5	ft^2
Length of Exterior	45	
APPLIED LOADS		
Number of Members	4	(1-4)
Member 1 DL	35	plf
Member 1 Length	25	ft
Member 2 DL	460	plf
Member 2 Length	50	ft
Member 3 DL	377	plf
Member 3 Length	20	ft
Member 4 DL	141.625	plf
Member 4 Length	40	ft
Floor Service LL	100	psf
Roof DL	80	psf
Roof Snow Load	40	psf
Superimposed DL	85	psf
Total Member DL	65.9813	psf
Exterior Enclosure DL	0.00	psf
Total DL	250.98	psf
Total LL	200	psf
Total Snow Load	40	psf

FINAL COLUMN SIZE	
Floor 4	W12x190
Floor 3	W12x230
Floor 2	W12x279
Floor 1	W12x336
Basement - Floor 0	W14x370

Legend
Input Cells
Formula Cells
Given Data

FLOOR 4		
CALCULATION OF Pu		
1.4DL	561.84	kips
1.2DL+1.6LL+0.5S	893.83	kips
Pu	2027.73	kips
Column Size		
Column Size	W12x190	
Self Weight	190	lb/ft
ϕcPn (must be >Pu)	2010	kips
Total Self Weight	4.56	kips
Tot. Column Load	2032.29	kips

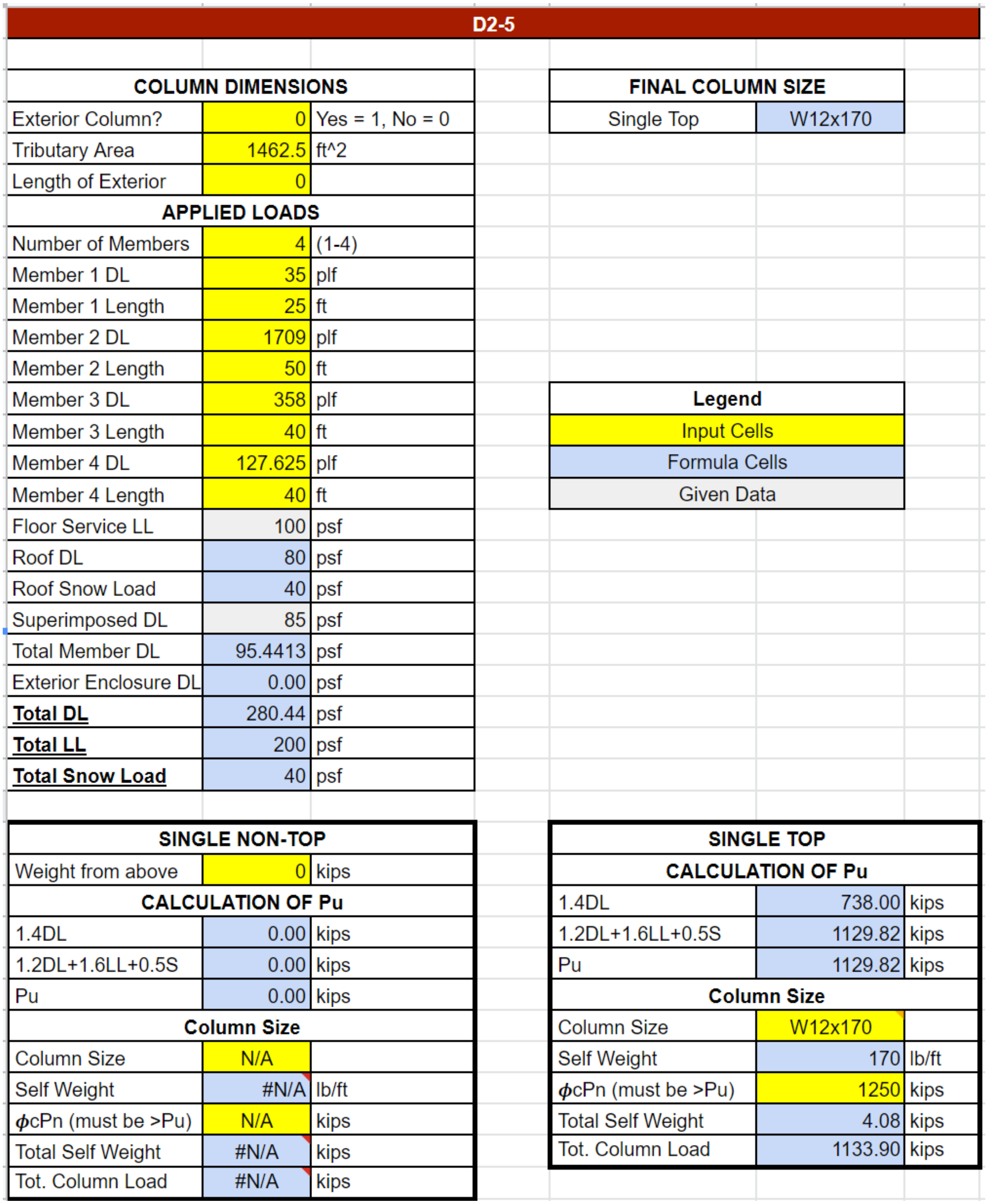
FLOOR 3		
CALCULATION OF Pu		
1.4DL	426.04	kips
1.2DL+1.6LL+0.5S	753.18	kips
Pu	2785.47	kips
Column Size		
Column Size	W12x230	
Self Weight	230	lb/ft
ϕcPn (must be >Pu)	2450	kips
Total Self Weight	3.45	kips
Tot. Column Load	2788.92	kips

FLOOR 2		
CALCULATION OF Pu		
1.4DL	426.04	kips
1.2DL+1.6LL+0.5S	753.18	kips
Pu	3542.09	kips
Column Size		
Column Size	W12x279	
Self Weight	279	lb/ft
ϕcPn (must be >Pu)	3000	kips
Total Self Weight	4.185	kips
Tot. Column Load	3546.28	kips

FLOOR 1		
CALCULATION OF Pu		
1.4DL	426.04	kips
1.2DL+1.6LL+0.5S	753.18	kips
Pu	4299.46	kips
Column Size		
Column Size	W12x336	
Self Weight	336	lb/ft
ϕcPn (must be >Pu)	3660	kips
Total Self Weight	5.04	kips
Tot. Column Load	4304.50	kips

BASEMENT - Floor 0		
Weight from above	3536.94	kips
CALCULATION OF Pu		
1.4DL	426.04	kips
1.2DL+1.6LL+0.5S	753.18	kips
Pu	4290.12	kips
Column Size		
Column Size	W14x370	
Self Weight	370	lb/ft
ϕcPn (must be >Pu)	4310	kips
Total Self Weight	5.55	kips
Tot. Column Load	4295.67	kips

Figure M.2: Column Design Spreadsheet for Column D2 For Floors 0-4. Floor 5 is not included due to the 5th Floor having a Different Tributary Area. Pu *for the 4th Floor includes the Total Column Load for the 5th Floor - See Figure M.3 Below for the Calculation.*



D2-5

COLUMN DIMENSIONS		
Exterior Column?	0	Yes = 1, No = 0
Tributary Area	1462.5	ft^2
Length of Exterior	0	
APPLIED LOADS		
Number of Members	4	(1-4)
Member 1 DL	35	plf
Member 1 Length	25	ft
Member 2 DL	1709	plf
Member 2 Length	50	ft
Member 3 DL	358	plf
Member 3 Length	40	ft
Member 4 DL	127.625	plf
Member 4 Length	40	ft
Floor Service LL	100	psf
Roof DL	80	psf
Roof Snow Load	40	psf
Superimposed DL	85	psf
Total Member DL	95.4413	psf
Exterior Enclosure DL	0.00	psf
Total DL	280.44	psf
Total LL	200	psf
Total Snow Load	40	psf

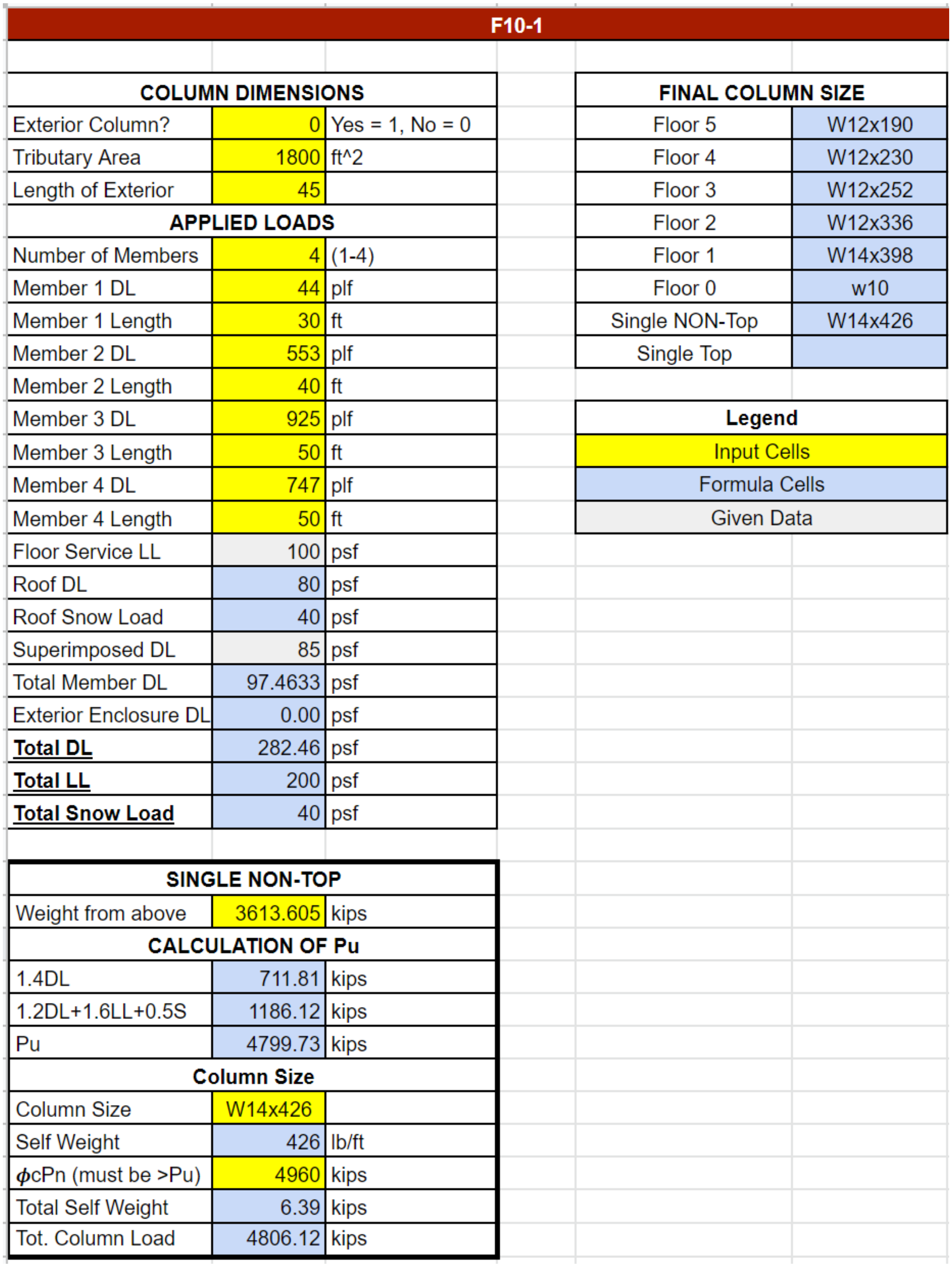
FINAL COLUMN SIZE	
Single Top	W12x170

Legend
Input Cells
Formula Cells
Given Data

SINGLE NON-TOP		
Weight from above	0	kips
CALCULATION OF Pu		
1.4DL	0.00	kips
1.2DL+1.6LL+0.5S	0.00	kips
Pu	0.00	kips
Column Size		
Column Size	N/A	
Self Weight	#N/A	lb/ft
ϕcPn (must be >Pu)	N/A	kips
Total Self Weight	#N/A	kips
Tot. Column Load	#N/A	kips

SINGLE TOP		
CALCULATION OF Pu		
1.4DL	738.00	kips
1.2DL+1.6LL+0.5S	1129.82	kips
Pu	1129.82	kips
Column Size		
Column Size	W12x170	
Self Weight	170	lb/ft
ϕcPn (must be >Pu)	1250	kips
Total Self Weight	4.08	kips
Tot. Column Load	1133.90	kips

Figure M.3: Column Design Spreadsheet for Column D2 on the 5th Floor. Note the Different Tributary Area and Members it supports. The Total Column Load in the "Single Top" Section was Added to Figure M.2 Above. The "Single Top" Template was used for all Columns that have one-time conditions on the 5th Floor, where columns are 24 feet tall.



F10-1

COLUMN DIMENSIONS		
Exterior Column?	0	Yes = 1, No = 0
Tributary Area	1800	ft^2
Length of Exterior	45	
APPLIED LOADS		
Number of Members	4	(1-4)
Member 1 DL	44	plf
Member 1 Length	30	ft
Member 2 DL	553	plf
Member 2 Length	40	ft
Member 3 DL	925	plf
Member 3 Length	50	ft
Member 4 DL	747	plf
Member 4 Length	50	ft
Floor Service LL	100	psf
Roof DL	80	psf
Roof Snow Load	40	psf
Superimposed DL	85	psf
Total Member DL	97.4633	psf
Exterior Enclosure DL	0.00	psf
Total DL	282.46	psf
Total LL	200	psf
Total Snow Load	40	psf

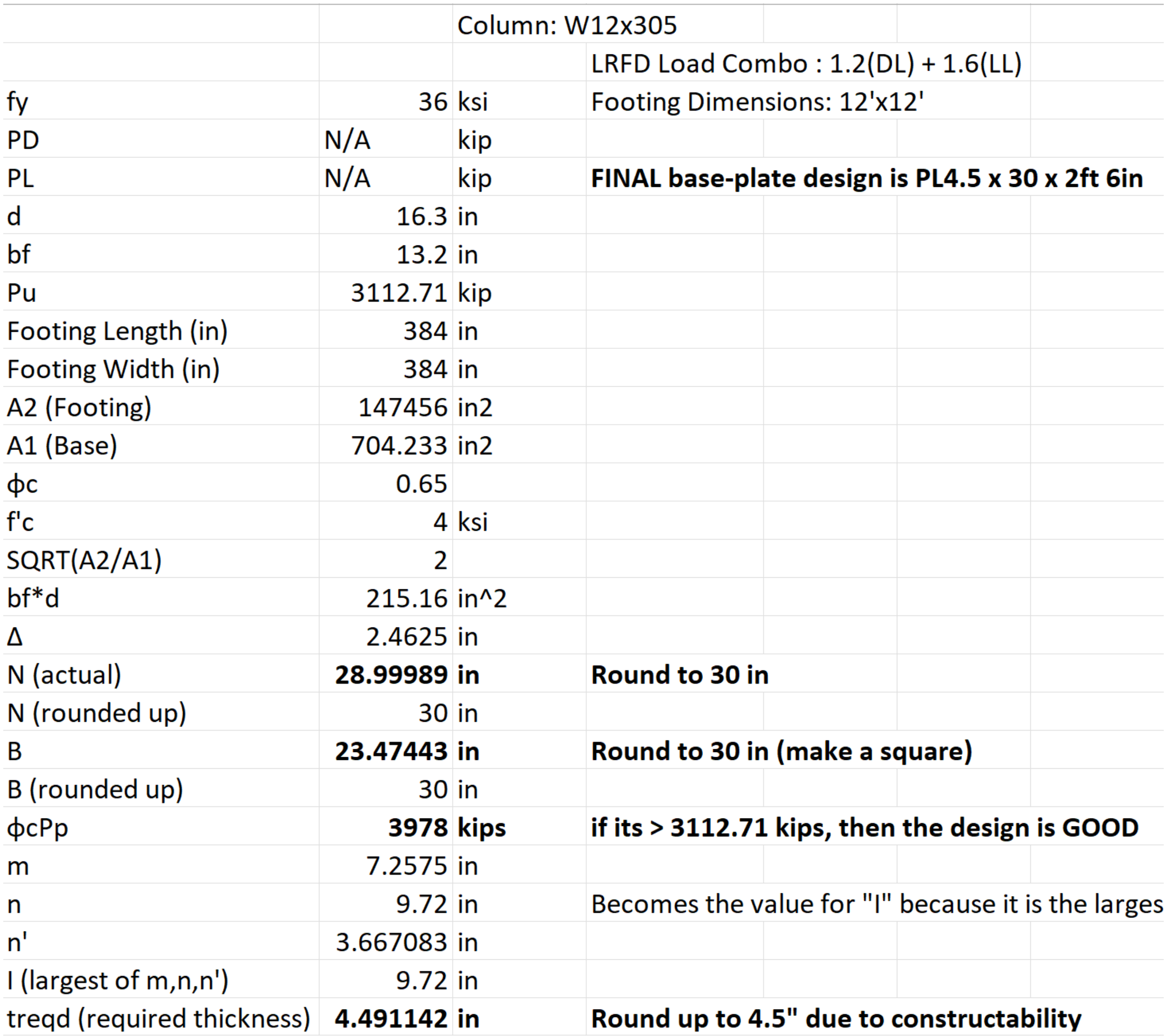
SINGLE NON-TOP		
Weight from above	3613.605	kips
CALCULATION OF Pu		
1.4DL	711.81	kips
1.2DL+1.6LL+0.5S	1186.12	kips
Pu	4799.73	kips
Column Size		
Column Size	W14x426	
Self Weight	426	lb/ft
*ϕ*cPn (must be >Pu)	4960	kips
Total Self Weight	6.39	kips
Tot. Column Load	4806.12	kips

FINAL COLUMN SIZE	
Floor 5	W12x190
Floor 4	W12x230
Floor 3	W12x252
Floor 2	W12x336
Floor 1	W14x398
Floor 0	w10
Single NON-Top	W14x426
Single Top	

Legend
Input Cells
Formula Cells
Given Data

Figure M.4: Design of Column F10-1, or F10 on the 1st Floor only. The "Single Non-Top" Template was used. A Weight From Above Field to include the Total Column Load from F10-2 above

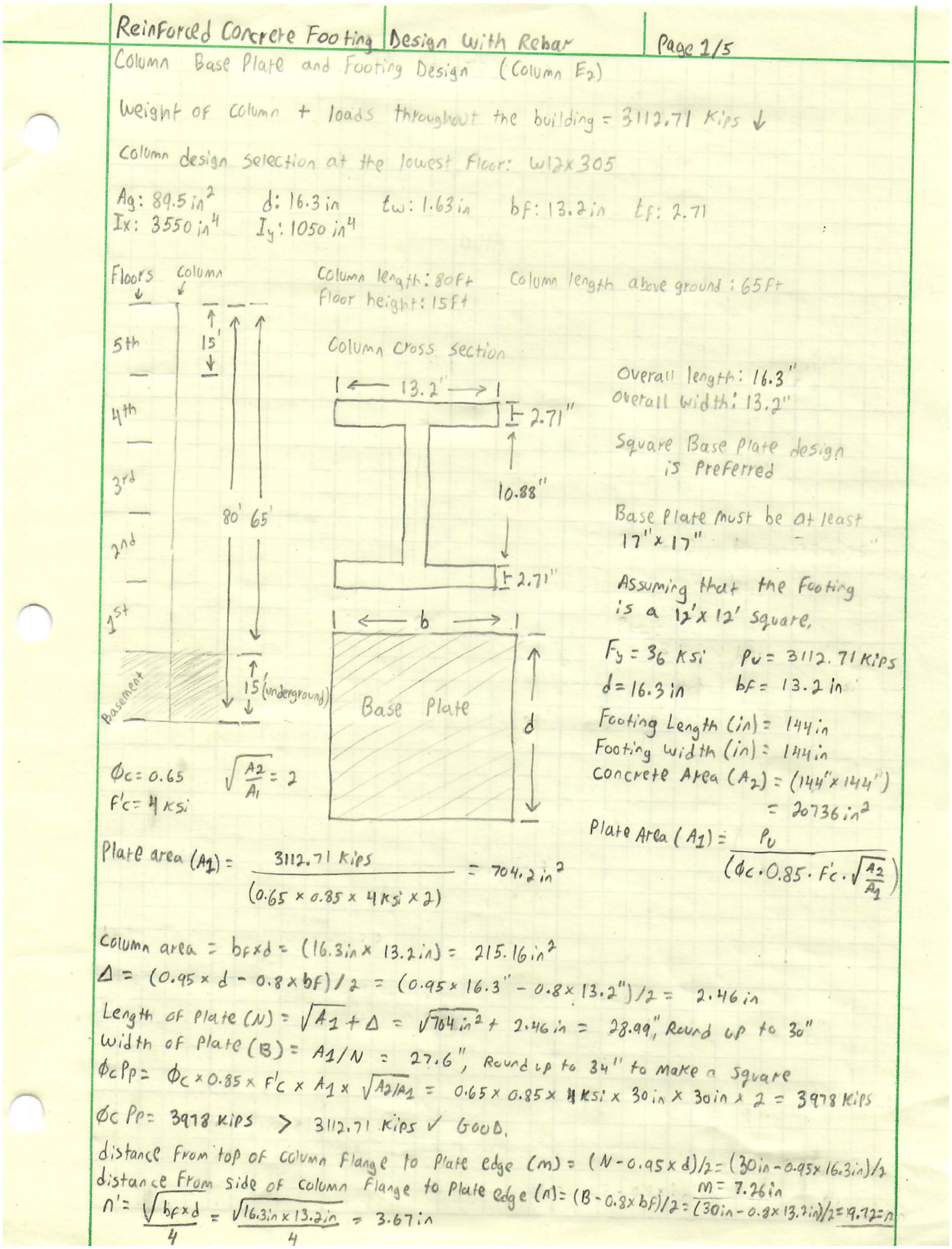
Appendix N: Column Base Plate Design Spreadsheet



		Column: W12x305	
			LRFD Load Combo : 1.2(DL) + 1.6(LL)
fy	36	ksi	Footing Dimensions: 12'x12'
PD	N/A	kip	
PL	N/A	kip	**FINAL base-plate design is PL4.5 x 30 x 2ft 6in**
d	16.3	in	
bf	13.2	in	
Pu	3112.71	kip	
Footing Length (in)	384	in	
Footing Width (in)	384	in	
A2 (Footing)	147456	in2	
A1 (Base)	704.233	in2	
ϕc	0.65		
f'c	4	ksi	
SQRT(A2/A1)	2		
bf*d	215.16	in^2	
Δ	2.4625	in	
N (actual)	**28.99989**	**in**	**Round to 30 in**
N (rounded up)	30	in	
B	**23.47443**	**in**	**Round to 30 in (make a square)**
B (rounded up)	30	in	
ϕcPp	**3978**	**kips**	**if its > 3112.71 kips, then the design is GOOD**
m	7.2575	in	
n	9.72	in	Becomes the value for "I" because it is the larges
n'	3.667083	in	
I (largest of m,n,n')	9.72	in	
treqd (required thickness)	**4.491142**	**in**	**Round up to 4.5" due to constructability**

Figure N.1: Column Base Plate Design Sample using the LRFD Method

Appendix O: Column Footing Design Sample Hand Calculations



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Column Base Plate and Footing Design (Column E_2)

Weight of Column + loads throughout the building = 3112.71 Kips ↓

Column design selection at the lowest Floor: W12x305

A_g: 89.5 in^2 d: 16.3 in t_w: 1.63 in b_f: 13.2 in t_f: 2.71
I_x: 3550 in^4 I_y: 1050 in^4

Column length: 80ft Column length above ground: 65ft
Floor height: 15ft

Column Cross section

Overall length: 16.3"
Overall width: 13.2"

Square Base plate design is preferred

Base plate must be at least 17"x 17"

Assuming that the Footing is a 12'x 12' square,

F_y = 36 ksi P_u = 3112.71 Kips
d = 16.3 in b_f = 13.2 in

Footing Length (in) = 144in
Footing width (in) = 144in
Concrete Area (A_2) = (144"x 144")
= 20736 in^2

Plate Area (A_1) = $\frac{P_u}{(\phi_c \cdot 0.85 \cdot F'_c \cdot \sqrt{\frac{A_2}{A_1}})}$

$\phi_c = 0.65$ $\sqrt{\frac{A_2}{A_1}} = 2$
$F'_c = 4$ ksi

Plate area (A_1) = $\frac{3112.71 \text{ Kips}}{(0.65 \times 0.85 \times 4 \text{ksi} \times 2)} = 704.2 \text{ in}^2$

Column area = $b_f \times d$ = (16.3in x 13.2in) = 215.16 in^2

$\Delta = (0.95 \times d - 0.8 \times b_f)/2 = (0.95 \times 16.3" - 0.8 \times 13.2")/2 = 2.46$ in

Length of plate (N) = $\sqrt{A_1} + \Delta = \sqrt{704 \text{ in}^2} + 2.46$ in = 28.99", Round up to 30"

Width of plate (B) = A_1/N = 27.6", Round up to 34" to make a square

$\phi_c P_p = \phi_c \times 0.85 \times F'_c \times A_1 \times \sqrt{A_2/A_1} = 0.65 \times 0.85 \times 4 \text{ksi} \times 30\text{in} \times 30\text{in} \times 2 = 3978$ Kips

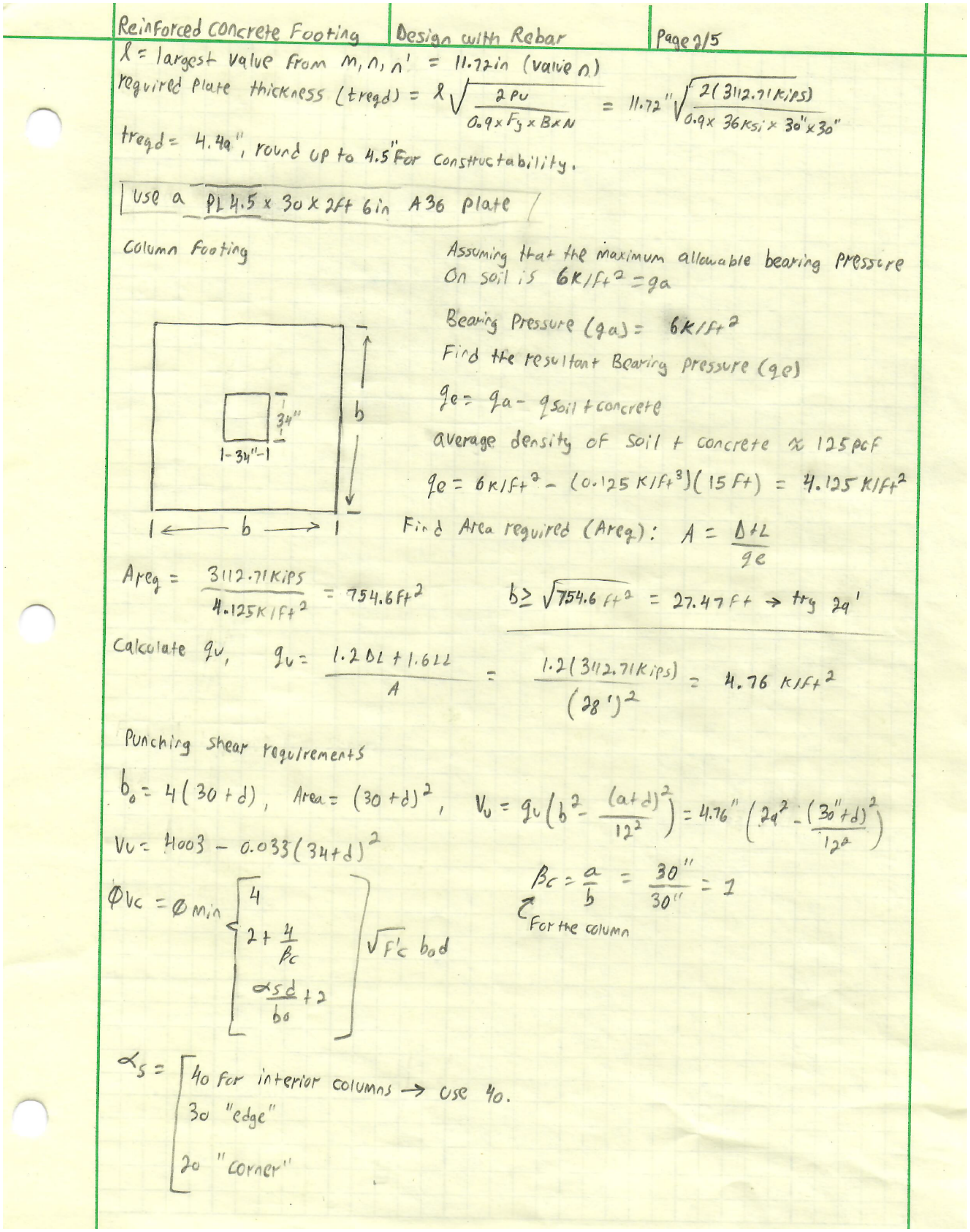
$\phi_c P_p$ = 3978 Kips > 3112.71 Kips ✓ Good.

distance from top of column Flange to Plate edge (m) = $(N - 0.95 \times d)/2 = (30\text{in} - 0.95 \times 16.3\text{in})/2$
m = 7.26in

distance from side of column Flange to Plate edge (n) = $(B - 0.8 \times b_f)/2 = (30\text{in} - 0.8 \times 13.2\text{in})/2 = 9.72 = n$

$n' = \frac{\sqrt{b_f \times d}}{4} = \frac{\sqrt{16.3\text{in} \times 13.2\text{in}}}{4} = 3.67$ in

Figure O.1: Column Footing Design Sample Calculation Page 1. Continued in Figures O.2-O.6



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ℓ = largest value from m, n, n' = 11.72in (value n)

required plate thickness (t_{reqd}) $= \ell\sqrt{\dfrac{2P_u}{0.9 \times F_y \times B \times N}} = 11.72''\sqrt{\dfrac{2(3112.71\,kips)}{0.9 \times 36\,ksi \times 30'' \times 30''}}$

t_{reqd} = 4.49'', round up to 4.5'' for constuctability.

$\boxed{\text{Use a PL 4.5} \times 30 \times \text{2ft 6in A36 plate}}$

Column Footing

Assuming that the maximum allowable bearing pressure on soil is $6\,K/ft^2 = q_a$

Bearing Pressure (q_a) = $6\,K/ft^2$

Find the resultant Bearing pressure (q_e)

$q_e = q_a - q_{soil + concrete}$

average density of soil + concrete ≈ 125pcf

$q_e = 6\,K/ft^2 - (0.125\,K/ft^3)(15\,ft) = 4.125\,K/ft^2$

Find Area required (A_{req}): $A = \dfrac{D+L}{q_e}$

$A_{req} = \dfrac{3112.71\,kips}{4.125\,K/ft^2} = 754.6\,ft^2$

$b \geq \sqrt{754.6\,ft^2} = 27.47\,ft \rightarrow$ try 29'

Calculate q_u, $q_u = \dfrac{1.2DL + 1.6LL}{A} = \dfrac{1.2(3112.71\,kips)}{(28')^2} = 4.76\,K/ft^2$

Punching shear requirements

$b_o = 4(30+d)$, Area $= (30+d)^2$, $V_u = q_u\left(b^2 - \dfrac{(a+d)^2}{12^2}\right) = 4.76''\left(29^2 - \dfrac{(30''+d)^2}{12^2}\right)$

$V_u = 4003 - 0.033(34+d)^2$

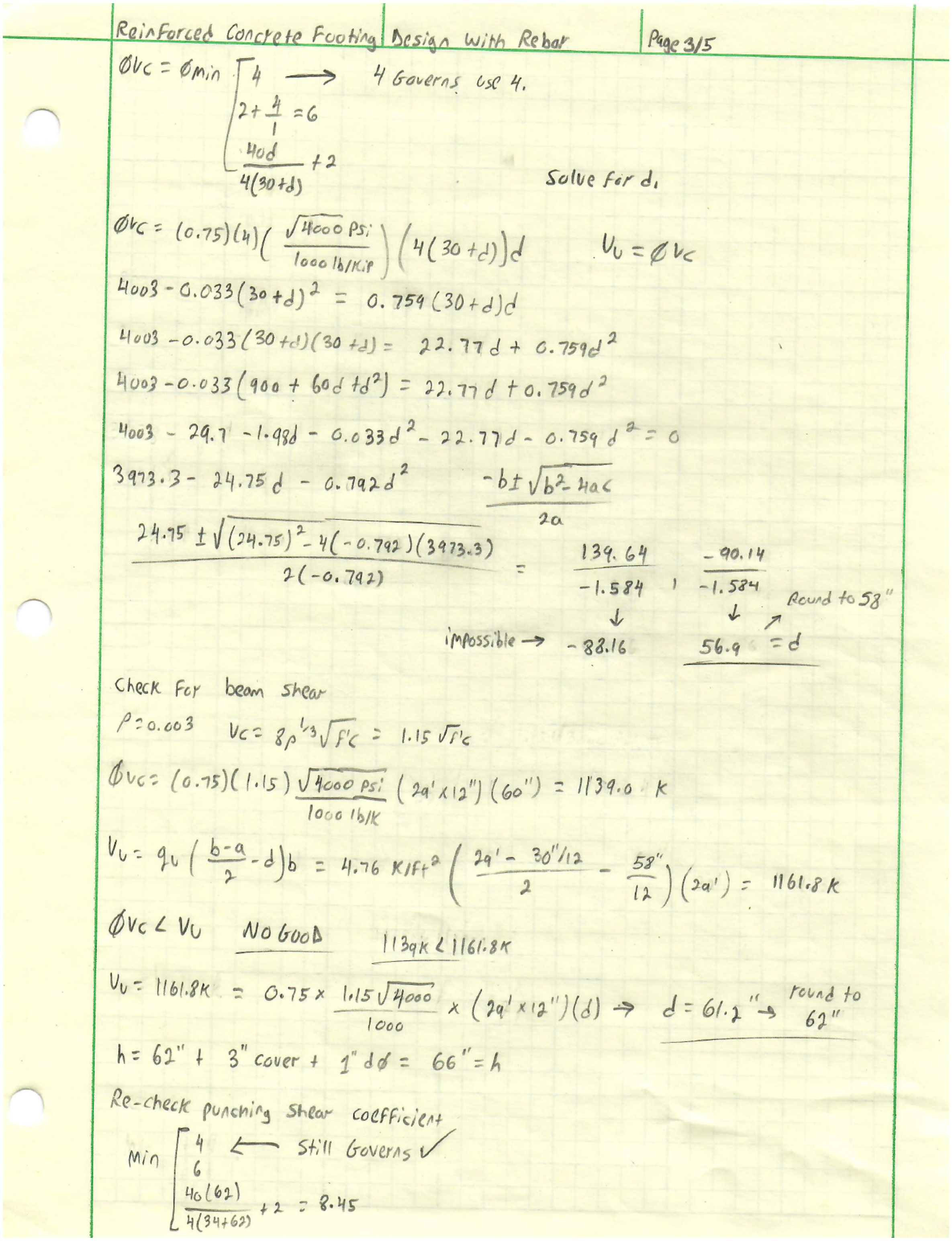
$\beta_c = \dfrac{a}{b} = \dfrac{30''}{30''} = 1$

For the column

$$\phi V_c = \phi \min \begin{bmatrix} 4 \\ 2 + \dfrac{4}{\beta_c} \\ \dfrac{\alpha_s d}{b_o} + 2 \end{bmatrix} \sqrt{f'_c}\, b_o d$$

$\alpha_s = \begin{bmatrix} \text{40 for interior columns} \rightarrow \text{use 40.} \\ \text{30 "edge"} \\ \text{20 "corner"} \end{bmatrix}$

Figure O.2: Column Footing Design Sample Calculation Page 2. Continued in Figures O.3-O.6



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$$\emptyset v_c = \emptyset \min \begin{bmatrix} 4 \longrightarrow & 4 \text{ Governs use } 4. \\ 2+\frac{4}{1}=6 & \\ \frac{40d}{4(30+d)}+2 & \end{bmatrix}$$

Solve for d.

$$\emptyset v_c = (0.75)(4)\left(\frac{\sqrt{4000\text{ psi}}}{1000\text{ lb/kip}}\right)\left(4(30+d)\right)d \qquad V_u = \emptyset v_c$$

$$4003 - 0.033(30+d)^2 = 0.759(30+d)d$$

$$4003 - 0.033(30+d)(30+d) = 22.77d + 0.759d^2$$

$$4003 - 0.033(900 + 60d + d^2) = 22.77d + 0.759d^2$$

$$4003 - 29.7 - 1.98d - 0.033d^2 - 22.77d - 0.759d^2 = 0$$

$$3973.3 - 24.75d - 0.792d^2 \qquad \frac{-b \pm \sqrt{b^2-4ac}}{2a}$$

$$\frac{24.75 \pm \sqrt{(24.75)^2 - 4(-0.792)(3973.3)}}{2(-0.792)} = \frac{139.64}{-1.584}, \frac{-90.14}{-1.584}$$

$$\text{impossible} \rightarrow -88.16 \qquad \underline{56.9 = d} \nearrow \text{Round to } 58''$$

Check for beam shear

$$\rho = 0.003 \qquad V_c = 8\rho^{1/3}\sqrt{f'c} = 1.15\sqrt{f'c}$$

$$\emptyset v_c = (0.75)(1.15)\frac{\sqrt{4000\text{ psi}}}{1000\text{ lb/k}}(29' \times 12'')(60'') = 1139.0\text{ k}$$

$$V_u = q_u\left(\frac{b-a}{2} - d\right)b = 4.76\text{ k/ft}^2\left(\frac{29' - 30''/12}{2} - \frac{58''}{12}\right)(29') = 1161.8\text{ k}$$

$$\emptyset v_c < V_u \qquad \underline{\text{No Good}} \qquad \underline{1139\text{k} < 1161.8\text{k}}$$

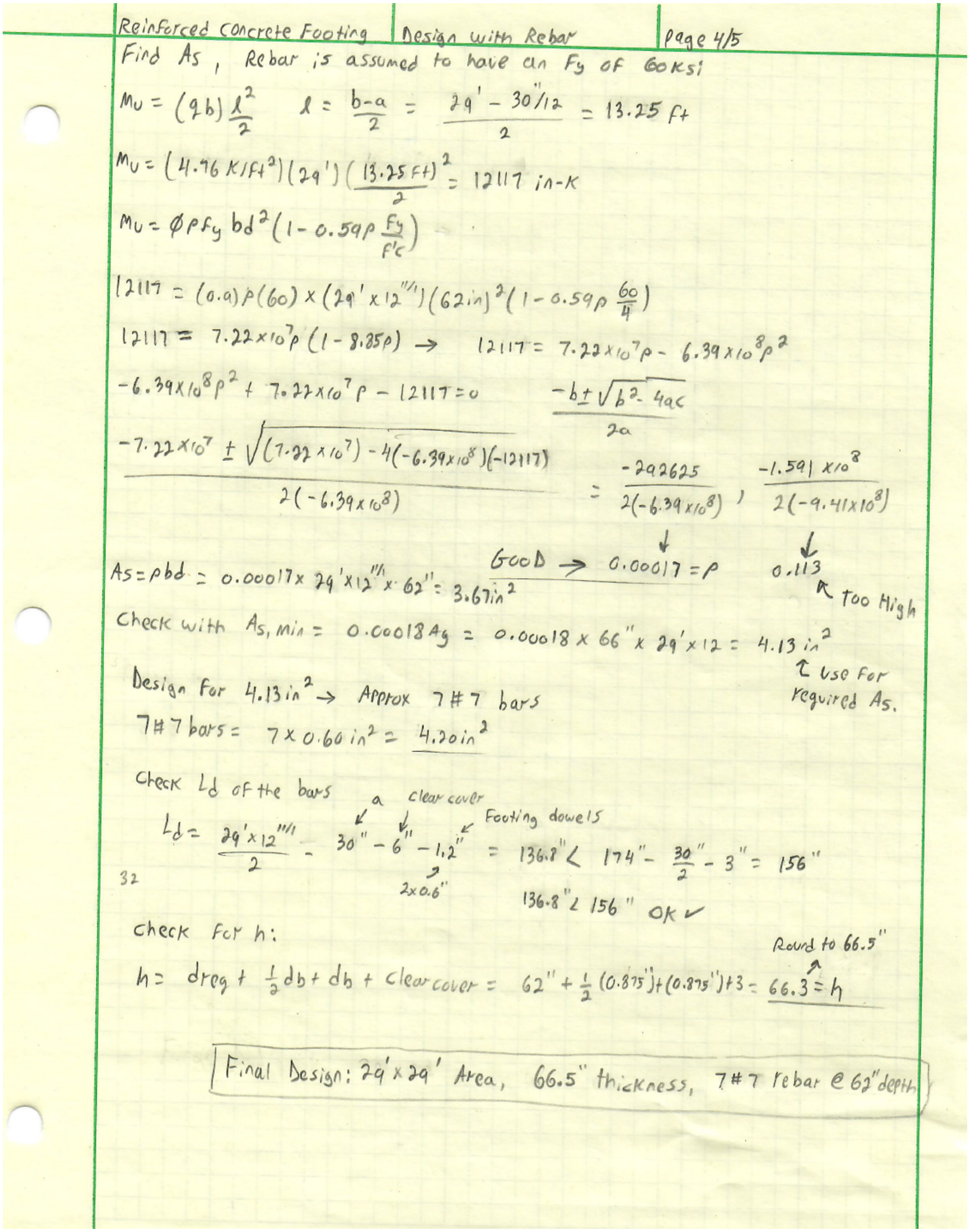
$$V_u = 1161.8\text{k} = 0.75 \times \frac{1.15\sqrt{4000}}{1000} \times (29' \times 12'')(d) \rightarrow \underline{d = 61.2'' \rightarrow \text{round to } 62''}$$

$$h = 62'' + 3''\text{ cover} + 1''\text{ d}\emptyset = 66'' = h$$

Re-check punching shear coefficient

$$\min \begin{bmatrix} 4 \longleftarrow \text{Still Governs ✓} \\ 6 \\ \frac{40(62)}{4(34+62)} + 2 = 8.45 \end{bmatrix}$$

Figure O.3: Column Footing Design Sample Calculation Page 3. Continued in Figures O.4-O.6



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Find As, Rebar is assumed to have an Fy of 60ksi

$M_u = (q b)\frac{l^2}{2} \quad l = \frac{b-a}{2} = \frac{29' - 30''/12}{2} = 13.25\ ft$

$M_u = (4.96\ K/ft^2)(29')\left(\frac{13.25\ ft}{2}\right)^2 = 12117\ in\text{-}K$

$M_u = \phi \rho f_y b d^2 \left(1 - 0.59\rho \frac{F_y}{f'c}\right)$

$12117 = (0.9)\rho(60) \times (29' \times 12''/1)(62in)^2\left(1 - 0.59\rho \frac{60}{4}\right)$

$12117 = 7.22\times10^7 \rho (1 - 8.85\rho) \rightarrow \quad 12117 = 7.22\times10^7\rho - 6.39\times10^8\rho^2$

$-6.39\times10^8\rho^2 + 7.22\times10^7\rho - 12117 = 0 \qquad \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$

$$\frac{-7.22\times10^7 \pm \sqrt{(7.22\times10^7) - 4(-6.39\times10^8)(-12117)}}{2(-6.39\times10^8)} = \frac{-292625}{2(-6.39\times10^8)}, \quad \frac{-1.591\times10^8}{2(-9.41\times10^8)}$$

$\downarrow \qquad \downarrow$

GOOD → $0.00017 = \rho \qquad 0.113$ ↖ Too High

$As = \rho b d = 0.00017 \times 29' \times 12''/1 \times 62'' = 3.67 in^2$

Check with $A_{s,min} = 0.0018 A_g = 0.0018 \times 66'' \times 29' \times 12 = 4.13\ in^2$ ↖ Use for required As.

Design for $4.13 in^2$ → Approx 7#7 bars

7#7 bars $= 7 \times 0.60\ in^2 = \underline{4.20 in^2}$

Check L_d of the bars

$$L_d = \frac{29' \times 12''/1}{2} - \overset{a}{30''} - \overset{\text{clear cover}}{6''} - \overset{\text{Footing dowels}}{\underset{2\times0.6''}{1.2''}} = 136.8'' < 174'' - \frac{30''}{2} - 3'' = 156''$$

32

$136.8'' < 156''$ OK ✓

Check for h:

$h = d_{req} + \frac{1}{2}d_b + d_b + \text{clear cover} = 62'' + \frac{1}{2}(0.875'') + (0.875'') + 3 = \underline{\overset{\text{Round to } 66.5''}{66.3} = h}$

$\boxed{\text{Final Design: } 29' \times 29' \text{ Area}, \quad 66.5'' \text{ thickness}, \quad 7\#7 \text{ rebar @ } 62'' \text{depth}}$

Figure O.4: Column Footing Design Sample Calculation Page 4. Continued in Figures O.5-O.6

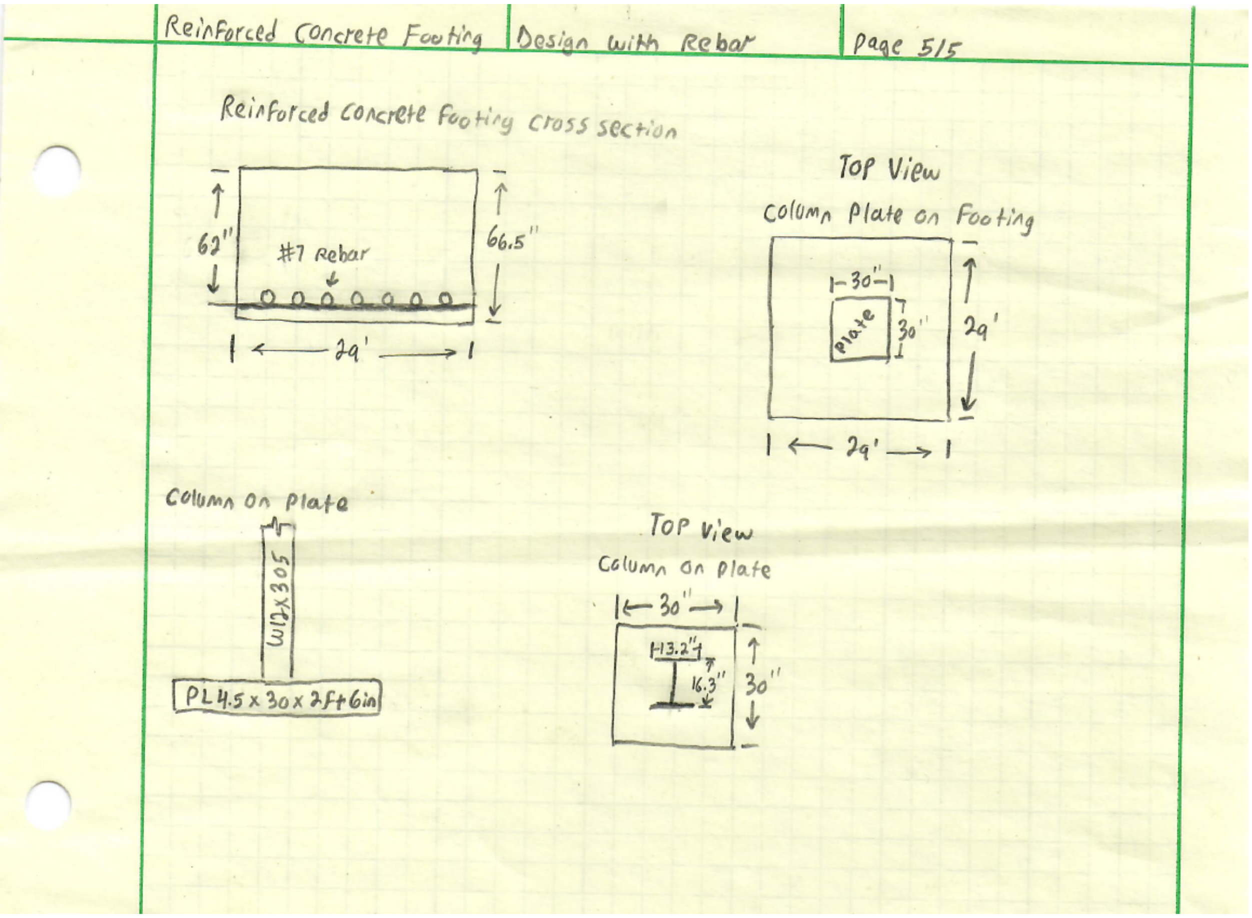
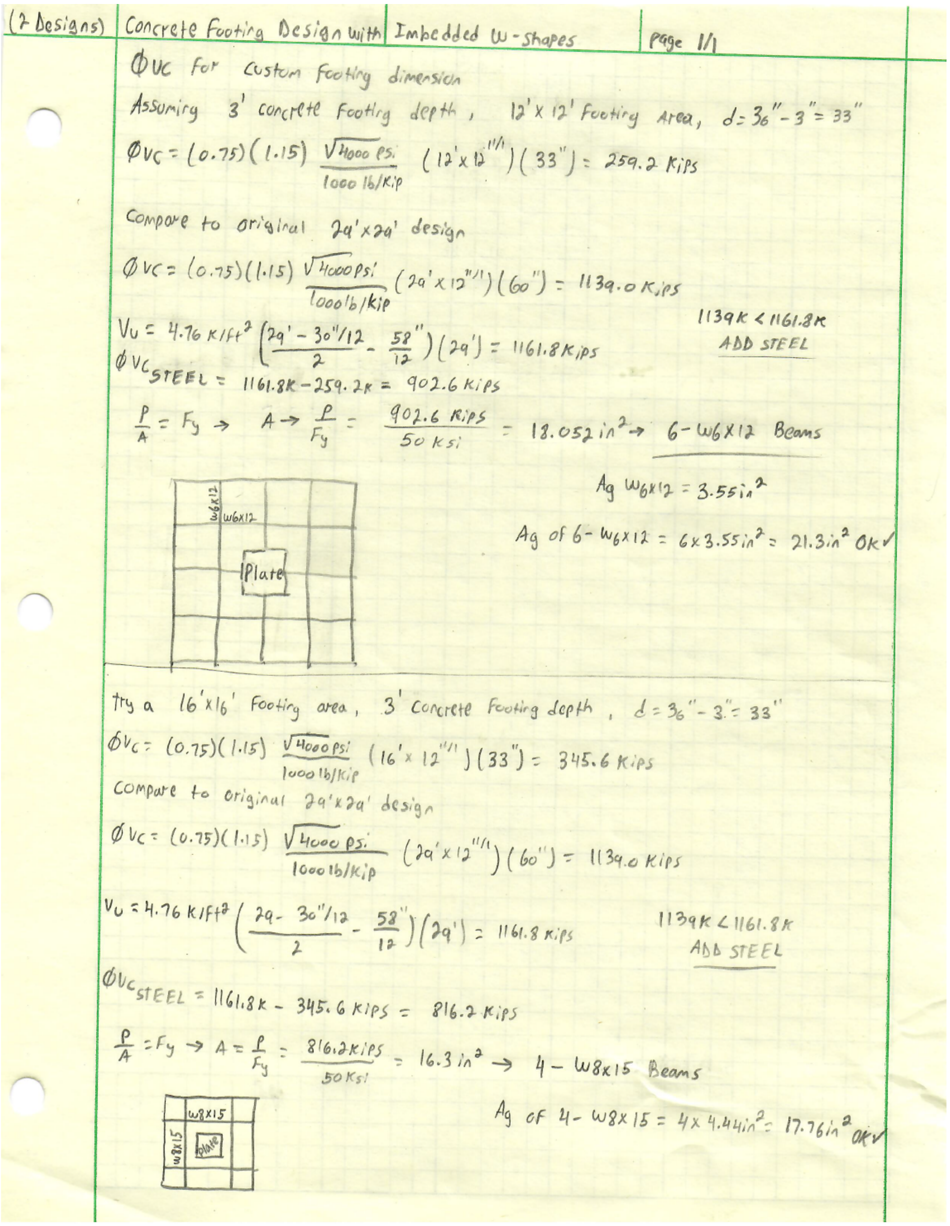


Figure O.5: Column Footing Design Sample Calculation Page 5. Concluded in Figure O.6.



(2 Designs) | Concrete Footing Design with Imbedded W-shapes | Page 1/1

ϕV_C for custom footing dimension

Assuming 3' concrete footing depth, 12'x12' Footing Area, $d = 36'' - 3'' = 33''$

$$\phi V_C = (0.75)(1.15)\frac{\sqrt{4000\text{ psi}}}{1000\text{ lb/kip}}(12' \times 12''/1)(33'') = 259.2\text{ kips}$$

Compare to original 29'x29' design

$$\phi V_C = (0.75)(1.15)\frac{\sqrt{4000\text{ psi}}}{1000\text{ lb/kip}}(29' \times 12''/1)(60'') = 1139.0\text{ kips}$$

$$V_u = 4.76\text{ k/ft}^2\left(\frac{29' - 30''/12}{2} - \frac{58''}{12}\right)(29') = 1161.8\text{ kips}$$

1139K < 1161.8K
ADD STEEL

$$\phi V_{C_{STEEL}} = 1161.8K - 259.2K = 902.6\text{ kips}$$

$$\frac{P}{A} = F_y \rightarrow A \rightarrow \frac{P}{F_y} = \frac{902.6\text{ kips}}{50\text{ ksi}} = 18.052\text{ in}^2 \rightarrow 6 - W6X12\text{ Beams}$$

$A_g\ W_{6x12} = 3.55\text{ in}^2$

A_g of 6-W_{6x12} = $6 \times 3.55\text{ in}^2 = 21.3\text{ in}^2$ OK✓

try a 16'x16' Footing area, 3' Concrete Footing depth, $d = 36'' - 3'' = 33''$

$$\phi V_C = (0.75)(1.15)\frac{\sqrt{4000\text{ psi}}}{1000\text{ lb/kip}}(16' \times 12''/1)(33'') = 345.6\text{ kips}$$

Compare to original 29'x29' design

$$\phi V_C = (0.75)(1.15)\frac{\sqrt{4000\text{ psi}}}{1000\text{ lb/kip}}(29' \times 12''/1)(60'') = 1139.0\text{ kips}$$

$$V_u = 4.76\text{ k/ft}^2\left(\frac{29 - 30''/12}{2} - \frac{58''}{12}\right)(29') = 1161.8\text{ kips}$$

1139K < 1161.8K
ADD STEEL

$$\phi V_{C_{STEEL}} = 1161.8k - 345.6\text{ kips} = 816.2\text{ kips}$$

$$\frac{P}{A} = F_y \rightarrow A = \frac{P}{F_y} = \frac{816.2\text{ kips}}{50\text{ ksi}} = 16.3\text{ in}^2 \rightarrow 4 - W8x15\text{ Beams}$$

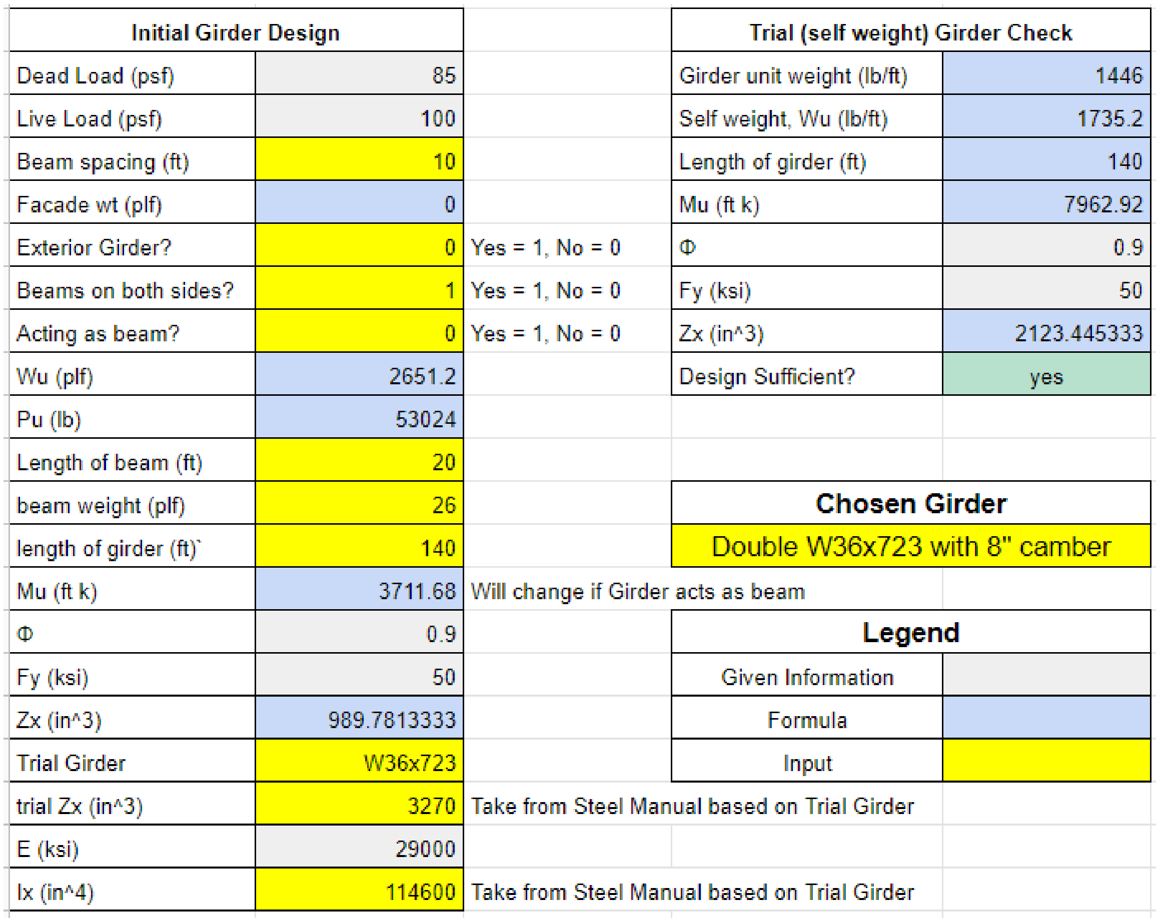
A_g of 4-W8x15 = $4 \times 4.44\text{ in}^2 = 17.76\text{ in}^2$ OK✓

Figure O.6: Column Footing Design Sample Calculation Page 6.

Concrete Density = 150 pcf	Footing Size	Footing Thickness	Total Concrete Weight (lbs)	W-Shapes used in Footing	Total Weight of Steel (lbs)	Total Weight of Footings (lbs)
	29'x29'	5.49'	692563.5	N/A	Negligible	692563.5
	16'x16'	3'	115200	4, W8x15 Beams	960	116160
	12'x12'	**3'**	**64800**	**6, W6x12 Beams**	**864**	**65664**

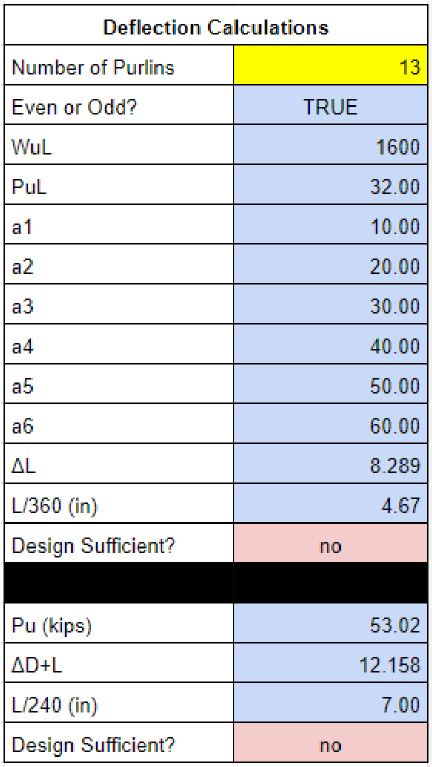
Figure O.7: Footing Weight Calculations using an Excel Spreadsheet, the lightest design is labeled ***(in bold)***

Appendix P: Long-Span Double-Webbed Girder Design

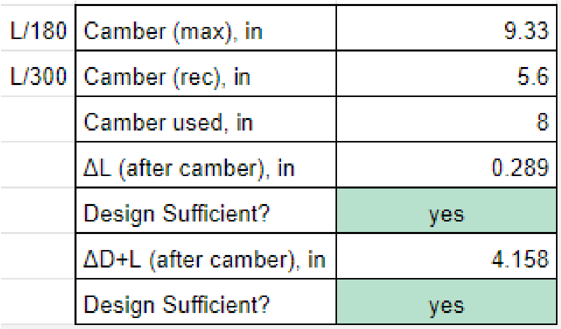


Initial Girder Design			**Trial (self weight) Girder Check**	
Dead Load (psf)	85		Girder unit weight (lb/ft)	1446
Live Load (psf)	100		Self weight, Wu (lb/ft)	1735.2
Beam spacing (ft)	10		Length of girder (ft)	140
Facade wt (plf)	0		Mu (ft k)	7962.92
Exterior Girder?	0	Yes = 1, No = 0	Φ	0.9
Beams on both sides?	1	Yes = 1, No = 0	Fy (ksi)	50
Acting as beam?	0	Yes = 1, No = 0	Zx (in^3)	2123.445333
Wu (plf)	2651.2		Design Sufficient?	yes
Pu (lb)	53024			
Length of beam (ft)	20			
beam weight (plf)	26		**Chosen Girder**	
length of girder (ft)`	140		Double W36x723 with 8" camber	
Mu (ft k)	3711.68	Will change if Girder acts as beam		
Φ	0.9		**Legend**	
Fy (ksi)	50		Given Information	⬜
Zx (in^3)	989.7813333		Formula	🟦
Trial Girder	W36x723		Input	🟨
trial Zx (in^3)	3270	Take from Steel Manual based on Trial Girder		
E (ksi)	29000			
Ix (in^4)	114600	Take from Steel Manual based on Trial Girder		

Figure P.1: Long-span Girder Calculations Part 1: Moment Calculation based on Length, Interior Purlin Distribution, and Self-weight. Final Member Size is Shown with Camber (see below for calculations)



Deflection Calculations	
Number of Purlins	13
Even or Odd?	TRUE
WuL	1600
PuL	32.00
a1	10.00
a2	20.00
a3	30.00
a4	40.00
a5	50.00
a6	60.00
ΔL	8.289
L/360 (in)	4.67
Design Sufficient?	no
Pu (kips)	53.02
ΔD+L	12.158
L/240 (in)	7.00
Design Sufficient?	no



L/180	Camber (max), in	9.33
L/300	Camber (rec), in	5.6
	Camber used, in	8
	ΔL (after camber), in	0.289
	Design Sufficient?	yes
	ΔD+L (after camber), in	4.158
	Design Sufficient?	yes

Figure P.2 and P.3: Long-span Girder Calculations Part 2: Deflection Calculations using Superposition and Equations from AISC Steel Manual Table 3-23, which Failed Deflection Limits (left) and Camber Calculations to Offset Member Deflections at Midspan (right)

Appendix Q: Long Span Moment Frame Details

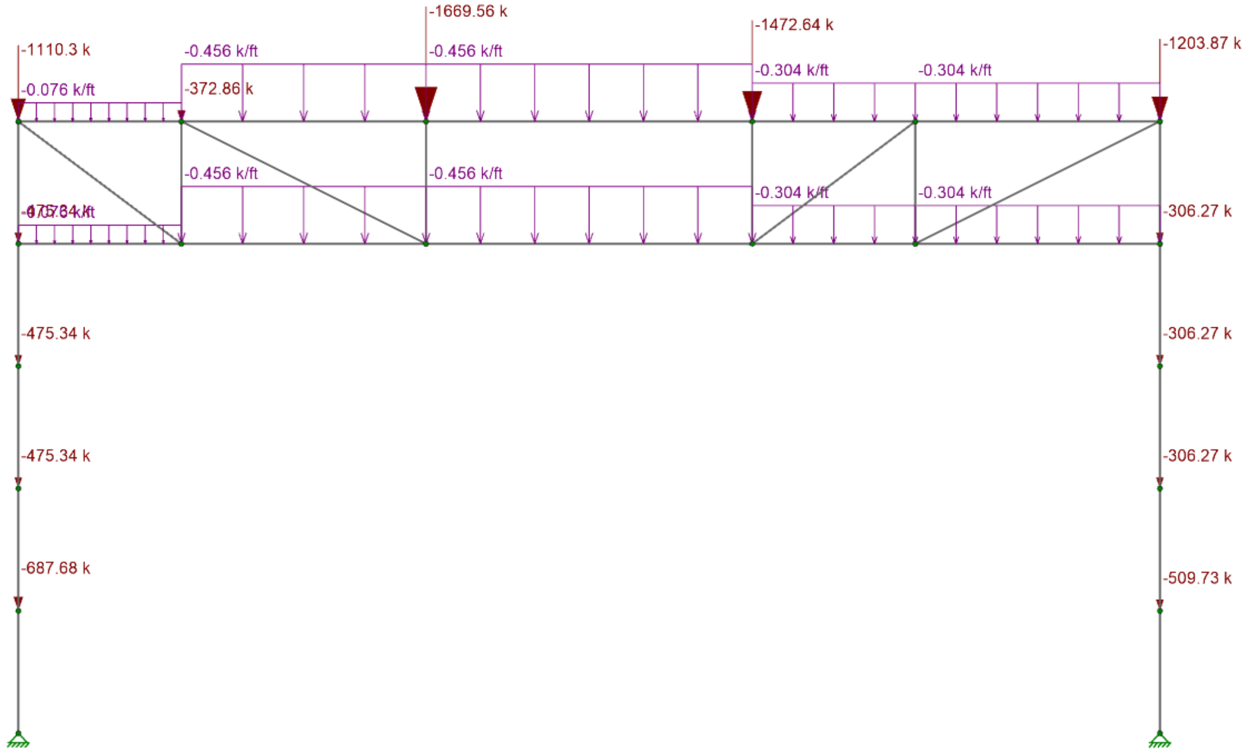
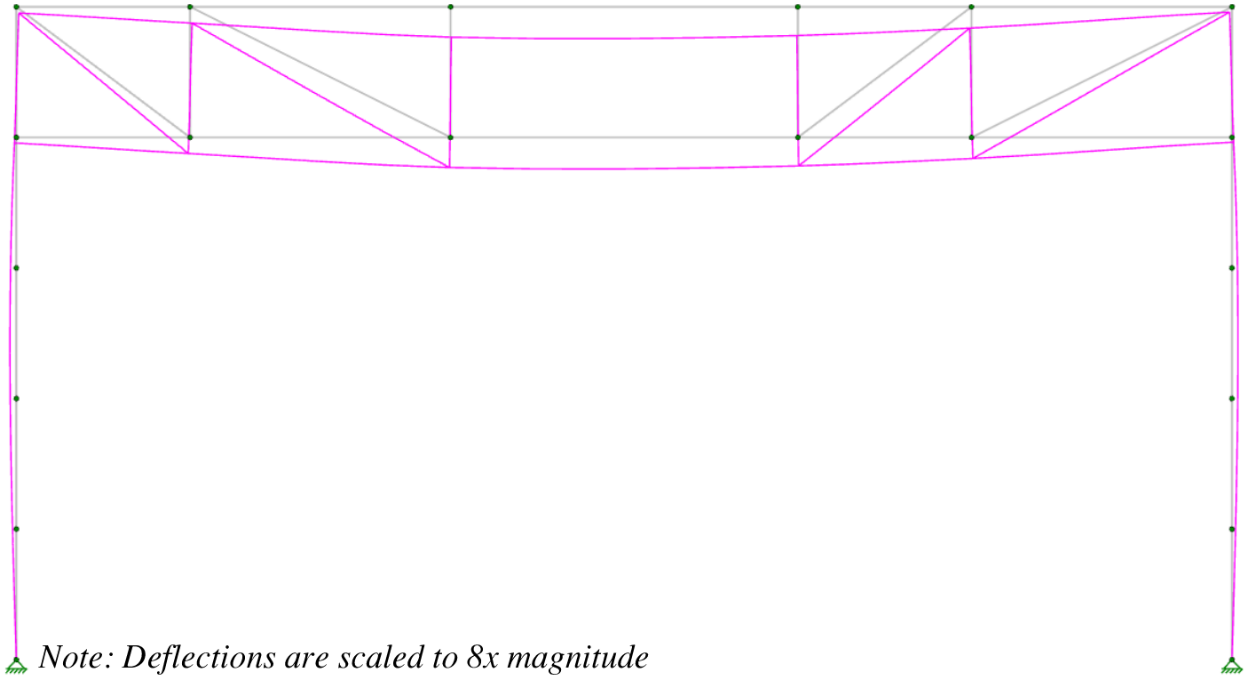


Figure Q.1: Loadings Applied to the Row 4 Frame with its Supporting Columns. Loads on Columns were from Tributary Area Supported by that Column.



Note: Deflections are scaled to 8x magnitude

Figure Q.2: Deflected Shape of Row 4 with Supporting Columns. Deflections are scaled to Eight Times their Magnitude to show the Structural Behavior of the Frame is Consistent with Expected Conditions

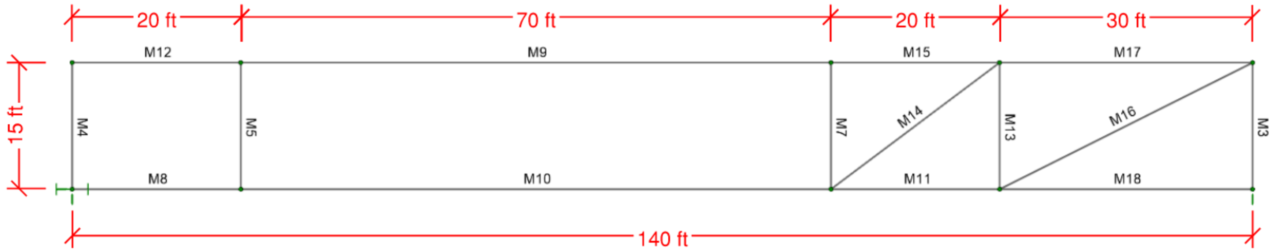
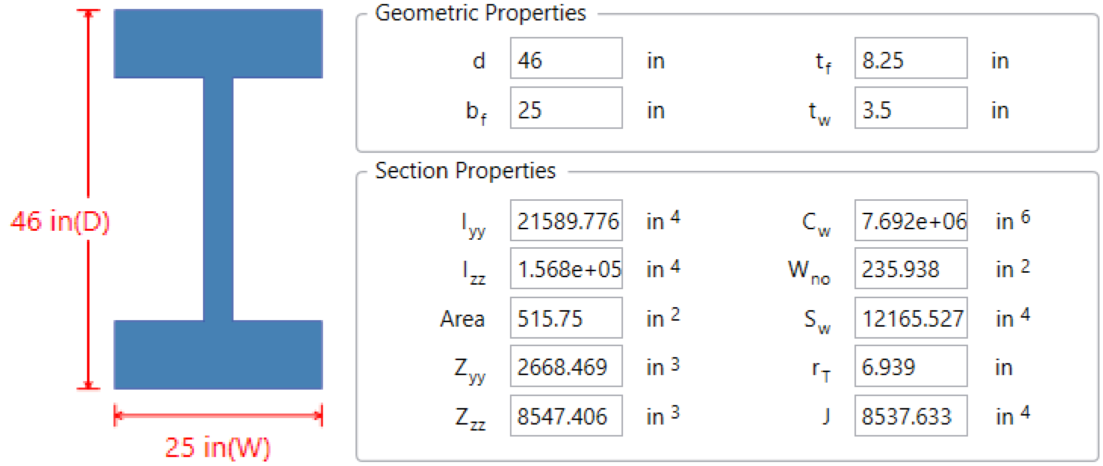


Figure Q.3: Moment-resistant Frame Design for Row 7 Across the Auditorium

Table Q.1: Row 7 Frame member sizes based on labels in Figure Q.3 above

Member Type	Applicable Labels from Figure Q.3	Selected Sections	Member Wt. (lb/ft) for A992 steel
Long-Span Girder	M8, M9, M10, M11, M12, M15	Built-up Section 2 (See Figures Q.4 and Q.5 below for detail)	1755.2
Column	M3, M4, M5, M7, M1713	W40X593	593
Lateral Brace	M14, M16	HSS24X12X12	171.16



Geometric Properties

d	46	in	t_f	8.25	in
b_f	25	in	t_w	3.5	in

Section Properties

I_{yy}	21589.776	in ^{4}	C_w	7.692e+06	in ^{6}
I_{zz}	1.568e+05	in ^{4}	W_{no}	235.938	in ^{2}
Area	515.75	in ^{2}	S_w	12165.527	in ^{4}
Z_{yy}	2668.469	in ^{3}	r_T	6.939	in
Z_{zz}	8547.406	in ^{3}	J	8537.633	in ^{4}

Figures Q.4 & Q.5: Detail for 140-foot Girder in the Row 7 Frame

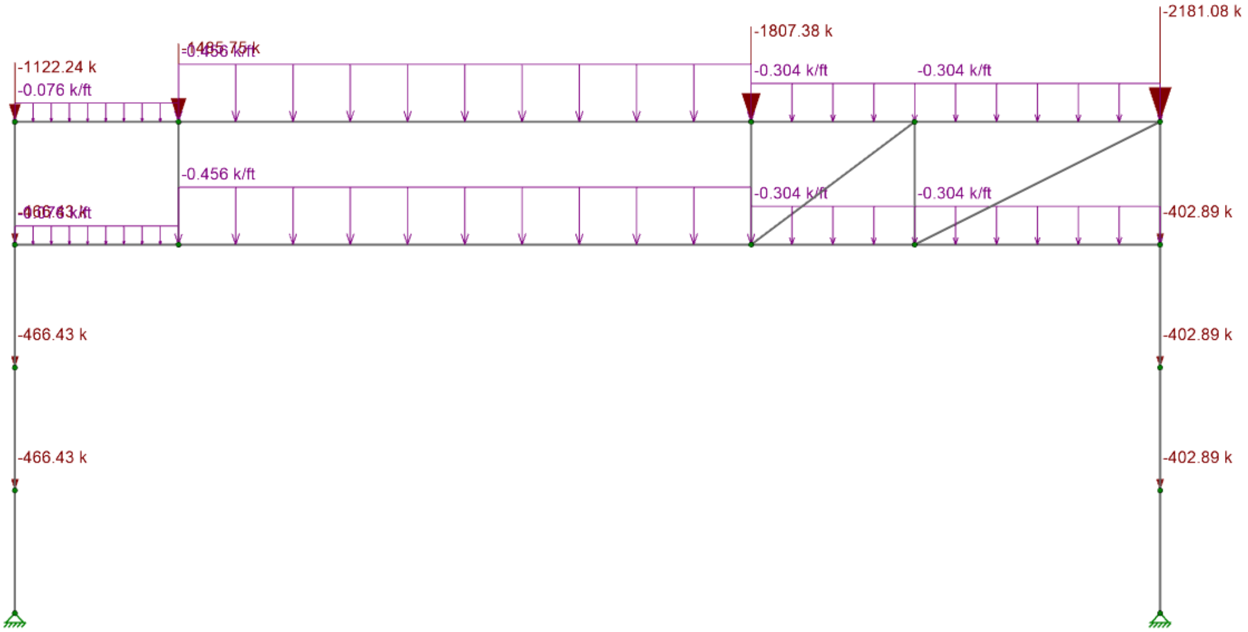
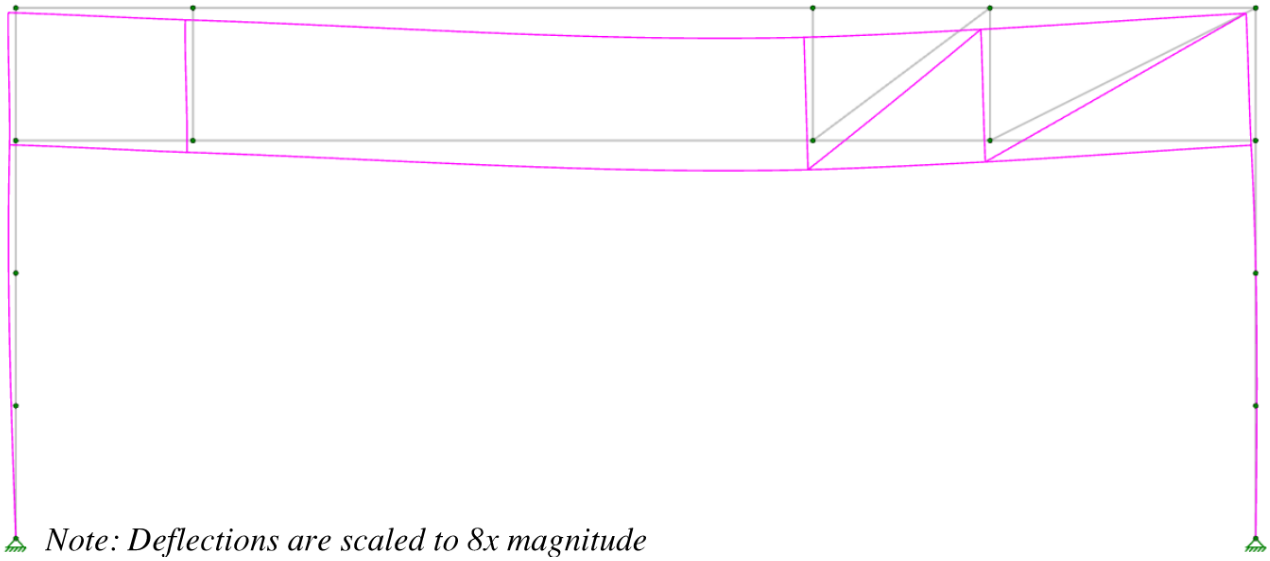


Figure Q.6: Loadings Applied to the Row 7 Frame with its Supporting Columns



Note: Deflections are scaled to 8x magnitude

Figure Q.7: Deflected Shape of Row 7 with Supporting Columns. Deflections are scaled to Eight Times their Magnitude to show the Structural Behavior of the Frame is Consistent with Expected Conditions

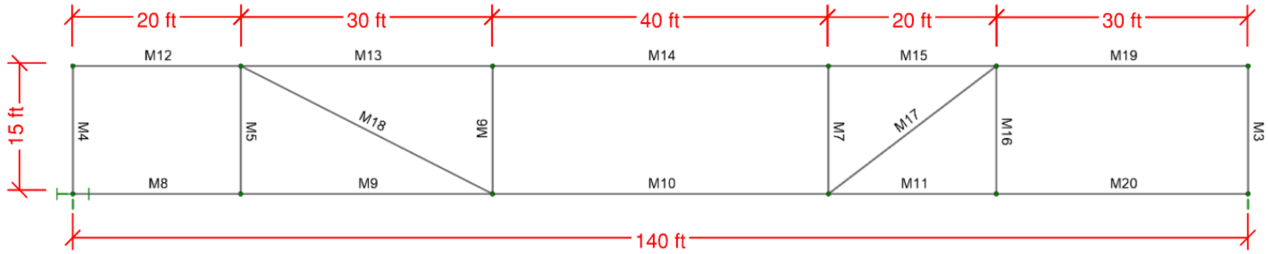
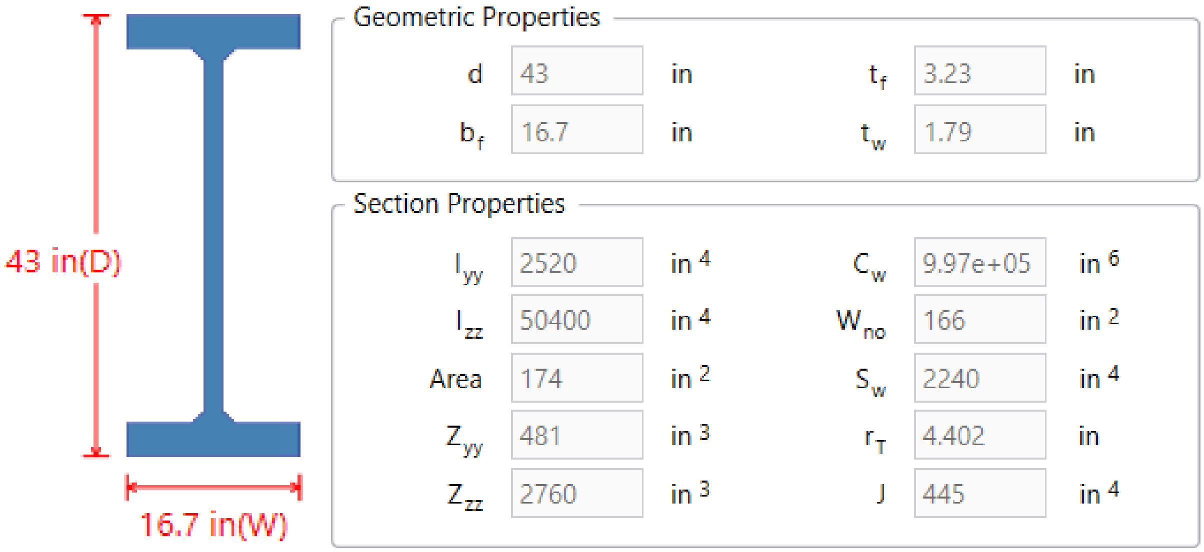


Figure Q.8: Moment-resistant Frame Design for Row 9 Across the Auditorium

Table Q.2: Row 9 Frame member sizes based on labels in Figure Q.8 above

Member Type	Applicable Labels from Figure Q.8	Selected Sections	Member Wt. (lb/ft) for A992 steel
Long-Span Girder	M8, M9, M10, M11, M12, M13, M14, M15, M19, M20	W40X593	593
Column	M3, M4, M5, M6, M7, M16	W40X297	297
Lateral Brace	M17, M18	HSS24X12X12	171.16



d 43 in
t_f 3.23 in
b_f 16.7 in
t_w 1.79 in

I_{yy} 2520 in^4
C_w 9.97e+05 in^6
I_{zz} 50400 in^4
W_{no} 166 in^2
Area 174 in^2
S_w 2240 in^4
Z_{yy} 481 in^3
r_T 4.402 in
Z_{zz} 2760 in^3
J 445 in^4

Figures Q.9 & Q.10: Detail for 140-foot W40X593 Girder in the Row 9 Frame. W40X593 is a Rolled-Shape Section, so Geometric and Section Properties here are Consistent with Unchanged from Standard Properties

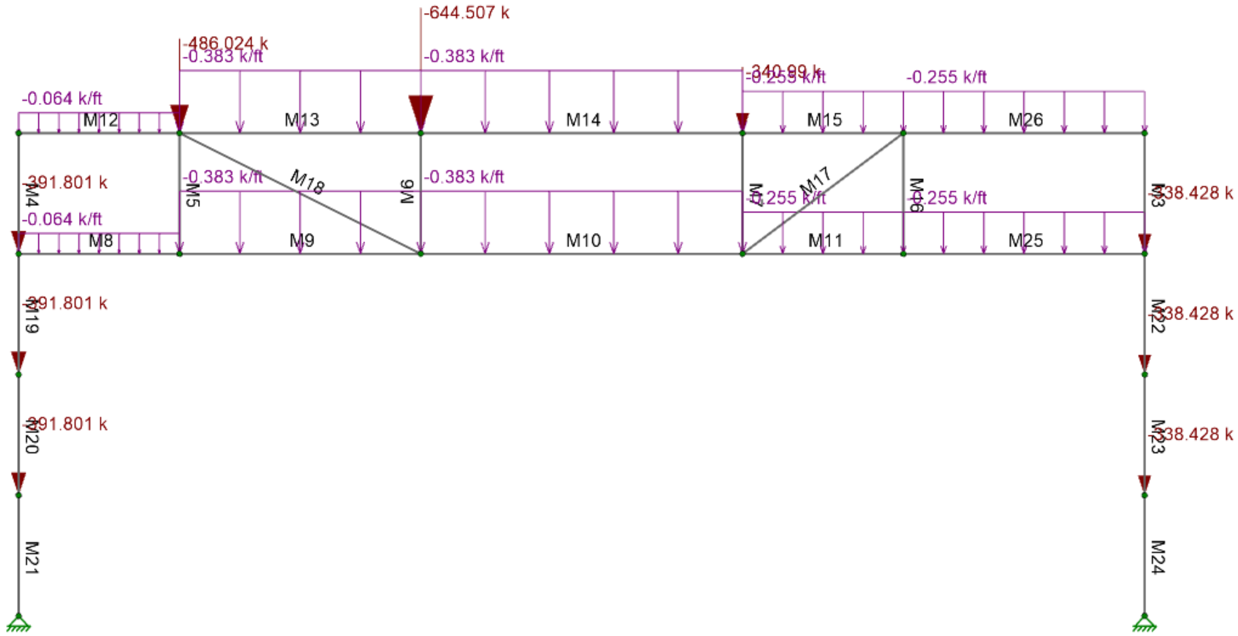
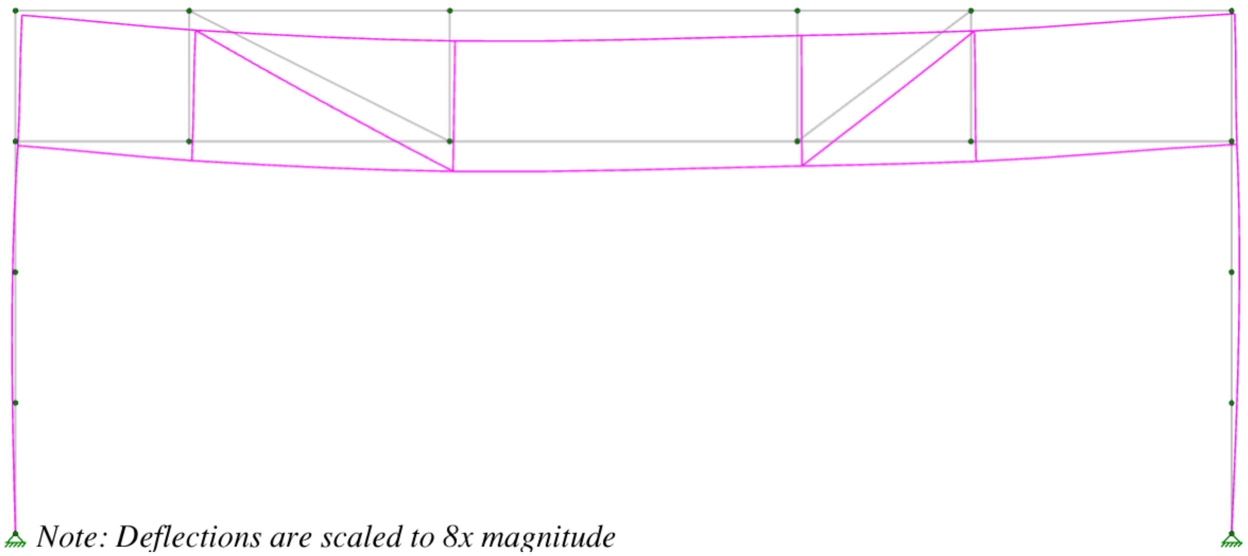


Figure Q.11: Loadings Applied to the Row 9 Frame with its Supporting Columns



Note: Deflections are scaled to 8x magnitude

Figure Q.12: Deflected Shape of Row 9 with Supporting Columns. Deflections are scaled to Eight Times their Magnitude to show the Structural Behavior of the Frame is Consistent with Expected Conditions

Appendix R: Design of Columns with Combined Axial and Bending Forces

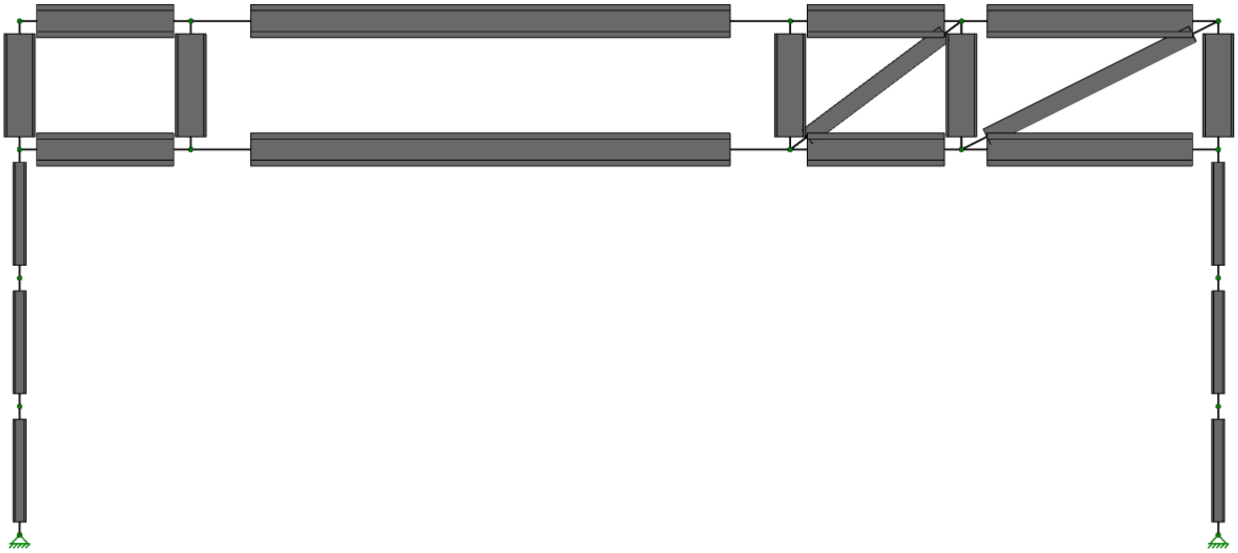
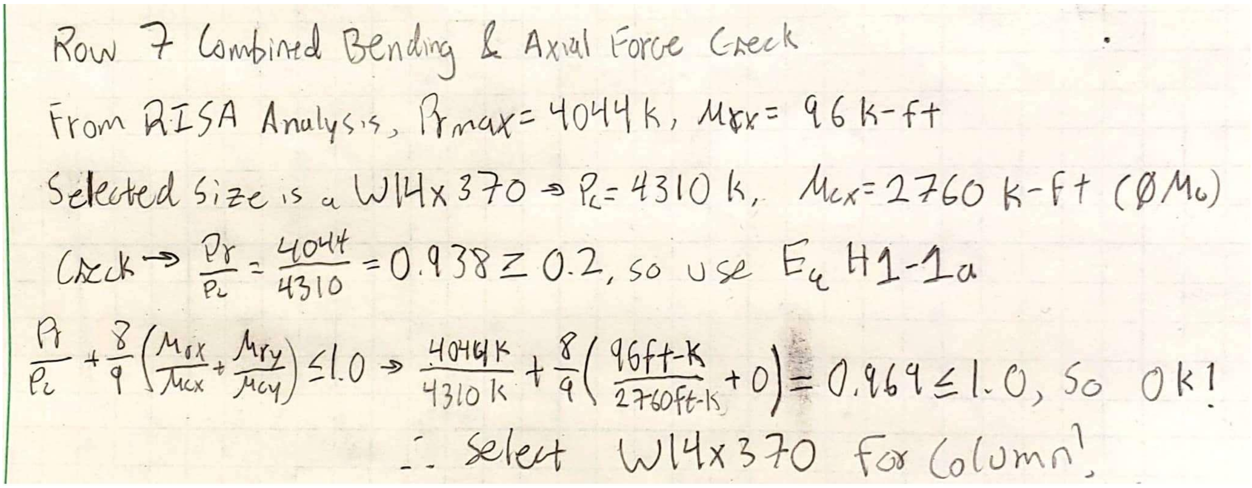


Figure R.1: Row 7 Frame with Supporting Columns to the 1st Floor. Final Column Size was W14x370, and each was 15 feet tall (Lc=15 feet)



Row 7 Combined Bending & Axial Force Check

From RISA Analysis, $P_{rmax} = 4044$ k, $M_{rx} = 96$ k-ft

Selected Size is a W14x370 → $P_c = 4310$ k, $M_{cx} = 2760$ k-ft (ϕM_n)

Check → $\frac{P_r}{P_c} = \frac{4044}{4310} = 0.938 \geq 0.2$, so use Eq H1-1a

$$\frac{P_r}{P_c} + \frac{8}{9}\left(\frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}}\right) \leq 1.0 \Rightarrow \frac{4044\text{ k}}{4310\text{ k}} + \frac{8}{9}\left(\frac{96\text{ ft-k}}{2760\text{ ft-k}} + 0\right) = 0.969 \leq 1.0\text{, so ok!}$$

∴ Select W14x370 for Column!

Figure R.2: Combined Axial and Bending check for a 1st Floor Column in Row 7

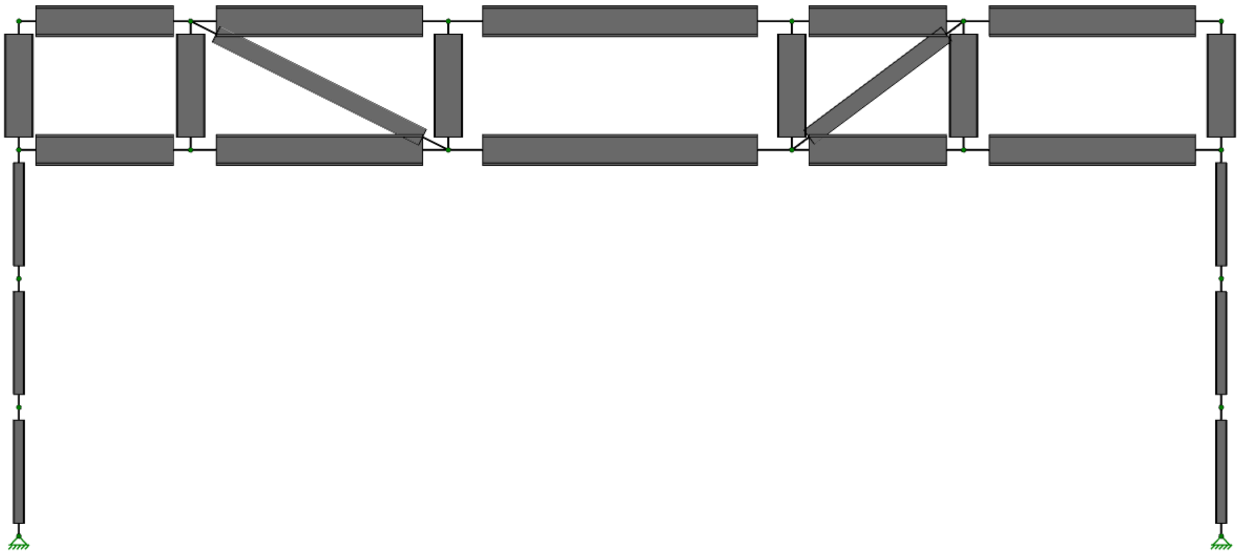
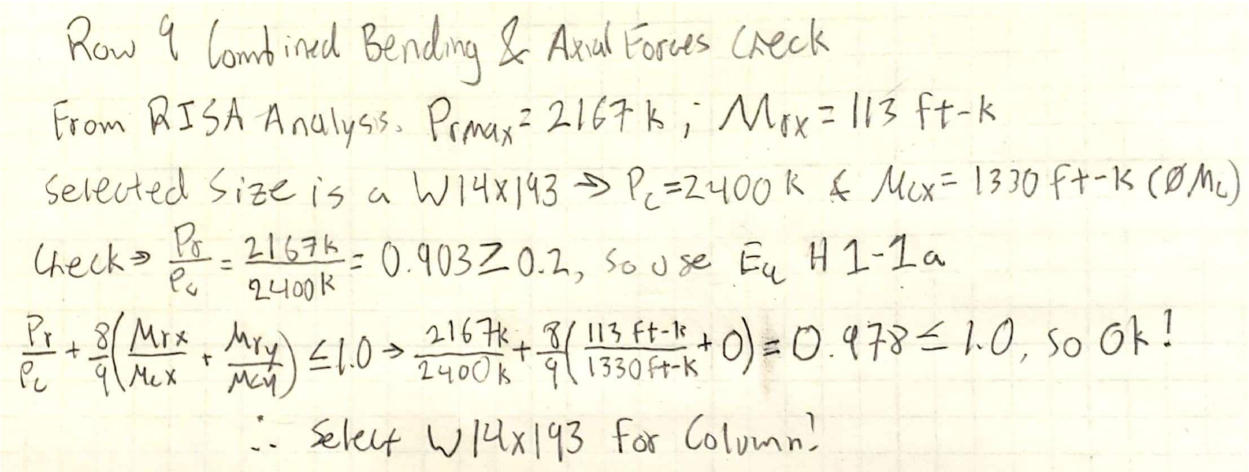


Figure R.3: Row 9 Frame with Supporting Columns to the 1st Floor. Final Column Size was W14x193, and each was 15 feet tall (Lc=15 feet)



Row 9 Combined Bending & Axial Forces Check

From RISA Analysis. $P_{rmax} = 2167$ k ; $M_{rx} = 113$ ft-k

Selected Size is a W14x193 $\Rightarrow$ $P_c = 2400$ k & $M_{cx} = 1330$ ft-k ($\emptyset M_c$)

Check $\Rightarrow$ $\frac{P_r}{P_c} = \frac{2167\text{k}}{2400\text{k}} = 0.903 \geq 0.2$, so use Eq H1-1a

$\frac{P_r}{P_c} + \frac{8}{9}\left(\frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}}\right) \leq 1.0 \rightarrow \frac{2167\text{k}}{2400\text{k}} + \frac{8}{9}\left(\frac{113\text{ ft-k}}{1330\text{ ft-k}} + 0\right) = 0.978 \leq 1.0$, so Ok!

$\therefore$ Select W14x193 For Column!

Figure R.4: Combined Axial and Bending check for a 1st Floor Column in Row 9

Appendix S: Framing Schemes

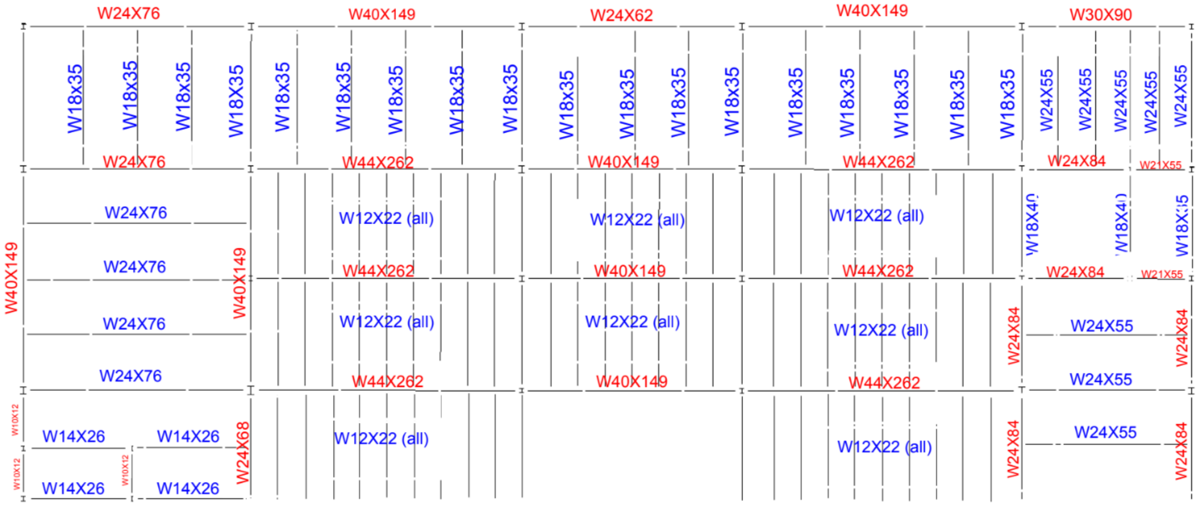


*Figure S.1: **Basement** Framing Scheme*

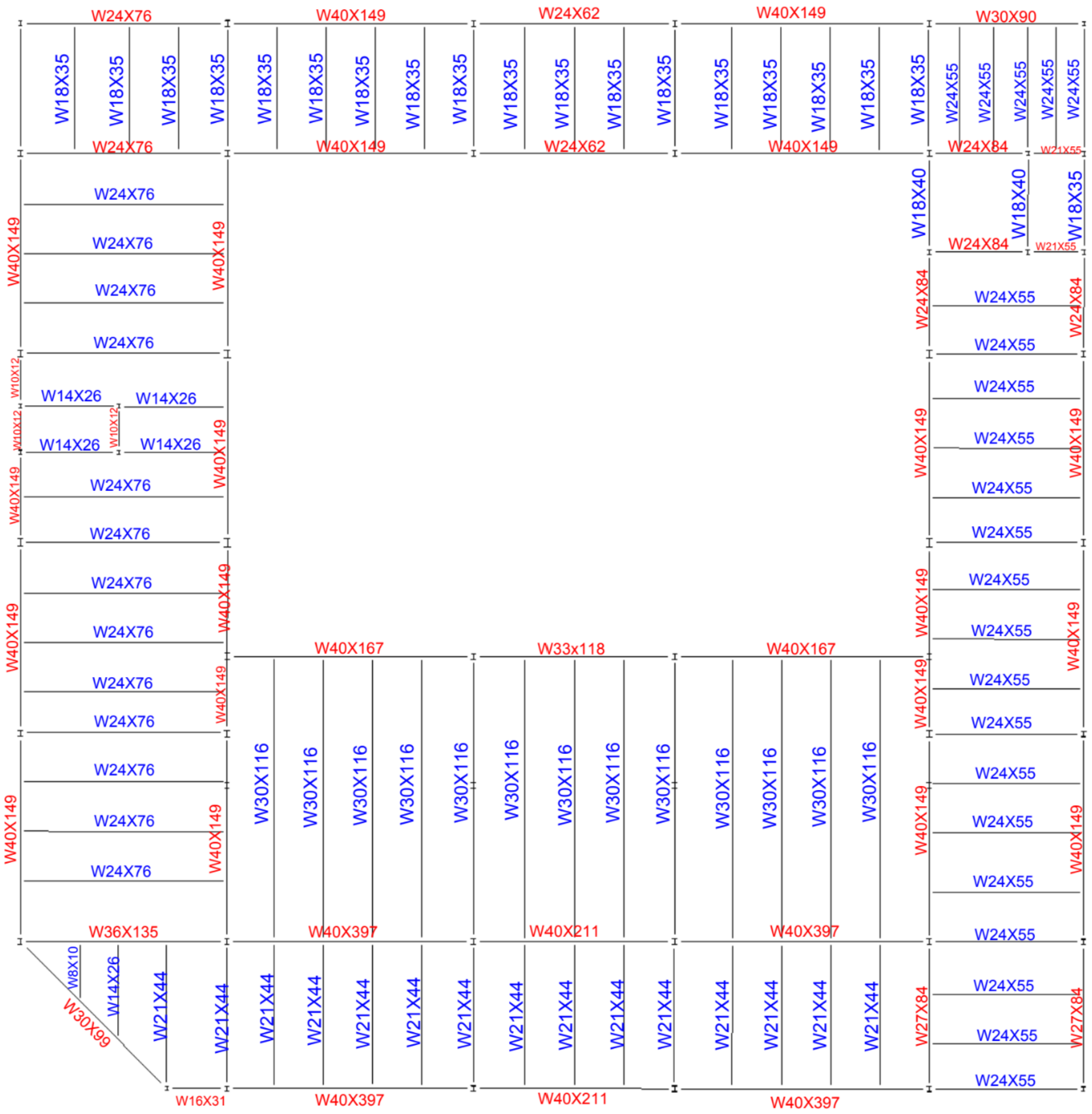


Figure S.2: ***Floor 1*** *Framing Scheme*

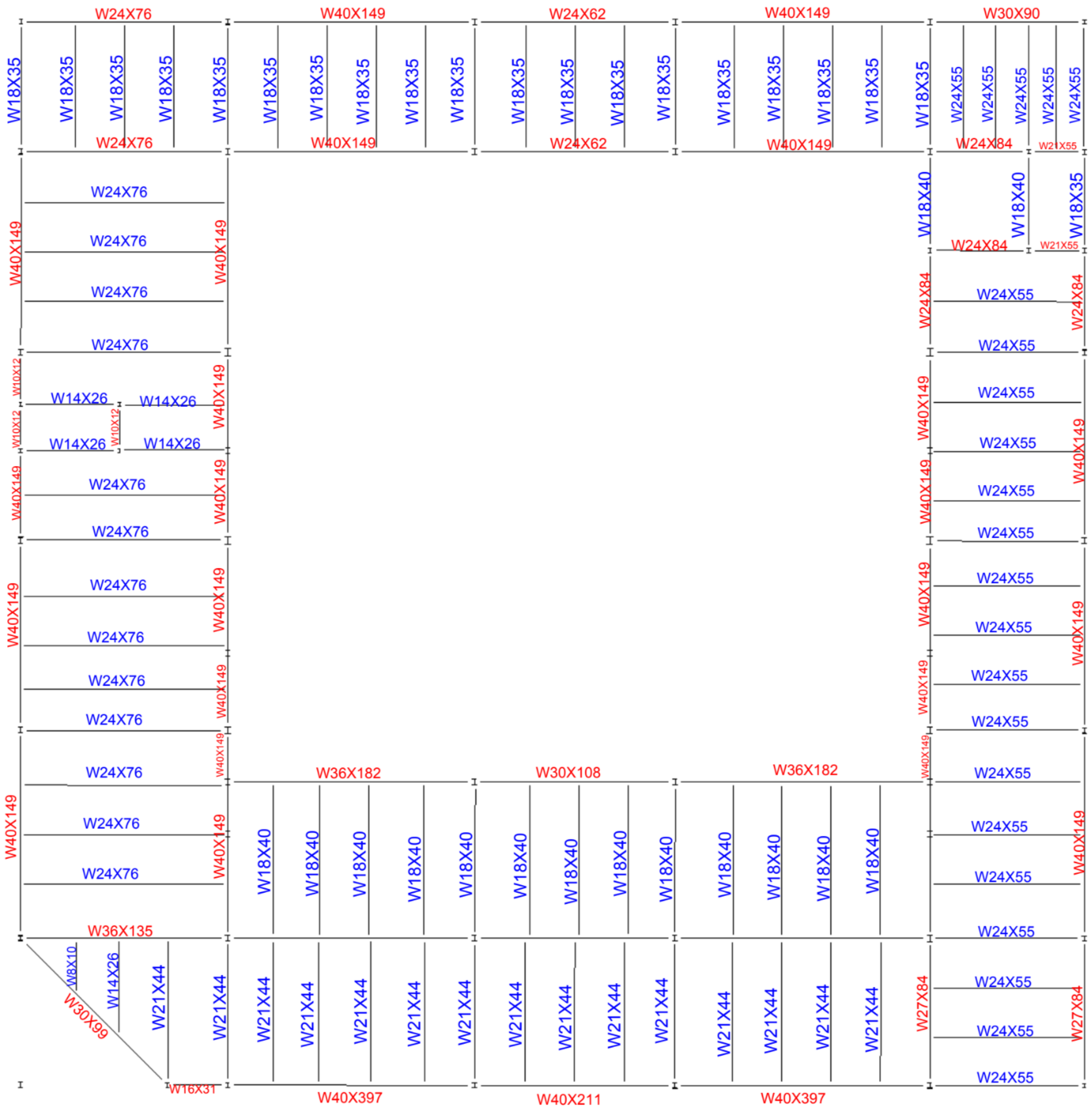


*Figure S.3: **Floor 2** Framing Scheme*

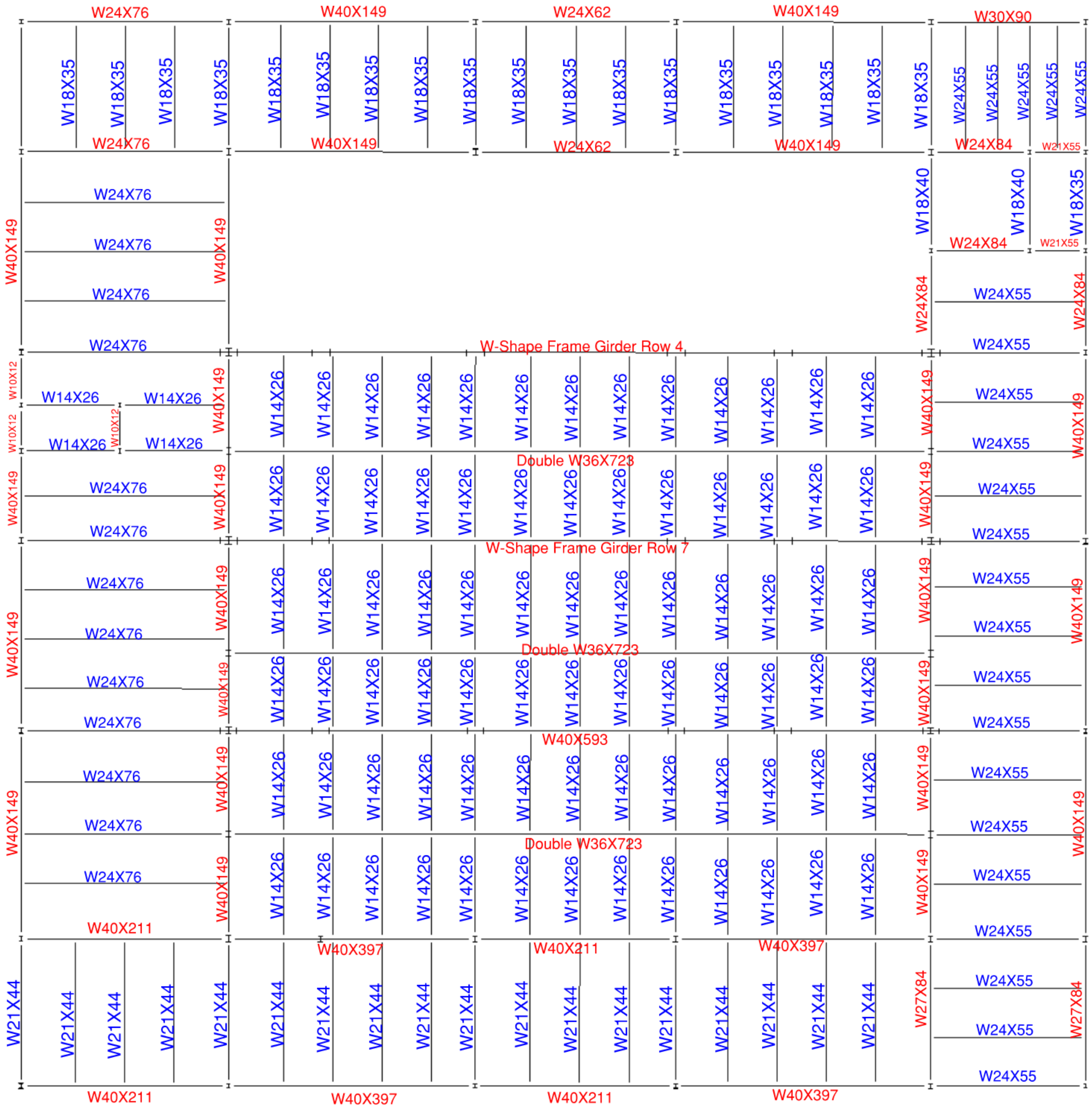


Figure S.4: ***Floor 3*** *Framing Scheme*

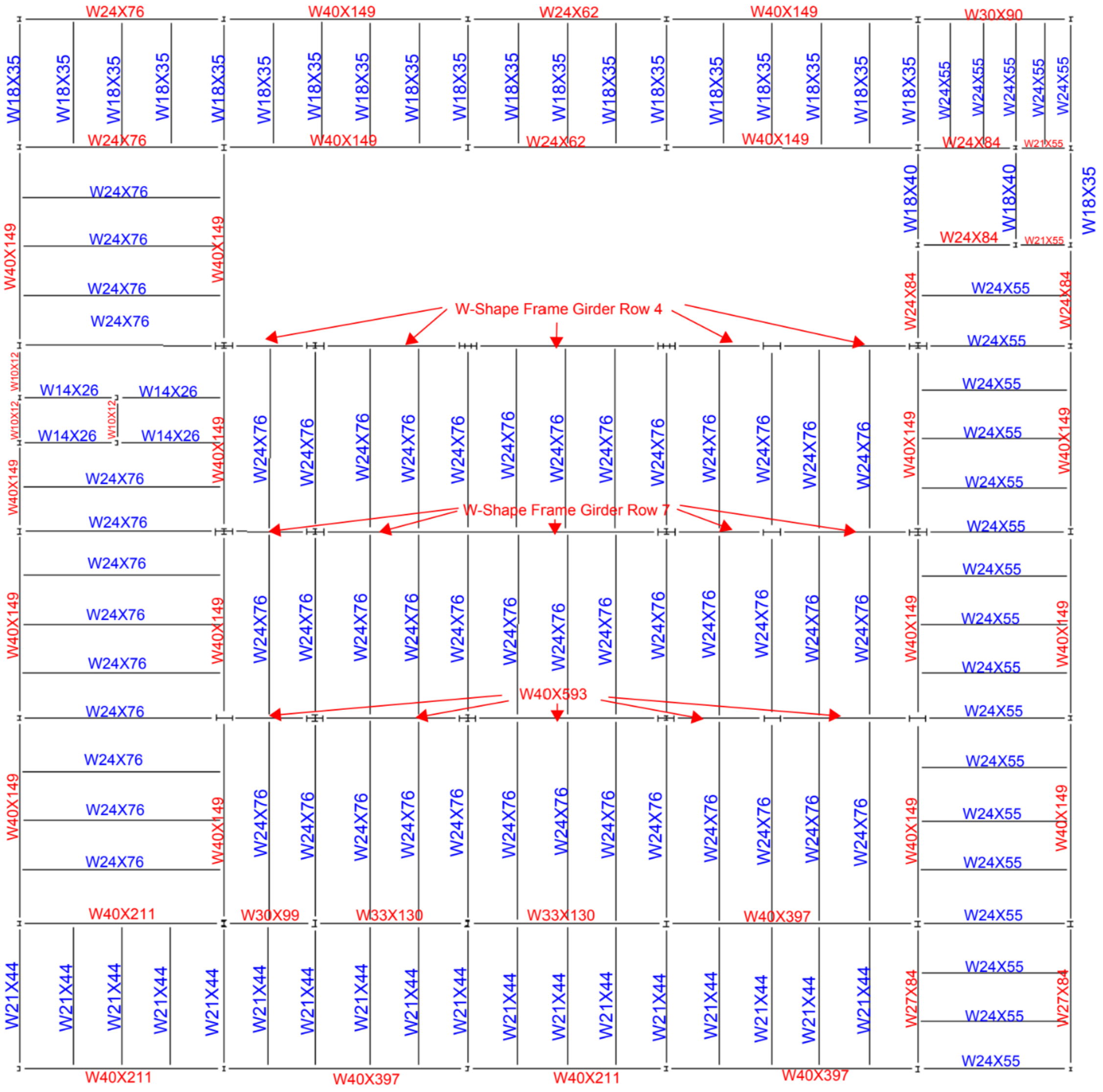


*Figure S.5: **Floor 4** Framing Scheme*

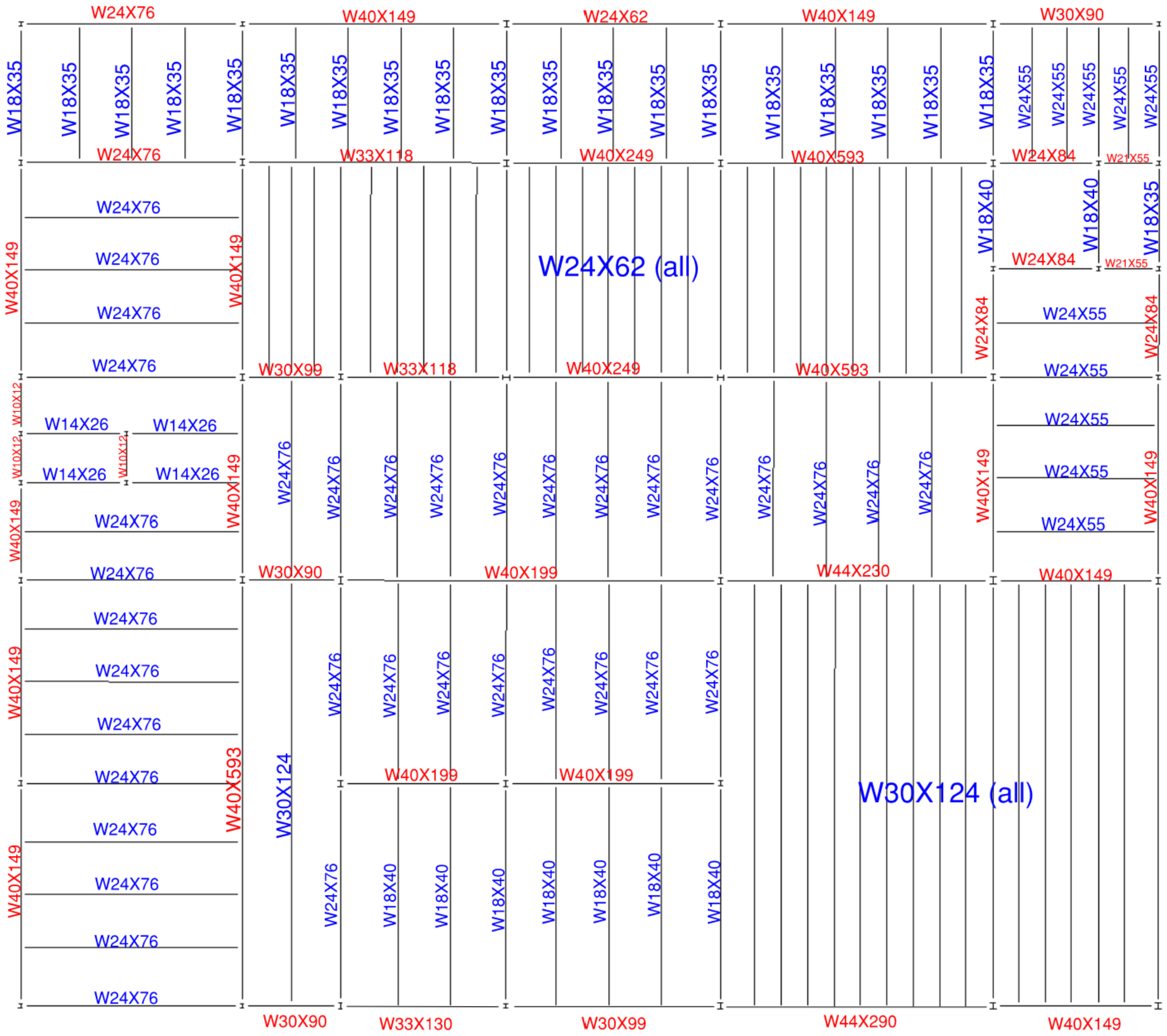
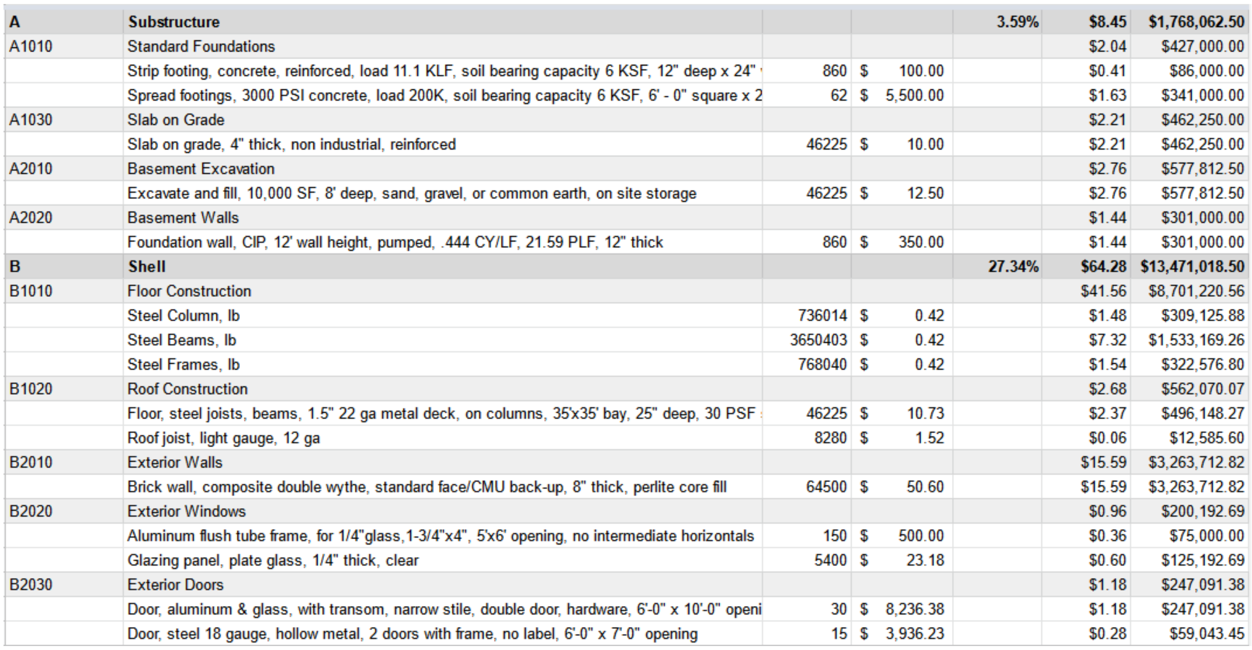


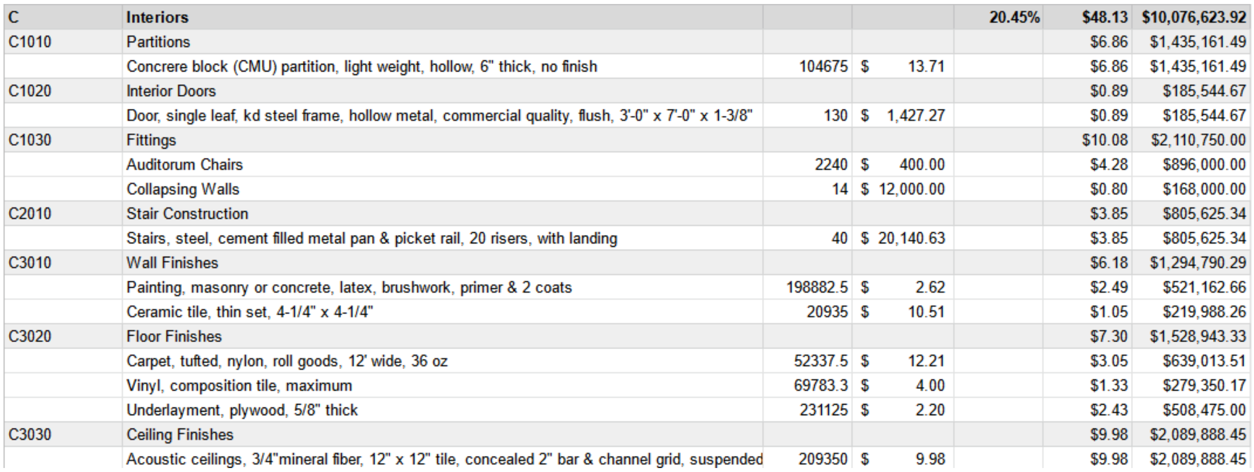
Figure S.6: ***Floor 5*** *Framing Scheme*

Appendix T: Cost Estimation Data



A	**Substructure**			**3.59%**	**$8.45**	**$1,768,062.50**
A1010	Standard Foundations				$2.04	$427,000.00
	Strip footing, concrete, reinforced, load 11.1 KLF, soil bearing capacity 6 KSF, 12" deep x 24"	860	$ 100.00		$0.41	$86,000.00
	Spread footings, 3000 PSI concrete, load 200K, soil bearing capacity 6 KSF, 6' - 0" square x 2	62	$ 5,500.00		$1.63	$341,000.00
A1030	Slab on Grade				$2.21	$462,250.00
	Slab on grade, 4" thick, non industrial, reinforced	46225	$ 10.00		$2.21	$462,250.00
A2010	Basement Excavation				$2.76	$577,812.50
	Excavate and fill, 10,000 SF, 8' deep, sand, gravel, or common earth, on site storage	46225	$ 12.50		$2.76	$577,812.50
A2020	Basement Walls				$1.44	$301,000.00
	Foundation wall, CIP, 12' wall height, pumped, .444 CY/LF, 21.59 PLF, 12" thick	860	$ 350.00		$1.44	$301,000.00
B	**Shell**			**27.34%**	**$64.28**	**$13,471,018.50**
B1010	Floor Construction				$41.56	$8,701,220.56
	Steel Column, lb	736014	$ 0.42		$1.48	$309,125.88
	Steel Beams, lb	3650403	$ 0.42		$7.32	$1,533,169.26
	Steel Frames, lb	768040	$ 0.42		$1.54	$322,576.80
B1020	Roof Construction				$2.68	$562,070.07
	Floor, steel joists, beams, 1.5" 22 ga metal deck, on columns, 35'x35' bay, 25" deep, 30 PSF	46225	$ 10.73		$2.37	$496,148.27
	Roof joist, light gauge, 12 ga	8280	$ 1.52		$0.06	$12,585.60
B2010	Exterior Walls				$15.59	$3,263,712.82
	Brick wall, composite double wythe, standard face/CMU back-up, 8" thick, perlite core fill	64500	$ 50.60		$15.59	$3,263,712.82
B2020	Exterior Windows				$0.96	$200,192.69
	Aluminum flush tube frame, for 1/4"glass,1-3/4"x4", 5'x6' opening, no intermediate horizontals	150	$ 500.00		$0.36	$75,000.00
	Glazing panel, plate glass, 1/4" thick, clear	5400	$ 23.18		$0.60	$125,192.69
B2030	Exterior Doors				$1.18	$247,091.38
	Door, aluminum & glass, with transom, narrow stile, double door, hardware, 6'-0" x 10'-0" openi	30	$ 8,236.38		$1.18	$247,091.38
	Door, steel 18 gauge, hollow metal, 2 doors with frame, no label, 6'-0" x 7'-0" opening	15	$ 3,936.23		$0.28	$59,043.45

Figure T.1: Key Cost Data for Substructure and Shell



C	**Interiors**			**20.45%**	**$48.13**	**$10,076,623.92**
C1010	Partitions				$6.86	$1,435,161.49
	Concrere block (CMU) partition, light weight, hollow, 6" thick, no finish	104675	$ 13.71		$6.86	$1,435,161.49
C1020	Interior Doors				$0.89	$185,544.67
	Door, single leaf, kd steel frame, hollow metal, commercial quality, flush, 3'-0" x 7'-0" x 1-3/8"	130	$ 1,427.27		$0.89	$185,544.67
C1030	Fittings				$10.08	$2,110,750.00
	Auditorum Chairs	2240	$ 400.00		$4.28	$896,000.00
	Collapsing Walls	14	$ 12,000.00		$0.80	$168,000.00
C2010	Stair Construction				$3.85	$805,625.34
	Stairs, steel, cement filled metal pan & picket rail, 20 risers, with landing	40	$ 20,140.63		$3.85	$805,625.34
C3010	Wall Finishes				$6.18	$1,294,790.29
	Painting, masonry or concrete, latex, brushwork, primer & 2 coats	198882.5	$ 2.62		$2.49	$521,162.66
	Ceramic tile, thin set, 4-1/4" x 4-1/4"	20935	$ 10.51		$1.05	$219,988.26
C3020	Floor Finishes				$7.30	$1,528,943.33
	Carpet, tufted, nylon, roll goods, 12' wide, 36 oz	52337.5	$ 12.21		$3.05	$639,013.51
	Vinyl, composition tile, maximum	69783.3	$ 4.00		$1.33	$279,350.17
	Underlayment, plywood, 5/8" thick	231125	$ 2.20		$2.43	$508,475.00
C3030	Ceiling Finishes				$9.98	$2,089,888.45
	Acoustic ceilings, 3/4"mineral fiber, 12" x 12" tile, concealed 2" bar & channel grid, suspended	209350	$ 9.98		$9.98	$2,089,888.45

Figure T.2: Key Data for Interiors

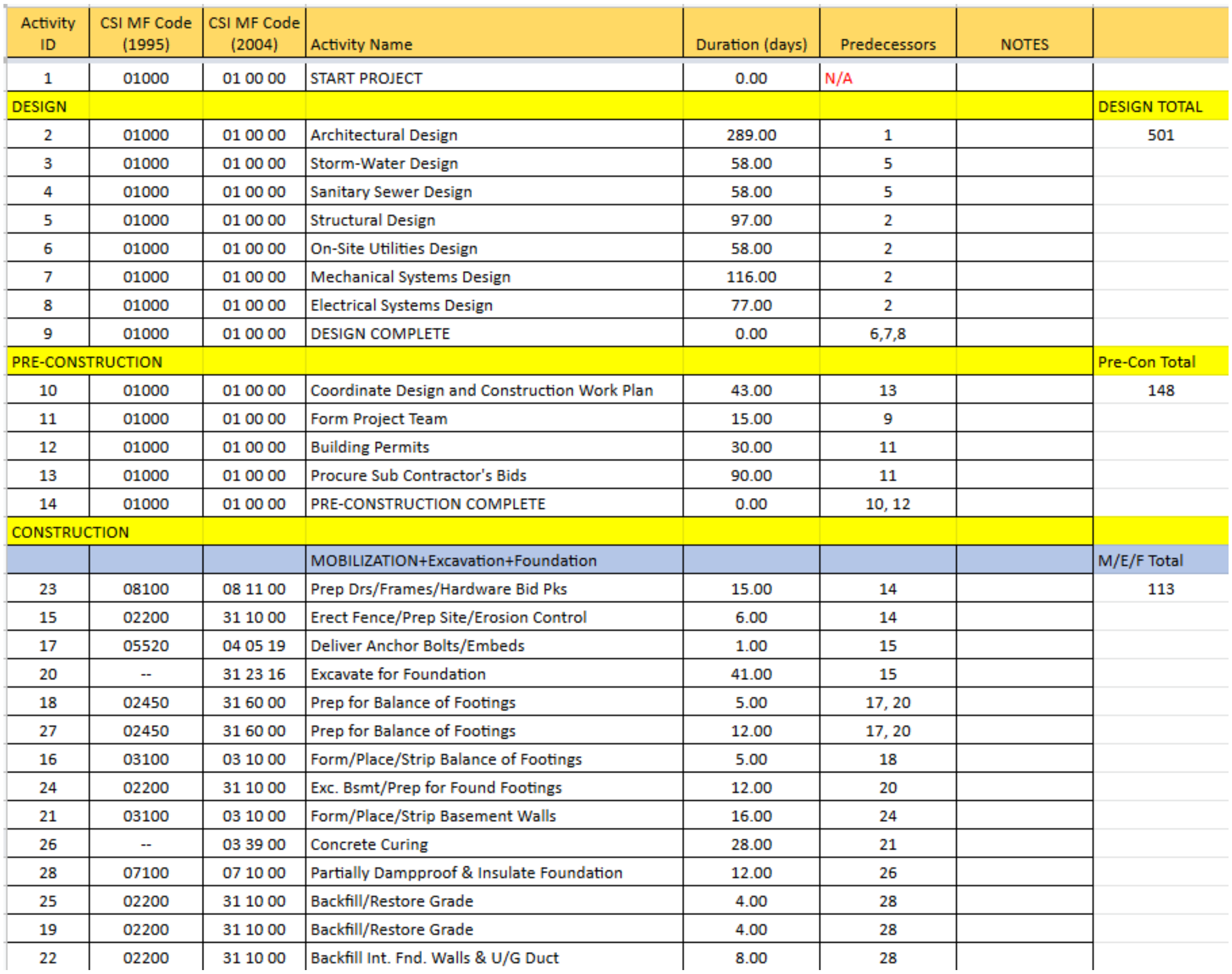
D	**Services**			**32.82%**	**$77.26**	**$16,173,943.17**
D1010	Elevators and Lifts				$1.77	$371,225.00
	Hydraulic passenger elevator, 2500 lb., 2 floor, 125 FPM	2	$ 87,125.00		$0.83	$174,250.00
	Hydraulic freight elevator	1	$196,975.00		$0.94	$196,975.00
D2010	Plumbing Fixtures				$9.11	$1,907,877.62
	Water closet, vitreous china, bowl only with flush valve, wall hung	350	$ 3,155.02		$5.27	$1,104,255.67
	Urinal, vitreous china, wall hung	80	$ 1,816.45		$0.69	$145,316.13
	Lavatory w/trim, wall hung, vitreous china, 19" x 17"	250	$ 1,912.66		$2.28	$478,164.74
	Water cooler, electric, wall hung, wheelchair type, 7.5 GPH	72	$ 2,501.96		$0.86	$180,141.08
D2020	Domestic Water Distribution				$2.52	$528,481.10
	Gas fired water heater, commercial, 100< F rise, 600 MBH input, 576 GPH	18	$ 29,360.06		$2.52	$528,481.10
D3050	Terminal & Package Units				$32.50	$6,803,875.00
	Rooftop, multizone, air conditioner, schools and colleges, 25,000 SF, 95.83 ton	209350	$ 32.50		$32.50	$6,803,875.00
D4010	Sprinklers				$4.02	$840,669.41
	Wet pipe sprinkler systems, steel, light hazard, 1 floor, 10,000 SF	104675	$ 4.53		$2.26	$474,022.32
	Wet pipe sprinkler systems, steel, light hazard, each additional floor, 10,000 SF	104675	$ 3.50		$1.75	$366,647.10
D4020	Standpipes				$0.44	$92,928.43
	Dry standpipe risers, class III, steel, black, sch 40, 6" diam pipe, 1 floor	6	$ 12,007.61		$0.34	$72,045.64
	Dry standpipe risers, class III, steel, black, sch 40, 6" diam pipe, additional floors	5	$ 4,176.56		$0.10	$20,882.79
D5010	Electrical Service/Distribution				$1.52	$317,723.52
	Service installation, includes breakers, metering, 20' conduit & wire, 3 phase, 4 wire, 120/208	2	$ 51,918.80		$0.50	$103,837.60
	Feeder installation 600 V, including RGS conduit and XHHW wire, 2000 A	200	$ 711.79		$0.68	$142,358.00
	Switchgear installation, incl switchboard, panels & circuit breaker, 2000 A	1	$ 71,527.92		$0.34	$71,527.92
D5020	Lighting and Branch Wiring				$16.14	$3,378,382.97
	Receptacles incl plate, box, conduit, wire, 10 per 1000 SF, 1.2 W per SF, with transformer	209350	$ 4.40		$4.40	$921,855.56
	Central air conditioning power, 4 watts	251220	$ 0.74		$0.89	$185,942.46
	Fluorescent fixtures recess mounted in ceiling, 2.4 watt per SF, 60 FC, 15 fixtures @ 32 watt	209350	$ 10.05		$10.05	$2,102,982.99
D5030	Communications and Security				$7.47	$1,563,588.56
	Communication and alarm systems, includes outlets, boxes, conduit and wire, sound systems	7	$ 47,878.25		$1.60	$335,147.76
	Fire alarm command center, addressable with voice, excl. wire & conduit	4	$ 15,043.11		$0.29	$60,172.46
	Communication and alarm systems, includes outlets, boxes, conduit and wire, master clock s	6	$ 40,869.12		$1.17	$245,214.74
	Internet wiring, 8 data/voice outlets per 1000 S.F.	150.61	$ 3,030.23		$2.18	$456,383.00
D5090	Other Electrical Systems				$0.76	$159,007.50
	Generator sets, w/battery, charger, muffler and transfer switch, gas/gasoline operated, 3 phase	350	$ 454.31		$0.76	$159,007.50

Figure T.3: Key Data for Services

E	**Equipment & Furnishings**			**15.80%**	**$37.18**	**$7,783,936.80**
	Woodshop	1	$ 6,500.00		$0.03	$6,500.00
	Musical Instruments (Pianos)	10	$ 10,000.00		$0.48	$100,000.00
	Auditorium Equipment	1	$5,000,000		$23.88	$5,000,000.00
	Art Gallery	1	$ 12,000.00		$0.06	$12,000.00
	Lobby Video Wall	1	$ 25,000.00		$0.12	$25,000.00
	Recording Studio	1	$250,000.00		$1.19	$250,000.00
	Projectors	12	$ 6,598.90		$0.38	$79,186.80
	Solar Panels	46225	$ 50.00		$11.04	$2,311,250.00
F	**Building Sitework**			**1.98%**	**$4.66**	**$975,375.00**
	Sitework	65025	$ 15.00		$4.66	$975,375.00

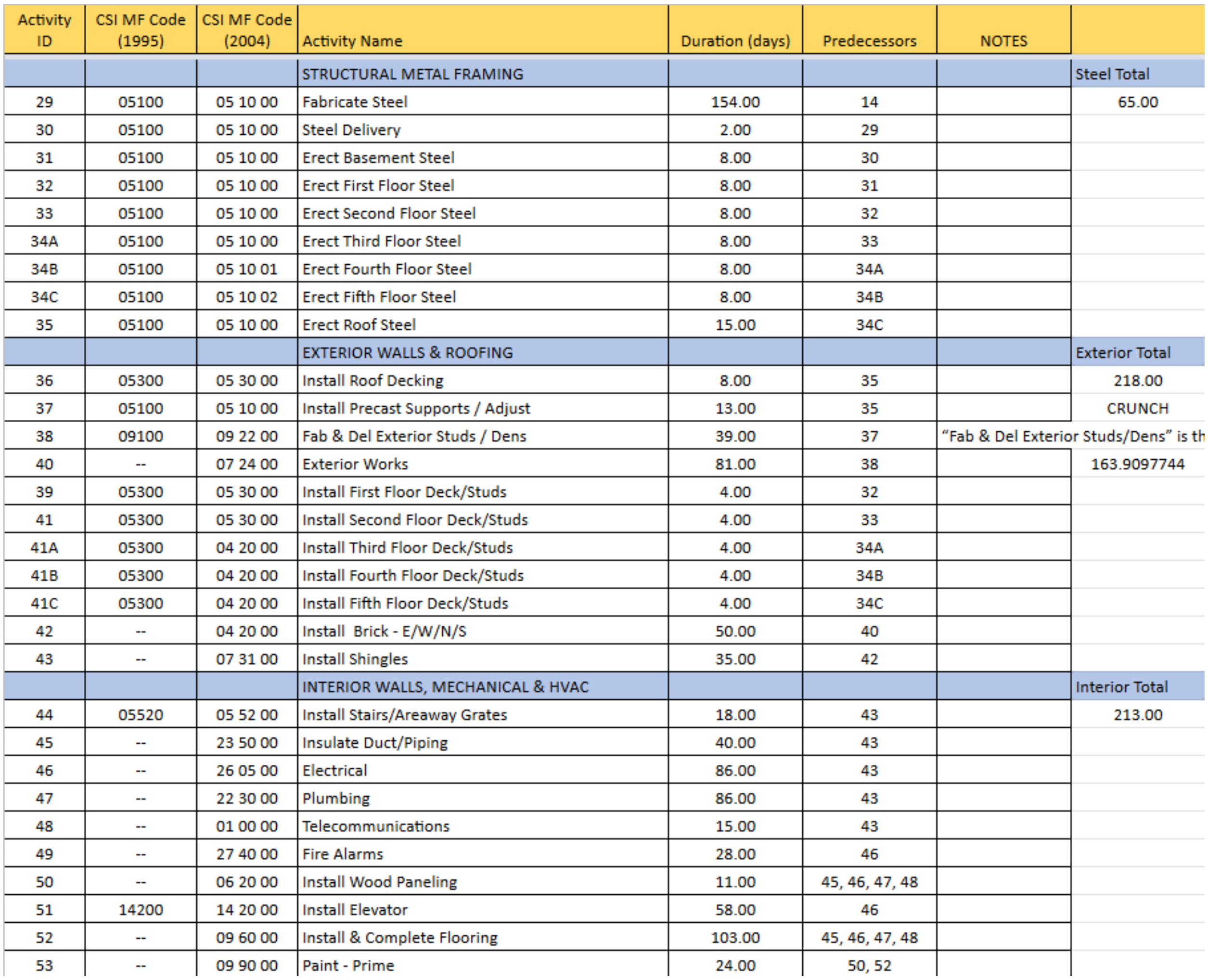
Figure T.4: Key Data for Equipment & Furnishing and Building Sitework

Appendix U: Project Schedule Data



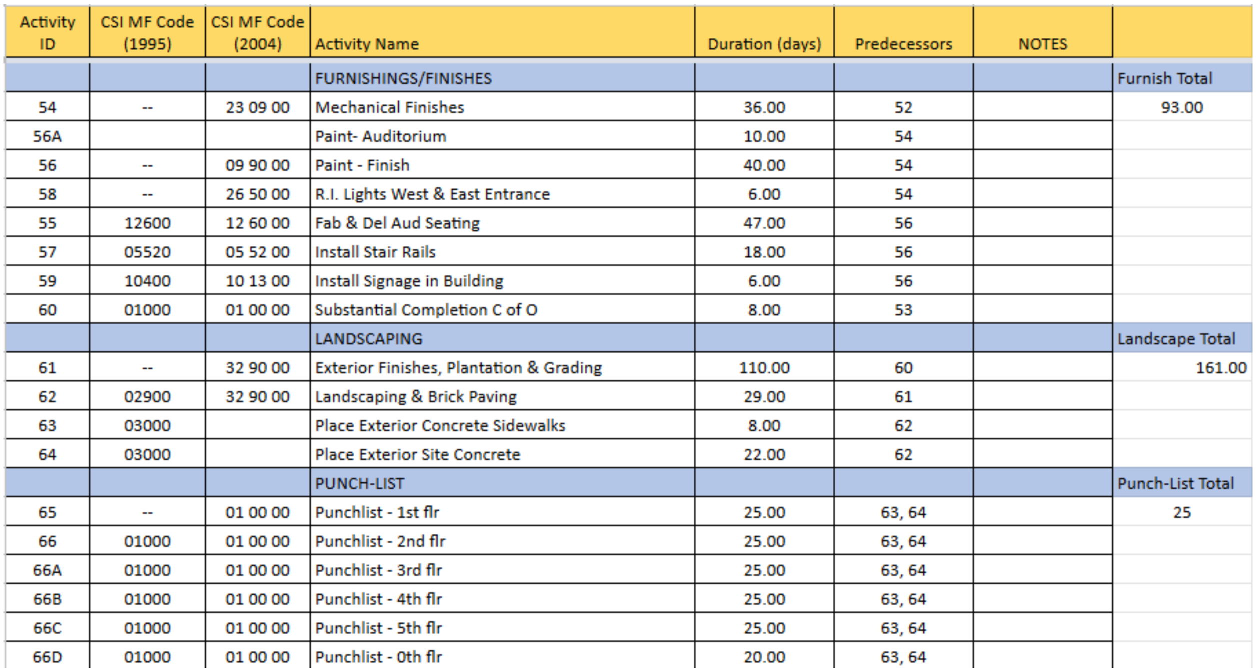
Activity ID	CSI MF Code (1995)	CSI MF Code (2004)	Activity Name	Duration (days)	Predecessors	NOTES	
1	01000	01 00 00	START PROJECT	0.00	N/A		
DESIGN							DESIGN TOTAL
2	01000	01 00 00	Architectural Design	289.00	1		501
3	01000	01 00 00	Storm-Water Design	58.00	5		
4	01000	01 00 00	Sanitary Sewer Design	58.00	5		
5	01000	01 00 00	Structural Design	97.00	2		
6	01000	01 00 00	On-Site Utilities Design	58.00	2		
7	01000	01 00 00	Mechanical Systems Design	116.00	2		
8	01000	01 00 00	Electrical Systems Design	77.00	2		
9	01000	01 00 00	DESIGN COMPLETE	0.00	6,7,8		
PRE-CONSTRUCTION							Pre-Con Total
10	01000	01 00 00	Coordinate Design and Construction Work Plan	43.00	13		148
11	01000	01 00 00	Form Project Team	15.00	9		
12	01000	01 00 00	Building Permits	30.00	11		
13	01000	01 00 00	Procure Sub Contractor's Bids	90.00	11		
14	01000	01 00 00	PRE-CONSTRUCTION COMPLETE	0.00	10, 12		
CONSTRUCTION							
			MOBILIZATION+Excavation+Foundation				M/E/F Total
23	08100	08 11 00	Prep Drs/Frames/Hardware Bid Pks	15.00	14		113
15	02200	31 10 00	Erect Fence/Prep Site/Erosion Control	6.00	14		
17	05520	04 05 19	Deliver Anchor Bolts/Embeds	1.00	15		
20	--	31 23 16	Excavate for Foundation	41.00	15		
18	02450	31 60 00	Prep for Balance of Footings	5.00	17, 20		
27	02450	31 60 00	Prep for Balance of Footings	12.00	17, 20		
16	03100	03 10 00	Form/Place/Strip Balance of Footings	5.00	18		
24	02200	31 10 00	Exc. Bsmt/Prep for Found Footings	12.00	20		
21	03100	03 10 00	Form/Place/Strip Basement Walls	16.00	24		
26	--	03 39 00	Concrete Curing	28.00	21		
28	07100	07 10 00	Partially Dampproof & Insulate Foundation	12.00	26		
25	02200	31 10 00	Backfill/Restore Grade	4.00	28		
19	02200	31 10 00	Backfill/Restore Grade	4.00	28		
22	02200	31 10 00	Backfill Int. Fnd. Walls & U/G Duct	8.00	28		

Figure U.1: Time Data for Start, Design, Pre-Construction, and Mobilization+Excavation+Foundation



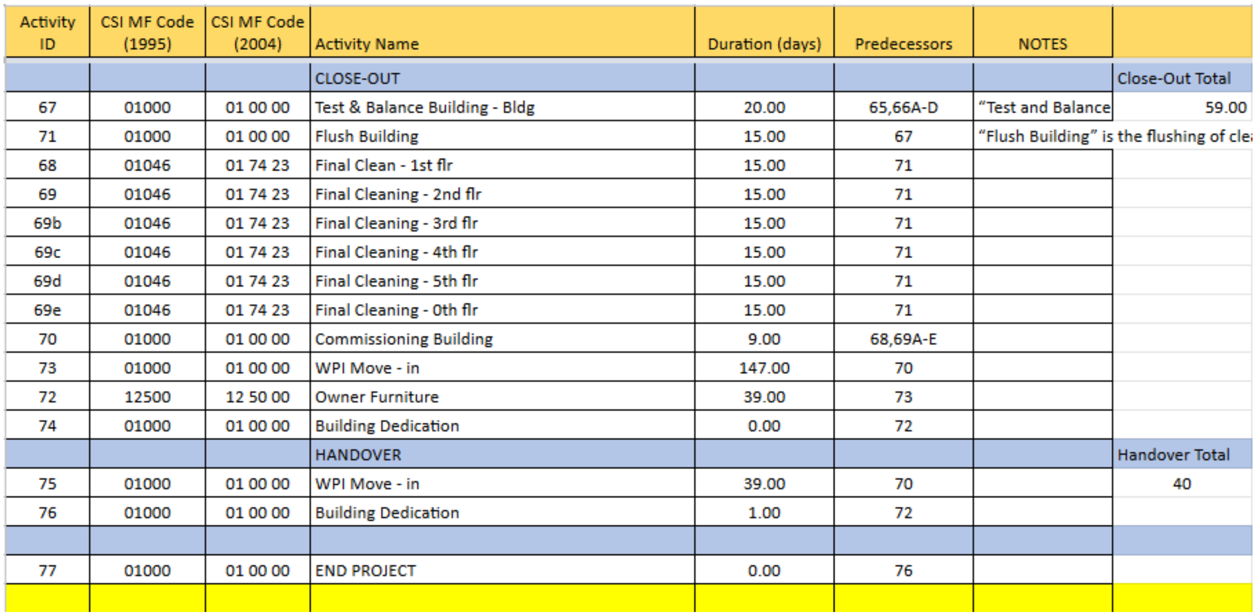
Activity ID	CSI MF Code (1995)	CSI MF Code (2004)	Activity Name	Duration (days)	Predecessors	NOTES	
			STRUCTURAL METAL FRAMING				Steel Total
29	05100	05 10 00	Fabricate Steel	154.00	14		65.00
30	05100	05 10 00	Steel Delivery	2.00	29		
31	05100	05 10 00	Erect Basement Steel	8.00	30		
32	05100	05 10 00	Erect First Floor Steel	8.00	31		
33	05100	05 10 00	Erect Second Floor Steel	8.00	32		
34A	05100	05 10 00	Erect Third Floor Steel	8.00	33		
34B	05100	05 10 01	Erect Fourth Floor Steel	8.00	34A		
34C	05100	05 10 02	Erect Fifth Floor Steel	8.00	34B		
35	05100	05 10 00	Erect Roof Steel	15.00	34C		
			EXTERIOR WALLS & ROOFING				Exterior Total
36	05300	05 30 00	Install Roof Decking	8.00	35		218.00
37	05100	05 10 00	Install Precast Supports / Adjust	13.00	35		CRUNCH
38	09100	09 22 00	Fab & Del Exterior Studs / Dens	39.00	37	“Fab & Del Exterior Studs/Dens” is th	
40	--	07 24 00	Exterior Works	81.00	38		163.9097744
39	05300	05 30 00	Install First Floor Deck/Studs	4.00	32		
41	05300	05 30 00	Install Second Floor Deck/Studs	4.00	33		
41A	05300	04 20 00	Install Third Floor Deck/Studs	4.00	34A		
41B	05300	04 20 00	Install Fourth Floor Deck/Studs	4.00	34B		
41C	05300	04 20 00	Install Fifth Floor Deck/Studs	4.00	34C		
42	--	04 20 00	Install Brick - E/W/N/S	50.00	40		
43	--	07 31 00	Install Shingles	35.00	42		
			INTERIOR WALLS, MECHANICAL & HVAC				Interior Total
44	05520	05 52 00	Install Stairs/Areaway Grates	18.00	43		213.00
45	--	23 50 00	Insulate Duct/Piping	40.00	43		
46	--	26 05 00	Electrical	86.00	43		
47	--	22 30 00	Plumbing	86.00	43		
48	--	01 00 00	Telecommunications	15.00	43		
49	--	27 40 00	Fire Alarms	28.00	46		
50	--	06 20 00	Install Wood Paneling	11.00	45, 46, 47, 48		
51	14200	14 20 00	Install Elevator	58.00	46		
52	--	09 60 00	Install & Complete Flooring	103.00	45, 46, 47, 48		
53	--	09 90 00	Paint - Prime	24.00	50, 52		

Figure U.2: Time Data for Structural Metal Framing, Exterior Walls & Roofing, and Interior Walls, Mechanical & HVAC



Activity ID	CSI MF Code (1995)	CSI MF Code (2004)	Activity Name	Duration (days)	Predecessors	NOTES	
			FURNISHINGS/FINISHES				Furnish Total
54	--	23 09 00	Mechanical Finishes	36.00	52		93.00
56A			Paint- Auditorium	10.00	54		
56	--	09 90 00	Paint - Finish	40.00	54		
58	--	26 50 00	R.I. Lights West & East Entrance	6.00	54		
55	12600	12 60 00	Fab & Del Aud Seating	47.00	56		
57	05520	05 52 00	Install Stair Rails	18.00	56		
59	10400	10 13 00	Install Signage in Building	6.00	56		
60	01000	01 00 00	Substantial Completion C of O	8.00	53		
			LANDSCAPING				Landscape Total
61	--	32 90 00	Exterior Finishes, Plantation & Grading	110.00	60		161.00
62	02900	32 90 00	Landscaping & Brick Paving	29.00	61		
63	03000		Place Exterior Concrete Sidewalks	8.00	62		
64	03000		Place Exterior Site Concrete	22.00	62		
			PUNCH-LIST				Punch-List Total
65	--	01 00 00	Punchlist - 1st flr	25.00	63, 64		25
66	01000	01 00 00	Punchlist - 2nd flr	25.00	63, 64		
66A	01000	01 00 00	Punchlist - 3rd flr	25.00	63, 64		
66B	01000	01 00 00	Punchlist - 4th flr	25.00	63, 64		
66C	01000	01 00 00	Punchlist - 5th flr	25.00	63, 64		
66D	01000	01 00 00	Punchlist - 0th flr	20.00	63, 64		

Figure U.3: Time Data for Furnishing/Finishes, Landscaping, and Punch-List



Activity ID	CSI MF Code (1995)	CSI MF Code (2004)	Activity Name	Duration (days)	Predecessors	NOTES	
			CLOSE-OUT				Close-Out Total
67	01000	01 00 00	Test & Balance Building - Bldg	20.00	65,66A-D	“Test and Balance	59.00
71	01000	01 00 00	Flush Building	15.00	67	“Flush Building” is the flushing of cle	
68	01046	01 74 23	Final Clean - 1st flr	15.00	71		
69	01046	01 74 23	Final Cleaning - 2nd flr	15.00	71		
69b	01046	01 74 23	Final Cleaning - 3rd flr	15.00	71		
69c	01046	01 74 23	Final Cleaning - 4th flr	15.00	71		
69d	01046	01 74 23	Final Cleaning - 5th flr	15.00	71		
69e	01046	01 74 23	Final Cleaning - 0th flr	15.00	71		
70	01000	01 00 00	Commissioning Building	9.00	68,69A-E		
73	01000	01 00 00	WPI Move - in	147.00	70		
72	12500	12 50 00	Owner Furniture	39.00	73		
74	01000	01 00 00	Building Dedication	0.00	72		
			HANDOVER				Handover Total
75	01000	01 00 00	WPI Move - in	39.00	70		40
76	01000	01 00 00	Building Dedication	1.00	72		
77	01000	01 00 00	END PROJECT	0.00	76		

Figure U.4: Time Data for Close-Out, Handover, and End

Appendix V: Revit Drawings and Renderings

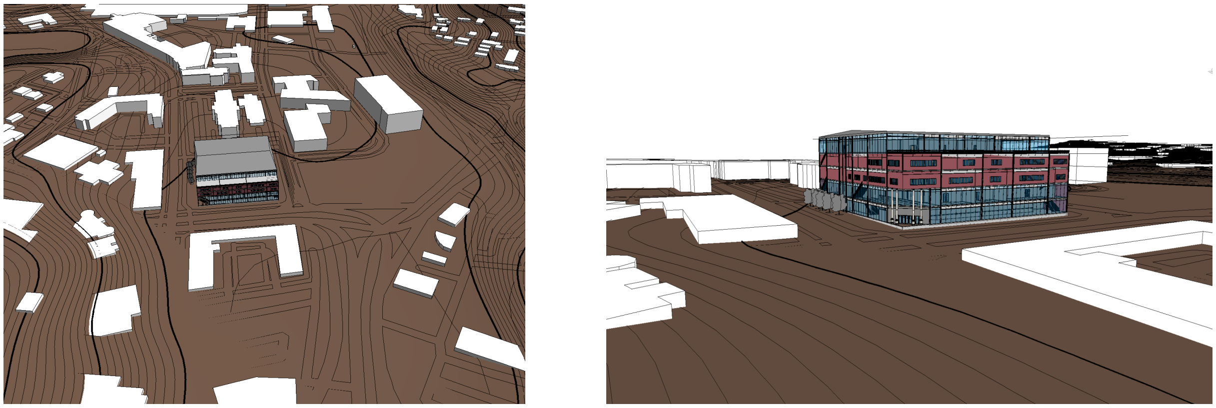


Figure V.1(left): Site Location in Salisbury Square
Figure V.2 (right): Close-up in front of Salisbury St.

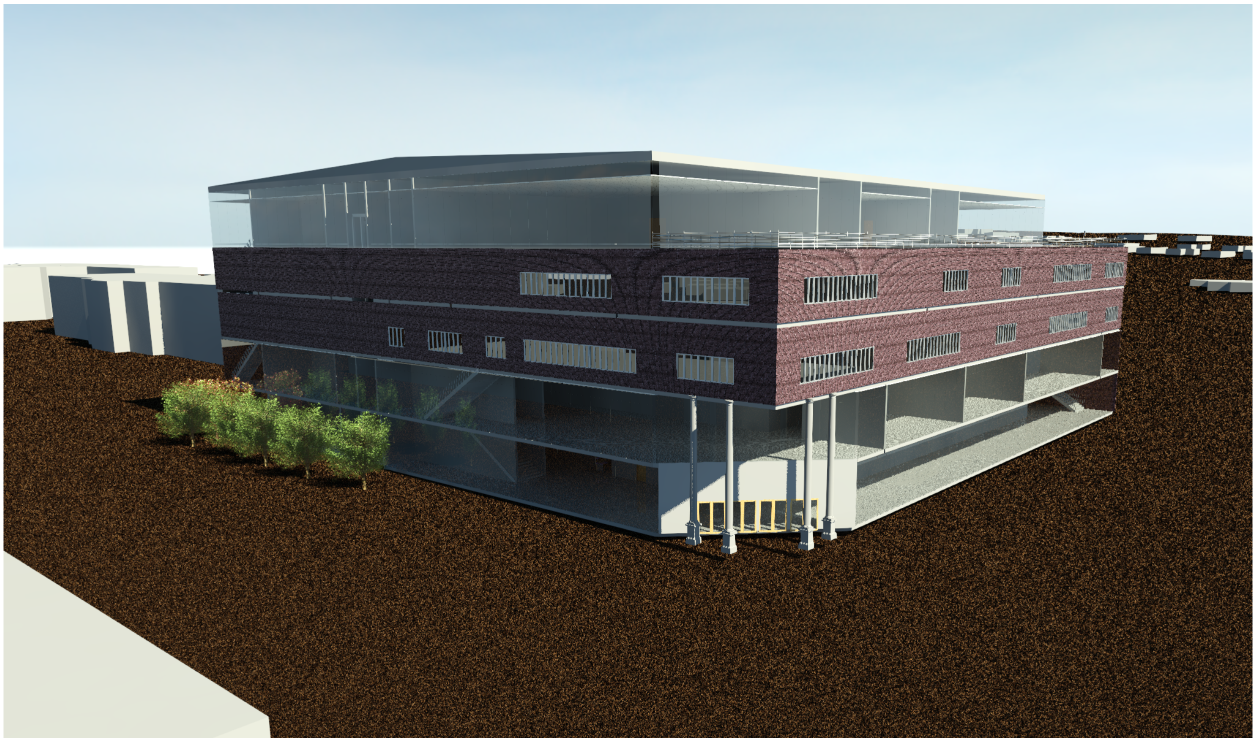


Figure V.3: Exterior Rendering

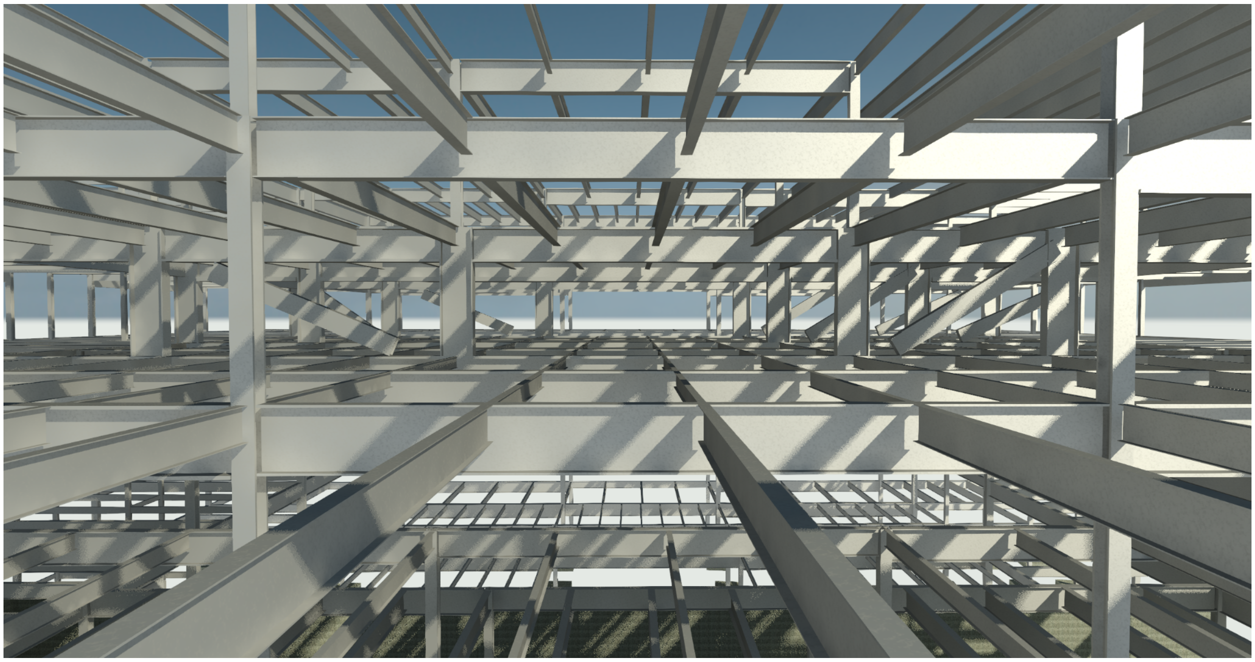


Figure V.4: Interior Structural Scheme with Lateral Bracing Rendering

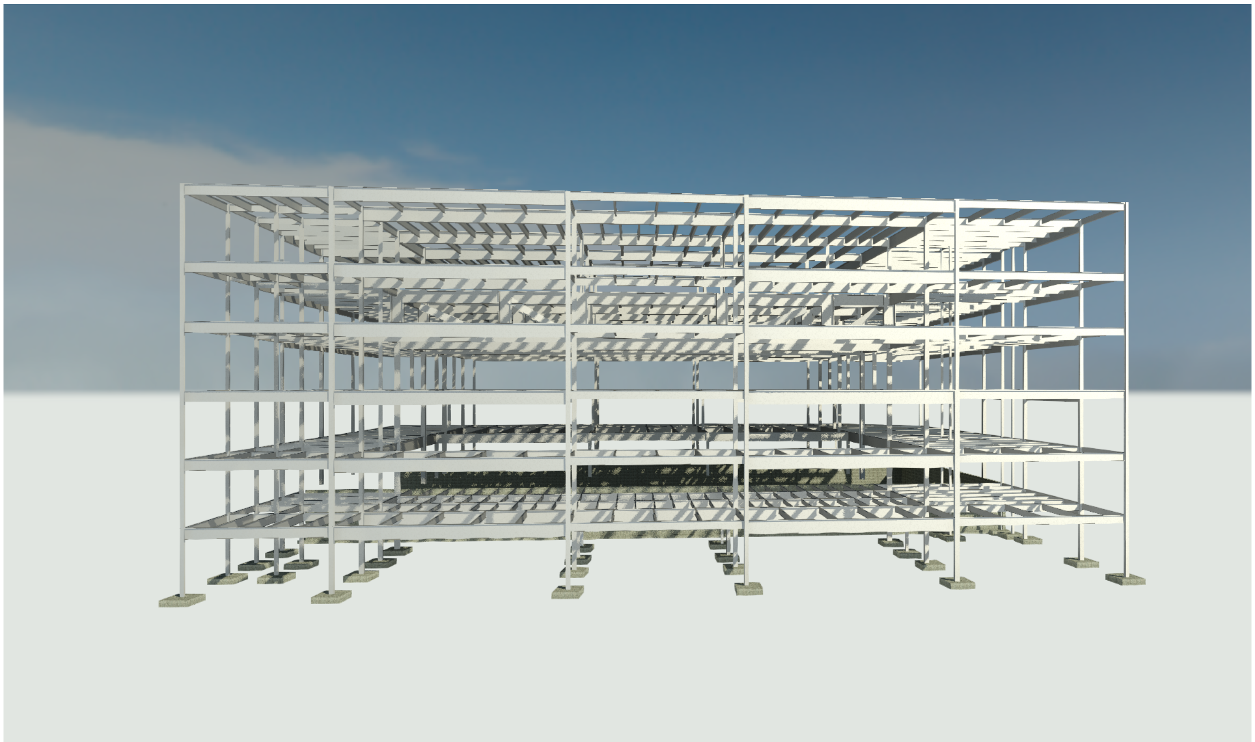


Figure V.5: Back of Performing Arts Center Structural Rendering

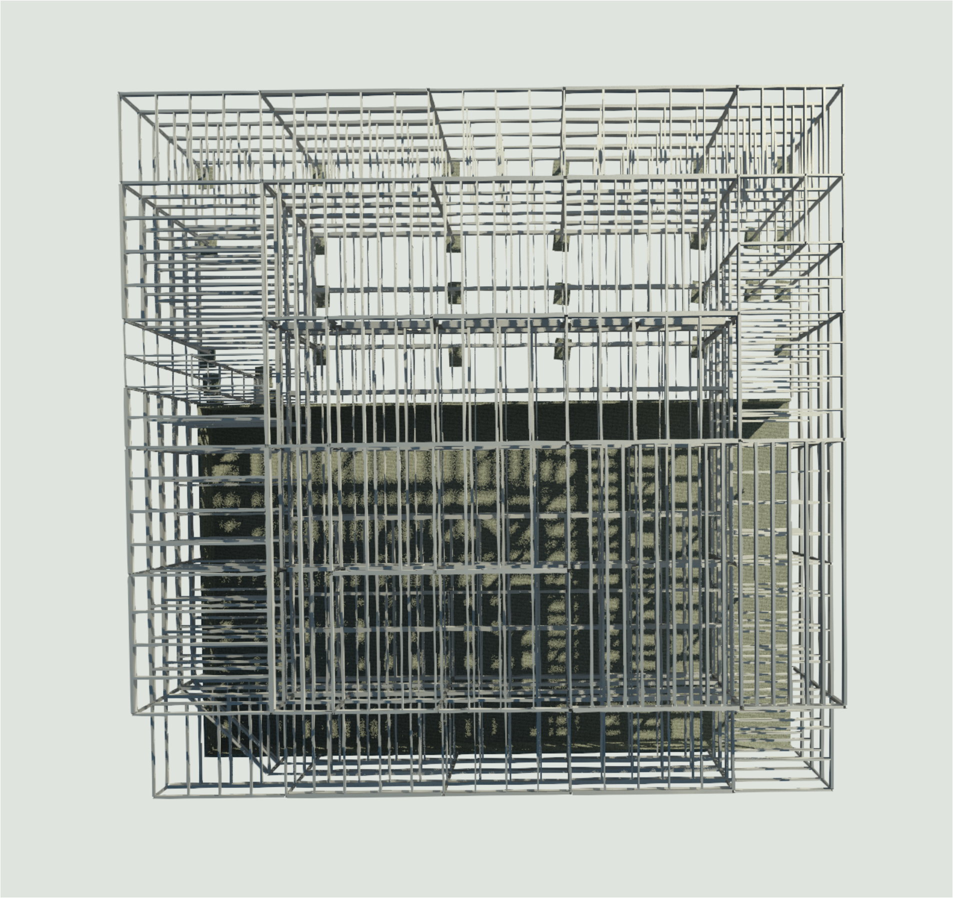


Figure V.6: Structural Framing Top View Rendering

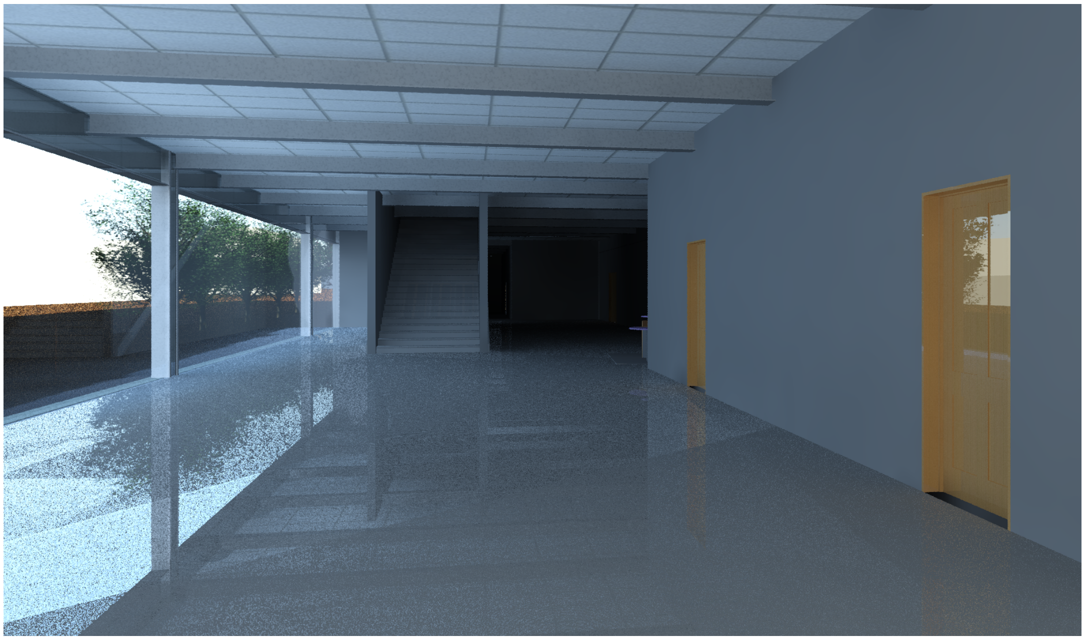


Figure V.7: Interior Lobby Rendering

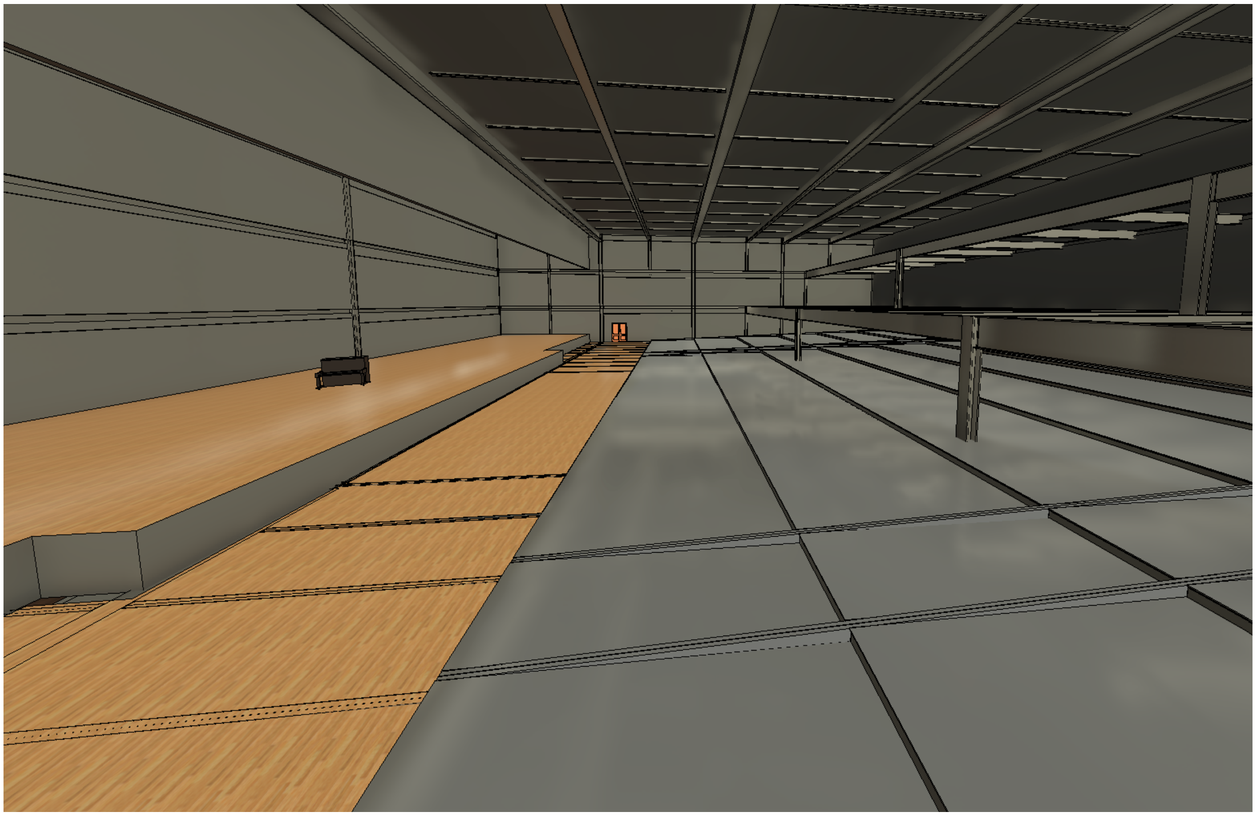


Figure V.8: Interior of Theatre Space

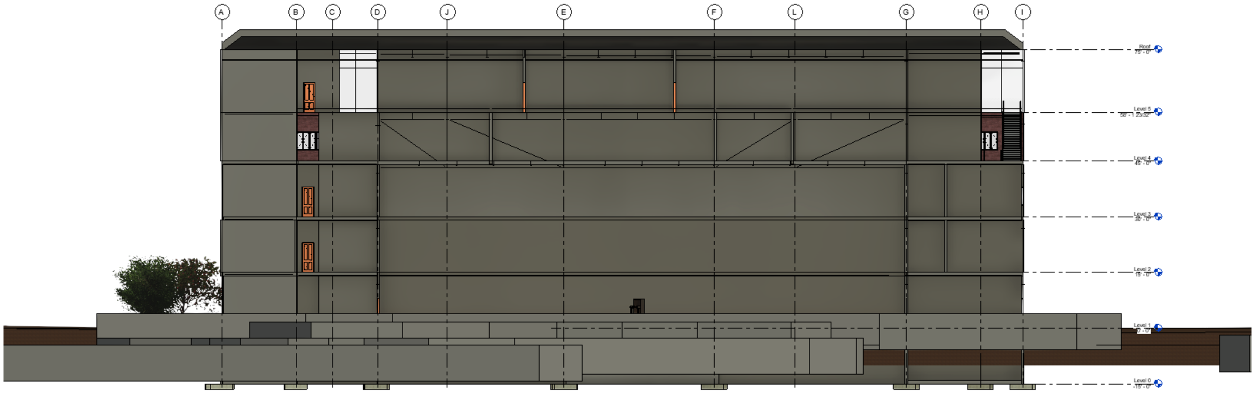
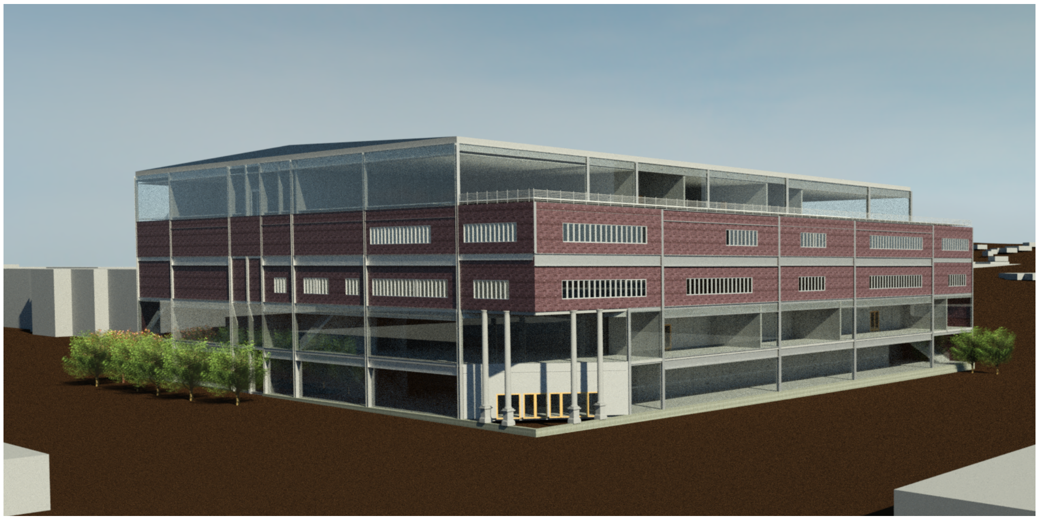


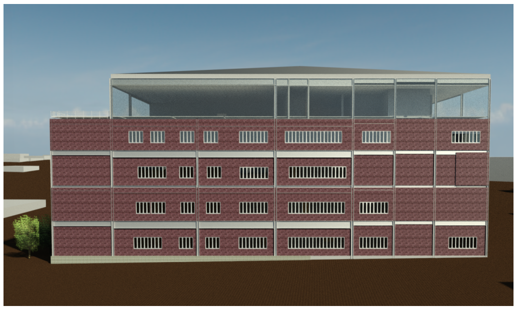
Figure V.9: Section Cut West to East in Front of Stage

Table V.1: Elevation Renderings



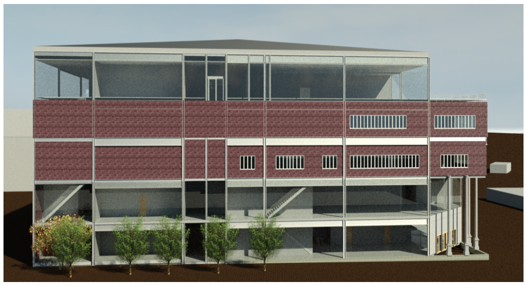
Entrance Rendering

South Elevation Rendering



North Elevation Rendering

East Elevation Rendering



West Elevation Rendering