Mass Timber

A Major Qualifying Project

Submitted on

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Abstract

The goal of this project was to research and evaluate the usage of mass timber in structures. An 8-story residential building was designed and analyzed by remodeling a 5-story residential/commercial building. To gain more insight on the challenges of using mass timber in buildings, background research and several interviews were conducted by reaching out to engineers, architects, contractors, and manufacturers that have experience designing and constructing buildings using mass timber. The results of the structural analysis and interview data were used to create a decision framework to help evaluate the usage of mass timber instead of steel or concrete in structures.

Acknowledgments:

The team would like to acknowledge and thank Professor Leonard Albano for his continued support of the group. Professor Albano provided his expertise in building design and the construction industry making it possible for the team to complete all objectives of the project. Professor Albano also made himself available to answer any questions that arose and helped to keep the project moving forward throughout its duration.

Additionally, the team would like to acknowledge Mike Richard for taking the time to meet in person and provide important feedback to the project. Mike's knowledge of CLT and steel construction was helpful in working past key objects in the project. Meeting in person also allowed for the team to share examples of their work and work through specific issues with ease.

The team also acknowledges Dean Lewis, Michael Moore and Scott MacLellan for agreeing to take part in phone interviews. These three are all experts in the field of CLT construction or design and provided valuable information both towards our background knowledge of CLT and specific questions regarding the design done for the project. In addition the team thanks Andy Canniff for helping to coordinate these phone interviews.

Lastly the team would like to thank all of the survey respondents. The responses from these people were used to collect data about their priorities in regards to construction projects. The compilation of these responses were analysed and used in part to come to conclusions for the project.

Authorship

All members of the group contributed to the writing of this report as well as the project proposal and creation of figures. Editing of the report was also done by all members of the group. The following details some of the major responsibilities of each member.

Grant Gilbert:
Worked to complete Objective 1 with background research about the advantages and disadvantages of mass timber compared to steel. Coordinated and scheduled phone interviews as well as helped conduct the interviews. Coordinated and scheduled trip to UMass mass timber building and helped with taking photos and questioning. Created survey as well as collected and organized survey data using qualtrics. Also, with the help of Professor Albano, worked to find qualified respondents and distribute the survey to these people. Helped to complete the decision framework needed for Objective 3.

Christopher Hagerman:
Completed background research on the advantages and disadvantages of mass timber for Objective 1. Worked to complete the steel design portion of Objective 2. Created and worked through excel tables in order to complete calculations involved with sizing steel members. Worked to make adjustments to member sizes and building load capacity based on location determinate values for loads such as wind, snow, seismic and shear. Used RISA to model the steel frame and check for accuracy in calculations of capacities. Used Revit to create a structural model of the steel frame. Helped complete the decision framework in Objective 3 as well as the cost analysis of steel and CLT designs. Helped to conduct phone interviews and participated in questioning during UMass visit.

Jack Hughes:

Worked to complete Objective 1 through background research. Investigated the advantages of mass timber compared to steel. Worked to complete timber design outlined in Objective 2. Conducted research in CLT handbook to find how design practices would apply to the project. Helped to design floor plan layout of CLT building as well as location and sizing of bearing walls, shear walls and floor panels. Created Revit architectural model with floor plan of the CLT structure. Helped to conduct phone interviews as well as questioning during the group's visit to UMass.

Professional Licensure Statement

A professional licensure is required in order to maximize the impact a Civil Engineer can have on his or her community. Only a professionally licensed engineer has the ability to seal or sign off on a design to confirm it is safe and effective for societal use.

In order to achieve a professional license, an aspiring Civil Engineer must first graduate from an ABET-accredited university. Second, an aspiring Civil Engineer must pass the Fundamentals of Engineering (F.E.) Exam to become an Engineer in Training (E.I.T.) in the eyes of the state and local government. E.I.T.s must then practice under the direct supervision of a Professional Engineer for a number of years (typically four) determined by the state. In some states, earning a Master's degree can fast track this period by up to a year. After gaining proper experience working under a P.E., an E.I.T. can apply to take the Principles and Practice of Engineering (P.E.) Exam. An E.I.T. must submit a portfolio and pass the P.E. Exam in order to earn a license and seal.

A P.E. must maintain his or her license by paying annual dues to renew it. A P.E. must work ethically and responsibly as his or her work will have direct impacts on the rest of the community. A professional licensure will also help to further advance the career of a Civil Engineer. Professional Engineers are recognized as trustworthy by potential clients, and are easily recognized and respected by their peers in the design and construction industry. Many companies require their engineers to have professional licensures and will not promote you without it.

Capstone Design Statement:

To accomplish the Capstone Design aspect of the project the team remodelled a 5-story residential/commercial building. Three stories were added to the existing design to create an 8-story building. The structural analysis in accordance with interview data collected from industry experts were used to develop a decision framework that can help the design and construction industry compare the benefits of building with mass timber versus steel or concrete in structures. Several constraints were addressed during the design of this project.

Sustainability:

To address the sustainability constraint of our capstone design two 8-story buildings were designed: one with mass timber and one with steel. The team focused on cross-laminated timber, a sustainable alternative to other structural materials such as steel and concrete.

Economics:

Economics is another constraint to consider during the design of the building at 126 Chandler Street. In order to analyze and compare the economical differences between mass timber versus steel and concrete, used RS Means and past projects and case studies using mass timber or using steel and concrete.

Health and Safety:

For our project we addressed the structural safety concerns that come with the design of a multistory residential building made with CLT or steel. In order to effectively create a safe and livable design, we will use guidelines for CLT found in the *CLT Handbook, ANSI, American Wood Council National Design Specification, and the International Building Code*, and the *Massachusetts State Building Code 9th edition.* In addition, the structural steel followed *American Steel Institute of Steel Construction* provisions.

Ethics:

There are multiple ethical constraints to the design procedure that were addressed by the team over the duration of the project. These concerns include the use of inexpensive, substandard materials in order to save on project costs or not thoroughly completing certain aspects of design to save time. *The American Society of Civil Engineers* (ASCE) states that "Ethics is integral to all decisions, designs, and services performed by civil engineers." The team has worked with good ethics throughout the project and adhered to the guidelines put in place by the ASCE.

Constructability:

Constructability is another constraint of the design capstone. Two constructability constraints the team addressed are the lack of experience in construction of mass timber in North America and the use of standard sections for both the CLT panels and structural steel members.

To address regulations, design factors, and structural analysis the team referenced the *CLT Handbook*, *International Building Code*, and *American Institute of Steel Construction Manual of Steel Construction.*

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1.0 Introduction:

Mass timber is a growing alternative to steel and concrete materials in large buildings and structures. Mass timber, or cross-laminated timber, is a wood panel consisting of several layers of panels stacked in alternating directions, held together by structural adhesives or laminates. Mass timber construction practices started to gain popularity in Europe and Australia over 20 years ago, and it is starting to spread to North America. In North America, mass timber is currently a big topic of interest among the design and construction industry which includes engineers, professors, architects, designers, project managers, superintendents, laborers, etc. This is due to the numerous advantages to constructing with mass timber, including speed of construction, lightweight frame, and a negative carbon footprint. However, some limitations have hindered the application of mass timber in North America. Some disadvantages are the lack of mass timber experience in North America, inflexibility during construction, and the cost.

The goal of this project was to research and evaluate the usage of mass timber in structures. Three objectives were identified to accomplish this goal:

Objective 1: Identify the advantages and disadvantages of using mass timber in structures

Objective 2: Compare structural design solutions with mass timber and steel

Objective 3: Develop a decision framework to quantify the effectiveness of mass timber compared to steel and concrete in vertical structures

Two 8-story residential buildings were designed and analyzed by remodeling a 5-story residential building built on 126 Chandler Street in Worcester, Massachusetts. To gain more insight on the challenges of using mass timber in buildings, background research and interviews with engineers, architects, contractors, and manufacturers that have experience with the design and construction of buildings using mass timber were completed. The results of the structural analysis and interview data collected were used to create a decision framework that can help to evaluate the usage of mass timber instead of steel or concrete in structures.

2.0 Background:

Mass timber was first introduced in Austria and Germany during the 1990s. It slowly gained popularity, but the rise of mass timber use in structures is a result of the threat of global climate change. Buildings are responsible for almost 40% of the world's carbon dioxide emissions (*UN Environment and the International Energy Agency*, 2017). Shortly after the turn of the 21st century, the engineering and architecture world became fixated with building 'green' buildings with a focus on sustainability. Mass timber's sustainable advantages make it an ideal choice when designing a building for sustainability. At the start of the 21st century, climate change concerns and the green building movement gave mass timber an introduction to the European structural materials market. Although still a small market, many mass timber buildings, or 'plyscrapers', have been built all over the world.

2.1 Mass Timber Building Examples

One building that helped promote the plyscraper/green building movement in Europe in Australia is Forté, in Victoria Harbour, Melbourne (Figure 1). When constructed back in 2012, it was the first mass timber building constructed in Australia. Standing over ten stories tall, Forté was also the tallest mass timber structure in the world at the time of its completion. Forté is a residential building hosting 23 apartments and 4 town houses. Forté's design and construction were a vital piece to the spread of mass timber usage across Australia and Europe because it demonstrated that mass timber could be used in tall buildings.

Figure 2.1.1: Forté (McAlpine, 2017)

Mjøstårnet, the largest timber building in the world, was designed and constructed in Norway in March 2019 (Figure 2). It has 18 stories and measures an impressive 280 feet tall. It is the third largest building in all of Norway and is home to a hotel, restaurants, offices, and apartments. Øystein Elgsaas, a partner at Voll Arkitekter, the designers of Mjøstårnet, said “The most important part of this building is to show that it is possible to build, large, complex timber buildings, and in that fashion inspire others to do the same."(O'Neill, 2019).

Figure 2.1.2: Mjøstårnet (Franklin, 2019)

The current tallest mass timber building in North America is the University of British Columbia's Brock Commons Tallwood House located in Vancouver, Canada (Figure 3). Although it holds the same amount of stories as Mjøstårnet (18), Brock Commons is 90 feet shorter than the Nordic plyscraper. It was recently completed in September 2016 and is home to over 400 students this Fall.

Figure 2.1.3: Brock Commons (*Naturally: Wood,* 2018)

2.2 Advantages of Mass Timber:

Mass timber is more sustainable than steel or concrete. Wood has the ability to store carbon dioxide throughout its lifecycle. Brock Commons, a mass timber building completed in 2016, has estimated saving over 2432 metric tons of carbon dioxide emissions just by using mass timber and other wood products. That estimate is equivalent to removing 511 cars off the road for a year (*Naturally: Wood*, 2018). Mass timber can also increase the efficiency of energy usage in a building. The tight connections between mass timber panels leave less space for air flow causing an increase in efficiency of heating and cooling systems. Some mass timber buildings have reported up to 2/3rds on energy savings when compared to steel and concrete (*WoodWorks*, 2012).

Another advantage to constructing buildings with mass timber is increased speed of construction. Cross-laminated timber panels are typically 2, 4, 8, or 10 feet in width, up to 60 feet long, and up to 20 inches thick (*CLT Handbook*, 2013*)*. Since mass timber panels are prefabricated, details such as wall or floor connections, window or door frames, and stairs can all be precisely pre-cut to meet the demands of the project. This allows for a shorter project timeline and the option of reducing the amount of workers on site, leading to savings on overall project cost. Brock Commons, a 162,700 square foot building was constructed in only 70 days. This was nine weeks faster than an equivalent steel and concrete structure.

2.3 Disadvantages of Mass Timber:

One disadvantage of mass timber is the current lack of experience in the North American industry. There are few North American designers, contractors, subcontractors, and skilled workers who are experienced with mass timber. This is largely due to the lack of mass timber manufacturers. The lack of North American manufacturers also ties in to the disadvantage of cost. Because the design of these mass timber panels is so specific it is often difficult to find domestic manufacturers, thus making the ones that are available very expensive. In contrast, material costs for mass timber in mid-rise residential, commercial, or industrial buildings in

Europe are actually 10-25% less expensive than the material costs of buildings using steel and concrete (*WoodWorks, 2012)*.

Another disadvantage of mass timber is the inflexibility during the construction phase. Once mass timber panels have been designed and fabricated, amendments to design cannot be made. This really highlights the importance of communication throughout the project. The owner, designers, and contractors must all be on the same page before construction begins to ensure that the project will be completed to the owner's satisfaction.

One more disadvantage is the lack of knowledge and testing of the lateral load resistance in North America. Engineers, professors, students, researchers, owners and others in the construction industry are currently trying to agree upon a safe R-value, or seismic response modification factor. FEMA P965 has recently declared an R-value of 4.5 for CLT (Richard, 2019). Other buildings have used an R-value that differs from the 4.5 value that FEMA P965 had determined. For example, the John W. Olver Design Building at the University of Massachusetts Amherst was designed by Simpson Gumpertz and Heger in 2017 and an R-value of 3 was used.

*design lateral load = (Sds * Ie / R) * weight of building*

2.4 Design Standards and Specifications

The rise of mass timber has led to its inclusion in several engineering publications such as the *CLT Handbook*, *ANSI*, *American Wood Council National Design Specification*, and the *International Building Code*. These publications are creating a standardization of constraints and requirements for the usage of mass timber in design and construction. The *2021 International Building Code* approved the addition of tall wooden structures of up to 18 stories of mass timber. The changes to the *2021 International Building Code* could not have been made without the influence of tall mass timber buildings across the globe such as Forté, Mjøstårnet, and Brock Commons.

3.0 Methodology:

The scope of this project can be defined by three separate objectives. Objective 1: Identify the advantages and disadvantages of using mass timber in structures. This objective was completed through background research and interviews to give the team an understanding of the benefits of using mass timber to use a basis for comparison. Objective 2: Compare structural design solutions with mass timber and steel. The capstone design portion of the project was completed with Objective 2. Objective 3: Develop a decision framework to quantify the usage of mass timber in structures. To complete this objective the team compared the construction techniques of mass timber to typical concrete and steel construction. Comparisons were made through a decision framework that clearly showed which areas of construction certain materials excel. The goal for the final project deliverable was to create something easy to understand that could be used by members of the design and construction industry when deciding on what materials to use during construction.

3.1 Identify the Advantages and Disadvantages of Using Mass Timber in Structures

The purpose of Objective 1 was to complete thorough background research and interview design and construction industry professionals in order to gain an understanding of the elements of construction and design for mass timber projects. This knowledge was vital to complete the proceeding objectives in the project and also give the team a level of expertise on the topic. The knowledge gained throughout Objective 1 was important to have during Project Presentation Day where the team will be expected to give in-depth answers to questions on the topic.

A survey was designed using qualtrics. A layout of the survey can be found in Appendix C. A description was provided at the beginning of the survey stating, “This form is intended to help collect data for a senior project at Worcester Polytechnic Institute. The goal of our project is to research and evaluate the usage of mass timber in construction. We will use this data to develop a decision framework and quantify the effectiveness of mass timber. Then we will compare its effectiveness to steel and concrete alternatives.” The purpose of this was to give the participant a purpose to the survey. The survey went on to ask what role the participant has in the construction industry. It then listed 8 different criteria which included: cost, schedule, ease of construction, aesthetic, environmental/sustainable impact, construction impact, access to materials, and performance. Where it prompted the participant to rank them from 1 to 8 on level of importance. 1 was the most important while 8 was the least.

The survey then asked the level of knowledge on mass timber the participant had and then prompted them to write their individual experience with mass timber. Each participant’s knowledge on mass timber was observed to gain a better understanding of previous experience with mass timber has any effect on how they rank criteria. It was also an opportunity to determine the relevance of mass timber in the construction industry. The purpose of the survey being designed was to help gain knowledge on the level of importance each criteria is to certain professions in the construction industry.

The survey was first released on December 10th, 2019. Data has been collected for 17 individuals. The data was inconclusive because of the limited number of responses. Data was observed using qualtrics report tab. The report tab provided many detailed reports including the data found in Table C1. Using the mean section in the table, a criteria's level of importance was quickly observed. The criteria with the lowest average score represented the highest level of importance while the one with the highest average score demonstrated the lowest level of importance.

The team requested interviews with professionals in the design and construction industry. We will target manufacturers, owners, engineers, researchers, superintendents, project managers, and union/laborers. This group was targeted to diversify the value of criteria for decision framework among different professions.

3.2: Compare Structural Design Solutions with Mass Timber and Steel

The second objective was to **c**ompare structural design solutions with mass timber and steel. The goal of the design and analysis objective was to learn more about the challenges of designing buildings with mass timber, and to compare and contrast two buildings while satisfying our capstone design requirement. Two buildings were designed: one using a steel frame and one using a cross-laminated timber construction. Both buildings were modeled off of the drawings of a local 5-story commercial/residential building on 126 Chandler Street in Worcester, Massachusetts. This building was selected because it is residential, local, and the architectural layouts and structural drawing sets were accessible. First, a steel frame was designed and analyzed. Then timber panels were sized for the design of the mass timber frame. When designing both buildings, the team first designed for the gravitational and vertical loads of the buildings including self-weight. Next, a lateral load resistance system was designed for each building.

The *American National Standards Institute*, *CLT Handbook*, and the *American Wood Council National Design Specification* from 2018 were used as references for CLT design factors and codes. Other references include the city of Worcester and state of Massachusetts building codes. RISA was a software used to aid in the design and analysis process. The team gained knowledge from background research and the analysis to create a decision framework to compare and contrast the two designs.

3.2.1 Steel Frame

The steel frame was conceptualized using the 126 Chandler Street building plans as a reference. To determine the flexural capacity, the value of Wu was calculated by using the ASCE load case: 1.2D+1.6L. This value was plugged into the equation $(Wu*L^2)/8$ to calculate the flexural capacity. Once the flexural capacity was determined, the girders were sized using the AISC Steel Construction Manual. The girder sizes were then checked to meet the allowable live load and superimposed load deflections.

Since the girders had all been designed using W-shapes, it was decided preferable to use W-shapes for the columns as well. Even though the columns would be over-designed, the W-shape was still the better option to make connections less expensive and easier during construction.

To evaluate the seismic loads, an individual bay was analyzed using the seismic base shear loads with an LRFD factor of 1.0, dead load values with an LRFD factor of 1.2, snow load values with LRFD factor of .2 and live load load values with an LRFD factor of 0.5. The girders and columns were resized to meet the capacities of the updated dead and live loads. After calculating the seismic loads, diagonal braces were added to create a lateral load resisting system. In order to meet lateral deflection limits the depths of the diagonal braces and columns in the steel frame were doubled. This satisfied the deflection limit, but required a lot of diagonal braces. The shape of the diagonal braces were reconsidered to decrease the amount of steel being used for diagonal braces. Eventually a combination of two HSS 8x8x6 braces were selected and placed in four bays on every floor. A gusset plate connection was used for all of the HSS-to-W-shape connections.

Table 3.2.1.1 Loads Considered in the Steel Frame

Load Type	Element	LRFD Factor
Dead Loads	Concrete Decking (54 psf)	1.2
	MEP (20 psf)	
	Self-weight of structural elements	
	Fencing on roof (5 psf)	
Live Loads	Floor (100 psf)	.5
Seismic Loads	Calculated Base Shear Loads (24.04 kips)	1.0
Snow Loads	Worcester Snow Load (35psf)	.2

3.2.2 Mass Timber

The Mass Timber framing plan was designed to be consistent with the layout of the steel frame design. The timber framing plan includes 14 cross-laminated timber floor panels, 14 cross-laminated timber bearing wall panels, and 8 shear wall panels per floor. The same floor plan from the steel design was used and each floor has an area of 3456 square feet. To design the

CLT floor panels the edgewise bending and deflection limits were calculated using equations and values from Table 2 of ANSI-APA PRG 320-2018. CLT bearing wall panels were calculated by finding axial compression capacities. CLT shear walls were added to create a lateral load resistance system. The through-thickness shear of the walls and seismic base shear were used to design the shear walls.

Table 3.2.1.1 Loads Considered in the Timber Frame

Load Type	Element	LRFD Factor
Dead Loads	MEP (20 psf)	1.2
	Self-weight of structural elements	
	Fencing on roof (5 psf)	
Live Loads	Floor (100 psf)	.5
Seismic Loads	Calculated Base Shear Loads (17.56 kips)	1.0
Snow Loads	Worcester Snow Load (35 psf)	.2

3.3 Develop a Decision Framework to Quantify the Effectiveness of Mass Timber Compared to Steel and Concrete in Structures

The third objective was to develop a decision framework. The mission of Objective 3 was to quantify the advantages and disadvantages of using mass timber in North America. To accomplish this, background research and interviews from Objective 1 were used to help identify criteria and their respective weights for the decision framework. The interview and survey data collected from Objective 1 was used to prioritize and weight the criteria.

From this criteria, three matrices were produced: a performance criteria matrix, a performance rating matrix, and then the final deliverable of a performance measure form that ultimately determined the effectiveness of mass timber in comparison to that of steel and concrete. The main purpose of the performance criteria matrix (Figure 3.3.1) was to assign a list criteria a weight to numerically represent the importance of each criteria. The next matrix was the performance rating matrix (Table 1.2) to show the comparison of performance between mass timber and steel/concrete for each of the criteria. Next, a decision framework form (Table 1.3) was created. It measures (degree of impact), rating (scale 1-10 for each criteria), weight (from evaluation criteria matrix), and contribution (rating times weight). All of this calculated a total performance for both mass timber and steel/concrete. From that a net change in performance between the two were calculated. The purpose of these matrices was to quantify and clearly identify the advantages and disadvantages of mass timber to determine a numerical measure of comparison with steel and concrete.

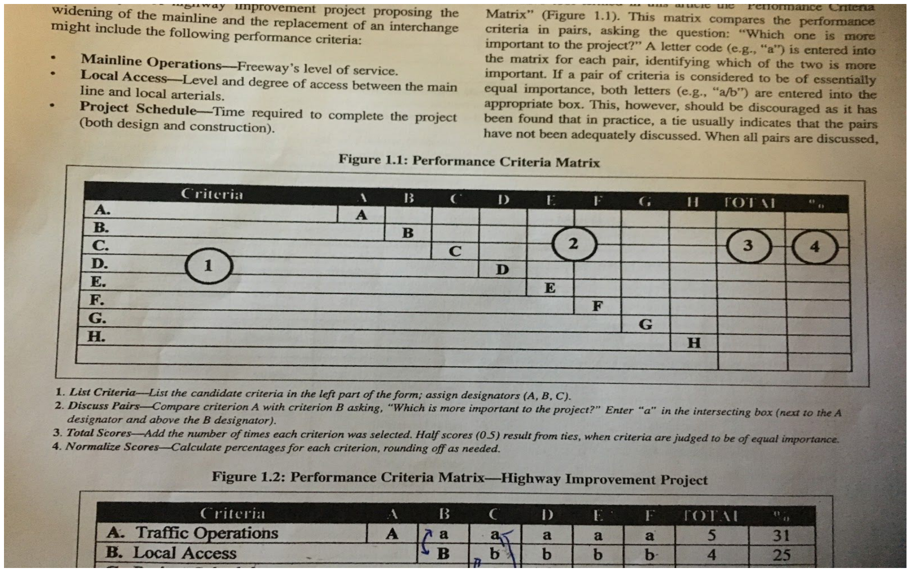


Figure 3.3.1 Performance Criteria Matrix (Hunter & Stewert, 2002)

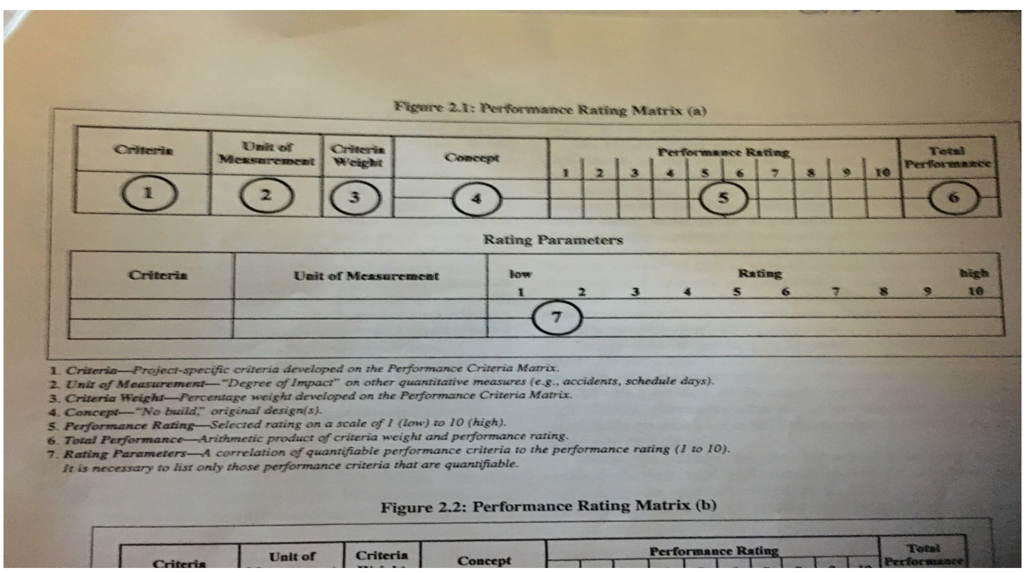
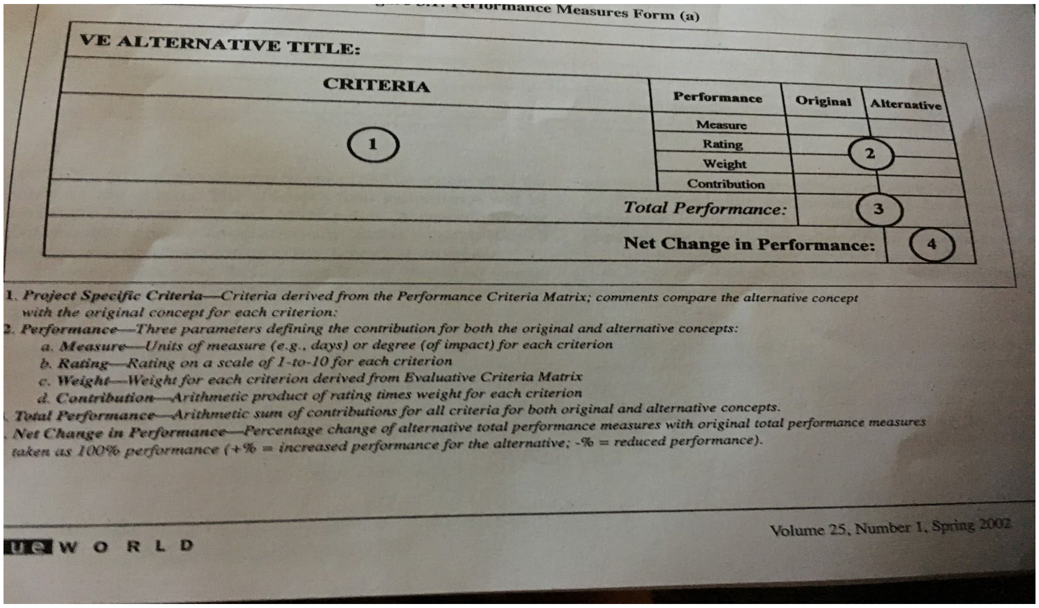


Figure 3.3.2 Performance Rating Matrix (Hunter & Stewert, 2002)



…Performance Measures Form (a)

VE ALTERNATIVE TITLE:			
CRITERIA	**Performance**	**Original**	**Alternative**
1	Measure		
	Rating	2	
	Weight		
	Contribution		
	Total Performance:	3	
	Net Change in Performance:		4

1. ***Project Specific Criteria***—*Criteria derived from the Performance Criteria Matrix; comments compare the alternative concept with the original concept for each criterion:*
2. ***Performance***—*Three parameters defining the contribution for both the original and alternative concepts:*
   - *a.* ***Measure***—*Units of measure (e.g., days) or degree (of impact) for each criterion*
   - *b.* ***Rating***—*Rating on a scale of 1-to-10 for each criterion*
   - *c.* ***Weight***—*Weight for each criterion derived from Evaluative Criteria Matrix*
   - *d.* ***Contribution***—*Arithmetic product of rating times weight for each criterion*
3. ***Total Performance***—*Arithmetic sum of contributions for all criteria for both original and alternative concepts.*
4. ***Net Change in Performance***—*Percentage change of alternative total performance measures with original total performance measures taken as 100% performance (+% = increased performance for the alternative; -% = reduced performance).*

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Figure 3.3.3 Decision Framework (Hunter & Stewert, 2002)

4.0 Results:

4.1 Identify the Advantages and Disadvantages of Using Mass Timber in Structures

4.1.1 Survey Data

Our survey was intended to research various industry professionals including: engineers, researchers/professors, architects, designers, project managers, owners, laborers, and superintendents. For responses there were 7 engineers, 1 architect, 5 project managers, 3 owners, and 1 other. Most of whom have some knowledge of mass timber. The level of knowledge and experience the individuals have with mass timber can be found in Appendix C.

Table 4.1.1 Survey Prioritization Criteria

#	Field	1	2	3	4	5	6	7	8	Total
1	Cost	50.00% 8	31.25% 5	6.25% 1	12.50% 2	0.00% 0	0.00% 0	0.00% 0	0.00% 0	16
2	Schedule/being on time	12.50% 2	37.50% 6	12.50% 2	6.25% 1	25.00% 4	0.00% 0	6.25% 1	0.00% 0	16
3	Ease of Construction	0.00% 0	12.50% 2	12.50% 2	25.00% 4	25.00% 4	12.50% 2	0.00% 0	12.50% 2	16
4	Aesthetic	12.50% 2	6.25% 1	31.25% 5	6.25% 1	12.50% 2	25.00% 4	6.25% 1	0.00% 0	16
5	Environmental/Sustainable Impact	6.25% 1	0.00% 0	12.50% 2	18.75% 3	0.00% 0	25.00% 4	37.50% 6	0.00% 0	16
6	Construction Impacts (noise pollution, traffic impedence)	0.00% 0	0.00% 0	0.00% 0	0.00% 0	6.25% 1	6.25% 1	37.50% 6	50.00% 8	16
7	Access to Materials	0.00% 0	0.00% 0	12.50% 2	0.00% 0	6.25% 1	31.25% 5	12.50% 2	37.50% 6	16
8	Performance	18.75% 3	12.50% 2	12.50% 2	31.25% 5	25.00% 4	0.00% 0	0.00% 0	0.00% 0	16

Showing rows 1 - 8 of 8

These individual responses were used to determine which criteria are important in a construction project. This was completed to determine the criteria to be used when comparing a mass timber to a steel and concrete design of a building. The criteria that the industry professionals were asked to identify included: cost, schedule, ease of construction, aesthetic, environment, construction impacts, access to materials, and performance. After analysis it was determined that the construction impacts and the access to materials criteria were of the least importance among the participants in the survey. Construction impacts was the least prioritized and was removed from the list of criteria to consider when comparing the two buildings. Having access to materials less prioritized could be due to a lack of representation from the superintendent group. One engineer and one project manager saw the importance of having access to materials and ranked it 3rd on their list of criteria. For that reason the access to materials criteria remained on the criteria list. The primary way the criteria was measured was through a series of interviews with construction professionals who have dealt with mass timber, along with steel and concrete projects. Some key takeaways from these interviews were confirming some of the trends our survey data was showing: Cost is among the most important criteria among industry professionals. Many owners will not elect to pay a premium price just to be more sustainable, or for their building to be more aesthetically pleasing. There are still many associated risks for engineers and contractors because of the limited work experience and number of manufacturers of mass timber products. This can lead to more increases in building costs, and more challenges in the design, and coordination from the design to the construction phase. The complete set of notes derived from the interviews can be found in Appendix G.

4.2 Compare Structural Design Solutions with Mass Timber and Steel

4.2.1 Steel Frame

The 126 Chandler Street steel frame was altered to create a symmetric shape in order to simplify the design process. This laid the groundwork for a framing plan consisting of 27 girders and 17 columns per floor. Each floor has an area of 3408 square feet. The first floor is 12 feet in height and floors 2-8 are each 10 feet in height for a total building height of 82 feet. After the framing plan was completed, the floor plan was developed. The 126 Chandler Street building plans were referenced again to help visualize ideas to layout four apartments, an elevator, a staircase, and a corridor. The girders were originally designed to meet the flexural capacity of dead and live loads acting on the frame. Weight of the concrete slab, weight of MEP, and self-weight of the girders were considered when calculating the dead loads. Composite concrete slabs were selected using Vulcraft's product catalog as a reference. A concrete slab with a depth of 5.5 inches and a weight of 54 psf (including decking) was chosen. The concrete slabs are 10 feet wide and span a length of 24 feet to align with the bays of the building. To simplify the live load values 100 psf was used for the entire floor. The steel girders were designed by checking flexural and deflection capacities. The usage of Microsoft Excel was helpful during the iterative design process. The steel frame is composed of six 20'x24' bays, two 6'x20' bays, and two 6'x24' bays.

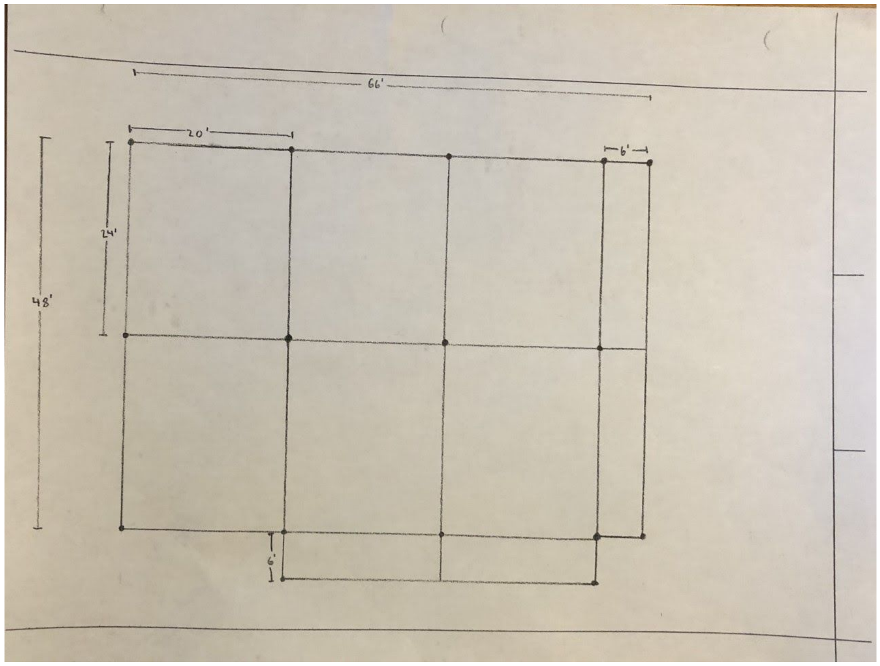


Figure 4.2.1.1 Steel Frame

The first floor is designed to have a reception area, a mailroom, and a small gym. Floors 2-8 are all divided into four apartments. There is one elevator and one main staircase with access to all levels. The roof was designed to be a recreational space for tenants to use as a terrace. There is a concrete floor with metal decking on the roof level and fencing around the perimeter.

The lateral load resisting frame was created by calculating the seismic base shear of the frame. RISA was used to analyze individual bays with all lateral and vertical loads applied to the bay to analyze the performance of diagonal bracing. The braces had to contain all the deflections to under 1" (the maximum deflection capacity). After several iterations, it was determined that using two HSS 8x8x6 braces placed in four bays on every floor would meet the desired deflection limits.

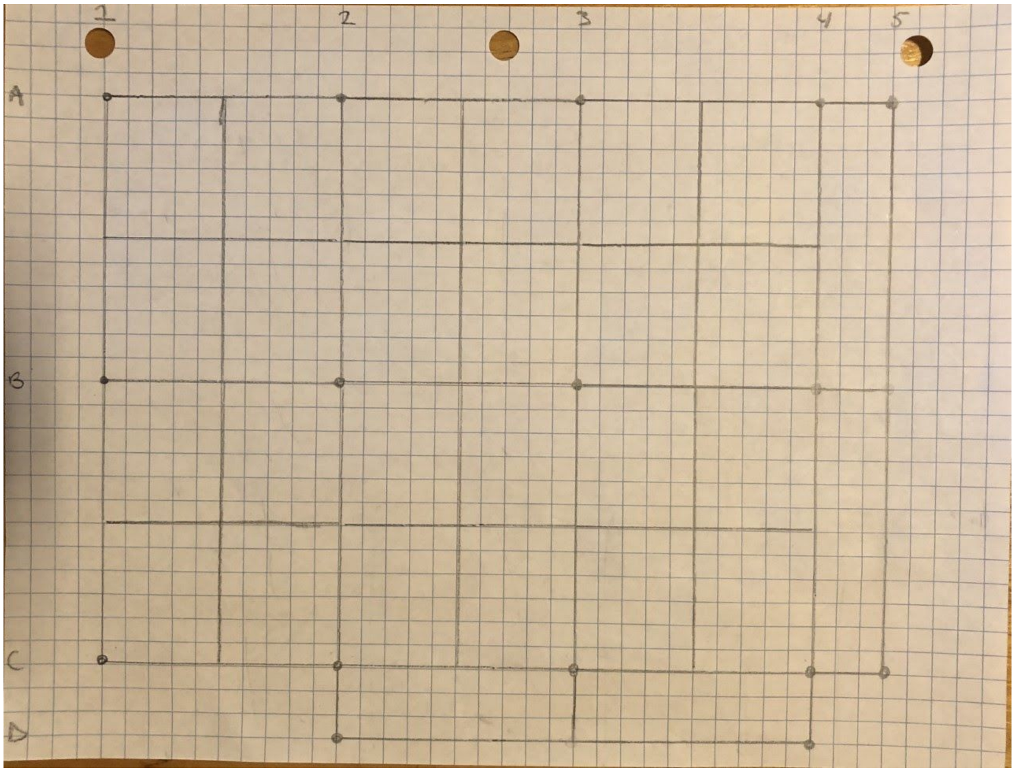
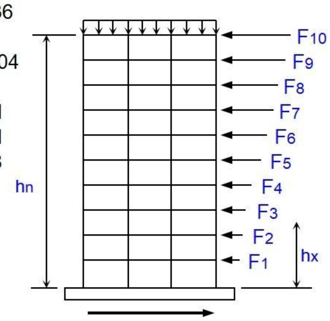


Figure 4.2.1.2 Typical Floor Framing Plan with Infill Beams

Job Name:	MQP	Subject:	Steel Building		
Job Number:		Originator:		Checker:	

Input Data:

Risk Category =	II	IBC 2012, Table 1604.5, page 336
Importance Factor, I =	1.00	ASCE 7-10 Table 1.5-2, page 5
Soil Site Class =	B	ASCE 7-10 Table 20.3-1, page 204
Location Zip Code =	0.01609	
Spectral Accel., S_S =	0.188	ASCE 7-10 Figures 22-1 to 22-11
Spectral Accel., S_1 =	0.070	ASCE 7-10 Figures 22-1 to 22-11
Long. Trans. Period, T_L =	6.000	sec. ASCE 7 Fig's. 22-12 to 22-18
Structure Height, h_n =	82.000	ft.
Actual Calc. Period, T_c =	6.000	sec. from independent analysis
Seismic Resist. System =	C4	Steel ordinary moment frames (ASCE 7-10 Table 12.2-1)



V = Cs*W = Σ(Fi) = 24.04 kips

Seismic Base Shear

(Regular Bldg. Configurations Only)

Structure Weight Distribution:

No. of Seismic Levels = 9

Figure 4.2.1.3 Base Shear Calculation

Seismic Design Category:

Category(for S_{DS}) =	A	ASCE 7-10 Table 11.6-1, page 67
Category(for S_{D1}) =	A	ASCE 7-10 Table 11.6-2, page 67
Use Category =	A	Most critical of either category case above controls

Fundamental Period:

Period Coefficient, C_T =	0.028	ASCE 7-10 Table 12.8-2, page 90
Period Exponent, x =	0.8	ASCE 7-10 Table 12.8-2, page 90
Approx. Period, T_a =	0.951	sec., $T_a = C_T*h_n$^(x), ASCE 7-10 Section 12.8.2.1, Eqn. 12.8-7
Upper Limit Coef., C_u =	1.700	ASCE 7-10 Table 12.8-1, page 90
Period max., $T_{(max)}$ =	1.617	sec., $T_{(max)} = C_u*T_a$, ASCE 7-10 Section 12.8.2, page 90
Fundamental Period, T =	1.617	sec., T = Tc <= Cu*Ta, ASCE 7-05 Section 12.8.2, page 129

Seismic Design Coefficients and Factors:

Response Mod. Coef., R =	3.5	ASCE 7-10 Table 12.2-1, pages 73-75
Overstrength Factor, Ω_o =	3	ASCE 7-10 Table 12.2-1, pages 73-75
Defl. Amplif. Factor, C_d =	3	ASCE 7-10 Table 12.2-1, pages 73-75
C_S =	0.036	$C_S = S_{DS}/(R/I)$, ASCE 7-10 Section 12.8.1.1, Eqn. 12.8-2
$C_{S(max)}$ =	0.008	For T<=TL, CS(max) = SD1/(T*(R/I)), ASCE 7-10 Eqn. 12.8-3
$C_{S(min)}$ =	0.010	CS(min) = 0.044*SDS*I >= 0.01, ASCE 7-10 Eqn. 12.8-5
Use: C_S =	0.010	$C_{S(min)} <= C_S <= C_{S(max)}$

Seismic Base Shear:

V = 24.04 kips, $V = C_S*W$, ASCE 7-10 Section 12.8.1, Eqn. 12.8-1

Seismic Shear Vertical Distribution:

Distribution Exponent, k = 1.56 k = 1 for T<=0.5 sec., k = 2 for T>=2.5 sec.

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

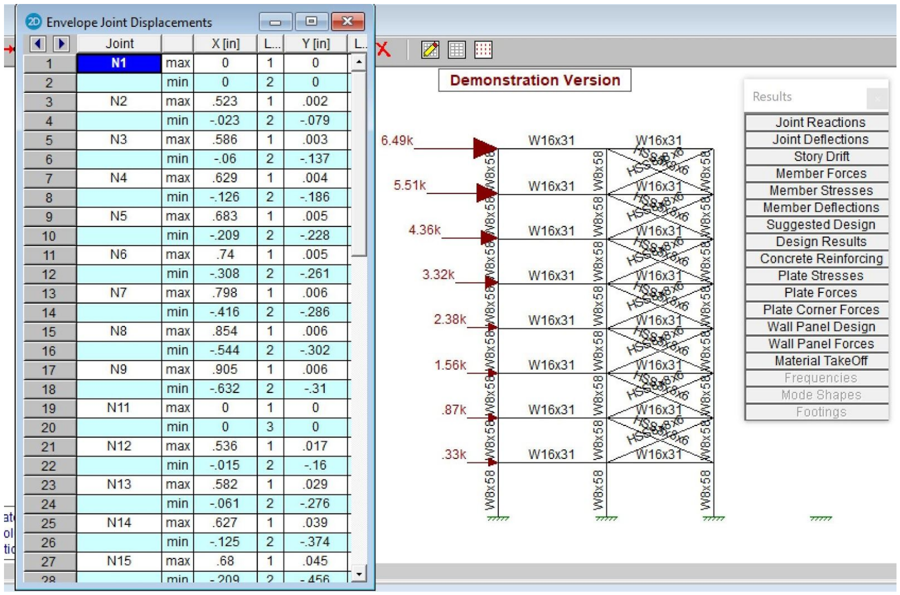
Lateral Force at Any Level: $F_x = C_{vx}*V$, ASCE 7-10 Section 12.8.3, Eqn. 12.8-11, page 91

Vertical Distribution Factor: $C_{vx} = W_x*h_x$^k/(ΣWi*hi^k), ASCE 7-10 Eqn. 12.8-12, page 91

Figure 4.2.1.4 Base Shear Information

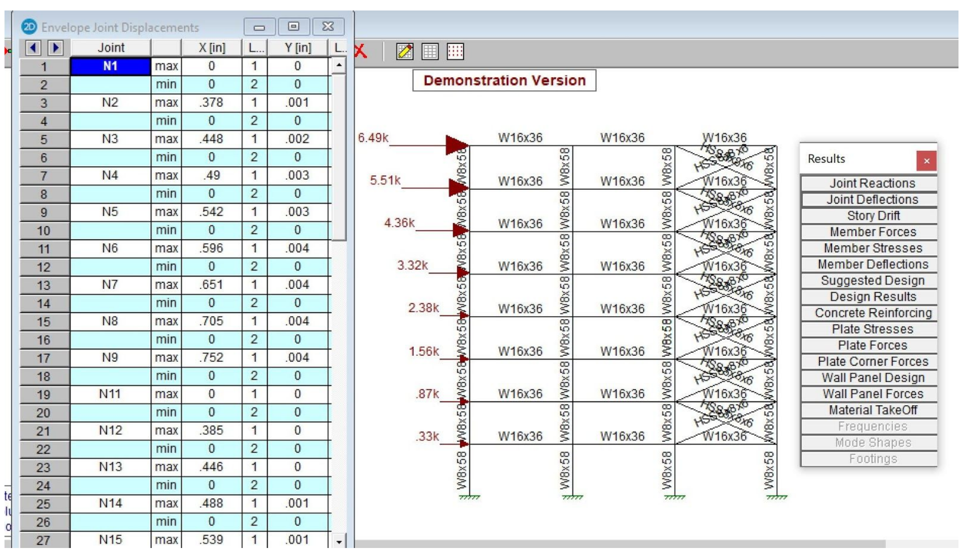
Table 4.2.1.1 Base Shear

Seismic Level x	Weight, Wx (kips)	h_x^k (ft.)	W_x*h^k (ft-kips)	C_{vx} (%)	Shear, F_x (kips)	Σ Story Shears
9	286.50	960.492	275176.9	0.265	6.37	6.37
8	292.36	784.283	229292.7	0.221	5.31	11.68
7	292.36	621.254	181629.5	0.175	4.21	15.89
6	292.36	472.308	138083.7	0.133	3.20	19.09
5	292.36	338.592	98990.7	0.095	2.29	21.38
4	292.36	221.631	64796.0	0.062	1.50	22.88
3	292.36	123.605	36137.1	0.035	0.84	23.72
2	289.56	48.062	13916.9	0.013	0.32	24.04
1	73.73	0.000	0.0	0.000	0.00	24.04
Σ =	2403.95		1038023.5	1.000	24.04	



	Joint		X [in]	L...	Y [in]
1	N1	max	0	1	0
2		min	0	2	0
3	N2	max	.523	1	.002
4		min	-.023	2	-.079
5	N3	max	.586	1	.003
6		min	-.06	2	-.137
7	N4	max	.629	1	.004
8		min	-.126	2	-.186
9	N5	max	.683	1	.005
10		min	-.209	2	-.228
11	N6	max	.74	1	.005
12		min	-.308	2	-.261
13	N7	max	.798	1	.006
14		min	-.416	2	-.286
15	N8	max	.854	1	.006
16		min	-.544	2	-.302
17	N9	max	.905	1	.006
18		min	-.632	2	-.31
19	N11	max	0	1	0
20		min	0	3	0
21	N12	max	.536	1	.017
22		min	-.015	2	-.16
23	N13	max	.582	1	.029
24		min	-.061	2	-.276
25	N14	max	.627	1	.039
26		min	-.125	2	-.374
27	N15	max	.68	1	.045
28		min	-.209	2	-.456

Figure 4.2.1.5 RISA Check



	Joint		X [in]	L...	Y [in]
1	N1	max	0	1	0
2		min	0	2	0
3	N2	max	.378	1	.001
4		min	0	2	0
5	N3	max	.448	1	.002
6		min	0	2	0
7	N4	max	.49	1	.003
8		min	0	2	0
9	N5	max	.542	1	.003
10		min	0	2	0
11	N6	max	.596	1	.004
12		min	0	2	0
13	N7	max	.651	1	.004
14		min	0	2	0
15	N8	max	.705	1	.004
16		min	0	2	0
17	N9	max	.752	1	.004
18		min	0	2	0
19	N11	max	0	1	0
20		min	0	2	0
21	N12	max	.385	1	0
22		min	0	2	0
23	N13	max	.446	1	0
24		min	0	2	0
25	N14	max	.488	1	.001
26		min	0	2	0
27	N15	max	.539	1	.001

Figure 4.2.1.6 RISA Check

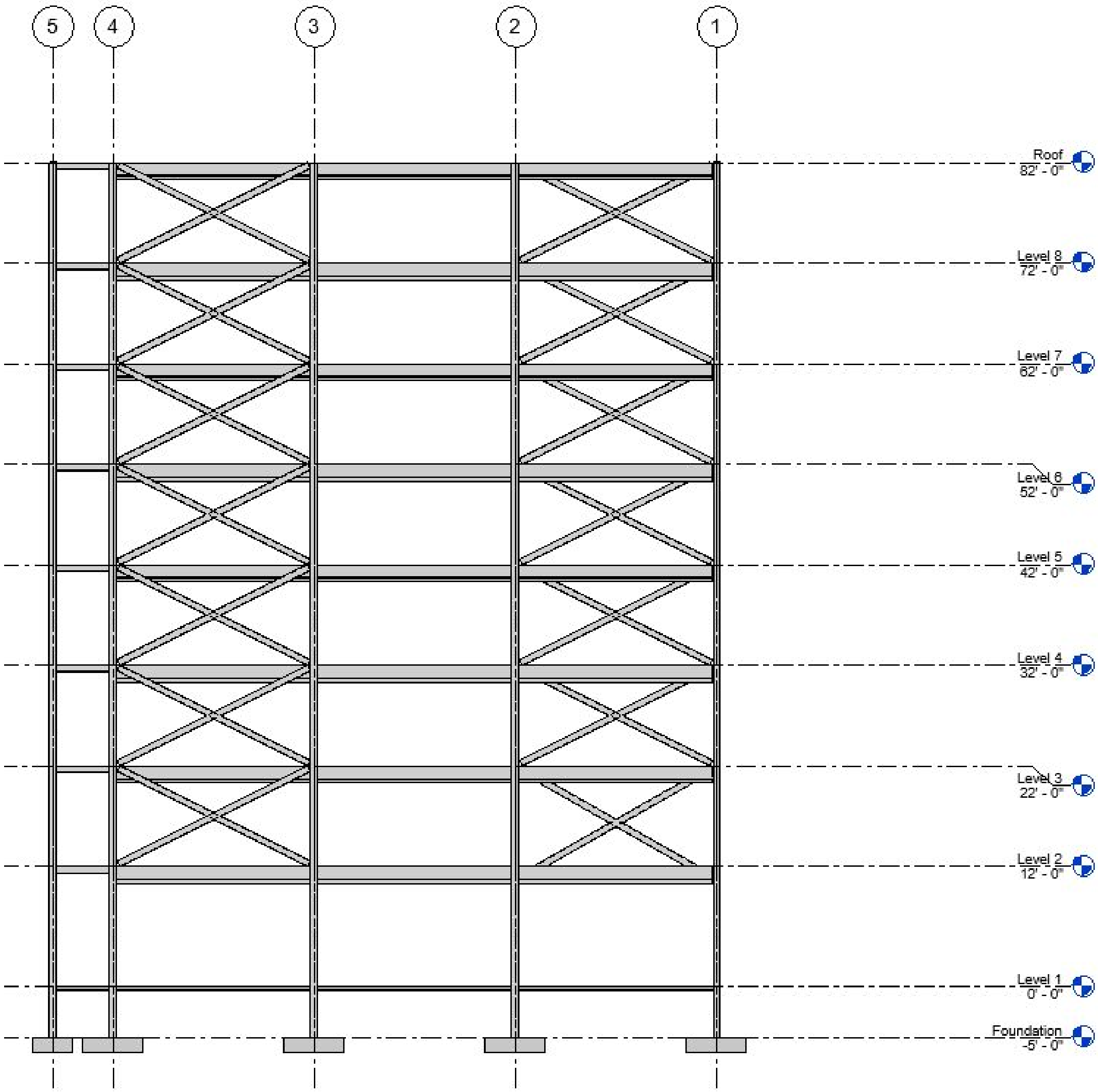


Figure 4.2.1.7 Steel Architectural Model North Elevation View

The structural material costs for the steel frame design were calculated using RSMeans. In the cases of missing information, conservative extrapolations were made to best estimate the cost. The structural material cost estimation for the steel frame includes the costs of the columns, girders, beams, and diagonal braces as well as the concrete decking. The total structural material cost of the steel frame was estimated to be $403,700.

Table 4.2.1.2 Structural Steel Material Costs

Structural Element	Unit Cost	Total
Columns (W8x58)	$71.25/ft	$99,400
Girders (W16x36)	$44.50/ft	$49,900
Girders (W21x44)	$54.50/ft	$26,200
Girders (W8x28)	$34.50/ft	$16,000
Beams (W16x31)	$38.50/ft	$14,800
Beams (W16x57)	$72.50/ft	$66,100
Beams (W16x77)	$96.00/ft	$73,700
Diagonal Braces (HSS8x8x6)	$1.25/lb	$10,200
Concrete Deck (5.5" thick)	$1.80/SF	$47,400
	Total	$403,700

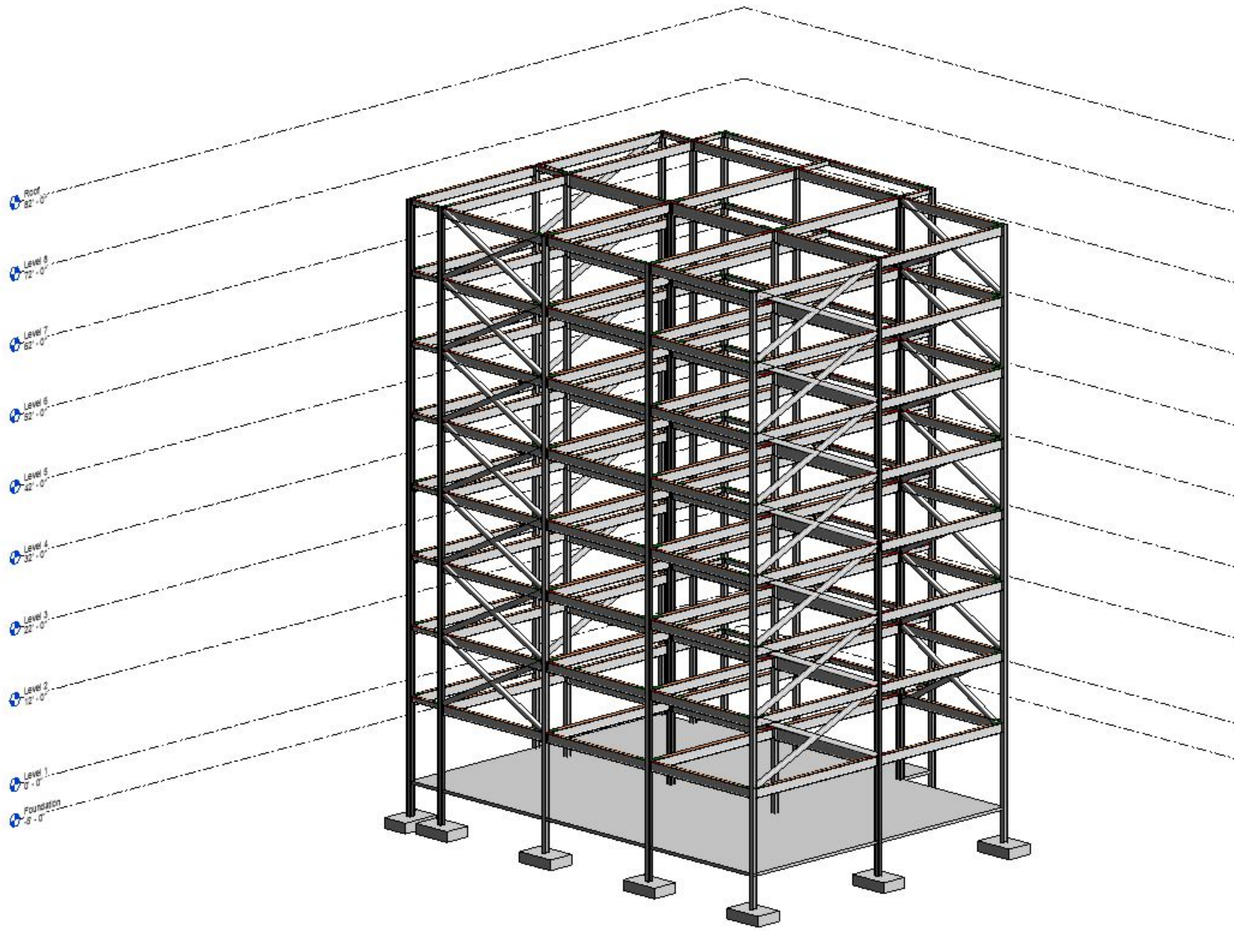


Figure 4.2.1.8 Steel Architectural Model 3D View

4.2.2 Mass Timber Frame

One major consideration when designing the cross-laminated timber panels was the ability to deliver the panels on trucks to the project site. After several interviews and conversations with our sponsor, Michael Richard, the maximum panel width decided was 10’ in order to fit on truck beds. The 20’ bays of the steel brace frame were split into two 10’ floor panels. The timber building was extended by a foot in order to place three 9’ panels. They span 24’ or 30’ to a bearing wall at the midpoint of the building in the main hallway of the floor. Half lapped joints connect all the floor panels together. Half lapped joints were chosen for floor panel connections because prefabrication of the joints allows for quick and easy construction. Additionally these joints carry normal and transverse loads. Below is a cross section example of a half lapped joint connection. After calculating the edgewise bending and deflection limits of the floor panels, 7-ply E1 panel sizes were selected.

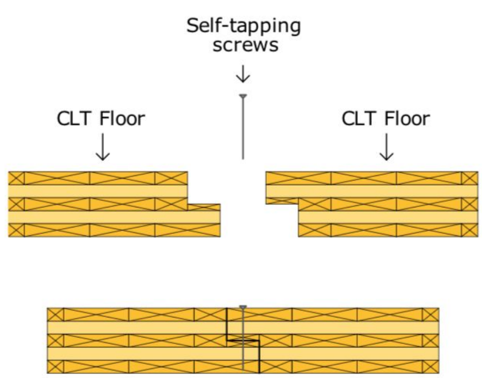


Figure 4.2.2.1 Lap Joints (Karacabeyli & Douglas, 2013)

The bearing wall design started with deciding the number of walls to use. Three bearing walls are included in the timber frame: two edge walls and an interior bearing wall on the north side of the hallway. The following figure shows the floor plan of the building. The red lines depict a rough layout of the CLT floor panels, and blue lines depict the location of CLT bearing walls. The gaps in the center bearing wall along the hallway are caused by doorways.

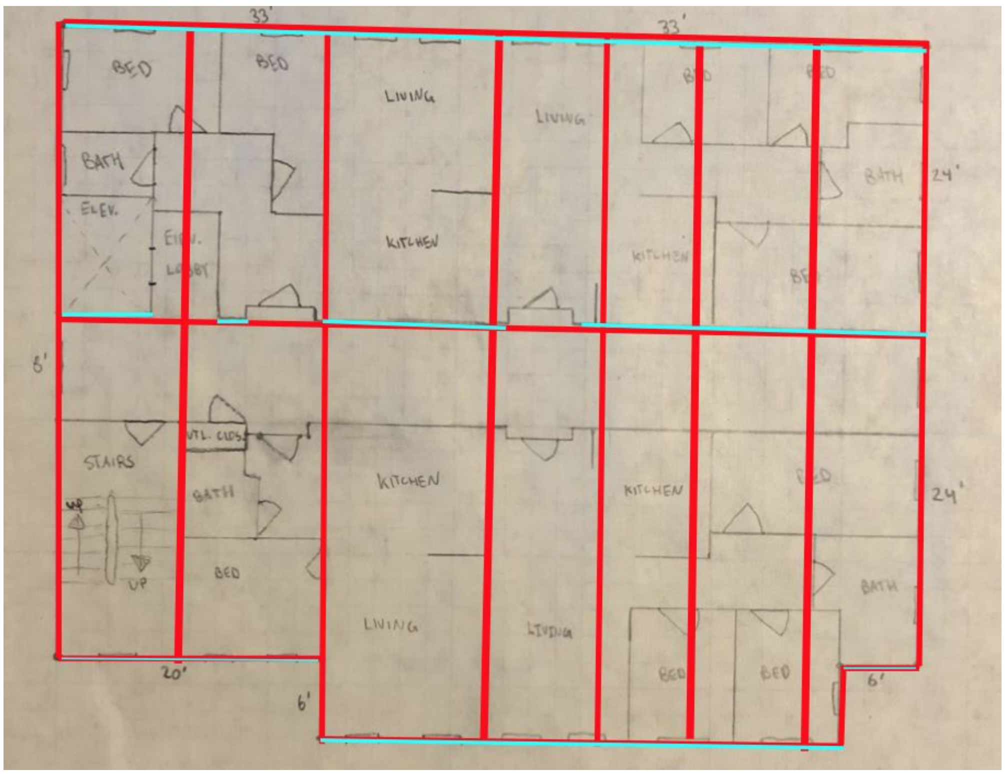
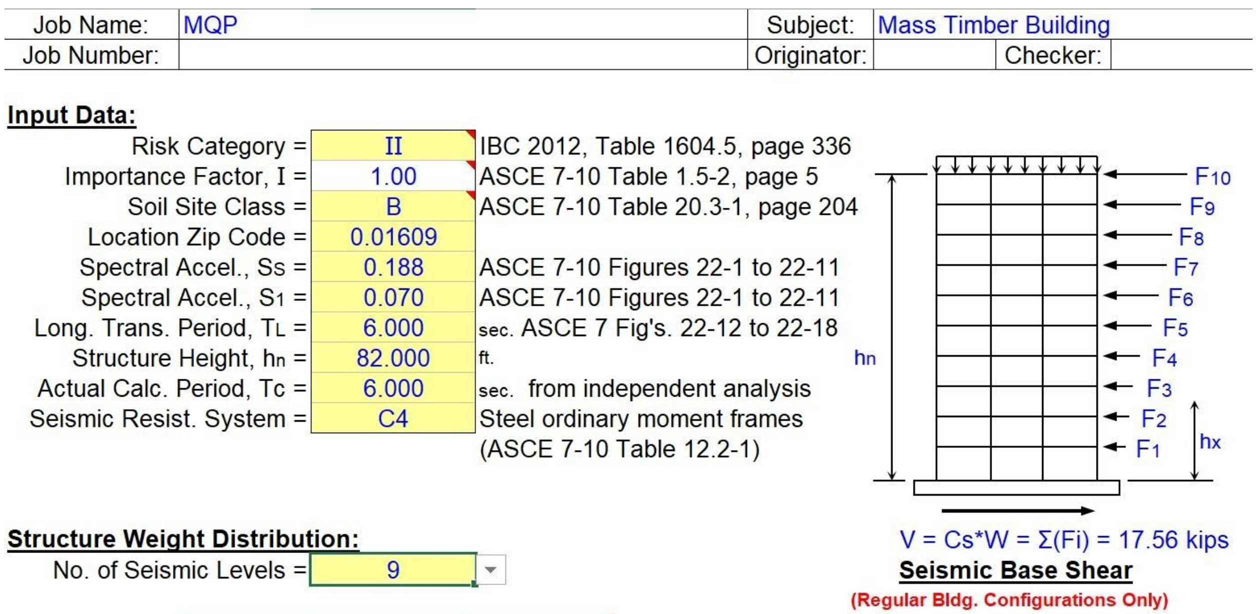


Figure 4.2.2.2 Bearing Wall Layout

A chart of axial compression capacities of timber panels listed in Table A2 of ANSI-APA PRG 320-2018 was created to simplify the iterative design process.

The axial compression test revealed either a 5-ply E1 or E3 panel could be used, and E1 wall panels were selected for ease of manufacturing and constructability.

The lateral load resisting frame includes four shear walls: two located on either side of the hallway spanning East-West and two shear walls spanning North-South near the center of the floor. The seismic base shear was calculated using an R factor of 3.5. Through-thicknesses of the two shear walls were calculated and 5-ply E1 wall panels were selected.



Job Name:	MQP	Subject:	Mass Timber Building		
Job Number:		Originator:		Checker:	

Input Data:

Risk Category =	II	IBC 2012, Table 1604.5, page 336
Importance Factor, I =	1.00	ASCE 7-10 Table 1.5-2, page 5
Soil Site Class =	B	ASCE 7-10 Table 20.3-1, page 204
Location Zip Code =	0.01609	
Spectral Accel., S_s =	0.188	ASCE 7-10 Figures 22-1 to 22-11
Spectral Accel., S_1 =	0.070	ASCE 7-10 Figures 22-1 to 22-11
Long. Trans. Period, T_L =	6.000	sec. ASCE 7 Fig's. 22-12 to 22-18
Structure Height, h_n =	82.000	ft.
Actual Calc. Period, T_c =	6.000	sec. from independent analysis
Seismic Resist. System =	C4	Steel ordinary moment frames (ASCE 7-10 Table 12.2-1)

Structure Weight Distribution:

No. of Seismic Levels = 9

Figure 4.2.2.3 Base Shear Calculations

Seismic Design Category:

Category(for S_{DS}) =	A	ASCE 7-10 Table 11.6-1, page 67
Category(for S_{D1}) =	A	ASCE 7-10 Table 11.6-2, page 67
Use Category =	A	Most critical of either category case above controls

Fundamental Period:

Period Coefficient, C_T =	0.028	ASCE 7-10 Table 12.8-2, page 90
Period Exponent, x =	0.8	ASCE 7-10 Table 12.8-2, page 90
Approx. Period, T_a =	0.951	sec., $T_a = C_T*h_n$^(x), ASCE 7-10 Section 12.8.2.1, Eqn. 12.8-7
Upper Limit Coef., C_u =	1.700	ASCE 7-10 Table 12.8-1, page 90
Period max., $T_{(max)}$ =	1.617	sec., $T_{(max)} = C_u*T_a$, ASCE 7-10 Section 12.8.2, page 90
Fundamental Period, T =	1.617	sec., T = Tc <= Cu*Ta, ASCE 7-05 Section 12.8.2, page 129

Seismic Design Coefficients and Factors:

Response Mod. Coef., R =	3.5	ASCE 7-10 Table 12.2-1, pages 73-75
Overstrength Factor, Ωo =	3	ASCE 7-10 Table 12.2-1, pages 73-75
Defl. Amplif. Factor, C_d =	3	ASCE 7-10 Table 12.2-1, pages 73-75
C_S =	0.036	$C_S = S_{DS}/(R/I)$, ASCE 7-10 Section 12.8.1.1, Eqn. 12.8-2
$C_{S(max)}$ =	0.008	For T<=TL, CS(max) = SD1/(T*(R/I)), ASCE 7-10 Eqn. 12.8-3
$C_{S(min)}$ =	0.010	CS(min) = 0.044*SDS*I >= 0.01, ASCE 7-10 Eqn. 12.8-5
Use: C_S =	0.010	$C_{S(min)} <= C_S <= C_{S(max)}$

Seismic Base Shear:

V =	17.56	kips, V = C_S*W, ASCE 7-10 Section 12.8.1, Eqn. 12.8-1

Seismic Shear Vertical Distribution:

Distribution Exponent, k = 1.56 k = 1 for T<=0.5 sec., k = 2 for T>=2.5 sec.
k = (2-1)*(T-0.5)/(2.5-0.5)+1, for 0.5 sec. < T < 2.5 sec.

Lateral Force at Any Level: $F_x = C_{vx}*V$, ASCE 7-10 Section 12.8.3, Eqn. 12.8-11, page 91

Vertical Distribution Factor: $C_{vx} = W_x*h_x$^k/(ΣW_i*h_i^k), ASCE 7-10 Eqn. 12.8-12, page 91

Figure 4.2.2.4 Base Shear Information

Table 4.2.2.1 Base Shear

Seismic Level x	Weight, Wx (kips)	hx^k (ft.)	Wx*h^k (ft-kips)	Cvx (%)	Shear, Fx (kips)	Σ Story Shears
9	115.63	960.492	111059.2	0.165	2.90	2.90
8	214.76	784.283	168433.0	0.251	4.40	7.31
7	214.76	621.254	133420.7	0.199	3.49	10.80
6	214.76	472.308	101433.0	0.151	2.65	13.45
5	214.76	338.592	72716.2	0.108	1.90	15.35
4	214.76	221.631	47597.6	0.071	1.24	16.60
3	214.76	123.605	26545.4	0.040	0.69	17.29
2	214.76	48.062	10321.8	0.015	0.27	17.56
1	137.10	0.000	0.0	0.000	0.00	17.56
Σ =	1756.05		671526.9	1.000	17.56	

The structural material costs for the timber frame presented a challenge because of the lack of accessibility of information and limited number of manufactures in the country. To determine the structural material costs, a case study was referenced to calculate an estimated cost of mass timber panels by volume (Burback & Pei, 2017). The cross-laminated timber floor panels, bearing wall panels and shear wall panels were considered for the structural material cost estimate. The total structural material cost for the mass timber frame was estimated to be $5,464,000.

Table 4.2.2.2 Timber Structural Material Costs

Structural Element	Volume ($114.76/ft^3)	Total
CLT Floor Panel	22,176 ft^3	$2,545,000
CLT Wall Panel	21,914 ft^3	$2,515,000
	Total	$5,464,000

Figure 4.2.2.5 Mass Timber Architectural Model 3D View

4.3 Develop a Decision Framework to Quantify the Effectiveness of Mass Timber Compared to Steel and Concrete in Structures

The survey data collected provided a ranking of which criteria was considered most important by industry professionals when designing a building. Table 4.3.1 shows the criteria listed from ranked most to least important. The exception to this was the ‘Performance’ criteria, as the team determined through Objective 2 and interviews with industry professionals that when designed correctly, both steel and timber will perform.

Table 4.3.1 Performance Criteria Matrix

Criteria	A	B	C	D	E	F	G	Total	%
A. Cost	A	a	a	a	a	a	a	6	27%
B. Schedule		B	b	b	b	b	g	4	18%
C. Ease of Construction			C	d	c	c	g	2	9%
D. Aesthetic				D	d	d	g	3	14%
E. Environmental/Sustainable Impact					E	e	g	1	5%
G. Acess to Materials						F	g	1	5%
H. Performance							G	5	23%

The team then ranked the performance of each material in each criteria listed from a scale of 1-10 based on the knowledge gained from completing the previous Objectives. This created a quantifiable measurement of how each material will perform.

Table 4.3.2 Performance Rating Matrix

Criteria	Unit of Measurement	Criteria Weight	Concept	Performance Rating										Total Performance
				1	2	3	4	5	6	7	8	9	10	
COST	iew, Survey Data, Case	27	Steel						6					162
			Mass Timber					5						135
SCHEDULE	Interview, Survey Data	18	Steel						6					108
			Mass Timber							7				126
EASE OF CONSTRUCTION	Interview, Survey Data	9	Steel							7				63
			Mass Timber								8			72
AESTHETIC	Interview, Survey Data	14	Steel						6					84
			Mass Timber								8			112
ENVIRONMENT	Interview, Survey Data	5	Steel				4							20
			Mass Timber					5						25
ACESS TO MATERIALS	Qualitative	5	Steel									9		45
			Mass Timber	1										5
PERFORMANCE	Interview, Survey Data	23	Steel									9		207
			Mass Timber									9		207

The final product of this objective was the Performance Measure Form (Table 4.3.3). The form contains a numerical based breakdown of how each material performs under each set of criteria. It also sums the total performance in order to compare the overall performance of steel and mass timber. The takeaways from this form were that according to Table 4.3.3 a steel building would perform 1% better than a mass timber building.

Table 4.3.3: Performance Measure Form (Decision Framework)

CRITERIA	Performance	Steel Design	Mass Timber
Cost	Measure	Interview, Su	Interview, Survey Data, Case Study
	Rating	6	5
	Weight	27	27
	Contribution	162	135
Schedule	Measure	Interview, Su	Interview, Survey Data
	Rating	6	7
	Weight	18	18
	Contribution	108	126
Ease of Construction	Measure	Interview, Su	Interview, Survey Data
	Rating	7	8
	Weight	9	9
	Contribution	63	72
Aesthetic	Measure	Interview, Su	Interview, Survey Data
	Rating	6	8
	Weight	14	14
	Contribution	84	112
Environment	Measure	Interview, Su	Interview, Survey Data
	Rating	4	5
	Weight	5	5
	Contribution	20	25
Access to Materials	Measure	Qualitative	Qualitative
	Rating	9	1
	Weight	5	5
	Contribution	45	5
Performance	Measure	Interview, Su	Interview, Survey Data
	Rating	9	9
	Weight	23	23
	Contribution	207	207
	Total Performance:	837	826
	Net Change in Performance:		-1%

5.0 Conclusion

The three objectives of the project were completed. The project team members learned a lot about the advantages and disadvantages of mass timber through background research, and interview and survey data. Objective 2 was completed by designing a steel building and a mass timber building.Objective 3 was completed by using the information we had compiled and creating a measurement form that could quantifiably compare the usage of mass timber and steel in buildings. After completing these objectives the team concluded that although mass timber has many benefits it will still take time for it to become widespread and truly compete with concrete and steel in the United States. Our survey data suggested that the most important criteria to members of the construction and design industry is cost. Although our structural cost estimates do not provide an accurate estimate for the cost of the entire buildings, (especially the steel frame which does not include any walls or enclosures) it still showed a noticeable gap in the current cost of raw materials. There are still too many variables in the construction industry to measure cost other than material cost. This was emphasized by the construction professionals that we interviewed. Since there is a lack of knowledge, experience, and manufacturing, contractors will offset these unknowns through the bid process. This associated risk and lack of knowledge can lead to higher initial costs for a cross-laminated timber project when compared to steel and concrete projects. Our interview contacts informed us that only clients that are concerned about sustainability impacts over cost have been choosing mass timber materials over steel and concrete. However, our interview data also shows that the construction and design industry has significant interest in mass timber products, and many believe that in the long run a cross-laminated building can be less expensive due to the factors like its decrease in construction time, lightweight design, and energy efficiency. If those interests can create more opportunities for hybrid building designs, it could provide a demand for increased manufacturing. This would create competition to begin to offset the material costs while increasing experience and familiarity within the industry.

6.0 Discussion of Future Projects

After completing this project some ideas and suggestions for future projects include: the investigation and design of a hybrid timber and steel building. The building at UMass visited by the team was a hybrid timber and steel building. This building showed that hybrid buildings can be often easier to construct and a viable option for building owners and designers. Looking into the benefits of a hybrid style building versus a full CLT building could create an interesting project. Researching the connections of steel to timber members could also be useful.

Another area of research that could be useful to the CLT community is vibration analysis. One of the issues and relatively little researched areas of CLT construction is how sounds and vibrations travel through CLT members. Looking into the design of noise dampening or vibration proof wooden members could be important research.

Through the research done in this report it was determined that one of the main hindrances in the CLT is the lack of knowledge and experience in the field. Because of the initial costs and bidding prices of projects are higher. A future project could research ways in which to lower these costs and help the expanded use of CLT in construction.

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Appendix A: Project Proposal

Mass Timber

A Major Qualifying Project Proposal

Submitted on

October 10th, 2019

Submitted to:

Project Advisor: Professor Leonard Albano, Civil and Environmental Engineering, WPI

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Introduction:

Mass timber is a growing alternative to steel and concrete materials in high-rise structures. Mass timber, or cross-laminated timber, is a wood panel consisting of several layers of panels stacked in alternating directions, held together by structural adhesives or laminates. Mass timber construction practices started to gain popularity in Europe and Australia over 20 years ago, and it is starting to spread to North America. In North America, mass timber is currently a big topic of interest among the design and construction industry which includes engineers, professors, architects, designers, project managers, superintendents, laborers, etc. This is due to the numerous advantages to constructing with mass timber, including speed of construction, lightweight frame, and a negative carbon footprint. However, some limitations have hindered the application of mass timber in North America. Some disadvantages are the lack of mass timber experience in North America, inflexibility during construction, and the cost.

The goal of our project is to research and evaluate the usage of mass timber in vertical high-rise structures. To accomplish this goal we have identified three objectives:

Objective 1: Identify the advantages and disadvantages of using mass timber in high-rise structures

Objective 2: Design and analyze an 8-story residential building to compare the usage of mass timber and steel

Objective 3: Develop a decision framework to quantify the effectiveness of mass timber compared to steel and concrete in high-rise structures

We plan on completing the structural design and analysis of an 8-story high-rise residential building by remodeling a 5-story residential/commercial building built on 126 Chandler Street. To gain more insight on the challenges of using mass timber in high-rise buildings, we will be performing background research and reaching out to engineers, architects, contractors, and manufacturers that have experience with the design and construction of buildings using mass timber. The results of our structural analysis and interview data collected will be used to create a decision framework that can help to evaluate the usage of mass timber instead of steel or concrete in high-rise structures.

Capstone Design Statement:

To accomplish the Capstone Design aspect of the project we plan on remodelling a 5-story residential/commercial building. We will be adding three stories to the existing design to create an 8-story high-rise building. We will use this analysis in accordance with interview data collected from industry experts in order to develop decision framework that can help the design and construction industry compare the benefits of building with mass timber versus steel or concrete in high-rise structures. We plan on addressing several constraints during the design of this project.

Sustainability:

To address the sustainability constraint of our capstone design we will be designing two 8-story high-rise buildings: one with mass timber and one with steel. We will be focusing on cross-laminated timber, a sustainable alternative to other structural materials such as steel and concrete. The analyze the sustainability of the two buildings we will be using a number of factors such as CO2 emissions and energy savings.

Economics:

Economics is another constraint to consider during the design of the building at 126 Chandler Street. In order to analyze and compare the economical differences between mass timber versus steel and concrete, the team intends to define different cost parameters such as materials, manufacturing, labor, and estimated time of construction. These cost parameters will help create a more specific comparison between the two strategies. Rather than just calculating the price of the physical building it illustrates a more complete cost of what it takes to produce the building. To accomplish this we will analyze past projects using mass timber along with projects using steel and concrete.

Health and Safety:

For our project we will be addressing the safety concerns that come with the design of a multistory residential building made with CLT or steel. In order to effectively create a safe and livable design, we will use guidelines for CLT found in the *CLT Handbook, ANSI, American Wood Council National Design Specification, and the International Building Code*. For the steel design portion of the project we will adhere to guidelines found in *Massachusetts State Building Code 9th edition* as well as the *American Society of Civil Engineers* and the *International Building Code.*

Ethics:

There are multiple ethical constraints to the design procedure that must be addressed by our group as we complete the project. These concerns include the use of cheap, substandard materials in order to save on project costs or not thoroughly completing certain aspects of design to save time. *The American Society of Civil Engineers* (ASCE) states that "Ethics is integral to all decisions, designs, and services performed by civil engineers." We plan on working ethically throughout the project and adhering the guidelines put in place by the ASCE.

Constructability:

Constructability is another constraint of our design capstone. One constructability constraint the team will address is the lack of experience in construction of mass timber in North America. To address regulations, design factors, and structural analysis the team will reference the *CLT Handbook*, *International Building Code*, and *American Institute of Steel Construction Manual of Steel Construction.*

Background:

Mass timber was first introduced in Austria and Germany during the 1990s. It slowly gained popularity, but the rise of mass timber use in structures is a result of the threat of global climate change. Buildings are responsible for almost 40% of the world's carbon dioxide emissions. Shortly after the turn of the 21st century, the engineering and architecture world became fixated with building 'green' buildings with a focus on sustainability. Mass timber's sustainable advantages make it an ideal choice when designing a building for sustainability. At the start of the 21st century, climate change concerns and the green building movement gave mass timber an introduction to the European structural materials market. Although still a small market, many high-rise mass timber buildings, or 'plyscrapers', have been built all over the world.

One building that helped promote the plyscraper/green building movement in Europe in Australia is Forté, in Victoria Harbour, Melbourne. When constructed back in 2012, it was the first mass timber building constructed in Australia. Standing over ten stories tall, Forte was the tallest mass timber structure in the world at the time of its completion. Forte is a residential building hosting 23 apartments and 4 town houses. Forte's design and construction were a vital piece to the spread of mass timber usage across Australia and Europe because it demonstrated that mass timber could be used in vertical high-rise buildings.

Figure 1: Forte (McAlpine, 2017)

Mjøstårnet, the largest timber building in the world, was designed and constructed in Norway in March 2019. It has 18 stories and measures an impressive 280 feet tall. It is the third largest building in all of Norway and is home to a hotel, restaurants, offices, and apartments. Øystein Elgsaas, a partner at Voll Arkitekter, the designers of Mjøstårnet, said “The most important part of this building is to show that it is possible to build, large, complex timber buildings, and in that fashion inspire others to do the same.”(O’Neill, 2019).

Figure 2: Mjøstårnet (Franklin, 2019)

The current tallest mass timber building in North America is the University of British Columbia's Brock Commons Tallwood House located in Vancouver, Canada. Although it holds the same amount of stories as Mjøstårnet (18), Brock Commons is 90 feet shorter than the Nordic plyscraper. It was recently completed in September 2016 and is home to over 400 students this Fall.

Figure 3: Brock Commons (*Naturally: Wood,* 2018)

Advantages of Mass Timber:

Mass timber is more sustainable than steel or concrete. Wood has the ability to store carbon dioxide throughout its lifecycle. Brock Commons, a mass timber building completed in 2016, has estimated saving over 2432 metric tons of carbon dioxide emissions just by using mass timber and other wood products. That estimate is equivalent to removing 511 cars off the road for a year (*Naturally: Wood*, 2018). Mass timber can also increase the efficiency of energy usage in a building. The tight connections between mass timber panels leave less space for air flow causing an increase in efficiency of heating and cooling systems. Some mass timber buildings have reported up to 2/3rds on energy savings when compared to steel and concrete (*WoodWorks*, 2012).

Another advantage to constructing buildings with mass timber is increased speed of construction.Cross-laminated timber panels are typically 2, 4, 8, or 10 feet in width, up to 60 feet long, and up to 20 inches thick (*CLT Handbook*, 2013*)*. Since mass timber panels are prefabricated, details such as wall or floor connections, window or door frames, and stairs can all be precisely pre-cut to meet the demands of the project. This allows for a shorter project timeline and the option of reducing the amount of workers on site, leading to savings on overall project cost. Brock Commons, a 162,700 square foot building was constructed in only 70 days.

Disadvantages of Mass Timber:

One disadvantage of mass timber is the current lack of experience in the North American industry. There are few North American designers, contractors, subcontractors, and skilled workers who are experienced with mass timber. This is largely due to the lack of mass timber manufacturers. The lack of North American manufacturers also ties in to the disadvantage of cost. Because the design of these mass timber panels is so specific it is often difficult to find domestic manufacturers, thus making the ones that are available very expensive. In contrast, material costs for mass timber in mid-rise residential, commercial, or industrial buildings in Europe are actually 10-25% less expensive than the material costs of buildings using steel and concrete (*WoodWorks, 2012)*.

Another disadvantage of mass timber is the inflexibility during the construction phase. Once mass timber panels have been designed and fabricated, amendments to design cannot be made. This really highlights the importance of communication throughout the project. The owner, designers, and contractors must all be on the same page before construction begins to ensure that the project will be completed to the owner's satisfaction.

One more disadvantage is the lack of knowledge and testing of the lateral load resistance in North America. Engineers, professors, students, researchers, owners and others in the construction industry are currently trying to agree upon a safe R-value, or seismic response modification factor. FEMA P965 has recently declared a R-value of 4.5 for CLT (Richard, 2019). Other buildings have used an R-value that differs from the 4.5 value that FEMA P965 had determined. For example, the John W. Olver Design Building at the University of Massachusetts Amherst was designed by Simpson Gumpertz and Heger in 2017 and an R-value of 3 was used.

*design lateral load = (Sds * Ie / R) * weight of building*

Design Standards and Specifications

The rise of mass timber has led to its inclusion in several engineering publications such as the *CLT Handbook*, *ANSI*, *American Wood Council National Design Specification*, and the *International Building Code*. These publications are creating a standardization of constraints and requirements for the usage of mass timber in design and construction. The *2021 International Building Code* approved the addition of tall wooden structures of up to 18 stories of mass timber. The changes to the *2021 International Building Code* could not have been made without the influence of tall mass timber buildings across the globe such as Forte, Mjøstårnet, and Brock Commons.

Methodology:

The scope of our project can be defined by three separate objectives. Objective 1: Identify the advantages and disadvantages of using mass timber in high-rise structures. This objective will be completed through background research and interviews to give the team an understanding of the benefits of using mass timber to use a basis for comparison. Objective 2: Design and analyze an 8-story residential building to compare the usage of mass timber and steel. The capstone design portion of the project will be completed with Objective 2. Objective 3: Develop a decision framework to quantify the usage of mass timber in high-rise structures. To complete this objective the team will compare the construction techniques of mass timber to typical concrete and steel construction. Comparisons will be made through a decision framework that will clearly show in which areas of construction certain materials excel. The goal for our final project deliverable is to create something easy to understand that could be used by members of the design and construction industry when deciding on what materials to use during construction.

Objective 1: Identify the advantages and disadvantages of using mass timber in high-rise structures

In order to complete Objective 1, the method content analysis will be used. The purpose of Objective 1 is to complete thorough background research and interview design and construction industry professionals in order to gain an understanding of the elements of construction and design for mass timber projects. This knowledge will be vital to complete the proceeding objectives in the project and also give the team a level of expertise on the topic. The knowledge gained throughout Objective 1 will be important to have during project presentation day where the team will be expected to give in-depth answers to questions on the topic.

Content analysis will be completed by identifying thematic codes within various publications. Thematic codes will be chosen based on the scope of the project. Codes need to be relevant to the design and construction processes for the materials researched for the project. Additional codes will be added as more research is done and new information emerges. The team will need to read through research papers, peer reviewed articles, and other documents to determine a list of themes relevant to the scope of the project. From there, information can be gathered from multiple sources and organized by theme. This form of information coding allows for specific subtopics to be researched in depth and multiple sources to be compared. By combining information from multiple sources, data can be inferred and analysed for each separate theme. Analysis of the coded data will lead the team to make inferences about the advantages and disadvantages of using mass timber.

The method of content analysis through text coding will also be used in documents related to steel and concrete construction. One main purpose for coding data is to identify trends or recurring patterns that may appear. Coding our research by grouping the information thematically will create an organizational structure that can easily be referenced and analyzed. By gathering data for the same themes for timber, steel and concrete construction, comparisons can easily be made between materials. The research and gathering of information will contribute to the team's overall expertise on the topic, while the analysis of the coded data will provide a basis for the creation of a decision framework.

We will be requesting interviews with professionals in the design and construction industry. We will target manufacturers, owners, engineers, researchers, superintendents, project managers, and union/laborers. This group will be targeted to diversify the value of criteria for our decision framework among different professions.

Objective 2: Design and analyze an 8-story residential building to compare the usage of mass timber and steel

Our second objective is to design and analyze an 8-story residential building using mass timber in place of steel and concrete. The goal of our design and analysis objective is to learn more about the challenges of designing buildings with mass timber, and to compare and contrast two buildings while satisfying our capstone design requirement. Our plan is to design two buildings: one using a steel frame and one using a cross-laminated timber construction. Both buildings will be modeled off of the drawings of a local 5-story commercial/residential building on 126 Chandler Street in Worcester, Massachusetts. We will start by designing and analyzing the steel frame. We will then size timber panels for the design of our mass timber frame. First, the team will be designing for the gravitational and vertical loads of the buildings. The first design complication of mass timber the team will run into is the design for lateral loads. The team will be considering two options: a lateral steel brace and a concrete core. The team has not yet defined a lateral force-resisting system but will choose the system that best fits the design of the mass timber frame.

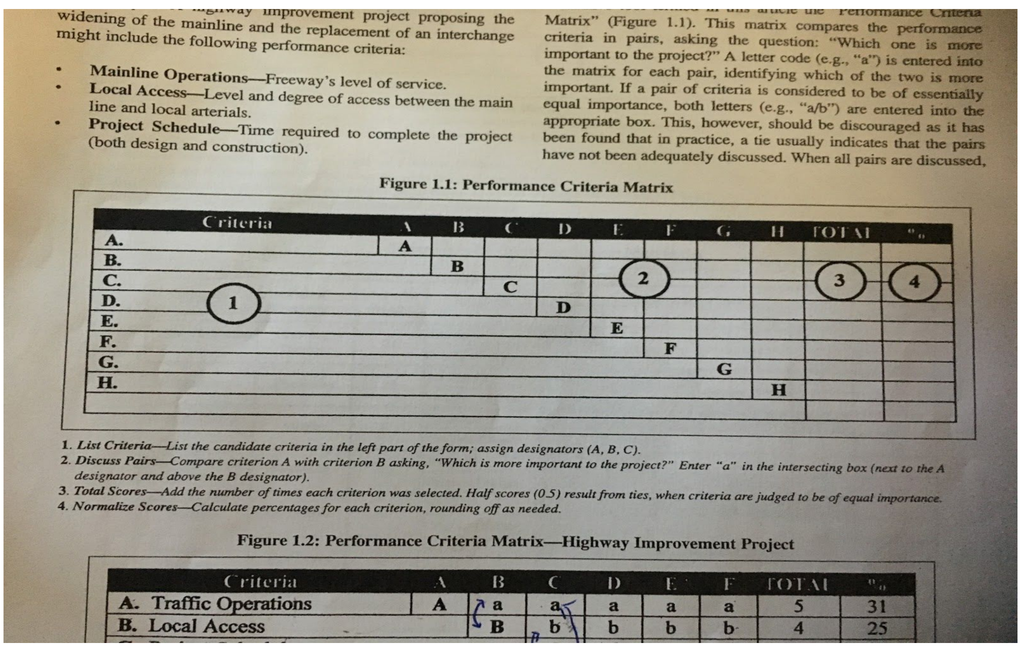
The team will be referencing the *American National Standards Institute*, *CLT Handbook*, and the *American Wood Council National Design Specification* from 2018 for CLT design factors and codes. It will also be referencing the city of Worcester and state of Massachusetts building codes. The team will use structural analysis software to aid in the design and analysis process. Once the design of the two buildings are completed, the team will use the knowledge gained from background research and analysis to create a decision framework to compare and contrast the two designs.

Objective 3: Develop a decision framework to quantify the effectiveness of mass timber compared to steel and concrete in high-rise structures

Our third objective is to develop a decision framework. The mission of objective 3 is to quantify the advantages and disadvantages of using mass timber in North America. To accomplish this, background research and interviews from Objective 1 will be used to help identify criteria and their respective weights for the decision framework.

From this criteria, three or four matrices will be produced, a performance criteria matrix, a performance rating matrix, a performance measure form, and then the final deliverable of a decision framework that will ultimately determine if the effectiveness of mass timber outweighs that of steel and concrete. The main purpose of the performance criteria matrix (Table 1.1) is to assign a list criteria a weight to numerically represent the importance of each criteria. The next matrix will be the performance rating matrix (Table 1.2) to show the comparison of performance between mass timber and steel/concrete for each of the criteria. Next, a decision framework form (Table 1.3) will be created. It will have the measure (degree of impact), rating (scale 1-10 for each criteria), weight (from evaluation criteria matrix), and contribution (rating times weight). All of this will calculate a total performance for both mass timber and steel/concrete. From that a net change in performance between the two will be calculated. The purpose of these matrices is to quantify and clearly identify the advantages and disadvantages of mass timber to determine if it is more effective to use in place of steel and concrete.

Table 1.1 Performance Criteria Matrix



widening of the mainline and the replacement of an interchange might include the following performance criteria:

- **Mainline Operations**—Freeway's level of service.
- **Local Access**—Level and degree of access between the main line and local arterials.
- **Project Schedule**—Time required to complete the project (both design and construction).

Matrix" (Figure 1.1). This matrix compares the performance criteria in pairs, asking the question: "Which one is more important to the project?" A letter code (e.g., "a") is entered into the matrix for each pair, identifying which of the two is more important. If a pair of criteria is considered to be of essentially equal importance, both letters (e.g., "a/b") are entered into the appropriate box. This, however, should be discouraged as it has been found that in practice, a tie usually indicates that the pairs have not been adequately discussed. When all pairs are discussed,

Figure 1.1: Performance Criteria Matrix

Criteria	A	B	C	D	E	F	G	H	TOTAL	%
A.	A									
B.		B								
C.			C		2				3	4
D. 1				D						
E.					E					
F.						F				
G.							G			
H.								H		

1. *List Criteria—List the candidate criteria in the left part of the form; assign designators (A, B, C).*
2. *Discuss Pairs—Compare criterion A with criterion B asking, "Which is more important to the project?" Enter "a" in the intersecting box (next to the A designator and above the B designator).*
3. *Total Scores—Add the number of times each criterion was selected. Half scores (0.5) result from ties, when criteria are judged to be of equal importance.*
4. *Normalize Scores—Calculate percentages for each criterion, rounding off as needed.*

Figure 1.2: Performance Criteria Matrix—Highway Improvement Project

Criteria	A	B	C	D	E	F	TOTAL	%
A. Traffic Operations	A	a	a	a	a	a	5	31
B. Local Access		B	b	b	b	b	4	25

Table 1.2 Performance Rating Matrix

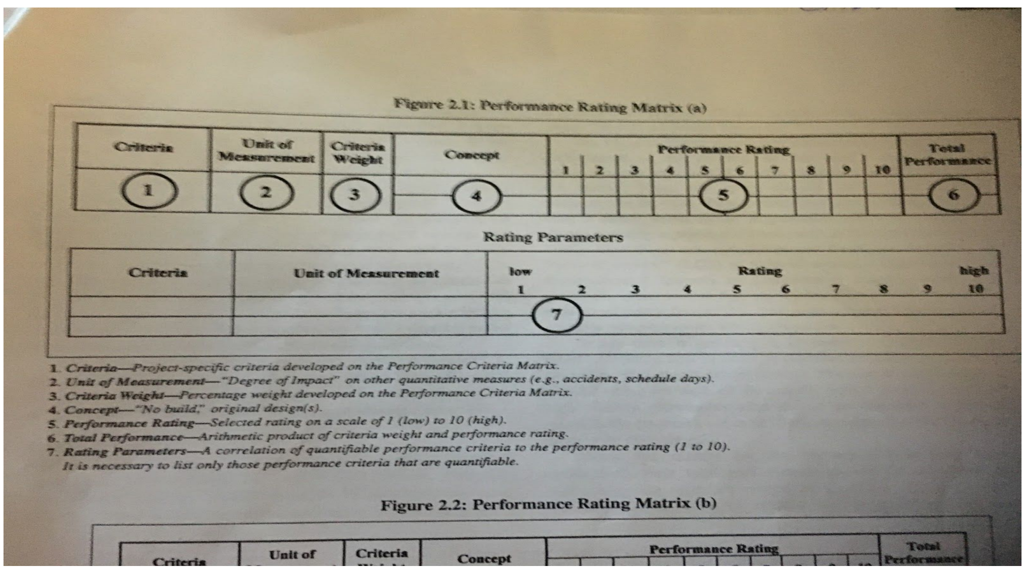


Figure 2.1: Performance Rating Matrix (a)

Criteria	Unit of Measurement	Criteria Weight	Concept	Performance Rating										Total Performance
				1	2	3	4	5	6	7	8	9	10	
1	2	3	4					5						6

Rating Parameters

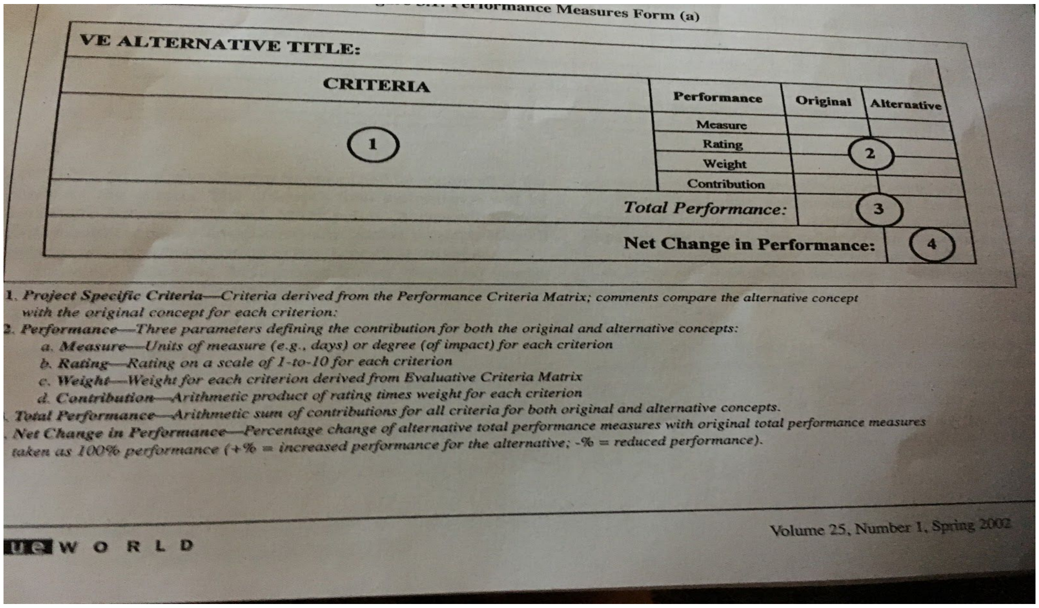
Criteria	Unit of Measurement	low 1	2	3	4	Rating 5	6	7	8	9	high 10
		7									

1. *Criteria—Project-specific criteria developed on the Performance Criteria Matrix.*
2. *Unit of Measurement—"Degree of Impact" on other quantitative measures (e.g., accidents, schedule days).*
3. *Criteria Weight—Percentage weight developed on the Performance Criteria Matrix.*
4. *Concept—"No build," original design(s).*
5. *Performance Rating—Selected rating on a scale of 1 (low) to 10 (high).*
6. *Total Performance—Arithmetic product of criteria weight and performance rating.*
7. *Rating Parameters—A correlation of quantifiable performance criteria to the performance rating (1 to 10).*
   It is necessary to list only those performance criteria that are quantifiable.

Figure 2.2: Performance Rating Matrix (b)

Criteria	Unit of	Criteria	Concept	Performance Rating	Total Performance

Table 1.3 Decision Framework



...Performance Measures Form (a)

VE ALTERNATIVE TITLE:			
CRITERIA	Performance	Original	Alternative
1	Measure		
	Rating	2	
	Weight		
	Contribution		
	Total Performance:	3	
	Net Change in Performance:		4

1. *Project Specific Criteria*—*Criteria derived from the Performance Criteria Matrix; comments compare the alternative concept with the original concept for each criterion:*
2. *Performance*—*Three parameters defining the contribution for both the original and alternative concepts:*
   a. *Measure*—*Units of measure (e.g., days) or degree (of impact) for each criterion*
   b. *Rating*—*Rating on a scale of 1-to-10 for each criterion*
   c. *Weight*—*Weight for each criterion derived from Evaluative Criteria Matrix*
   d. *Contribution*—*Arithmetic product of rating times weight for each criterion*
3. *Total Performance*—*Arithmetic sum of contributions for all criteria for both original and alternative concepts.*
4. *Net Change in Performance*—*Percentage change of alternative total performance measures with original total performance measures taken as 100% performance (+% = increased performance for the alternative; -% = reduced performance).*

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If we decide to look into additional design strategies, The final table developed will be the performance rating matrix of overall production (Table 1.4). This will be used to compare all of the different design strategies and their net performances.

Table 1.4 Performance Rating Matrix of Overall Production

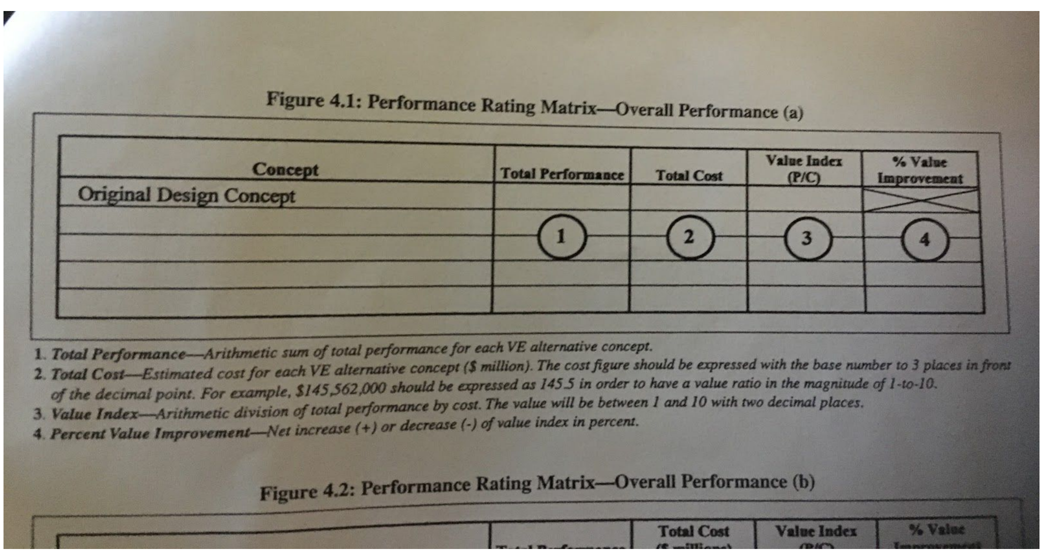


Figure 4.1: Performance Rating Matrix—Overall Performance (a)

Concept	Total Performance	Total Cost	Value Index (P/C)	% Value Improvement
Original Design Concept				
	1	2	3	4

1. *Total Performance*—*Arithmetic sum of total performance for each VE alternative concept.*
2. *Total Cost*—*Estimated cost for each VE alternative concept ($ million). The cost figure should be expressed with the base number to 3 places in front of the decimal point. For example, $145,562,000 should be expressed as 145.5 in order to have a value ratio in the magnitude of 1-to-10.*
3. *Value Index*—*Arithmetic division of total performance by cost. The value will be between 1 and 10 with two decimal places.*
4. *Percent Value Improvement*—*Net increase (+) or decrease (-) of value index in percent.*

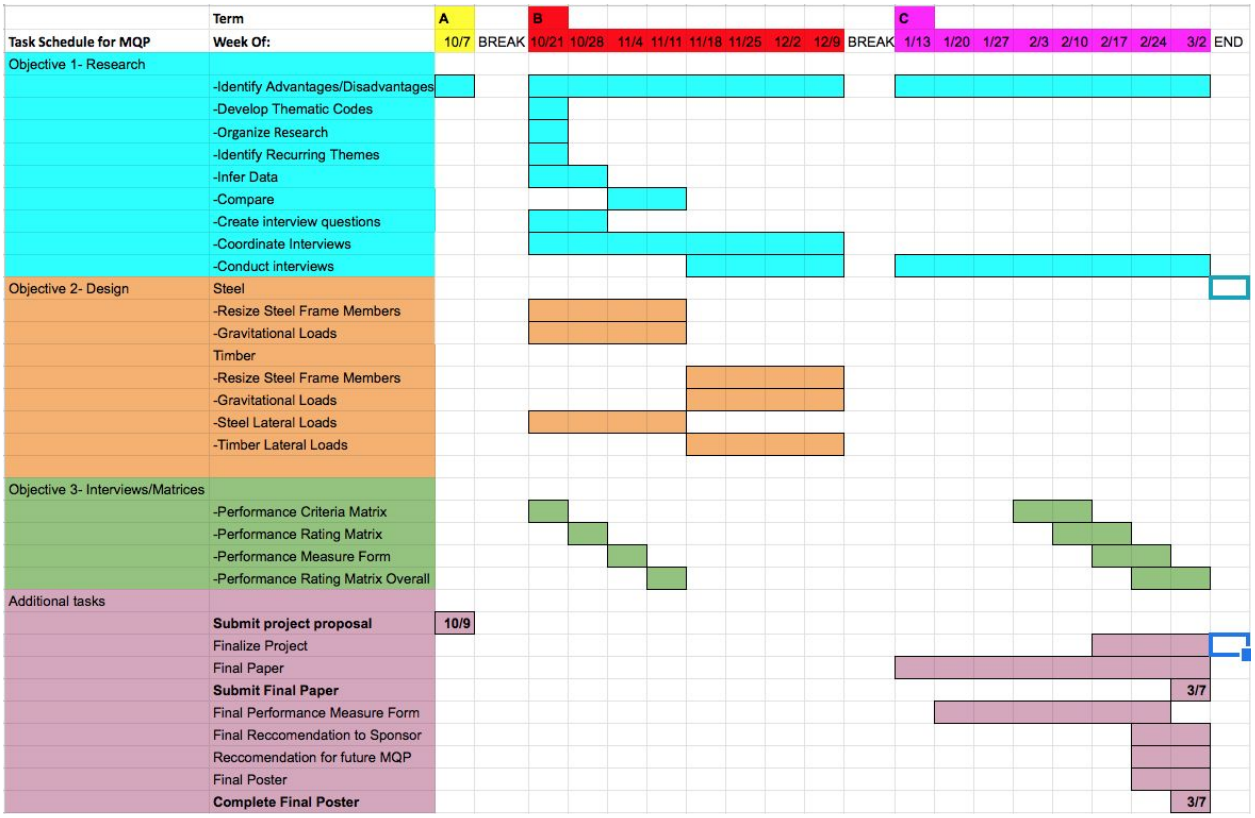
Figure 4.2: Performance Rating Matrix—Overall Performance (b)

	Total Performance	Total Cost ($ millions)	Value Index (P/C)	% Value Improvement

Deliverables

The final deliverables for this project will include the design and analysis of the 8 story residential building at 126 Chandler Street. This design will be completed using both steel and CLT materials. Analysis of each design will be done and in accordance with research and interview data, be used to complete a decision framework. This decision framework will lay out the advantages of each material in an easy to read format. We hope that this could help project owners compare the usage of CLT versus steel and guide them to make decisions that are best for their own particular project. The completion of this project will produce a final MQP report that will document the work done and research collected over the duration of the project. The final MQP report will also include our final capstone design statement and an appendix detailing the work completed. Additionally a poster will be created to be used on project presentation day.

Figure _: Gantt Chart


Term
A
B
C
Task Schedule for MQP
Week Of:
10/7
BREAK
10/21
10/28
11/4
11/11
11/18
11/25
12/2
12/9
BREAK
1/13
1/20
1/27
2/3
2/10
2/17
2/24
3/2
END
Objective 1- Research
-Identify Advantages/Disadvantages
-Develop Thematic Codes
-Organize Research
-Identify Recurring Themes
-Infer Data
-Compare
-Create interview questions
-Coordinate Interviews
-Conduct interviews
Objective 2- Design
Steel
-Resize Steel Frame Members
-Gravitational Loads
Timber
-Resize Steel Frame Members
-Gravitational Loads
-Steel Lateral Loads
-Timber Lateral Loads
Objective 3- Interviews/Matrices
-Performance Criteria Matrix
-Performance Rating Matrix
-Performance Measure Form
-Performance Rating Matrix Overall
Additional tasks
Submit project proposal
10/9
Finalize Project
Final Paper
Submit Final Paper
3/7
Final Performance Measure Form
Final Reccomendation to Sponsor
Reccomendation for future MQP
Final Poster
Complete Final Poster
3/7

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Appendix B: Design Calculations/Figures

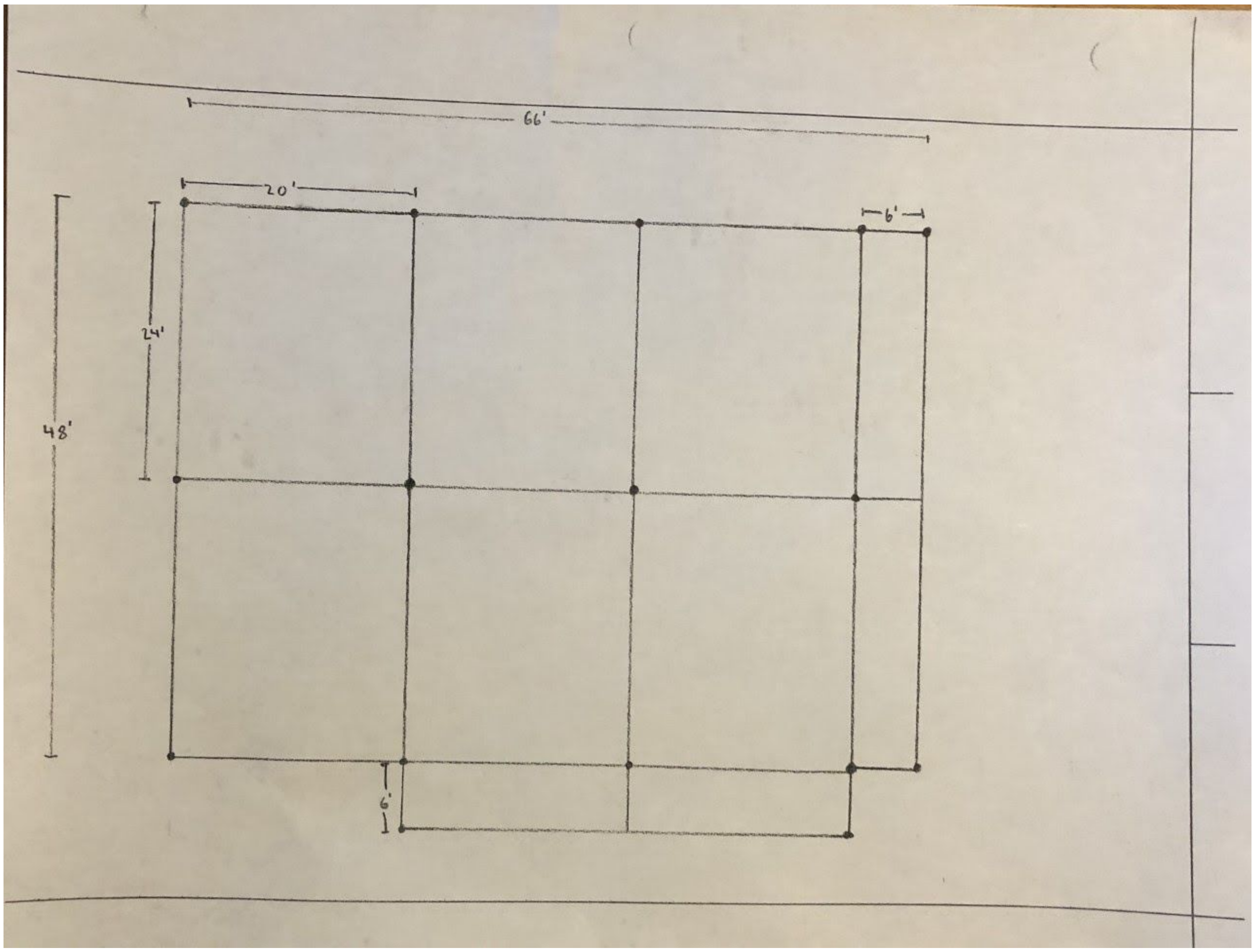


Figure B1: Framing Plan

	A1-2	A2-3	A3-4	B1-2	B2-3	B3-4	C1-2	C2-3	C3-4	D (int)	A4-5	B4-5	C4-5	D2-3	D3-4
DL	1038	1038	1038	1776	1776	1776	1038	1110	1110	648	1038	1776	1038	372	372
LL	1200	1200	1200	2400	2400	2400	1200	1500	1500	1200	1200	2400	1200	300	300
Length	20	20	20	20	20	20	20	20	20	20	6	6	6	20	20
Wu	3165.6	3165.6	3165.6	5971.2	5971.2	5971.2	3165.6	3732	3732	2697.6	3165.6	5971.2	3165.6	926.4	926.4
Mu	158280	158280	158280	298560	298560	298560	158280	186600	186600	134880	14245.2	26870.4	14245.2	46320	46320
kips	158.28	158.28	158.28	298.56	298.56	298.56	158.28	186.6	186.6	134.88	14.2452	26.8704	14.2452	46.32	46.32
Z	42.208	42.208	42.208	79.616	79.616	79.616	42.208	49.76	49.76	35.968	3.79872	7.16544	3.79872	12.352	12.352
	W16x36	W16x36	W16x36	W21x44	W21x44	W21x44	W16x36	W16x36	W16x36	W16x36	W8x28	W8x28	W8x28	W8x28	W8x28
Self Weight	864	864	864	1056	1056	1056	864	864	864	864	201.6	201.6	201.6	672	672
New DL	2109.6	2109.6	2109.6	3187.2	3187.2	3187.2	2109.6	2196	2196	1641.6	1447.2	2332.8	1447.2	1118.4	1118.4
New Wu	4029.6	4029.6	4029.6	7027.2	7027.2	7027.2	4029.6	4596	4596	3561.6	3367.2	6172.8	3367.2	1598.4	1598.4
New Mu	201480	201480	201480	351360	351360	351360	201480	229800	229800	178080	15152.4	27777.6	15152.4	79920	79920
New kips	201.48	201.48	201.48	351.36	351.36	351.36	201.48	229.8	229.8	178.08	15.1524	27.7776	15.1524	79.92	79.92
Phi Check	240.75	240.75	240.75	357.75	357.75	357.75	240.75	240.75	240.75	240	102	102	102	102	102
				95.4											
LL Def	0.000192	0.000192	0.000192	0.000205	0.00018	0.00018	0.000192	0.000241	0.000241	0.000192	7.1253E-06	1.43E-05	7.13E-06	0.00022	0.00022
	0.332512	0.332512	0.332512	0.353418	0.310668	0.310668	0.332512	0.41564	0.41564	0.332512	0.01231246	0.024625	0.012312	0.380014	0.380014
Super Def	0.000359	0.000359	0.000359	0.000356	0.000313	0.000313	0.000359	0.000419	0.000419	0.000296	1.3289E-05	2.48E-05	1.33E-05	0.000493	0.000493
	0.620135	0.620135	0.620135	0.614947	0.540563	0.540563	0.620135	0.723214	0.723214	0.512069	0.02296273	0.042847	0.022963	0.851232	0.851232
Allowable	1	1	1	1	1	1	1	1	1	1	0.3	0.3	0.3	1	1

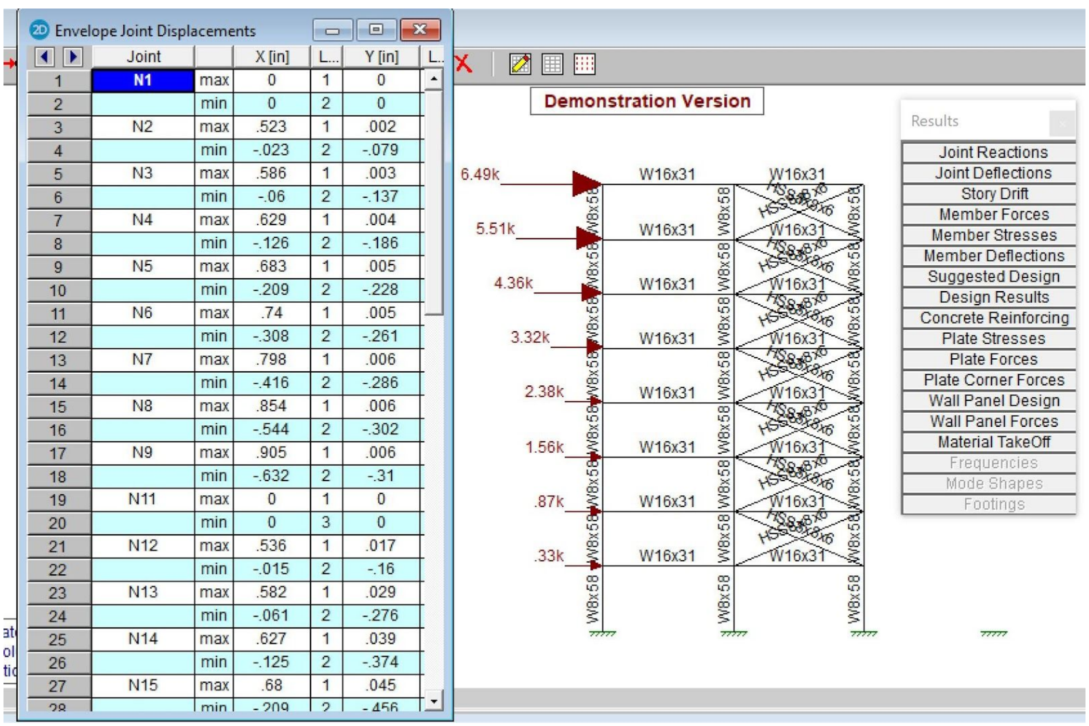
Figure B2: B term Girder Design Calculation Table (East-West)

	A1-B1	A2-B2	A3-B3	A4-B4	B1-C1	B2-C2	B3-C3	B4-C4	D-int	A5-B5	B5-C5	C2-D2	C3-D3	C4-D4
DL	1020	1740	1740	1131	1020	1740	1740	1131	540	372	372	890	1480	890
LL	1000	2000	2000	1300	1000	2000	2000	1300	1000	300	300	1000	2000	1000
Length	24	24	24	24	24	24	24	24	24	24	24	6	6	6
Wu	2824	5288	5288	3437.2	2824	5288	5288	3437.2	2248	926.4	926.4	2668	4976	2668
Mu	203328	380736	380736	247478.4	203328	380736	380736	247478.4	161856	66700.8	66700.8	12006	22392	12006
kips	203.328	380.736	380.736	247.4784	203.328	380.736	380.736	247.4784	161.856	66.7008	66.7008	12.006	22.392	12.006
Z	54.2208	101.5296	101.5296	65.99424	54.2208	101.5296	101.5296	65.99424	43.1616	17.78688	17.78688	3.2016	5.9712	3.2016
	W16x57	W16x77	W16x77	W16x57	W16x57	W16x77	W16x77	W16x57	W16x36	W16x31	W16x31	W8x28	W8x28	W8x28
Self Weigh	1641.6	2217.6	2217.6	1641.6	1641.6	2217.6	2217.6	1641.6	1036.8	892.8	892.8	223.2	201.6	223.2
New DL	2865.6	4305.6	4305.6	2998.8	2865.6	4305.6	4305.6	2998.8	1684.8	1339.2	1339.2	1291.2	1977.6	1291.2
New Wu	4465.6	7505.6	7505.6	5078.8	4465.6	7505.6	7505.6	5078.8	3284.8	1819.2	1819.2	2891.2	5177.6	2891.2
New Mu	321523.2	540403.2	540403.2	365673.6	321523.2	540403.2	540403.2	365673.6	236505.6	130982.4	130982.4	13010.4	23299.2	13010.4
New kips	321.5232	540.4032	540.4032	365.6736	321.5232	540.4032	540.4032	365.6736	236.5056	130.9824	130.9824	13.0104	23.2992	13.0104
Phi Check	393.75	562.5	562.5	393.75	393.75	562.5	562.5	393.75	240	202.5	202.5	102	102	102
LL Def	0.000197	0.000268	0.000487	0.000255	0.000197	0.000268	0.000268	0.000255	0.000197	0.000119	0.000119	5.94E-06	1.18754E-05	5.94E-06
	0.339594	0.463806	0.841217	0.441472	0.339594	0.463806	0.463806	0.441472	0.339594	0.20593	0.20593	0.01026	0.02052076	0.01026
Super Def	0.000397	0.000502	0.00091	0.000478	0.000397	0.000502	0.000502	0.000478	0.000303	0.000267	0.000267	4.04E-05	7.44485E-05	4.04E-05
	0.68598	0.867318	1.573076	0.825554	0.68598	0.867318	0.867318	0.825554	0.522975	0.461283	0.461283	0.069869	0.128647059	0.069869
Allowable	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	0.3	0.3	0.3

Figure B3: B term Girder Design Calculation Table (North-South)

LL	12000	24000	24000	15600	24000	48000	48000	31200	12000	27000	30000	18600
SL	4800	9600	9600	6240	9600	19200	19200	12480	4800	10800	12000	7440
Pu	214041.6	138297.6	138297.6	94125.6	144715.2	213715.2	212635.2	142713.6	214041.6	130122	137646	97614
kips	214.0416	138.2976	138.2976	94.1256	144.7152	213.7152	212.6352	142.7136	214.0416	130.122	137.646	97.614
Size	W8x31											
K	1											
L	12											
rx	3.4744											
ry	2.02											
Capacity Check [r]	41.44601	71.28713										
Fe	56.32167											
Fcr	37.27998											
Pn	306.3296											

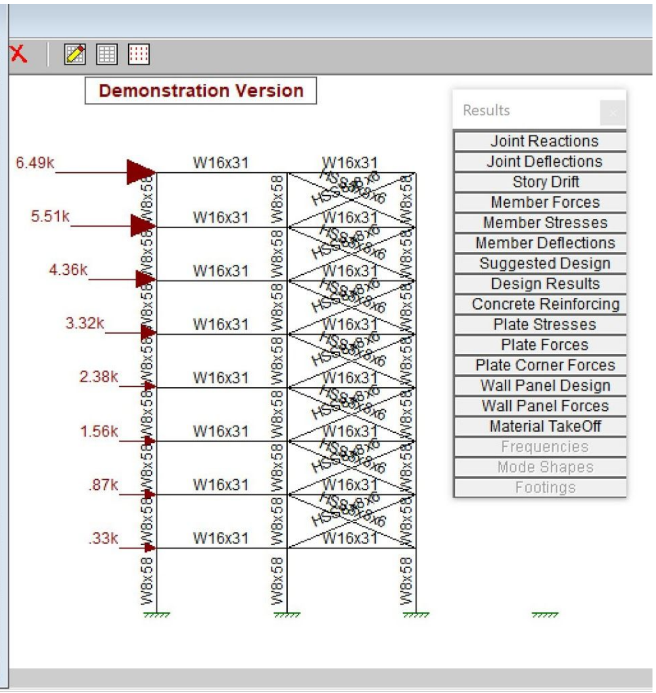
Figure B4: B term Column Calculations



	Joint		X [in]	L...	Y [in]
1	N1	max	0	1	0
2		min	0	2	0
3	N2	max	.523	1	.002
4		min	-.023	2	-.079
5	N3	max	.586	1	.003
6		min	-.06	2	-.137
7	N4	max	.629	1	.004
8		min	-.126	2	-.186
9	N5	max	.683	1	.005
10		min	-.209	2	-.228
11	N6	max	.74	1	.005
12		min	-.308	2	-.261
13	N7	max	.798	1	.006
14		min	-.416	2	-.286
15	N8	max	.854	1	.006
16		min	-.544	2	-.302
17	N9	max	.905	1	.006
18		min	-.632	2	-.31
19	N11	max	0	1	0
20		min	0	3	0
21	N12	max	.536	1	.017
22		min	-.015	2	-.16
23	N13	max	.582	1	.029
24		min	-.061	2	-.276
25	N14	max	.627	1	.039
26		min	-.125	2	-.374
27	N15	max	.68	1	.045
28		min	-.209	2	-.456

Envelope Joint Displacements

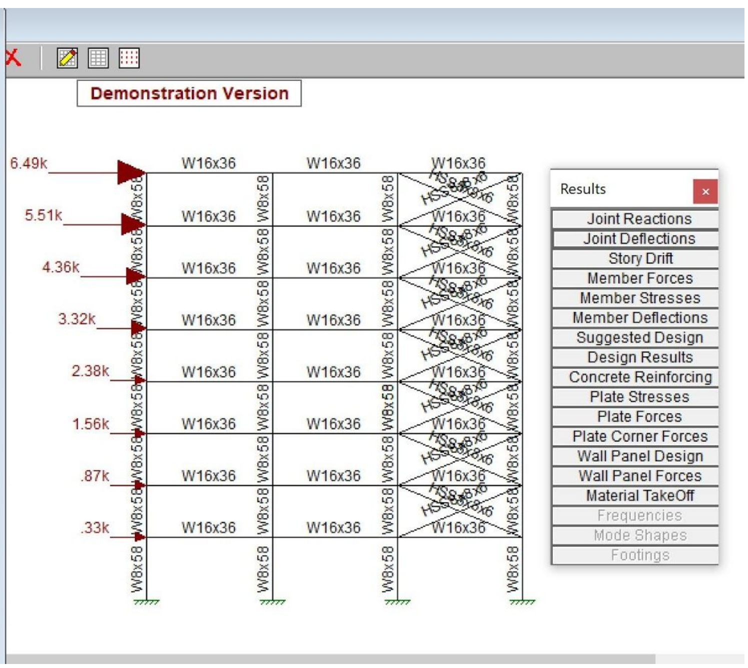
	Joint		X [in]	L...	Y [in]
28		min	-.209	2	-.456
29	N16	max	.735	1	.05
30		min	-.307	2	-.521
31	N17	max	.792	1	.052
32		min	-.417	2	-.571
33	N18	max	.846	1	.053
34		min	-.539	2	-.604
35	N19	max	.897	1	.054
36		min	-.652	2	-.621
37	N20	max	0	1	0
38		min	0	4	0
39	N21	max	.54	1	0
40		min	0	4	-.079
41	N22	max	.58	1	-.002
42		min	-.039	2	-.135
43	N23	max	.627	1	-.002
44		min	-.107	2	-.184
45	N24	max	.679	1	-.003
46		min	-.194	2	-.225
47	N25	max	.735	1	-.004
48		min	-.295	2	-.258
49	N26	max	.791	1	-.005
50		min	-.41	2	-.282
51	N27	max	.845	1	-.005
52		min	-.528	2	-.298
53	N28	max	.895	1	-.006
54		min	-.666	2	-.306

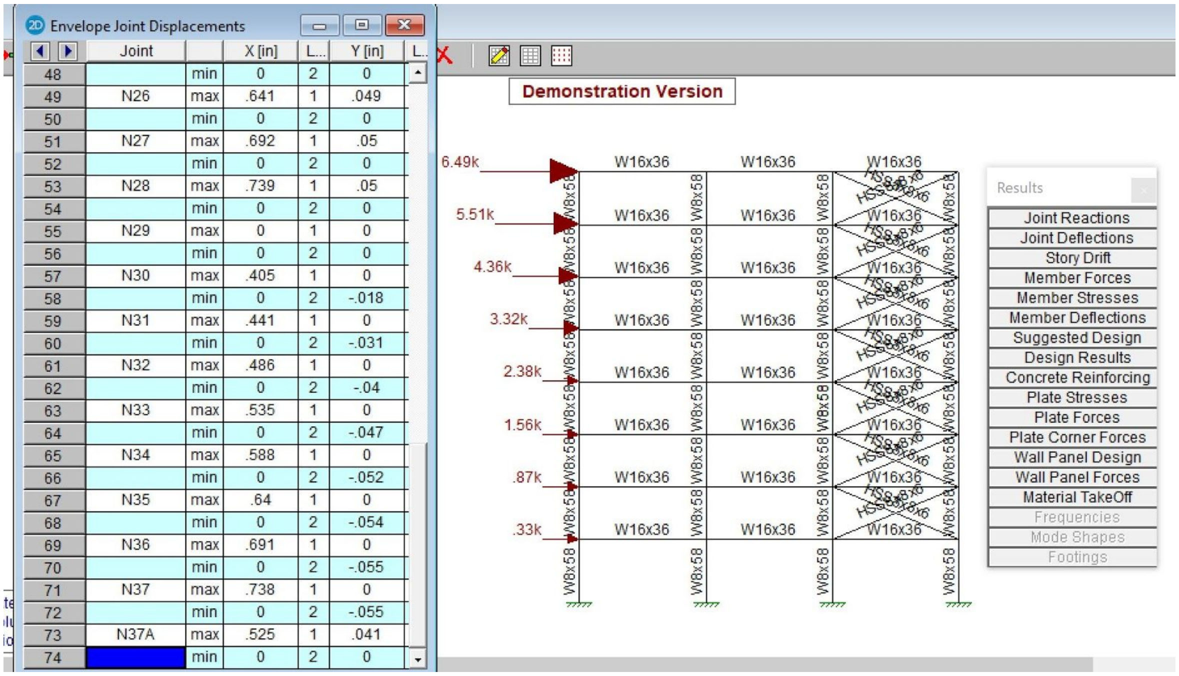


Figures B5.1-2: B term Lateral Load Resisting Braces Girder Bay (East-West)

Envelope Joint Displacements

	Joint		X [in]	L...	Y [in]
1	N1	max	0	1	0
2		min	0	2	0
3	N2	max	.378	1	.001
4		min	0	2	0
5	N3	max	.448	1	.002
6		min	0	2	0
7	N4	max	.49	1	.003
8		min	0	2	0
9	N5	max	.542	1	.003
10		min	0	2	0
11	N6	max	.596	1	.004
12		min	0	2	0
13	N7	max	.651	1	.004
14		min	0	2	0
15	N8	max	.705	1	.004
16		min	0	2	0
17	N9	max	.752	1	.004
18		min	0	2	0
19	N11	max	0	1	0
20		min	0	2	0
21	N12	max	.385	1	0
22		min	0	2	0
23	N13	max	.446	1	0
24		min	0	2	0
25	N14	max	.488	1	.001
26		min	0	2	0
27	N15	max	.539	1	.001




Envelope Joint Displacements

	Joint		X [in]	L...	Y [in]	L...
48		min	0	2	0	
49	N26	max	.641	1	.049	
50		min	0	2	0	
51	N27	max	.692	1	.05	
52		min	0	2	0	
53	N28	max	.739	1	.05	
54		min	0	2	0	
55	N29	max	0	1	0	
56		min	0	2	0	
57	N30	max	.405	1	0	
58		min	0	2	-.018	
59	N31	max	.441	1	0	
60		min	0	2	-.031	
61	N32	max	.486	1	0	
62		min	0	2	-.04	
63	N33	max	.535	1	0	
64		min	0	2	-.047	
65	N34	max	.588	1	0	
66		min	0	2	-.052	
67	N35	max	.64	1	0	
68		min	0	2	-.054	
69	N36	max	.691	1	0	
70		min	0	2	-.055	
71	N37	max	.738	1	0	
72		min	0	2	-.055	
73	N37A	max	.525	1	.041	
74		min	0	2	0	

Figure B6.1-2: B term Lateral Load Resisting Braces Girder Bay (North- South)

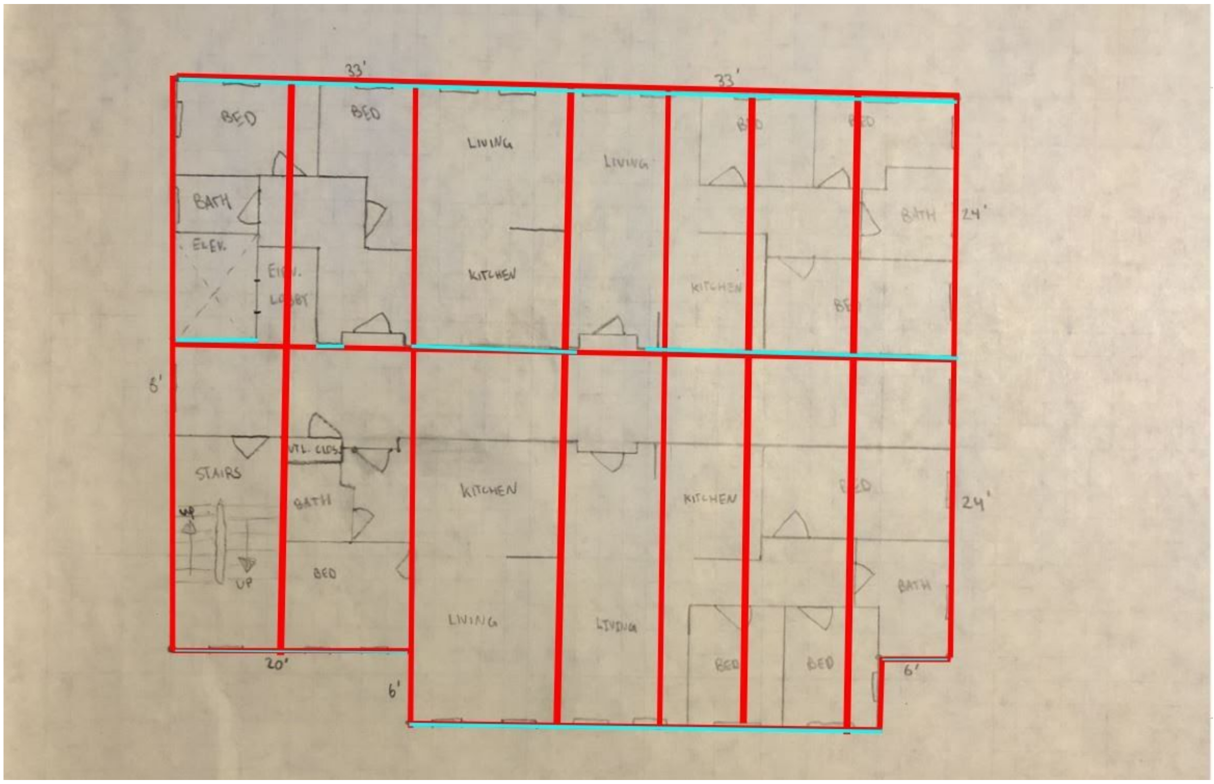


Figure B8: Timber Frame Floor Plan with Panel and Bearing Wall Overlay

Type	F*c (psi)	A (sq. in.)	P*c (kips)	(EI)eff	Ks (=11.8	(GA)eff	L (in)	(EI)app	(EI)'app-min	Pce	Pce/P*c	c (=.9 for CLT)	1st Term	Cp	P' (k/ft width)
3-ply															
E1	1800	33	59.4	115000000	11.8	460000	144	1.01E+08	52191057	24841.1	418.2004	0.9	232.8891	0.99976	59.38576907
E2	1700	33	56.1	102000000	11.8	530000	144	91931899	47657496.52	22683.29	404.3367	0.9	225.187	0.999752	56.08609793
E3	1400	33	46.2	81000000	11.8	350000	144	71573964	37103943.2	17660.17	382.2547	0.9	212.9193	0.999738	46.18788848
E4	1800	33	59.4	115000000	11.8	500000	144	1.02E+08	52716306.01	25091.1	422.4091	0.9	235.2273	0.999763	59.38591113
V1	1350	33	44.55	108000000	11.8	530000	144	96777739	50169579.71	23878.95	536.0034	0.9	298.3352	0.999813	44.54167606
V2	1150	33	37.95	95000000	11.8	460000	144	85009438	44068892.42	20975.24	552.7072	0.9	307.6151	0.999819	37.94312385
V3	1250	33	41.25	95000000	11.8	490000	144	85560326	44354473.17	21111.16	511.7858	0.9	284.881	0.999804	41.24192737
5-ply															
E1	1800	49.5	89.1	440000000	11.8	920000	144	3.46E+08	179298415.6	85339.72	957.7971	0.9	532.665	0.999896	89.09068963
E2	1700	49.5	84.15	389000000	11.8	1100000	144	3.24E+08	167874553.6	79902.36	949.523	0.9	528.0684	0.999895	84.14113018
E3	1400	49.5	69.3	311000000	11.8	690000	144	2.48E+08	128311853.1	61071.92	881.2686	0.9	490.1492	0.999886	69.29212919
E4	1800	49.5	89.1	440000000	11.8	1000000	144	3.52E+08	182420497.4	86825.72	974.475	0.9	541.9305	0.999897	89.0908491
V1	1350	49.5	66.825	415000000	11.8	1100000	144	3.42E+08	177111811.1	84298.97	1261.489	0.9	701.3825	0.999921	66.81969933
V2	1150	49.5	56.925	363000000	11.8	910000	144	2.96E+08	153365516.5	72996.57	1282.329	0.9	712.9605	0.999922	56.92055804
V3	1250	49.5	61.875	363000000	11.8	980000	144	3E+08	155419302.9	73974.1	1195.541	0.9	664.745	0.999916	61.86982105
7-ply															
E1	1800	66	118.8	1089000000	11.8	1400000	144	7.55E+08	391320858.4	186254.9	1567.802	0.9	871.5569	0.999936	118.7924186
E2	1700	66	112.2	963000000	11.8	1600000	144	7.17E+08	371857276	176990.9	1577.459	0.9	876.9219	0.999937	112.1928837
E3	1400	66	92.4	769000000	11.8	1000000	144	5.35E+08	277300994.5	131985.5	1428.414	0.9	794.1191	0.99993	92.39352766
E4	1800	66	118.8	1089000000	11.8	1500000	144	7.71E+08	399492597.1	190144.4	1600.542	0.9	889.7455	0.999937	118.7925738
V1	1350	66	89.1	1027000000	11.8	1600000	144	7.52E+08	389958717.8	185606.6	2083.127	0.9	1157.848	0.999952	89.09572113
V2	1150	66	75.9	898000000	11.8	1400000	144	6.58E+08	341040021	162323	2138.643	0.9	1188.691	0.999953	75.89644969
V3	1250	66	82.5	899000000	11.8	1500000	144	6.7E+08	347518422.1	165406.5	2004.927	0.9	1114.404	0.99995	82.4958835

Figure B9: Table A2 Axial Compression Capacity Table

Appendix C: Survey Using Qualtrics

Figure C1: Format of the Qualtrics Survey

WPI

This form is intended to help collect data for a senior project at Worcester Polytechnic Instit
The goal of our project is to research and evaluate the usage of mass timber in constructio
We will use this data to develop a decision framework and quantify the effectiveness of mas
timber. Then we will compare it's effectiveness to steel and concrete alternatives.

What role do you have in the construction industry?

- Engineer
- Researcher/Professor
- Architect
- Designer
- Project Manager
- Superintendent
- Laborer
- Owner
- other

Prioritze the listed criteria for a construction project (1 being most important, 8 being least important)

Cost

Schedule/being on time

Ease of Construction

Aesthetic

Environmental/Sustainable Impact

Construction Impacts (noise pollution, traffic impedence)

Access to Materials

Performance

Do you have any prior knowledge of mass timber or cross laminated timber?

- Yes
- No
- Maybe

Figure C2: Professions among survey participants

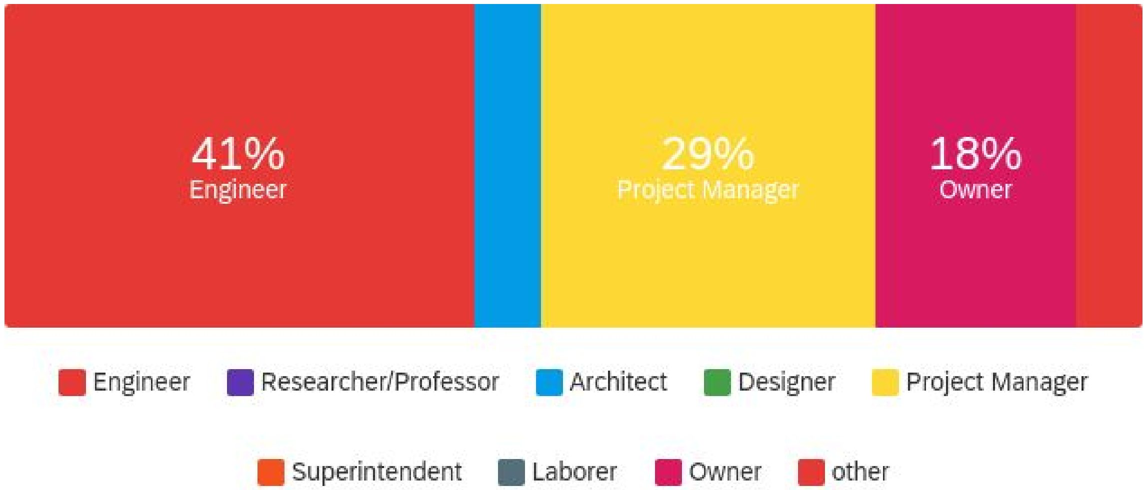


Figure C3: Percentages of prioritization of criteria

Table C4: Survey Criteria Prioritization Data

#	Field	1	2	3	4	5	6	7	8	Total
1	Cost	50.00% 8	31.25% 5	6.25% 1	12.50% 2	0.00% 0	0.00% 0	0.00% 0	0.00% 0	16
2	Schedule/being on time	12.50% 2	37.50% 6	12.50% 2	6.25% 1	25.00% 4	0.00% 0	6.25% 1	0.00% 0	16
3	Ease of Construction	0.00% 0	12.50% 2	12.50% 2	25.00% 4	25.00% 4	12.50% 2	0.00% 0	12.50% 2	16
4	Aesthetic	12.50% 2	6.25% 1	31.25% 5	6.25% 1	12.50% 2	25.00% 4	6.25% 1	0.00% 0	16
5	Environmental/Sustainable Impact	6.25% 1	0.00% 0	12.50% 2	18.75% 3	0.00% 0	25.00% 4	37.50% 6	0.00% 0	16
6	Construction Impacts (noise pollution, traffic impedence)	0.00% 0	0.00% 0	0.00% 0	0.00% 0	6.25% 1	6.25% 1	37.50% 6	50.00% 8	16
7	Access to Materials	0.00% 0	0.00% 0	12.50% 2	0.00% 0	6.25% 1	31.25% 5	12.50% 2	37.50% 6	16
8	Performance	18.75% 3	12.50% 2	12.50% 2	31.25% 5	25.00% 4	0.00% 0	0.00% 0	0.00% 0	16

Showing rows 1 - 8 of 8

Table C5: Performance Criteria Matrix

Criteria	A	B	C	D	E	F	G	Total	%
A. Cost	A	a	a	a	a	a	a	6	27%
B. Schedule		B	b	b	b	b	g	4	18%
C. Ease of Construction			C	d	c	c	g	2	9%
D. Aesthetic				D	d	d	g	3	14%
E. Environmental/Sustainable Impact					E	e	g	1	5%
G. Acess to Materials						F	g	1	5%
H. Performance							G	5	23%

Table C6: Performance Rating Matrix

Criteria	Unit of Measurement	Criteria Weight	Concept	Performance Rating 1	2	3	4	5	6	7	8	9	10	Total Performance
COST	iew, Survey Data, Case	27	Steel						6					162
			Mass Timber					5						135
SCHEDULE	Interview, Survey Data	18	Steel						6					108
			Mass Timber							7				126
EASE OF CONSTRUCTION	Interview, Survey Data	9	Steel							7				63
			Mass Timber								8			72
AESTHETIC	Interview, Survey Data	14	Steel						6					84
			Mass Timber								8			112
ENVIRONMENT	Interview, Survey Data	5	Steel				4							20
			Mass Timber					5						25
ACESS TO MATERIALS	Qualitative	5	Steel									9		45
			Mass Timber	1										5
PERFORMANCE	Interview, Survey Data	23	Steel									9		207
			Mass Timber									9		207

Table C7: Performance Measure Form (Decision Framework)

CRITERIA	Performance	Steel Design	Mass Timber
Cost	Measure	Interview, Su	Interview, Survey Data, Case Study
	Rating	6	5
	Weight	27	27
	Contribution	162	135
Schedule	Measure	Interview, Su	Interview, Survey Data
	Rating	6	7
	Weight	18	18
	Contribution	108	126
Ease of Construction	Measure	Interview, Su	Interview, Survey Data
	Rating	7	8
	Weight	9	9
	Contribution	63	72
Aesthetic	Measure	Interview, Su	Interview, Survey Data
	Rating	6	8
	Weight	14	14
	Contribution	84	112
Environment	Measure	Interview, Su	Interview, Survey Data
	Rating	4	5
	Weight	5	5
	Contribution	20	25
Access to Materials	Measure	Qualitative	Qualitative
	Rating	9	1
	Weight	5	5
	Contribution	45	5
Performance	Measure	Interview, Su	Interview, Survey Data
	Rating	9	9
	Weight	23	23
	Contribution	207	207
	Total Performance:	837	826
		Net Change in Performance:	-1%

Appendix D: Umass Design Building

While gaining information on mass timber and CLT, The team was able to organize a trip to the John W. Olver Design Building at the University of Massachusetts Amherst. The team witnessed a ‘glue up.’ A glue up is when the individual pieces of wood are glued together to form a singular piece of CLT. The adhesive that was used was a polyethylene chemical. The process had to be done very quickly within an hour of starting because the adhesive would dry quickly. Once a thin coating of adhesive was applied the pieces of wood were stacked on top of eachother in a form. The pieces were then compressed together even further by putting a weight on top of the last layer of wood.

The John W. Olver Design Building is a mass timber/steel hybrid building at the University of Massachusetts Amherst. This building was observed for ideas for the mass timber building designed for 126 Chandler Street such as different connection types, a composite of wood and concrete, among other things. Images from the trip can be found below.

This trip would not have been possible without the help of Conrado Araujo and the UMass professors at the John W. Olver Design Building.

Figure D1: Glue Up Process

Figure D2: Spider Connection and 7-ply CLT Staircase

Figure D3: Angled Spline Connection

Figure D4: An example of the Concrete Mass Timber Design

Appendix E: Revit Architectural Model-Timber

The figures in Appendix E present an architectural model of the CLT Building designs. This model is used for visual representation only and does not incorporate actual CLT materials into the design. The floor plan of the building is included with accurate dimensions.

Figure E1: 3D View 1

Figure E2: 3D View 2

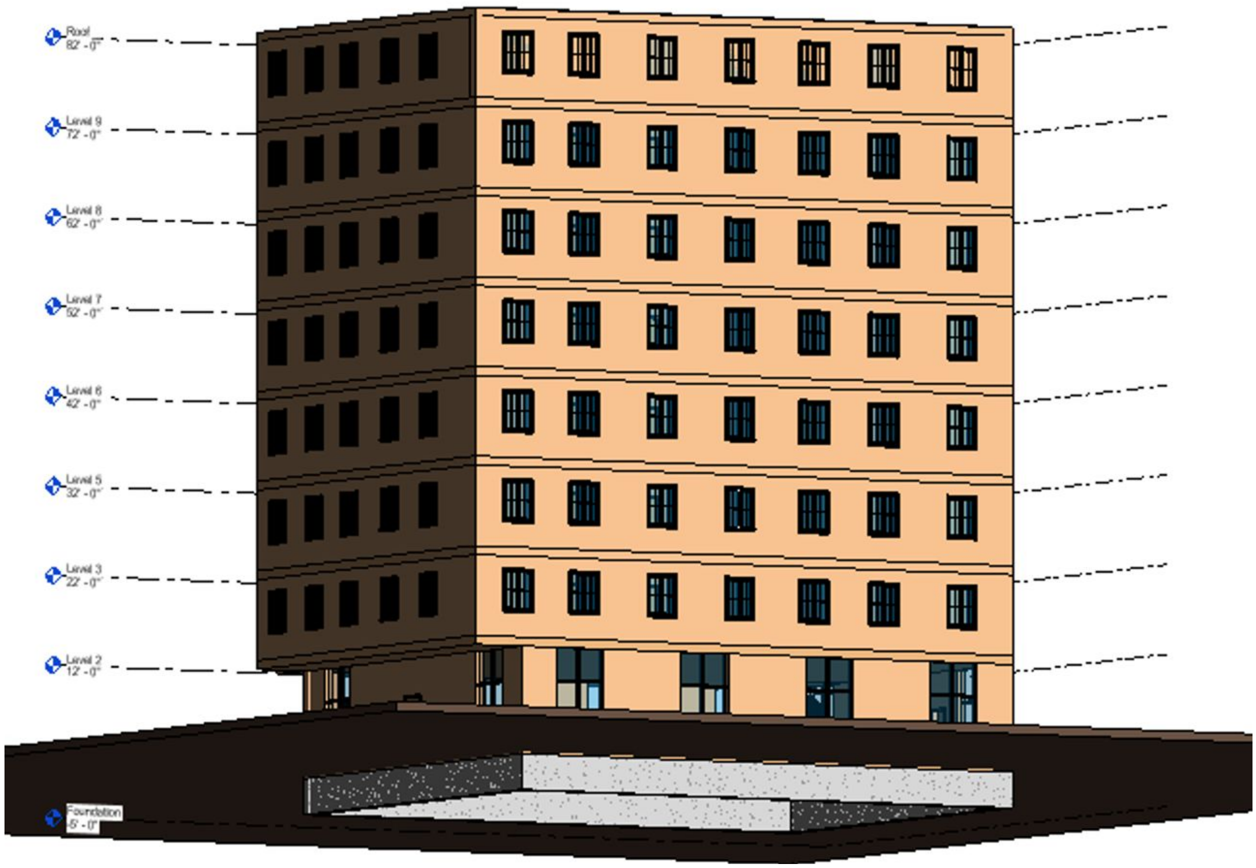


Figure E3: Floor Plan (1st Floor)

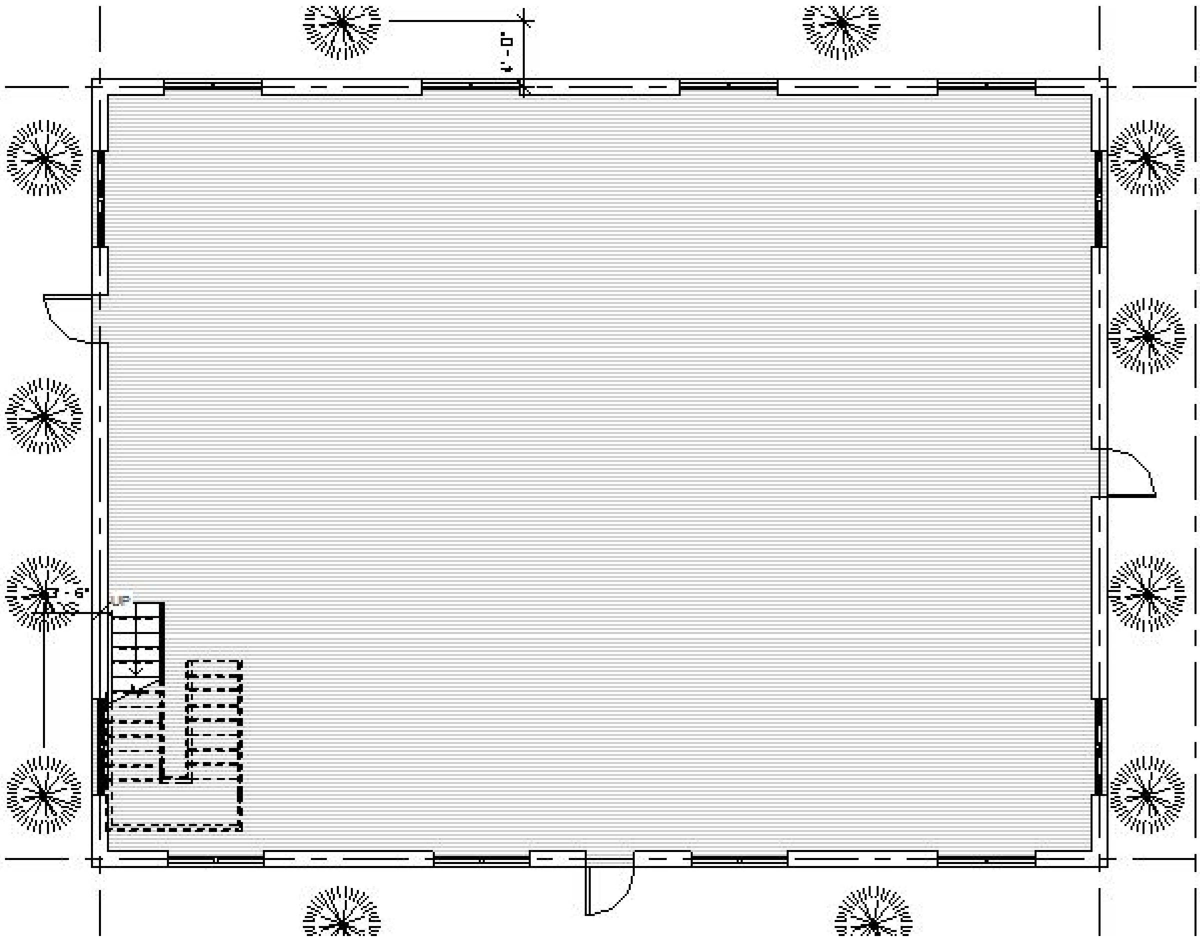


Figure E4: Floor Plan (Floors 2-8)

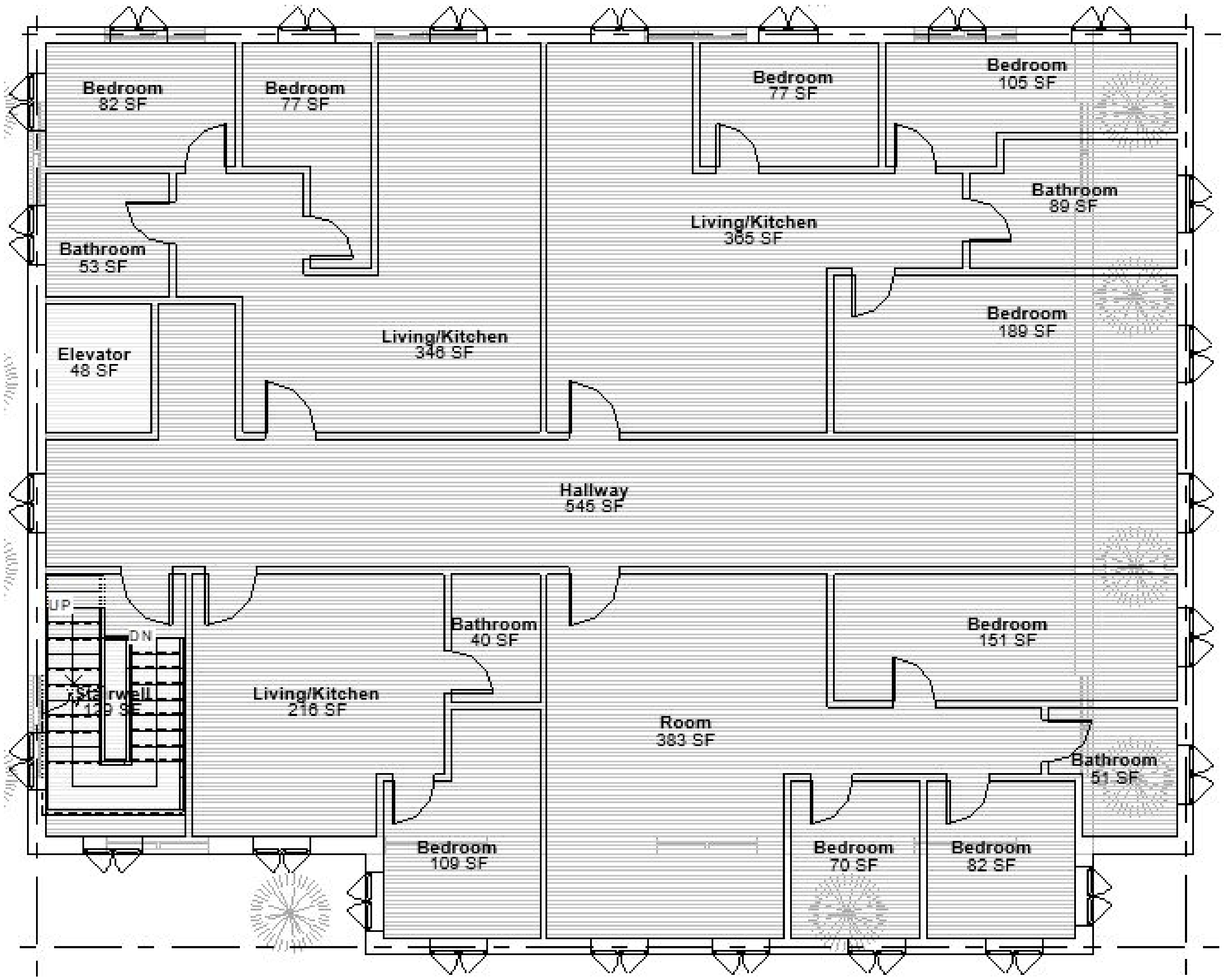


Figure E5: East Elevation View

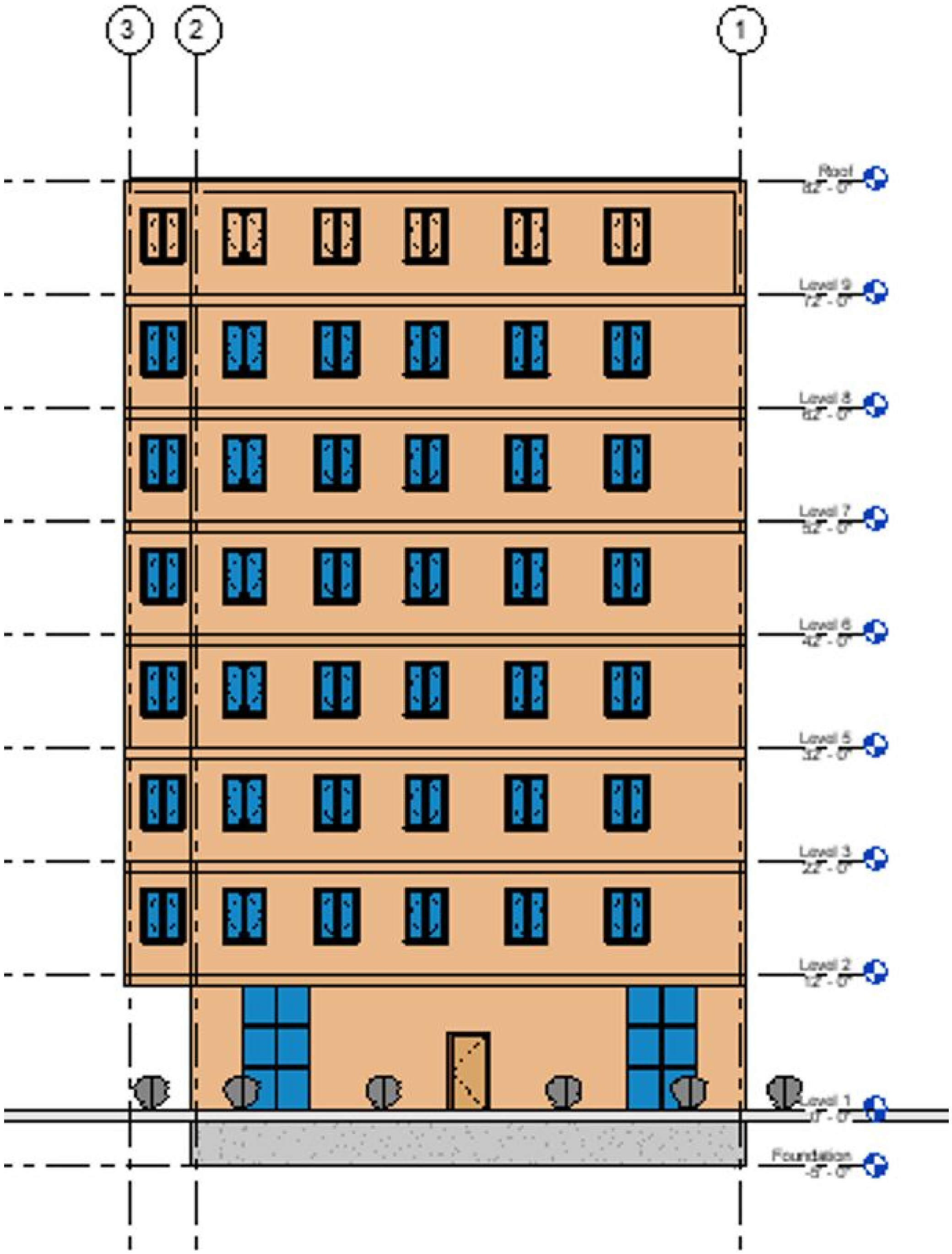


Figure E6: North Elevation View

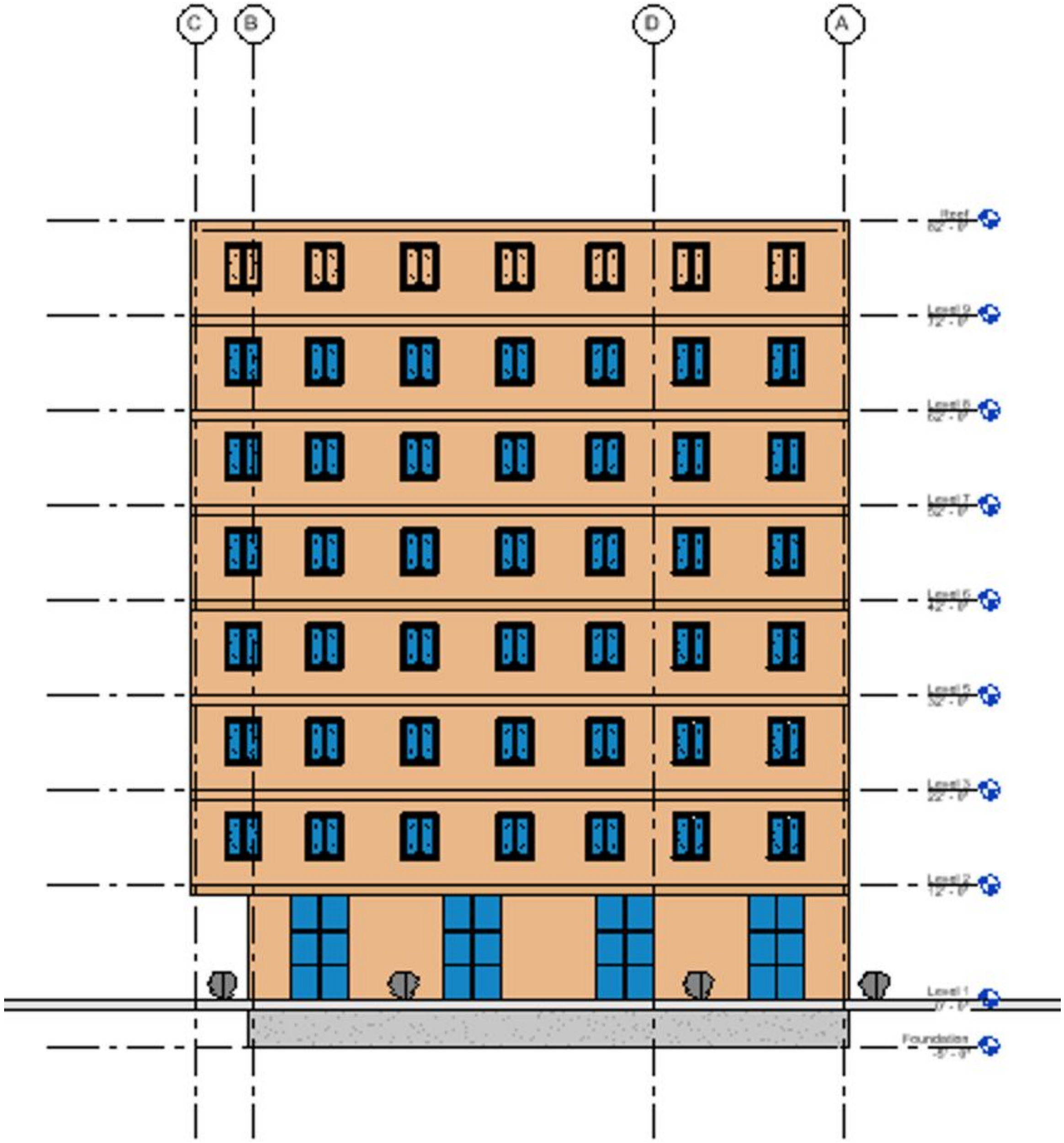


Figure E7: South Elevation View

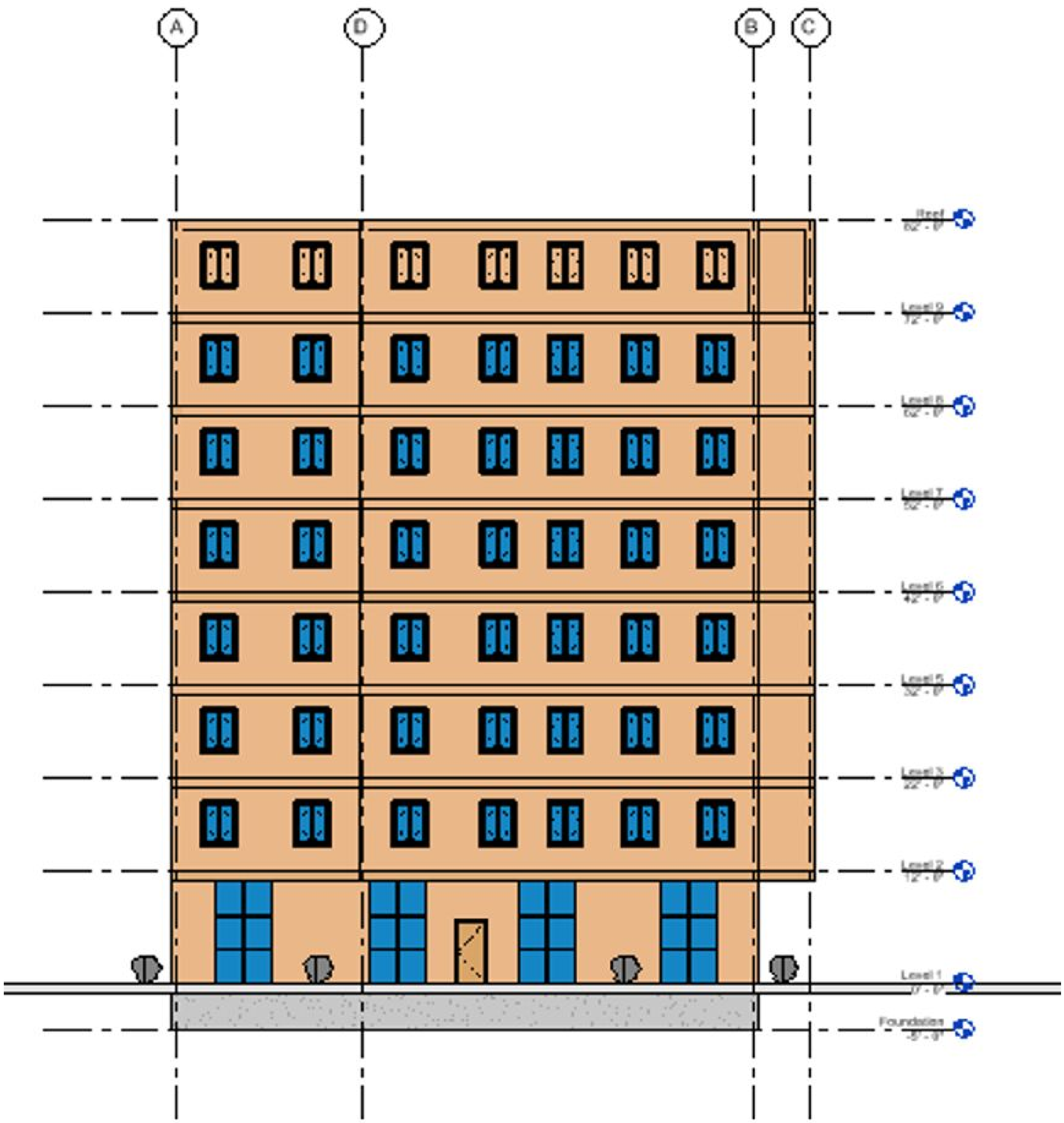
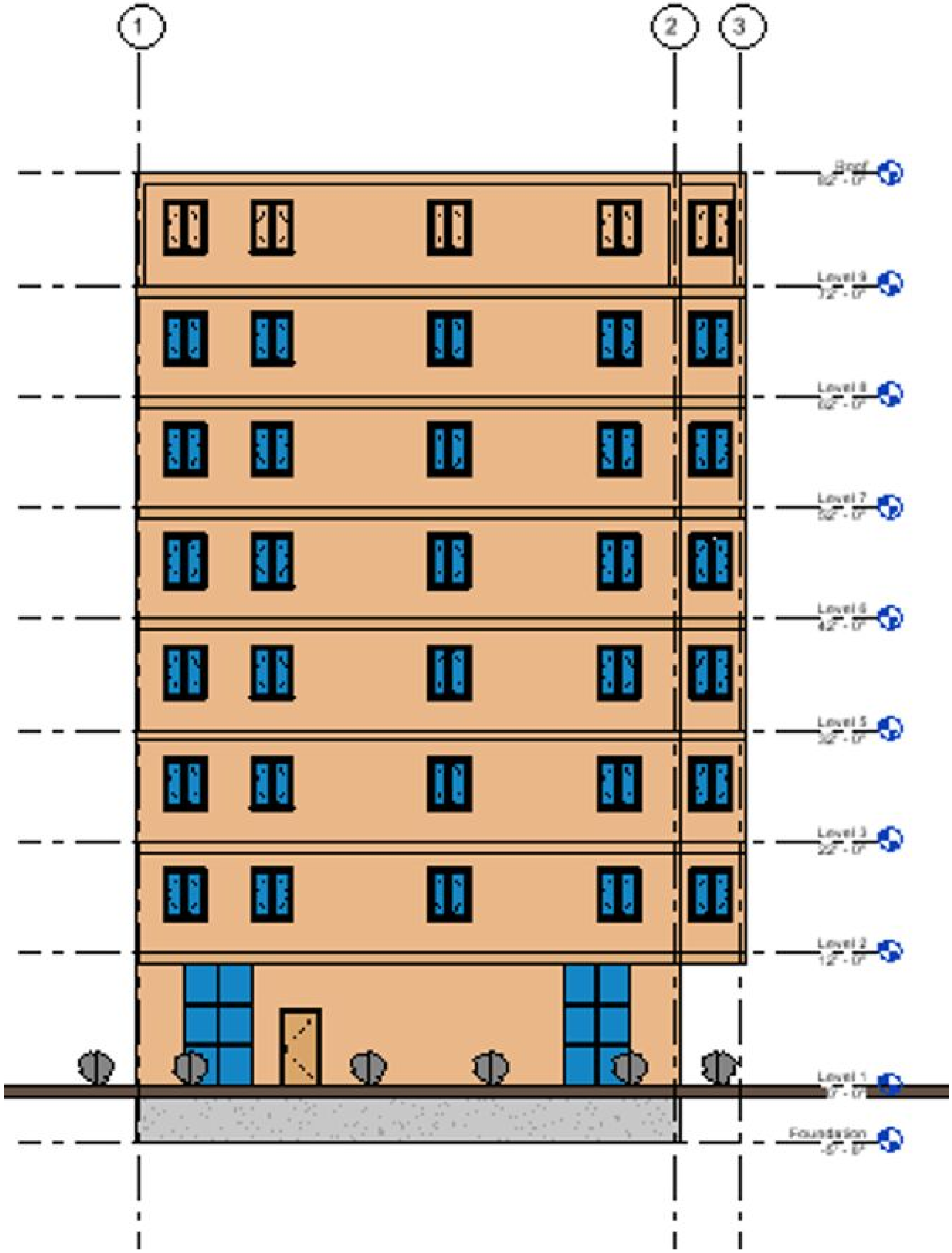


Figure E8: West Elevation View



Appendix F: Revit Architectural Model-Steel

The figures in Appendix F present a structural model of the steel frame design. This model is used for visual representation only. It incorporates the steel member section sizes into the design.

Figure F1: 3D View 1

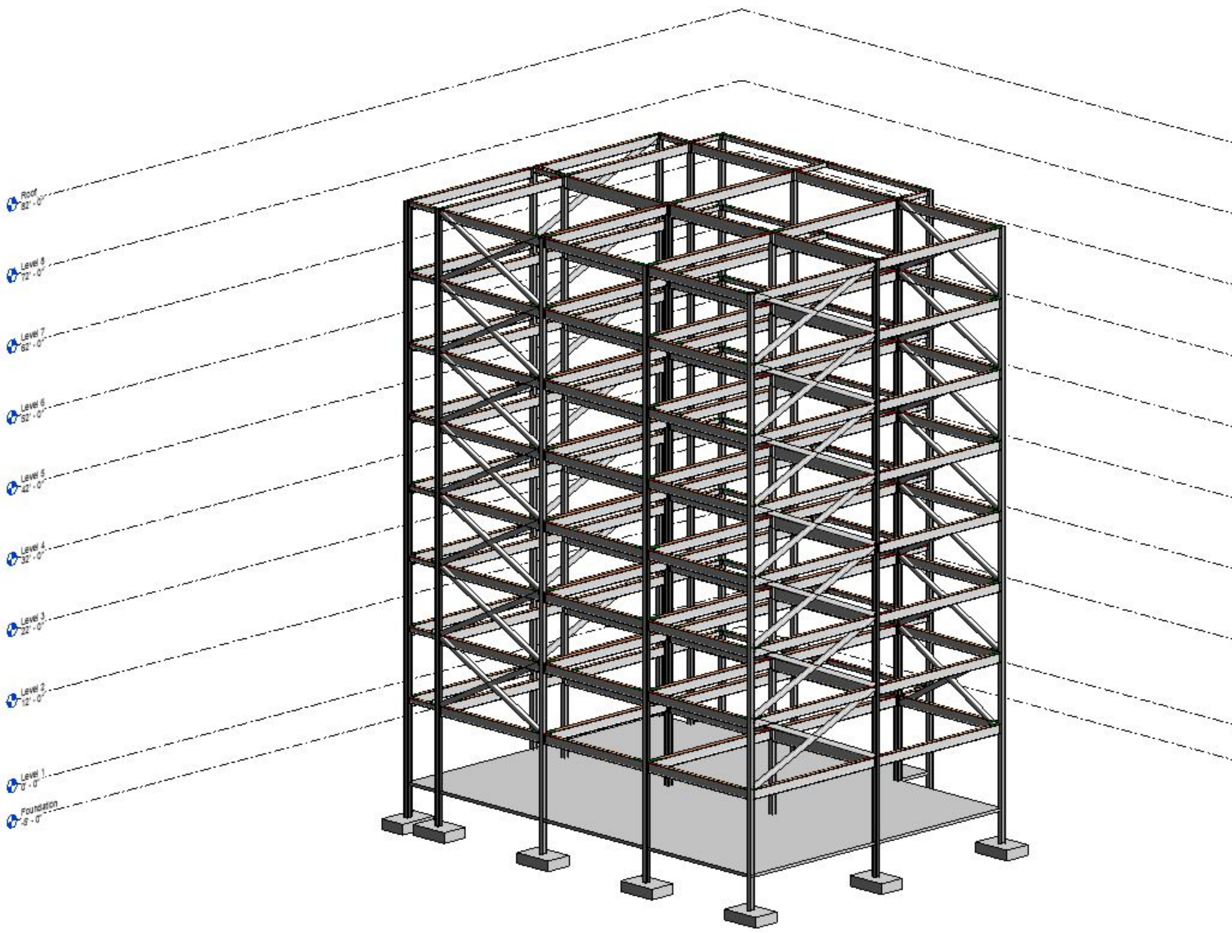


Figure F2: 3D View 2

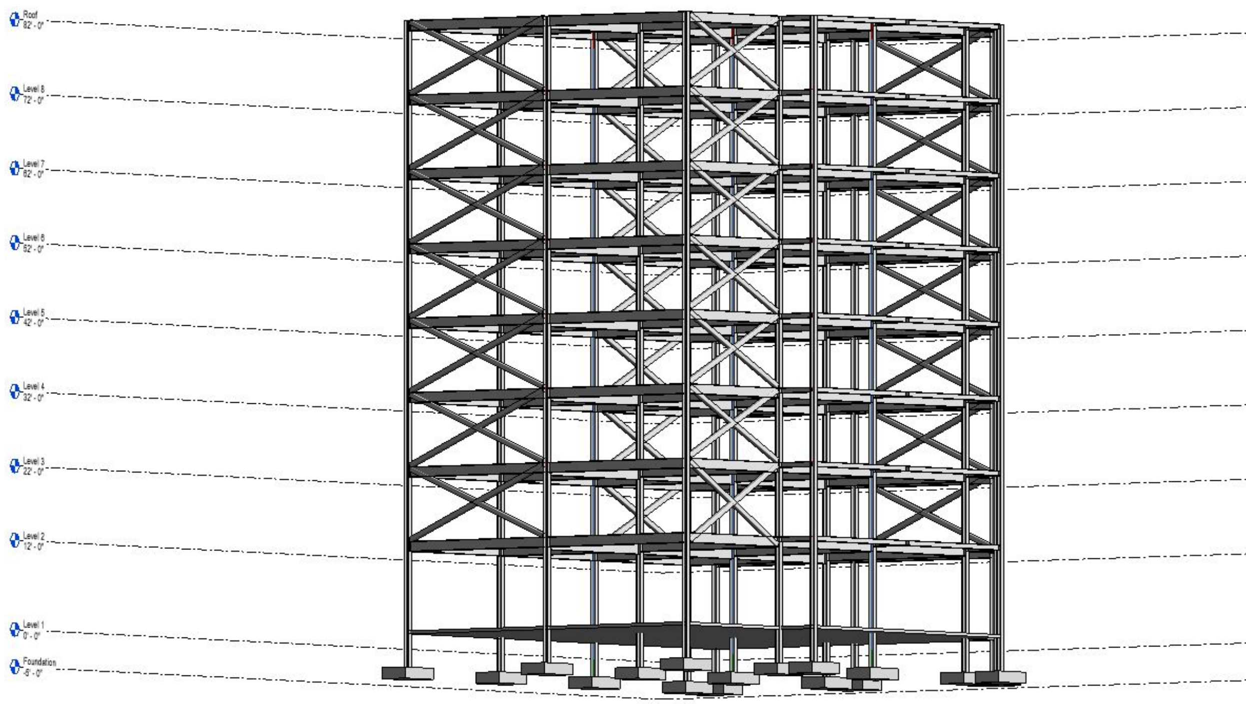


Figure F3: East Elevation View

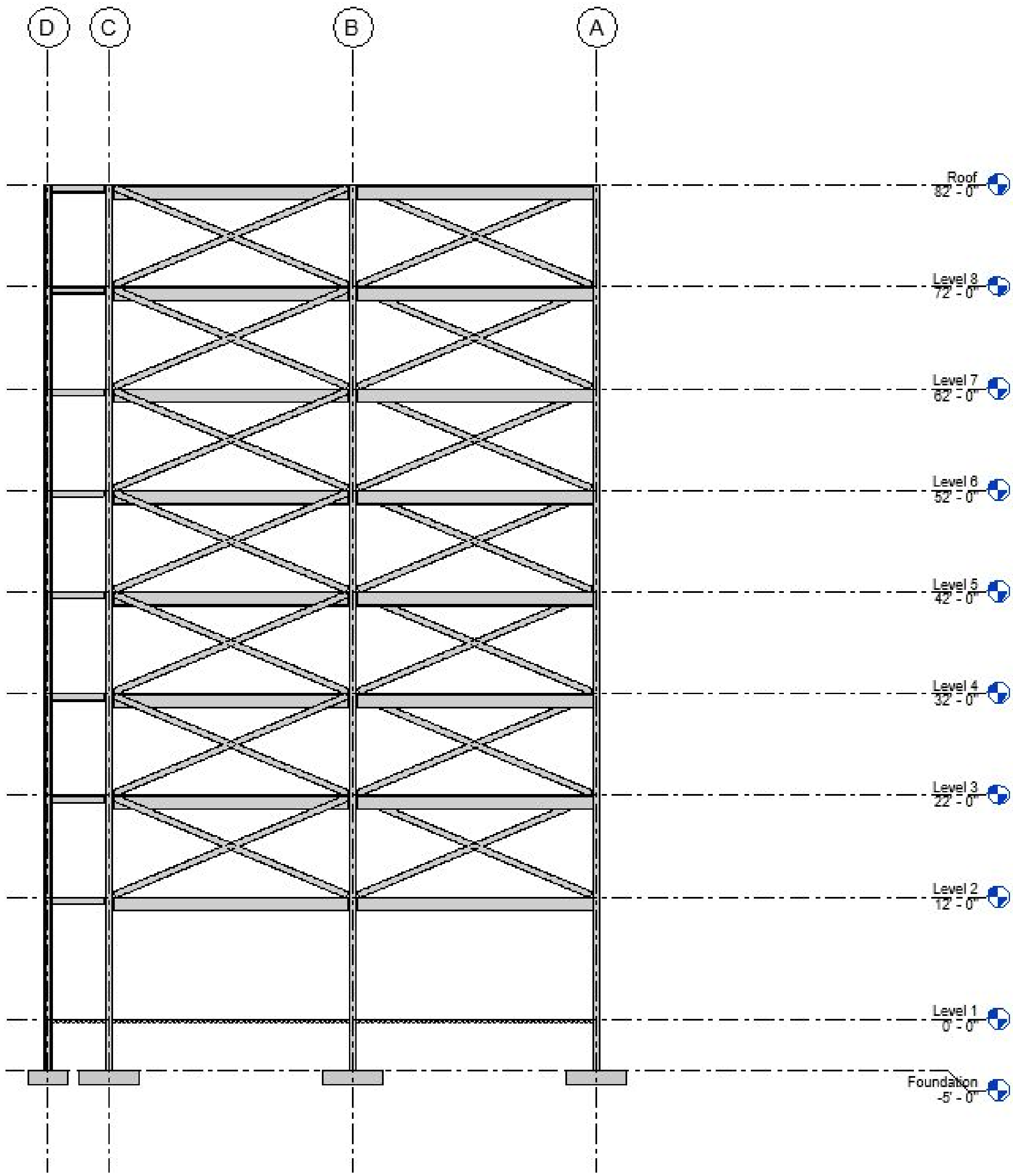


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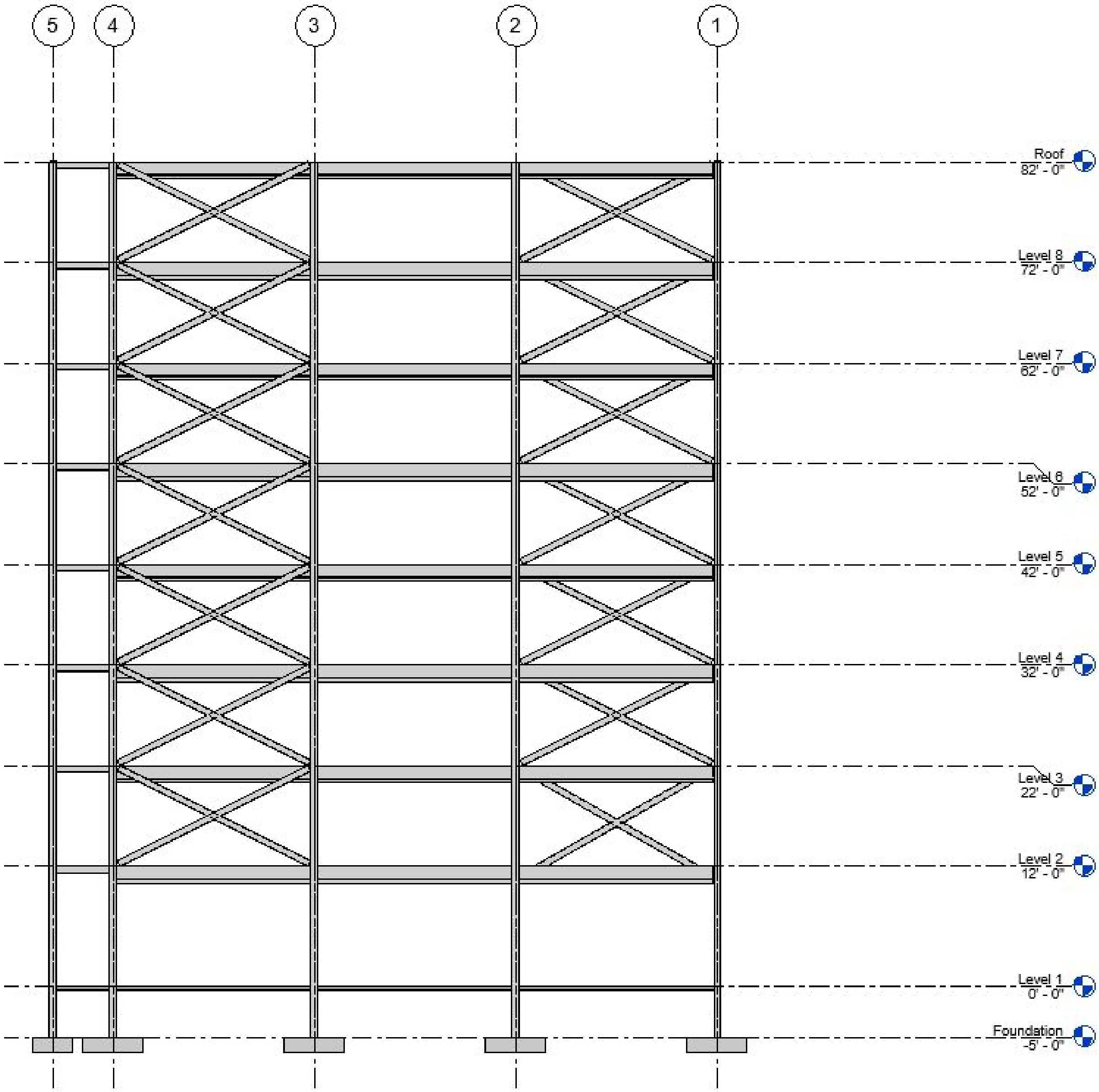
Figure F4: North Elevation View



Appendix G: Interview Notes

Phone interview Outline:

- Introduce ourselves
- Describe our project
- Ask about his experience with CLT
    - Compared to steel
        - Cost
    - Challenges with CLT
- Ask general and specific questions about mass timber
- Thank him for his time speaking with us.

Interview with Mike Moore

Friday 2/7/2020 1-2pm
Mike Moore is the General Superintendent from Suffolk who led the UMASS Amherst CLT project. He is one of the few people who has actually built a CLT project successfully in the US.

Questions for Mike:

What are some CLT projects you've worked on?
    Mainly Umass
Why was CLT used over other materials in the project?
    Originally designed to be a “0” impact building
What was your involvement/role in these projects?
    Superintendent, worked closely with engineers in design and construction process
What do you see as the main advantages of using CLT compared to steel and concrete construction?
    Aesthetic appeal, Environmental factors
Any setbacks or challenges?
    There is a lack of manufacturers. Also for constructing the Umass building since it was one of the first mass timber buildings in the US, Mike and his crew had to come up with a plan to put the panels in place.
How does the cost of CLT compare to steel and concrete?
    In lifespan and in the long run CLT is cheaper
    Initial construction it is more expensive
    More variation “own flavor to it”
Do you have a crew specifically for the mass timber project?
    Timber framers were used and did not require any additional training

What was the largest panel of CLT you have ever seen shipped? Were special accommodations made? How do you choose CLT manufacturers? Any difficulties with a lack of manufacturers in the area? Long shipping distances.

8’ wide x 55’ long

Future of CLT?

Manufacturing?

Continuously growing, more and more manufactures are popping up.

Interview with Dean Lewis

4:30pm February 5th, 2020

Dean is a structural engineer who is a subject matter expert on CLT in Northern California/Pacific Northwest.

Questions for Dean:

What are some CLT projects you've worked on?

Conceptual, different options

Why was CLT used over other materials?

Aesthetics, environmental sustainability, owner wanted something new

What was your involvement/role in these projects?

Structural engineer

What do you see as the main advantages of using CLT compared to steel and concrete construction? As an engineer.

Any setbacks or challenges?

Safety, acoustics, contractor familiarity and permitting are all concerns with CLT. “Knowledge gap”

Cost?

An office building that was 5 stories of concrete and the upper three were in mass timber. The mass timber was 40% more expensive.

1 challenge being: Vibration analysis? How do they adjust for vibrations?

Future of CLT

Manufacturers

2 in 2010

13 in 2020

More robust lumber supply chain is needed for it to grow

-Properly harvest trees

Interview with Andrew Canniff

Friday 2/7/20 from 12pm-1pm

Questions for Andrew:

What are some CLT projects you've worked on?

Limited experience. Company, suffolk worked on Umass (was not involved).

Why was CLT used over other materials in the project?

Environmental factors, sustainable, aesthetics

What was your involvement/role in these projects?

n/a

What do you see as the main advantages of using CLT compared to steel and concrete construction?

Environmentally more friendly than steel concrete, sustainable, aesthetics, fire is not a concern b/c char factor

Any setbacks or challenges?

Coordination and just an overall lack of knowledge

Cost?

There is an additional learning curve cost because of the lack of knowledge.

Labor is much less of a cost. Material is more expensive.

Elevator shafts?

Structural systems

Closing

Future of CLT?

The Bay area (California) is main focus right now.