MASS TIMBER IN TALL BUILDING DESIGN

A Major Qualifying Project Report:
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Abstract

The goal of this project was to investigate the viability of a tall mass timber frame in the US through direct comparison to a steel counterpart. The designs for both structures were modeled after FRAMEWORK, an 11 story mixed-use mass timber building approved for construction in Portland, Oregon. While the mass timber structure had many advantages, such as a lightweight frame, general ease of construction, and a negative carbon footprint, it was more expensive than the steel design. However, as mass timber grows in popularity, it is likely to grow in economic viability as well.

Acknowledgements

We would like to thank everyone that helped us get through this project. It certainly would not have been possible to bring this to completion without the assistance of those who guided us along the way. First we would like to thank our advisor, Professor Nima Rahbar, for his boundless patience and exuberant energy that pushed us through to the end. Secondly, we would like to thank Professor Leonard Albano for his suggestions and guidance that he provided in times of need.

Authorship

Throughout the research, analysis, design and the calculations of the project both of the team members contributed equally on their own areas of interest. The work was split within the team in the following way:

Michael Fager-Thompson was responsible on the Mass Timber calculations and design of the structure. He also wrote all of the sections relevant to the use of mass timber, as well as the initial draft of the background.

Emanuela Sherifi was responsible on the Steel calculations and design of the structure. She also wrote all of the sections relevant to the steel design, and revised the background.

Capstone Design Statement

The growing popularity of Mass Timber in Europe has led to an increasing demand for quality and sustainability into the US. This mass timber movement in tall building design, eventually made a foothold in the US with a 2014 design competition sanctioned by the Softwood Lumber Board and Department of Agriculture. In 2015, the city of Portland, Oregon approved the winner of the competition for construction. This building was called FRAMEWORK, an 11 story multi-use Mass Timber building designed by Lever Architecture (Tall Wood Competition). Seeing the approval of such a large timber building, the team decided to find out if it was truly viable to build a tall building entirely out of wood. The objective of our project was to determine the most economical approach to the design of a multistory building, using either Mass Timber, or the more conventional building material of Steel.

Using architectural drawings available online, the team designed a functional structural conjugate to Lever architecture's FRAMEWORK. This exclusively Mass Timber frame was then analyzed to ensure that it was structurally sound when subjected to Gravity, Live, Wind, and Seismic loads. With the general dimensions and floor usage found for the Mass Timber frame, the team then designed a Steel structure counterpart for the sake of comparison. Like its Mass Timber counterpart, this steel frame was also designed to withstand any loading combination it would be likely to be subject to in Portland, Oregon. With both options finished, the team proceeded to compare them on a number of criteria.

Through the team's analysis it was found that the use of Mass Timber in the design of tall buildings was quite viable, resulting in a light but sturdy structure. Due to its weight, the Mass Timber was especially resistant against seismic loads, requiring minimal lateral reinforcement. Additionally, its light frame required a notably smaller foundation than its steel counterpart.

However, despite its many benefits the cost of its Mass Timber members were notably larger than the steel frame. The light frame's expedited construction schedule due to ease of construction, as well as the decreased foundation cost helped lower its total cost, but not enough to overtake the steel frame. When it came to environmental impact though, the Mass Timber frame performed a lot more favorably. Due to the fact that wood is a carbon sink, constructing buildings out of Mass Timber essentially traps carbon dioxide, preventing its release into the atmosphere, and decreasing the entire project's carbon footprint (Martin). While the steel structure ended up being a bit more economically favorable, the team sees a bright future for the proliferation of Mass Timber buildings. As the green initiative is growing, Mass Timber should become more appealing in US. It is likely that, as the building practice becomes more mainstream, the limiting price of materials will drop, further increasing its viability in the built world.

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Chapter 1: Introduction

Currently, half of the world's population lives in urban settings. Furthermore, in the next twenty years, the number of people living in cities is expected to increase to an estimated five billion (Newman, Beatley and Boyer, 2009). Considering the large number of people living in cities, together with an inefficient energy grid, many cities – especially in the United States – are headed for inevitable collapse because enormous quantities of fossil fuels are consumed. Consequently, high levels of greenhouse gases are emitted in the atmosphere. “In forty years we need to have reduced our greenhouse gas emissions by at least 50% to avoid the worst-case scenarios of climate change.” – said Sylvie Lemmet, director in the Technology, Industry and Economics division at UNEP (United Nations Environment Program) (2009). This means that we are not only running out of the fossil fuels, which have powered urban settings for centuries, but our planet is also rapidly responding to climate change events. So what’s behind this shift?

“The fundamental reason for me is climate change,” was stated also from Michael Green. “We’re taking two materials - steel and concrete - that have high carbon footprints, and replacing them with a low-energy material.”(Green, 2012) By contrast, the transition to a more resilient energy material is happening faster in Europe. With origins in 1990s in Central Europe, particularly in Switzerland, Germany and Austria, the mass timber construction is well developed and makes up to $2 billion industry, producing 500,000 cubic meters of Cross Laminated Timber (CLT) annually throughout Europe. (Kobelt, 2016) When it comes to adapting mass timber in tall building construction in the United States seems to have many problems meeting the same standard building codes as the other materials. Hence, the question is: What are the barriers to adapting these new technologies in the United States, and how can we overcome these barriers for a resilient building construction? This questions leads us to the two main objectives of this study which consist of :

(i) comparing mass timber construction to a more conventional material such as steel and

(ii) determining the most effective material related to strength, cost effectiveness, energy consumption, and minimization of construction time.

Chapter 2: Background

2.1 Mass Timber

Mass Timber is defined as several solid panels of wood combined together in different layers to increase their compressive and tensile strength. The three main Mass Timber include: Cross Laminated Timber, Glue Laminated Timber (Glulam) and Nail Laminated Timber (NLT) . Cross Laminated Timber (CLT) is made of layers of solid wood known as lamellas set at 90 degree angles, which contribute by adding additional strength and rigidity to the layers. Currently CLT is the mass timber commonly used.

Glue Laminated Timber is composed of wide parallel layers of wood gathered together based on their strength performance. This kind of timber is usually used for beams, trusses, and sometimes for columns. Nail Laminated Timber works in a similar way but it is smaller in size. It is used in floors, decks, and also for timber elevator.

CLT was developed in Germany and Austria in the 1990s but only in last few years the idea of building tall wood buildings is taking place. As the green initiative is growing, mass timber is becoming more appealing. "The use of timber as a structural material in tall buildings is an area of emerging interest for its variety of potential benefits; the most obvious being that it is a renewable resource, unlike prevailing construction methods which use concrete and steel," said a statement from the University of Cambridge. (Univeristy of Cambridge, 2016) In addition to its ratio of weight to strength, the biggest advantage is carbon sequestration. While trees are growing, they pull in carbon from the atmosphere and store it in the wood: The wood used in a 20-story building could sequester 3,150 tons of carbon. (Redshift, 2016) The amount of concrete used to build such a structure would emit 1,215 tons of carbon. These emissions savings are the equivalent of taking 900 cars off the road for a year. (Redshift, 2016) Appealing mass timber into tall building design shows excellent workability and demonstrates a decrease during the construction time.

2.2 Mass Timber Abroad

Cross Laminated Timber has been available to Europe since its invention in the early 1990s mainly in Germany and Austria in small structures, but only within the last decade the development of tall wooden structures with the use of Mass Timber construction is taking place. Europe is the continent where the CLT is used most, and there are currently more than one hundred projects located there. (1.Mohammad et al. , n.d.) The main reason of the use of Mass Timber in these projects is associated with the green building initiative in construction. With the growing popularity of Mass Timber in tall building constructions, many unknown benefits of this material have been discovered, leading in the increase of its popularity in the construction sector. (1.Mohammad et al. , n.d.) The increase in the production of CLT is shown in Fig 1 In 2014 the global annual production of cross laminated timber was estimated to be over 600,000 cubic meter, and is expected to exceed 3 million cubic meter within the next decade (2.Espinoza et al. , 2015)

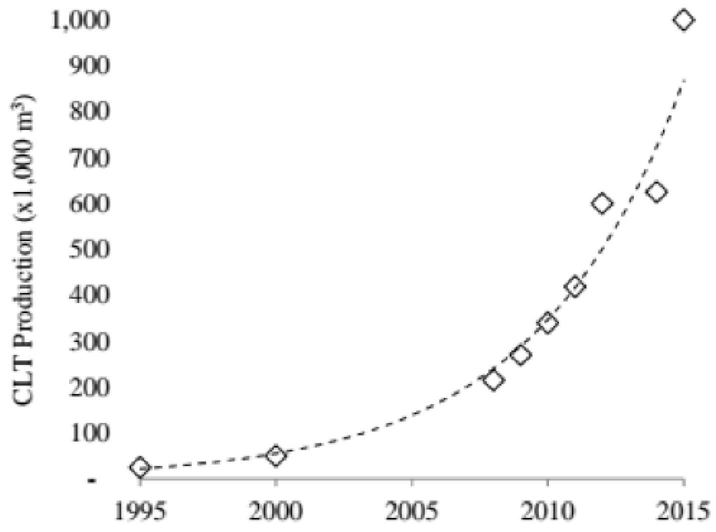


Fig 1: Global Production of Cross Laminated Timber for the past decade (2)

Since most of the CLT's projects are placed in Central Europe, most of the production of the CLT is also placed there, particularly in German speaking countries where the construction sector is very developed compared to the other Eastern European countries. (2.Espinoza et al , 2015)

One of the first and most notable examples of mass timber structures is Waugh Thistleton Architects' Stadthaus, built in London in 2009. (Green, 2012) This residential building stands a total of nine stories tall, and consists of a concrete ground floor with eight consecutive CLT slab floors. This building is the first urban housing project to be constructed completely from pre-fabricated solid mass timber including here its load bearing walls and floor slabs and is currently the tallest timber building in the world. This projected was built in a period of 49 weeks and successfully met all the required building codes in UK. By using mass timber, it is estimated 181 tons of carbon to be stored by the building; additionally 125 tons of carbon are prevented from polluting the atmosphere, playing a huge rule in the green initiative building design. (Green, 2012)

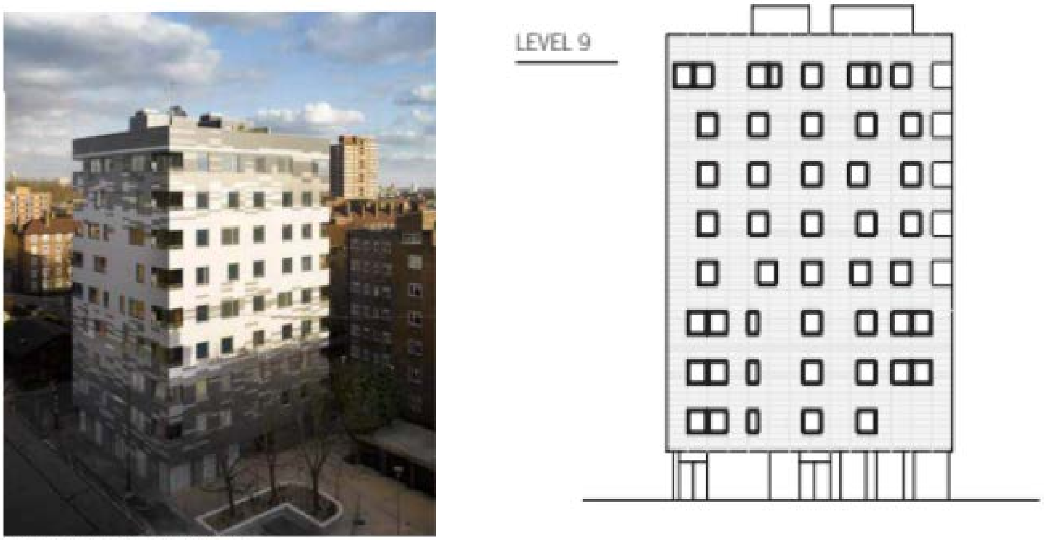


Image: Waugh Thistleton Architects

Figure 2: Stadthaus

Another exciting timber project is taking place at the university of British Columbia in Vancouver, Canada by Acton Ostry Architects. This project, which began construction in November 2015, includes an 18-story student residence building and is expected to be completed in May 2017. (3) Once the constructions are finalized, the building will provide housing for 404 students and it will be the tallest mass timber structure in the world. The building contains one story concrete podium, two concrete cores and 17 stories of mass timber. The roof is made of prefabricated steel beams and metal deck roof. The concrete cores carry lateral loads, while the timber structure members support the vertical loads. The building is expected to save 25% more energy compared to a building with the same use made a more conventional material such as steel or concrete. (3) Michael Giroux, the President of the Canadian Wood Council, stated about this project: "As the tallest wood building in Canada, this project will serve as a great example of the research and technology that is involved in taking wood construction to new heights- resulting in innovative solutions that are safe, sustainable and viable “

Figure 3: Mass Timber Construction

2.3 Mass Timber in the United States

Following the recent international trend towards the use of Mass Timber in tall building design, the United States Softwood Lumber Board commissioned Engineering/Design firm Skidmore, Owings & Merrill to research the use of Mass Timber as a primary structural material. This resulted in the study and eventual 2013 release of the *Timber Tower Project*, a redesign of the firm’s own Dewitt-Chestnut Apartments, a 42 story building in Chicago, IL [TTP]. Much like Michael Green’s *Tall Wood*, this study was devised to add viability to the idea of Mass Timber’s use in tall building design, making a case for its use in a hybrid frame, or even as the sole structural elements. In the final report, SOM utilized a hybrid structure of GLULAM beams/columns, CLT structural walls/floors, with additional reinforced concrete support at the joints. While an all timber frame was considered, it was passed over due to an increased structural complexity and cost of materials for such a tall design. In total, this case study showed that the chosen frame was comparable to the original design comprised of steel and concrete. In addition to its structural viability, this new design also proved to be much more environmentally sustainable, with an estimated 60-75% decrease in the building’s carbon footprint [TTP].

2.3.1 Mass Timber Stigma

As Mass Timber design proliferated throughout the international market, several factors stopped it from spreading as quickly to the United States. In many US cities, local building code prevents the construction of wood framed buildings over the height of 6 stories without special considerations. The reasoning behind many of these restrictions are heavily inspired by the historical performance of wooden frames, lacking many of the new technologies utilized today. Like these codes, many people have misconceptions about the durability, structural integrity, and sustainability of Mass Timber Construction.

One of the primary reservations many have is based on the perceived flammability of wood. This is actually responsible for a great number of the regulations on timber construction. While this fear is not totally unfounded, Mass Timber members have been found to be much more fire resistant than some may believe.

2.3.2 US Push for Increased Mass Timber Usage

Three years after the release of the *Timber Tower Project*, the United States saw the construction of its first modern tall Mass Timber building, Minneapolis' Timber, Technology, Transit, or T3. While it is no 42 story behemoth like SOM's redesign of the Dewitt-Chestnut Apartments, this scrappy 7 story office building represents a large step forward by the United States.

Seeing the growing interest in tall Mass Timber buildings, and the imminent construction of Minneapolis' T3, a bipartisan coalition in the United States House of Representatives proposed and passed the *Timber Innovation Act*. This law aims to foster the growing interest in Mass timber construction by providing necessary funds to research the technology and its potential application in taller buildings. Additionally, the wording within its pages acknowledge the increased fire resistance, etc. of these materials when compared to conventional wooden construction, and make direct reference to the obsolescence of the United States' wood building codes. One of the primary goals of the aforementioned research is to modernize the US building code to better accommodate tall Mass Timber buildings in the future. Finally, this document establishes a yearly competition for tall Mass Timber building design, awarding a yearly grant to one winner per year. The aforementioned competition was likely to have been inspired by a similar one held by the US Department of Agriculture in partnership with the Softwood Lumber Board from late 2014 to late 2015.

2.4 FRAMEWORK

An eleven-story mixed residential and office space building made of cross-laminated timber will be constructed in Portland, Oregon. This building tends to be the highest mass timber building in the US. The building is located between two main streets, 10 Northwest Avenue and Northwest Glisan Street and it will provide affordable housing and office space for Beneficial Bank, which is currently occupying the site. (nextportland, 2016) The first five floors will serve as office spaces, the consecutive five floors will provide residential housing and the top floor will be an open roof garden. At the ground floor there will be provided 69 bicycle parking spaces to be used by the residents. The structure is shown in fig 4**.**

Figure 4: Framework

The project was awarded at the 2015 U.S Tall Wood Building Prize Competition with 1.5 million grants from the U.S Department of Agriculture, which will also be used to conduct the additional necessary fire and seismic tests to ensure the building's stability and to demonstrate that cross laminated timber can resist the required requirements associated with fire, seismic loads and noise. (nextportland, 2016) These tests will help on determining the viability of mass timber in tall building design, and meeting all the required building codes according to fire performance. When the possible challenges of mass timber in tall building design were addressed to Robinson, the founder of Lever Architecture firm, he said that his team thought it through by "oversizing" the structure, giving the building more time as a fire burns at a constant rate. (nextportland, 2016) He also pointed out that the wood panels comprising the building would be very different from the timber frames that most people are used to see at daily basis. The floors and ceilings of the building will be constructed using cross-laminated wood panels, engineered of stacked lumber, and the beams and columns using glue-laminated timber for this building, demonstrating a sustainable urban development, with a close attention to carbon emissions and the use of less energy than those made from traditional materials like steel or concrete. (nextportland, 2016)

Chapter 3: Methods

Seeing as the idea of using mass timber for tall building construction has been getting international traction, and has begun to seep into the United States, the team felt it reasonable to test the viability of mass timber in tall building design. Throughout the course of this report the team will be comparing Framework, an 11 story mass timber multi-use building approved for construction in Portland Oregon, to an alternative building made from the more conventional building material of steel. This secondary steel building will be designed by the team to serve all of the same purposes of the original and meet all the required building codes. These two will then be compared on a number of important criteria such as: strength, fire performance, cost, construction ease and sustainability.

This study will have a stronger focus on the structural stability and outcomes of these two buildings over the legal concerns. As discussed in the background, the US and many of its component states still have very restrictive building codes when it comes to timber construction. Undoubtedly, Framework's developers had to jump through some legal hoops in order to secure approval in Portland. Since the team plans on emulating the building as closely as possible with the given information, they will assume that the final product will meet whatever criteria were put before the designers at Lever Architecture. The team's steel design, however will be subject to the building codes and ordinances of Portland, Oregon.

Due to time constraints, the team limited their scope to just the two buildings: The original Framework design, and a steel counterpart. Ideally, this study would be conducted with a wider range of construction materials, including reinforced concrete, and a hybrid use of RC and steel members. This would result in a more comprehensive look at the differences in price, construction time, and ecological footprint. However, due to a limit on time, as well as the manpower restrictions that come with a two person team, a more stripped down study had to be adopted.

In its totality, this task can be broken up into three primary sections. The first section will consist with the 3D recreation of Lever Architecture’s Framework to the best of the team's capabilities using cross laminated timber for the floor panels and glue-laminated timber for beams and columns and ensuring the building’s stability when subjected to Gravity, Live, Wind and Seismic loads. The second section will include the design of the steel counterpart from the parameters used on the original building. Finally, the comparison of the two based mainly upon economic feasibility, ecological impact, as well as the ease and speed of construction, providing recommendations to better serve the increasing demand in US for quality and sustainability.

3.1 Scope of Project

In order to compare the Cross-Laminated-Timber design of Lever Architecture’s Framework to a counterpart designed using conventional building materials, the team will first have to recreate the original design in digital modeling software.

The team’s model of Framework’s Cross-Laminated-Timber design will be based off of architectural floor plans found online, as well as still rendered images of the firm’s own 3D model. Seeing as there are no public records of the finished structural plans, the team will not be able to create a model identical to the final design, but will interpret the plans available, and revise them based off of structural analysis, and loading minimums required by the city of Portland, OR.

As one can see throughout the plans, each of floors serve one of three main uses: Office space, residential, and a lobby area present on the first floor. The overall floor layout changes depending on its use, however the structure is designed in such a way that it maintains its form throughout all 11 floors with only minor variations on the 1st and 12th. Even though one can see the addition of walls on the residential floors 7-11, it is clear that they are not structural, but merely there to create saleable parcels. The only other difference one sees between the floors is in their height, which ranges from 16’ in the lobby to 12’ offices and 10’ residential.

The first step the team took towards modeling Framework’s mass timber design was to create a 2D CAD overlay for the architectural floor plans found online. Seeing as there are not exact measurements regarding the placement of columns and structural walls, the team used known measurements on the plans to resize them to an appropriate scale. With a newly to-scale approximation of FRAMEWORK’s layout, the team was then able to simplify it into something more befitting the scope of this project.

Applying the necessary loading conditions, the team will roughly analyze representative beams and columns from every other floor. Using the results of said analysis, the team will design the nominal beam and column sizes required to sustain the varying loads throughout the building. Extra attention will be paid to the member sizes specified, insuring that the required areas are common Glulam sizes, or are possible through the use of custom members.

3.2 Constant Factors

Even though the end product of this project is two unique structural frames constructed from different materials, there were several factors that these designs had in common. First, both designs were constrained to the same simplified footprint of Lever Architecture’s Framework. This meant base dimensions of 82’ x 88’, as well as eleven stories with floor heights varying on floor usage. The first floor is a 16’ tall lobby, topped with five 12’ office floors and five 10’ residential floors. The twelfth floor, made up of half rooftop garden, and half penthouse was simplified to just include one full rooftop garden. Image references used to determine these constant factors can be found in **Appendix B**. In addition to constant dimensions and floor heights, both the Mass Timber and Steel structural frames shared the same floor usages as the original building, leading to the same live loading.

Figure 5: Render of the mass timber frame with color coded loading conditions

Seeing that the two structures were designed for the sake of comparison, it is only natural that they would share some loading conditions. By referencing the 2014 Oregon Structural Specialty Code's chapter 16 on Structural Design, the team found the minimum live loading required for this building's different uses. Additionally, an assumption of 5 psf of dead loading was made for the Mechanical, Electrical, and Plumbing, as well as another 5 psf dead load for other miscellaneous ceiling construction loadings. According to the City of Portland's Development Services website, the minimum snow load to be considered is 20 psf with an additional 5 psf rain on snow surcharge. For the sake of simplicity when applied to the loading conditions, the team assumed a total of 25 psf snow loading on the top, Rooftop garden level of the structure.

Load Name	Load	Load Type
Rooftop Garden	100 psf	Live
Residential	40 psf	Live
Office	50 psf	Live
Mechanical, Electrical, and Plumbing (MEP)	5 psf	Dead
Misc Ceiling Construction	5 psf	Dead
Snow	25 psf	Snow

Table 1: Shared Loading

3.3 Mass Timber Design

The mass timber design was created to stay as loyal as possible to the source building. As with Lever Architecture's FRAMEWORK, the planned building this design is based off of, the entire structure was to be made of mass timber. Beams and Columns would be constructed from Glue Laminated Timber, while the flooring and structural walls used Cross Laminated Timber. Throughout the design process, especially during the planning phase, the team aimed to emulate the design of FRAMEWORK. As such, the final ceiling support plans mirrored a simplified version of preliminary architectural plans that acted as the team's guidelines **Appendix B**.

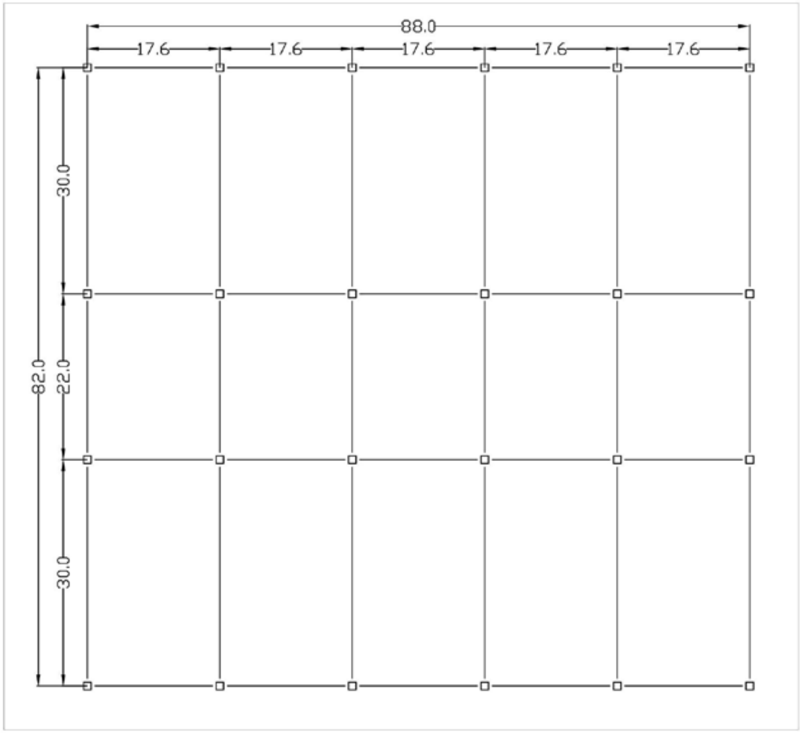


Figure 6: Typical Floor Member Layout (ft)

As noted in Section 3.2, the design had to fit within a 82’ by 88’ footprint, and carry all of the common loading, along with its own dead loading. In order to carry these loads, a total of 24 columns were placed, with 4 rows of 6 columns each. Four rows were chosen instead of the original 5 in order to cut down on the total number of span lengths that needed to be designed, while staying true to the spirit of the original drawings. As one can see when referencing figure 6 to Appendix B, the middle row of columns were removed, getting rid of the small corridor. The choice to have six columns per row was made to allow for the same layout of shear walls seen in Appendix B without blocking any passage from one side of the building to the other.

This structural floor plan was used as a basis for the design of all of the structural members in the Mass Timber frame. All of the members listed below were designed in accordance with the

2015 National Design Specification for Wood Construction, using Load and Resistance Factor Design (LRFD).

3.3.1 Typical Floor

The first step the team took was to design a typical system to support the structure's loading floor by floor. As mentioned above in section 3.2, Lever Architecure's FRAMEWORK is a multi-use building, meaning that a unique set of members had to be designed for each different use and loading case. In the end, three separate structural bays had to be designed: One to support the loads from an office floor, one to support the loads of a residential floor, and one to support the loads of the roof garden located at the top of the building. Even though the final frame would have a total of eleven such structural support systems, only these three had to be designed, as all floors that shared the same loading would be functionally identical to one another.

Using the minimum live loading detailed in the 2014 Oregon Structural Specialty Code's Chapter 16: Structural Design as well as the common dead load figures from section 3.2, the team designed a flooring support system for each of the three loading conditions. Following the primary design principle for this structure, the flooring system had to be constructed from mass timber, like the rest of the structure. Seeing this, the clear material option was Cross-Laminated Timber, as described in section 2.1 above. Due to its structural strength, the CLT flooring does not require the support of beams other than the girders pictured in figure 6.

3.3.2 Gravity Loading

One of the most important portions of the design of a structural frame is the creation of a structure that can adequately withstand the given Gravity Loading.

3.3.2.1 Beam Design

Given the multi-use nature of the structure at hand, each floor support structure and all of their members had to be designed individually. As seen in figure 7, each floor is supported by beams of three different spans, for a total of nine unique loading and span combinations. Using rough calculations including the Snow loads, the controlling load combination was found to be 1.2 Dead + 1.6 Live + 0.5 Snow. In order to ensure the serviceability of the designed members, the following steps were taken.

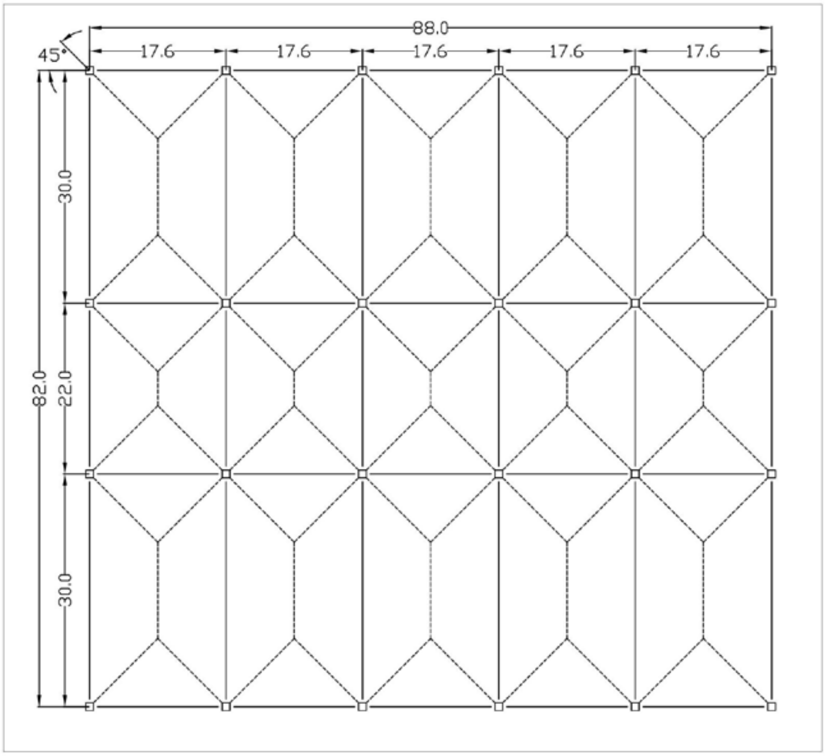


Figure 7: Tributary Area of Beams in Typical Floor Layout (ft)

Using the factored loading and tributary area of a sample floor and member, a total linear loading was determined. It was found that, in order to support the loading of the spans determined in **Figure 6**, the member required a larger cross-sectional area than those offered by current US Glulam distributors. This did not serve to be that large of a problem, as many such distributors offer custom sizing in increments of 1.5” in width, and 1.5” in depth. However, this meant that one couldn’t just refer to design tables, and calculations had to be done by hand. The reference bending design value (Fb) and reference shear design value parallel to grain (Fv) used to determine serviceability were taken from the product manual. In order to expedite calculation time, an Excel spreadsheet with references was used throughout the calculation process. This allowed for quicker iterations of design by changing member variables such as height, width, span, etc. Additionally, this made it much simpler to design all 9 unique loading and span combinations through copying and altering the span, tributary area, loading, and cross-sectional dimensions of these members. These calculations can be found in **Appendix A**.

3.3.2.2 Column Design

Using the structural layout found in Section 3.3, the team was able to find the tributary area of each of the 24 columns on a typical floor. As one can see in **Figure 8** below, each floor contains four different column categories with a unique tributary area, and therefore loading. For the sake of simplicity, a single column type was chosen to design. Using the total tributary area, as well as beam spans supported by each column type shown in **Table 2**, the group decided to model the structure’s columns after Type D. This was done because a column designed for the largest carried load could easily support that of the others.

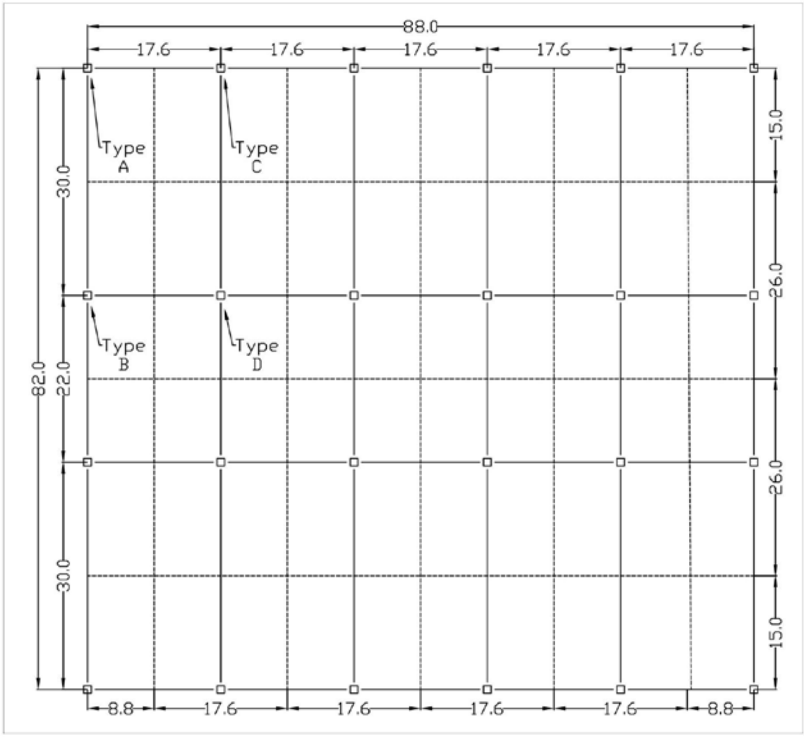


Figure 8: Tributary Area of Columns in Typical Floor Layout (ft)

Column Type	Tributary Area	Long Spans in Tributary Area	Middle Spans in Tributary Area	Short Spans in Tributary Area
A	132 ft^2	½ Span - 15’	0 Spans - 0’	½ Span - 8.8’
B	228.8 ft^2	½ Span - 15’	½ Span - 11’	½ Span - 8.8’
C	264 ft^2	½ Span - 15’	0 Spans - 0’	1 Span - 17.6’
D	457.6 ft^2	½ Span - 15’	½ Span - 11’	1 Span - 17.6’

Table 2: Number of Beam Spans in Columns’ Tributary Area

In order to avoid unnecessary calculation, the team grouped all 11 functional stories into sections of three, with one section of two at the base of the structure. In these smaller sections, the team would only design the lowest of the available columns, and apply it to the members above. As with the selection of Column Type D, this way every column in each section would either perfectly fit with standards, or err on the side of safety. By applying both of these time-saving measures, the team was able to cut down the required number of columns designed elevenfold.

As seen with the beams, many of the cross sectional areas required for the Glue Laminated columns were larger than the generic sizes on offer by US manufacturers. This was especially true at the bottom of the frame, as each needed to carry quite a large load. The same action was taken during this design phase as with the beams, by assuming that the required sizes would be custom made, a feature offered by most companies. As these columns were not of standard sizing, one could not find the allowable axial load on product sheets. In place of this, the team used the reference compression design Value (Fc) found on said product sheets. Much like with the design of the beams, Excel was used to calculate the required column dimensions, making it much easier to iterate, and design new members based on changing variables. This document was also interlinked with itself, allowing for quick recalculation of any changes were made to the base parameters, or even any of the beam section’s variables. These calculations can be found in **Appendix A**.

3.3.3 Lateral Loading

After designing for the gravity loads inflicted on the frame, the team then had to take into account lateral loading. Seeing that FRAMEWORK is a tall tower, it is quite susceptible to wind loading, as well as seismic loading in case of an earthquake.

3.3.3.1 Seismic Loading

Using the member sizing determined in sections 3.3.1 and 3.3.2, a total dead weight was found for each floor in the mass timber structure. For the sake of the calculations for seismic loading, a floor was defined by the flooring itself, as well as the beams and column supporting it. In order to accurately determine the lateral loading applied to each floor of the structure, the team first had to find the spectral response acceleration parameters S_{DS} and S_{D1}. To do this, the team used the United States Geological Survey (USGS) Seismic Design Map app on the building's proposed location in Portland, Oregon. The 2010 ASCE 7 Design Code Reference Document was used and referenced 2008 USGS hazard data **Appendix A**. Seeing as the team was not able to find soils information for the building site, Site Class D – "Stiff Soil" was chosen, as it was the default option. With the above seismic data, the team was able to use ASCE 7 equations to find the total seismic base shear V, and distribute it vertically throughout the structure **Appendix A**.

3.3.3.2 Wind Loading

Much like seismic loading, wind loads are heavily reliant on the location of the building being designed. Using Portland Oregon's Development services website, it was determined that for a risk category II building such as FRAMEWORK, the 3-second gust wind speed was 120 mph. This was applied to ASCE 7 equations to determine the total wind pressure the building underwent on each individual wall at each floor level. Using the area of the walls, and heights of the buildings themselves, these air pressures were then translated to direct loading on each individual floor. In order to keep track of the complex calculations required for this section, the team used excel to visually map out the data in a comprehensive manner **Appendix A**.

3.3.3.3 Shear Wall Design

Using the controlling loading in the following load combination 1.6 W + 1.0 E, the CLT shear walls were designed Appendix A.

3.4 Steel Design

For the steel counterpart of the Framework, the structural design of the building was archived using the 2010 AISC Specification for Structural Steel Building and the 14th Edition AISC Steel Construction Manual. The design of steel structural members was completed in accordance with the Load and Resistance Factor Design (LRFD), an adequate AISC specification method. Three different load combinations were evaluated for the Gravity loads, depending on the use of the building; consisting of the office space for the first five floors, residential spaces for the next five floors and the garden roof which obtained a larger gravity load. Once the gravity loads were determined, the team designed the structural members of the building including here: beams, girders and the columns. All steel members consisted of ASTM A992 steel.

3.4.1 Dead loads

Dead loads consist of the total weight of the structure and other materials that are attached permanently to the structures such as the weight of the metal slab, the weight of the beams and columns. The following dead loads were assumed through the calculations according to the building's occupancy.

5 " Concrete Slab & 2" Metal Deck	50 psf
Structural Steel frame/ floor	5 psf
Ceiling Construction	5 psf
Mechanical, Electrical & Plumbing (MEP)	5 psf

Table 3: Steel Frame Gravity Loads

3.4.2 Live loads

Live Loads refer to the temporary loads of the buildings caused by the use of the building. The position of the live loads keep changing constantly, and the structural members are designed based on the maximum expected occupancy load. The magnitude of the live loads differs for each structure and is determined based on the building's codes for Portland OR. Since our 12th story building is multi-used different live loads are considered in each case. See Table 1.

3.4.3 Typical Floor

The footprint of the building is a 88 x 82 ft rectangle. The interior of the building consists of four bays of of 22 ft in the East- West direction and bays of 33ft, 16 ft and 33 ft in the North-Side direction. Furthermore, the interior is left as an open space area, subjected to change based on the occupancy.

3.4.4 Beam Design

All beams were considered to be simple supported and they were assumed to have continuous lateral bracing. All the LRFD Load Combinations were calculated and the largest one it was chosen, in order to determine the required design load that needs to be resisted by the beam. For the Roof Garden it was used WU= 1.2D + 1.6l+ 0.5S and for the office/ residential spaces it was used WU= 1.2D + 1.6L. The spacing of the beams was determined to be 8ft oc, based on the floor metal deck. Once the desired design load it was determined the designed moment it was calculated using the equation MU= WU*L2/8. Based on the desired moment and the unbraced length of the span a W shape was chosen from Table 3-10 of the AISC Manual of Steel Construction. There were three different checks were performed to verify the adequacy of each beam. The first check consisted with the moment capacity of the beam, which was calculated based on their zones of behavior. There are three different ranges depending on the beam's lateral bracing situation. (McCormac, 2012) Once the moment capacity of the beam was determined it was compared with the bending moment previously calculated. The second check was for the shear. Shear Check was achieved by determining the shear caused by the weight on the beam using the formula : Vu=Wu*L/2 and comparing it to the shear capacity of the beam. Once Vu>Vn the shear check was satisfactory. The last check was for the Deflection. Two different deflection's checks were done. The first one was associated with the live load and the second one was related with the total weight on the beam, using the formula $5WL^4/384EI$. Once the three checks were defined, the concluded the W-Shape was adequate to resist the given loads of the structure.

Girders were designed in a similar way as the beams. The only difference was that the girders also support the weight of the beams.

3.4.5 Column Design

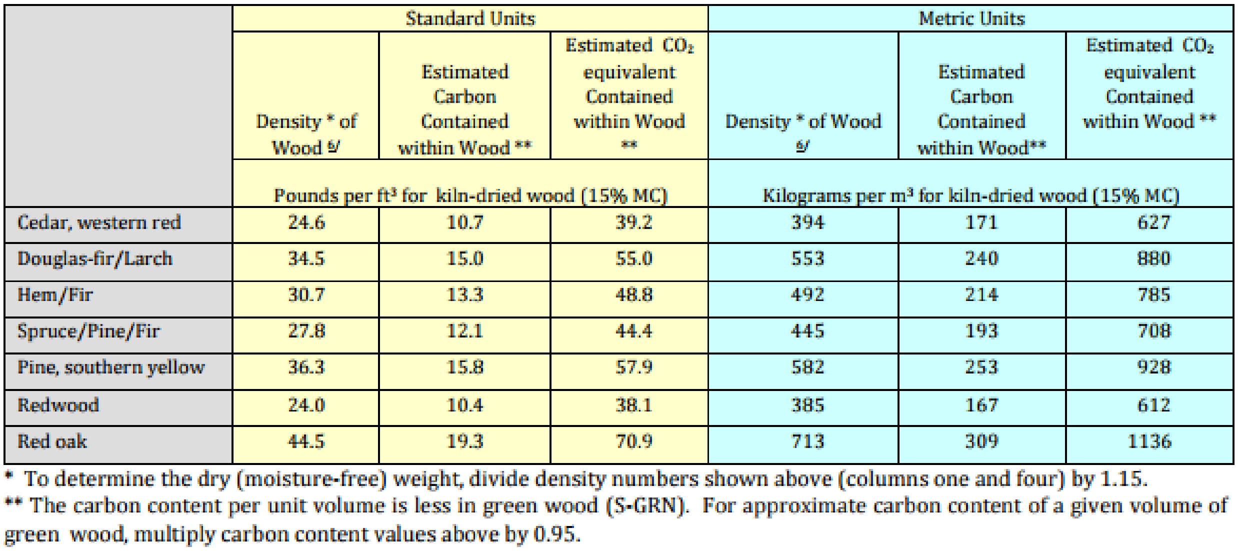
The process of the column designs started from the top floor, going to the bottom floor and it was performed once in three floors assuming the same column size for every three floor First the tributary area of the column was determined based on the location of each column The design loads on each level were determined. Same as before, for the Roof Garden it was used the equation WU= 1.2D + 1.6l+ 0.5S and for the office and the residential spaces it was used the equation WU= 1.2D + 1.6L The constant K was assumed to be 1.0 as an acceptable approach for the gravity columns Based on the required load a W-Shape was chosen from table 4-1 of the AISC Manual of Steel Construction satisfying the equation ϕcPn>Pu. The same process was repeated for the consequent floors with the same tributary area, taking into the account the addition effect of the column and floors applied to the floors above them. As you go into the bottom floors, the column's size gets larger. This happens because the load that needs to be resisted increases as well.

3.5 Material Comparison

Seeing that the primary purpose of this project is to compare the economic and environmental viability of Mass Timber usage in tall building design, procedures were created to do so with the Mass Timber and Steel structural frames designed. Using the models created by following the procedures in sections 3.3 and 3.4, the team compared the two frames on their estimated cost and environmental footprint. Additional research was done to back up the conclusions drawn from the team's own comparisons on factors beyond the scope of this study.

3.5.2 Estimated Carbon Footprint

As mentioned in sections above, all forms of wood act as carbon sinks. This means that, as a tree grows, it absorbs a large amount of carbon dioxide from the atmosphere and keeps that carbon locked within itself in a semi-permanent fashion. Unless the wood products from these trees are burned or decompose, that carbon trapped inside will not escape back into the atmosphere. As such, the use of wood in construction projects net a smaller carbon footprint than the use of other materials. Even though wood production does create pollution, this fact is greatly overshadowed by the amount of carbon dioxide sealed within.



	Standard Units			Metric Units		
	Density * of Wood 6/	Estimated Carbon Contained within Wood **	Estimated CO_2 equivalent Contained within Wood **	Density * of Wood 6/	Estimated Carbon Contained within Wood**	Estimated CO_2 equivalent Contained within Wood **
	Pounds per ft^3 for kiln-dried wood (15% MC)			Kilograms per m^3 for kiln-dried wood (15% MC)		
Cedar, western red	24.6	10.7	39.2	394	171	627
Douglas-fir/Larch	34.5	15.0	55.0	553	240	880
Hem/Fir	30.7	13.3	48.8	492	214	785
Spruce/Pine/Fir	27.8	12.1	44.4	445	193	708
Pine, southern yellow	36.3	15.8	57.9	582	253	928
Redwood	24.0	10.4	38.1	385	167	612
Red oak	44.5	19.3	70.9	713	309	1136

* To determine the dry (moisture-free) weight, divide density numbers shown above (columns one and four) by 1.15.
** The carbon content per unit volume is less in green wood (S-GRN). For approximate carbon content of a given volume of green wood, multiply carbon content values above by 0.95.

Table 4: Wood Density and Carbon Content of Commonly Used Wood Species
(http://www.dovetailinc.org/land_use_pdfs/carbon_in_wood_products.pd)

Throughout the design of the mass timber structure, it was assumed that all Glue Laminated and Cross Laminated Timber members were made of southern pine. This species of wood is capable of sequestering 57.9 pounds of carbon dioxide per cubic foot. In order to calculate the total amount of carbon dioxide held within the finished structure, the volume of every member, shear wall, and flooring panel had to be added together **Appendix A**. Once the estimated total amount of carbon sequestered was added up, it was checked against results found on a Wood Product Council carbon summary app. Both of these values were used to corroborate the feasibility of the other, ensuring that there were no problems during calculation.

Unlike wood, the production of steel creates a large amount of carbon dioxide, along with other emissions. For each ton of steel produced, the industry also creates 1.9 tons of carbon dioxide. In order to find the total amount of CO2 released during the production of the steel frame's material components, the total weight of the steel structural members were added up **Appendix A**. This amount was then compared to the carbon footprint of the Mass Timber frame, and results were tallied.

It should be noted that more components factor into the total carbon footprint of a building than just that of the core materials. Transportation to and from the construction site, as well as the long term costs of power and heating can also play a part in a building's environmental impact. However, the team chose to disregard these factors due to the limited scope of the study at hand.

Chapter 4: Findings

4.1 Mass Timber Design

In order to complete a design of the Mass Timber structure, the team must design the flooring, the beam system supporting the flooring, the columns supporting those, and a number of shear walls to resist lateral loads caused by wind or seismic loads.

4.1.1 Flooring

Load	Office (psf)	Residential (psf)	Roof (psf)	Load Type
CLT Floor	18.33	18.33	18.33	Live
Live	50	40	100	Live
Mechanical, Electrical, and Plumbing (MEP)	5	5	5	Dead
Misc. Ceiling Construction	5	5	5	Dead
Snow	0	0	25	Snow
Total	78.33	68.33	153.33	Unfactored
Total	114	98	206.5	Factored

Table 5: Area Loading on each floor

4.1.2 Beams

As mentioned in the above sections, there were three major floor layouts that were designed, each sustaining a notably different live loading based on usage.

Off	Long Span		Mid Span		Small Span	
Span	30	feet	22	feet	17.6	feet
Width	8.75	inches	6.75	inches	5.125	inches
Depth	27	inches	22.5	inches	15	inches
Factored Loading	2.06	kip/ft	2.04	kip/ft	1.02	kip/ft
Moment	232.18	kip*ft	123.62	kip*ft	39.57	kip*ft
Allowable Moment	337.28	kip*ft	187.61	kip*ft	65.12	kip*ft
Shear	30.96	kip	22.48	kip	8.99	kip
Allowable Shear	65.3184	kip	41.9904	kip	21.2544	kip
Deflection	1.45	inches	0.93	inches	0.85	inches
Allowable Deflection	1.5	inches	1.1	inches	0.88	inches

Table 6: Office Beams Mass Timber

	Long Span		Mid Span		Small Span	
Span	30	feet	22	feet	17.6	feet
Width	8.75	inches	6.75	inches	4.75	inches
Depth	25.5	inches	21	inches	15	inches
Factored Loading	1.78	kip/ft	1.76	kip/ft	0.88	kip/ft
Moment	200.14	kip*ft	106.43	kip*ft	34.06	kip*ft
Allowable Moment	301.70	kip*ft	163.99	kip*ft	60.09	kip*ft
Shear	26.69	kip	19.35	kip	7.74	kip
Allowable Shear	61.6896	kip	39.19104	kip	19.6992	kip
Deflection	1.49	inches	0.99	inches	0.79	inches
Allowable Deflection	1.5	inches	1.1	inches	0.88	inches

Table 7: Residential Beams Mass Timber

	Long Span		Mid Span		Small Span	
Span	30	feet	22	feet	17.6	feet
Width	10.75	inches	8.75	inches	5.125	inches
Depth	31	inches	24	inches	19.5	inches
Factored Loading	3.72	kip/ft	3.69	kip/ft	1.84	kip/ft
Moment	417.98	kip*ft	222.97	kip*ft	71.30	kip*ft
Allowable Moment	536.92	kip*ft	272.25	kip*ft	108.96	kip*ft
Shear	55.73	kip	40.54	kip	16.21	kip
Allowable Shear	92.13696	kip	58.0608	kip	27.63072	kip
Deflection	1.41	inches	1.07	inches	0.70	inches
Allowable Deflection	1.5	inches	1.1	inches	0.88	inches

Table 8: Roof Beams Mass Timber

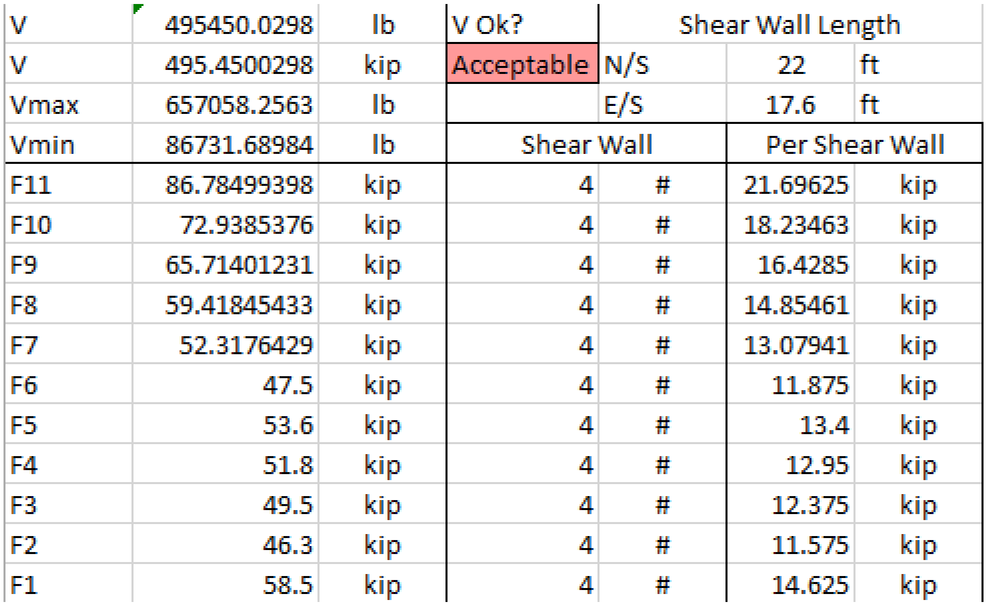
All of the beams shown above in Tables 6-8, were designed using an iterative process, starting with bending moment, then moving on to shear resistance and allowable deflection. Throughout the early calculation stages, the cross-sectional dimensions chosen for bending moment were always enough to resist failure due to shear along the beam's span. However, when it came to test the beams for deflection, they would always fail. Through this it was found that the controlling factor among all of the beams throughout the structure were their deflections. This was likely due to the fact that many of the beams throughout the structural frame have quite large spans, which are more susceptible. However, even in the short span beams designed, deflection still controlled by quite noticeable margins.

4.1.3 Columns

	9th Floor	6th Floor	3rd Floor	1st Floor
Supported Loading	1 Roof 2 Residential	3 Residential	3 Office	2 Office
Tributary Area	457.6 ft^2	457.6 ft^3	457.6 ft^4	457.6 ft^5
Length	10 ft	12 ft	12 ft	16 ft
Total Loading	189.82 kip	329.70 kip	492.25 kip	601.37 kip
Width	7.5	10.5	12	13.5
Allowable Loading	209.18 kip	419.64 kip	555.02 kip	630.62 kip

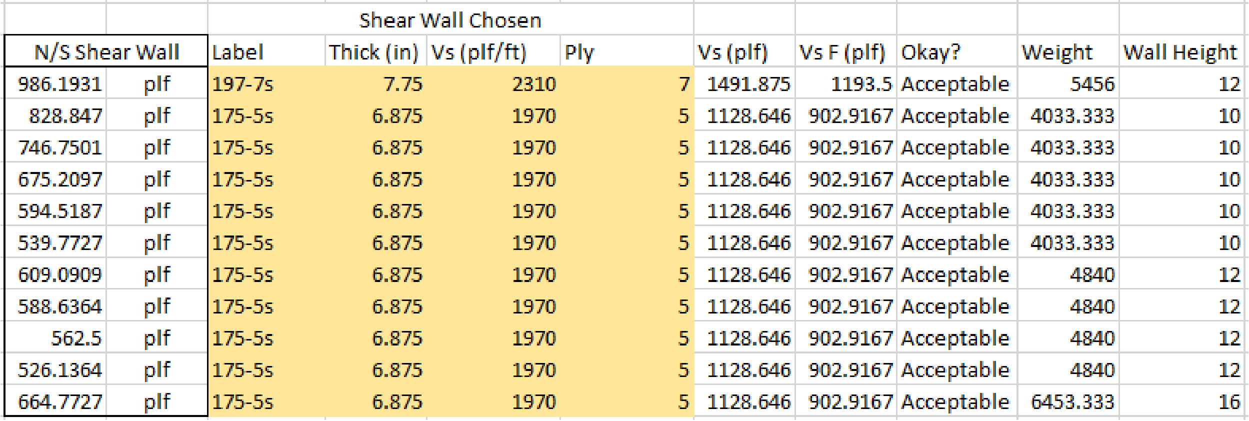
Table 9: Mass Timber Columns and their

4.1.4 Shear Walls



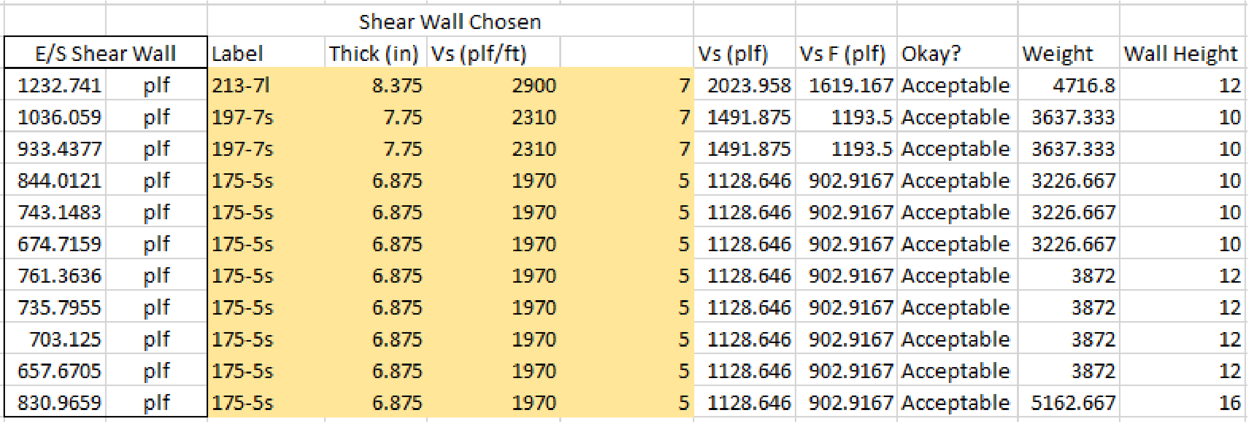
V	495450.0298	lb	V Ok?	Shear Wall Length		
V	495.4500298	kip	Acceptable	N/S	22	ft
Vmax	657058.2563	lb		E/S	17.6	ft
Vmin	86731.68984	lb	Shear Wall		Per Shear Wall	
F11	86.78499398	kip	4	#	21.69625	kip
F10	72.9385376	kip	4	#	18.23463	kip
F9	65.71401231	kip	4	#	16.4285	kip
F8	59.41845433	kip	4	#	14.85461	kip
F7	52.3176429	kip	4	#	13.07941	kip
F6	47.5	kip	4	#	11.875	kip
F5	53.6	kip	4	#	13.4	kip
F4	51.8	kip	4	#	12.95	kip
F3	49.5	kip	4	#	12.375	kip
F2	46.3	kip	4	#	11.575	kip
F1	58.5	kip	4	#	14.625	kip

Table 10: Lateral Shear Loading Per Shear Wall Per Floor



		Shear Wall Chosen								
N/S Shear Wall		Label	Thick (in)	Vs (plf/ft)	Ply	Vs (plf)	Vs F (plf)	Okay?	Weight	Wall Height
986.1931	plf	197-7s	7.75	2310	7	1491.875	1193.5	Acceptable	5456	12
828.847	plf	175-5s	6.875	1970	5	1128.646	902.9167	Acceptable	4033.333	10
746.7501	plf	175-5s	6.875	1970	5	1128.646	902.9167	Acceptable	4033.333	10
675.2097	plf	175-5s	6.875	1970	5	1128.646	902.9167	Acceptable	4033.333	10
594.5187	plf	175-5s	6.875	1970	5	1128.646	902.9167	Acceptable	4033.333	10
539.7727	plf	175-5s	6.875	1970	5	1128.646	902.9167	Acceptable	4033.333	10
609.0909	plf	175-5s	6.875	1970	5	1128.646	902.9167	Acceptable	4840	12
588.6364	plf	175-5s	6.875	1970	5	1128.646	902.9167	Acceptable	4840	12
562.5	plf	175-5s	6.875	1970	5	1128.646	902.9167	Acceptable	4840	12
526.1364	plf	175-5s	6.875	1970	5	1128.646	902.9167	Acceptable	4840	12
664.7727	plf	175-5s	6.875	1970	5	1128.646	902.9167	Acceptable	6453.333	16

Table 11: Cross Laminated Timber Panels Chosen for North-South Shear Walls



		Shear Wall Chosen								
E/S Shear Wall		Label	Thick (in)	Vs (plf/ft)		Vs (plf)	Vs F (plf)	Okay?	Weight	Wall Height
1232.741	plf	213-7l	8.375	2900	7	2023.958	1619.167	Acceptable	4716.8	12
1036.059	plf	197-7s	7.75	2310	7	1491.875	1193.5	Acceptable	3637.333	10
933.4377	plf	197-7s	7.75	2310	7	1491.875	1193.5	Acceptable	3637.333	10
844.0121	plf	175-5s	6.875	1970	5	1128.646	902.9167	Acceptable	3226.667	10
743.1483	plf	175-5s	6.875	1970	5	1128.646	902.9167	Acceptable	3226.667	10
674.7159	plf	175-5s	6.875	1970	5	1128.646	902.9167	Acceptable	3226.667	10
761.3636	plf	175-5s	6.875	1970	5	1128.646	902.9167	Acceptable	3872	12
735.7955	plf	175-5s	6.875	1970	5	1128.646	902.9167	Acceptable	3872	12
703.125	plf	175-5s	6.875	1970	5	1128.646	902.9167	Acceptable	3872	12
657.6705	plf	175-5s	6.875	1970	5	1128.646	902.9167	Acceptable	3872	12
830.9659	plf	175-5s	6.875	1970	5	1128.646	902.9167	Acceptable	5162.667	16

Table 12: Cross Laminated Timber Panels Chosen for East-West Shear Walls

4.2 Steel Design

Span Length	Garden Roof	Residential/Office Space
33 ft	W18X76	W14X61
22ft	W12X45	W10X39
16ft	W12X26	W10X22

Table 13: Steel Beams

Column Design

Floor Level

Floor Level	**Column Size**
11th	**W10X30**
7th-10th	**W10X45**
4th -6th	**W14X132**
1st -3rd	**W36X529**

Table 14: Steel Columns

4.3 Material Comparison

4.3.1 Weight

	Mass Timber	Steel
Beams (tons)	185.14	319.27
Columns (tons)	45.54	279.94
Flooring (tons)	1124.36	2381.28
Total (tons)	1355.04	2980.49

Table 15: Weight Comparison of Mass Timber and Steel Structural Frames

4.3.3 Carbon Footprint

	Steel
Beams (tons)	319.27
Columns (tons)	279.94
Flooring (tons)	2381.28
Total (tons)	2980.49
CO2 (tons/ton steel)	1.90
CO2 (tons)	5662.922

Table 16: Amount of Carbon Dioxide released during production of Steel frame's materials

	Mass Timber
Beams (ft^3)	10579.24
Columns (ft^3)	2602.5
Flooring (ft^3)	45475.83
Total (ft^3)	58657.58
CO2 (lb/ft^3)	-57.90
CO2 (tons)	-1698.14

Table 17: Amount of Carbon Dioxide Released during production of Mass Timber frame's materials

Chapter 5: Conclusions

Throughout this section, the team will gather the results and research discussed in the previous sections, and [Compare/Contrast]. By compiling all of the above information, relate it to the real world and stuff like that. By the end, after weighing the factors brought up throughout the study, as well as additional research, the team will determine whether or not they feel like Mass Timber is a viable material for the design and construction of tall buildings.

5.1 Weight

When it comes to construction, the overall weight of a structure is a very important factor. One of the great benefits of wood as a structural material is that it has an incredibly high strength to weight ratio when compared to other materials such as steel or concrete. As seen in section 4.3.1, even though the live and snow loading conditions were identical between the mass timber and steel frames, the wooden frame was significantly lighter than its steel counterpart. This can lead to a great many benefits throughout the design process. A lighter overall structure means that the foundations can be much smaller than on a more conventional building. This can serve as a cost-saving mechanism, to help make up for the increased price of mass timber members. Additionally, a mass timber frame can reduce the seismic loading on each floor, meaning the building requires less shear reinforcement, further reducing weight and cost.

Additionally, mass timber members are much easier to handle than their steel or concrete counterparts. With lighter building components, construction teams require less heavy-duty equipment to assemble the structure. Lighter cranes mean additional savings on the part of the developer. The fact that mass timber members are made of wood also can play a beneficial part during construction. Seeing as the only real tools needed for construction are high powered screwdrivers, one can save by not needing specialty equipment or specialist laborers. This, combined with lightweight prefabricated members, which are easily manipulated can lead to notably increased construction schedules.

However, despite the many benefits that come with wood’s lightweight designs, there are also a few shortcomings. While the strength to weight ratio on wood is quite high, its strength to volume ratio is not as good. This means that, while a structure made of wood will often be lighter than a steel or concrete counterpart, the size of its members will be noticeably larger. One can see an example of this in the study conducted above. Even though both long span beams on a typical office floor are carrying a similar load, the W14x74 steel girder has a depth of 14.17” and a width of 10.07”, while the Glue Laminated Timber member is 8.75” x 27”. The designer must make a trade-off of functional space vs. overall weight. While the lure of a significantly decreased weight might be tempting, one would have to deal with increased ceiling clearances, and taller individual stories.

5.2 Cost

Mass Timber is notably more expensive than the steel counterpart when compared with just raw materials. As a consequence of mass timber not being so popular in the US, there is fewer demand, resulting with only a couple of mass timber manufacturers in US. Therefore, the price of Mass Timber is higher, affecting the total cost of the structure. As the demand for Mass Timber expands, the competitiveness between MT’s manufacturers will increase resulting with a reduction of the price for Mass Timber. As the cost of Mass Timber drops, it will became a more affordable material and therefore, more appealing into the construction sector.

As mentioned in section 5.1, there are some advantages associated with the lightweight of mass timber that can lead to economic benefits during design and construction phases. As a result of the mass timber structure being lighter, the cost of the foundation is reduced. Furthermore, mass timber structures take less time during the construction time, due to their panels that are already prefabricated, and the installation process being faster.

5.3 Carbon Footprint

Mass timber, as a carbon sink has a negative carbon footprint, unlike steel, which actively creates Carbon Dioxide in its production.

5.4 Other Considerations

5.4.1 Fire Safety

The main challenge associated with every wood building is the risk during a fire performance. Mass timber acts different from the other wood structures during a fire, because of its composite heavy timber, which requires a lot of energy to burn. Thick timber provides a great resistance to the fire, building up a layer of char, but still maintaining structural stability on the bottom layers for required amounts of time. The Lever Architecture firm also proved this during two different fire tests that were taken in order to show the viability of mass timber in high-rise construction. The fire performances resulted positive, archiving the two- hour required fire rate on both the glulam beams and also in the CLT floors. These tests will play a crucial role on shaping the behavior of mass timber during a fire and at the same time will definitely contribute on the acceptance of the CLT on tall building design.

5.4.2 Stigma

U.S is acting slowly compared to other European countries to enable the development and expansion of mass timber in tall building construction. So what are the obstacles that the U.S has to overcome in order to tackle the misconception of mass timber in high structures and consider it on the same level as any other convention material? This is associated with the lack of knowledge about mass timber in U.S and the misconceptions of its behavior during a fire performance. Lever Architecture opened their new exhibition in Washington, DC on September, 2016 called Timber City presenting all their work using mass timber. The exhibition will be open until May, 2017 and the purpose of the exhibition is described as “challenges the assumption that wood is an outmoded building material, highlighting emerging timber construction techniques and their potential to revolutionize building in the US.” (shown in the figure below) (2016)

Furthermore, it would be very helpful if there would be investment in additional tests and analysis to prove that mass timber is a viable material. Since fire performance and seismic behavior are two of the main challenges associated with mass timber, additional tests should be done on these two fields. As we learn more about the behavior of mass timber in construction, the easier would be its adaption in the construction sector.

5.4.3 Overall Sustainability

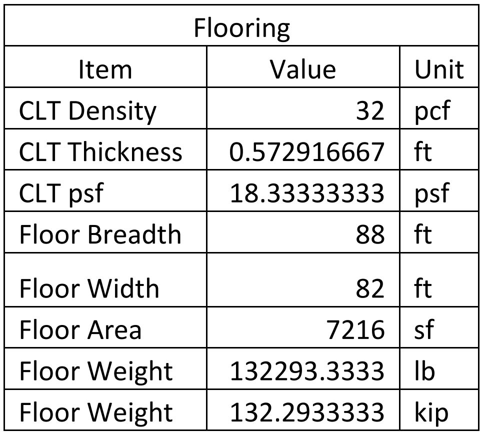
"Framework stands as a model for sustainable urban ecology," Robinson, the founder of the Lever Architecture has stated and described the interest of his company on the construction world as "exploring the relationship between materials, experience, and the environment—how the way we build impacts the way we live and the environment as a whole." (Pardes, 2016) This is associated with the wood's ability on producing lower carbon emissions and less energy than any other material such as steel or concrete. Furthermore, just recently Lever architecture was selected to be part of the Architectural League of New York's Emerging Program for 2017, promoting influential designs by architects and designers. (2017)

Framework features many sustainable qualities, with a close attention to green building design, energy use and the air quality. Through the use of the mass timber, a natural and recyclable material, framework provides a good indoor air quality, which is key to a healthy living. Moreover, the roof garden on the top floor is used as a way to promote sustainability and consequently increases revenue for the developer for providing recreational spaces for the residents. In addition, the bicycle parking spaces located in the ground floor shows one more time the implement of green features by the Lever Architecture's firm.

Using mass timber in construction has an enormous potential to make our cities more resilient in the face of hazards, simultaneously serving the needs of our planet and growing population. The net carbon emissions of producing a ton of softwood lumber is 33 kg carbon per metric ton. If we compare it to steel results with 220 kg per metric ton and 265 kg per metric ton for concrete. (Crampton, 2017) "Because of this huge discrepancy in embodied energy, the carbon savings from simply using wood instead of concrete as your primary building material can offset decades of emissions associated with the building's operation," (Crampton, 2017) As the green initiative is growing, Mass Timber should become more appealing in US.

Appendix A: Structural Calculations

A.1 Excel Calculation of Mass Timber CLT Flooring Dead Weight



Flooring		
Item	Value	Unit
CLT Density	32	pcf
CLT Thickness	0.572916667	ft
CLT psf	18.33333333	psf
Floor Breadth	88	ft
Floor Width	82	ft
Floor Area	7216	sf
Floor Weight	132293.3333	lb
Floor Weight	132.2933333	kip

A.2 Excel Calculations for All Mass Timber Office Beam Spans

Long Span (Office)			
Item	Value	Unit	
Length	30	ft	
T width	17.6	ft	
T Area	528	ft^2	
Self-Weight	57.42188	plf	
T-Self	1722.656	lb	
Lin Load	2063.822	plf	
Lin Load	2.063822	klf	
Tot Load	61914.66	lb	
Tot Load	61.91466	kip	
Mom	232180	lb*ft	Bending?
Mom	232.18	kip*ft	
Mom-in	2786160	lb*in	
Mom-in	2786.16	kip*in	
Fb	2400	psi	
F'b	3807.009	psi	
CM	1	-	
Ct	1	-	
Ci	1	-	
CL	0.979421	-	Acceptable
CV	0.918396	-	
KF (Bend)	2.54	-	
Phi (Bend)	0.85	-	
TE factor	0.8	-	
S req	731.8499	in^3	
b	8.75	in	
h	27	in	
S	1063.125	in^3	
V	30957.33	lb	Horizontal Shear?
V	30.95733	kip	
Fv	240	psi	
F'v	414.72	psi	
CM	1	-	
Ct	1	-	
Ci	1	-	
KF (Shear)	2.88	-	Acceptable
Phi (Shear)	0.75	-	
TE factor	0.8	-	
A req	111.9695	in^2	
A	236.25		
E	1800000	psi	Deflection?
I	14352.19	in^4	
A-deflection	1.5	in	
Deflection	1.452177	in	
Emin	1800000	psi	
Emin'	2692800	psi	
le	667.8		Acceptable
RB	15.34607		
FbE	13721.17		
F*b	4145.28		
CL	0.979421		

Mid Span (Office)			
Item	Value	Unit	
Length	22	ft	
T width	17.6	ft	
T Area	387.2	ft^2	
Self-Weight	36.91406	plf	
T-Self	812.1094	lb	
Lin Load	2043.314	plf	
Lin Load	2.043314	klf	
Tot Load	44952.91	lb	
Tot Load	44.95291	kip	
Mom	123620.5	lb*ft	Bending?
Mom	123.6205	kip*ft	
Mom-in	1483446	lb*in	
Mom-in	1483.446	kip*in	
Fb	2400	psi	
F'b	3952.876	psi	
CM	1	-	
Ct	1	-	
Ci	1	-	
CL	0.978182	-	Acceptable
CV	0.953585	-	
KF (Bend)	2.54	-	
Phi (Bend)	0.85	-	
TE factor	0.8	-	
S req	375.2827	in^3	
b	6.75	in	
h	22.5	in	
S	569.5313	in^3	
V	22476.45	lb	Horizontal Shear?
V	22.47645	kip	
Fv	240	psi	
F'v	414.72	psi	
CM	1	-	
Ct	1	-	
Ci	1	-	
KF (Shear)	2.88	-	Acceptable
Phi (Shear)	0.75	-	
TE factor	0.8	-	
A req	81.29505	in^2	
A	151.875		
E	1800000	psi	Deflection?
I	6407.227	in^4	
A-deflection	1.1	in	
Deflection	0.9314	in	
Emin	1800000	psi	
Emin'	2692800	psi	
le	497.82		Acceptable
RB	15.67919		
FbE	13144.32		
F*b	4145.28		
CL	0.978182		

Short Span (Office)			
Item	Value	Unit	
Length	17.6	ft	
T width	8.8	ft	
T Area	154.88	ft^2	
Self-Weight	18.6849	plf	
T-Self	328.8542	lb	
Lin Load	1021.885	plf	
Lin Load	1.021885	klf	
Tot Load	17985.17	lb	
Tot Load	17.98517	kip	
Mom	39567.38	lb*ft	Bending?
Mom	39.56738	kip*ft	
Mom-in	474808.6	lb*in	
Mom-in	474.8086	kip*in	
Fb	2400	psi	
F'b	4066.315	psi	
CM	1	-	
Ct	1	-	
Ci	1	-	
CL	0.980951	-	Acceptable
CV	0.997677	-	
KF (Bend)	2.54	-	
Phi (Bend)	0.85	-	
TE factor	0.8	-	
S req	116.7663	in^3	
b	5.125	in	
h	15	in	
S	192.1875	in^3	
V	8992.587	lb	Horizontal Shear?
V	8.992587	kip	
Fv	240	psi	
F'v	414.72	psi	
CM	1	-	
Ct	1	-	
Ci	1	-	
KF (Shear)	2.88	-	Acceptable
Phi (Shear)	0.75	-	
TE factor	0.8	-	
A req	32.52527	in^2	
A	76.875		
E	1800000	psi	Deflection?
I	1441.406	in^4	
A-deflection	0.88	in	
Deflection	0.848099	in	
Emin	1800000	psi	
Emin'	2692800	psi	
le	389.256		Acceptable
RB	14.90972		
FbE	14536.05		
F*b	4145.28		
CL	0.980951		

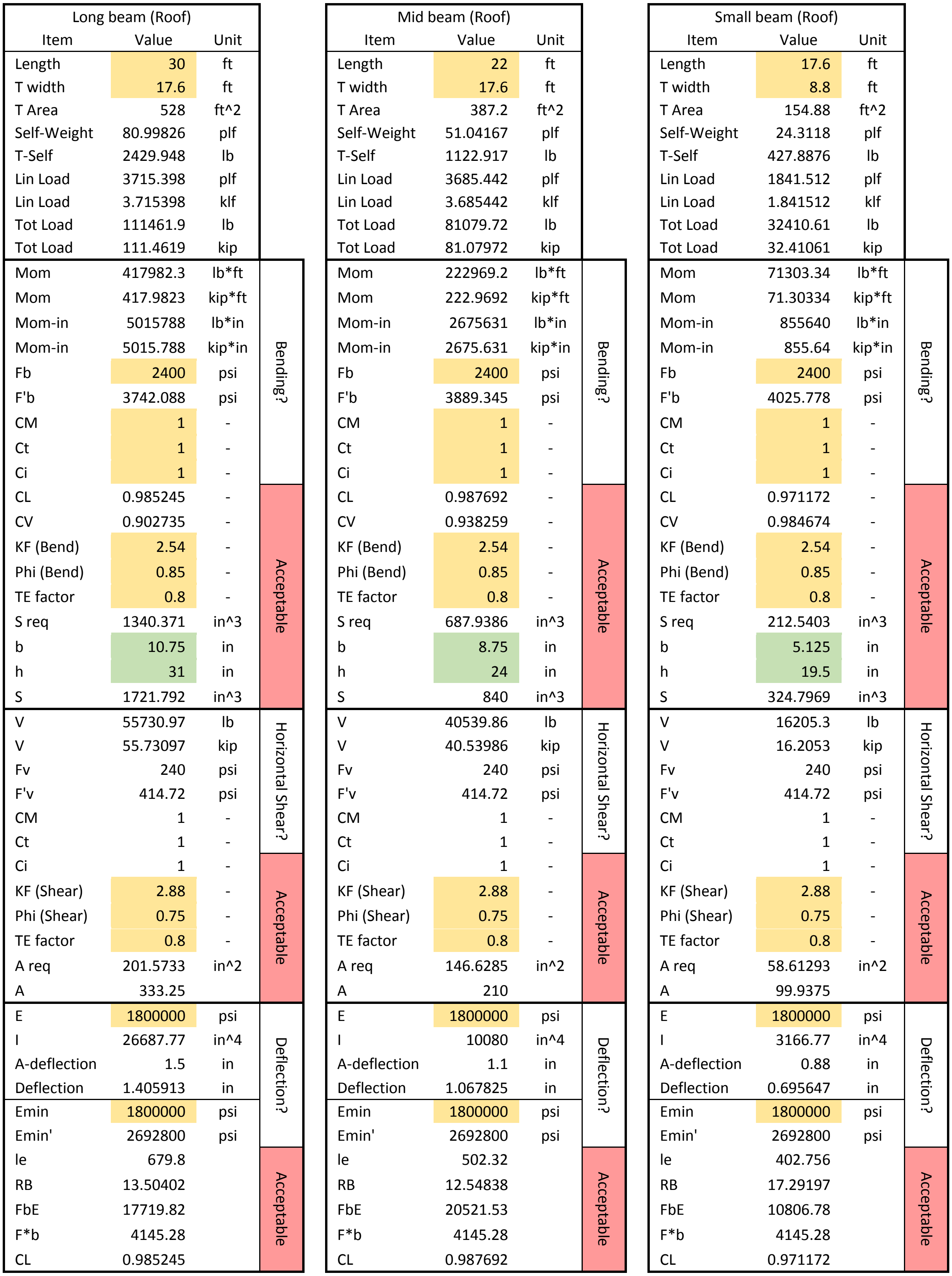
A.3 Excel Calculations for All Mass Timber Residential Beam Spans

Long beam (Residential)			
Item	Value	Unit	
Length	30	ft	
T width	17.6	ft	
T Area	528	ft^2	
Self-Weight	54.23177	plf	
T-Self	1626.953	lb	
Lin Load	1779.032	plf	
Lin Load	1.779032	klf	
Tot Load	53370.95	lb	
Tot Load	53.37095	kip	
Mom	200141.1	lb*ft	Bending?
Mom	200.1411	kip*ft	
Mom-in	2401693	lb*in	
Mom-in	2401.693	kip*in	
Fb	2400	psi	
F'b	3817.905	psi	
CM	1	-	
Ct	1	-	
Ci	1	-	
CL	0.981107	-	Acceptable
CV	0.921025	-	
KF (Bend)	2.54	-	
Phi (Bend)	0.85	-	
TE factor	0.8	-	
S req	629.0604	in^3	
b	8.75	in	
h	25.5	in	
S	948.2813	in^3	
V	26685.48	lb	Horizontal Shear?
V	26.68548	kip	
Fv	240	psi	
F'v	414.72	psi	
CM	1	-	
Ct	1	-	
Ci	1	-	Acceptable
KF (Shear)	2.88	-	
Phi (Shear)	0.75	-	
TE factor	0.8	-	
A req	96.51865	in^2	
A	223.125		
E	1800000	psi	Deflection?
I	12090.59	in^4	
A-deflection	1.5	in	
Deflection	1.485942	in	
Emin	1800000	psi	
Emin'	2692800	psi	
le	663.3		Acceptable
RB	14.86336		
FbE	14626.87		
F*b	4145.28		
CL	0.981107		

Mid beam (Residential)			
Item	Value	Unit	
Length	22	ft	
T width	17.6	ft	
T Area	387.2	ft^2	
Self-Weight	34.45313	plf	
T-Self	757.9688	lb	
Lin Load	1759.253	plf	
Lin Load	1.759253	klf	
Tot Load	38703.57	lb	
Tot Load	38.70357	kip	
Mom	106434.8	lb*ft	Bending?
Mom	106.4348	kip*ft	
Mom-in	1277218	lb*in	
Mom-in	1277.218	kip*in	
Fb	2400	psi	
F'b	3966.535	psi	
CM	1	-	
Ct	1	-	
Ci	1	-	
CL	0.980369	-	Acceptable
CV	0.95688	-	
KF (Bend)	2.54	-	
Phi (Bend)	0.85	-	
TE factor	0.8	-	
S req	321.9984	in^3	
b	6.75	in	
h	21	in	
S	496.125	in^3	
V	19351.78	lb	Horizontal Shear?
V	19.35178	kip	
Fv	240	psi	
F'v	414.72	psi	
CM	1	-	
Ct	1	-	
Ci	1	-	Acceptable
KF (Shear)	2.88	-	
Phi (Shear)	0.75	-	
TE factor	0.8	-	
A req	69.99343	in^2	
A	141.75		
E	1800000	psi	Deflection?
I	5209.313	in^4	
A-deflection	1.1	in	
Deflection	0.986323	in	
Emin	1800000	psi	
Emin'	2692800	psi	
le	493.32		Acceptable
RB	15.07892		
FbE	14211.66		
F*b	4145.28		
CL	0.980369		

Mid beam (Residential)			
Item	Value	Unit	
Length	17.6	ft	
T width	8.8	ft	
T Area	154.88	ft^2	
Self-Weight	17.31771	plf	
T-Self	304.7917	lb	
Lin Load	879.7177	plf	
Lin Load	0.879718	klf	
Tot Load	15483.03	lb	
Tot Load	15.48303	kip	
Mom	34062.67	lb*ft	Bending?
Mom	34.06267	kip*ft	
Mom-in	408752	lb*in	
Mom-in	408.752	kip*in	
Fb	2400	psi	
F'b	4048.179	psi	
CM	1	-	
Ct	1	-	
Ci	1	-	
CL	0.976575	-	Acceptable
CV	1.001474	-	
KF (Bend)	2.54	-	
Phi (Bend)	0.85	-	
TE factor	0.8	-	
S req	100.9718	in^3	
b	4.75	in	
h	15	in	
S	178.125	in^3	
V	7741.516	lb	Horizontal Shear?
V	7.741516	kip	
Fv	240	psi	
F'v	414.72	psi	
CM	1	-	
Ct	1	-	
Ci	1	-	Acceptable
KF (Shear)	2.88	-	
Phi (Shear)	0.75	-	
TE factor	0.8	-	
A req	28.00027	in^2	
A	71.25		
E	1800000	psi	Deflection?
I	1335.938	in^4	
A-deflection	0.88	in	
Deflection	0.78775	in	
Emin	1800000	psi	
Emin'	2692800	psi	
le	389.256		Acceptable
RB	16.0868		
FbE	12486.65		
F*b	4145.28		
CL	0.976575		

A.4 Excel Calculations for All Mass Timber Rooftop Garden Beam Spans

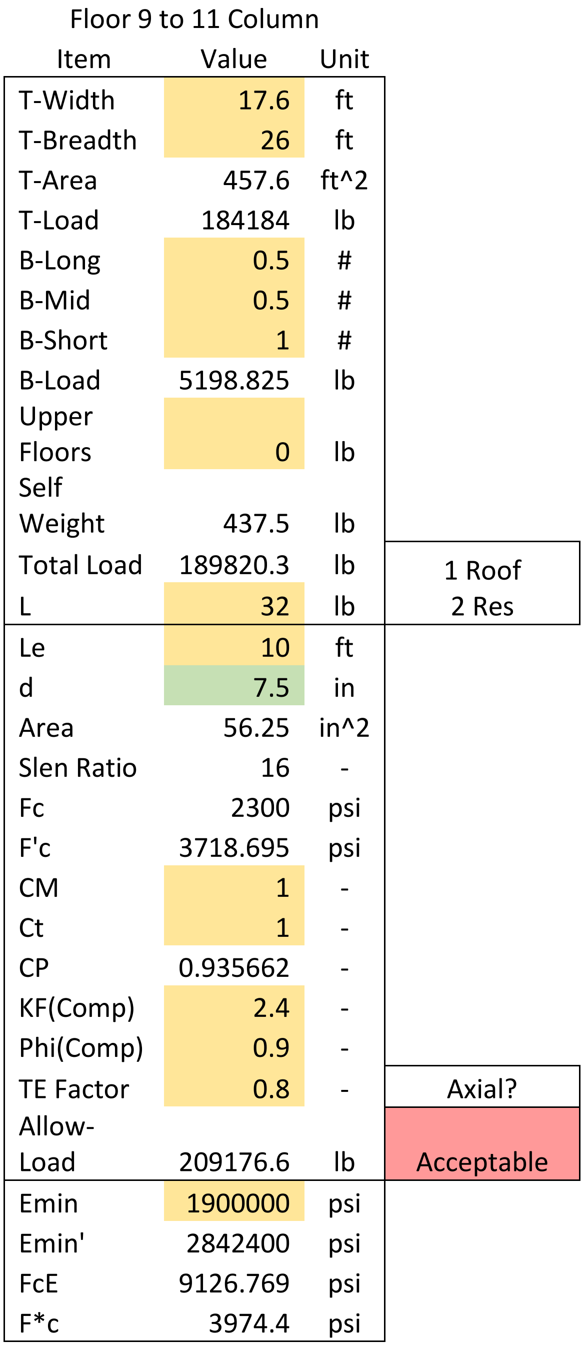


Long beam (Roof)			
Item	Value	Unit	
Length	30	ft	
T width	17.6	ft	
T Area	528	ft^2	
Self-Weight	80.99826	plf	
T-Self	2429.948	lb	
Lin Load	3715.398	plf	
Lin Load	3.715398	klf	
Tot Load	111461.9	lb	
Tot Load	111.4619	kip	
Mom	417982.3	lb*ft	Bending?
Mom	417.9823	kip*ft	
Mom-in	5015788	lb*in	
Mom-in	5015.788	kip*in	
Fb	2400	psi	
F'b	3742.088	psi	
CM	1	-	
Ct	1	-	
Ci	1	-	
CL	0.985245	-	Acceptable
CV	0.902735	-	
KF (Bend)	2.54	-	
Phi (Bend)	0.85	-	
TE factor	0.8	-	
S req	1340.371	in^3	
b	10.75	in	
h	31	in	
S	1721.792	in^3	
V	55730.97	lb	Horizontal Shear?
V	55.73097	kip	
Fv	240	psi	
F'v	414.72	psi	
CM	1	-	
Ct	1	-	
Ci	1	-	Acceptable
KF (Shear)	2.88	-	
Phi (Shear)	0.75	-	
TE factor	0.8	-	
A req	201.5733	in^2	
A	333.25		
E	1800000	psi	Deflection?
I	26687.77	in^4	
A-deflection	1.5	in	
Deflection	1.405913	in	
Emin	1800000	psi	
Emin'	2692800	psi	
le	679.8		Acceptable
RB	13.50402		
FbE	17719.82		
F*b	4145.28		
CL	0.985245		

Mid beam (Roof)			
Item	Value	Unit	
Length	22	ft	
T width	17.6	ft	
T Area	387.2	ft^2	
Self-Weight	51.04167	plf	
T-Self	1122.917	lb	
Lin Load	3685.442	plf	
Lin Load	3.685442	klf	
Tot Load	81079.72	lb	
Tot Load	81.07972	kip	
Mom	222969.2	lb*ft	Bending?
Mom	222.9692	kip*ft	
Mom-in	2675631	lb*in	
Mom-in	2675.631	kip*in	
Fb	2400	psi	
F'b	3889.345	psi	
CM	1	-	
Ct	1	-	
Ci	1	-	
CL	0.987692	-	Acceptable
CV	0.938259	-	
KF (Bend)	2.54	-	
Phi (Bend)	0.85	-	
TE factor	0.8	-	
S req	687.9386	in^3	
b	8.75	in	
h	24	in	
S	840	in^3	
V	40539.86	lb	Horizontal Shear?
V	40.53986	kip	
Fv	240	psi	
F'v	414.72	psi	
CM	1	-	
Ct	1	-	
Ci	1	-	Acceptable
KF (Shear)	2.88	-	
Phi (Shear)	0.75	-	
TE factor	0.8	-	
A req	146.6285	in^2	
A	210		
E	1800000	psi	Deflection?
I	10080	in^4	
A-deflection	1.1	in	
Deflection	1.067825	in	
Emin	1800000	psi	
Emin'	2692800	psi	
le	502.32		Acceptable
RB	12.54838		
FbE	20521.53		
F*b	4145.28		
CL	0.987692		

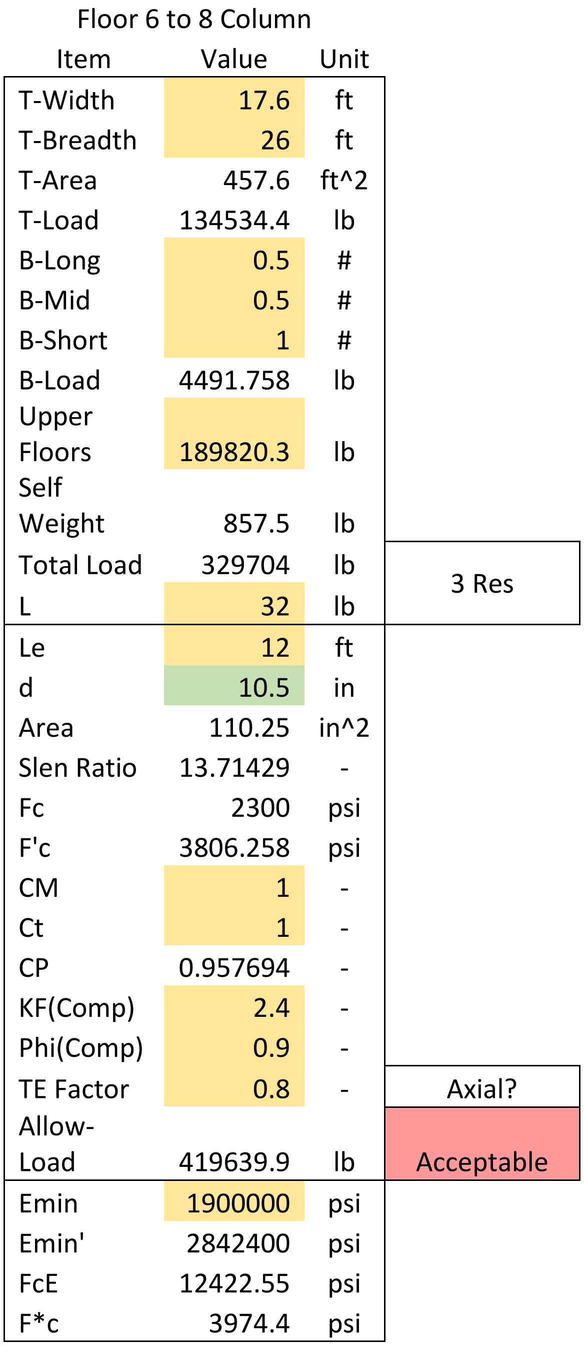
Small beam (Roof)			
Item	Value	Unit	
Length	17.6	ft	
T width	8.8	ft	
T Area	154.88	ft^2	
Self-Weight	24.3118	plf	
T-Self	427.8876	lb	
Lin Load	1841.512	plf	
Lin Load	1.841512	klf	
Tot Load	32410.61	lb	
Tot Load	32.41061	kip	
Mom	71303.34	lb*ft	Bending?
Mom	71.30334	kip*ft	
Mom-in	855640	lb*in	
Mom-in	855.64	kip*in	
Fb	2400	psi	
F'b	4025.778	psi	
CM	1	-	
Ct	1	-	
Ci	1	-	
CL	0.971172	-	Acceptable
CV	0.984674	-	
KF (Bend)	2.54	-	
Phi (Bend)	0.85	-	
TE factor	0.8	-	
S req	212.5403	in^3	
b	5.125	in	
h	19.5	in	
S	324.7969	in^3	
V	16205.3	lb	Horizontal Shear?
V	16.2053	kip	
Fv	240	psi	
F'v	414.72	psi	
CM	1	-	
Ct	1	-	
Ci	1	-	Acceptable
KF (Shear)	2.88	-	
Phi (Shear)	0.75	-	
TE factor	0.8	-	
A req	58.61293	in^2	
A	99.9375		
E	1800000	psi	Deflection?
I	3166.77	in^4	
A-deflection	0.88	in	
Deflection	0.695647	in	
Emin	1800000	psi	
Emin'	2692800	psi	
le	402.756		Acceptable
RB	17.29197		
FbE	10806.78		
F*b	4145.28		
CL	0.971172		

A.5 Excel Calculations for All Mass Timber Columns



Floor 9 to 11 Column

Item	Value	Unit	
T-Width	17.6	ft	
T-Breadth	26	ft	
T-Area	457.6	ft^2	
T-Load	184184	lb	
B-Long	0.5	#	
B-Mid	0.5	#	
B-Short	1	#	
B-Load	5198.825	lb	
Upper Floors	0	lb	
Self Weight	437.5	lb	
Total Load	189820.3	lb	1 Roof 2 Res
L	32	lb	
Le	10	ft	
d	7.5	in	
Area	56.25	in^2	
Slen Ratio	16	-	
Fc	2300	psi	
F'c	3718.695	psi	
CM	1	-	
Ct	1	-	
CP	0.935662	-	
KF(Comp)	2.4	-	
Phi(Comp)	0.9	-	
TE Factor	0.8	-	Axial?
Allow-Load	209176.6	lb	Acceptable
Emin	1900000	psi	
Emin'	2842400	psi	
FcE	9126.769	psi	
F*c	3974.4	psi	



Floor 6 to 8 Column

Item	Value	Unit	
T-Width	17.6	ft	
T-Breadth	26	ft	
T-Area	457.6	ft^2	
T-Load	134534.4	lb	
B-Long	0.5	#	
B-Mid	0.5	#	
B-Short	1	#	
B-Load	4491.758	lb	
Upper Floors	189820.3	lb	
Self Weight	857.5	lb	
Total Load	329704	lb	3 Res
L	32	lb	
Le	12	ft	
d	10.5	in	
Area	110.25	in^2	
Slen Ratio	13.71429	-	
Fc	2300	psi	
F'c	3806.258	psi	
CM	1	-	
Ct	1	-	
CP	0.957694	-	
KF(Comp)	2.4	-	
Phi(Comp)	0.9	-	
TE Factor	0.8	-	Axial?
Allow-Load	419639.9	lb	Acceptable
Emin	1900000	psi	
Emin'	2842400	psi	
FcE	12422.55	psi	
F*c	3974.4	psi	

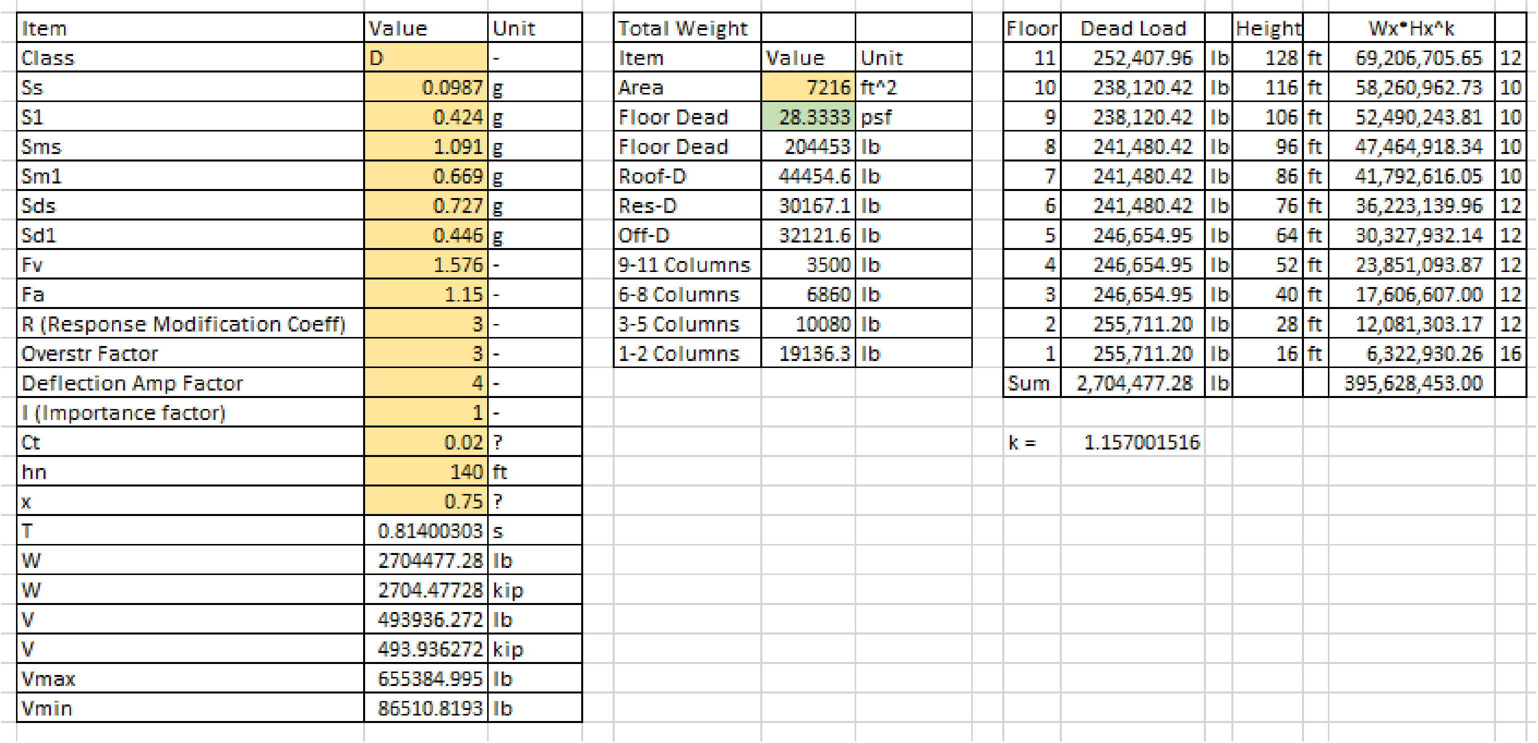
Floor 3 to 5 Column

Item	Value	Unit	
T-Width	17.6	ft	
T-Breadth	26	ft	
T-Area	457.6	ft^2	
T-Load	156499.2	lb	
B-Long	0.5	#	
B-Mid	0.5	#	
B-Short	1	#	
B-Load	4788.711	lb	
Upper Floors	329704	lb	
Self Weight	1260	lb	
Total Load	492251.9	lb	3 Office
L	36	lb	
Le	12	ft	
d	12	in	
Area	144	in^2	
Slen Ratio	12	-	
Fc	2300	psi	
F'c	3854.315	psi	
CM	1	-	
Ct	1	-	
CP	0.969785	-	
KF(Comp)	2.4	-	
Phi(Comp)	0.9	-	
TE Factor	0.8	-	Axial?
Allow-Load	555021.4	lb	Acceptable
Emin	1900000	psi	
Emin'	2842400	psi	
FcE	16225.37	psi	
F*c	3974.4	psi	

Floor 1 and 2 Column

Item	Value	Unit	
T-Width	17.6	ft	
T-Breadth	26	ft	
T-Area	457.6	ft^2	
T-Load	104332.8	lb	
B-Long	0.5	#	
B-Mid	0.5	#	
B-Short	1	#	
B-Load	3192.474	lb	
Upper Floors	492251.9	lb	
Self Weight	1594.688	lb	
Total Load	601371.9	lb	2 Office
L	36	lb	
Le	16	ft	
d	13.5	in	
Area	182.25	in^2	
Slen Ratio	14.22222	-	
Fc	2300	psi	
F'c	3789.395	psi	
CM	1	-	
Ct	1	-	
CP	0.953451	-	
KF(Comp)	2.4	-	
Phi(Comp)	0.9	-	
TE Factor	0.8	-	Axial?
Allow-Load	690617.2	lb	Acceptable
Emin	1900000	psi	
Emin'	2842400	psi	
FcE	11551.07	psi	
F*c	3974.4	psi	

A.6 Excel Calculations for Floor by Floor Seismic Shear Loads on Mass Timber Structure



Item	Value	Unit
Class	D	-
Ss	0.0987	g
S1	0.424	g
Sms	1.091	g
Sm1	0.669	g
Sds	0.727	g
Sd1	0.446	g
Fv	1.576	-
Fa	1.15	-
R (Response Modification Coeff)	3	-
Overstr Factor	3	-
Deflection Amp Factor	4	-
I (Importance factor)	1	-
Ct	0.02	?
hn	140	ft
x	0.75	?
T	0.81400303	s
W	2704477.28	lb
W	2704.47728	kip
V	493936.272	lb
V	493.936272	kip
Vmax	655384.995	lb
Vmin	86510.8193	lb

Total Weight		
Item	Value	Unit
Area	7216	ft^2
Floor Dead	28.3333	psf
Floor Dead	204453	lb
Roof-D	44454.6	lb
Res-D	30167.1	lb
Off-D	32121.6	lb
9-11 Columns	3500	lb
6-8 Columns	6860	lb
3-5 Columns	10080	lb
1-2 Columns	19136.3	lb

Floor	Dead Load		Height		Wx*Hx^k	
11	252,407.96	lb	128	ft	69,206,705.65	12
10	238,120.42	lb	116	ft	58,260,962.73	10
9	238,120.42	lb	106	ft	52,490,243.81	10
8	241,480.42	lb	96	ft	47,464,918.34	10
7	241,480.42	lb	86	ft	41,792,616.05	10
6	241,480.42	lb	76	ft	36,223,139.96	12
5	246,654.95	lb	64	ft	30,327,932.14	12
4	246,654.95	lb	52	ft	23,851,093.87	12
3	246,654.95	lb	40	ft	17,606,607.00	12
2	255,711.20	lb	28	ft	12,081,303.17	12
1	255,711.20	lb	16	ft	6,322,930.26	16
Sum	2,704,477.28	lb			395,628,453.00	

k = 1.157001516

A.7 Excel Calculations for Velocity Pressure on Mass Timber Structure

m	V (mph)	qs
0.00512	120	36.864

Floor	Height (ft)	qz	qs	I	Kz	Kzt	Kd
1	8	17.86061	36.864	1	0.57	1	0.85
2	22	19.92868	36.864	1	0.636	1	0.85
3	34	22.68611	36.864	1	0.724	1	0.85
4	46	24.75418	36.864	1	0.79	1	0.85
5	58	26.38356	36.864	1	0.842	1	0.85
6	70	27.88762	36.864	1	0.89	1	0.85
7	81	29.235	36.864	1	0.933	1	0.85
8	91	30.17503	36.864	1	0.963	1	0.85
9	101	31.09939	36.864	1	0.9925	1	0.85
10	111	31.88275	36.864	1	1.0175	1	0.85
11	122	32.74445	36.864	1	1.045	1	0.85
12	130.5	33.4103	36.864	1	1.06625	1	0.85
13	137.5	33.95866	36.864	1	1.08375	1	0.85
Roof	128	33.21446	36.864	1	1.06	1	0.85
		^ ^ qh ^ ^					

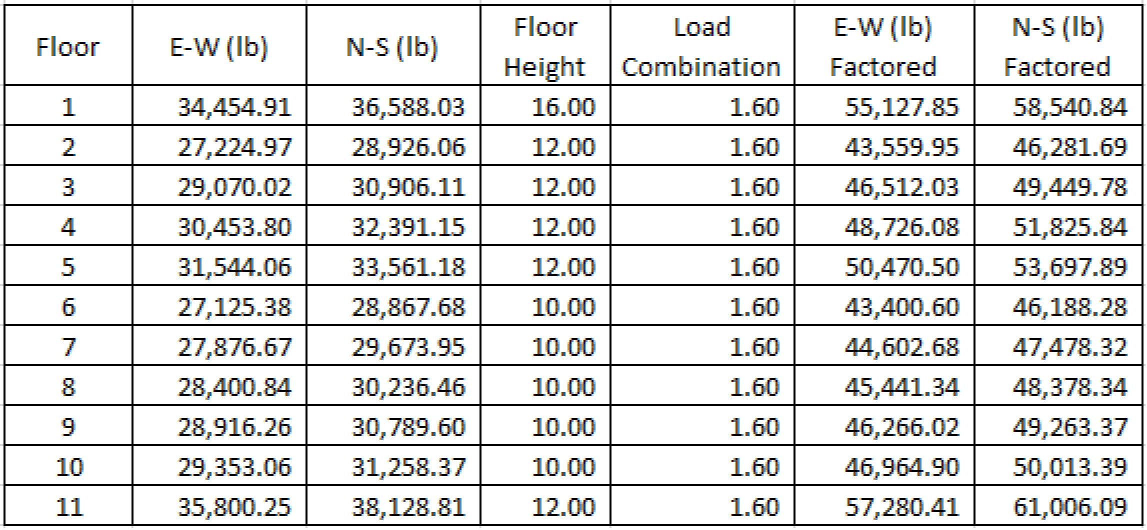
A.8 Excel Calculations for Wind Pressures Caused by North-South Winds

North-South Wind						L/B = 82/86 = 0.9535		
Windward Wall			Side Wall			Leeward Wall		
G	Cp	p	G	Cp	p	G	Cp	p
0.85	0.8	12.14521	0.85	-0.7	-19.7626	0.85	-0.5	-14.1161
0.85	0.8	13.5515	0.85	-0.7	-19.7626	0.85	-0.5	-14.1161
0.85	0.8	15.42655	0.85	-0.7	-19.7626	0.85	-0.5	-14.1161
0.85	0.8	16.83284	0.85	-0.7	-19.7626	0.85	-0.5	-14.1161
0.85	0.8	17.94082	0.85	-0.7	-19.7626	0.85	-0.5	-14.1161
0.85	0.8	18.96358	0.85	-0.7	-19.7626	0.85	-0.5	-14.1161
0.85	0.8	19.8798	0.85	-0.7	-19.7626	0.85	-0.5	-14.1161
0.85	0.8	20.51902	0.85	-0.7	-19.7626	0.85	-0.5	-14.1161
0.85	0.8	21.14759	0.85	-0.7	-19.7626	0.85	-0.5	-14.1161
0.85	0.8	21.68027	0.85	-0.7	-19.7626	0.85	-0.5	-14.1161
0.85	0.8	22.26622	0.85	-0.7	-19.7626	0.85	-0.5	-14.1161
0.85	0.8	22.71901	0.85	-0.7	-19.7626	0.85	-0.5	-14.1161
0.85	0.8	23.09189	0.85	-0.7	-19.7626	0.85	-0.5	-14.1161

A.9 Excel Calculations for Wind pressures Caused by East-West Winds

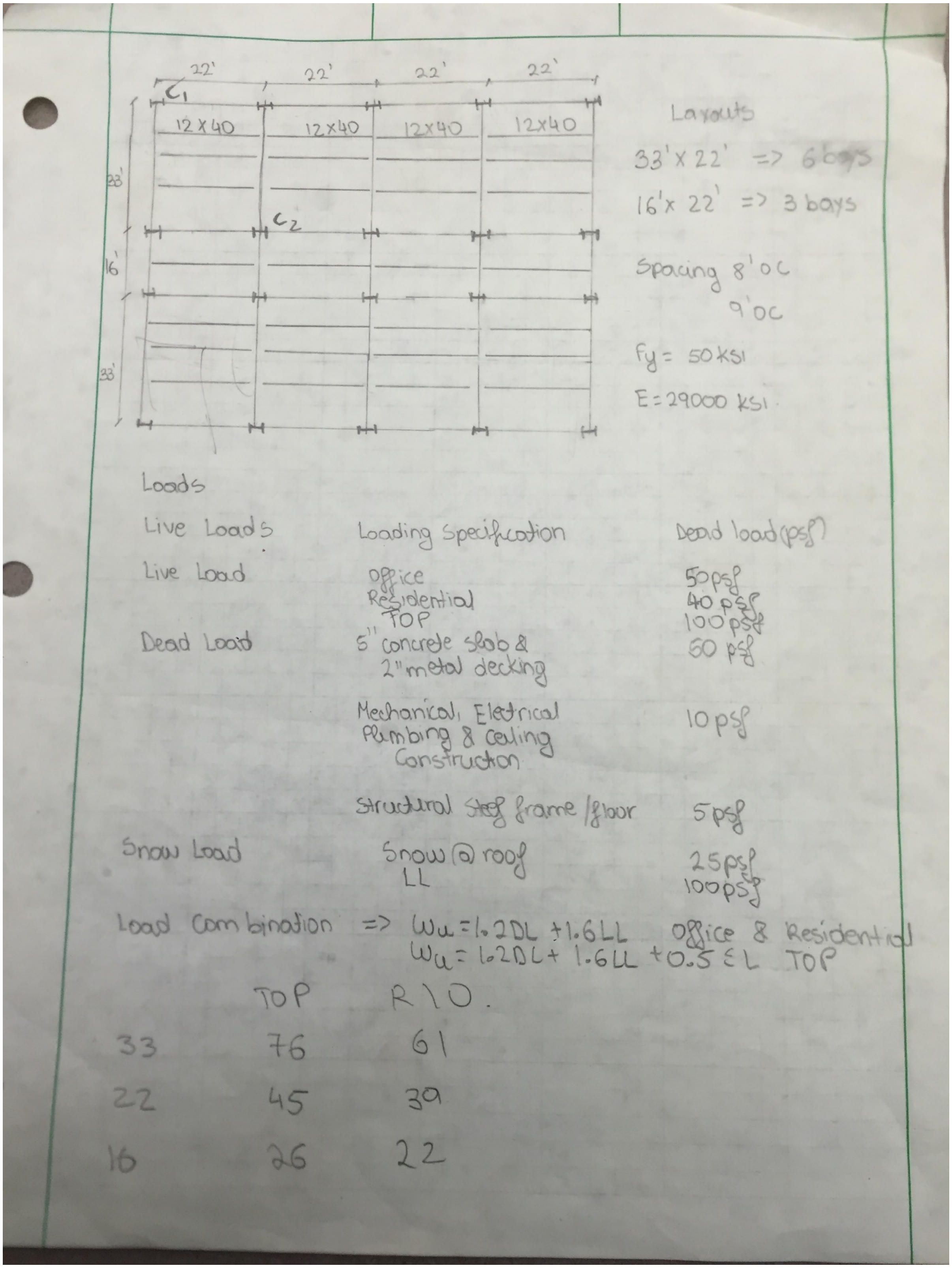
East-West Wind						L/B = 86/82 = 1.0488		
Windward Wall			Side Wall			Leeward Wall		
G	Cp	p	G	Cp	p	G	Cp	p
0.85	0.8	12.14521	0.85	-0.7	-19.7626	0.85	-0.49024	-13.8406
0.85	0.8	13.5515	0.85	-0.7	-19.7626	0.85	-0.49024	-13.8406
0.85	0.8	15.42655	0.85	-0.7	-19.7626	0.85	-0.49024	-13.8406
0.85	0.8	16.83284	0.85	-0.7	-19.7626	0.85	-0.49024	-13.8406
0.85	0.8	17.94082	0.85	-0.7	-19.7626	0.85	-0.49024	-13.8406
0.85	0.8	18.96358	0.85	-0.7	-19.7626	0.85	-0.49024	-13.8406
0.85	0.8	19.8798	0.85	-0.7	-19.7626	0.85	-0.49024	-13.8406
0.85	0.8	20.51902	0.85	-0.7	-19.7626	0.85	-0.49024	-13.8406
0.85	0.8	21.14759	0.85	-0.7	-19.7626	0.85	-0.49024	-13.8406
0.85	0.8	21.68027	0.85	-0.7	-19.7626	0.85	-0.49024	-13.8406
0.85	0.8	22.26622	0.85	-0.7	-19.7626	0.85	-0.49024	-13.8406
0.85	0.8	22.71901	0.85	-0.7	-19.7626	0.85	-0.49024	-13.8406
0.85	0.8	23.09189	0.85	-0.7	-19.7626	0.85	-0.49024	-13.8406

A.10 Excel Calculations for Floor by Floor Wind Loading on Mass Timber Structure



Floor	E-W (lb)	N-S (lb)	Floor Height	Load Combination	E-W (lb) Factored	N-S (lb) Factored
1	34,454.91	36,588.03	16.00	1.60	55,127.85	58,540.84
2	27,224.97	28,926.06	12.00	1.60	43,559.95	46,281.69
3	29,070.02	30,906.11	12.00	1.60	46,512.03	49,449.78
4	30,453.80	32,391.15	12.00	1.60	48,726.08	51,825.84
5	31,544.06	33,561.18	12.00	1.60	50,470.50	53,697.89
6	27,125.38	28,867.68	10.00	1.60	43,400.60	46,188.28
7	27,876.67	29,673.95	10.00	1.60	44,602.68	47,478.32
8	28,400.84	30,236.46	10.00	1.60	45,441.34	48,378.34
9	28,916.26	30,789.60	10.00	1.60	46,266.02	49,263.37
10	29,353.06	31,258.37	10.00	1.60	46,964.90	50,013.39
11	35,800.25	38,128.81	12.00	1.60	57,280.41	61,006.09

A.11 Hand Calculations for Steel Structure Layout, Beams and Columns



Layouts

33' x 22' => 6 bays

16' x 22' => 3 bays

Spacing 8' oc
9' oc

fy = 50 ksi

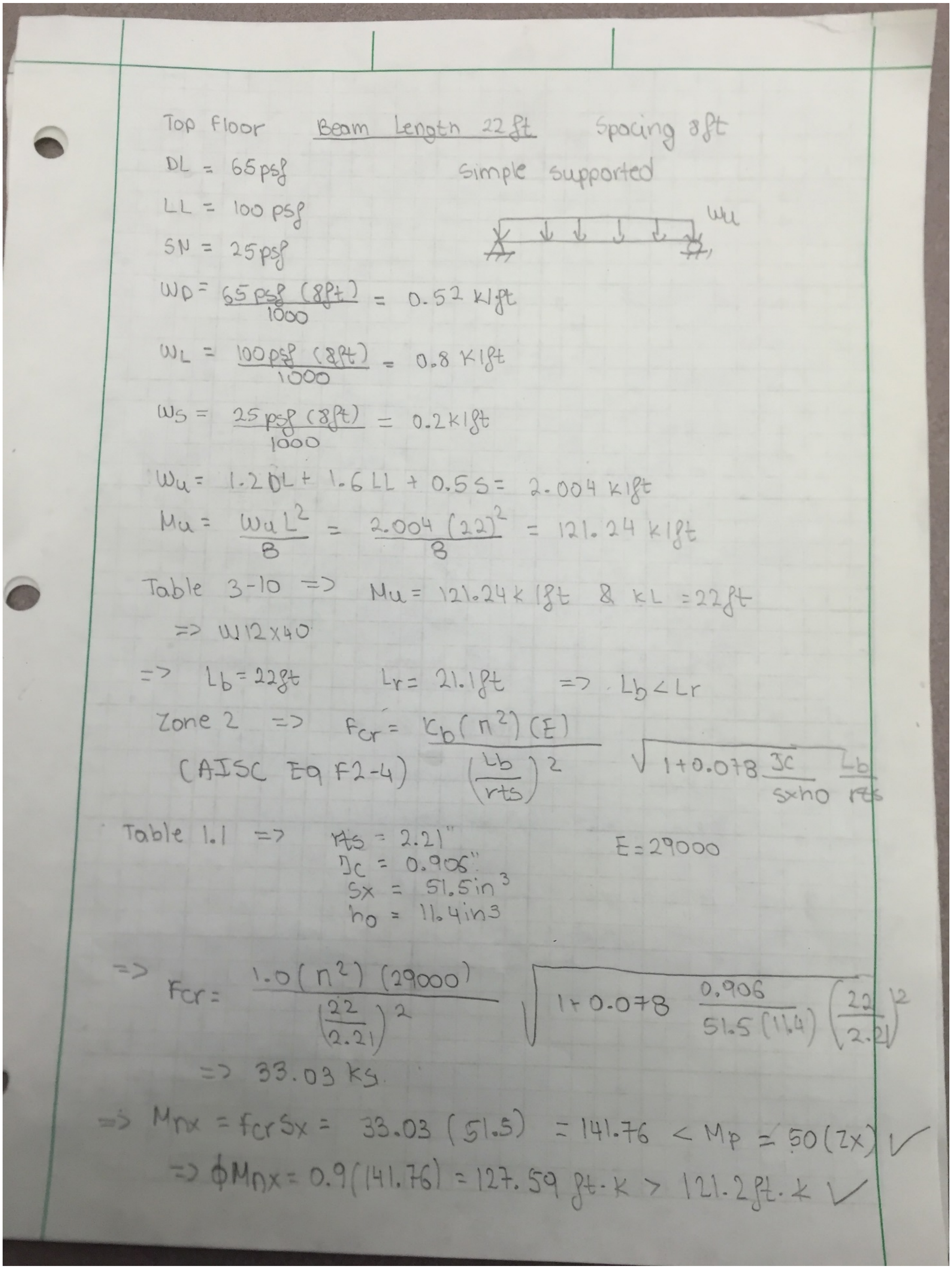
E = 29000 ksi

Loads

Live Loads	Loading Specification	Dead load (psf)
Live Load	office Residential TOP	50psf 40 psf 100psf
Dead Load	5" concrete slab & 2" metal decking	50 psf
	Mechanical, Electrical Plumbing & ceiling Construction	10 psf
	Structural steel frame/floor	5 psf
Snow Load	Snow @ roof LL	25psf 100psf

Load Combination => $W_u = 1.2DL + 1.6LL$ office & Residential
$W_u = 1.2DL + 1.6LL + 0.5SL$ TOP

	TOP	R10.
33	76	61
22	45	39
16	26	22



Top Floor   Beam Length 22 ft   Spacing 8 ft

$DL = 65\ psf$ Simple supported

$LL = 100\ psf$

$SN = 25\ psf$

$$W_D = \frac{65\ psf\ (8ft)}{1000} = 0.52\ k/ft$$

$$W_L = \frac{100\ psf\ (8ft)}{1000} = 0.8\ k/ft$$

$$W_S = \frac{25\ psf\ (8ft)}{1000} = 0.2\ k/ft$$

$$W_u = 1.2DL + 1.6LL + 0.5S = 2.004\ k/ft$$

$$M_u = \frac{W_u L^2}{8} = \frac{2.004\ (22)^2}{8} = 121.24\ k/ft$$

Table 3-10 => $M_u = 121.24\ k/ft$ & $KL = 22ft$

=> W12X40

=> $L_b = 22ft$ $L_r = 21.1ft$ => $L_b < L_r$

Zone 2 => $F_{cr} = \dfrac{C_b(\pi^2)(E)}{\left(\frac{L_b}{r_{ts}}\right)^2} \sqrt{1+0.078\frac{J_c}{S_x h_o}\frac{L_b}{r_{ts}}}$

(AISC Eq F2-4)

Table 1.1 => $r_{ts} = 2.21''$ $E = 29000$

$J_c = 0.906''$

$S_x = 51.5 in^3$

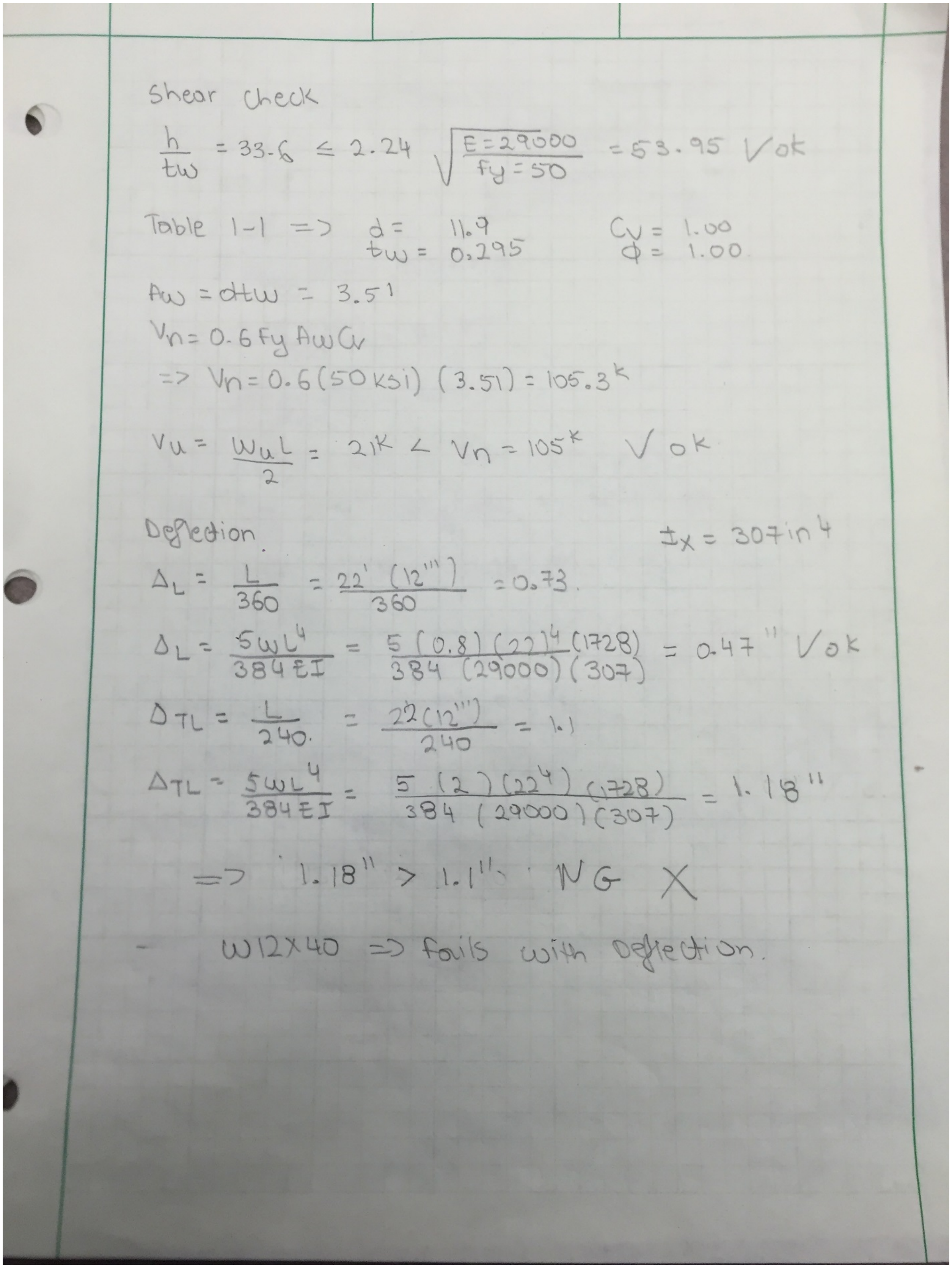
$h_o = 11.4 in^3$

$$\Rightarrow F_{cr} = \frac{1.0(\pi^2)(29000)}{\left(\frac{22}{2.21}\right)^2} \sqrt{1+0.078\frac{0.906}{51.5(11.4)}\left(\frac{22}{2.21}\right)^2}$$

=> 33.03 ks

=> $M_{nx} = F_{cr}S_x = 33.03\ (51.5) = 141.76 < M_p = 50(Z_x)$ ✓

=> $\phi M_{nx} = 0.9(141.76) = 127.59\ ft\cdot k > 121.2\ ft\cdot k$ ✓



Shear check

$$\frac{h}{t_w} = 33.6 \leq 2.24 \sqrt{\frac{E=29000}{f_y=50}} = 53.95 \checkmark \text{ok}$$

Table 1-1 => $d = 11.9$ $C_v = 1.00$

$t_w = 0.295$ $\phi = 1.00$

$A_w = dt_w = 3.51$

$V_n = 0.6 f_y A_w C_v$

=> $V_n = 0.6(50\text{ ksi})(3.51) = 105.3^k$

$$V_u = \frac{W_u L}{2} = 21^k < V_n = 105^k \checkmark \text{ ok}$$

Deflection $I_x = 307 \text{in}^4$

$$\Delta_L = \frac{L}{360} = \frac{22'(12''')}{360} = 0.73.$$

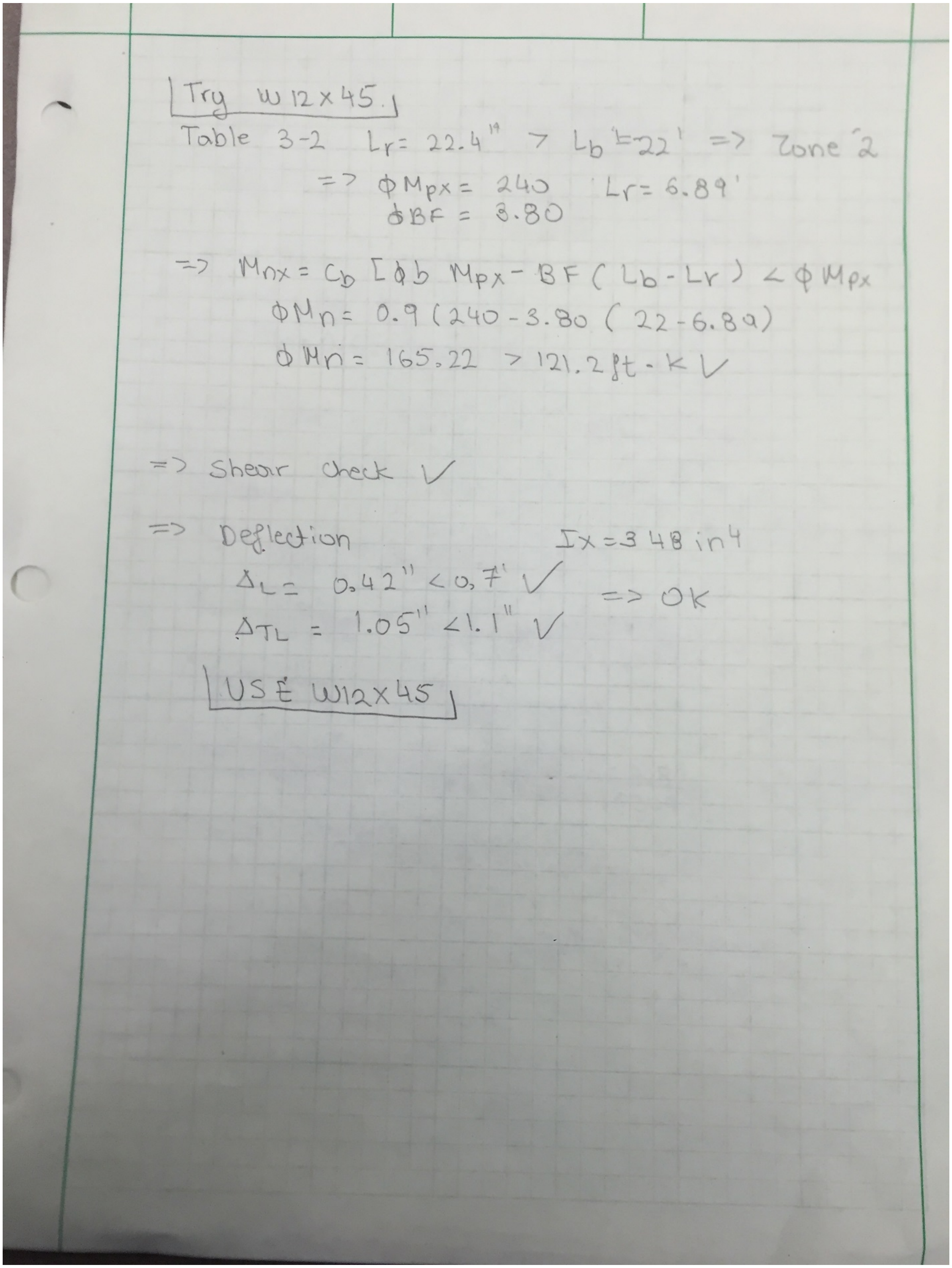
$$\Delta_L = \frac{5wL^4}{384EI} = \frac{5(0.8)(22)^4(1728)}{384(29000)(307)} = 0.47'' \checkmark \text{ok}$$

$$\Delta_{TL} = \frac{L}{240.} = \frac{22'(12''')}{240} = 1.1$$

$$\Delta_{TL} = \frac{5wL^4}{384EI} = \frac{5(2)(22^4)(1728)}{384(29000)(307)} = 1.18''$$

=> $1.18'' > 1.1''$ NG X

W12X40 => fails with deflection.



$\boxed{\text{Try W12} \times 45.}$

Table 3-2 $L_r = 22.4'' > L_b = 22' \Rightarrow$ Zone 2

$\Rightarrow \phi M_{px} = 240 \quad L_r = 6.89'$

$\phi BF = 3.80$

$\Rightarrow M_{nx} = C_b [\phi_b M_{px} - BF(L_b - L_r) < \phi M_{px}$

$\phi M_n = 0.9(240 - 3.80(22 - 6.89)$

$\phi M_n = 165.22 > 121.2 \text{ ft-k}$ ✓

$\Rightarrow$ Shear check ✓

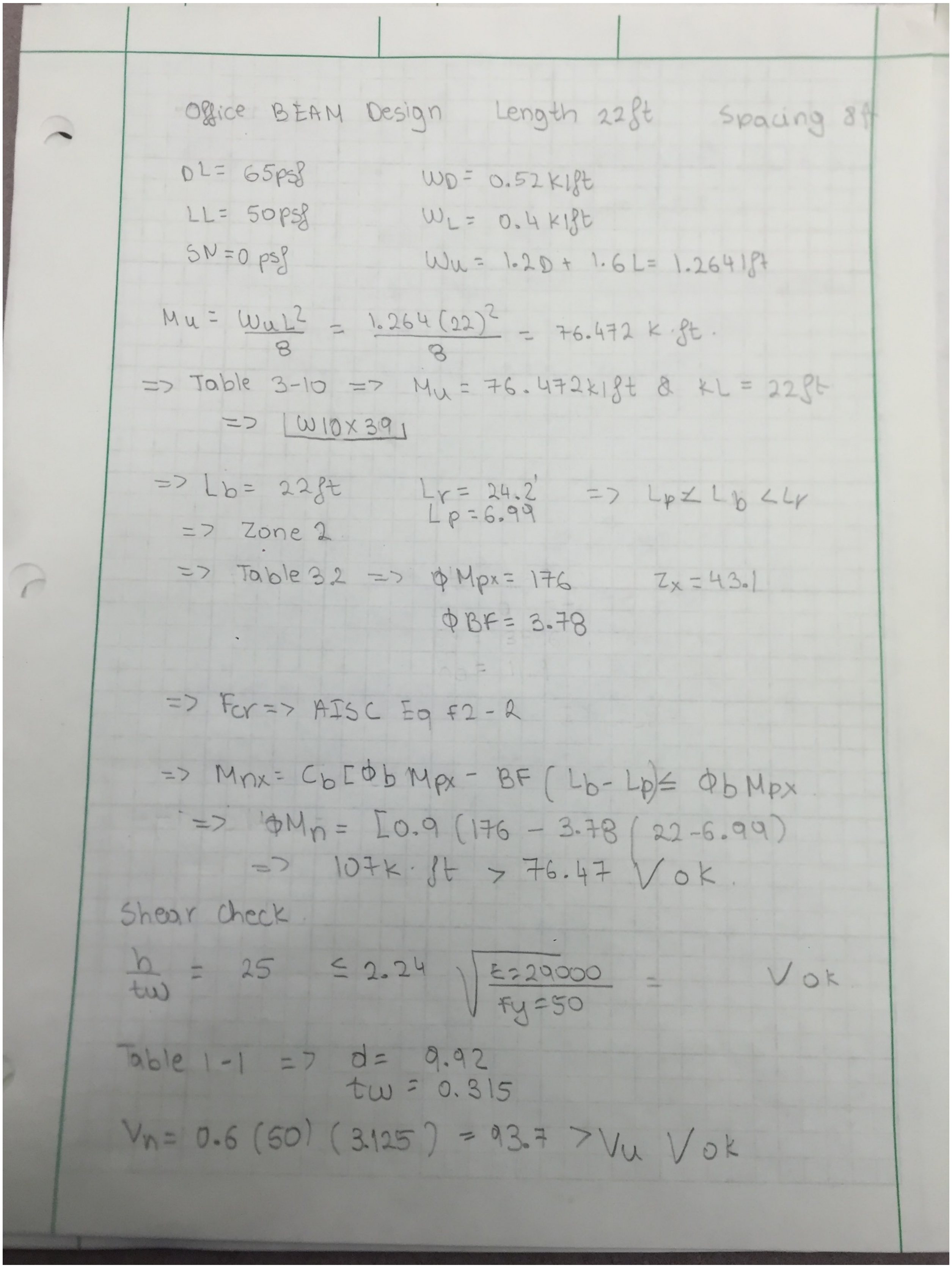
$\Rightarrow$ Deflection $\quad I_x = 348 \text{ in}^4$

$\Delta_L = 0.42'' < 0.7'$ ✓

$\Delta_{TL} = 1.05'' < 1.1''$ ✓

$\Rightarrow$ OK

$\boxed{\text{USE W12} \times 45}$



Office BEAM Design Length 22ft Spacing 8f

DL = 65psf $\qquad$ $w_D = 0.52$ k/ft

LL = 50psf $\qquad$ $w_L = 0.4$ k/ft

SN = 0 psf $\qquad$ $w_u = 1.2D + 1.6L = 1.264$ /ft

$$M_u = \frac{w_u L^2}{8} = \frac{1.264(22)^2}{8} = 76.472 \text{ k}\cdot\text{ft}.$$

=> Table 3-10 => $M_u = 76.472$ k/ft & $KL = 22$ft

=> $\boxed{W10\times39}$

=> $L_b = 22$ft $\qquad$ $L_r = 24.2'$ $\qquad$ => $L_p < L_b < L_r$

$L_p = 6.99$

=> Zone 2

=> Table 3.2 => $\phi M_{px} = 176$ $\qquad$ $Z_x = 43.1$

$\phi BF = 3.78$

=> F_{cr} => AISC Eq F2-2

=> $M_{nx} = C_b[\phi_b M_{px} - BF(L_b - L_p) \leq \phi_b M_{px}$

=> $\phi M_n = [0.9(176 - 3.78(22 - 6.99)$

=> $107\text{k}\cdot\text{ft} > 76.47$ ✓ ok.

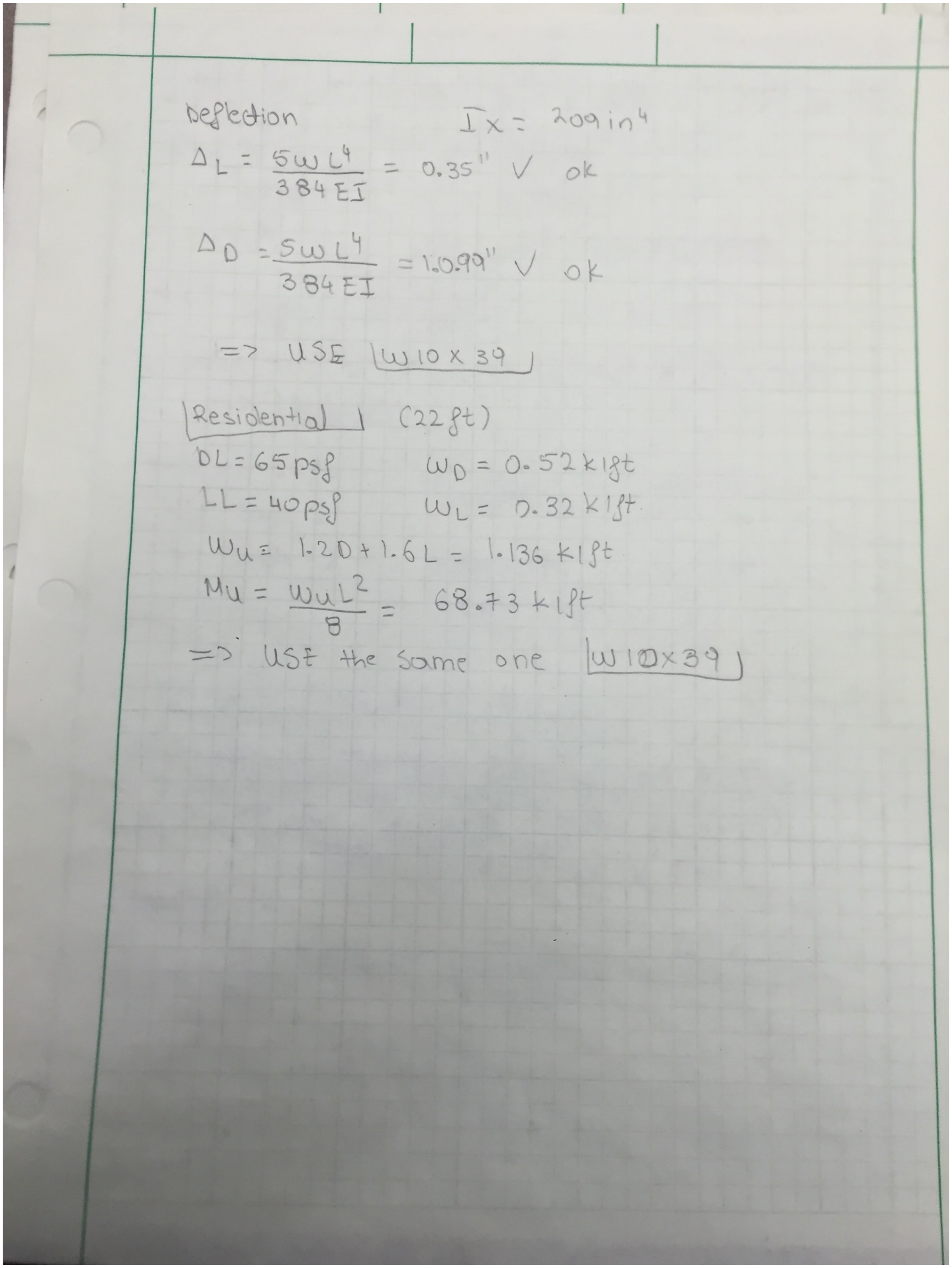
Shear check

$$\frac{h}{t_w} = 25 \leq 2.24\sqrt{\frac{E = 29000}{F_y = 50}} = \quad ✓ \text{ ok}$$

Table 1-1 => $d = 9.92$

$t_w = 0.315$

$V_n = 0.6(50)(3.125) = 93.7 > V_u$ ✓ ok



Deflection $I_x = 209 \text{ in}^4$

$$\Delta_L = \frac{5wL^4}{384EI} = 0.35'' \checkmark \text{ ok}$$

$$\Delta_D = \frac{5wL^4}{384EI} = 1.0.99'' \checkmark \text{ ok}$$

$\Rightarrow$ USE $\boxed{W10 \times 39}$

$\boxed{\text{Residential}}$ (22 ft)

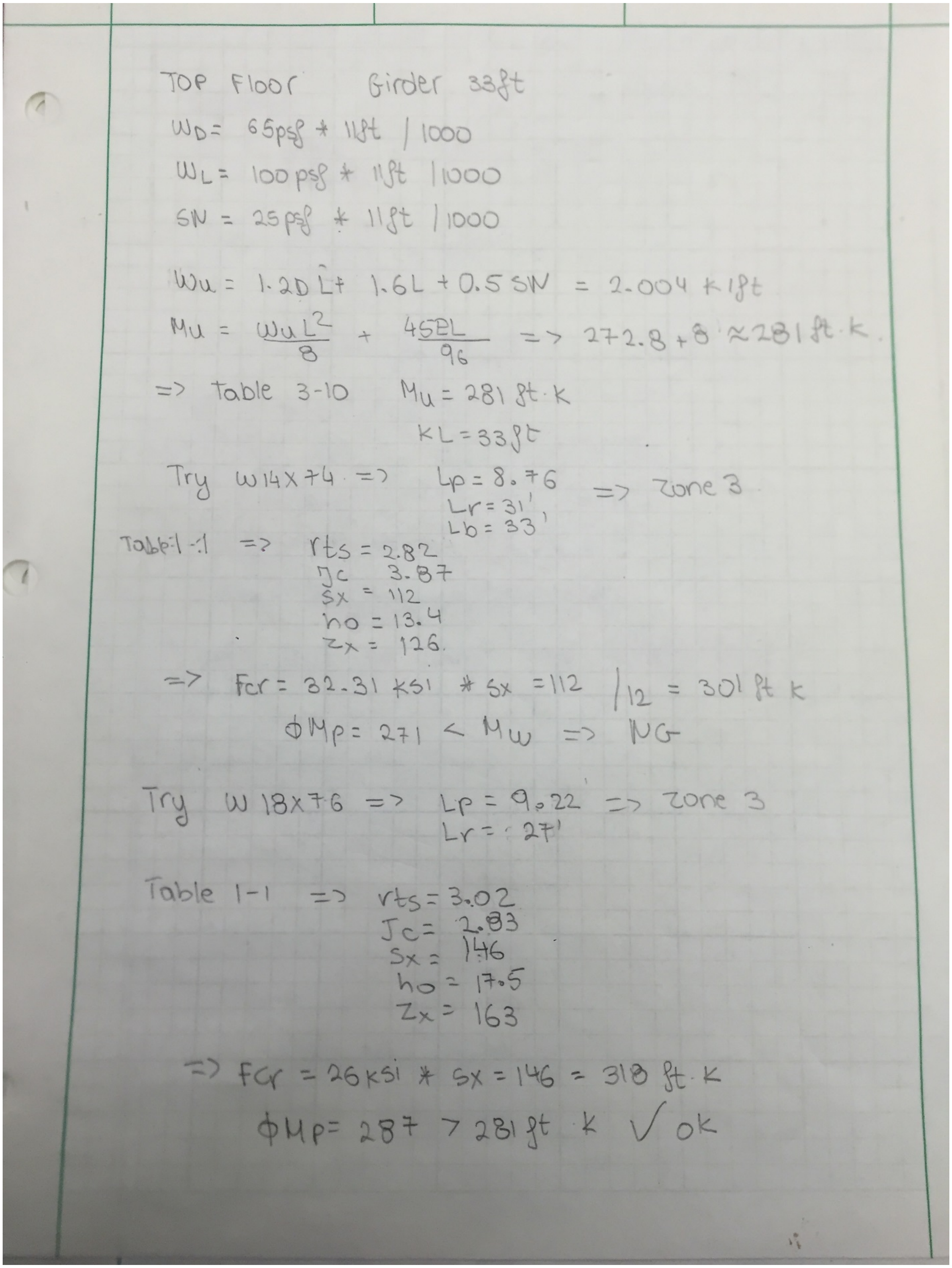
DL = 65 psf $w_D = 0.52$ k/ft

LL = 40 psf $w_L = 0.32$ k/ft

$W_u = 1.2D + 1.6L = 1.136$ k/ft

$$M_u = \frac{W_u L^2}{8} = 68.73 \text{ k/ft}$$

$\Rightarrow$ USE the same one $\boxed{W10 \times 39}$



TOP Floor Girder 33ft

$W_D = 65psf * 11ft / 1000$

$W_L = 100psf * 11ft / 1000$

$SN = 25psf * 11ft / 1000$

$W_u = 1.2D\,L + 1.6L + 0.5SN = 2.004\ k/ft$

$M_u = \frac{W_u L^2}{8} + \frac{45PL}{96} \Rightarrow 272.8 + 8 \approx 281\ ft \cdot k$

$\Rightarrow$ Table 3-10 $M_u = 281\ ft \cdot k$

$KL = 33ft$

Try W14x74 $\Rightarrow$ $L_p = 8.76$ $\Rightarrow$ Zone 3

$L_r = 31'$

$L_b = 33'$

Table 1-1 $\Rightarrow$ $r_{ts} = 2.82$

J_c 3.87

$S_x = 112$

$h_o = 13.4$

$Z_x = 126$

$\Rightarrow F_{cr} = 32.31\ ksi * S_x = 112 / 12 = 301\ ft\ k$

$\phi M_p = 271 < M_w \Rightarrow$ NG

Try W18x76 $\Rightarrow$ $L_p = 9.22$ $\Rightarrow$ Zone 3

$L_r = 27'$

Table 1-1 $\Rightarrow$ $r_{ts} = 3.02$

$J_c = 2.83$

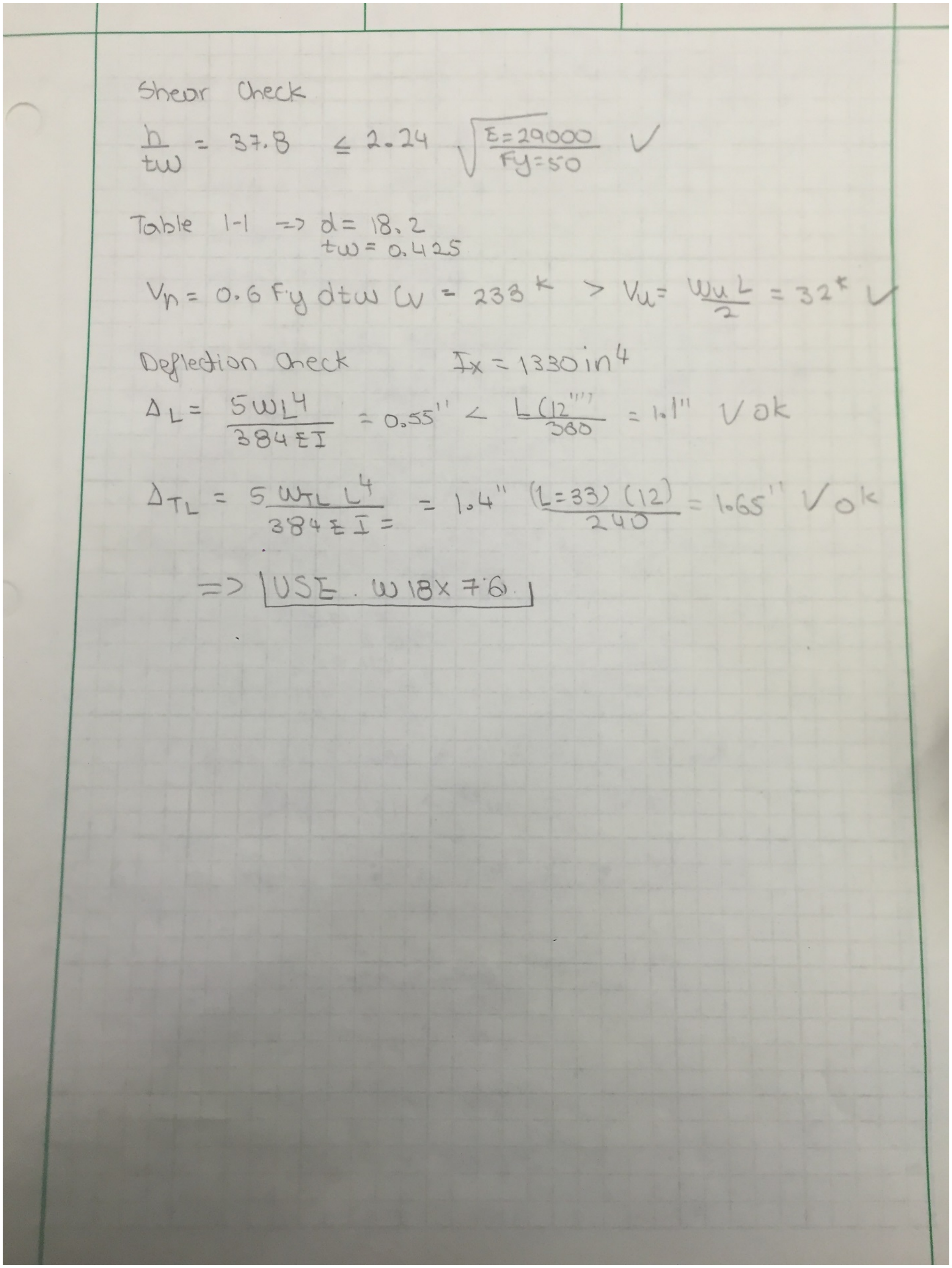
$S_x = 146$

$h_o = 17.5$

$Z_x = 163$

$\Rightarrow F_{cr} = 26ksi * S_x = 146 = 318\ ft \cdot k$

$\phi M_p = 287 > 281\ ft\ k$ ✓ ok



Shear Check

$$\frac{h}{t_w} = 37.8 \leq 2.24 \sqrt{\frac{E=29000}{Fy=50}} \checkmark$$

Table 1-1 => $d = 18.2$
$t_w = 0.425$

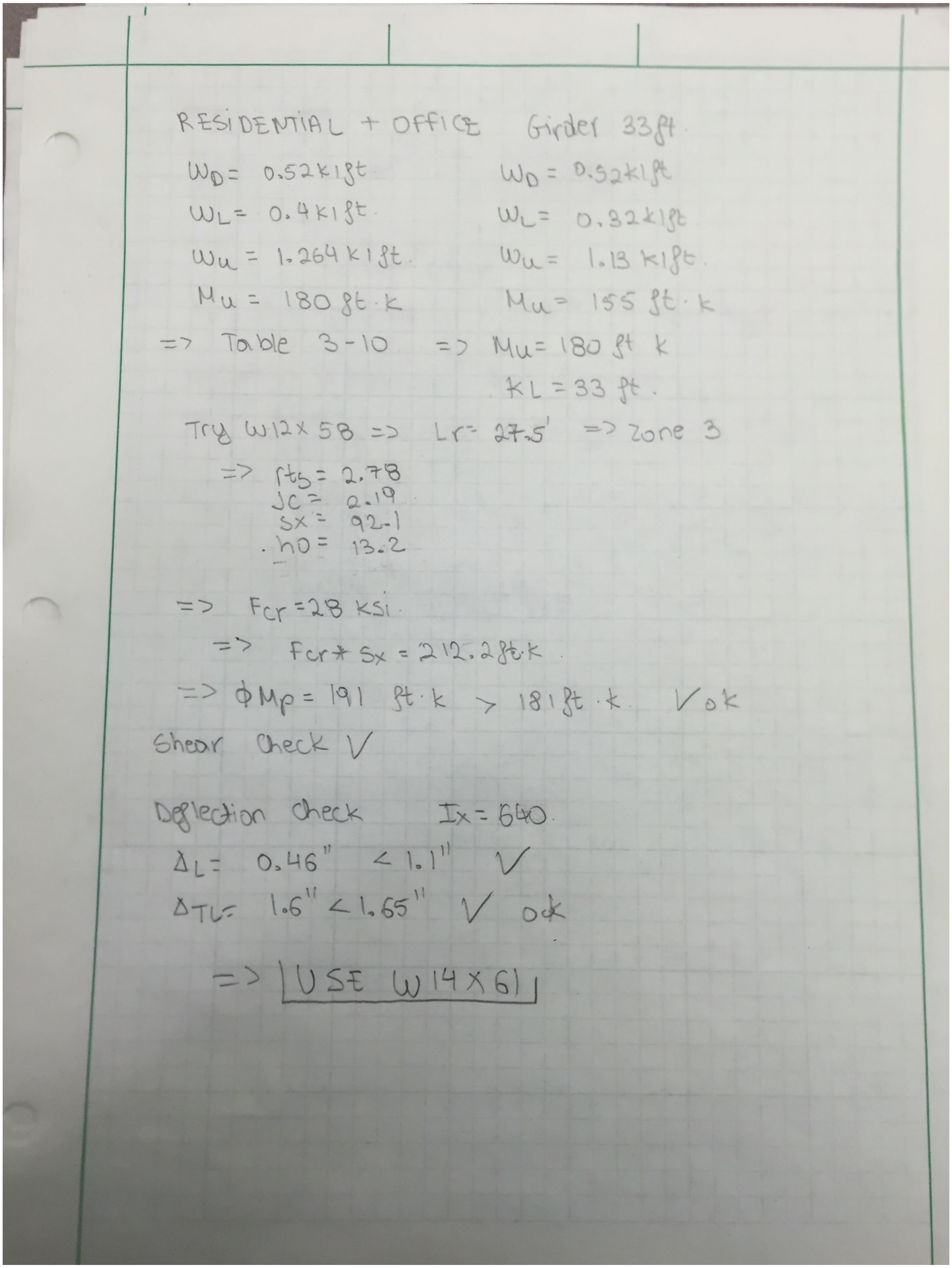
$$V_n = 0.6\, F_y\, d\, t_w\, C_v = 233^k > V_u = \frac{w_u L}{2} = 32^k \checkmark$$

Deflection Check $I_x = 1330\, in^4$

$$\Delta_L = \frac{5 w L^4}{384 EI} = 0.55'' < \frac{L(12''')}{360} = 1.1'' \checkmark ok$$

$$\Delta_{TL} = \frac{5 w_{TL} L^4}{384 EI =} = 1.4'' \frac{(L=33)(12)}{240} = 1.65'' \checkmark ok$$

$$\Rightarrow \boxed{\text{USE . W18X76.}}$$



RESIDENTIAL + OFFICE Girder 33 ft.

$W_D = 0.52$ k/ft $\qquad W_D = 0.52$ k/ft

$W_L = 0.4$ k/ft. $\qquad W_L = 0.32$ k/ft

$W_u = 1.264$ k/ft. $\qquad W_u = 1.13$ k/ft.

$M_u = 180$ ft·k $\qquad M_u = 155$ ft·k

=> Table 3-10 => $M_u = 180$ ft k

$KL = 33$ ft.

Try W12x58 => $L_r = 27.5'$ => Zone 3

=> $r_{ts} = 2.78$
$J_c = 2.19$
$S_x = 92.1$
$h_0 = 13.2$

=> $F_{cr} = 28$ ksi.

=> $F_{cr} * S_x = 212.2$ ft.k

=> $\phi M_p = 191$ ft·k > 181 ft·k ✓ ok

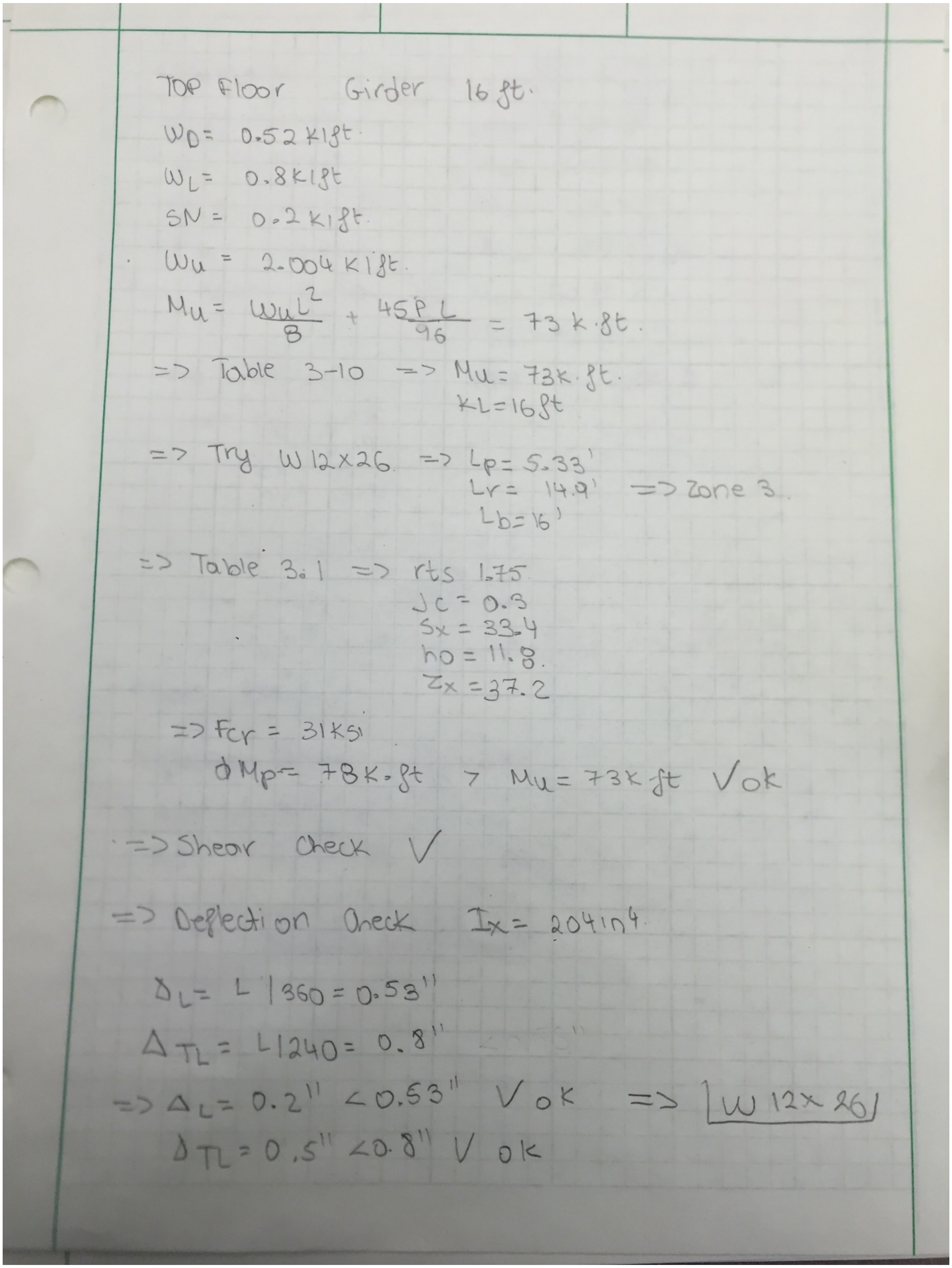
Shear Check ✓

Deflection check $I_x = 640$.

$\Delta_L = 0.46'' < 1.1''$ ✓

$\Delta_{TL} = 1.6'' < 1.65''$ ✓ ok

=> $\boxed{\text{USE W14X61}}$



Top Floor Girder 16 ft.

$w_D = 0.52$ k/ft

$w_L = 0.8$ k/ft

SN = 0.2 k/ft.

$w_u = 2.004$ k/ft.

$M_u = \frac{w_u L^2}{8} + \frac{45PL}{96} = 73$ k.ft.

=> Table 3-10 => $M_u = 73$ k.ft.
KL = 16 ft

=> Try W12x26 => $L_p = 5.33'$
$L_r = 14.9'$ => Zone 3.
$L_b = 16'$

=> Table 3.1 => rts 1.75
$J_c = 0.3$
$S_x = 33.4$
$h_o = 11.8.$
$Z_x = 37.2$

=> $F_{cr} = 31$ ksi
$\phi M_p = 78$ k.ft > $M_u = 73$ k.ft ✓ok

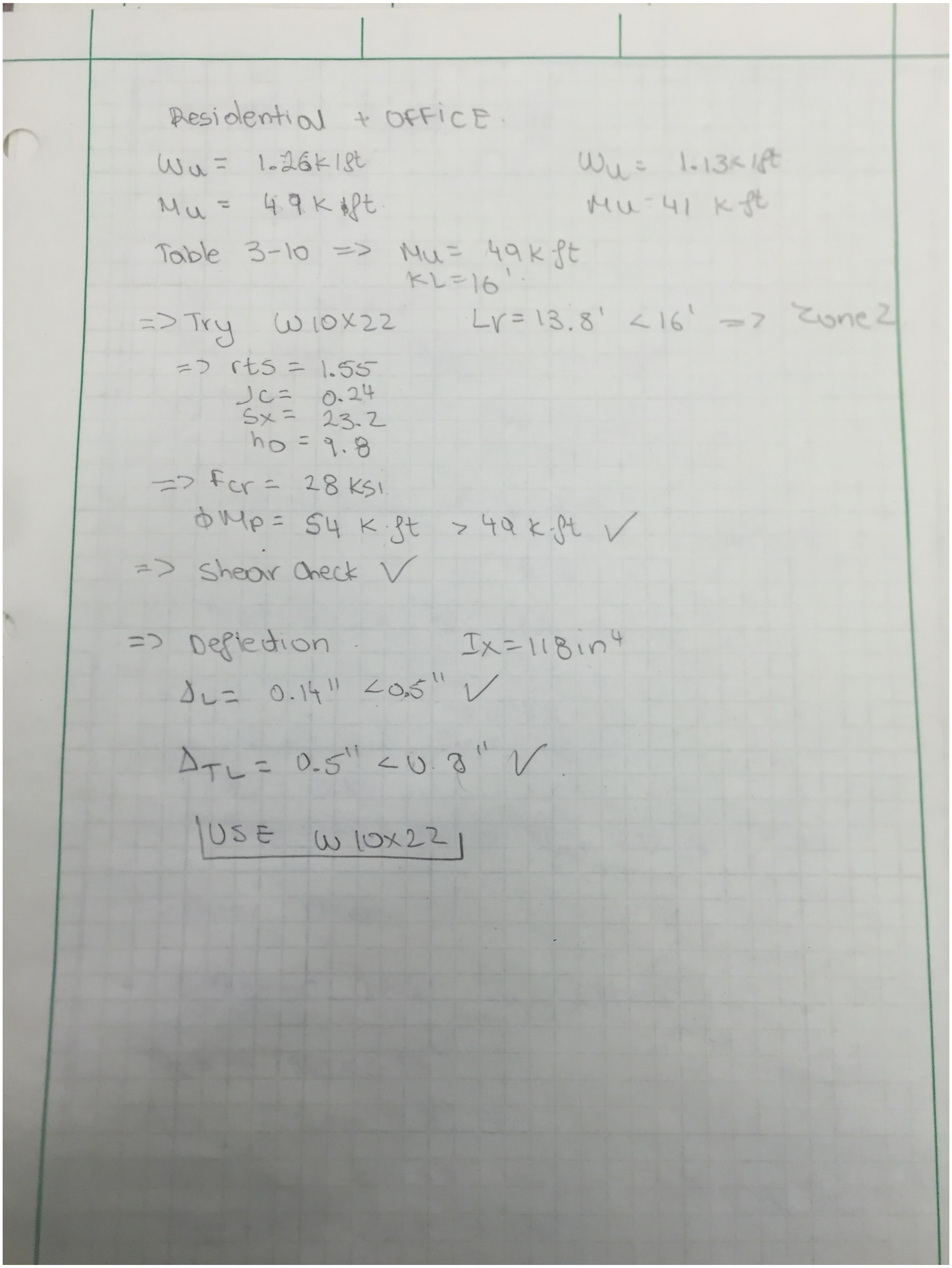
=> Shear Check ✓

=> Deflection Check $I_x = 204 in^4$

$\delta_L = L/360 = 0.53''$

$\Delta_{TL} = L/240 = 0.8''$

=> $\Delta_L = 0.2'' < 0.53''$ ✓ ok => $\boxed{W12x26}$
$\delta_{TL} = 0.5'' < 0.8''$ ✓ ok



Residential + OFFICE

$W_u = 1.26 k/ft$ $W_u = 1.13 k/ft$

$M_u = 49 k \cdot ft$ $M_u = 41 k \cdot ft$

Table 3-10 => $M_u = 49 k \cdot ft$

$KL = 16'$

=> Try W10X22 $L_r = 13.8' < 16'$ => Zone 2

=> $r_{ts} = 1.55$

$J_c = 0.24$

$S_x = 23.2$

$h_o = 9.8$

=> $F_{cr} = 28 ksi$

$\phi M_p = 54 k \cdot ft > 49 k \cdot ft$ ✓

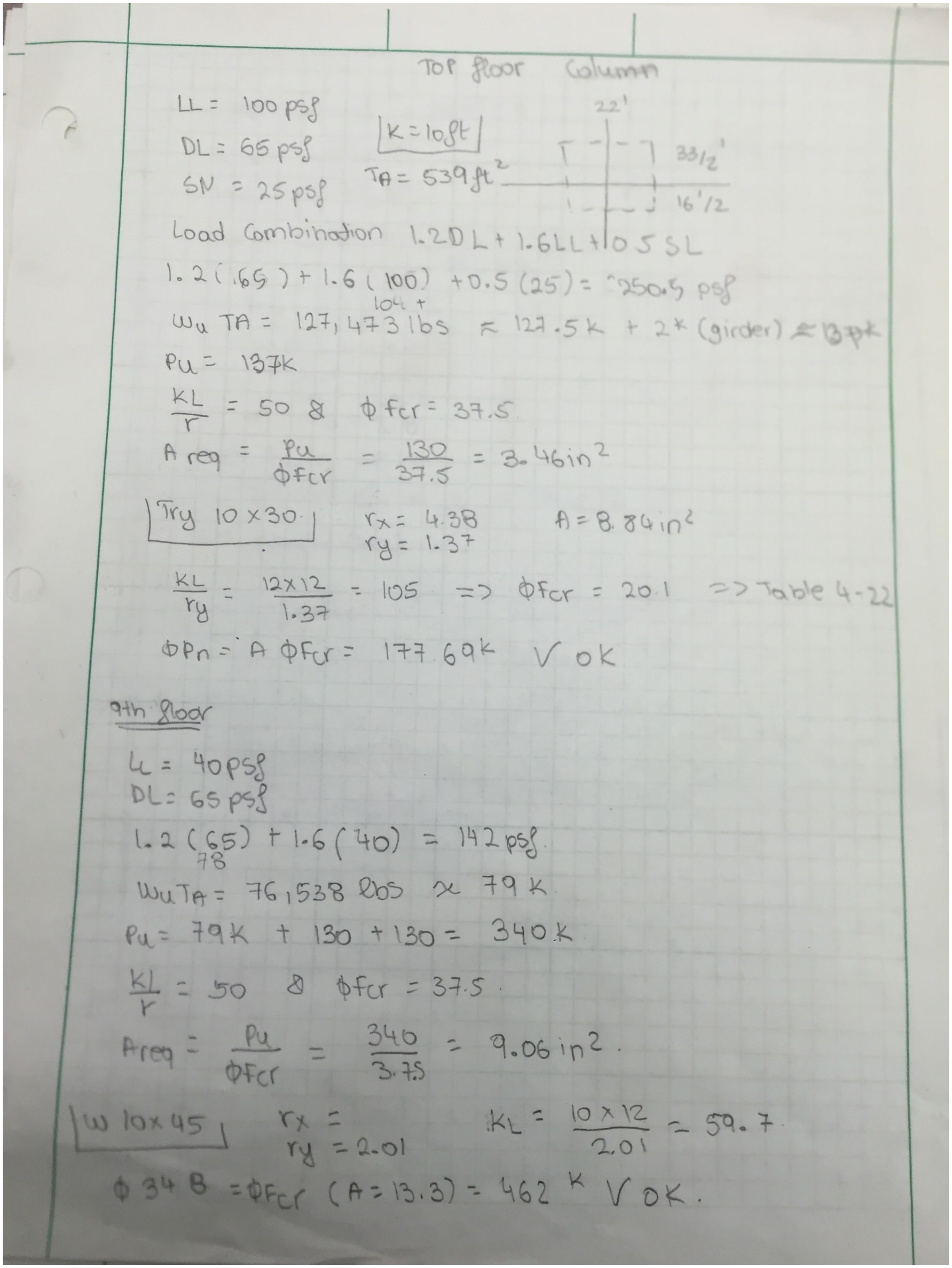
=> Shear Check ✓

=> Deflection $I_x = 118 in^4$

$\Delta_L = 0.14'' < 0.5''$ ✓

$\Delta_{TL} = 0.5'' < 0.8''$ ✓

$\boxed{\text{USE W10x22}}$



Top floor Column

LL = 100 psf

DL = 65 psf

SN = 25 psf

$\boxed{K = 10 ft}$

TA = 539 ft^2

22'

33/2'

16'/2

Load Combination 1.2DL + 1.6LL + 0.5 SL

1.2 (65) + 1.6 (100) + 0.5 (25) = 250.5 psf

$\overset{104 +}{}$

w_u TA = 127,473 lbs ≈ 127.5 k + 2* (girder) ≈ 13.7k

Pu = 137k

$\frac{KL}{r} = 50$ & $\phi F_{cr} = 37.5$

$A_{req} = \frac{P_u}{\phi F_{cr}} = \frac{130}{37.5} = 3.46 in^2$

$\boxed{\text{Try } 10 \times 30}$ $r_x = 4.38$ A = 8.84 in^2

$r_y = 1.37$

$\frac{KL}{r_y} = \frac{12 \times 12}{1.37} = 105 \Rightarrow \phi F_{cr} = 20.1$ => Table 4-22

$\phi P_n = A \phi F_{cr} = 177.69^k$ ✓ ok

9th floor

LL = 40psf

DL = 65 psf

$1.2(\underset{78}{65}) + 1.6(40) = 142 psf$

W_uTA = 76,538 lbs ≈ 79 k

Pu = 79k + 130 + 130 = 340 k

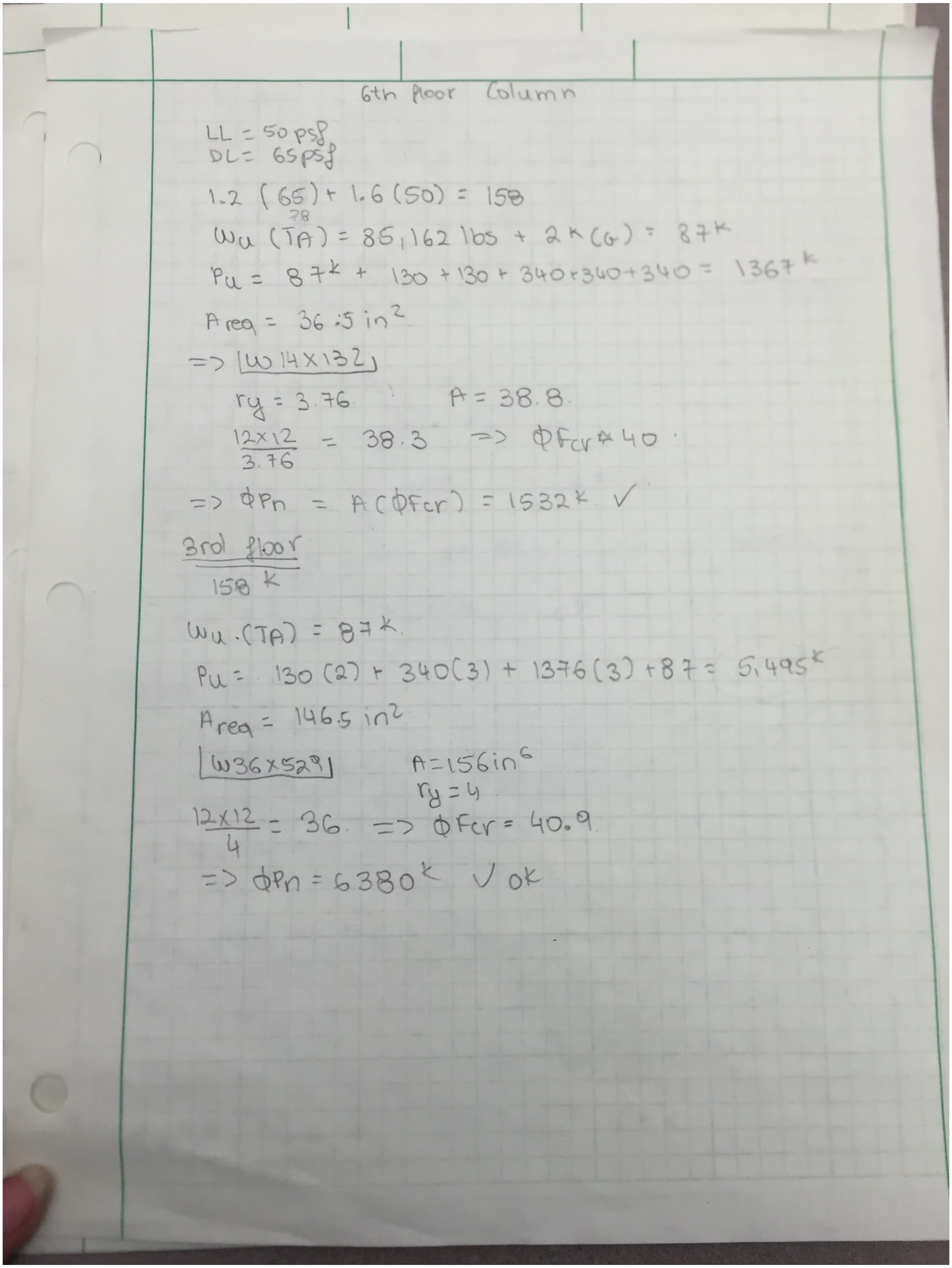
$\frac{KL}{r} = 50$ & $\phi F_{cr} = 37.5$

$A_{req} = \frac{P_u}{\phi F_{cr}} = \frac{340}{3.75} = 9.06 in^2$.

$\boxed{W 10 \times 45}$ $r_x =$ $KL = \frac{10 \times 12}{2.01} = 59.7$

$r_y = 2.01$

ϕ 34 B = ϕF_{cr} (A = 13.3) = 462^K ✓ OK.



6th floor Column

LL = 50 psf
DL = 65 psf

$1.2\,(\underset{78}{65}) + 1.6\,(50) = 158$

$w_u\,(TA) = 85{,}162\ \text{lbs} + 2^k(6) = 87^k$

$P_u = 87^k + 130 + 130 + 340 + 340 + 340 = 1367^k$

$A_{req} = 36.5\ in^2$

$\Rightarrow \boxed{W14 \times 132}$

$r_y = 3.76 \qquad A = 38.8$

$\frac{12 \times 12}{3.76} = 38.3 \Rightarrow \phi F_{cr} \approx 40$

$\Rightarrow \phi P_n = A(\phi F_{cr}) = 1532^k$ ✓

3rd floor

158^k

$w_u \cdot (TA) = 87^k$

$P_u = 130\,(2) + 340(3) + 1376\,(3) + 87 = 5{,}495^k$

$A_{req} = 146.5\ in^2$

$\boxed{W36 \times 529}$ $\qquad A = 156\,in^6$
$r_y = 4$

$\frac{12 \times 12}{4} = 36 \Rightarrow \phi F_{cr} = 40.9$

$\Rightarrow \phi P_n = 6380^k$ ✓ ok

A.12 Weight of All Mass Timber Structure Beams

	Office			Residential			Roof Garden		
Beam	Long	Mid	Short	Long	Mid	Short	Long	Mid	Short
Span (ft)	30.00	22.00	17.60	30.00	22.00	17.60	30.00	22.00	17.60
Width (in)	8.75	6.75	5.13	8.75	6.75	4.75	10.75	8.75	5.13
Height (in)	27.00	22.50	15.00	25.50	21.00	15.00	31.00	24.00	19.50
Volume (ft^3)	49.22	23.20	9.40	46.48	21.66	8.71	69.43	32.08	12.21
Density (pcf)	35.00	35.00	35.00	35.00	35.00	35.00	35.00	35.00	35.00
Weight (lb/beam)	1722.66	812.11	328.85	1626.95	757.97	304.79	2429.95	1122.92	427.51
Beams per floor	12	6	24	12	6	24	12	6	24
Weight (lb/floor)	20671.9	4872.7	7892.5	19523.4	4547.8	7315.0	29159.4	6737.5	10260.3
Floors in structure	5	5	5	5	5	5	1	1	1
Weight (lb/building)	103359	24363	39463	97617	22739	36575	29159	6738	10260
Total Weight (lb)	370273.53								
Total Weight (kip)	370.27								
Total Weight (tons)	185.14								

A.13 Weight of All Steel Structure Beams

	Office			Residential			Roof Garden		
Beam	Long	Mid	Short	Long	Mid	Short	Long	Mid	Short
Span (ft)	33.00	22.00	16.00	33.00	22.00	16.00	33.00	22.00	16.00
W Shape	W14x74	W12x30	W12x26	W14x74	W12x30	W12x26	W18x97	W12x50	W14x34
Weight (lb/ft)	74.00	30.00	26.00	74.00	30.00	26.00	97.00	50.00	34.00
Weight (lb/beam)	2442.00	660.00	416.00	2442.00	660.00	416.00	3201.00	1100.00	544.00
Beams per floor	10	44	5	10	44	5	10	44	5
Weight (lb/floor)	24420.0	29040.0	2080.0	24420.0	29040.0	2080.0	32010.0	48400.0	2720.0
Floors in structure	5	5	5	5	5	5	1	1	1
Weight (lb/building)	122100	145200	10400	122100	145200	10400	32010	48400	2720
Total Weight (lb)	638530.00								
Total Weight (kip)	638.53								
Total Weight (tons)	319.27								

A.14 Weight of All Mass Timber Structure Columns

Floor	Height (ft)	Column width (in)	Column Volume (ft^3)	Density (pcf)	Column Weight (lb)	Number of Columns	Floor Column Weight (lb)
11	12	7.5	4.6875	35	164.0625	24	3937.5
10	10	7.5	3.90625	35	136.7188	24	3281.25
9	10	7.5	3.90625	35	136.7188	24	3281.25
8	10	10.5	7.65625	35	267.9688	24	6431.25
7	10	10.5	7.65625	35	267.9688	24	6431.25
6	12	10.5	9.1875	35	321.5625	24	7717.5
5	12	12	12	35	420	24	10080
4	12	12	12	35	420	24	10080
3	12	12	12	35	420	24	10080
2	12	13.5	15.1875	35	531.5625	24	12757.5
1	16	13.5	20.25	35	708.75	24	17010
			Total Column Weight (kip)				91.0875
			Total Column Weight (Tons)				45.54375

A.15 Weight of all Mass Timber Structure Floors

Width (ft)	88
Length (ft)	82
Area (ft^2)	7216
Floor (psf)	18.33
MEP (psf)	5
Misc (psf)	5
Weight (lb/floor)	204429.3
Number of floors	11
Weight (kip)	2248.722
Weight (tons)	1124.361

A.16 Weight of All Steel Structure Columns

Floor	Height (ft)	W Shape	Weight (lb/ft)	Weight (lb/column)	Number of Columns	Floor Column Weight (lb)
11	12	W10x30	30	360	20	7200
10	10	W10x30	30	300	20	6000
9	10	W10x45	45	450	20	9000
8	10	W10x45	45	450	20	9000
7	10	W10x45	45	450	20	9000
6	12	W14x134	134	1608	20	32160
5	12	W14x134	134	1608	20	32160
4	12	W14x134	134	1608	20	32160
3	12	W36x529	529	6348	20	126960
2	12	W36x529	529	6348	20	126960
1	16	W36x529	529	8464	20	169280
		Total Column Weight (kip)				559.88
		Total Column Weight (Tons)				279.94

A.17 Weight of All Steel Structure Floors

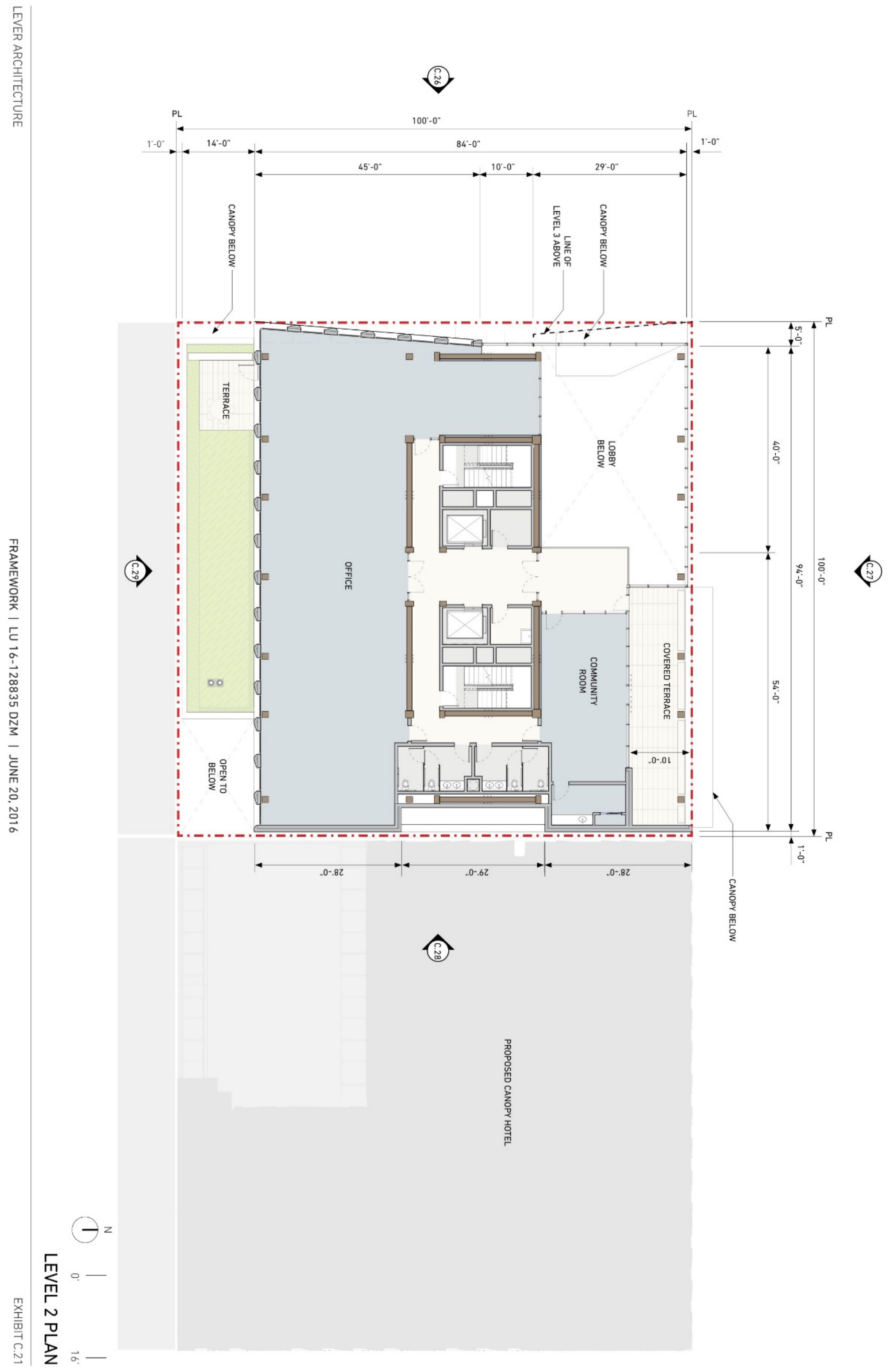
Width (ft)	88
Length (ft)	82
Area (ft^2)	7216
Floor (psf)	50
MEP (psf)	5
Misc (psf)	5
Weight (lb/floor)	432960
Number of floors	11
Weight (kip)	4762.56
Weight (tons)	2381.28

Appendix B: FRAMEWORK Reference Images

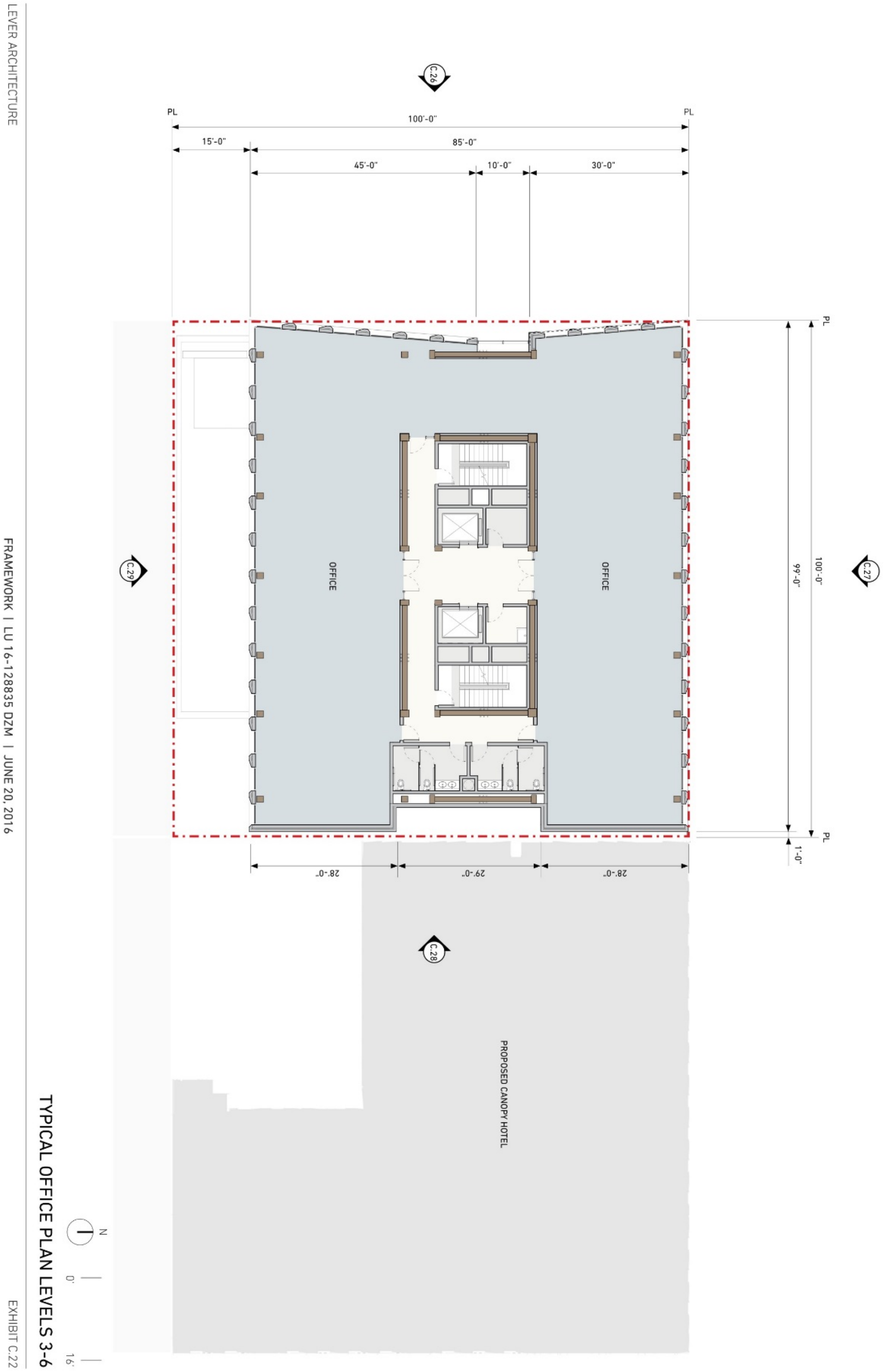
B.1 FRAMEWORK Section Elevation

B.2 FRAMEWORK Architectural Plans (Ground Floor)

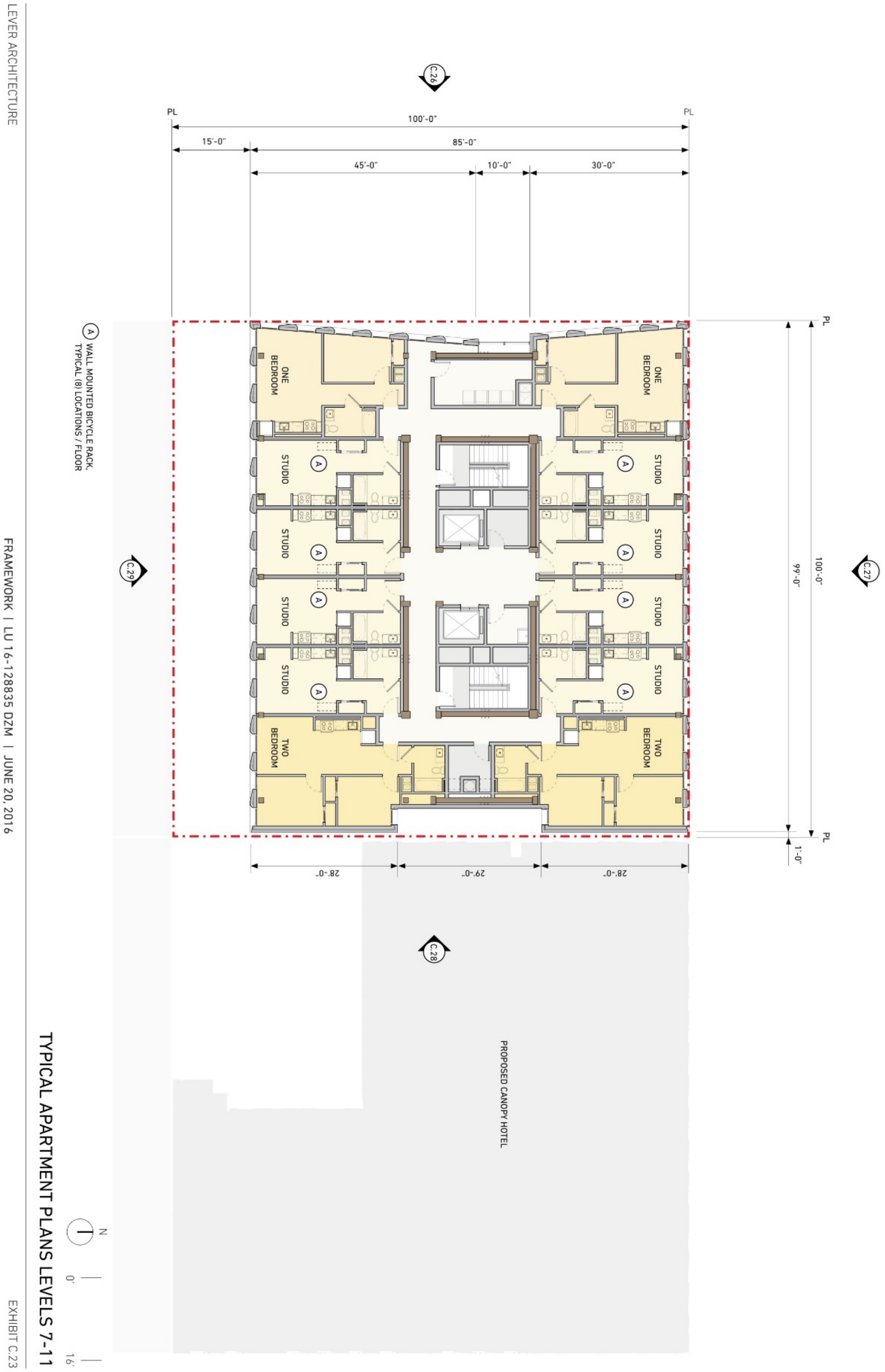
B.3 FRAMEWORK Architectural Plans (2nd Floor)



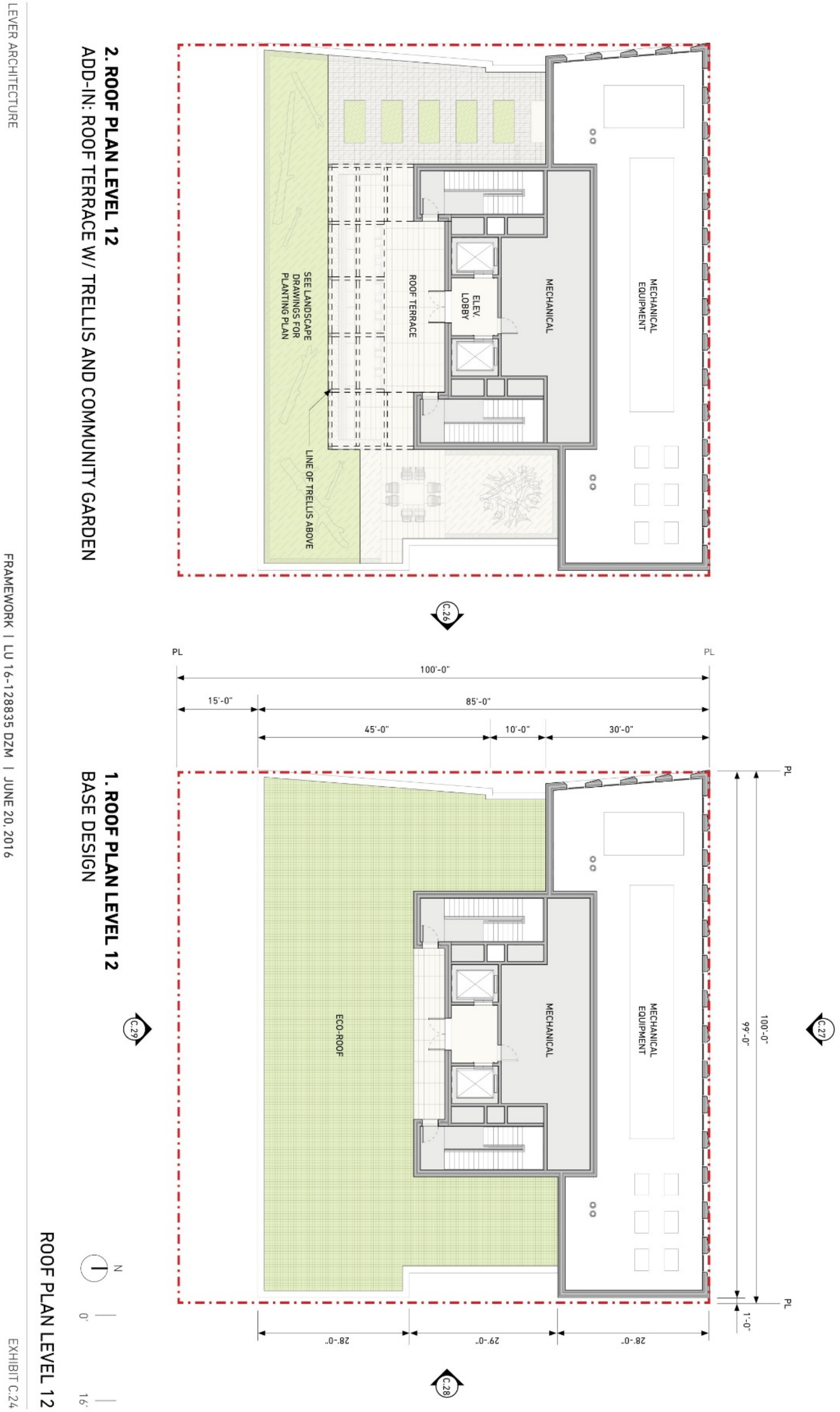
B.4 FRAMEWORK Architectural Plans (Floors 3-6)



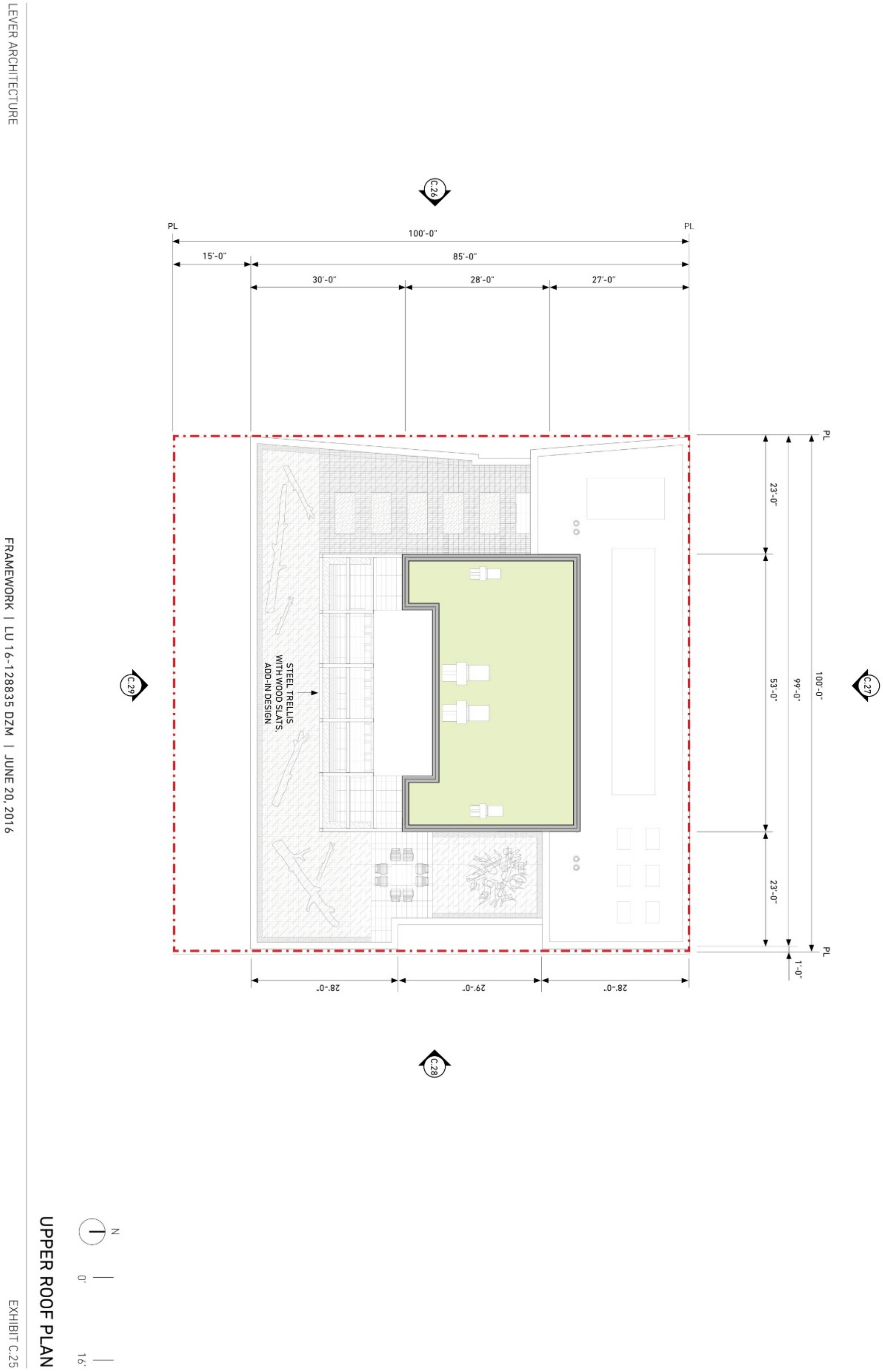
B.5 FRAMEWORK Architectural Plans (Floors 7-11)



B.6 FRAMEWORK Architectural Plans (12th Floor/Roof)



B.7 FRAMEWORK Architectural Plans (Upper Roof)



Works Cited

P. Newman, T. Beatley and H. M. Boyer. (2009). *Resilient Cities: Responding to Peak Oil and Climate Change*. Island Press. USA.

UNEP. (2009). Buildings and Climate Change: Summary for Decision-Makers. Paris: UNEP DTIE.

Oldfield, P. (2015, July 07). Tree houses: are wooden skyscrapers the future of tall buildings? Retrieved April 27, 2017, from https://www.theguardian.com/artanddesign/2015/jul/07/tree-houses-are-wooden-skyscrapers-the-future-of-tall-buildings

Kobelt, P. (2016, June 22). Branching out: Why cross-laminated timber is making advances in the US. Retrieved April 27, 2017, from http://www.constructiondive.com/news/branching-out-why-cross-laminated-timber-is-making-advances-in-the-us/421222/

Mohammad, M., Gagnon, S., Douglas, B., & Podesto, L. (n.d.). Introduction to Cross Laminated Timber . Retrieved April 27, 2017, from http://www.forestprod.org/buy_publications/resources/untitled/summer2012/Volume%2022,%20Issue%202%20Mohammad.pdf

Espinoza , O., Trujillo, V. R., Mallo, M. F., & Buehlmann, U. (n.d.). Cross -Laminated Timber: Status and Research Needs in Europe . Retrieved April 27, 2017, from https://www.ncsu.edu/bioresources/BioRes_11/BioRes_11_1_281_Epinoza_TMB_Cross%20Laminated_Timber_Research%20Needs_Europe_8002.pdf

N. (n.d.). Lever Architecture Archives. Retrieved April 27, 2017, from http://www.nextportland.com/category/lever-architecture/

McCormac, J. C., & Csernak, S. F. (2012). Structural steel design. Boston: Prentice Hall.

Timber skyscrapers could transform London's skyline. (2016, April 08). Retrieved April 27, 2017, from http://www.cam.ac.uk/research/news/timber-skyscrapers-could-transform-londons-skyline

"The City of Portland, Oregon." Structural Engineering RSS. N.p., 09 Oct. 2015. Web. 27 Apr. 2017.

U.S. Seismic Design Maps. N.p., n.d. Web. 27 Apr. 2017.

(2016, May 24). Experimental Tall Wood Buildings Material: Mass Timber. Retrieved April 27, 2017, from https://redshift.autodesk.com/mass-timber/

Architects Inc, A. (n.d.). Construction Underway on World's Tallest Timber . Retrieved April 27, 2017, from https://raic.org/sites/default/files/civicrm/persist/contribute/files/bulletin/2016/march/brock_eng.pdf