UNIVERSITY OF HARTFORD
COLLEGE OF ENGINEERING, TECHNOLOGY, AND ARCHITECTURE

Design of Multistory Balsa Wood & Steel Buildings

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CE 465 Civil Engineering Design Project II

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Note:

This document was modified from its original form for upload to timothybreiner.xyz. Sensitive information including the names of others was removed. This project was originally completed by a group of myself and three other persons.

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Abstract

Two multistory buildings were designed. One building was designed as a balsa wood scale model that would be able to compete in the Earthquake Engineering Research Institute's (EERI) Undergraduate Seismic Design Competition (SDC). Design loads and specifications defined by the competition rules were applied in the design. The original scope of work included the construction and testing of the design. Due to the COVID-19 pandemic, the project scope was changed to not include physical construction. The second building designed was a multistory steel building in coastal Connecticut. Fior this design, the American Institute of Steel Construction (AISC) and ASCE 7-10 Codes were applied.

Table of Contents

List of Figures & Tables

1.0 Introduction

The research done for this project was inspired by the Seventeenth Annual Undergraduate Seismic Design Competition organized by the Earthquake Engineering Research Institute's (EERI) Student Leadership Council. The project was assigned by [REMOVED] and solicited by [REMOVED] of the University of Hartford's Department of Civil & Environmental Engineering. The initial focus of the project involved designing a model balsa wood structure in SAP2000 and testing it against earthquake loading. The structure would stand at roughly five feet tall and have been oscillated by a shake table to mimic the impact of an earthquake. The structure would have been scored in compliance with the standards of the EERI Undergraduate Seismic Design Competition (SDC) such as acceleration and horizontal displacement.

The students were still in the process of selecting a design to fabricate when the University of Hartford had to close the campus due to the outbreak of COVID-19 in the nearby New York area. The project had to be reinvented as students no longer had the space to build a structure or the ability to meet in person. The project was revised to no longer construct a physical balsa wood model and instead focus on designing two virtual models. One model was designed using the material properties of balsa wood and still fit in the parameters of the EERI Seismic Design Competition. To supplement the balsa wood model, a second model was designed. It used the balsa wood design as a base model; however, this model was designed to be the size of a full scale building using the AISC Steel Construction Manual design guidelines. The building was hypothetically placed in New London, CT which added several new forces to account for.

The goal of the project was for the engineering team to complete an analysis of alternative designs to accommodate expected ground motions, produce a full engineering cost analysis, complete a comprehensive report on the design and analysis of the structure, and present a professional presentation/poster at the close of the project. The statement of work below indicates the team's expected tasks and project schedule.

2.0 Description of Original Tasks

Tasks were defined by the engineering team and the client [REMOVED]. Each task is listed below and a short description of the task is provided. This list of tasks is based on the original scope of the project, not considering changes to the project made as a result of the University of Hartford's response to the COVID-19 pandemic.

2.1 Initial Design

Using the EERI SDC official competition rules, an initial design of the structure was expected to be created. According to the SDC rules, the initial design had to accommodate an existing structure by reducing the building footprint in the first five stories. The building could occupy the entire site above a height of five stories. For this year's competition the hypothetical client also wanted a greater than average story height to maximize natural light. The top floor was planned to be a retail space to capitalize the top view, also the first floor was going to be used for retail space. The client entrusted the designer to choose how to maximize profit with the rest of the building.

2.2 Purchase of Construction Materials

Construction material such as balsa wood, tools for construction, and measuring devices were to be decided on by the engineering team and the client.

2.3 Initial Construction of Structure

The structure was to be constructed in accordance with the initial design and SDC construction specifications.

2.4 Testing of Structure

Testing of the structure would have been conducted using the shake table. The loading and testing of the structure would have been carried out in accordance with the SDC official rules.

2.5 Revision of Design

Based on the results of the initial testing, the design of the structure would have been revised to address shortcomings of the initial design.

2.6 Construction of Revised Structure

Using the revised design, a second structure would have been constructed. As with the initial construction, SDC construction specifications would have been followed.

2.7 Testing of Revised Structure

Testing of the revised structure would have also been conducted using the shake table. The loading and testing of the structure would have been carried out in accordance with the SDC official rules.

2.8 Finalized Design

Based on the results of secondary testing, a final design would have been created that addresses the shortcomings of the secondary design.

2.9 Construction of Finalized Design

A finalized structure would have been constructed using the finalized design and SDC construction specifications.

2.10 Testing of Finalized Design

Testing of the structure would have been conducted using the shake table. The loading and testing of the structure would have been carried out in accordance with the SDC official rules.

2.11 Construction of Demo Structures

The finalized structure would have been replicated to be used as demonstration pieces at the CETA Design Expo.

2.12 Engineering Cost Analysis

An engineering cost analysis would have been conducted. This cost analysis will involve material costs, construction costs, and labor costs.

2.13 Design Report

A design report would have been written in accordance with client demands. This design report would have included the final design of the structure, construction specifications, and a summary of the engineering cost analysis.

2.14 CETA Design Expo Poster and Presentation

In accordance with client demands, the engineering team would have presented the finalized structure at the University of Hartford's CETA Design Expo. This presentation would have consisted of a test of the structure using the shake table supplemented with a project poster.

3.0 Updated Description of Tasks

Due to the University of Hartford's response to the COVID-19 pandemic, the physical building of the model was no longer possible. Therefore, existing project tasks related to the physical construction and testing of a balsa wood model were removed and new tasks were assigned by the client in its place.

3.1 Removed Tasks due to COVID-19 Response

COVID-19 shutting down the physical campus at the University of Hartford stalled some of the tasks of the project. All tasks that involved construction of a structure had to be removed as the team was unable to meet under the current circumstances. This includes tasks 2.3, 2.6, 2.9, and 2.11. The testing of these structures was transitioned to be strictly virtual as there was no physical model to test. Task 2.14, presenting at the CETA Design Expo, also was altered as the Expo transitioned to a digital setting.

3.2 Scaled-Up Real Building Design

To supplement the removal of the physical building and testing of the balsa wood structure, an additional project was tasked by the client. This project was the design of a real building using a structural steel frame. Per the client's demands, the balsa wood framing plan was scaled up 40x and loaded as if the building were located in the city of New London, CT. The frame members would be modified in accordance with standard practices and recommendations from the client and then designed using the American Institute of Steel Construction (AISC) Code.

3.2.1 Loading of Structure

The steel structure would be loaded using the American Society of Civil Engineers (ASCE) Code 7 (ASCE-7) and the International Building Code (IBC).

3.2.2 Modeling Building in SAP2000

The steel structure would be modeled in SAP2000 similar to how the balsa wood structure was modeled.

3.2.3 Design of Structure Using SAP2000

The frame members of the steel structure would be designed using the AISC Code with computer software. Specifically, the auto-design functionality of SAP2000 would be utilized along with recommendations from the client. It was expected that the client be heavily involved with this task.

4.0 Deliverables

The engineering team was tasked with providing deliverables specified by the client.

4.1 Delivery of Essential Documentation

Essential documentation was defined by the engineering team and the client and was delivered either through this report or by other means. The documentation deemed essential is listed below.

- A proposal written in response to the initial RFP sent by the client.
- A statement of work prepared by the team that details tasks and a schedule.
- Meeting meetings for all team meetings, meetings with advisors, and meetings with the client.

- Weekly reports prepared by the team detailing project progress.
- Files from computer modeling of structures in SAP2000.
- Documentation of alternative solutions and the team's decision making process when selecting alternatives.
- Technical documentation including design calculations, initial sketches, etc.
- A bill of materials that will serve as an engineering cost analysis for the project.
- A design report, presentation, and performance at the University of Hartford's CETA Design Expo detailed in the following subsections.

4.2 Design Report

As specified in section two, a design report was produced by the team in accordance with client demands.

4.3 Presentation

The team prepared a presentation that will summarize the information included in the design report.

4.4 CETA Design Expo Poster and Presentation

A poster was prepared by the team and presented along with a demonstration model for the CETA Design Expo that was scheduled for May of 2020.

5.0 Initial Design Phase of Balsa Wood Model

The initial design phase of the balsa wood structure was carried out by the team in accordance with the Seismic Design Competition (SDC) rules. Once each team member was familiar with the given rules, alternative designs were generated and compared. Through brainstorming processes, the team decided upon four alternative designs that would be developed. Each team member was tasked with one alternative which they would model using SAP2000 and design. Upon all structures being loaded for gravity and sized, the team eliminated two of the four alternatives with the winning two designs going on to be loaded for approximate seismic motion. Of the two structures designed for lateral load, one would be eliminated with the winning structure to be developed as the final design.

5.1 Design Constraints from SDC Official Rules

Design constraints were provided by the Seismic Design Competition committee through several documents; the Seismic Design Competition Official Rules and Design Guide. The competition had participating teams develop a proposal in response to a fictional RFP for the construction of a highrise building on a level site in downtown San Diego, CA. The proposal put constraints on the buildable site area, story dimensions, rentable space, and frame dimensions. The proposal also defined structure loadings and materials.

Constraints on the buildable site area were defined by the SDC committee as follows. The site was defined as a 12” x 12” flat plot of land with an existing structure taking up 7.5” x7.5” in the bottom right corner. From the proposal, the existing site cannot be impeded on for the first five stories. From story six to the highest floor, the entire site can be built on. A visualization of the site is presented in Figure 1.

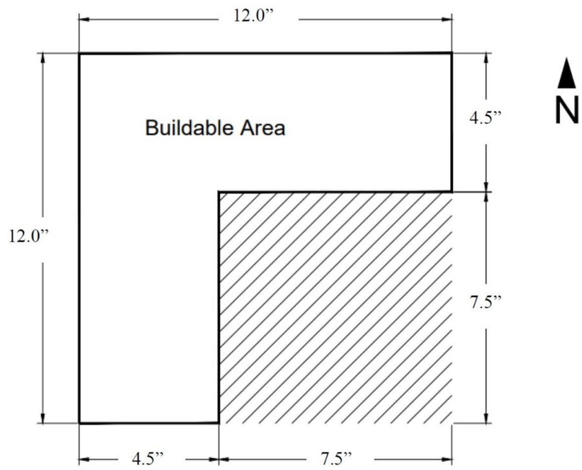

Figure 5-1: Maximum Floor Plan Dimensions Floors 1-5

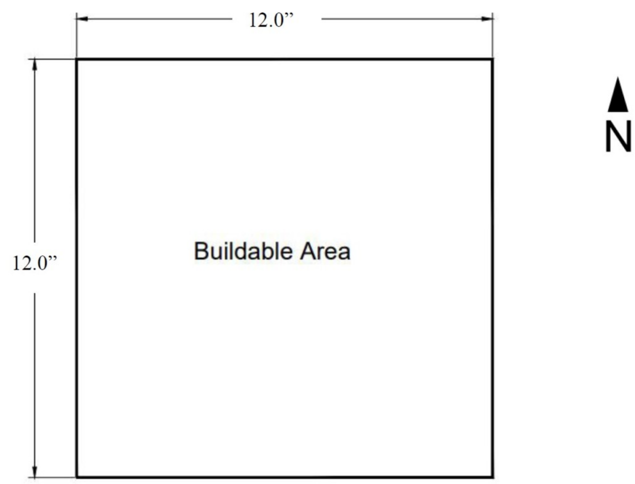

Figure 5-2: Maximum Floor Plan Dimensions Floors 6-19

Figure 1: Buildable Area Restrictions

The committee placed constraints on the number of allowable floors and floor heights. A minimum of 13 stories and a maximum of 19 stories was defined. Typical floor heights were defined to be 3” with the first floor being placed at “ground” level. As defined in the fictional proposal, the first floor was to have a story height of twice the typical height.

Building occupation was defined by the fictional proposal. The first and top floors of the building would be retail space with the client being flexible on how the remaining floors would be rented.

Restrictions on the dimensions of all frame members were put in place. No frame member was allowed to exceed a cross section of 0.200” x 0.200” and a length of 15.000”. For frame member connections, gusset plates of up to 0.100” x 1” x 1” were permitted. Restrictions on excess glue were also put into place.

Structure loads and loading materials were defined. Dead loads applied on each floor are the result of 20” long ½” diameter steel threaded rods, Simpson Strong Tie BP 5/8-2 plates, washers, and nuts. The placement of dead loads onto the structure is presented in Figure 2.

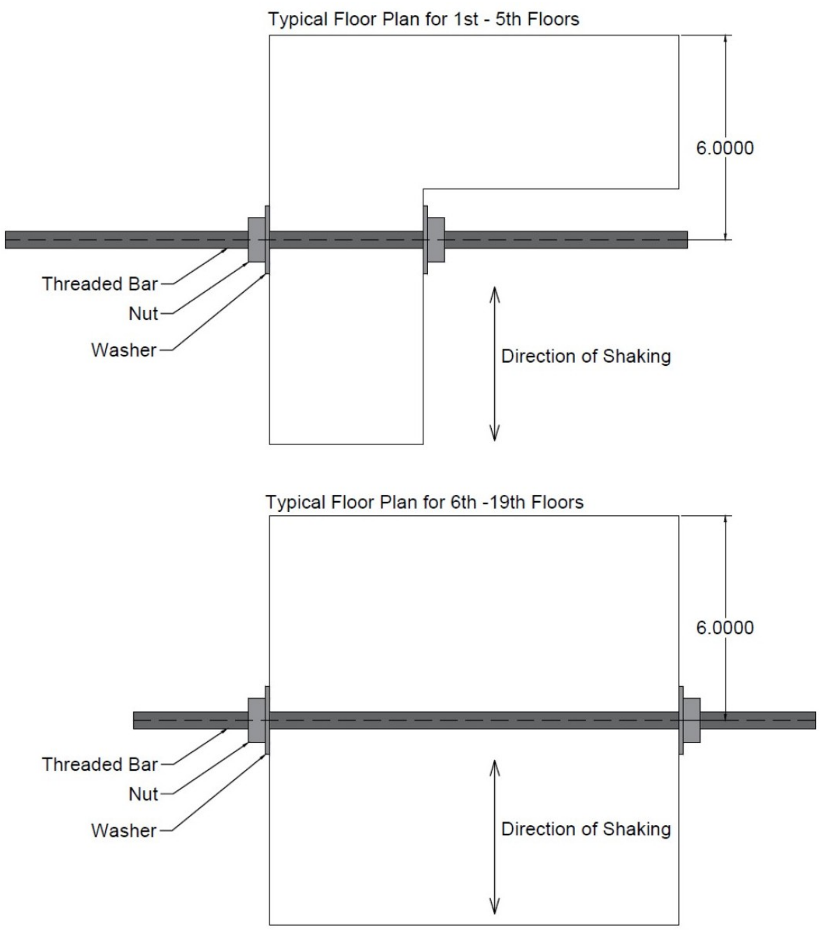

Figure 2: Floor Dead Load Placements

At the highest floor, the load was specified as one steel rod, 8 plates, 4 washers, and 4 nuts totaling 2.69 lb. At all other floors the load was specified as one steel rod, 4 plates, 4 washers, and 4 nuts totaling 1.96

lb. At the roof, an accelerometer and two C-claps were specified totaling 0.85 lb. These loads were represented as point loads at the edge of the structure at the location specified in Figure 2.

These design constraints were studied by the team and incorporated into the design of the four alternative structures that were developed.

5.2 Alternative #1

Alternative #1 was designed using only the buildable site area allowed for the first five stories for the maximum allowable floor limit, 19 floors. Model views of this alternative are presented in the following figures. Figure 3 presents a 3D view of the model. Figure 4 presents the typical floor framing plan. Figure 5 presents the typical elevation view of the structure.

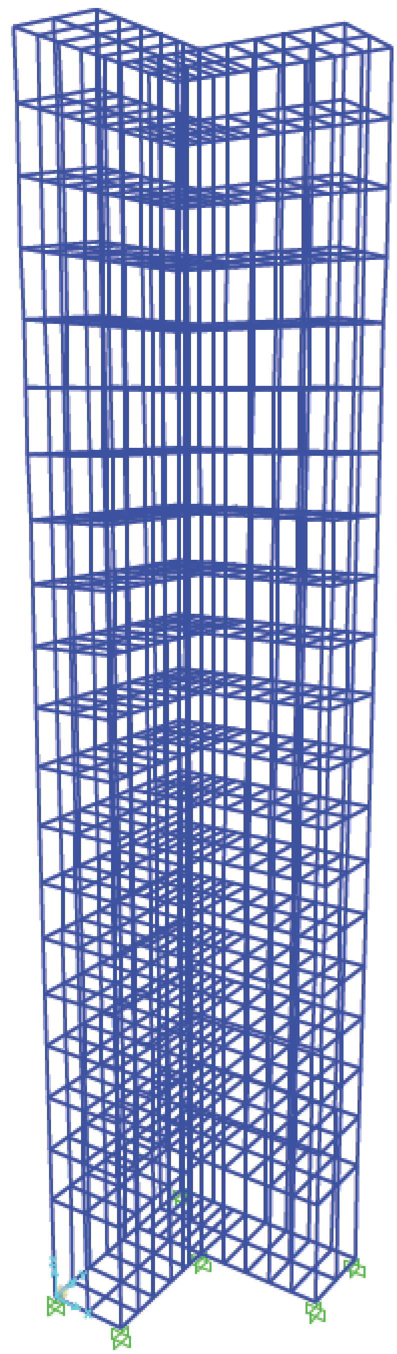

Figure 3: 3D View of Alternative #1

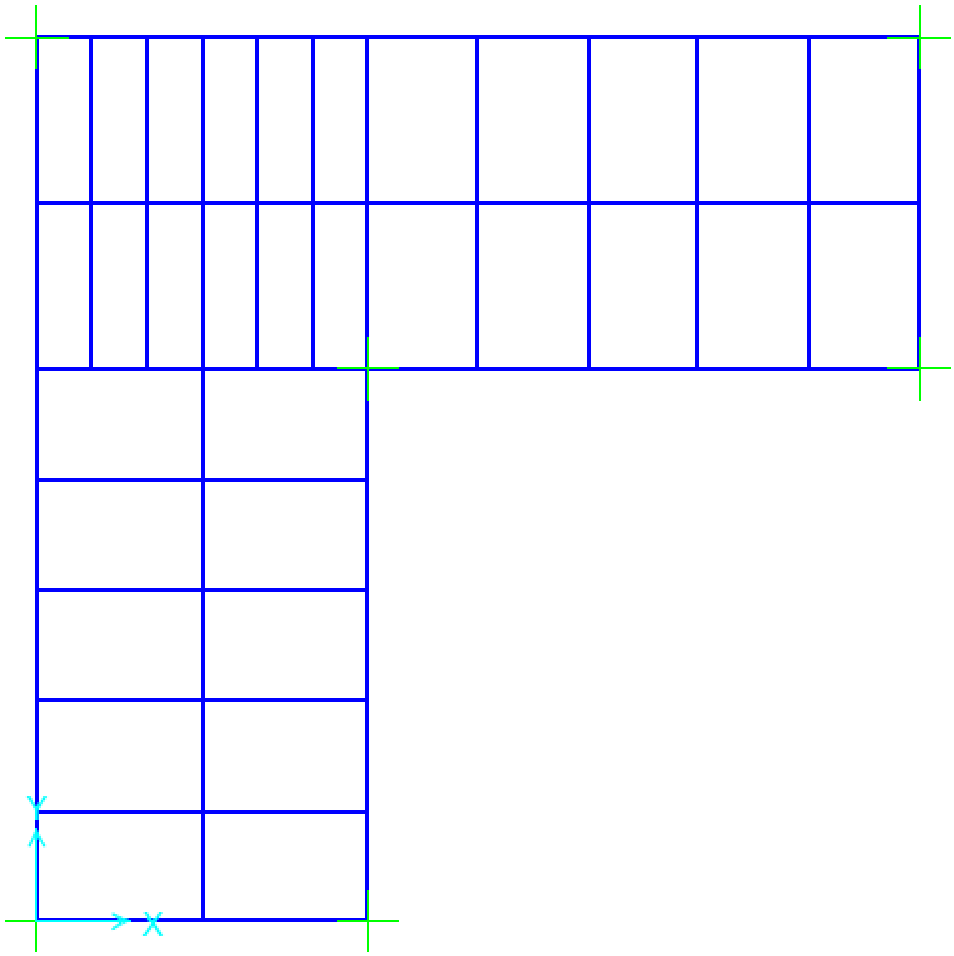

Figure 4: Typical Framing Plan for Alternative #1

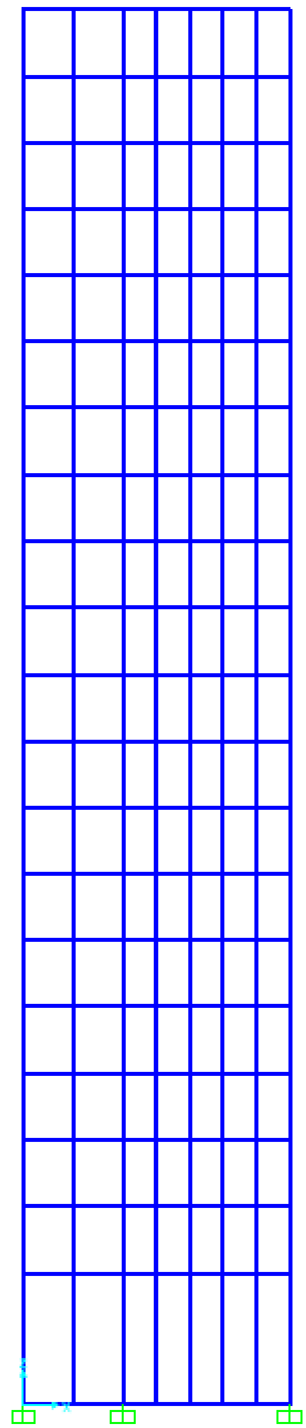

Figure 5: Elevation View for Alternative #1

This alternative was developed to explore the possible advantages of having a uniform frame. Before the project was affected by the University of Hartford's response to COVID-19, ease of construction was a strong consideration for the team. Having a structure with little variation in the framing plan per story would make constructing the physical balsa wood model significantly easier.

5.3 Alternative #2

Alternative #2 was designed to compromise floor space in comparison to alternative #3 in favor of additional structural support for the higher stories. The first five stories follow the buildable area restrictions outlined in the competition rules. Floors 6 through 8 serve as a transition region from the L-shape lower floors to the higher floors, which use the entire site area. Floors 6, 7, and 8 were designed as a transition region to provide structural support to areas of the higher floors that do not lie directly on top of the L-shape.

Model views for alternative #2 are presented in the following figures. Figure 6 presents a 3D view of the model. Figure 7 presents the typical floor plan for floors 1 - 5. Figure 8 presents the typical floor plan for floors 6 - 8. Figure 9 presents the typical floor plan for floors 9 - 19 and the roof.

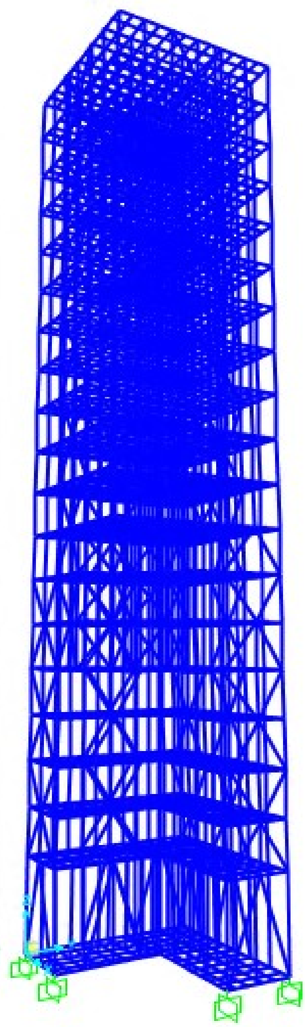

Figure 6: 3D View of Alternative #2

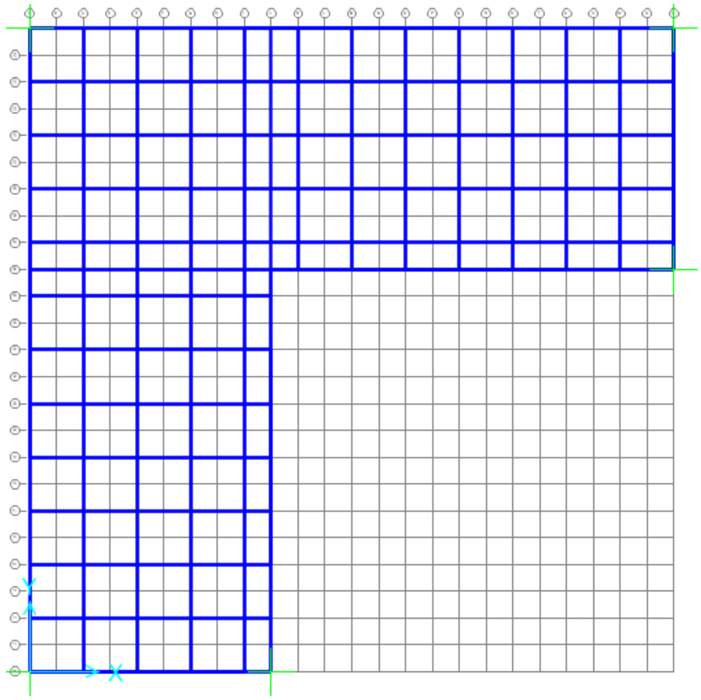

Figure 7: Typical Floor Plans for Floors 1 - 5 for Alternative #2

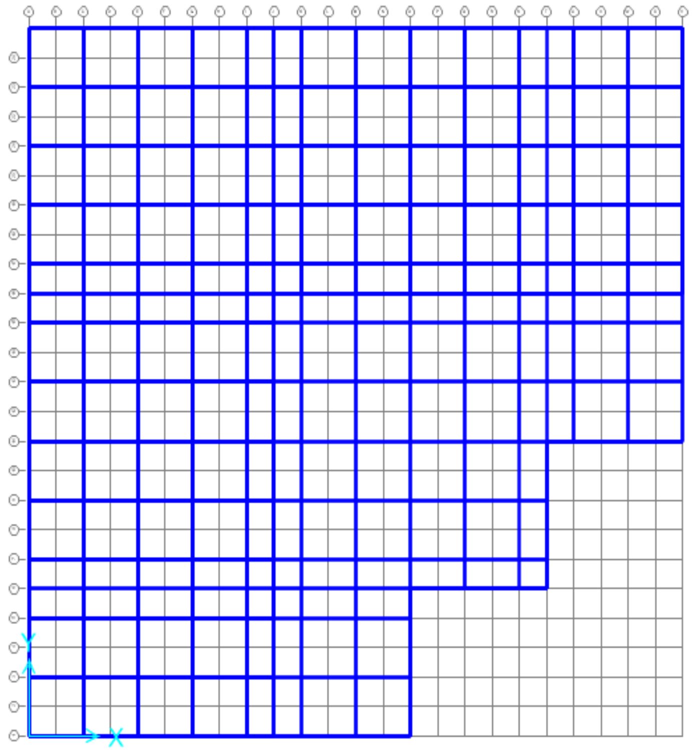

Figure 8: Typical Floor Plan for Floors 6 - 8 for Alternative #2

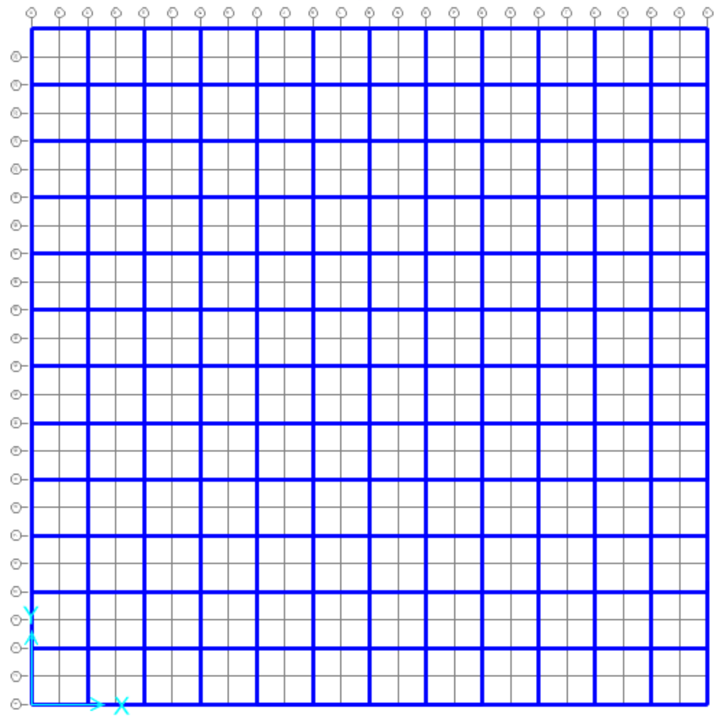

Figure 9: Typical Floor Plan for Floors 9 - 19 & Roof for Alternative #2

5.4 Alternative #3

Alternative #3 attempted to have the most available floor area of the alternative designs. The base was constrained by a neighboring structure, confining the initial floor layout to an L shape for the first five floors. At floor 6 to the top of the structure, the entire buildable site area was used. The building deflection was 6 inches after being loaded with just 5% of the dead load as lateral load. V shaped lateral bracing was provided, but found inadequate for seismic load. Model views of this alternative are presented in the following figures. Figure 10 presents a 3D view of the model. Figure 11 presents the typical floor plan for floors 6 to 19. Figure 12 presents an elevation view of the model. Figure 13 presents the elevation view.

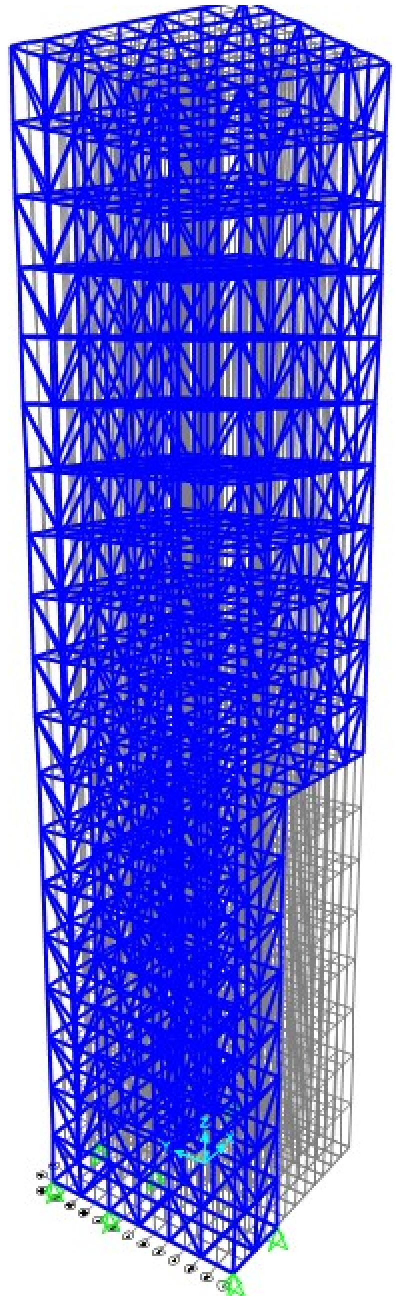

Figure 10: 3D View of Alternative #3

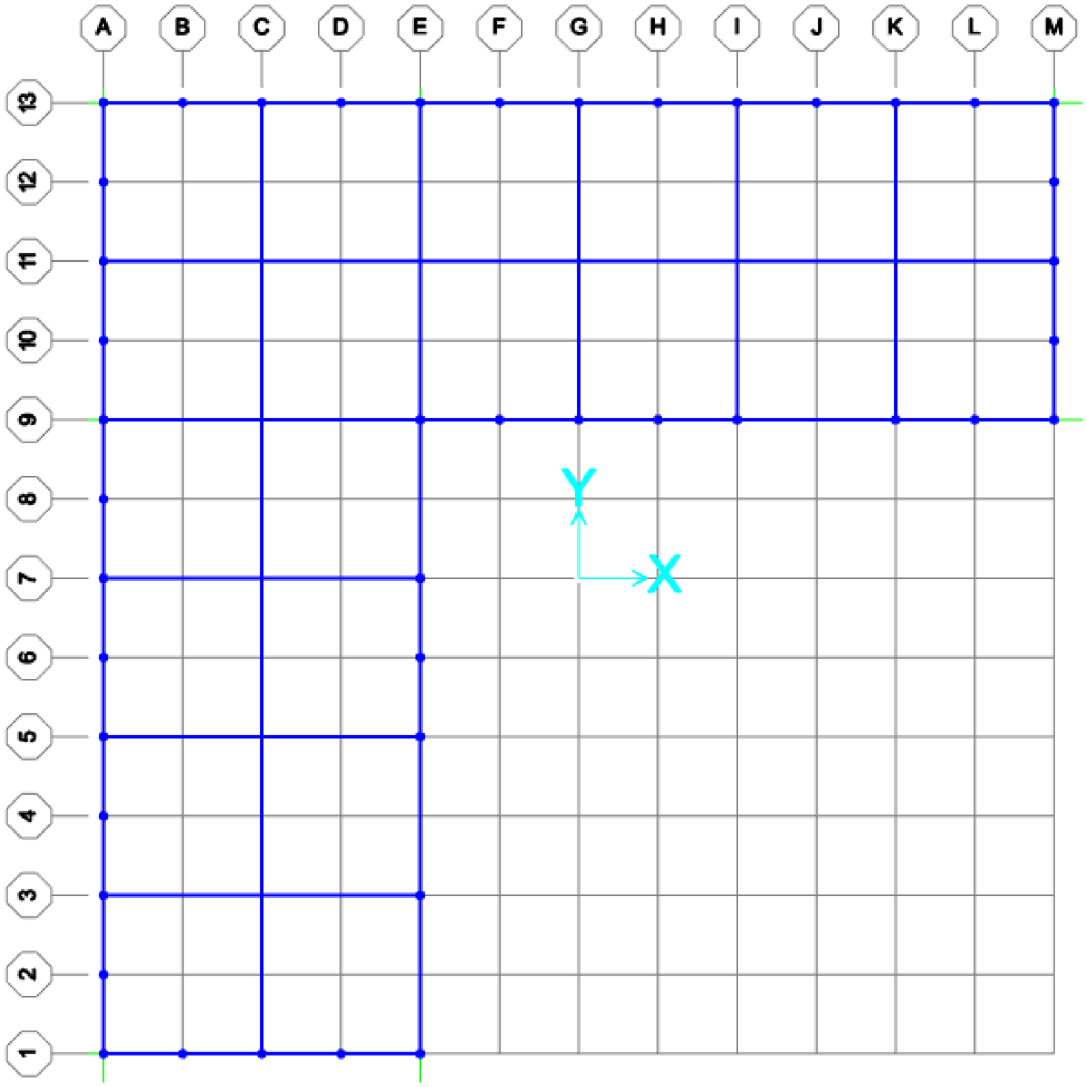

Figure 11: Typical Floor Plan for Floors 1 - 5 for Alternative #3

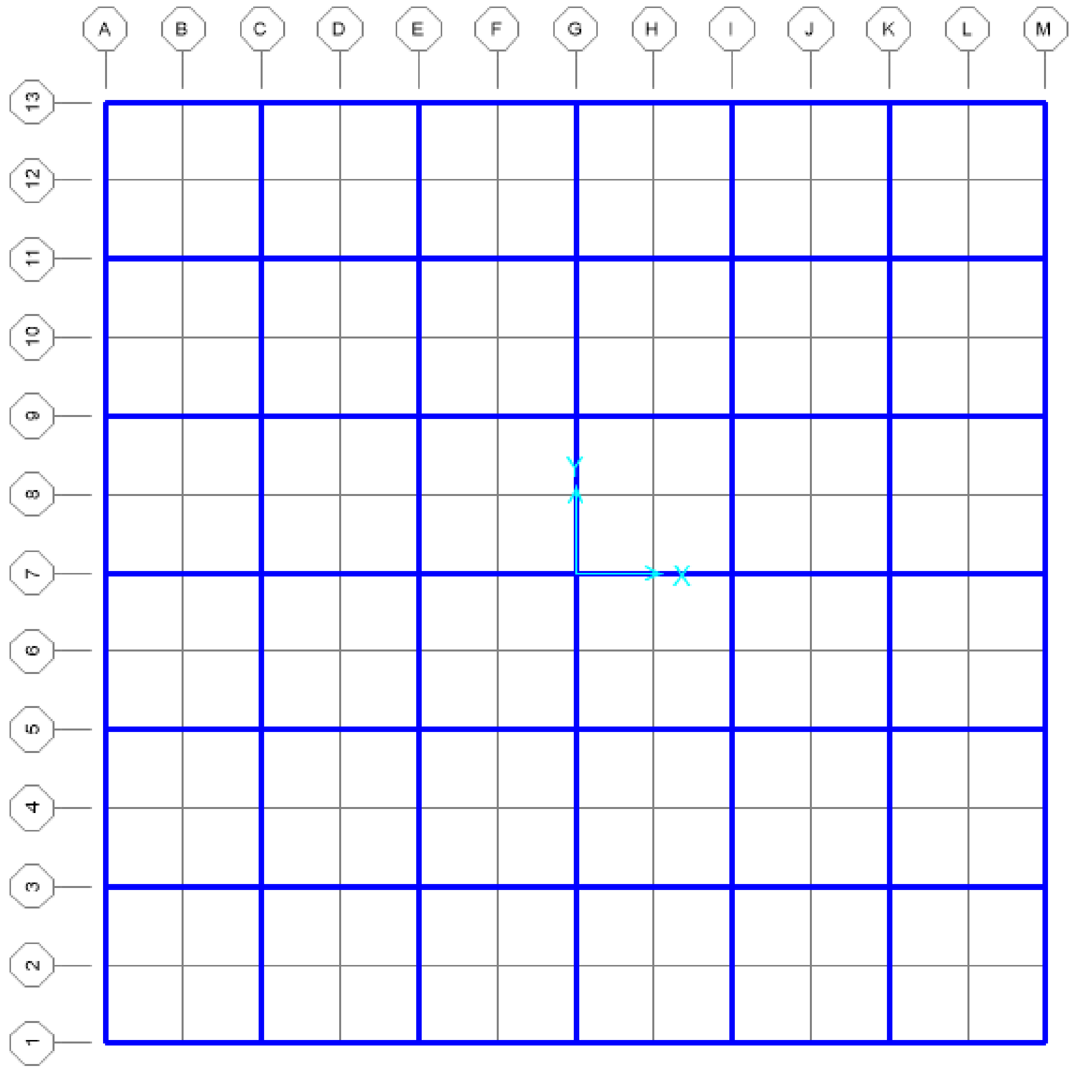

Figure 12: Typical Floor Plan for Floors 6 - 19 & Roof for Alternative #3

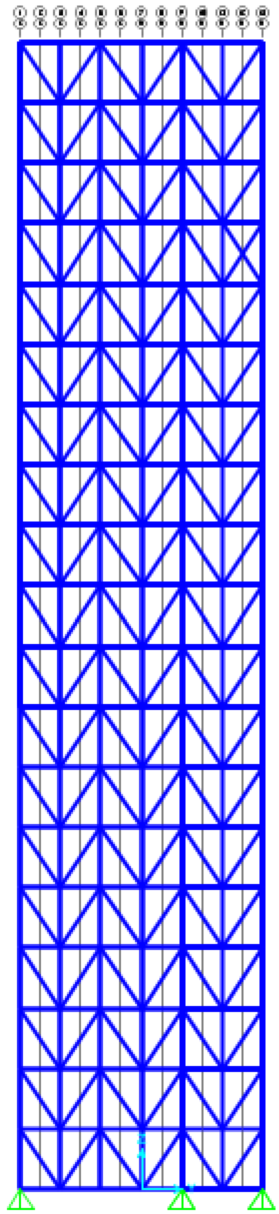

Figure 13: Elevation View for Alternative #3

5.5 Alternative #4

Alternative #4 was made to use less material than the other structures. The base was L-shaped to conform to the buildable site limit and retained the L-shape for the first 5 floors similar to alternative #1. Following floor 5 the building had a simple rectangular shape along one side of the L. The final reduction in size came from having 2 less floors than all other alternatives. Larger members compensated for the reduced number of members in this design. The following figures show the layout and a 3D representation of the model.

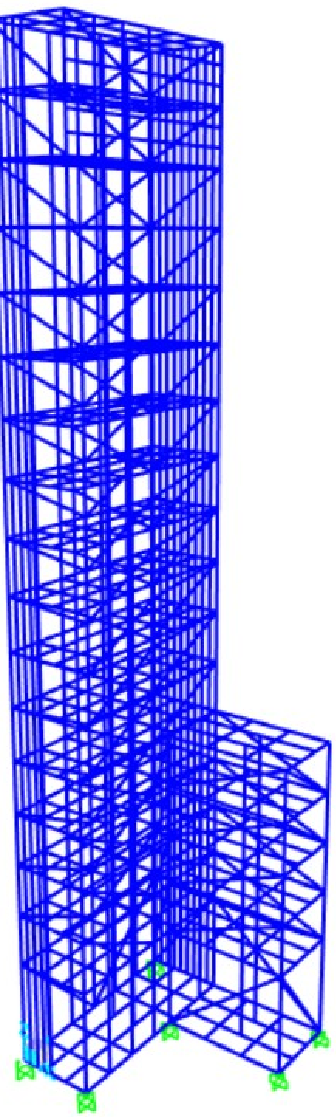

Figure 14: 3D View of Alternative #4

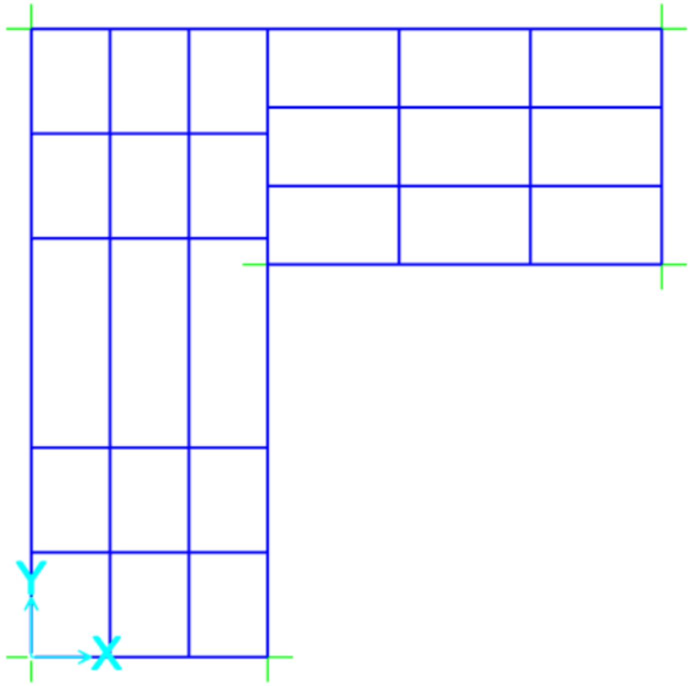

Figure 15: Typical Framing Plan for Alternative #4

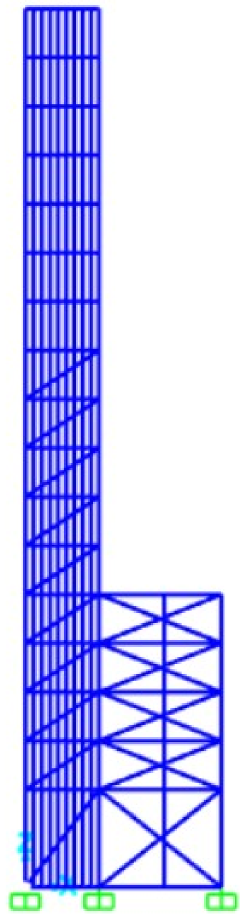

Figure 16: Elevation View of Alternative #4

5.6 Gravity Loading and Sizing of Each Alternative

The first loading condition applied to the models was gravity. According to the Seismic Design Competition committee, a threaded steel rod with nuts and washers was intended to be used to add a dead load to each individual floor as in Figure 2. The typical loading per floor was 1.96 lb with the exception of the highest floor and the roof. The highest floor had a load of 2.69 lb and the roof had a load of 0.85 lb. In SAP2000 these loads were represented as two point loads of half the magnitude placed on opposite ends of the structure. The use of two points was to simulate the rod resting on a physical model.

The resulting analysis from SAP2000 calculated the forces on each member of the structure and produced a deflected version of the model. Members on each alternative structure were sized using Balsa wood material properties that were researched online. All balsa properties found online had slight variations that were accounted for by averaging. A table of the Balsa wood material properties is presented in Table 1.

Table 1: Balsa Wood Material Properties

Material Property	**Value**
Comp. Str., Perp. to Grain (psi)	1196
Comp. Modulus ASTM C365 (psi)	37830
Tensile Str., Perp. to Grain (psi)	1710
Tensile Modulus (psi)	46620
Shear Str. ASTM C273 (psi)	324
Shear Modulus ASTM C273 (psi)	17325
Modulus of Rupture (psi)	0
Flexural Modulus (psi)	0
Density (pci)	0.00632

For each alternative, the members were sized using allowable stress design. This required the properties of balsa wood and the largest force on a member. The area was determined by comparing the tensile and compressive strength to the largest forces placed on the balsa wood. For each alternative, the largest and smallest cross-section and maximum deflections is presented in Table 2.

Table 2: Cross-Sections and Deflections for Each Alternative

	Largest Cross-Section (in)	Smallest Cross-Section (in)	Maximum Deflection (in)
Alt. #1	0.375	0.25	0.769
Alt. #2	0.375	0.25	0.181
Alt. #3	0.75	0.75	0.0065
Alt. #4	1.00	1.00	1.1

5.7 Selection of Two Alternatives

After the four alternatives were sized, the team began a selection process to eliminate two of the two models. The models' number of members, smallest cross-section, and maximum deflection were tabulated and compared using a decision matrix. The tabulated outputs from SAP2000 that were used to compare the models are presented in Table 3.

Table 3: SAP2000 Gravity Load Output for Alternatives

	Number of Members	Maximum Deflection (in)	Smallest Cross-Section (in)
Alt. #1	1939	0.769	0.25
Alt. #2	**550**	**0.181**	0.25
Alt. #3	**1470**	**0.0065**	0.75
Alt. #4	762	1.1	1

Using the data in Table 3, a decision matrix was made that would rank each alternative out of 4 points for each criteria with 4 points being the most preferable option. The filled-in decision matrix is presented in Table 4.

Table 4: Decision Matrix for Selection of Alternatives

	Members	Deflection	Cross-Sections	Totals
Alt. #1	1	2	4	7
Alt. #2	4	3	4	11
Alt. #3	2	4	2	8
Alt. #4	3	1	1	5

From the results of the decision matrix, alternatives #1 and #4 were eliminated. Alternatives #2 and #3 would continue to be designed for lateral loading. The team members that were working on the eliminated alternatives would assist those team members working on the selected alternatives.

5.8 Lateral Loading of Selected Alternatives

The two selected structures were laterally loaded with an approximate seismic load of 5% of the gravity load applied at the location where the dead load would be connected to the structure. These loads were applied on each floor in the positive horizontal direction. The resulting deflections of the two alternatives are presented in Table 5.

Table 5: Maximum Horizontal Deflections as a Result of Lateral Load

Structure	Maximum Horizontal Deflection (in)
Alt. #2	4.32”
Alt. #3	6.0”

5.9 Selection of Winning Balsa Wood Model

The results of lateral loading on the structure were used to select the alternative that would be designed under the provided seismic load, constructed, and tested. As seen in Section 5.8, the lateral load on alternative #2 resulted in a significantly smaller horizontal deflection than alternative #3. From these results, the team selected alternative #2 as the design that would be finalized.

6.0 Seismic Loading of Balsa Wood Model

The seismic load provided by the EERI SDC Competition was placed on the structure, replacing the approximate lateral load that was used in the selection process. The seismic data was provided to the team as text files that, when imported into SAP2000, modeled time history functions. Two time history functions were used, Ground Motion #1 and Ground Motion #2. Figure 17 presents a plot of Ground Motion #1. Figure 18 presents a plot of Ground Motion #2.

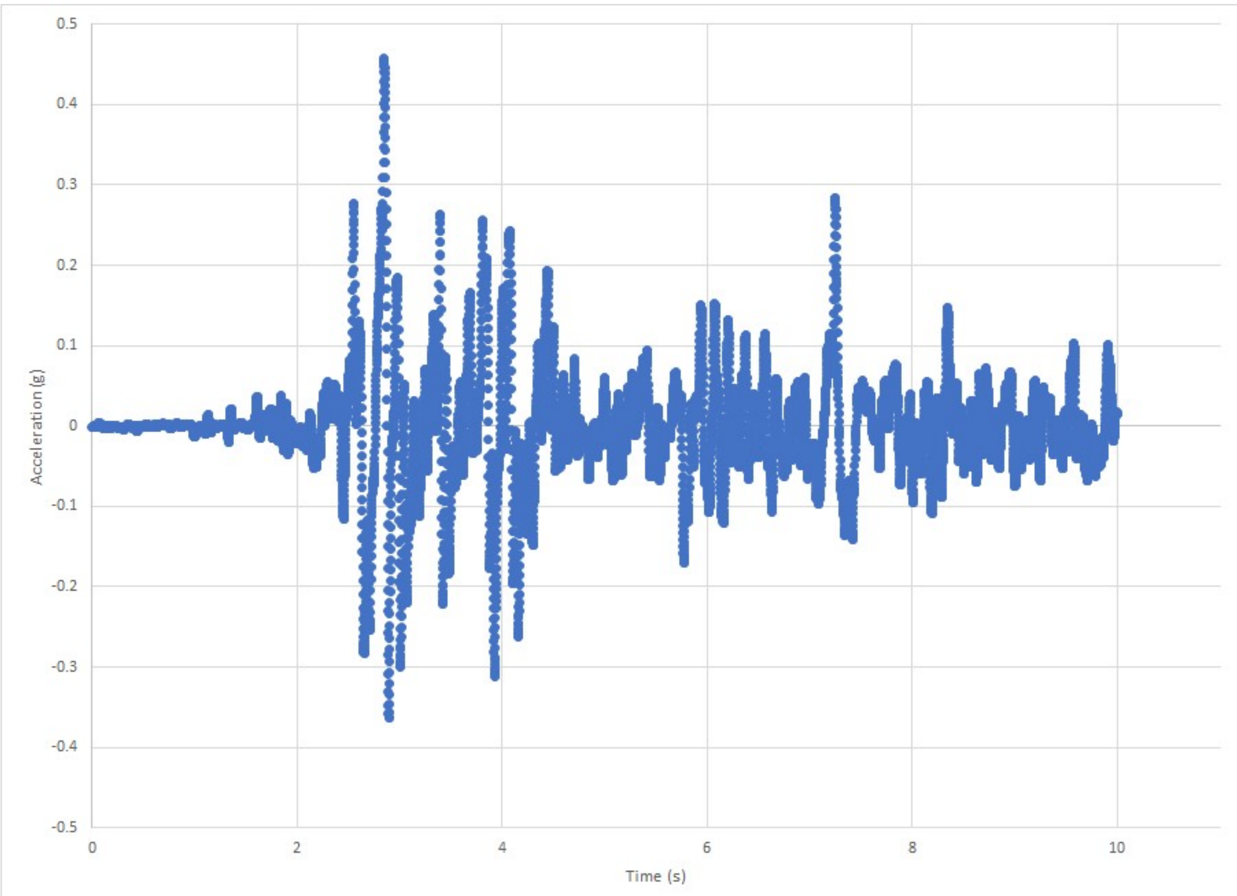

Figure 17: Ground Motion #1

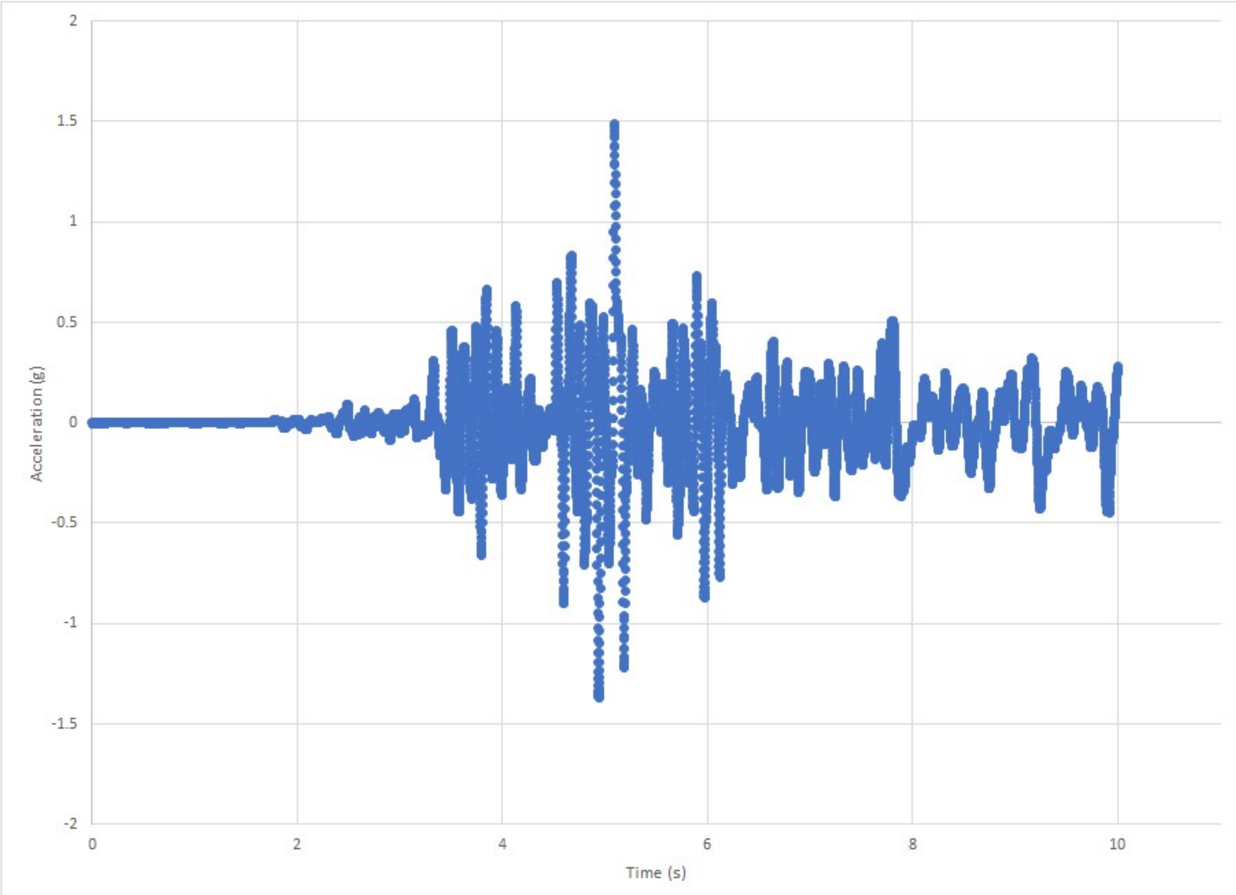

Figure 18: Ground Motion #2

7.0 Design of Balsa Wood Model

The design of the balsa wood model was a continuation of alternative #2. Alternative #2 was shown to maximize the usable space while also keeping structural integrity when load was applied. Methodology from the ACI 318 Code and AISC Code were applied to verify the structural integrity of the building with the given seismic load.

7.1 Design of Columns using ACI 318

The columns of the balsa wood model were initially sized for stiffness due to the gravity load. Following that initial size calculation, a ϕPn-ϕMn diagram was created by ACI 318-14 to verify the strength of columns under load. This interaction diagram compares the placement of axial load capacity and the bending moment capacity produced by loading. A column's axial load and moment were taken from the SAP2000 model and compared to the resultant curve. The data fell within the curve which means the columns were adequately sized for their loading.

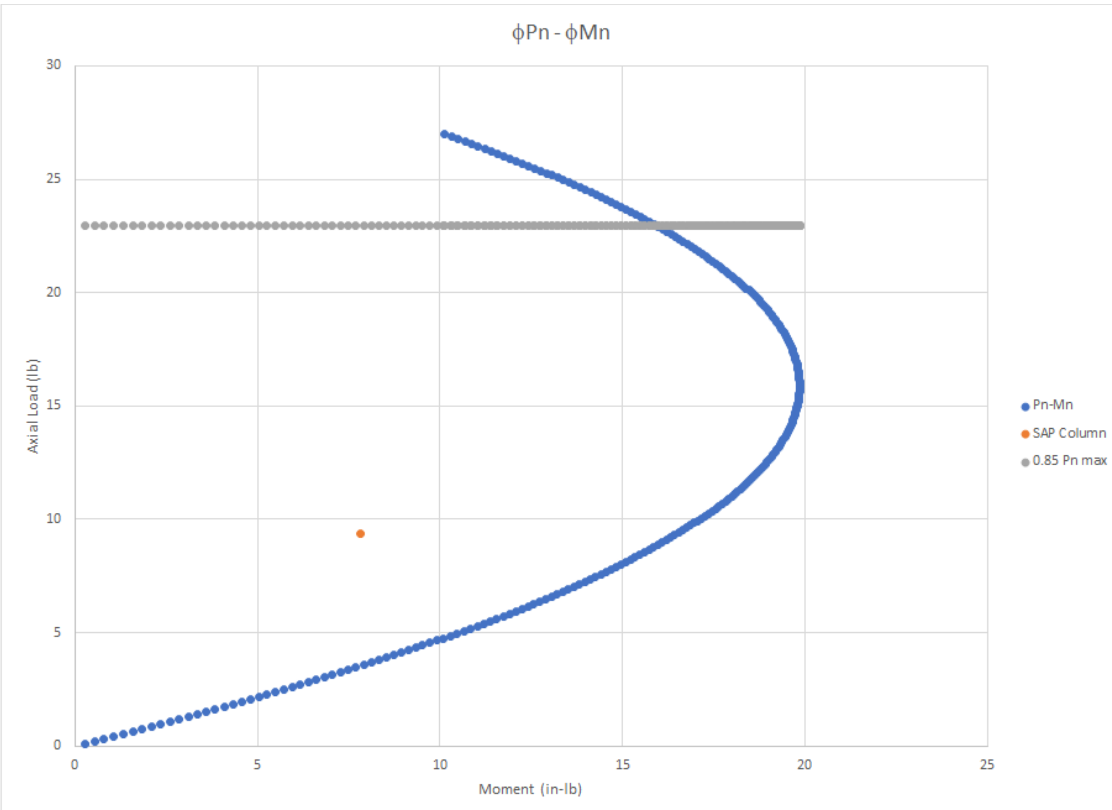

Figure 19: ϕPn - ϕMn Diagram for Column Design

7.2 Design of Members Using Allowable Stress Design

Girders and floor beams for the balsa wood model were designed using Allowable Stress Design. Using the analysis results from SAP2000, member stress and axial load was used to calculate the minimum allowable area of the cross section from the following equation,

$$\sigma = P / A_{min}.$$

Due to balsa wood being sold with typically square cross-sections, the required minimum cross section was calculated using the following relationship,

$$A_{min}=x^2.$$

The calculated cross-sections were rounded up to the nearest standard cross section.

From the results of this analysis, a cross-sectional area of ¼” x ¼” was deemed adequate for all structural members.

7.3 Design of Lateral Bracing

Lateral bracing was required for the structure to withstand the seismic ground motions as specified by the EERI SDC competition. It was recommended by the client that lateral bracing should be designed with one brace on each side of every rectangular area. Using the typical cross section of ¼” x ¼” defined in Section 7.2, several bracing iterations were tested to determine which produced the smallest horizontal deflection. The finalized bracing design is presented in Section 8.

7.4 Design of a Gusset Plate

A gusset plate is a type of connection for connecting beams and girders to columns. A typical gusset plate uses either bolts or welding to increase the load capacity of a joint. The EERI had a section dedicated to the joining of members and allowable glue application. If fabrication had continued to progress, connections of members would be handled with the use of Gorilla Wood glue applied to a faying surface on both members about to be connected. this would result in only an area of 0.25” x 0.25” where glue could be applied. The gusset plates that would be fabricated and applied would have been made 1.0” x 1.0” x 0.10” to accommodate EERI design rules. The added support would strengthen the joint and add additional contact area for glue to be applied. The $0.0625\ in^2$ area that glue could be applied to would increase to at least 0.375 in^2 depending on the orientation of the connection.

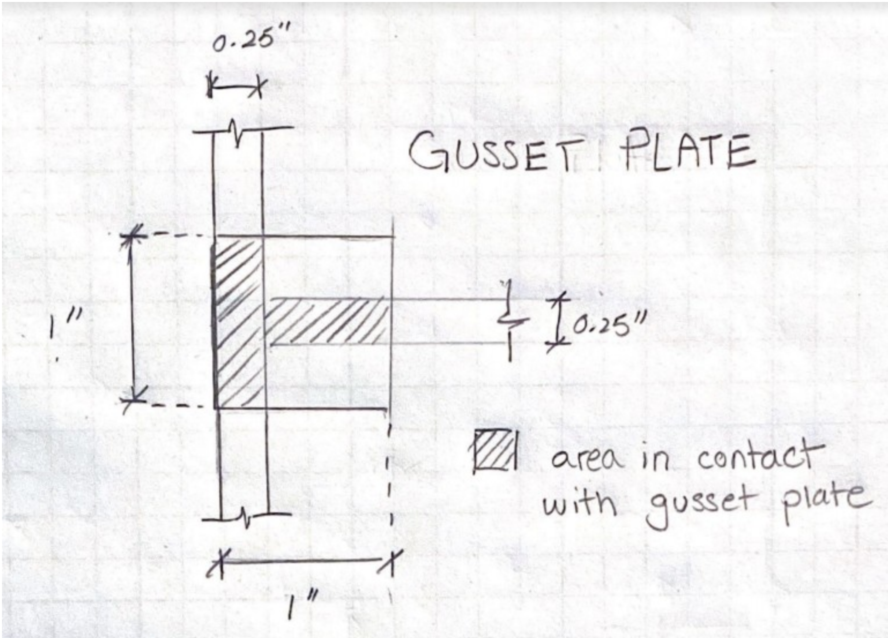

Figure 20: Balsa Wood Gusset Plate Profile View

8.0 Finalized Balsa Wood Model

Framing plans for the finalized balsa wood model with ¼" x ¼" cross sections typical of all members are provided in the following figures. Figure 21 presents a 3D view of the finalized model. Figure 22 presents the typical floor plan for floors 1 -5. Figure 23 presents the typical floor plan for figures 6 - 8. Figure 24 presents the typical floor plan for floors 9 - 19 and the roof. Figures 25 and 26 represent the North-South and East-West building elevations.

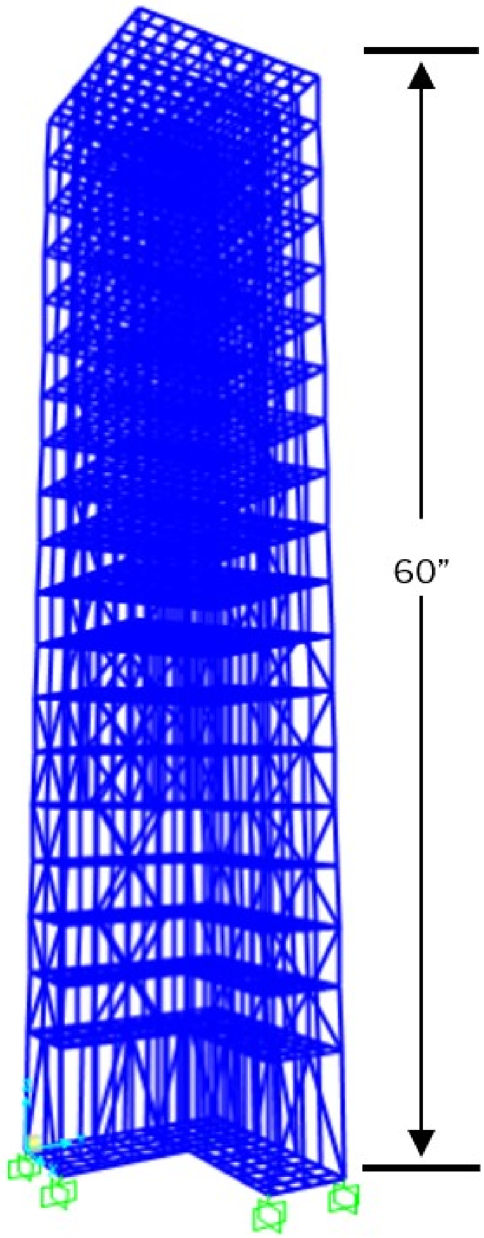

Figure 21: 3D View of Finalized Balsa Wood Model

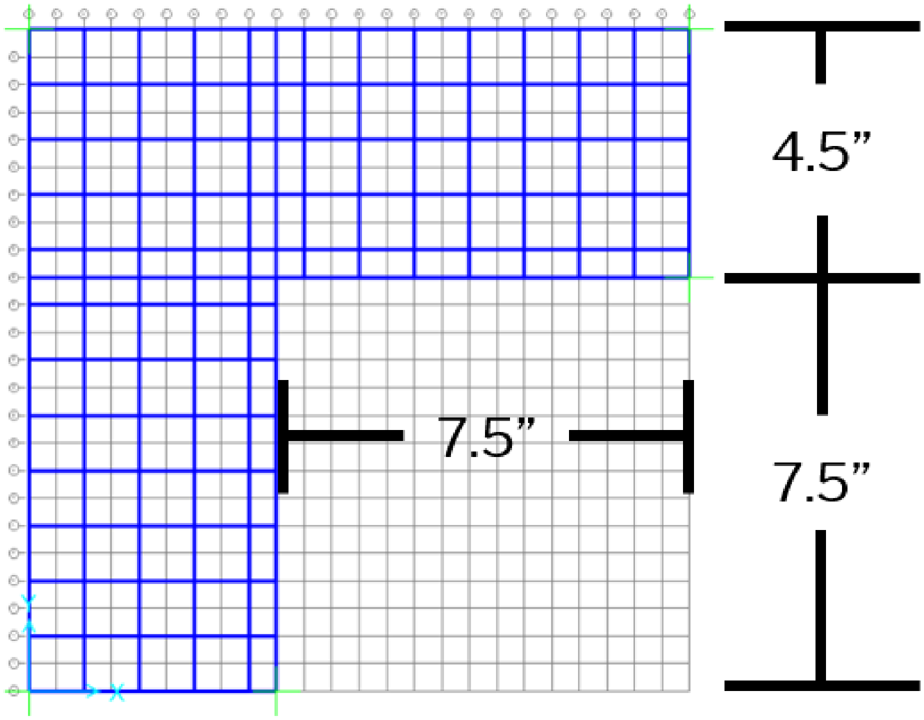

Figure 22: Typical Floor Plan for Floors 1 - 5 of Finalized Balsa Wood Model

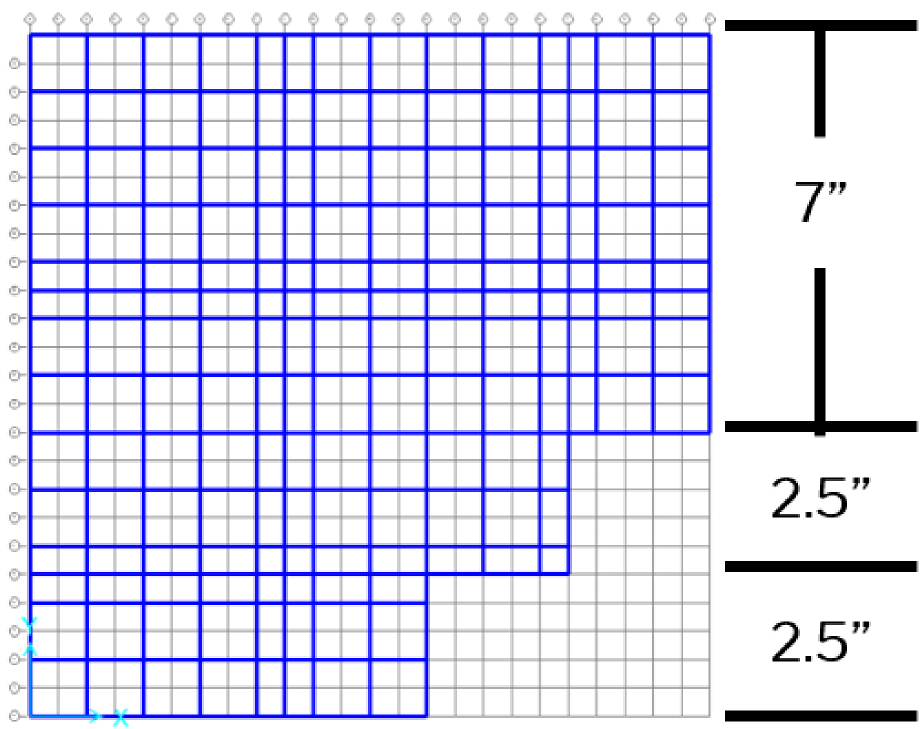

Figure 23: Typical Floor Plan for Floors 6 - 8 of Finalized Balsa Wood Model

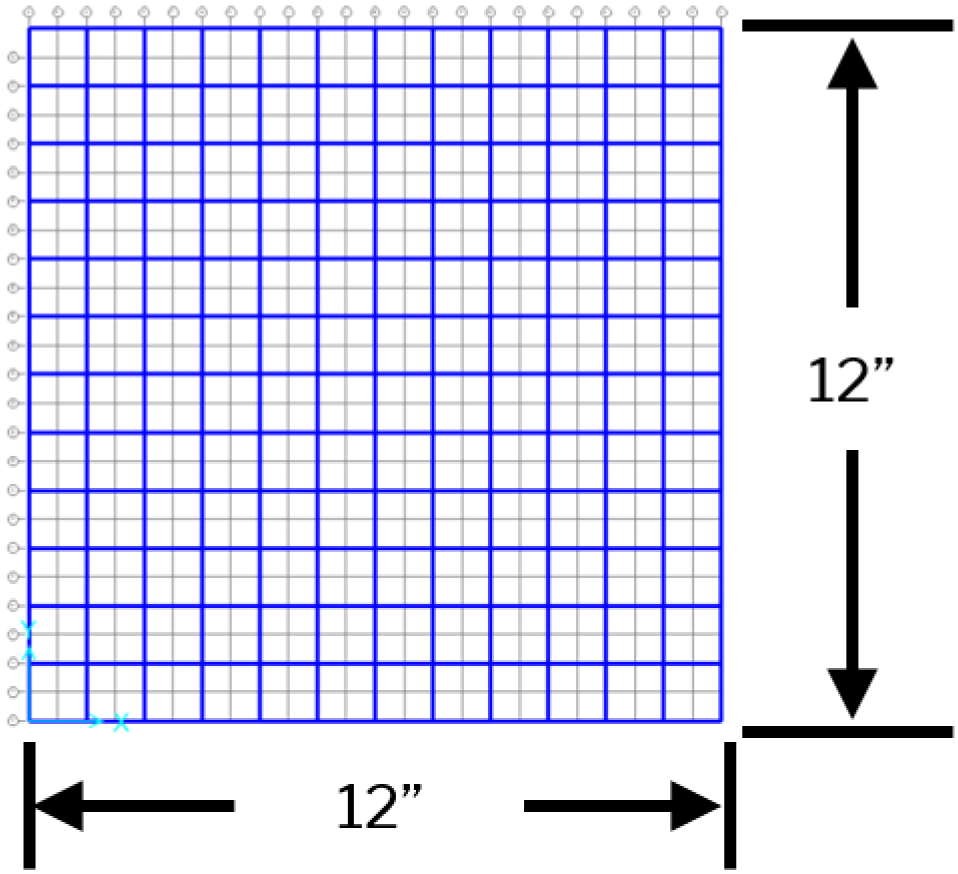

Figure 24: Typical Floor Plan for Floors 9 - 19 & Roof of Finalized Balsa Wood Model

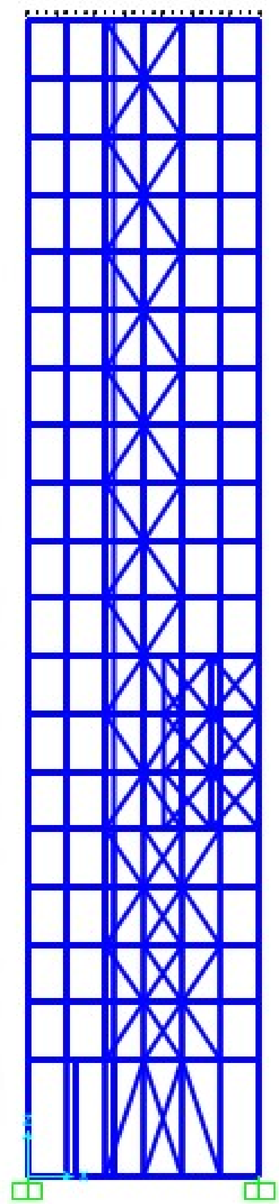

Figure 25: North-South Elevation View of Finalized Balsa Wood Model

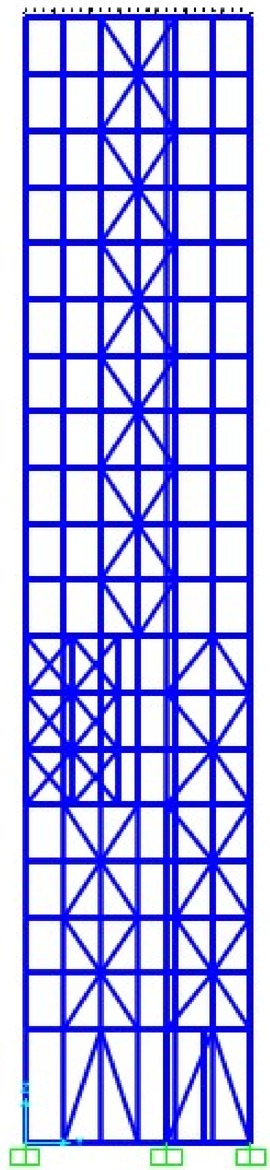

Figure 26: East-West Elevation View of Finalized Balsa Wood Model

9.0 Design of Scaled-Up Structure

Using the balsa wood model as a reference, a scaled-up building was modeled, loaded, and designed using structural steel. By scaling the balsa model dimensions by 40x, the buildable site area was increased to 40’ x 40’ and the height of the typical story was increased to 10’. By request of the client, the building loads were calculated under the assumption that this building would be located in the New

London, CT area. Once the structure was loaded, the building frame was designed using the AISC Code with SAP2000.

9.1 Structure Loads

Structure loads were researched and calculated using the ASCE 7 Minimum Design Loads for Buildings and Other Structures Code and recommendations from the client. Due to the nature of the project and the relationship with the client, recommendations from the client were taken into consideration over the ASCE 7 Code in the event of a conflict of information.

The loads that were calculated and placed onto the steel structure were dead loads, live loads, snow loads, rain loads, wind loads, and seismic loads. To properly calculate these loads, risk assessment using the ASCE 7 Code was required.

9.1.1 Risk Assessment via ASCE 7-10

As previously stated, risk assessment of the structure needed to occur in order to properly calculate structure loads. Per ASCE 7-10 Section 1.5, risk assessment is determined by how the failure of a structure will impact the physical risk to human life, local or greater economy, and general day-to-day life. The Code specifies that structures shall be classified in one of four Risk Categories described in ASCE 7-10 Table 1.5-1. This table is presented in Figure 27.

Table 1.5-1 Risk Category of Buildings and Other Structures for Flood, Wind, Snow, Earthquake, and Ice Loads

Use or Occupancy of Buildings and Structures	Risk Category
Buildings and other structures that represent a low risk to human life in the event of failure	I
All buildings and other structures except those listed in Risk Categories I, III, and IV	II
Buildings and other structures, the failure of which could pose a substantial risk to human life.	III
Buildings and other structures, not included in Risk Category IV, with potential to cause a substantial economic impact and/or mass disruption of day-to-day civilian life in the event of failure.	
Buildings and other structures not included in Risk Category IV (including, but not limited to, facilities that manufacture, process, handle, store, use, or dispose of such substances as hazardous fuels, hazardous chemicals, hazardous waste, or explosives) containing toxic or explosive substances where their quantity exceeds a threshold quantity established by the authority having jurisdiction and is sufficient to pose a threat to the public if released.	
Buildings and other structures designated as essential facilities.	IV
Buildings and other structures, the failure of which could pose a substantial hazard to the community.	
Buildings and other structures (including, but not limited to, facilities that manufacture, process, handle, store, use, or dispose of such substances as hazardous fuels, hazardous chemicals, or hazardous waste) containing sufficient quantities of highly toxic substances where the quantity exceeds a threshold quantity established by the authority having jurisdiction to be dangerous to the public if released and is sufficient to pose a threat to the public if released.[a]	
Buildings and other structures required to maintain the functionality of other Risk Category IV structures.	

[a] Buildings and other structures containing toxic, highly toxic, or explosive substances shall be eligible for classification to a lower Risk Category if it can be demonstrated to the satisfaction of the authority having jurisdiction by a hazard assessment as described in Section 1.5.2 that a release of the substances is commensurate with the risk associated with that Risk Category.

Figure 27: ASCE 7-10 Table 1.5-1 - Risk Category Definitions

The failure of a tall office building would result in significant danger to human life and have an impact on the economy and day-to-day human life. Therefore, a Risk Category of III was chosen for the steel scaled-up structure.

9.1.2 Dead Load

Per ASCE 7-10 Section 3.1, the dead loads placed on a structure consist of all the weights of construction materials. For the scaled-up steel structure, the construction materials consisted of the steel building frame and 6” concrete floor slabs on each floor. Per square foot, the floor slabs add 75 lb to the total dead load. The dead load was expressed using the following equation:

$D = 75\,lb/ft^{2} + ¿$Steel self weight.

9.1.3 Live Load

The live load placed on the structure was determined using recommendations from the client and ASCE 7 standard values. A table is provided that lists the live loads for all floors based on occupancy type. The source of the load is provided in the far-right column. This table of live loads is presented in Table 6.

Table 6: Live Loads for Scaled-Up Steel Building

Floor(s)	Occupancy Type	Load (lb/ft^2)	Source
1, 19	Retail	100	Client
2 - 18	Office	40	Client
Roof	Roof	20	ASCE 7-10

9.1.4 Snow Load

The expected snow load of the structure was calculated using ASCE 7-10 Chapter 7. Per ASCE 7-10 Section 7.3, the snow load for a flat roof shall be calculated as

$$p_f = 0.7\, C_e C_t I_s p_g$$

where C_e is the exposure factor, C_t is the thermal factor, I_s is the importance factor, and p_g is the ground snow load. From Table 7-2, the exposure factor was chosen to be 1.0. From Table 7-3, the thermal factor was chosen to be 1.2. From Table 1.5-2, the importance factor was chosen to be 1.10. Using data provided by the Applied Technology Council (ATC) Hazards by Location web app, the ground snow load for the New London Area is 30 lb/ft^2. Using these values, the flat roof snow load was calculated. The calculation was performed as follows,

$$p_f = 0.7\, C_e C_t I_s p_g = 0.7 * 1.0 * 1.2 * 1.10 * 30\, lb/ft^2 = 27.72\, lb/ft^2.$$

9.1.5 Rain Load

Per recommendations by the client, the rain load the structure may experience was calculated using local meteorological data. For a flat roof, the rain load may be calculated using the depth of the water pond that accumulates on the roof and the unit weight of water,

$$R = \gamma d_p.$$

According to data provided by Weather Atlas, the depth of the pond in the New London area is approximately 4.1". By the given equation the rain load was calculated,

$$R = \frac{4.1}{12\ in/ft} * 62.4\ pcf = 21.32\ lb/ft^2.$$

9.1.6 Wind Load

Wind load parameters were determined using ASCE 7-10 and inputted into SAP2000 where load patterns were automatically generated. The necessary wind parameters were the basic wind speed, exposure category, topographic factor, gust effect factor, and wind directionality factor. These parameters are presented in Table 7.

Table 7: Wind Load Factors from ASCE 7-10

Parameter	Governing Code in ASCE 7-10	Value
Basic Wind Speed	Fig. 26.5-1B	120 mph
Exposure Category	Section 26.7.3	C
Topographic Factor	Section 26.8.1	1.0
Gust Effect Factor	Section 26.9.1	0.85
Wind Directionality Factor	Table 26.6-1	0.85

Using these parameters, SAP2000 automatically generated wind load cases.

9.1.7 Seismic Load

Seismic load was applied to the structure using a response spectrum function. In SAP2000, a response spectrum function in line with the ASCE 7-16 Code was created by inputting required parameters. Data from the ATC Hazards by Location website was used to create the response spectrum function. The parameters and the values given by the ATC Hazards by Location website are presented in Table 8.

Table 8: Response Spectrum Parameters from ATC Hazards by Location

Parameter	Value
0.2 Second Spectral Acceleration	0.161
1 Second Spectral Acceleration	0.058
Long Period Transition (sec)	6
Site Class	D
Function Damping Ratio	Left as 0.05, SAP2000 Default Value

9.2 Preliminary Design of Frame Members Using SAP2000

Preliminary design of the structure was carried out once the building's dead loads were placed on the model. Design parameters pertaining to floor bracing and preferred shapes were established in SAP2000 before automatic design was run. Since concrete floor slabs were put in place on all floors, the unbraced length of all girders and floor beams was set to zero. For all frame members, W shapes were preferred. A table detailing specific W shape preferences for girders, floor beams, and columns is presented in Table 9.

Table 9: Preferred Cross-Sections for Scaled-Up Steel Building Members

Member Type	Preferred W Shape(s)
Girder	W12, W18, W24
Floor Beam	W12

Column	W10, W12, W14

Once the design parameters were established, design was carried out using SAP2000. The typical sizes of girders, floor beams, and columns is presented in Table 10.

Table 10: Typical Member Sizes for Preliminary Design of Scaled-Up Steel Building

Member Type	**Typical Size**
Exterior Girders	W12 x 336
Interior Girders	W18 x 119
Floor Beam	W12 x 106
Column	W14 x 730

The framing plans for the preliminary design of the scaled-up structures are presented in the following figures. Figure 28 presents the typical framing plan for floors 1 - 5. Figure 29 presents the typical framing plan for floors 5 - 8. Figure 30 presents the typical framing plan for floors 8 - 19 and the roof.

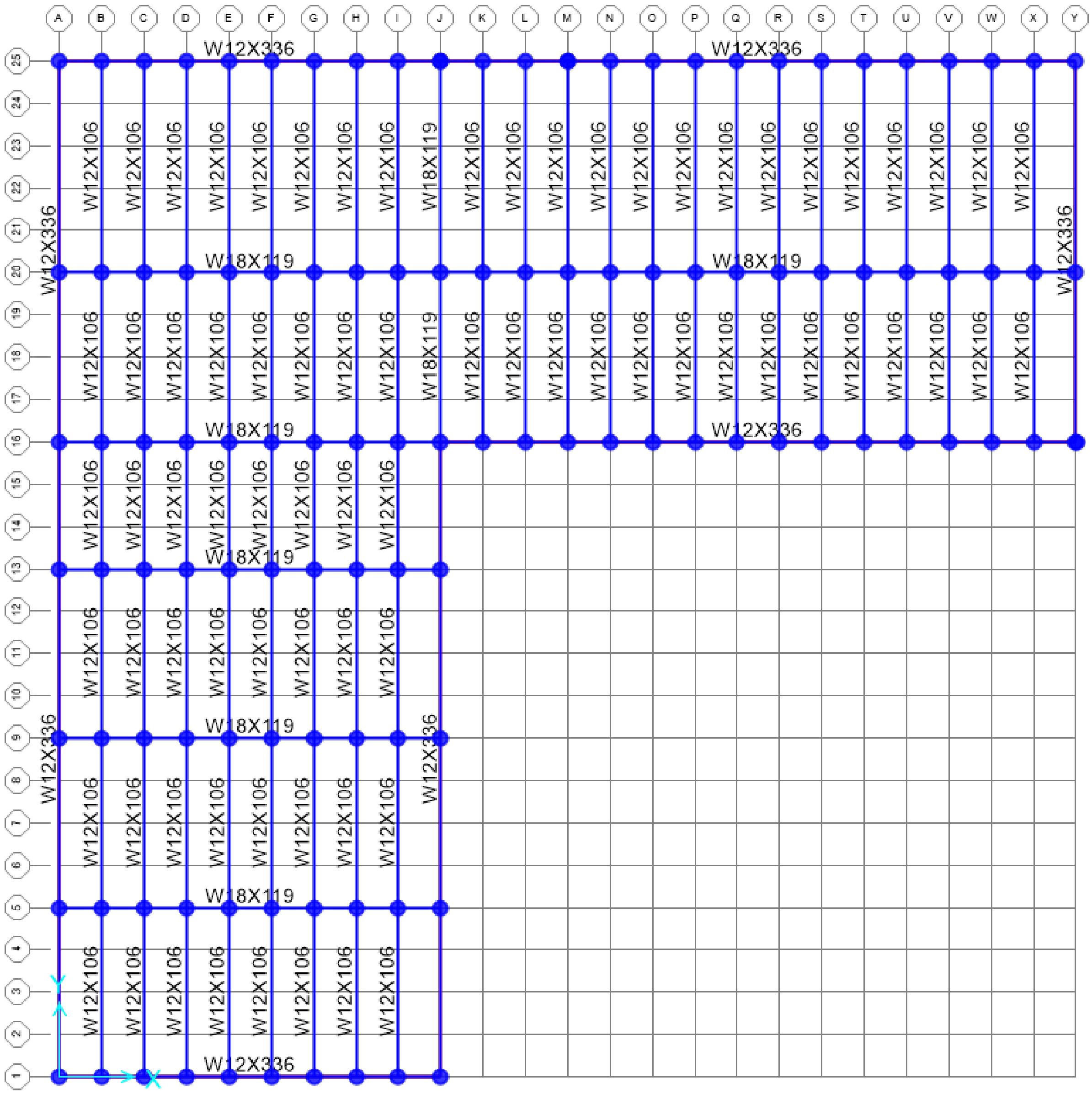

Figure 28: Typical Floor Plan for Floors 1 - 5 of Preliminary Design

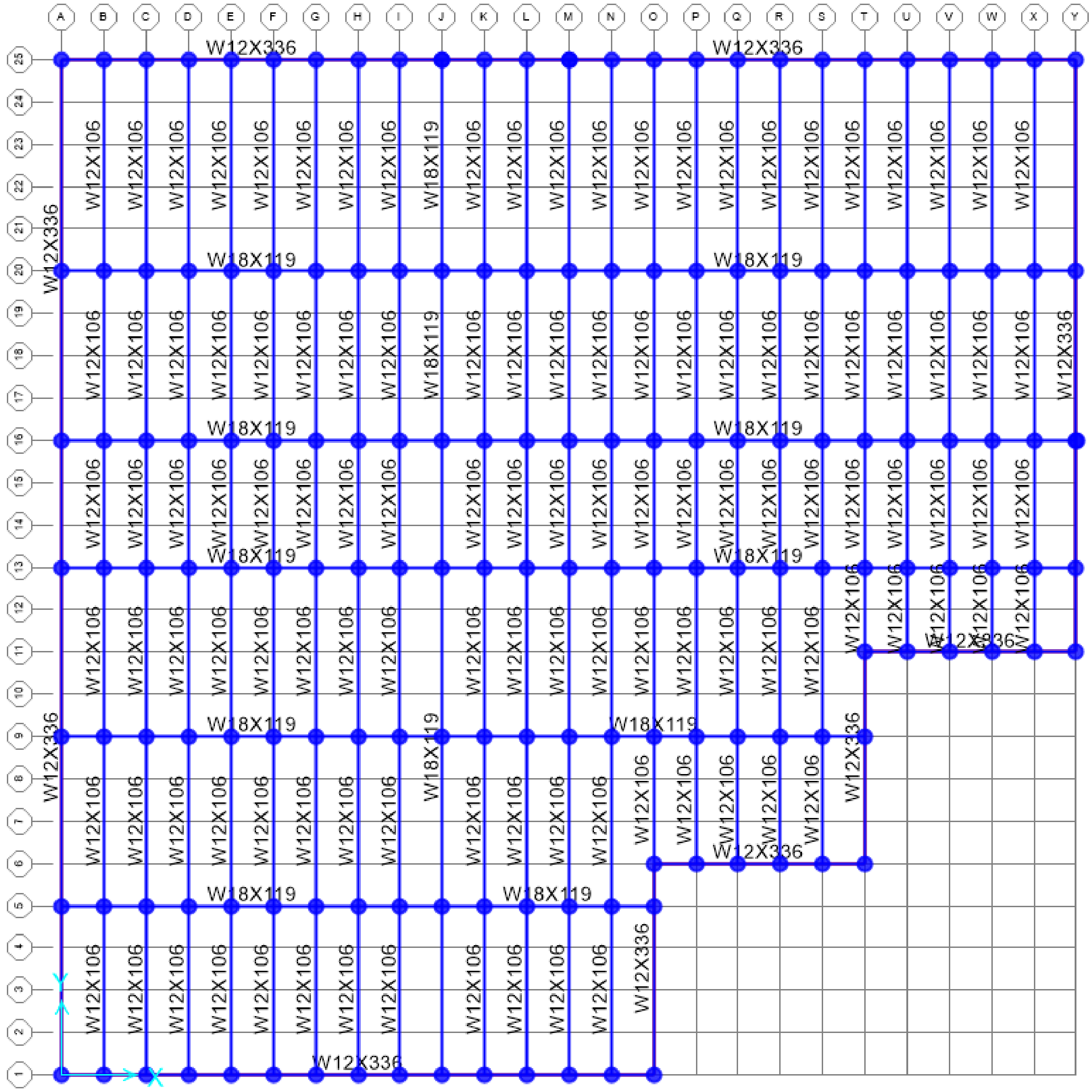

Figure 29: Typical Floor Plan for Floors 6 - 8 of Preliminary Design

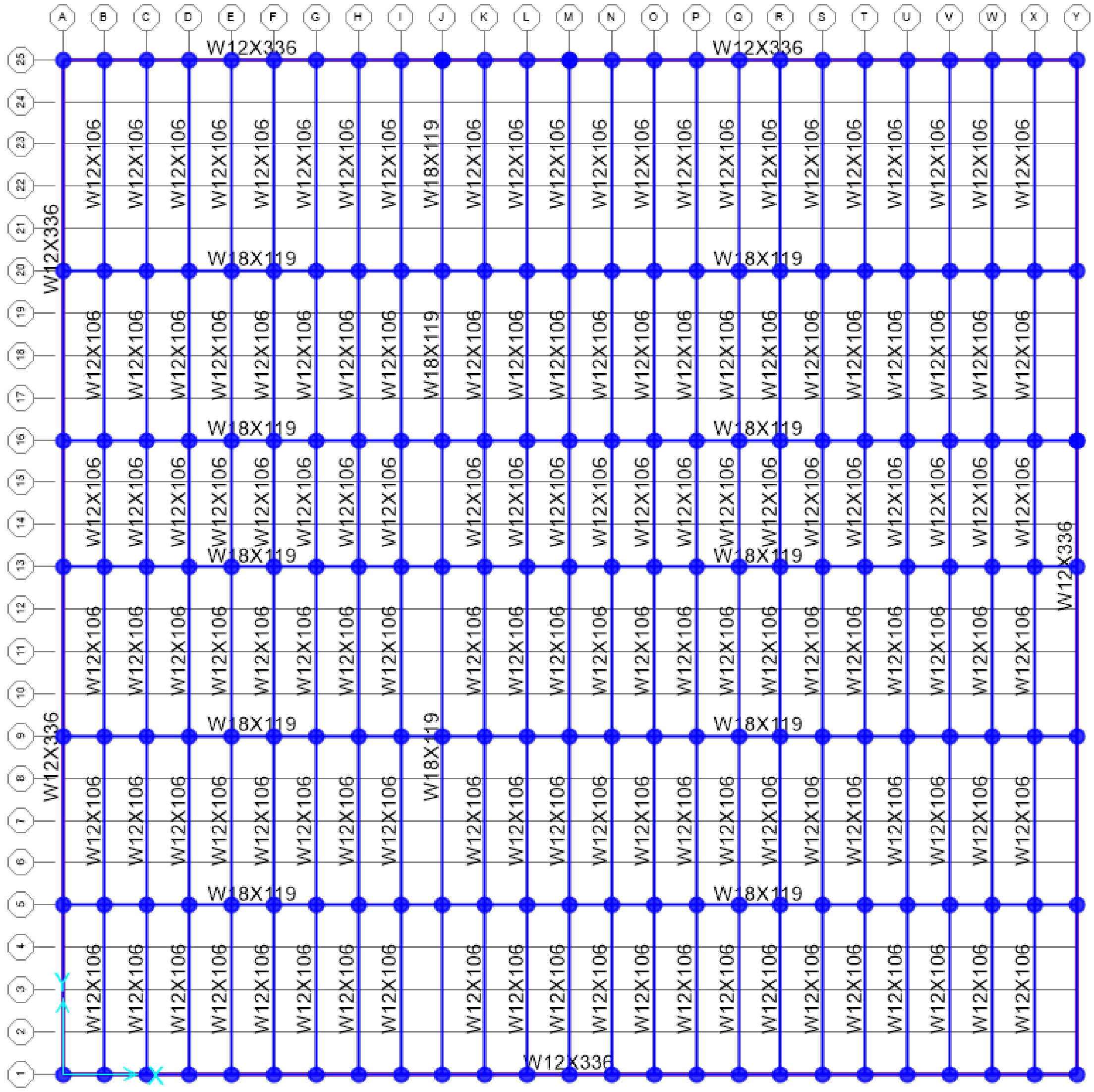

Figure 30: Typical Floor Plan for Floors 9 - 19 & Roof of Preliminary Design

9.3 Revision of Preliminary Design and Addition of Structure Loads

Once the preliminary design was completed, the additional loads were added onto the model. The structural integrity of the sized members were checked using SAP2000. When the results were reviewed by the client, it was decided that the structural design of the building was not adequate. Specifically, the client requested that smaller member sizes be used in the design.

To comply with the client's request, the team evaluated the SAP2000 model for any inconsistencies or errors that could have influenced the automatic design process. Once this analysis was complete, member sizes were changed both manually and through the automatic design process with the dead load applied to incorporate smaller sizes. Additional structure loads were applied and the structural integrity was verified with SAP2000.

This revision process proved to be challenging for the team. Due to the self weight of the steel members being a part of the dead load, changes made to any one member could result in surrounding members failing as a result of the load change. In addition, changes in strength due to size reduction caused members that were previously passing to fail in shear, bending, torsion, or buckling. All of these considerations resulted in this process taking up a considerable amount of time.

10.0 Finalized Scaled-Up Building Model

The scaled-up steel building model was finalized using the preliminary design from Section 9.2 and the structure loads from Section 9.1. The steel used for the design had a yield strength of 50 kips/in^2. Typical sizes for girders, floor beams, columns, and braces were selected through the design process and tested. The typical sizes for frame member types is presented in Table 11.

Table 11: Typical Member Sizes for Steel Building

Member Type	Typical Size
Girders (Exterior and Interior)	W18 x 143
Floor Beams	W12 x 40
Columns	W14 x 730
Lateral Bracing	2L8 x 8 x 1

Model views of the finalized design are presented in the following figures. Figure 31 presents a 3D view of the model. Figure 32 presents the typical floor plan for floors 1 - 5. Figure 33 presents the typical floor plan for floors 6 - 8. Figure 34 presents the typical floor plan for floors 9 - 19 and the roof.

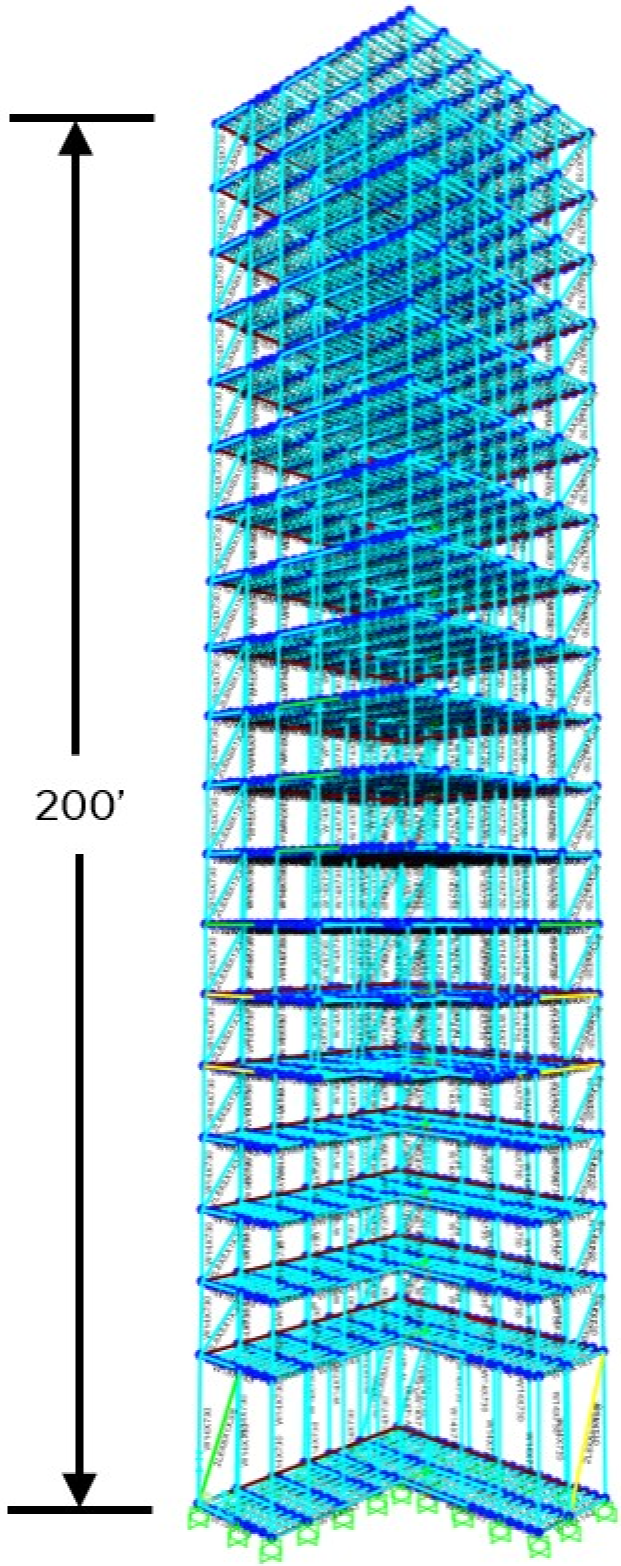
200’

Figure 31: 3D View of Steel Building Model

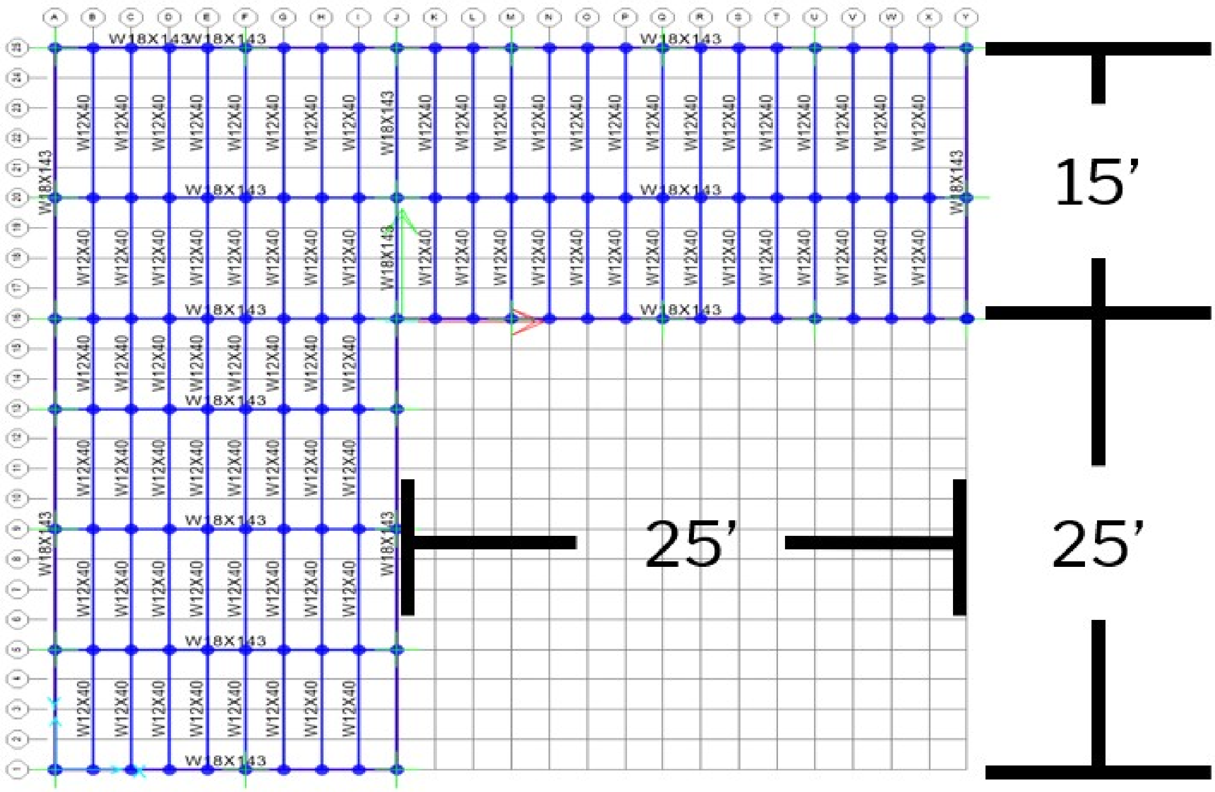

Figure 32: Typical Floor Plan for Floors 1 - 5 of Steel Building

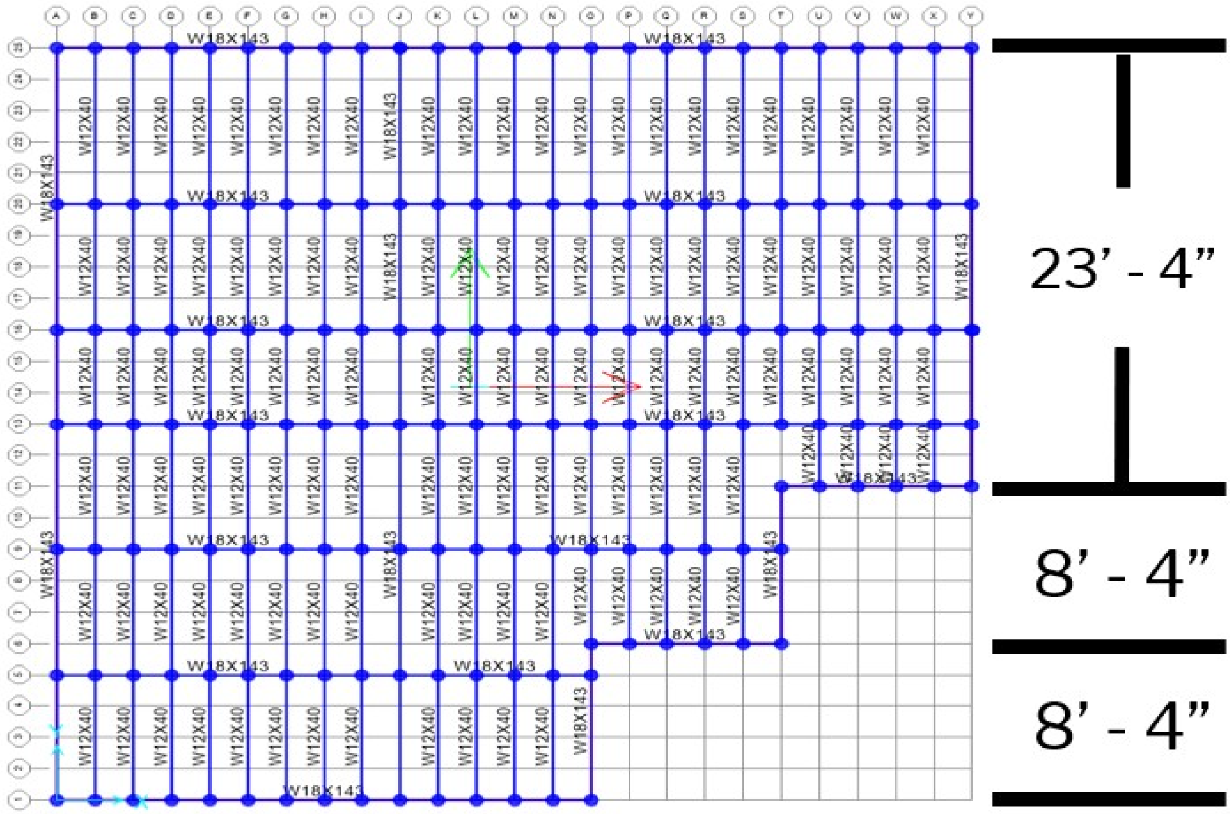

Figure 33: Typical Floor Plan for Floors 6 - 8 of Steel Building

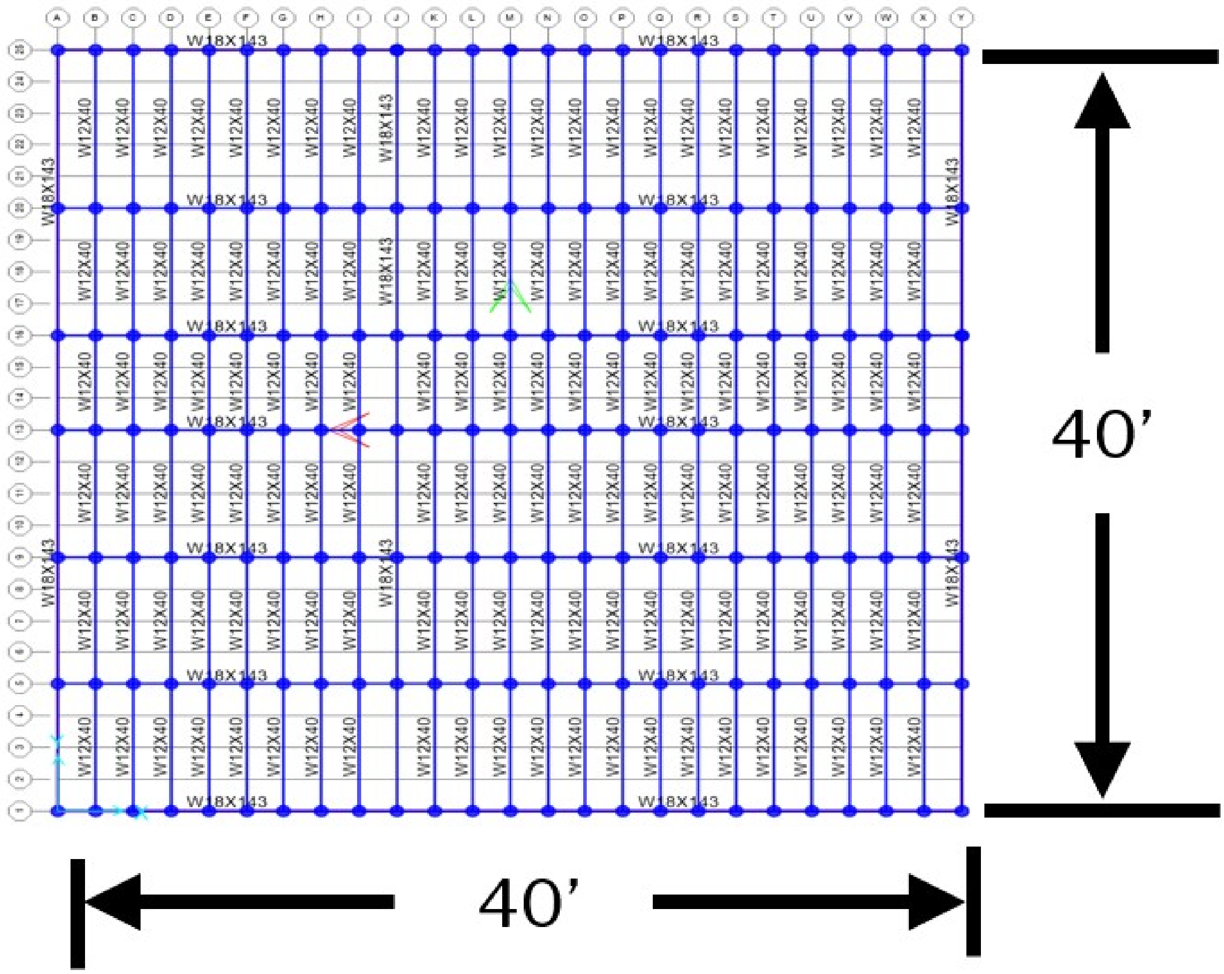

Figure 34: Typical Floor Plan for Floors 9 - 19 & Roof of Steel Building

11.0 Engineering Cost Analysis

An engineering cost analysis was performed by the team. The project cost was divided into a time cost and a monetary cost. In the team's project proposal, a time dedication of five hours a week per team member was established. It was expected that, with 13 weeks of work, approximately 260 hours of total work would go into the project. Since the team did not keep a timesheet for each team member, it is difficult to tell exactly how many hours were put into the project. However, it is believed by the team that the number of hours put into the project falls between 250 to 300 hours.

The monetary cost of the project was determined using the bill of materials created by the team for the construction of the balsa wood structure. A budget of $1500 was given by the University of Hartford to the team. Using this budget, materials were purchased that would either directly or indirectly help the team construct the balsa wood model.

Due to the COVID-19 pandemic, the construction of the balsa wood model could not occur. However, some of the materials placed on the bill of materials were purchased before the University of Hartford closed its campus for the remainder of the semester. Because of this, the bill of materials specifies the items that were purchased and those that would have been purchased if the project had continued as originally planned. The bill of materials is presented in Table 12.

Table 12: Bill of Materials

Product Name	Vendor	Price	Purchased?
Tools			
AmazonBasics Self-Locking Tape Measure - 25-Feet (8-Meters), Inch/Metric Scale, MID Accuracy, 2-Pack	Amazon	$ 13.58	Yes
Gimars 3 Pcs Nonslip Unique Measure on Both Ends Design 6 +12 inch Stainless Steel Metal Ruler Kit	Amazon	$ 9.99	Yes
GreatNeck BSB14 14 Inch Miter Box & Saw	Amazon	$ 12.98	Yes
DOWELL 9 Inch Magnetic Box Level Torpedo Level,3 Different Bubbles/45°/90°/180°Measuring Shock Resistant Torpedo Level	Amazon	$ 5.99	Yes
TOPS Engineering Computation Pad, 8-1/2" x 11", Glue Top, 5 x 5 Graph Rule on Back, Green Tint Paper, 3-Hole Punched, 100 Sheets (35500)	Amazon	$ 6.99	Yes
X-Acto Basic Knife Set | Set Contains 3 Precision Knives, 10 Precision Knife Blades, Wooden Chest for Storage (14 Count)	Amazon	$ 17.30	Yes
Construction Materials			
Gorilla Wood Glue, 4 ounce Bottle, (Pack of 4)	Amazon	$ 17.14	Yes
1/2 in. x 4 ft. x 8 ft. CDX Ground Contact Pressure-Treated Plywood	Home Depot	$ 25.57	Yes
Balsa Wood, 1/4" x 1/4" x 36" ($0.85 Each) **x500**	Balsa USA	$ 425.00	No
Dead Load Materials			
Steelworks 1/2-in dia x 2-ft L Coarse Steel Threaded Rod ($3.68 Each) **x19**	Lowes	$ 69.92	Yes
Hillman 13 x 1/2-in Zinc-Plated Steel Hex Nut ($0.21 Each) **x76**	Lowes	$ 15.96	Yes
Hillman 1 Count x 1.37-in Zinc-Plated Standard (SAE) Flat Washer ($0.22 Each) **x100**	Lowes	$ 22.00	Yes
Hillman 2-in x 2-in-Gauge Hot-dipped Galvanized Bearing Plates ($1.18 Each) **x80**	Lowes	$ 94.40	Yes
	Total Spent	$ 311.82	
	Hyopthetical Total	$ 736.82	

An engineering cost analysis was not performed on the scaled-up steel building. For this project, a cost analysis was out of scope since the team was not provided adequate information on the cost of construction materials, typical construction costs, and other project costs. The only consideration for this project was the design of the steel building frame.

References

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Appendix

The appendix was delivered as a zip folder to the required parties since a physical copy was unable to be delivered. In the appendix, the following are included in order:

1. Project Proposal & Scope of Work
2. Progress Reports
3. Meeting Minutes
4. Design Calculations
5. Data
6. Project Plans
7. References