

**CREATING A STANDARDIZED SYSTEM FOR
PRE - ENGINEERED MASS TIMBER STRUCTURAL
FRAMES FOR APPLICATIONS IN SINGLE STORY
BUILDINGS**



Simone O'Halloran
M.S. Mass Timber Design Focus
University of Oregon
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RETHINKING THE STEEL INDUSTRIAL ARCHETYPE IN TIMBER:

Creating a Standardized System for Pre-Engineered Mass Timber Structural
Frames for Applications in Single Story Buildings

Simone O'Halloran
Masters of Science in Architecture | Mass Timber Focus

Graduate Committee Members : Mark Fretz, Mikhail Gershfeld,
Judith Sheine (Chair)



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PART I :
PREDESIGN



An aerial photograph of a dense forest with various shades of green. Three thick white diagonal lines run from the top-left towards the bottom-right, crossing the forest canopy.

INTRODUCTION

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This goal of this project is to create a standardizable system for pre-engineered mass timber structural frames for a variety of spans and applications in single-story buildings. In creating this system, these frames will provide a more sustainable version of existing pre-engineered steel structural systems, such as the best known system of these frames, the Butler Buildings.

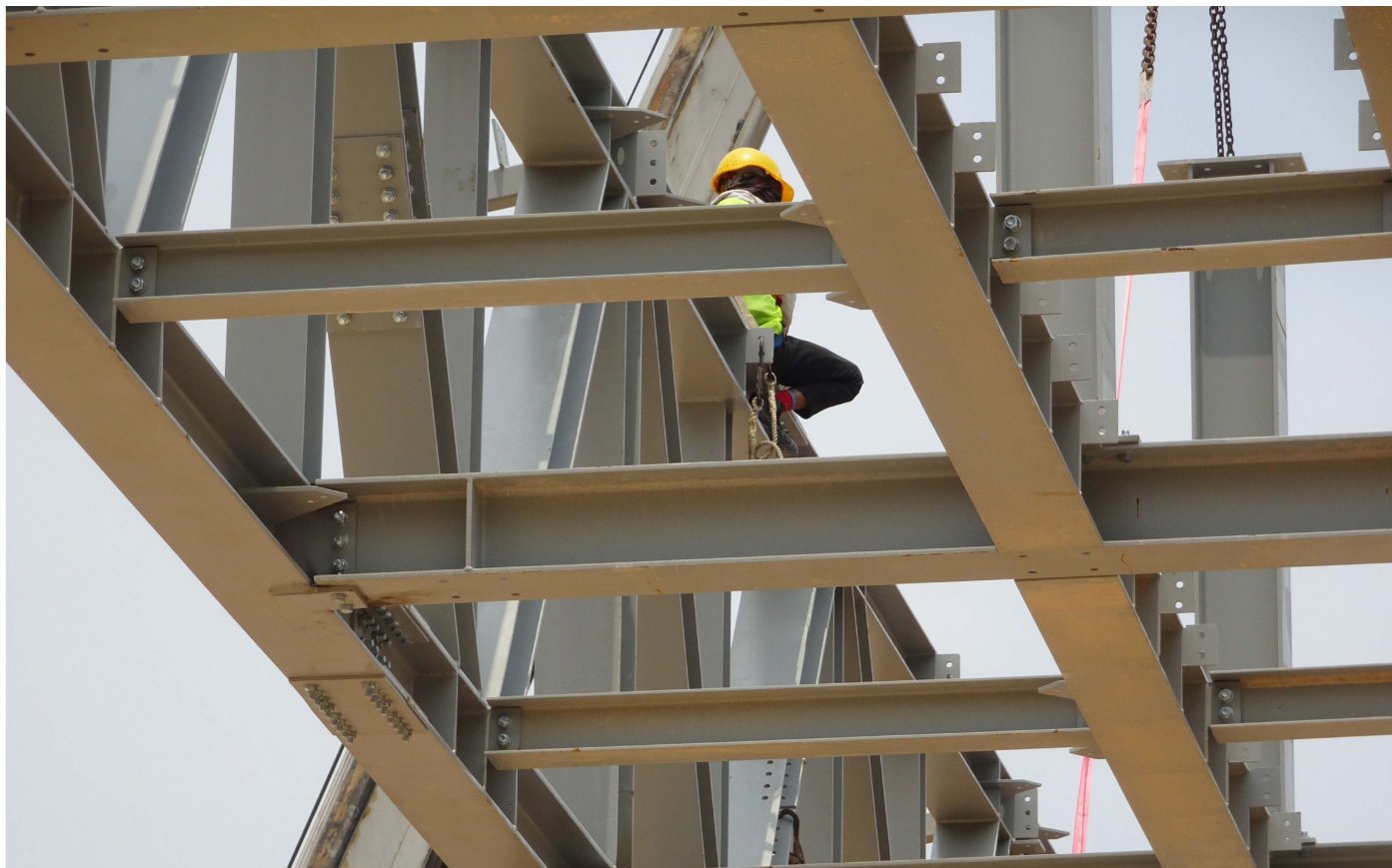
The Butler Building typology of pre-engineered steel buildings started in 1901 and has an industry reputation of being not only an economical way to construct a building but structurally optimized with very short construction times. The end result of this project is a system of mass timber members with steel components that can prove to be a viable alternative to traditional pre-engineered steel frame buildings.

Through the course of the project, several mass timber structural frames were analyzed and evaluated on the key determining factors that make the typology of the Butler Buildings so successful: structural optimization, financial feasibility, and fast construction.

These will be the key points of comparison between the developed mass timber frame systems and similar conventional steel systems. In addition, the comparative impacts on the environment were analyzed for both systems.

Once I developed a single mass timber frame type with several span conditions, the frame was illustrated in several demonstration building to show the flexibility and opportunities for the system. The scope of the project includes analyzing these new systems for their structural efficiency, the types of spaces and volumes that can be created, their financial feasibility and environmental impact compared to steel frame building systems.



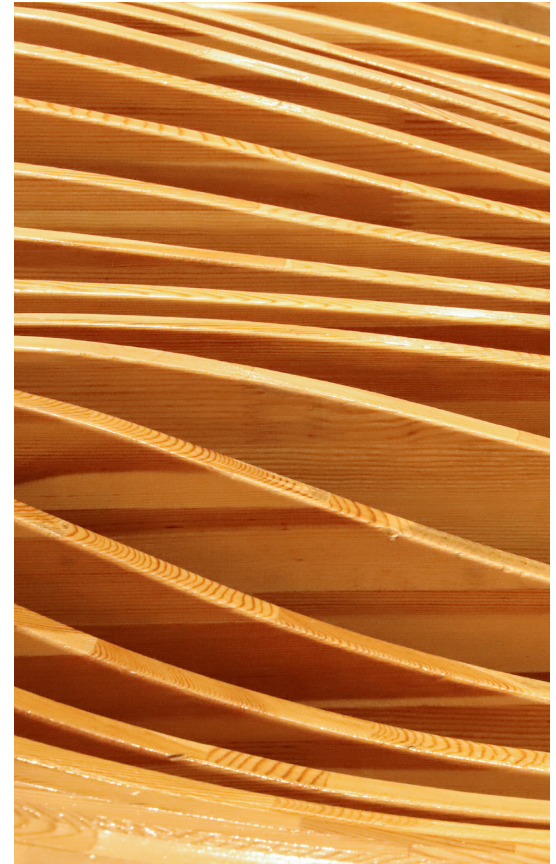




This project is centered around the creation of a mass timber pre-engineered system. Through the course of my time working on this project, the mass timber structural system went through preliminary structural analysis in collaboration with a structural engineering student. I did the analysis for the environmental impact of these systems, and for the space created by a variety of span conditions.

The following research questions have guided the advancement of this system are as follows:

- How can the material advantages of mass timber materials be best utilized to optimize their structural strength, and the long spans that may be created?
- What is the most efficient way to use timber across a variety of span conditions?
- What are the optimal mass timber products for this purpose?
- What are the environmental impacts of constructing a building with mass timber structural frames compared to steel frames?
- How can we create mass timber frame buildings that are economical and can create an alternative to typical steel frame systems?
- How can we maximize the use of mass timber to reduce off-cuts, and maximize the use of the wood fiber?
- How can these systems be translated into a kit of parts that can lead to a mass timber standardized system?







BACKGROUND

BACKGROUND

Today's interest in engineered wood buildings is driven by technological and manufacturing advances and the growing concern for sustainable construction. In many building types, mass timber is considered as an alternative structural system to concrete and steel building systems. Across the United States we see an increase in the use of mass timber in commercial office buildings, hotels, multifamily housing, houses, education buildings and civic buildings.

However, one building sector that has not seen the adoption of mass timber is the industrial realm which is dominated by pre-engineered metal buildings and concrete tilt-up construction. In my professional experience working on industrial projects, timber is rarely considered as a structural system. With the advances in engineered wood, this project aims to re-introduce wood into the industrial sector and show that mass timber can be a viable alternative.

As previously stated, mass timber is a fairly new technology within the United States. Unlike other building structural systems using concrete and steel which have well-known and documented systems and industry standards for design and construction, mass timber is not standardized.

In contrast the Butler Building typology has been highly standardized and optimized, which has led to its success

throughout the years. With an array of span conditions, the pre-engineered building has become the industry standard for inexpensive, efficient, quick, and easy construction of a building that can be flexible and adaptable to a variety of functions (Gawade et al., 2018). The key advantages of a pre-engineered building are the reduced time of construction, cost control, long span capabilities and the flexibility to expand by adding additional bays in the future. Other advantages are heightened quality control and precision as all the members are coming from a single manufacturer, as well as versatility in shape,



configuration, and façade systems. The success of the pre-engineered building comes from these advantages and the optimization of the system over the last hundred years. Due to the success of the pre-engineered typology, these buildings have not just been limited to the industrial typology, but are developed as churches, commercial spaces, recreation facilities, agricultural buildings, wineries, breweries and even houses.

One way that the pre-engineered metal building sector has innovated is by offering a complete kit of parts to construct a building. When working with a manufacturer, one can order cladding, roofing materials and all the fasteners and connections required for construction in addition to the primary structural system. This project offers a similar kit of parts to outfit the mass timber alternatives.

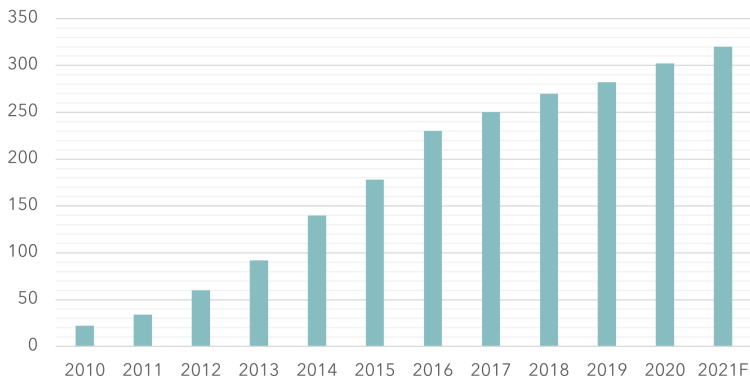


What is the market for pre-engineered metal buildings?

The rise of popularity of pre-engineered metal buildings can be attributed to the increasing demand of a globalized society. Demand is driven by e-commerce and distribution centers that are replacing traditional retail market (Adriot Research, 2021). The rise of the sectors of manufacturing, logistics and supply chain, and e-commerce have only solidified the demand for the construction of warehouses in the coming years.

In the United States, pre-engineered metal buildings currently capture 71 percent of the market share of commercial construction (Admin, 2019). However, there is a trend among developers to become increasingly more interested in using sustainable building materials in industrial settings . (Brown, 2022). Within an industry that currently does not consider wood as a viable building system, the opportunity to introduce a mass timber system that could disrupt even a small share of the market could have major environmental impacts.

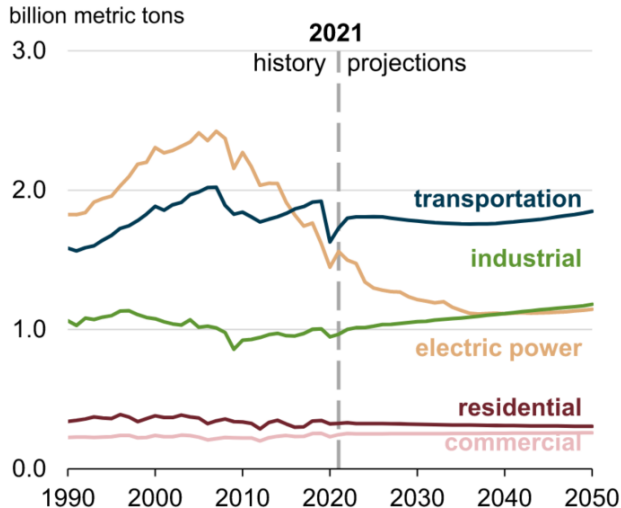
UNITED STATES INDUSTRIAL BUILDING MARKET
(MILLIONS \$)



Source : Prologis Research Report



Energy-related CO₂ emissions by sector AEO2022 Reference case



Environmental Impact

The relationship between the design and construction of buildings and environmental pollution is closely linked. In the UN Emissions Gap report, buildings are responsible for 40 - 50 percent of all greenhouse gas globally and 30 - 40 percent of the world's energy use. Of those emissions, the largest contribution stems from material production of steel, cement, and plaster (Environment, 2019).

According to the US Energy Information Administration (EIA) from a report published in 2022, since 2018 warehouses and storage buildings are the most common commercial building type in the Country (U.S. EIA, 2022). One of the incentives for creating a mass timber frame system is the possibility of designing a system that has environmental benefits, with a significantly smaller carbon footprint than the typical steel models. From the EIA report, industrial buildings have the largest carbon emissions in the construction of the building out of building sectors (U.S. EIA, 2022). While old, a survey done in 1992 complements the EIA report by showing that the structural members make up 74 percent of all emissions of the building (Cole et al., 1992). In a building sector where the structural members make up a majority of building sector carbon emissions, this research seeks to prove viability of a renewable, carbon sequestering material; timber.

If a mass timber system can be developed that is as efficient as a typical pre-engineered steel building, this would be a prime opportunity to revolutionize the industrial building sector and has the potential to reduce the emissions of the growing industrial building sector.

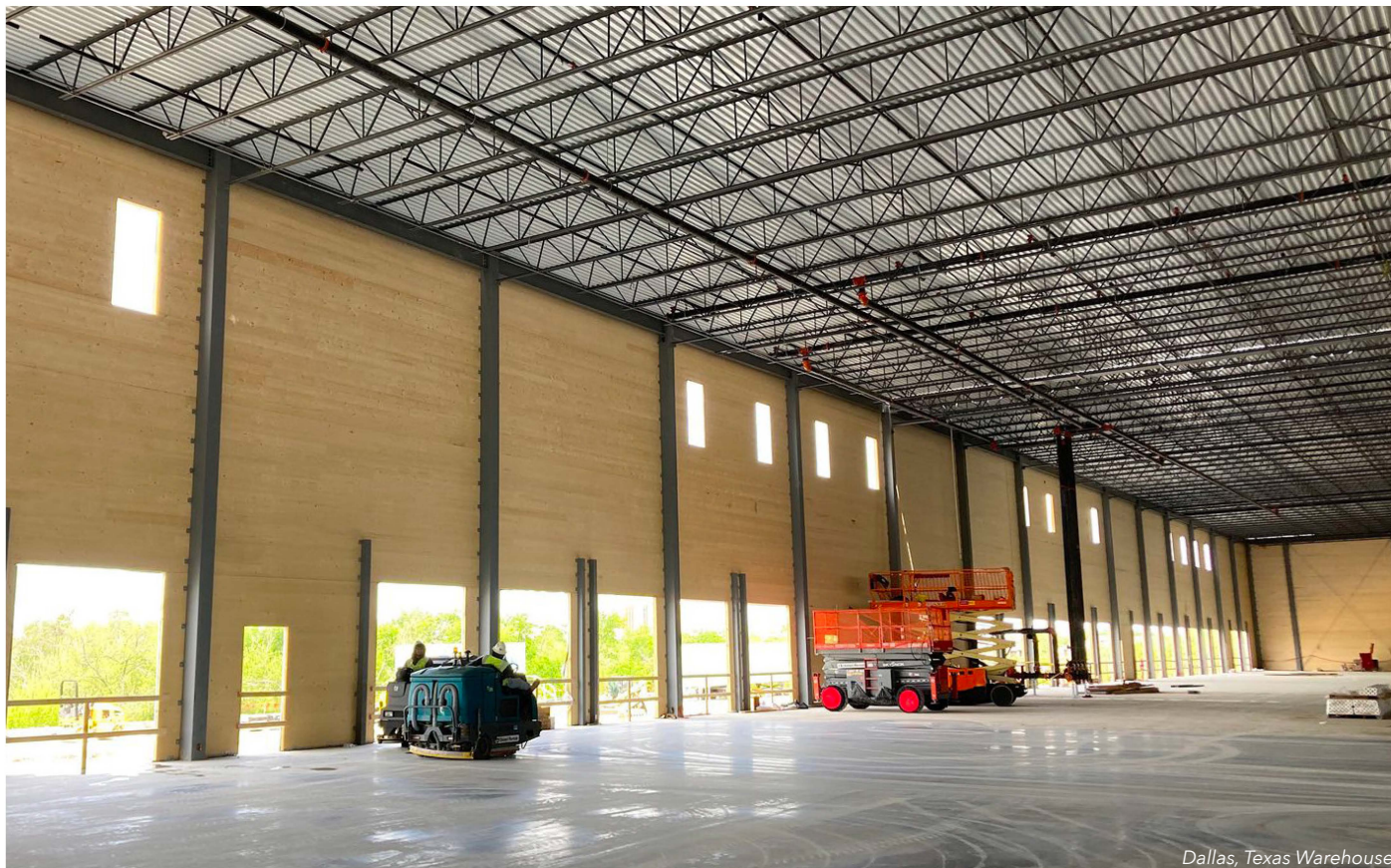
Why not Tilt-up?

There are very few explorations and studies looking at creating mass timber industrial buildings in North America. When I narrowed my scope to creating a mass timber alternative to industrial buildings there were two main types to investigate, a tilt-up construction, and moment frame construction. Initially, I looked into the tilt-up construction to see what the implications of replacing concrete wall panels with mass timber would be.

In my research, I found there to be a few mass timber tilt-up buildings built in Victoria Canada, including a 10,000 sf warehouse built from CLT tilt up panels (Cameron, 2020). Within the United States, there have been a few examples of mass timber tilt up construction: there is a 161,000 sf CLT tilt up panels under construction in Dallas Texas (Brown, 2022) as well as a tilt up warehouse for the library at the University of Arkansas (Binderholz, 2018).

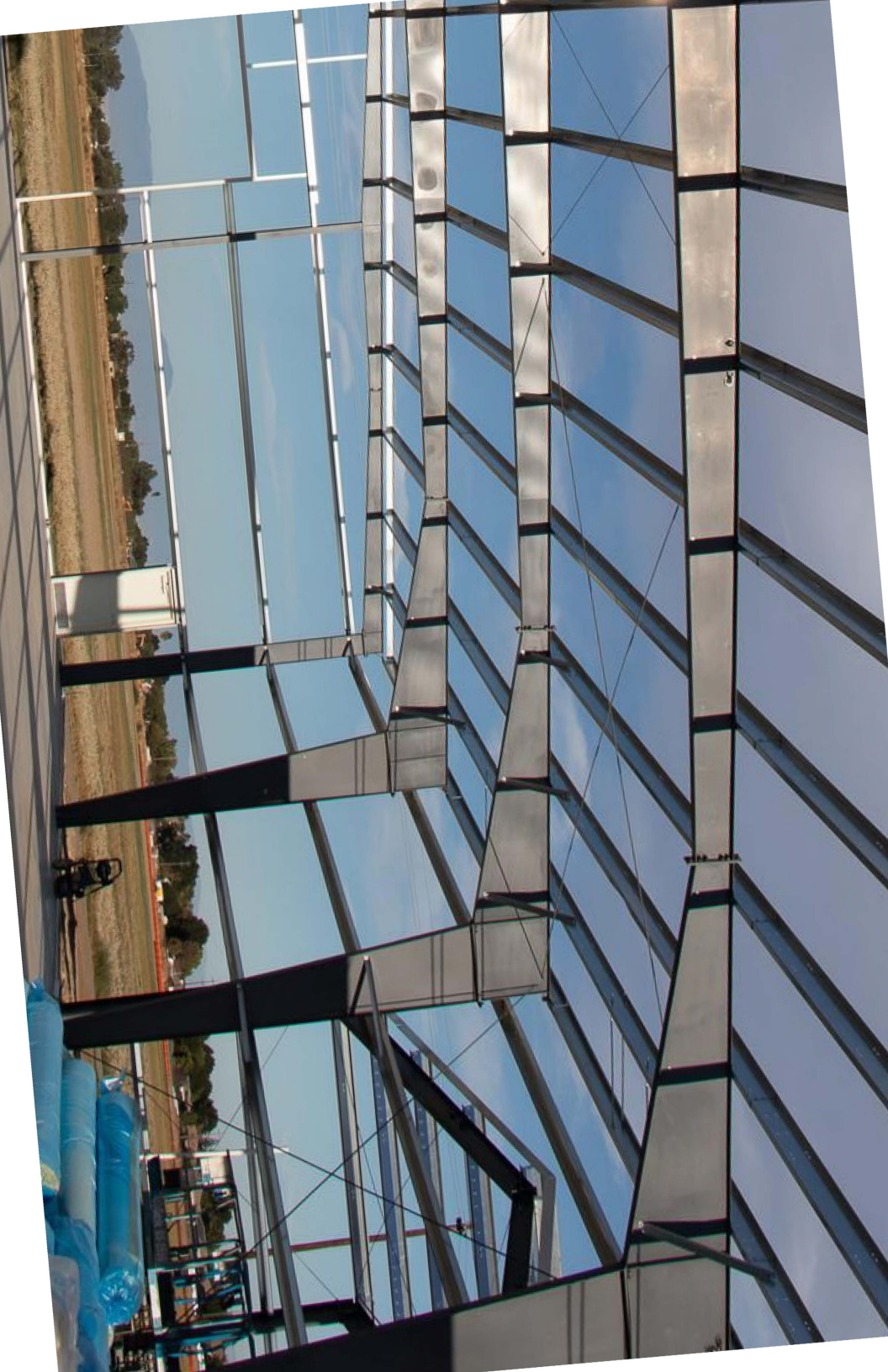
However, I focused the project towards creating a mass timber moment frame instead of tilt up. A project conducted in a TallWood Design Institute certificate program identified that it is challenging for a mass timber panel tilt up system to compete with concrete tilt up construction on cost in the Pacific Northwest (Blake et al., 2021). The extra cost for a mass timber tilt up building system is due to the exterior cladding (insulation, weather barrier and cladding) that is not included in a concrete tilt up building in the Pacific Northwest. Therefore, mass timber tilt up construction was not explored in this scope of the study.





Dallas, Texas Warehouse

BUILDING TYPES
Pre - Engineered Metal Buildings



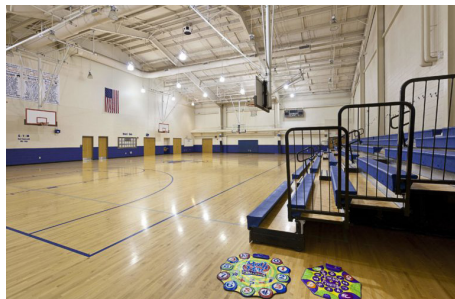
A wide-angle, low-perspective shot looking up at the intricate steel framework of a large industrial building's roof. The structure features a series of parallel steel beams supported by a network of diagonal bracing and vertical columns. The sky is visible through the open framework. In the lower portion of the image, the ground level shows construction materials, including stacks of concrete blocks and various tools, along with the lower walls of the building which are partially constructed with light-colored masonry blocks. Scaffolding is visible on the right side, indicating ongoing construction work.

A large part of the flexibility and adaptability of pre-engineered buildings is the large breadth of span range that the frame types allow for. The smallest span width is 10'-0", ranging up to the largest span of over 300'-0.

Main Frame Type Span Length Table

		0'	20'	40'	60'	80'	100'	120'	140'	160'	180'	200'	220'	240'	260'	280'	300'
L - Canopy span width range : 9'-9" - 19' - 6"																	
Lean - to span width range : 9'-9" - 59' - 0"																	
Butterfly Canopy span width range : 19'-6" - 40' - 0"																	
Space Saver span width range : 19' - 6" - 59' - 0"																	
Single Slope span width range : 19' - 6" - 59' - 0"																	
Rigid Frame span width range : 19' - 6" - 314' - 10"																	
Beam and Column span width range : 78' - 8" - 196' - 8"																	
Beam and Column span width range : 118' - 2" - 236' - 2"																	
Multi - Span span width range : 78' - 8" - 196' - 8"																	

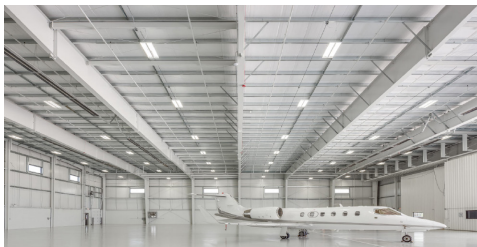
**Versatility of
Pre-Engineered
Building Types**



*Mary Blount Elementary School
Maryville, Tennessee | 108,000 sf*



*Riverwood Covenant Church
Rockford, Minnesota | 12,655 sf*



*Hawthorne Aviation Hangar
Prospect Heights, Illinois | 41,645 sf*



*Moshofsky Center
Eugene, Oregon | 135,000 sf*



*I&E Construction
Woodburn, Oregon | 30,000 sf*



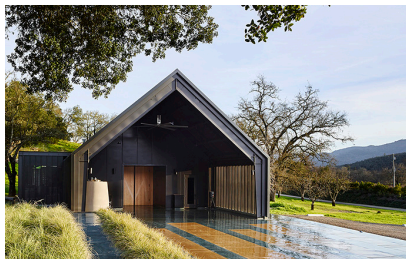
*Vertical Climbing Gym
Columbus, Ohio | 12,000 sf*



*Jackson Family Winery
McMinville, Oregon*



*PGE Fabrication Shop
Estacada, Oregon | 10,500 sf*



*Melka Estates
St Helena, California | 3,400 sf*



*Shake Shack
Denver, Colorado | 12,000 sf*



*B&D Dairy & Livestock Building
Pound, Wisconsin | 11,448 sf*



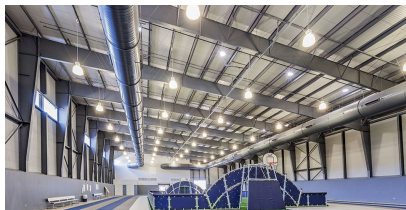
*SHED
Napa Valley, California | 6,390 sf*



*Generations Brewing Company
Freeport, Illinois | 22,000 sf*



*Coast Guard Hangar
Cold Bay, Alaska | 6,390 sf*

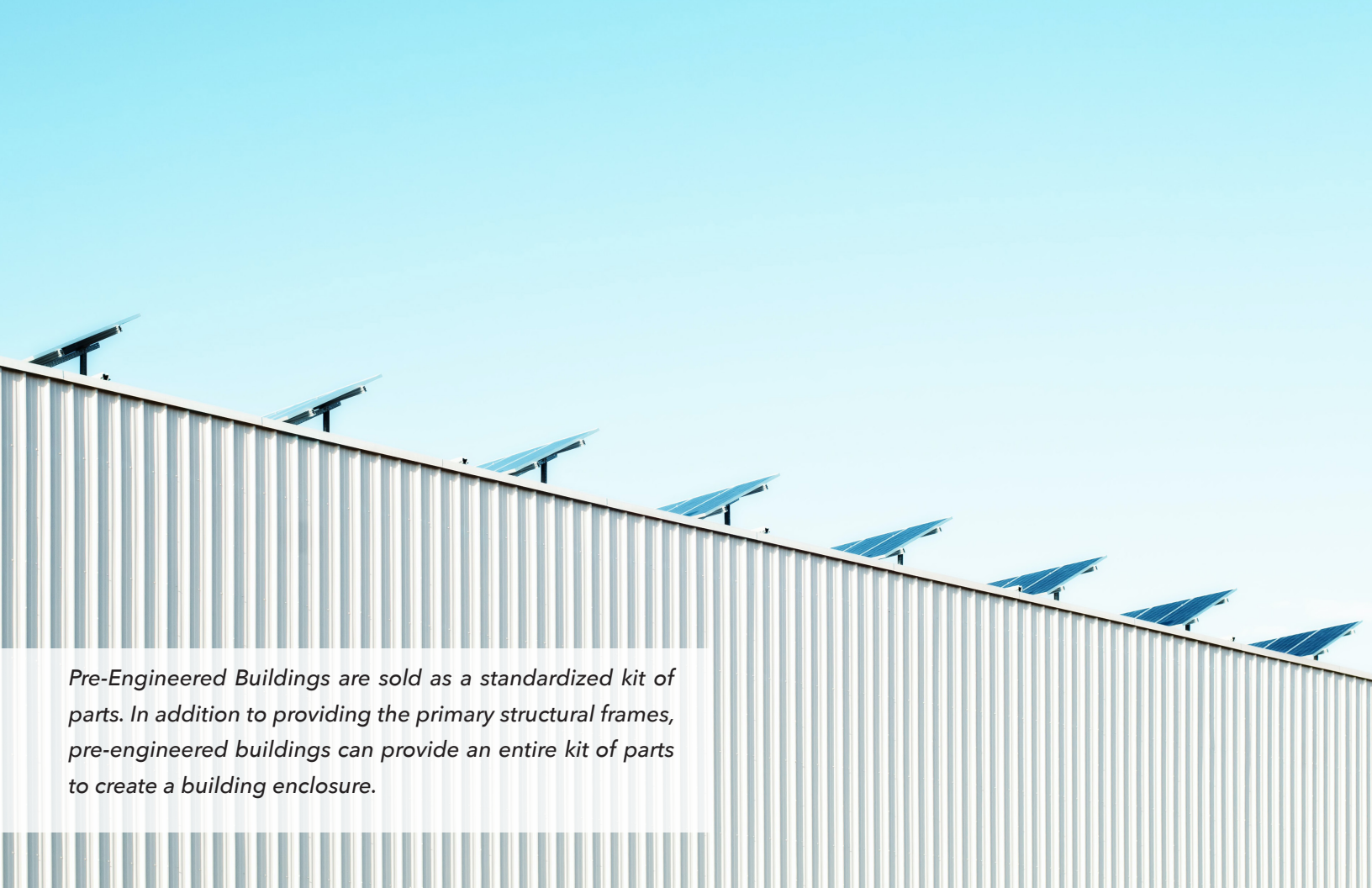


*Adams Sports
El Centro, California | 22,000 sf*



*Alexander Valley Winery
Napa Valley, California | 12,655 sf*

Across the country there are thousands of examples of pre-engineered buildings that take on a variety of building types and uses.

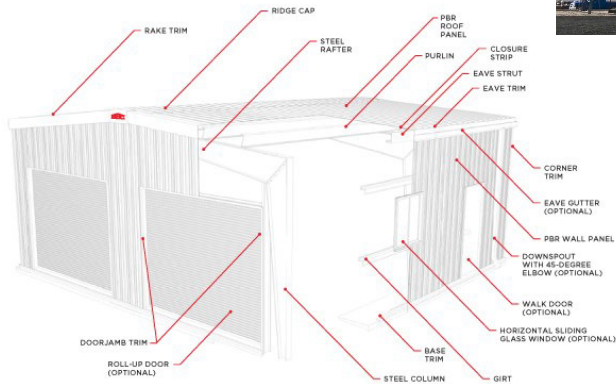


Pre-Engineered Buildings are sold as a standardized kit of parts. In addition to providing the primary structural frames, pre-engineered buildings can provide an entire kit of parts to create a building enclosure.

Kit of Parts Typology

The kit of parts that pre-engineered Butler Manufacturing offers in addition to the structural system are :

- Secondary Framing
- Wall Cladding
- Roofing System
- Door & Window Trim
- Corner, Base and Eave Trim
- Skylights





In starting to investigate which pre-engineered frames to create mass timber alternatives, three existing pre-engineered frame types from my case study research were selected as the most flexible and commonly found. The three frame types that were chosen are the column and beam consistent size and straight, tapered column and beam, and the tapered column and beam with a mid span column.

Straight Column, Straight Beam Typology

This frame features as the name suggests, straight columns and straight beam that have consistent shape and size. One of the common reasons for utilizing a straight column is the flexibility it provides for interior build-outs and clear height at the eave.

As the members are often slender where the beam and column connect, there is a larger moment connection compared to a tapered column. Due to the structural connection constraints, the span is limited on these frame systems to 70'-0".

Span tables for variations on frame dimensions have been provided in Appendix 1.

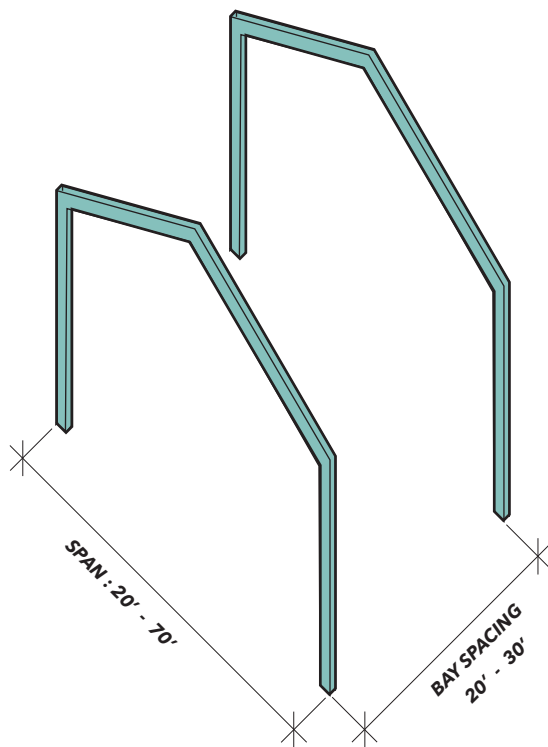
Typical Dimensions

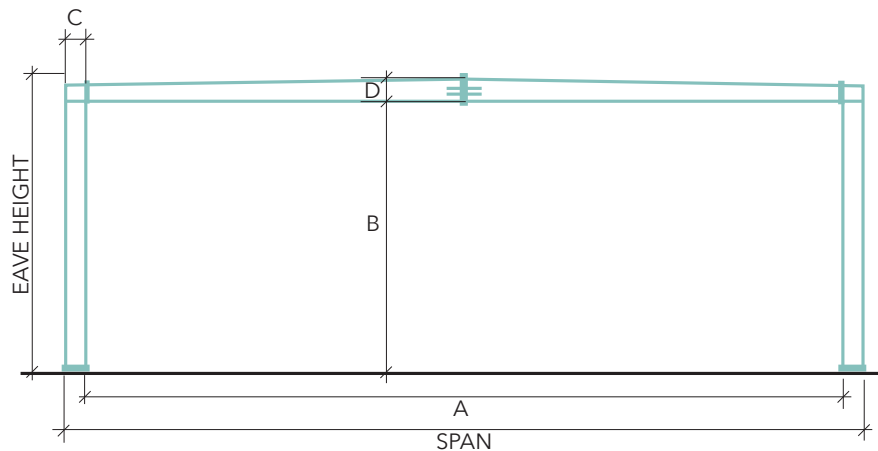
Spans : 20' - 0" to 70' - 0"

Bay Spacing : 20' - 0" to 30' - 0"

Eave Height : 10' - 0" to 20' - 0"

Roof Slope : 1/2 : 12 to 1 : 12





Tapered Column, Tapered Beam Typology

The majority of pre-engineered metal buildings utilize tapered beams and columns. The column is smaller at the base and grows wider as it reaches the connection point with the rafter. This design optimizes the steel where it is needed from a structural engineering design. The structural optimization in the material allows the maximum span up to be 150' - 0".

The tapered column design does harbor some interior flexibility for interior build outs.

Span tables for variations on frame dimensions have been provided in Appendix 1.

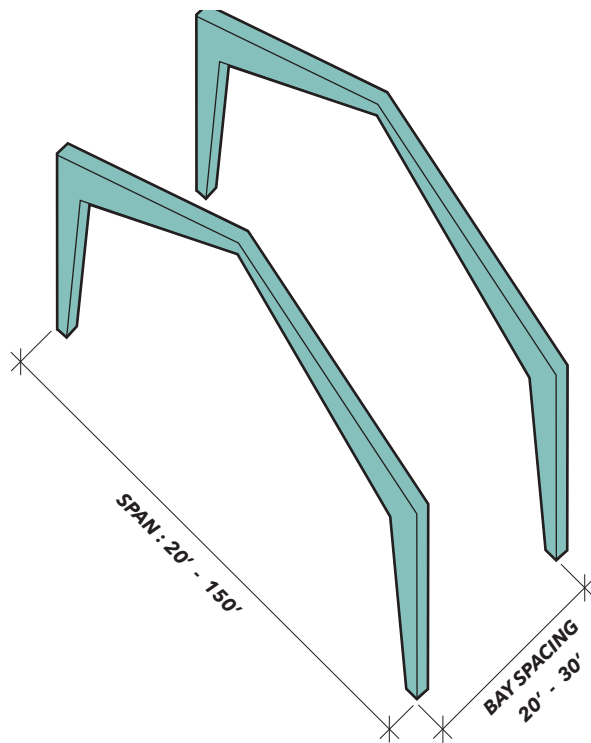
Typical Dimensions

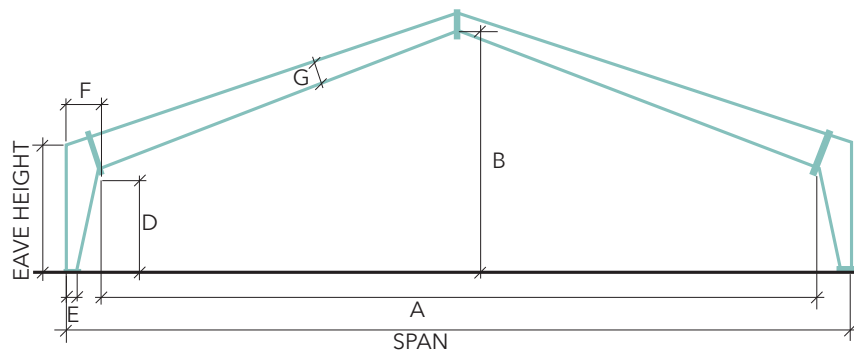
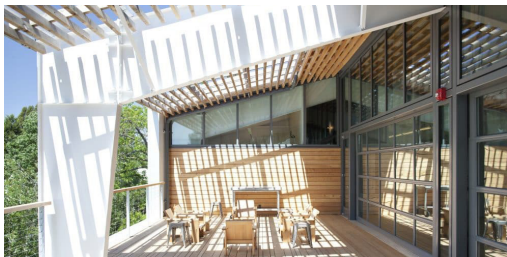
Spans : 20' - 0" to 150' - 0"

Bay Spacing : 20' - 0" to 30' - 0"

Eave Height : 10' - 0" to 40' - 0"

Roof Slope : 1/2 : 12 to 4 : 12



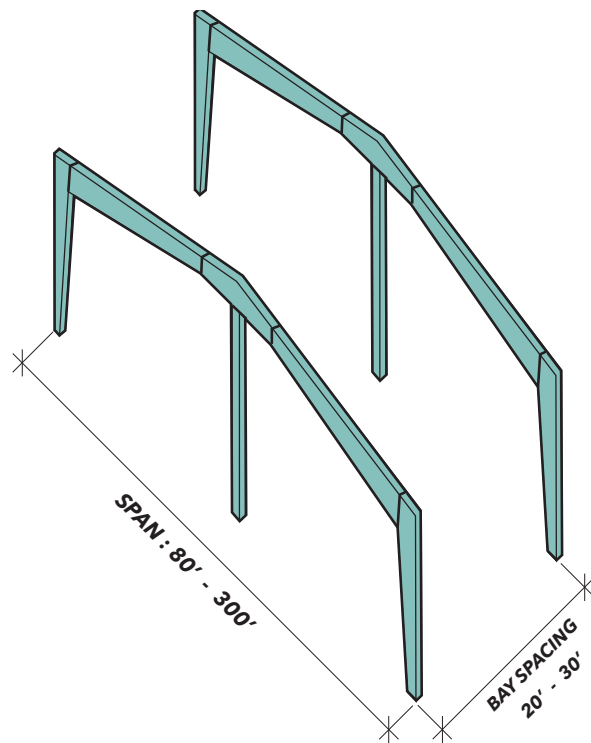


Tapered Column and Beam, Mid Span Column

For longer spans, a mid span column can be added to lengthen the maximum span up to 300'-0". These frame types can have tapered columns and beams, or utilize straight column and beams depending on the frame.

The interior column additionally allows for the easy inclusion for a crane system to be installed.

Span tables for variations on frame dimensions have been provided in Appendix 1.



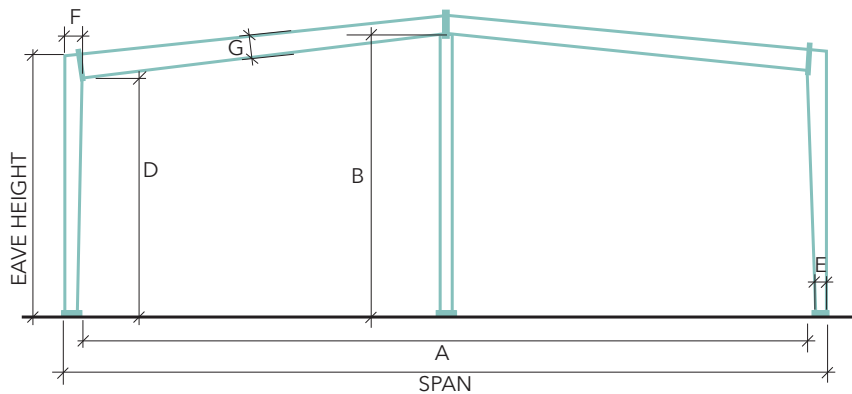
Typical Dimensions

Spans : 80' - 0" to 300' - 0"

Bay Spacing : 20' - 0" to 30' - 0"

Eave Height : 10' - 0" to 40' - 0"

Roof Slope : 1/2 : 12 to 4 : 12

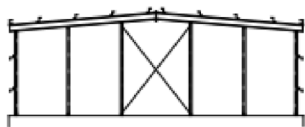


End Wall Bracing Options



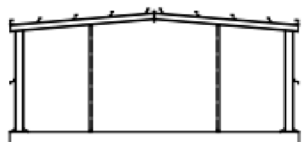
Diaphragm Action

The diaphragm frame featured a standard bearing frame with steel vertical girts. The lateral wind and seismic forces are transferred to the foundation through the diaphragm resistance of the end wall.



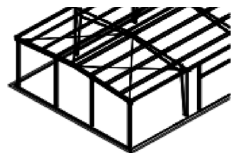
Cable / Rod 'X' Bracing

utilized when diaphragm is inadequate
provide cable or rod bracing between the end wall columns



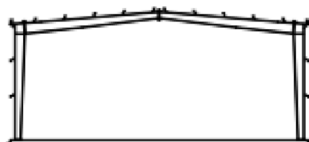
Fixed Base / Wind Column

The base of the columns are fixed, which induced a moment frame at the foundation requiring specialized foundation design.
These columns are to be located at the center of the building and each corner.



Brace to Interior Main Frame

In order to create an open bearing frame end wall, bracing is added in the roof to the next interior main frame. The lateral forces are transferred to first interior main frame which is designed to resist the additional lateral force.



Main End Frame

An additional main end frame may be provided in lieu of a bearing frame.



The image shows the interior of a large wooden building. The ceiling is a complex wooden truss system with many diagonal and horizontal beams. A single rectangular fluorescent light fixture is mounted on the ceiling, casting a bright glow. In the lower left, a dark metal beam with orange safety railings runs diagonally across the frame. The walls are also made of wood, and a black pipe runs along the wall on the right side.

BUILDING TYPES

Long Span Wood Buildings

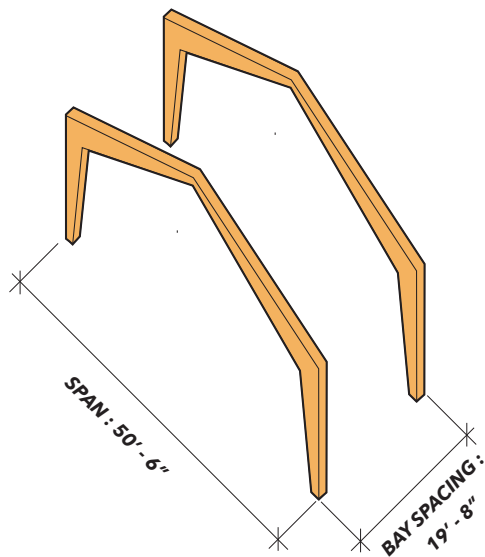




*Meyer Timber Warehouse
under construction*

In investigating existing mass timber case studies, most of the case studies were located in Europe or New Zealand where mass timber innovation has been occurring for much longer than in North America. These case studies feature a range of mass timber materials, frame shape and span width. The following case studies have been organized by frame shape.

**Koski Manor
Agricultural Building**



Location : Salo, Finland
Size : 15,930 square feet
Architect : RA Marko Lappalainen
Completed: 2020
Timber Used : LVL



The farm's new cowshed is constructed from LVL timber construction. Preferences from the owner lead the design team to a timber frame, from sustainability and the availability of LVL's in Finland.

The load bearing structure is LVL.

The column is LVL made from cross laminated veneers, while the beam is a LVL that is made from singular directional veneers. Connection between the two members is a simple circle of dowels.

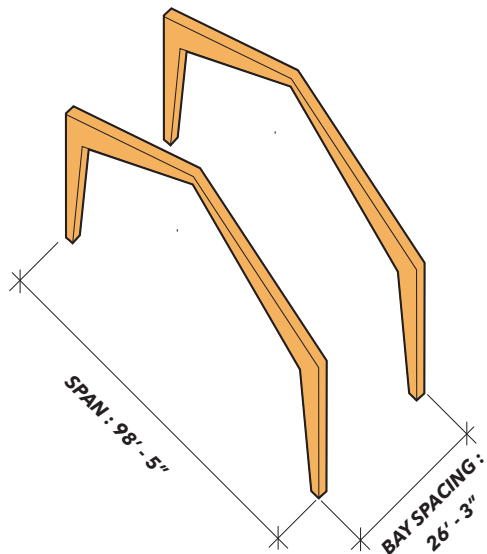


Above : Connection of the LVL beam and column come together with a single circular ring of dowels which provide a moment connection.



Above : Roof line extend out beyond edge of LVL frame to allow for large overhang.

Alpine MDF



Location : Wangaratta, Victoria Canada

Size : 25,833 square feet

Architect : Nelson Pine Industries

Completed: 2009

Timber Used : LVL



The new warehouse for Alpine MDF serves as a space for their MDF moulding and paint. Alpine looked to their sister company Nelson Pine in New Zealand as they had just constructed two larger LVL warehouses. Nelson Pine aided in altering the previous designs for Alpine.

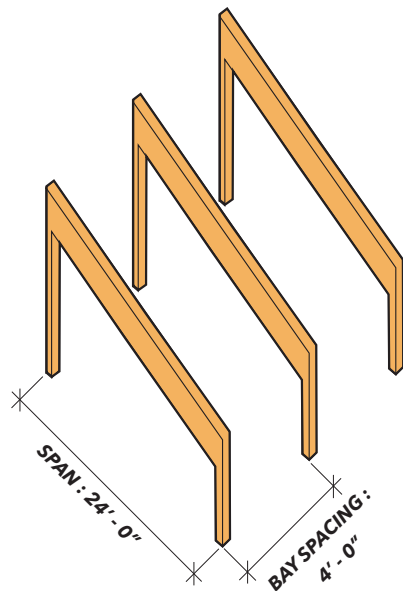
The secondary framing was installed flush with the top of the LVL beams, allowing the roof cladding to be fastened directly to the beams. This was important in for the building to be bird-proof, eliminating a place for to nesting.



Above : Frames were built on the concrete slab and hoisted into place with a crane. This was achieved through an innovative double beam system that

lapped the outside of the central column and used the column as the pivot leg. The joint was a simpler joint using just nails.

Workshop in a Forest



Location : Hinora Village, Tokyo Japan

Size : 6,663 square feet

Architect : Atelier Haretoke

Completed: 2011

Timber Used : Glulams



Workshop in a Forest is a factory constructed completely of wood utilizing glulam frames set in a forest on the outskirts of Tokyo.

Glulam frames are stiffened by a plywood gusset plate on both sides of the glulam to reinforce the column to

beam connection.

The architect's intention was to "build with the wood there," the timber was locally sourced for the structural frames, and the cladding.

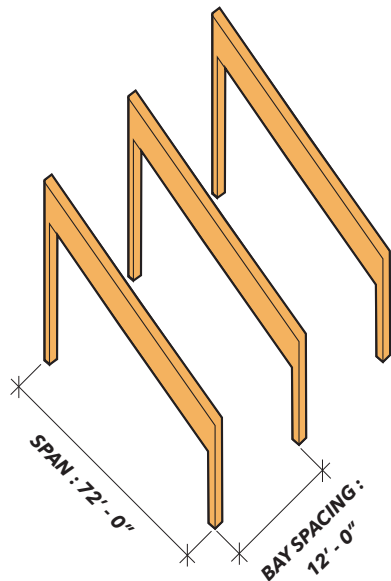


Above : As the walls are not bearing, clerestory windows wrap around the entire facade like ribbon.



Above : Glulam frames were constructed on the ground by hand, and then raised by crane into place.

Santiam Canyon High School Gym



Location : Mill City, Oregon

Size : 7,800 square feet

Architect : Soderstrom Architects

Completed: 2020

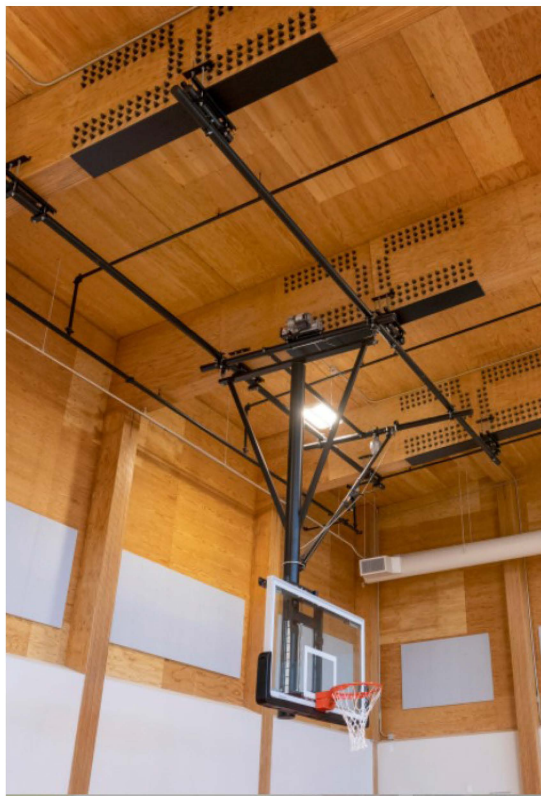
Timber Used : Mass Plywood Panel
(MPP)



The Santiam Canyon High School Gym features MPP for not only the structural frame system in the beams and columns, but also the walls and roof.

The building frame was pre-fabricated which lead to zero waste on site. The building only took 15 days to

construct, a quick construction time. Utilizing mass plywood was a decision by the designers to support the local engineered timber economy as the site and the manufacturing factory, the Freres MPP facility, are a few miles apart.



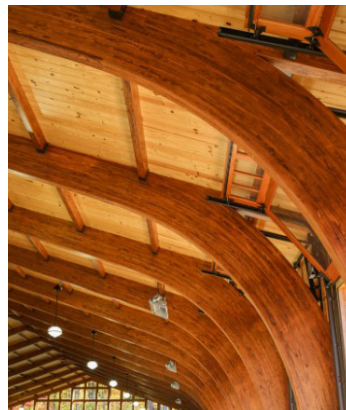
Above : Two large splice joints create a beam that spans the gym's 72'-0" multipurpose courts. The maximum length of mass plywood panel is 48'-0"; there a full 48'-0" panel was placed in the middle and two splice joints are added to the end.

Hartzband Barn Case Study



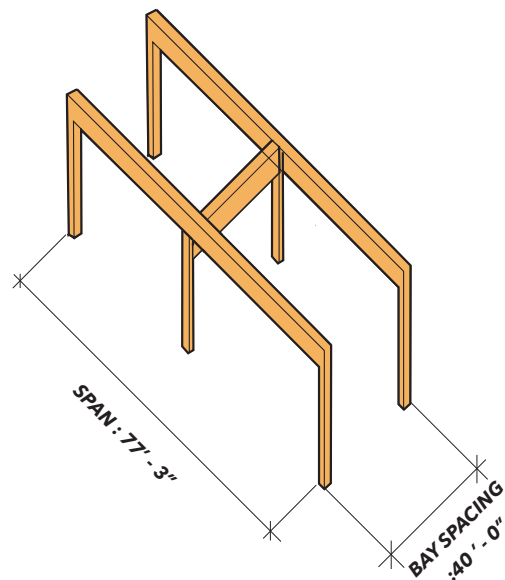
Above : Due to the frame construction, the walls are able to be operable windows.

Location : Rockleigh, New Jersey
Size : 30,000 square feet
Architect : Mark Meyers
Timber Used : Glulams



Above : Two Glulam bents are joined at the peak of the roof to provide a large clear span space for a horse barn.

Chantiers Chibougamu Manufacturing Plant



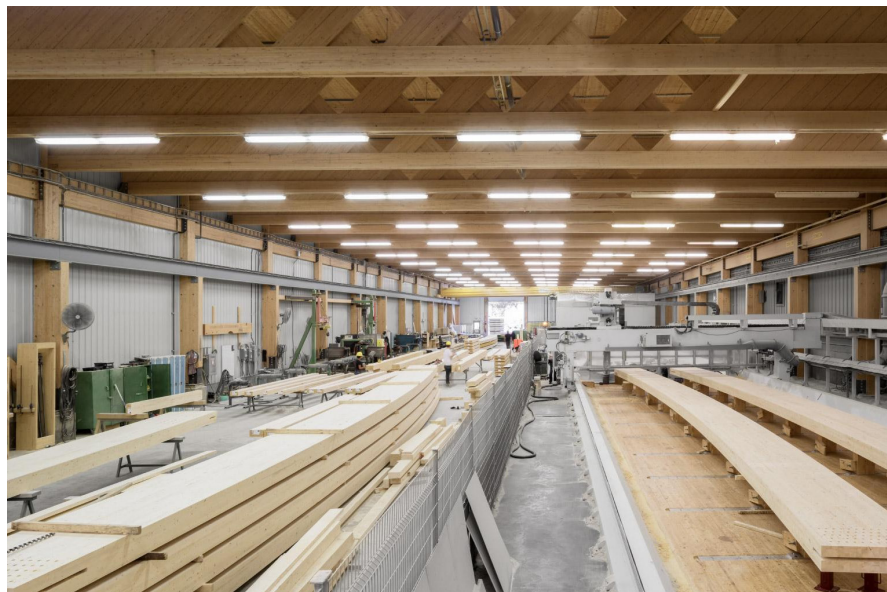
Location : Chibougamu, Quebec, Canada

Size : 31,538 square feet

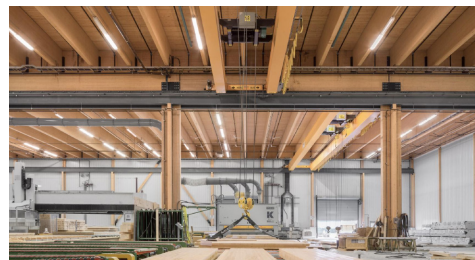
Architect : Nordic Structures

Completed: 2010

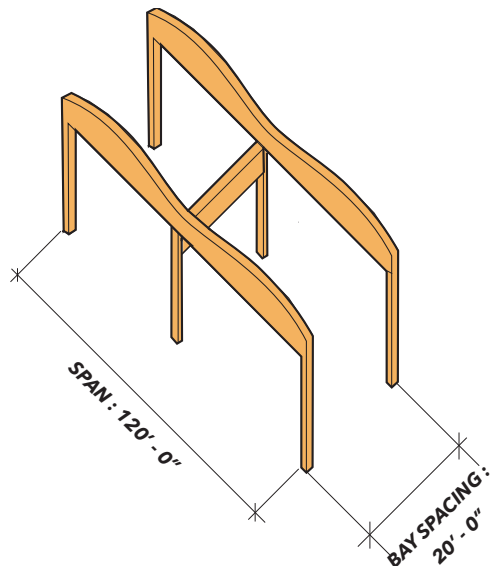
Timber Used : LVL



Nordic Structures built an LVL extension to their manufacturing plant in 2010. The LVL beams feature interlocking woven webbing in the long span space that allows for the continuous flow of machinery and an open space.



StructureCraft Manufacturing Plant



Location : Abbotsford, BC, Canada

Size : 50,000 square feet

Architect : Keystone

Completed: 2017

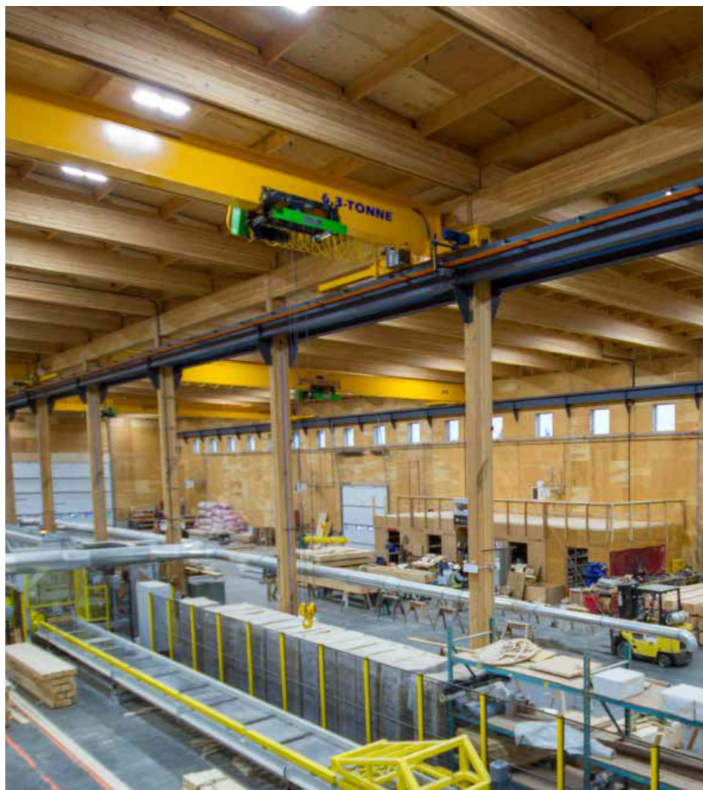
Timber Used : CLT, Glulam, NLT, DLT, LSL



In the construction and design, the key goal was the efficient use of material and speed of construction.

All of the CLT wall panels and the roof panels were prefabricated prior to construction. The entire structure was constructed in five days.

The structure consists of CLT tilt wall panels, glulam 'belly' beams that are deeper (for structural efficiency) at the center of the span that allows naturally creates slope to drain.

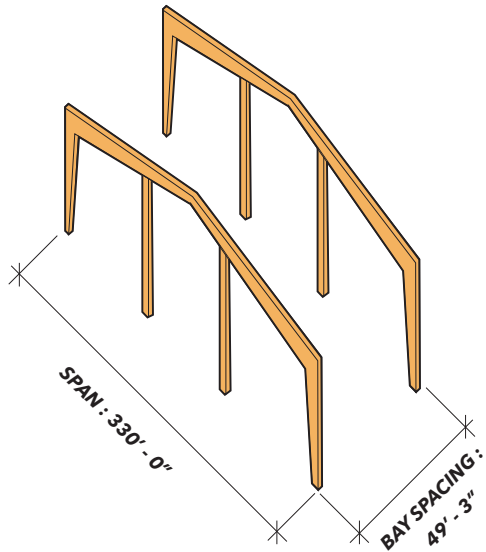


Above : The entire structure was designed to be both constructed quickly, as well as de-constructed and reassembled.



Above : Sections of the roof were constructed on the ground and craned into place to speed up the construction process.

Meyer Timber Warehouse



Location : New South Wales, Australia

Size : 215,278 square feet

Architect : Nicholas Alexander

Completed: 2011

Timber Used : LVL



The Meyer Timber Warehouse and Distribution Center was built for the Australian timber manufacturer, Meyer. The building was built for the timber company to prove the use of engineered wood in a large industrial projects as an economically viable alternative to a traditional steel building.

The building is over 200,000 square feet, the primary structure is a box beam portal frame construction. The middle portal section of box beam spans 104'-10". Large box beams are 3'-10" deep and are radiata pine LVL.



Above : End Wall Bracing is dealt with through precast concrete panels laid out horizontally.



Above : Middle Box Beam that spans 104'-10" getting craned into place made up of 3'-10" box beam and purlins.





**PROCESS &
COLLABORATION**



The image shows the interior of a large building under construction, featuring a mass plywood moment frame. The walls and ceiling are composed of large, light-colored plywood panels arranged in a grid pattern, held together by a network of horizontal and vertical wooden beams. The floor is a smooth, reflective concrete surface. A green scissor lift is positioned in the center of the room. To the right, a large opening reveals an outdoor area with a gravel lot, some greenery, and a grey industrial building with a window in the background. The lighting is bright, coming from the large opening on the right.

*Mass Ply Moment Frame at
Freres Engineered Wood*



CalPolyPomona

College of
Engineering

With the structural focus of this project, it was crucial to partner and collaborate with an engineer. One of my project advisors, Mikhail Gershfeld, SE is a Professional Practice Professor in Civil Engineering in the College of Engineering at Cal Poly Pomona. As I was developing the scope of my project, Professor Gershfeld identified a Masters of Science in Civil Engineering student, Patrick Meserkhani whose thesis project is developing mass timber portal frames. As his thesis project aligned with my terminal project, the intention was for the both of us to collaborate on this project.

Patrick and I met up through Zoom multiple times throughout the scope of the project to share our work and collaborate on structural optimization while Patrick ran the conceptual structural analysis of the frames that I designed.

A close-up, low-angle shot of several thick wooden planks stacked on top of each other. The wood has a warm, golden-brown hue and a visible grain. The lighting is soft and directional, coming from the upper right, which creates a strong sense of depth and texture. The planks are slightly curved, and the edges are sharp. The background is blurred, emphasizing the foreground planks.

DESIGN CRITERIA



DESIGN CRITERIA :

Aesthetics

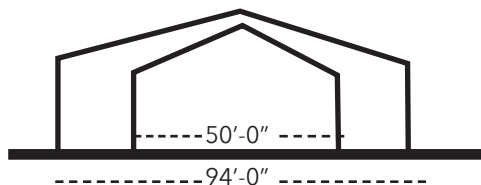
The first thought in the design criteria of these frames was the aesthetics. In such a seemingly simple design exercise, the beauty of these frames comes from the careful design and expression of connections as well as highlighting the beauty of the wood material as it accentuates the elegant appearance of the frames.

Optimal Space Criteria

In determining the initial design criteria, I broke down the frame into two sections, the spans and the clear heights.

SPANS :

Even though pre-engineered metal buildings can range from as low as 10'-0" in span width up to over 300'-0" in span width, the most common span width in built projects is 50'-0". Therefore, the building span that I first explored was 50'-0" in width. Once the conceptual structural analysis was done on the 50'-0", I explored pushing the mass timber panel to its maximum length in exploring a 94'-0" span.



CLEAR HEIGHTS :

Additionally, pre-engineered metal buildings typically have an eave height of 10'-0" up to 24'-0" based on the building end use that is required, or equipment and clear height requirements. In my initial frame explorations a variety of clear heights were explored ranging from 14'-0" up to 33'-0". The two clear heights that I further explored in my frame refinement stage were based on common eave heights in pre-engineered buildings.



Efficiency

One of the success of the pre-engineered metal building typology is the efficiency of the system. Including the structural efficiency which leads to an efficient use of the steel, an efficiency in manufacturing and the fast construction. These were all qualities that I knew would need to be emulated in a mass timber alternative system for it to be viable.

EFFICIENCY OF FABRICATION

Unlike the steel that is used in the pre-engineered typology, the frames explored here are a panelized product, therefore the efficiency of material does not just stop at structural optimization, but also includes minimizing wasteful off cuts. I tried to achieve this by incorporating the design of fabrication panel layouts while developing the design of the frames. I used a wood utilization ratio of the total wood fiber versus the total wood fiber in the structural system as a criteria on evaluating frame types.

EFFICIENCY OF CONSTRUCTION

While thinking of efficiency of construction there are two things that were part of my design criteria; minimizing construction waste and thinking about how these frames would be constructed on the job site and trying to optimize the construction sequence.

EFFICIENCY OF MATERIAL

The basis for material optimization is rooted in understanding the material in which it being optimized. In this case, one of the first things that was analyzed was the opportunities of different mass timber materials such as glulams, mass plywood panel (MPP) and laminated veneer lumber (LVL). Material efficiency boils down to using the correct material in the correct application.

Location

When developing the goals and criteria for this terminal project, the flexibility and adaptability of the frame system under different load and seismic conditions was a key goal. The initial location that was selected for code required load conditions is Terminal 2 at the Port of Portland located in Northwest Portland, Oregon.

This site was selected due to the potential use of a mass timber frame system building located on the site as a part of the proposal from the Oregon Mass Timber Coalition's Economic Development Administration Build Back Better phase 2 grant.

The original scope and design criteria of this project included structurally analyzing the frames developed under different load and seismic conditions in different locations, however with time constraints, the frames were just analyzed for the loads at Terminal 2. Although not realized within this project scope, these frames should be adaptable and flexibility to be placed in different locations around the country. An area of future research would be to include design load calculations at different locations to include a location with high snow load such as Colorado, a location with a high wind load such as Florida, and a location with higher seismic loads such as Southern California.



Port of Portland - Terminal 2
3556 NW Front Ave, Portland,
Oregon 97209



Material

As material efficiency is a key design criteria, knowledge of different engineered timber products and their strengths and weakness is crucial to optimizing the frame materials.

Glulams

Glue Laminated Timber is laid up boards glued together into very deep beam or column members. Due to the one direction lumber, the product is often used for columns (used vertically in the strong-axis) and beams (laid flat in the weak axis).



Laminated Veneer Lumber (LVL)

Laminated Veneer Lumber uses thin layers of veneer that are glued together to make large format panels. Generally, LVLs are all oriented in the same direction. LVL can be incredibly strong in the longitudinal direction parallel to wood fibers.



Mass Plywood Panel

Like Laminated Veneer Lumber, Mass Ply products are a veneer-based product. Mass Plywood panels are fabricated by Freres Engineered Wood in Mill City, Oregon. They are the only manufacturers of mass plywood. Each mass plywood panel is made up of 1" lamellas, the thinnest panels can be 2" thick, and up to 12" thick. Each lamella is made up of 9 layers of 1/8" veneers. There are two different layups, F16 grade where two of the nine plys are perpendicular to the other plys. F10 grade where alternating plys are orthogonal to the adjacent layer. F10 grades are better for bi-directional span requirements (Mass Plywood Design Guide). Because of this flexibility in size, structural layup and panelized nature, I will be exploring the frames primarily in Mass Plywood Panels.

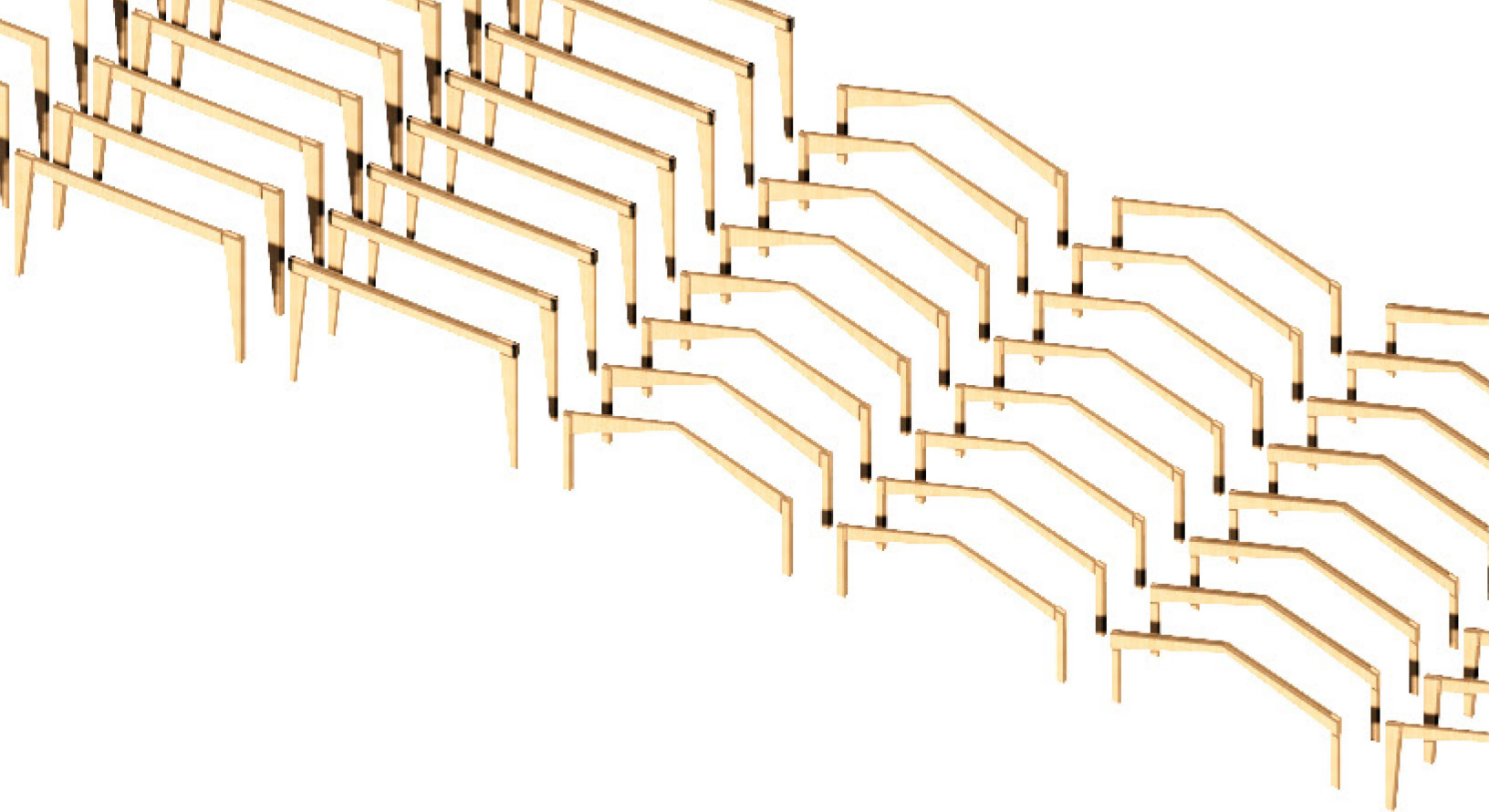
Freres Engineered Wood has recently expanded into Mass Ply Lam, which is designed for beam and column applications and differs from the Mass Ply Panel construction as there are no edge joints present. With this new expansion, Freres can provide all structural elements (floors, roofs, walls and newly beams and columns) to a mass timber project.

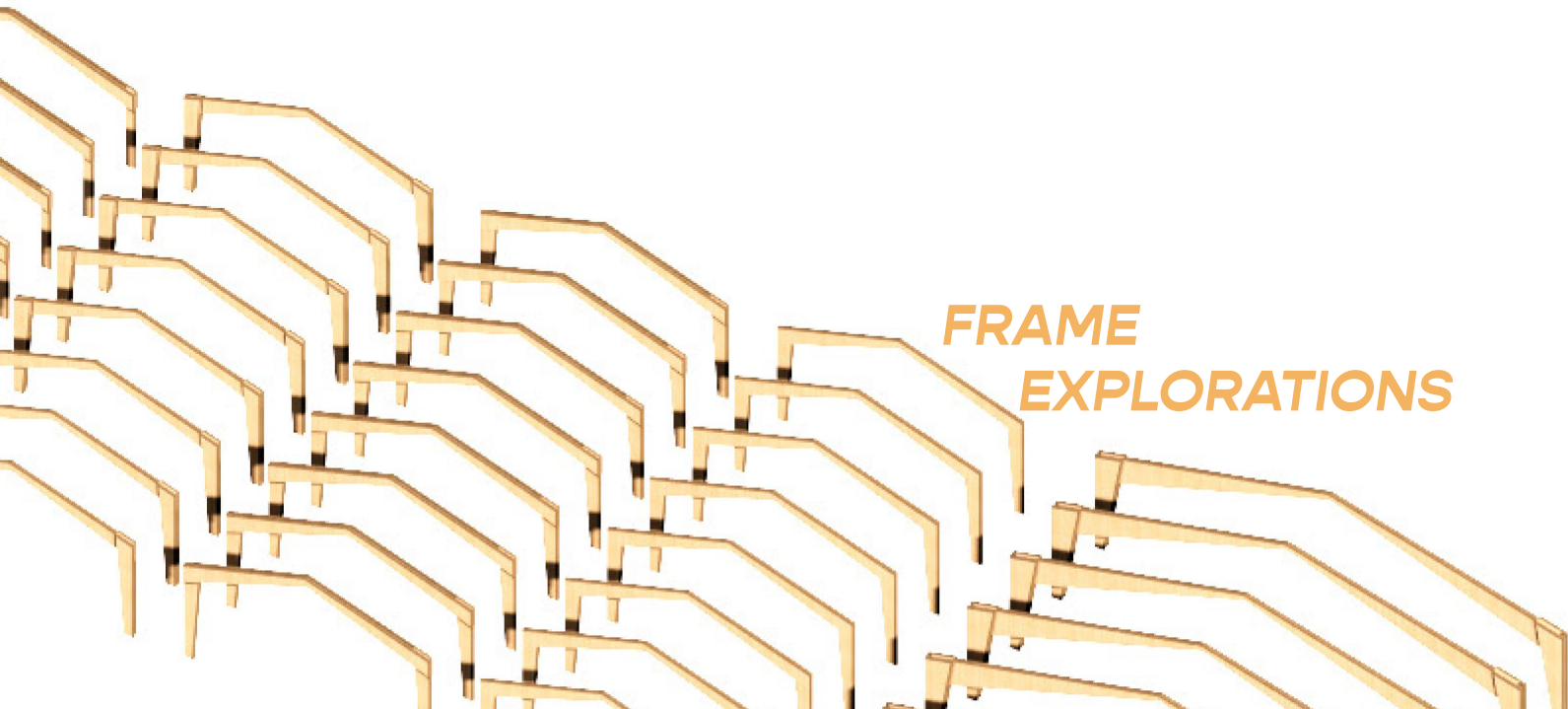
To guide my design of the frames, beam and column span tables provided by Freres in their Mass Ply design guide which are in Appendix 2, was used for the calculation throughout the project for evaluating the frames.





PART II :
ARCHITECTURAL AND
STRUCTURAL DESIGN

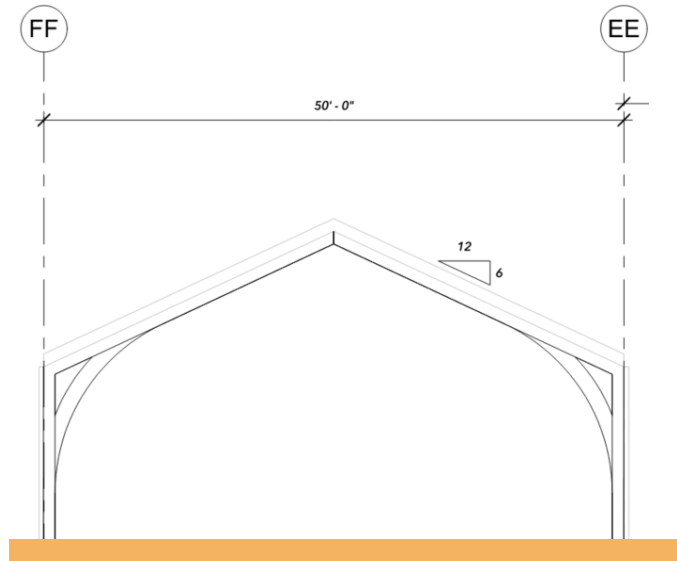




FRAME EXPLORATIONS

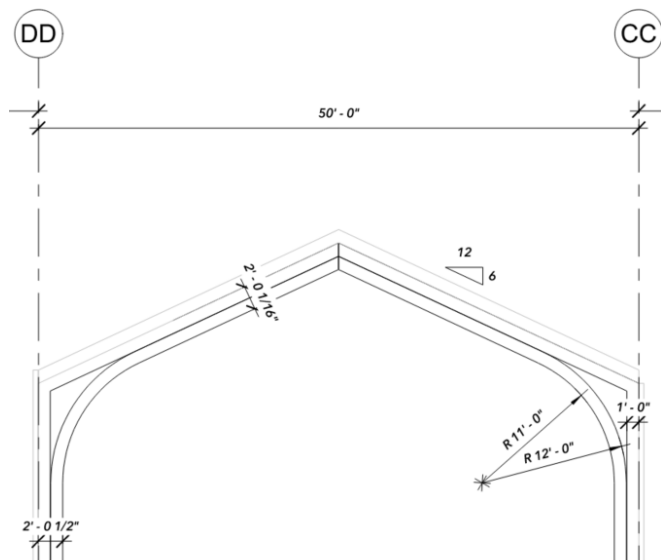
At the beginning of the frame explorations, I was initially investigated multiple frame types. These initial frame explorations included glulam bents, and sandwiched bents. These bent frames were not taken past this point due to the custom manufacturing nature of the curved glulams.

After ruling out glulams as a material, the rest of the structural frames were developed utilizing mass plywood panels. Although many case studies I looked at used LVL, mass plywood was chosen as it is a local material to Oregon as well as the recent beam and column manufacturing capabilities of Freres Engineered Wood.



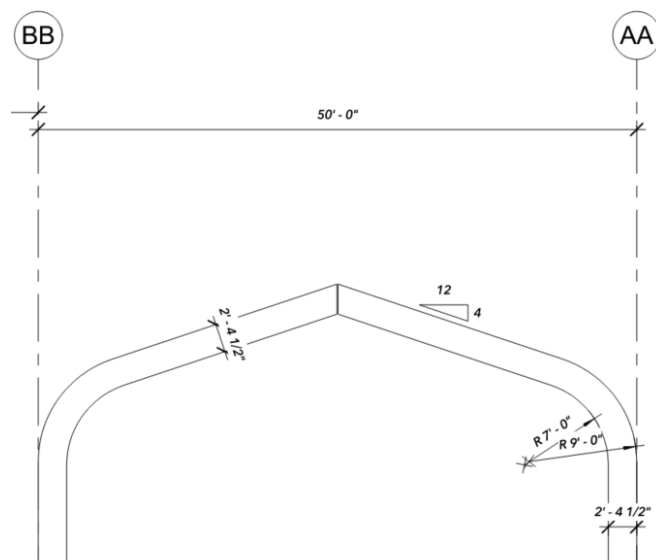
SANDWICHED DOUBLE GLULAM BENT

106 CF of wood fiber per frame



DOUBLE GLULAM BENT

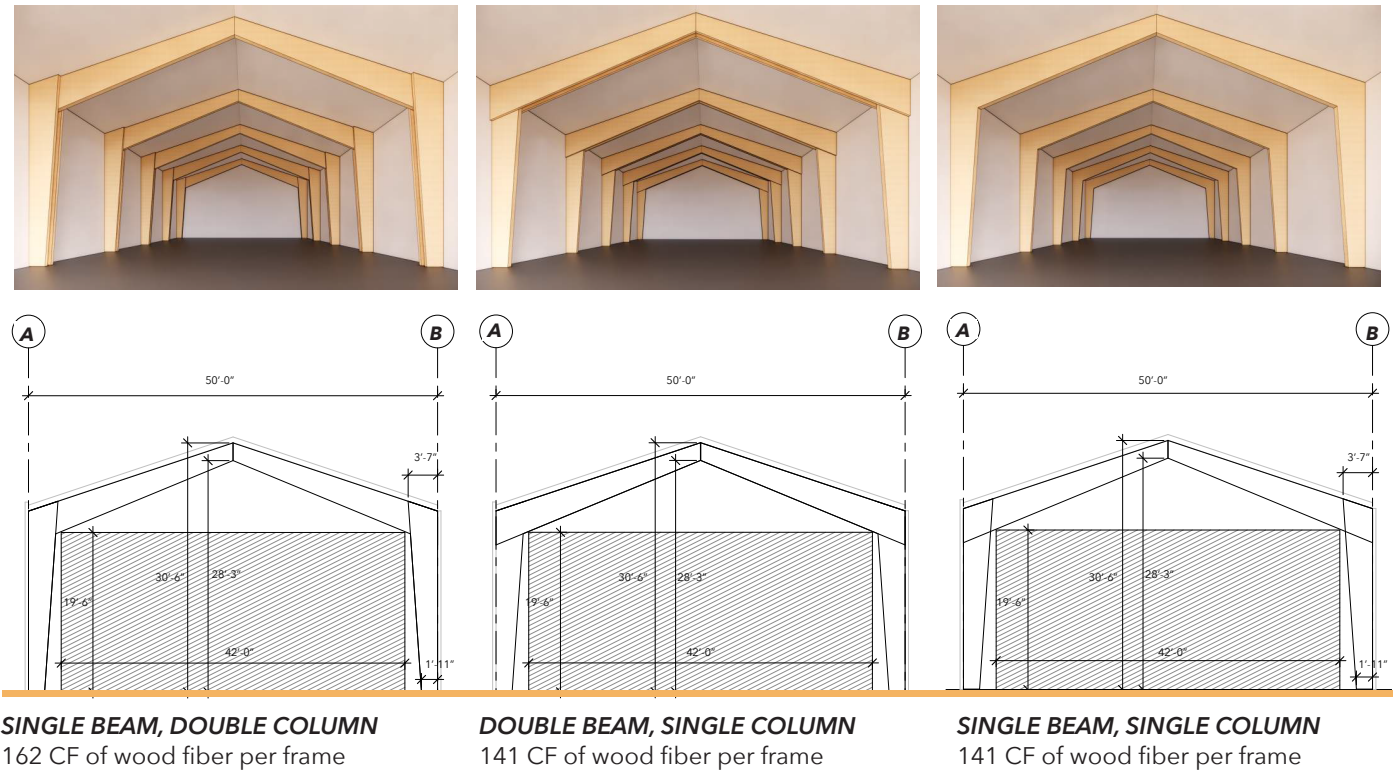
143 CF of wood fiber per frame

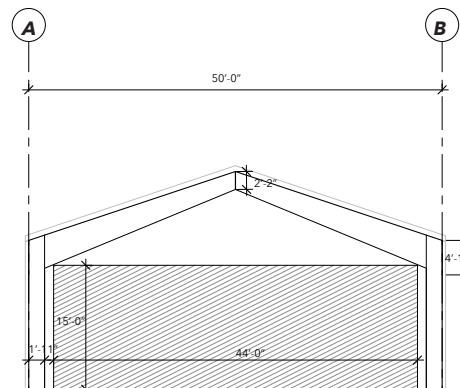


GLULAM BENT

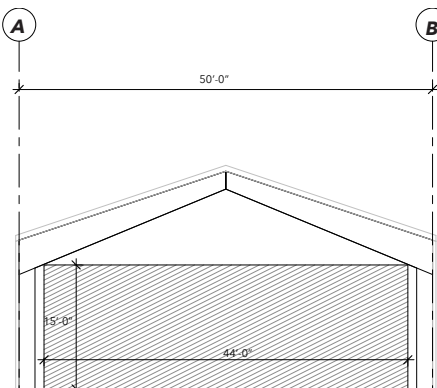
160 CF of wood fiber per frame

After ruling out glulam as a structural material for these frames, I re-focused and developed frames with based on what I saw in my wood case studies, and what frame shapes were the most efficient in pre-engineered metal buildings. I started out with the tapered beam and tapered column shape. Initially I was looking how member variations affected wood fiber utilization.

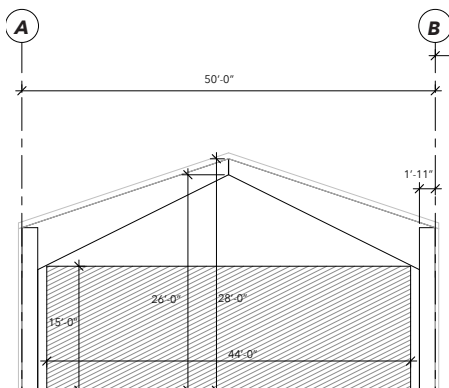
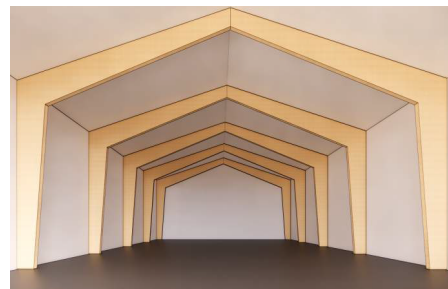




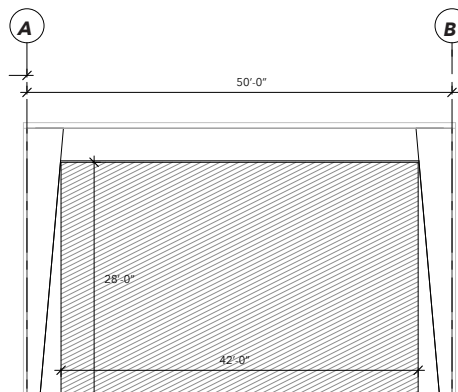
SINGLE BEAM, DOUBLE COLUMN
126 CF of wood fiber per frame



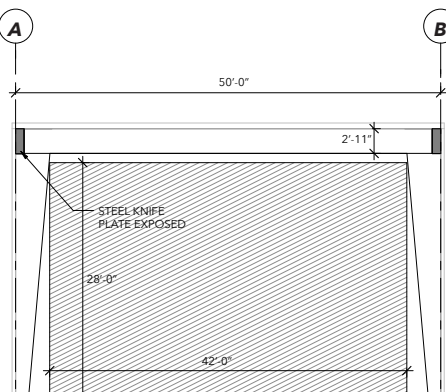
DOUBLE BEAM, SINGLE COLUMN
146 CF of wood fiber per frame



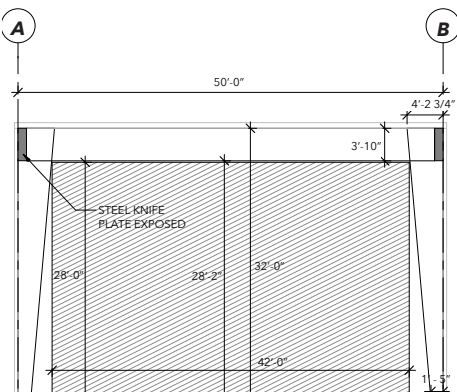
SINGLE BEAM, SINGLE COLUMN
138 CF of wood fiber per frame



SINGLE BEAM, DOUBLE COLUMN
259 CF of wood fiber per frame

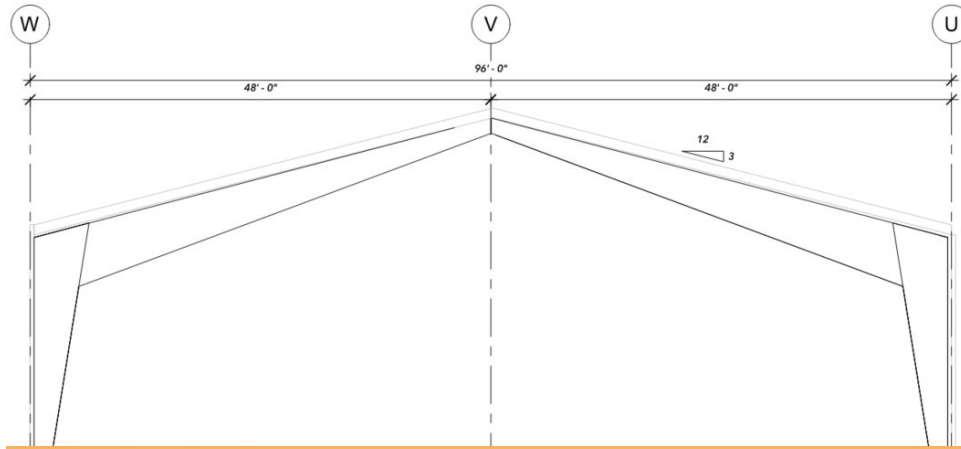


DOUBLE BEAM, SINGLE COLUMN
207 CF of wood fiber per frame



SINGLE BEAM, SINGLE COLUMN
204 CF of wood fiber per frame

In addition to the short fifty foot frame spans, I looked at a large span frame. With mass plywood panel the longest panel that they can manufacture is forty-eight feet long, to maximize the panel length, the long span frame I developed was ninety-four feet, mirroring two forty-eight panels.



**DOUBLE BEAM,
SINGLE COLUMN**

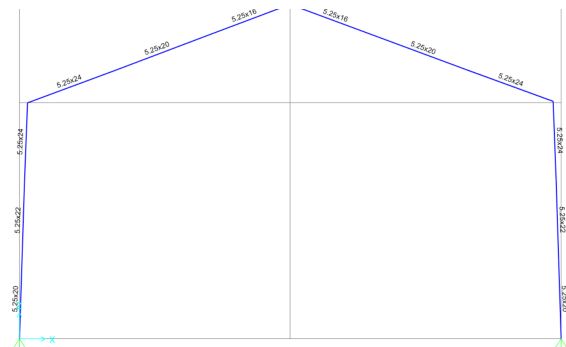
368 CF of
wood fiber
per frame

**SINGLE BEAM,
DOUBLE COLUMN**

364 CF of
wood fiber
per frame

**SINGLE BEAM,
SINGLE COLUMN**

360 CF of
wood fiber
per frame



Once the I developed the frames, I sent the initial elevations to Patrick for him to run conceptual structural analysis on.

He modeled the frames in SAP2000 for maximum moment, shear and story drift.

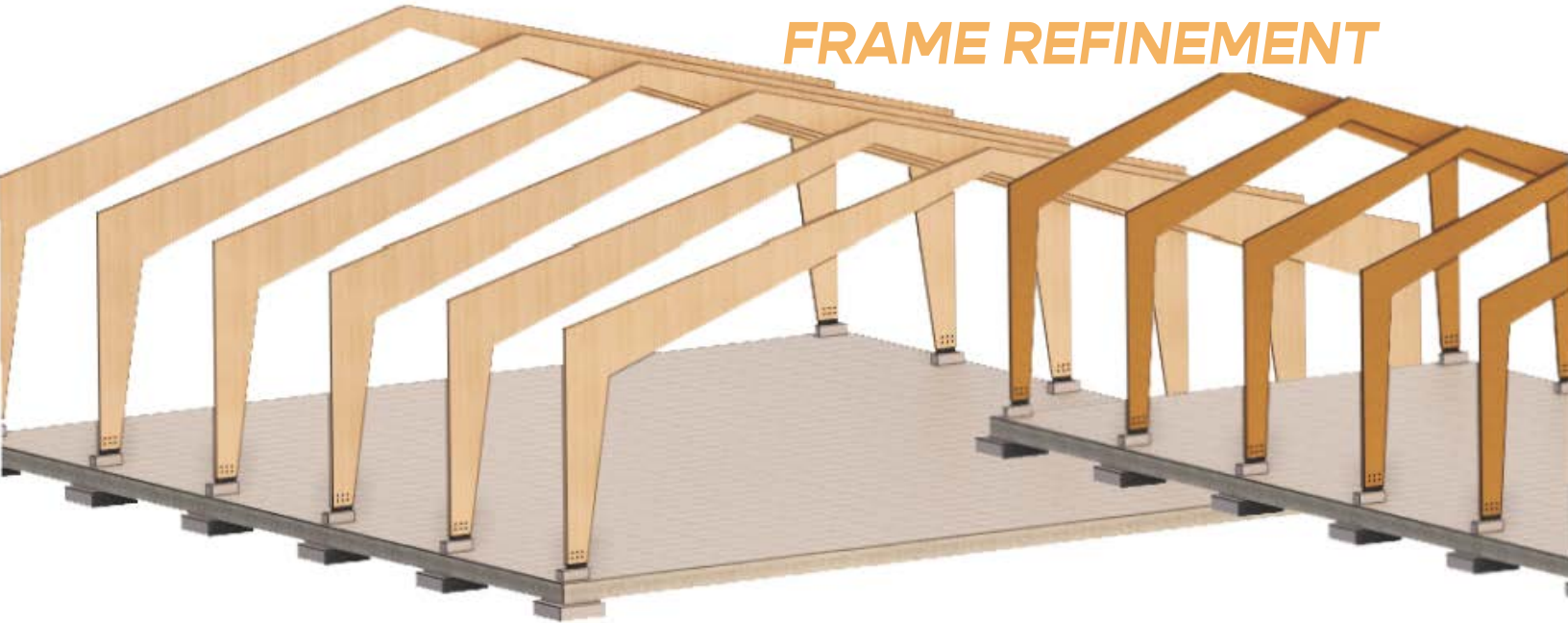
Once the forces were calculated the member sizes were adjusted and recorded for sufficient member size.

Below is his analysis.



Members and Lateral Drift							10 ft o.c. frame spacing		
Drift Calculation									
Drift Allowable = 2% x h =	0.025	x	25 ft	=	7.5	inches			
Deflection amp. factor =	1.5								
Actual Deflection (SAP) =	3.68	inches					Members:	3.5x24 tapered to 3.5x16	
Applied Drift =	1.5	x	3.7 inches	=	5.517	inches	PASS		
Actual Deflection (SAP) =	4.9	inches					Members:	3.5x22 tapered to x14	
Applied Drift =	1.5	x	4.9 inches	=	7.4	inches	PASS		

FRAME REFINEMENT







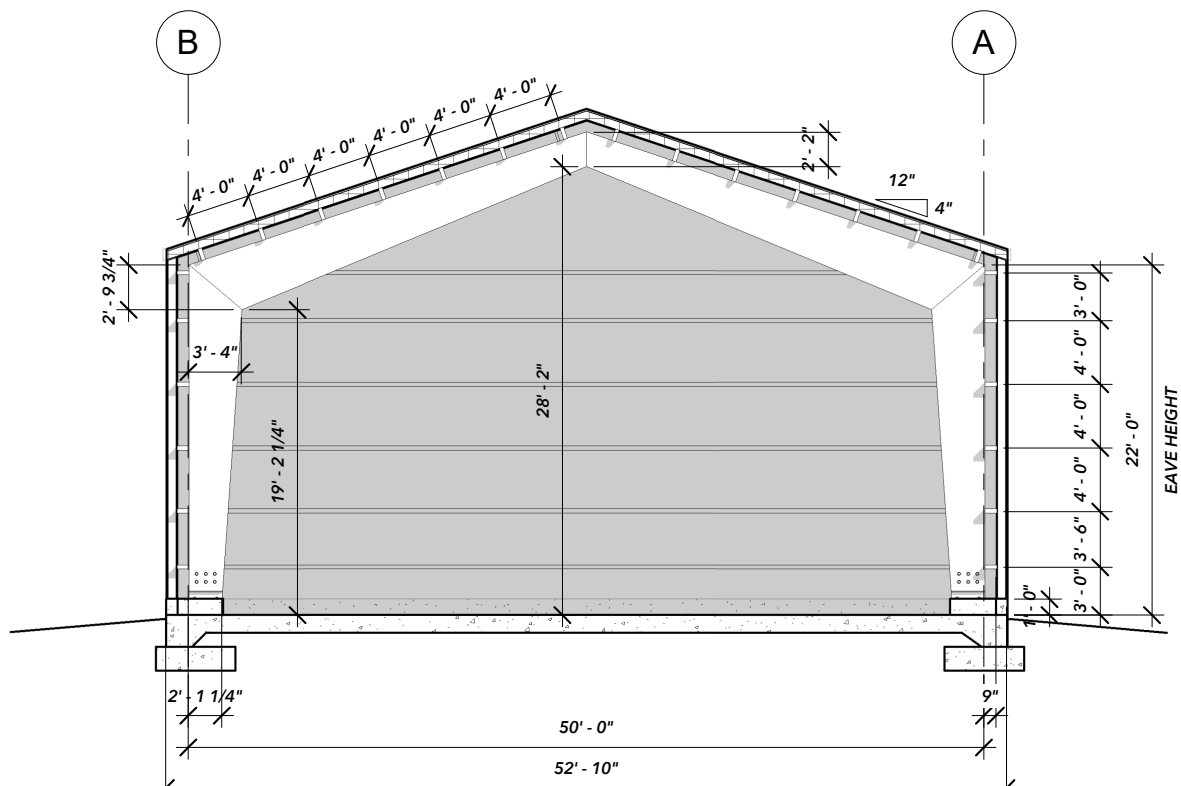
The image shows the interior of a large, modern building under construction. The structure is made of light-colored wood, featuring a prominent mass ply moment frame. The ceiling is composed of large, rectangular wooden panels supported by a network of horizontal and vertical wooden beams. Black metal brackets are visible at the joints where the beams meet the ceiling panels. The walls are also clad in wood. In the foreground, a person wearing a plaid shirt and a cap is seen from the back, looking towards the open end of the building. To the right, a red and black telescopic boom lift (SKYJACK) is parked. The lift has "SKYJACK" and "United Rentals" written on its side, and "4X4" on its base. The floor is wet and reflective. In the background, through the open end of the building, a green landscape with trees and a small structure is visible.

**Mass Ply Moment Frame at
Freres Engineered Wood**

The original scope of this project included refining multiple frame shapes through cross section optimization, schematic structural analysis and bay spacing optimization. However, with time constraints, not all the scope was able to be realized. The scope was limited to further refining one frame shape and two span widths. The frame that was refined is a tapered beam, tapered column frame shape investigated at fifty-foot and ninety-four-foot span width. These frame refinements were based on preliminary conceptual structural analysis to determine preliminary member sizes however, further structural optimization by a licensed engineer would need to occur.

The next few pages go into detail on the frames that were selected and feature the pre-engineered metal building alternative that will be used for comparative studies and analysis in the rest of the project criteria.

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SPECIFICS :

50'-0" SPAN

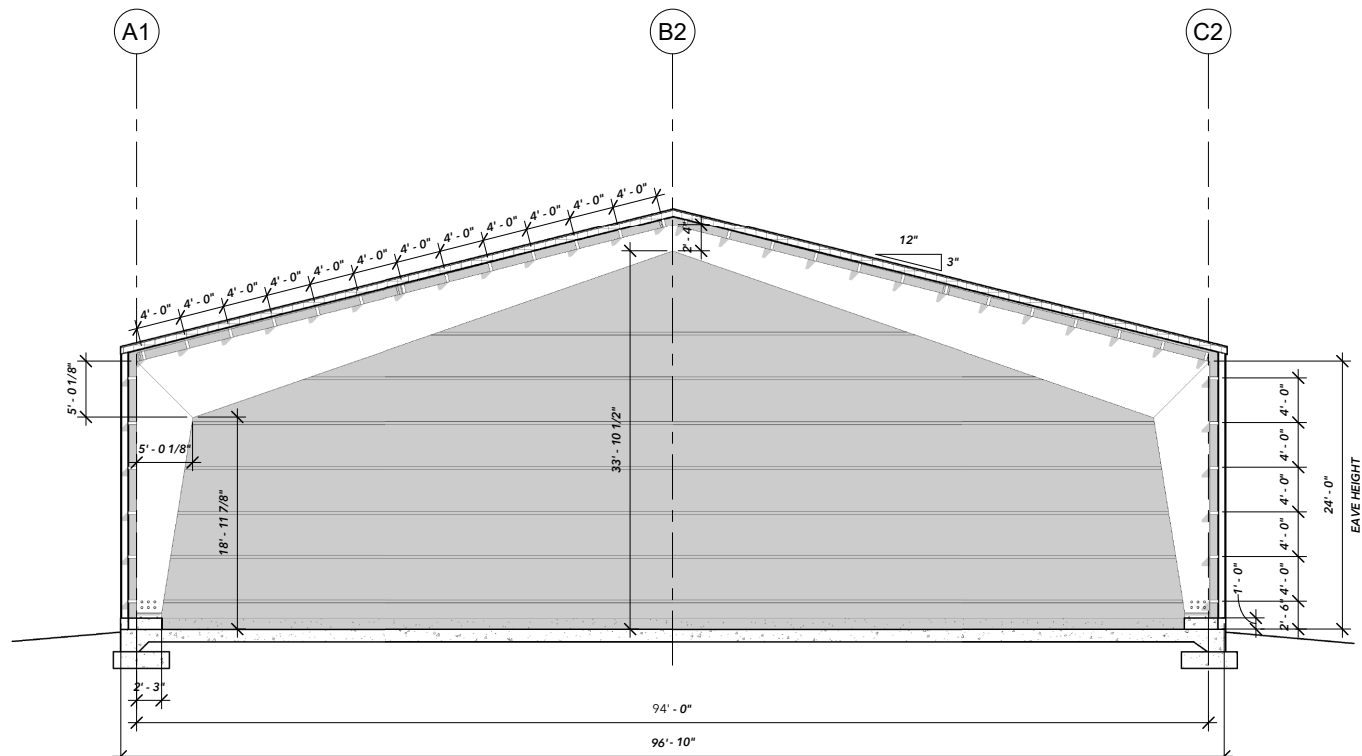
20'-0" BAY SPACING

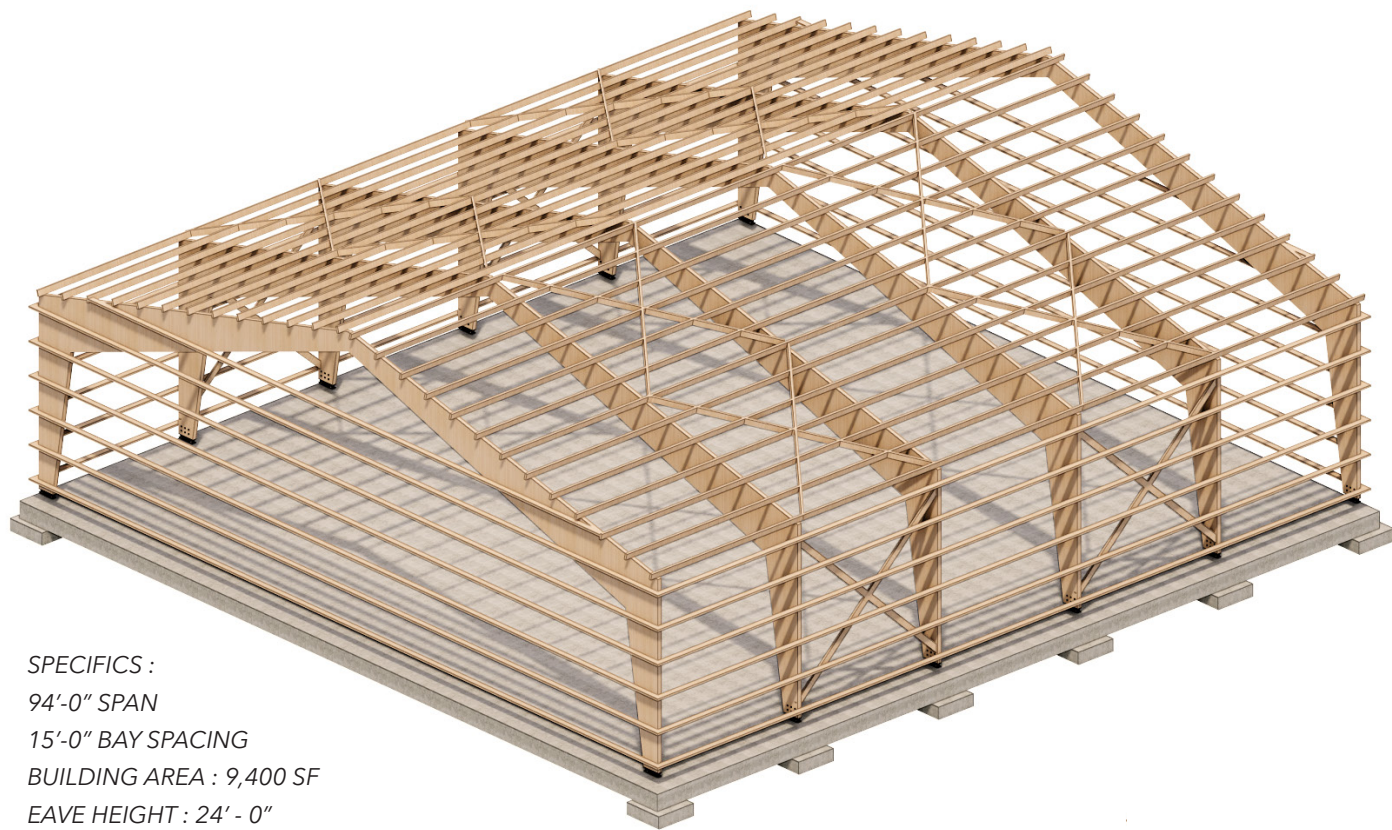
BUILDING AREA : 5,000 SF

EAVE HEIGHT : 22' - 0"

CUBIC FIBER PER FRAME : 125 CF

88





SPECIFICS :

94'-0" SPAN

15'-0" BAY SPACING

BUILDING AREA : 9,400 SF

EAVE HEIGHT : 24' - 0"

CUBIC FIBER PER FRAME : 276 CF

This pre-engineered metal building was adapted from publicly available permit drawings (City of Portland permit number 18-144954-000-00 CO). The metal building supplier was Varco Pruden Buildings. The overall building dimension was 47'-0" span x 65'-0" length with 19'-0" bay spacing. Due to the similar overall building dimensions and bay spacing, this pre-engineered frame was chosen as an equivalent for further analysis in this project.





SPECIFICS :

50'-0" SPAN

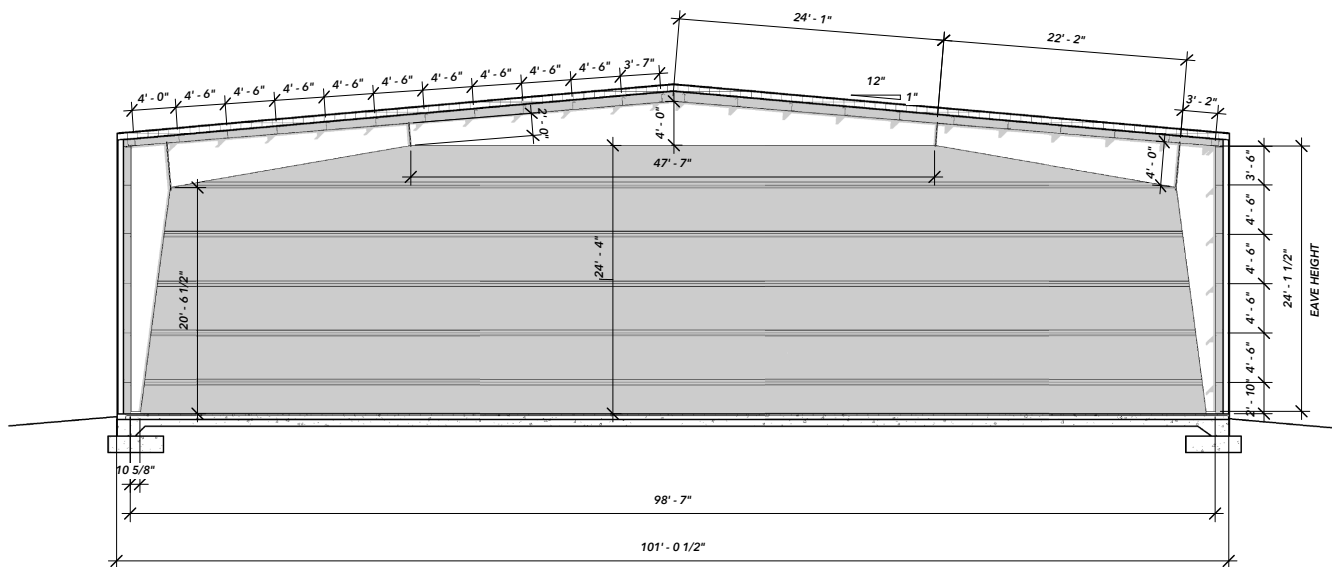
19'-0" BAY SPACING

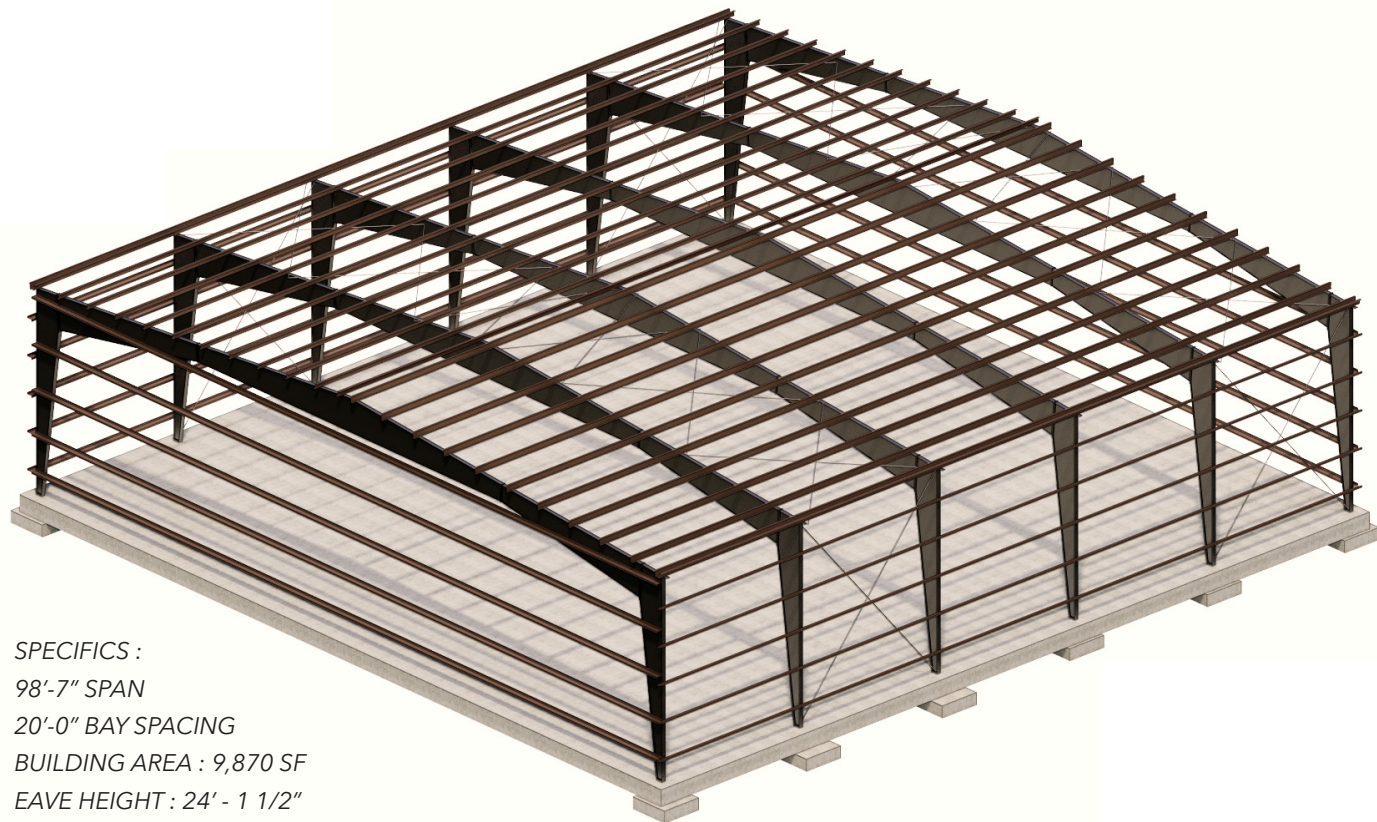
BUILDING AREA : 4,700 SF

EAVE HEIGHT : 18' - 2 1/2"

CUBIC FIBER PER FRAME : 8 CF

This pre-engineered metal building was adapted from publicly available permit drawing (City of Portland permit number 17-186129-000-00-CO). The metal building supplier was Pacific Building Systems. The overall building dimension was 100'-0" span x 100'-0" length with 20'-0" bay spacing. Due to the similar overall building dimensions and bay spacing, this pre-engineered frame was chosen as an equivalent for further analysis in this project.





SPECIFICS :

98'-7" SPAN

20'-0" BAY SPACING

BUILDING AREA : 9,870 SF

EAVE HEIGHT : 24' - 1 1/2"

CUBIC FIBER PER FRAME : 16 CF



CONNECTIONS



Connections

In such a simple structure connections between the members are the subtle detail that enhances the design. Connections between timber members are often perceived as one of the trickiest parts of design of the structure, due to limited knowledge for designing moment connections in wood frames. When designing my connections, I focused on the moment connection between a column and a beam, commonly referred to as a knee joint in portal frames.



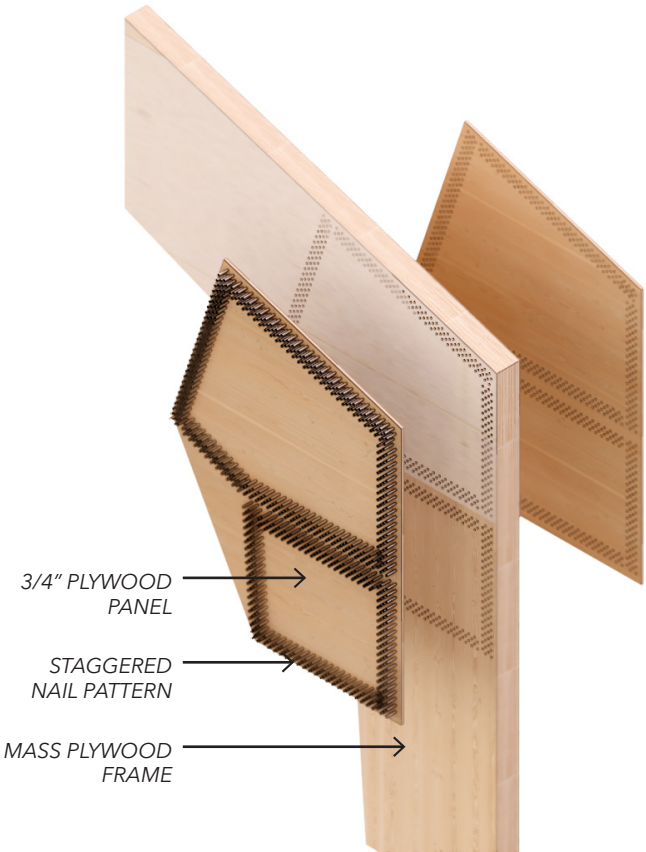
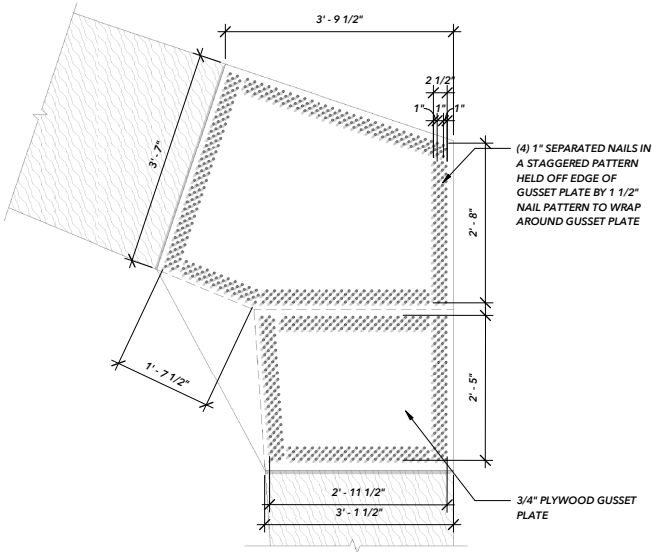
In the NZ Wood Connection Design Guide, the detailing of the connections included in this guide focus on fabrication, build ability, and practical installation. They break down the pros and cons of several connection types as well as the cost ratio. To the right is the table in the design guide.

After reviewing the connection guide and considering the aesthetic implications, I chose to further investigate the plywood nailed gusset to serve as the economical option, the epoxied rods with an open steel knee connector to serve as the easiest to construct on site, and the WS Dowel in a semicircle to serve as the aesthetic option.

Connection Type	Pros	Cons	Approximate Cost Ratio (assuming Nailed Ply Gusset is 1)
Nailed Ply Gusset	High moment capacity	Time consuming to nail off on site	1.0
	Cost effective	Industrial looking	
Lap Joint	1/2 the number of nails of a ply gusset	Requires blocking between double member	0.3
	No additional gusset material required	Constraint on Overlap area restricts moment capacity	
Screwed Steel Gusset	Higher moment capacity	Labour intensive to drive screws	2.0
		Low fire resistance - if not protected	
Epoxied rods (inc steel knee)	No visible connections - looks clean	Epoxy work should be done in factory	4.0
	Quick to erect on site	Steel knee expensive to fabricate	
		Fire protection maybe required	
Quick Connect	Quick to erect on site	May experience joint rotation	4.0
	High moment capacity	Expensive due to number of components	
WS Dowel and Steel Plate	Looks clean with only dowel heads exposed	Some specialist equipment and training required on site	1.6
	Inherent fire protection		
	Allows for complex joints		

Connection # 1 - Plywood Gusset Knee Connection

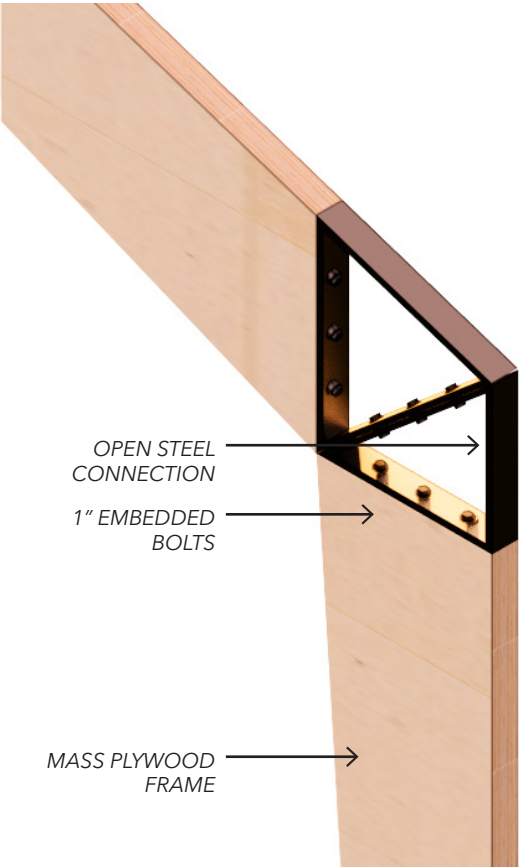
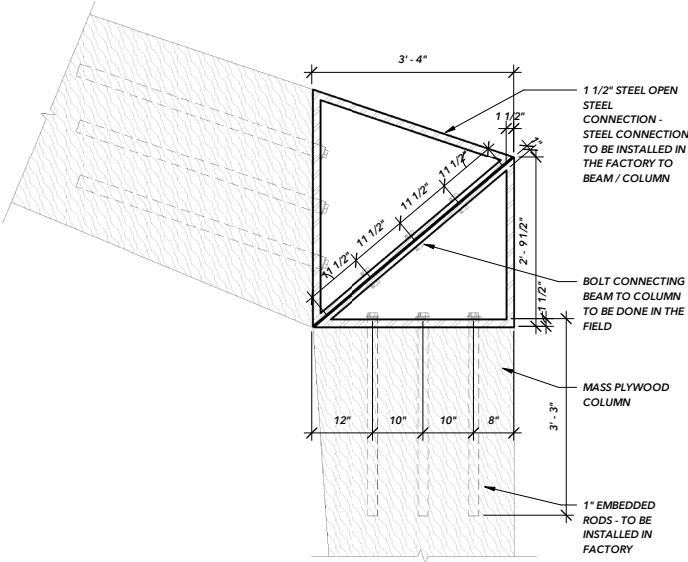
The plywood gusset connection features 3/4" plywood on either side of the mass plywood beam and column. Using nails in a four layer pattern, a moment connection is achieved. Although labor intensive, the connection is constructed from readily available materials.





Connection #2 - Open Steel Connection

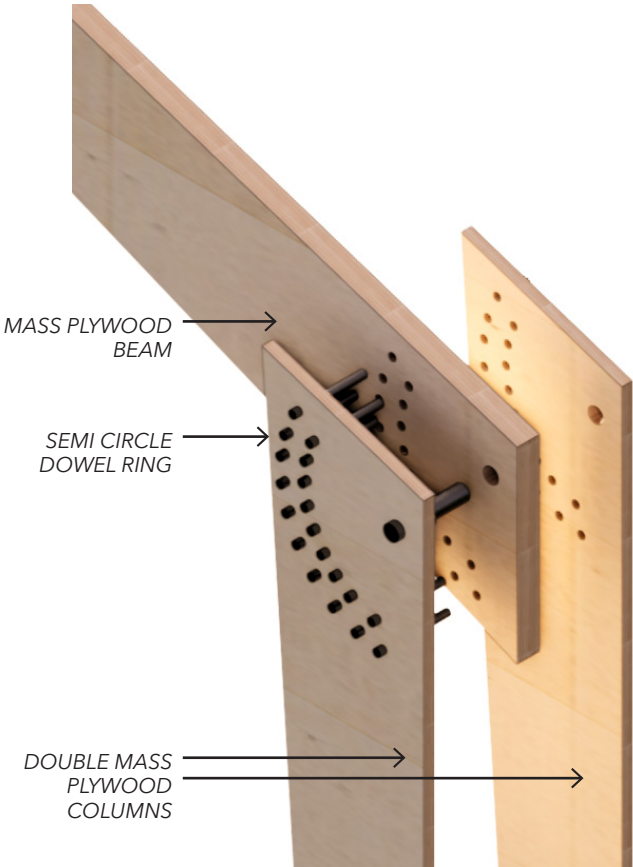
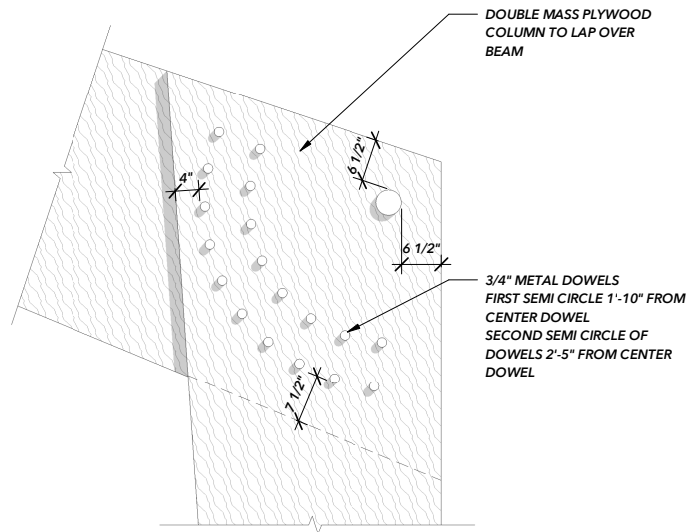
The open steel connection features two steel connections that are attached to the mass plywood beam and column through 1" embedded rods that would be installed in the factory. Geometric recommendations for the embedded rods were taken from the NZ Wood Guide. The two steel plates would be connected in the field, minimizing the labor on the construction site.





Connection #3 - Semi Circle Dowel Connection

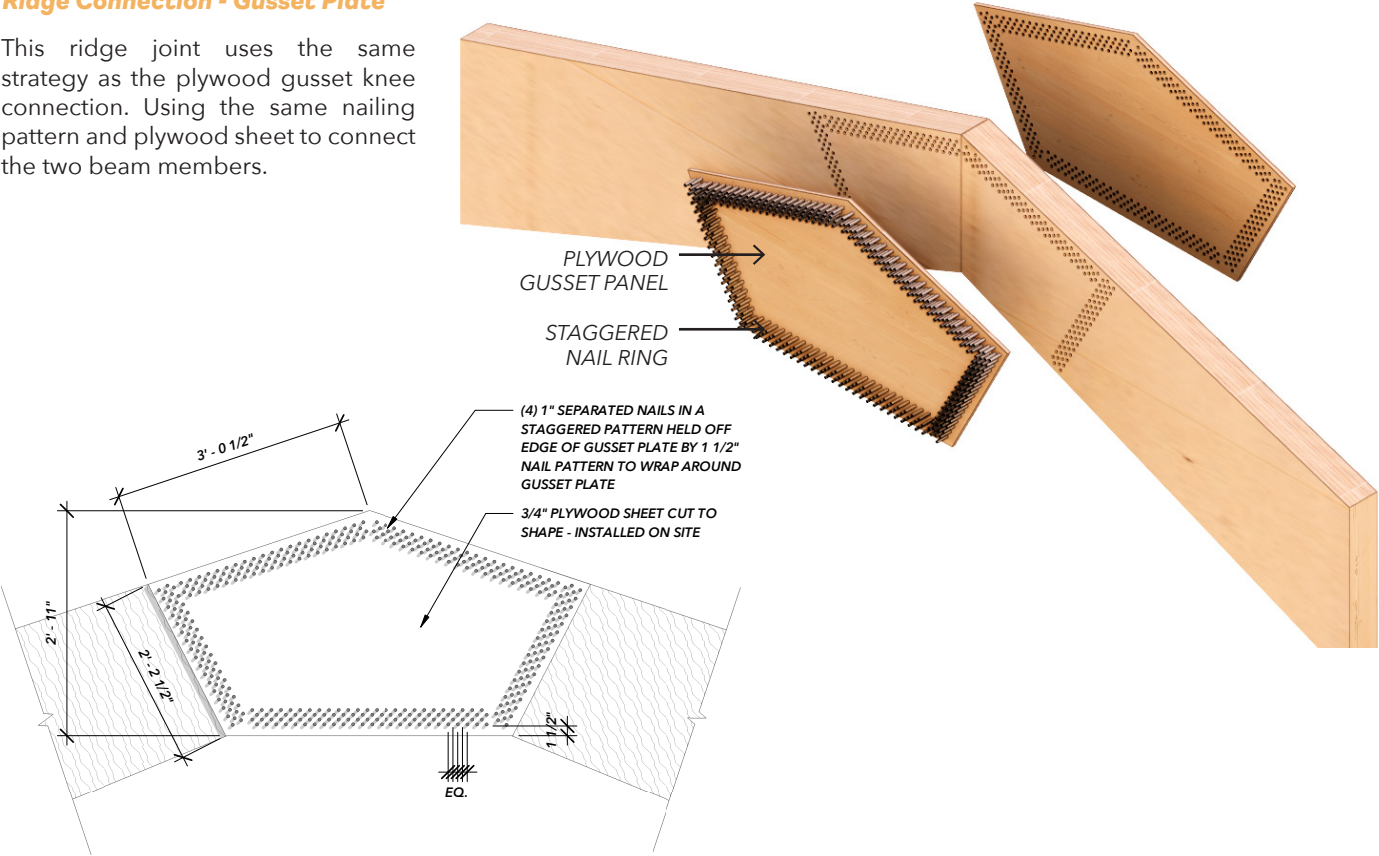
The semi-circular arrangement of the dowels features two rings of steel dowels radiating from a larger central dowel. In this connection, there are two mass plywood columns sandwiched around one mass plywood beam. Blocking was added 4'-0" O.C. between the columns.



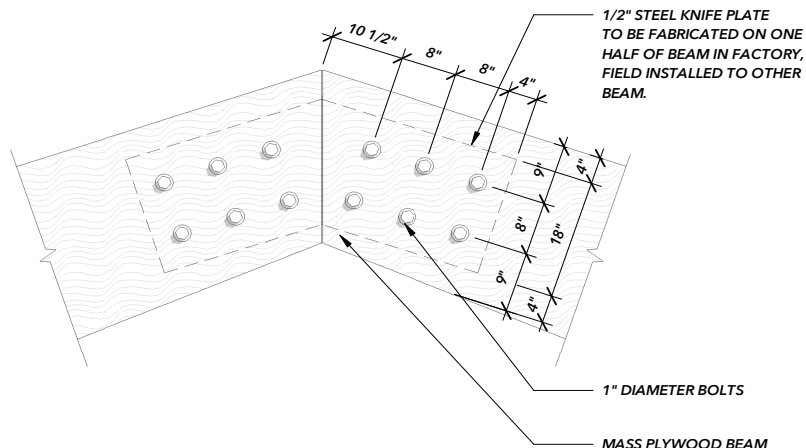


Ridge Connection - Gusset Plate

This ridge joint uses the same strategy as the plywood gusset knee connection. Using the same nailing pattern and plywood sheet to connect the two beam members.

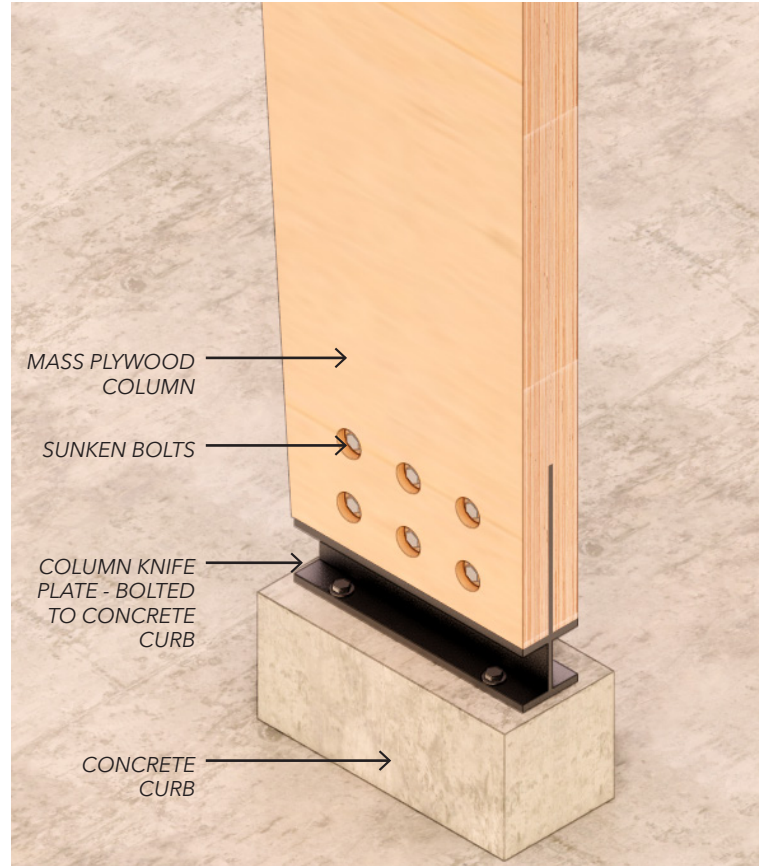
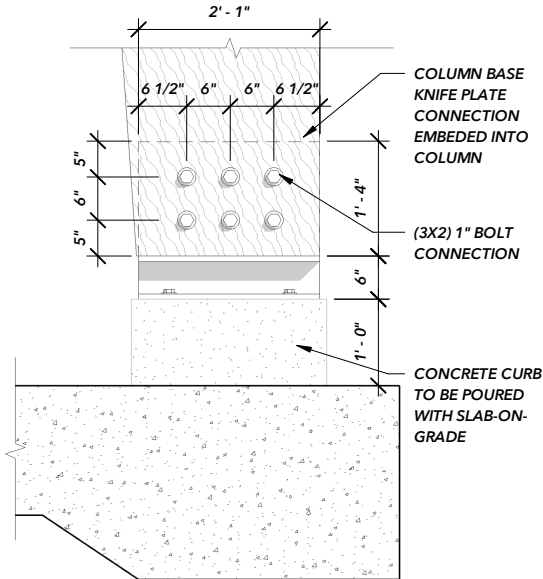


This ridge joint uses a steel knife plate to connect the beams. This results in a clean connection. To ease construction on site, the embedded knife plate would be installed on one mass plywood beam in the factory, transported and once on site, the other beam would be slid onto the knife plate and attached.



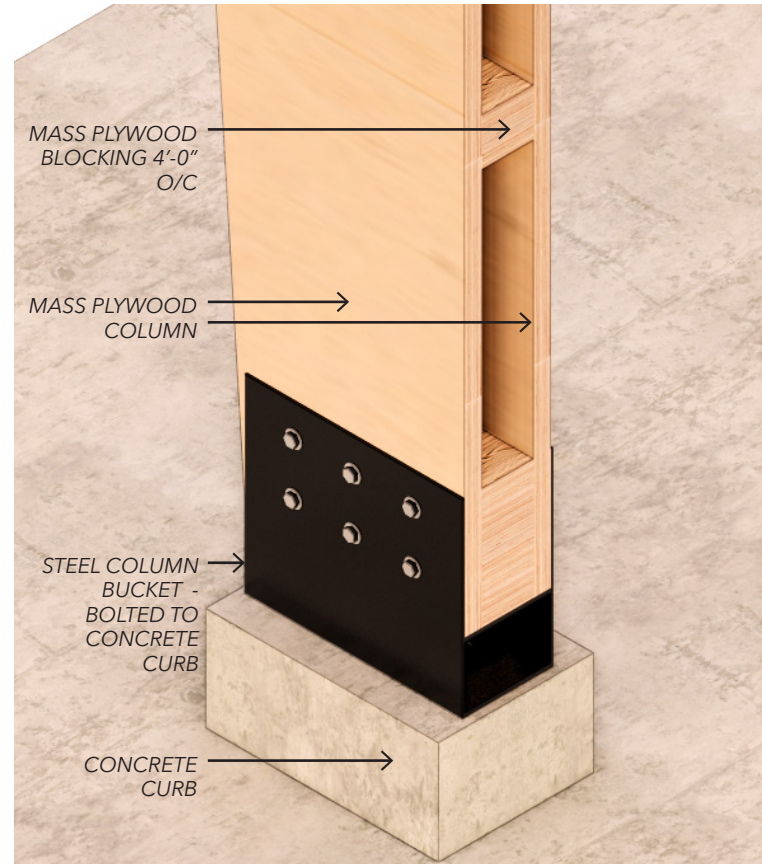
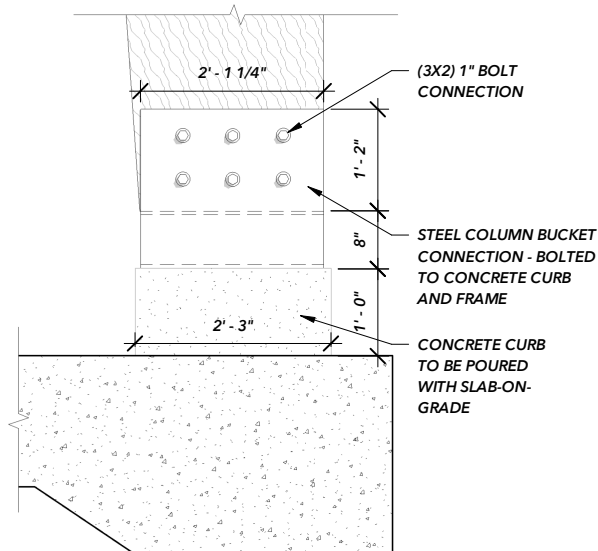
Base Connection - Knife Plate

In the design of the column base connection, the intention was to keep it simple and utilize a knife plate connection that will be bolted through the mass plywood column, and bolted into a 1'-0" concrete curb to be poured with a slab. The concrete curb keeps out moisture, pests from the wood structure.



Base Connection - Bucket

In the design of the alternative column base connection where there is a double column, a steel column bucket replaces the knife plate. There is blocking added between the columns every four feet on center. This design also employs a 1'-0" concrete curb to be poured with a slab for moisture and pest protection.





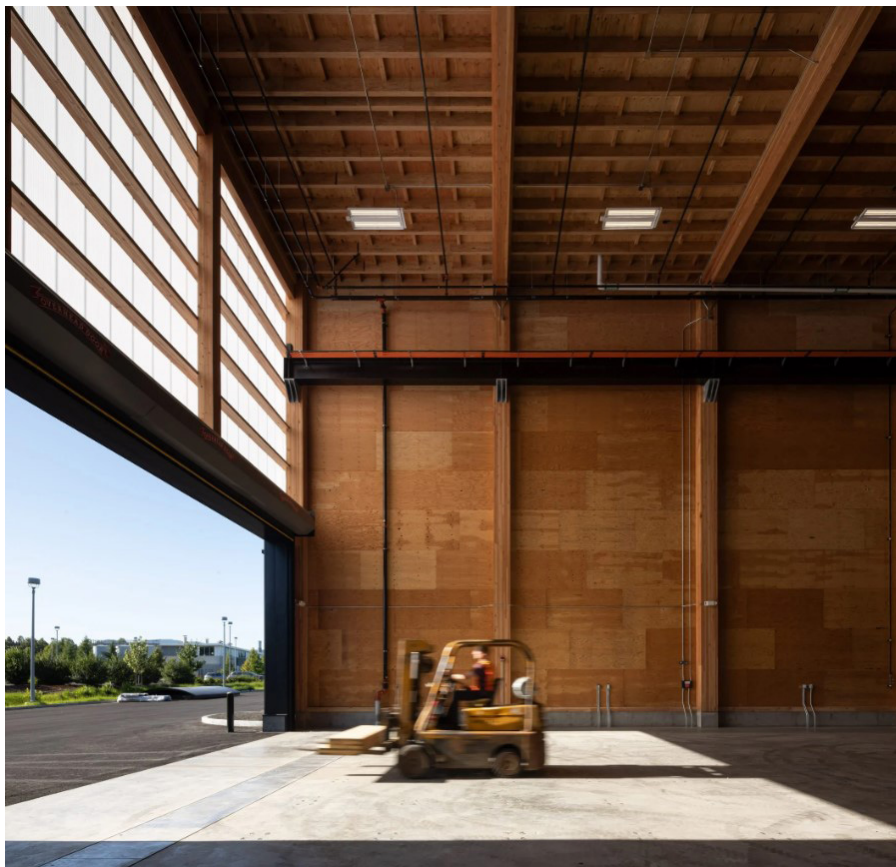
FABRICATION



Fabrication Methodology

When designing with a panelized material such as mass plywood, the fabrication process differs from conventional construction. One important distinction in designing in mass timber is to design with machine limitations in mind. These design of these frames are optimized with the tools at hand.

There are four set panel widths that Freres can manufacture, 3'-10", 7'-10", 9'-10" and 11'-10". When structurally optimizing the frame shape designs, the panel widths became the limitation for maximum member widths. In the next pages you will see how the member sizes were maximized given the panel widths and the CNC requirements. Freres has published a Mass Plywood Design and Construction Guide regarding fabrication limitations in processing panels with their CNC machine. I relied on this guide as guidelines for creating fabrication layouts for the frame systems.





*Fabrication facility at Freres
Engineered Wood*

Fabrication Methodology

Mass Timber Frame

Single Tapered Beam

Single Tapered Column

50' - 0" span

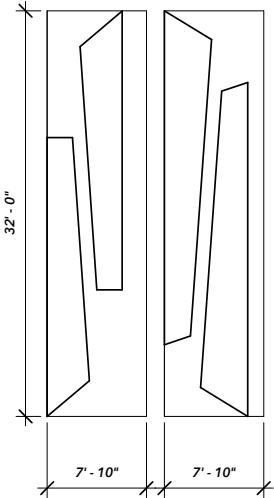
20' - 0" bay spacing
(6 frames per building)

Column : fabricated from
a both a 7'-10" and 11'-10"
panel by the maximum
length of panel, 48'-0"

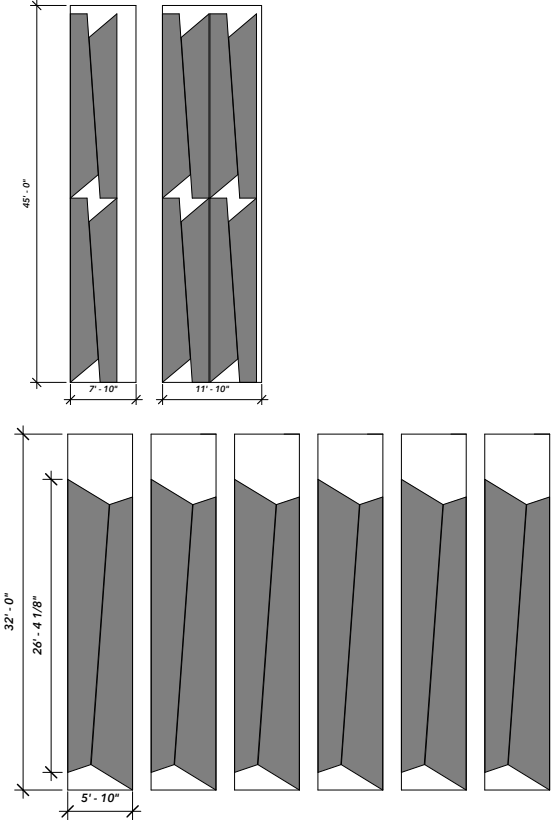
Beam : fabricated from a
7'-10" panel by the minimum
length of panel, 32'-0"

Total WASTE Fiber = 22 %
Total Wood Fiber

PER FRAME



PER BUILDING

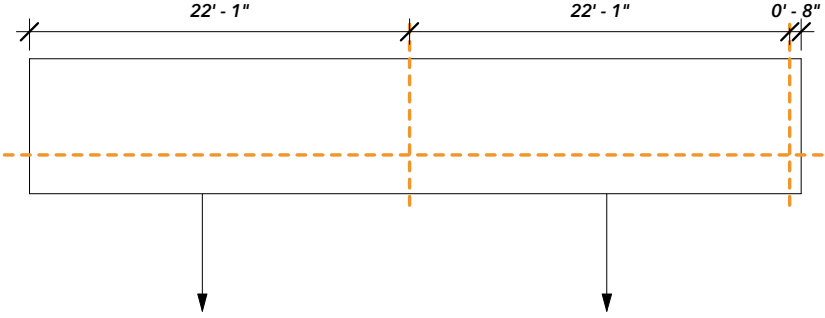


50' - 0" SPAN					
TOTAL WOOD PANEL FIBER PER FRAME		TOTAL WOOD FIBER UTILIZED PER FRAME		TOTAL WOOD FIBER WASTE PER FRAME	
This includes the total panel wood fiber regardless of whether it is used in the frame or not		This is the wood fiber from the panel that is used in the primary structural members		This is the wood fiber from the panel that is not used in the structural members, or the wood waste	
COLUMN	147.5 ft²	COLUMN	111.6 ft²	COLUMN	34.3 ft²
BEAM	186.7 ft²	BEAM	144.9 ft²	BEAM	39.9 ft²
TOTAL	334.2 ft²	TOTAL	256.5 ft²	TOTAL	74.3 ft²
Material Width	6.0 in panel	Material Width	6.0 in panel	Material Width	6.0 in panel
Total Volume per Frame	167.1 ft³	Total Volume per Frame	128.2 ft³	Total Volume per Frame	37.1 ft³
# of Structural Frames	6.0	# of Structural Frames	6.0	# of Structural Frames	6.0
Total Wood Panel Fiber REQ for Building	1,002.5 ft³	Total Wood Fiber USED for Building	769.4 ft³	Total WASTE Wood Fiber for Building	222.8 ft³
				Total WASTE Wood Fiber for Building / Total Wood Panel Fiber REQ for Building	
				WOOD WASTE RATIO 22%	

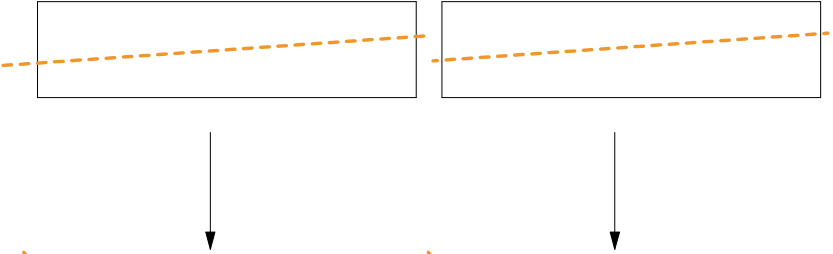
50'-0" SPAN MACHINING STEPS

COLUMN

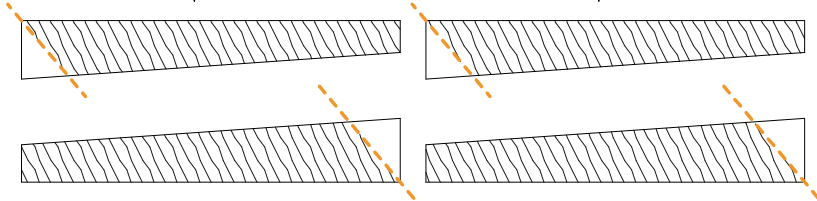
CUT ONE
CNC MACHINE
CIRCULAR SAW



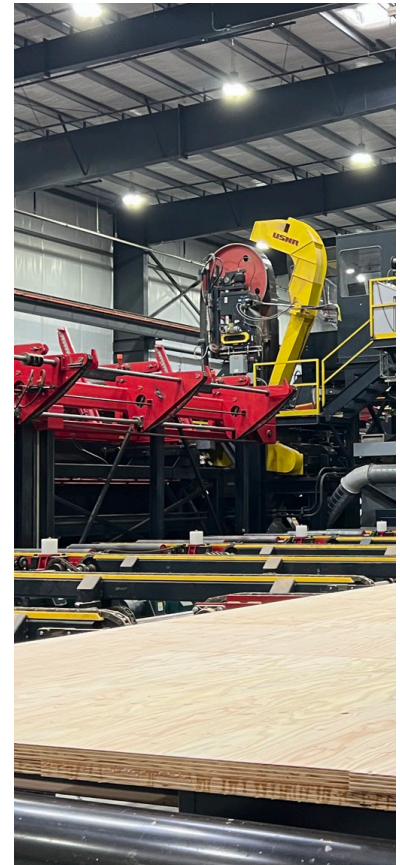
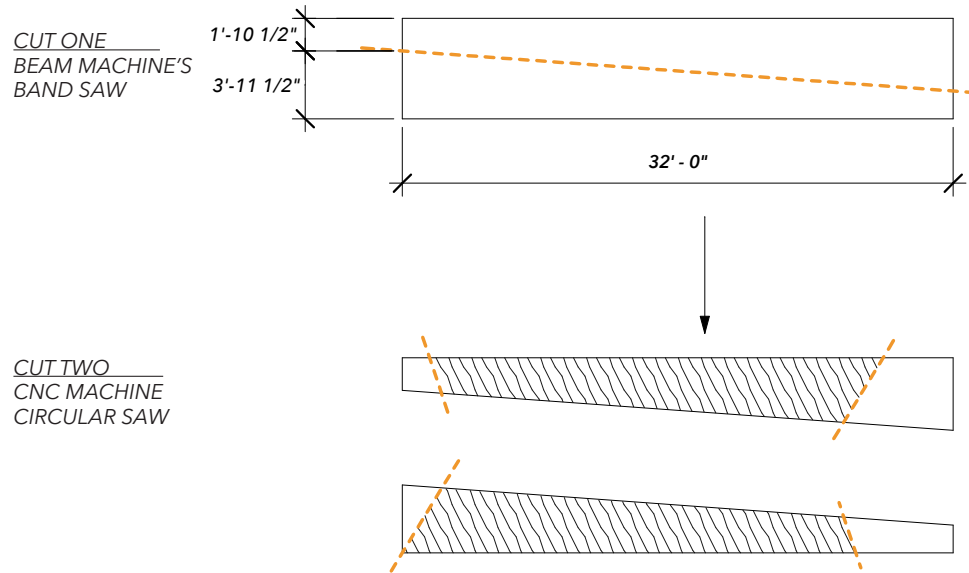
CUT TWO
CNC MACHINE
CIRCULAR SAW



CUT THREE
CNC MACHINE
CIRCULAR SAW



BEAM STEPS



Fabrication Methodology

Mass Timber Frame

Single Tapered Beam

Single Tapered Column

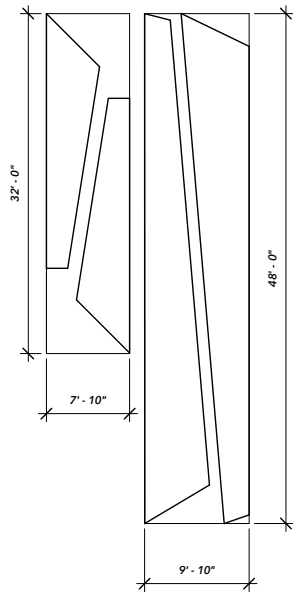
94' - 0" span

15' - 0" bay spacing
(8 frames per building)

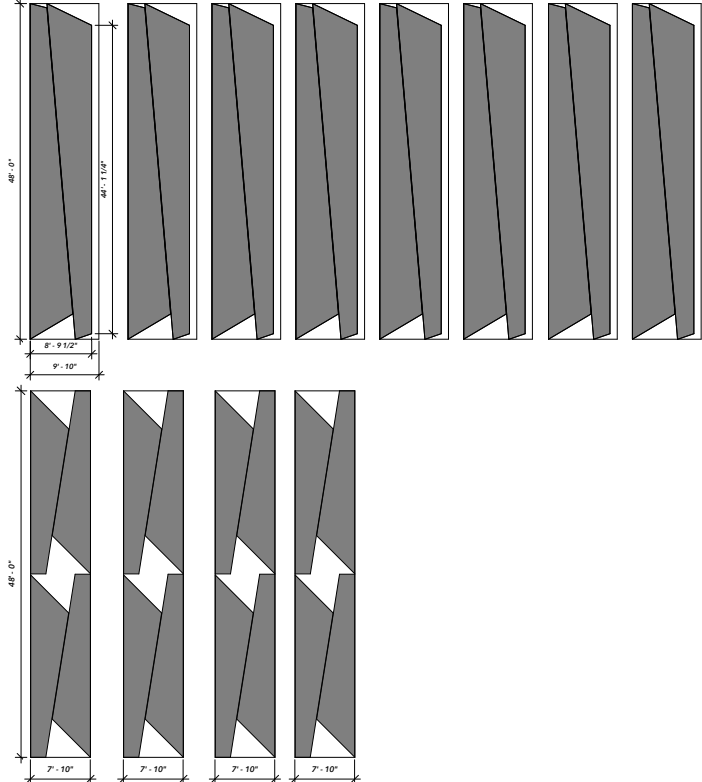
Column : fabricated from a
7'-10" panel by the minimum
length of panel, 32'-0"

Beam : fabricated from a 9'-
10" panel by the maximum
length of panel, 48'-0"

PER FRAME



PER BUILDING



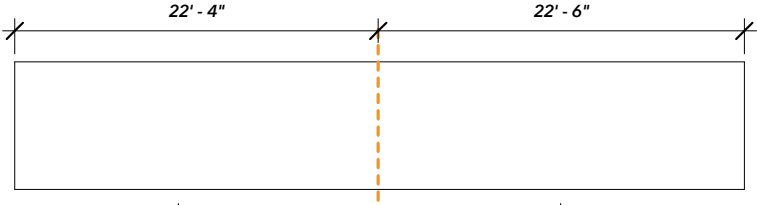
Total WASTE Fiber
Total Wood Fiber = 16 %

94' - 0" SPAN					
TOTAL WOOD PANEL FIBER PER FRAME		TOTAL WOOD FIBER UTILIZED PER FRAME		TOTAL WOOD FIBER WASTE PER FRAME	
This includes the total panel wood fiber regardless of whether it is used in the frame or not		This is the wood fiber from the panel that is used in the primary structural members		This is the wood fiber from the panel that is not used in the structural members, or the wood waste	
COLUMN	188.0 ft²	COLUMN	157.6 ft²	COLUMN	29.6 ft²
BEAM	472.0 ft²	BEAM	397.8 ft²	BEAM	73.2 ft²
TOTAL	660.0 ft²	TOTAL	555.4 ft²	TOTAL	102.8 ft²
Material Width	6.0 in panel	Material Width	6.0 in panel	Material Width	6.0 in panel
Total Volume per Frame	330.0 ft³	Total Volume per Frame	277.7 ft³	Total Volume per Frame	51.4 ft³
# of Structural Frames	8.0	# of Structural Frames	8.0	# of Structural Frames	8.0
Total Wood Panel Fiber REQ for Building	2,640.0 ft³	Total Wood Fiber USED for Building	2,221.5 ft³	Total WASTE Wood Fiber for Building	411.2 ft³
				Total WASTE Wood Fiber for Building / Total Wood Panel Fiber REQ for Building	
				WOOD WASTE RATIO 16%	

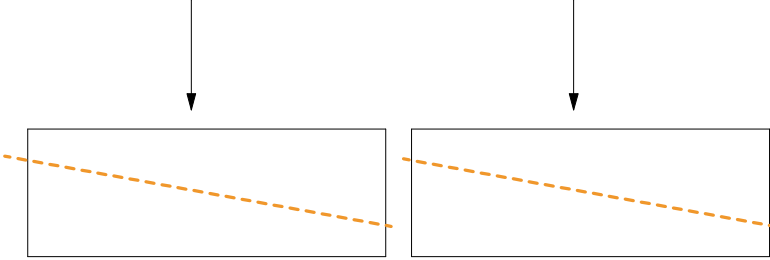
94' - 0" SPAN MACHINING STEPS

COLUMN

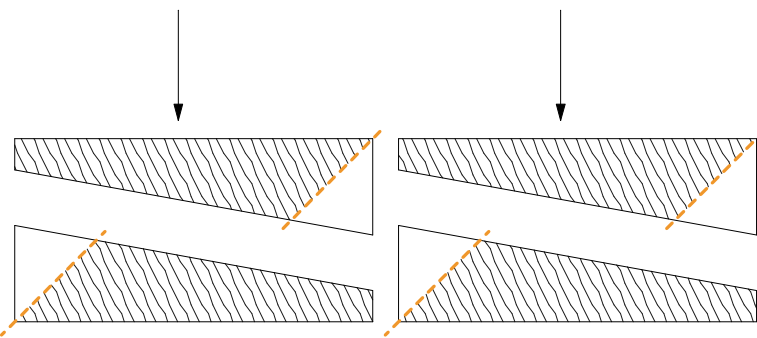
CUT ONE
CNC MACHINE
CIRCULAR SAW



CUT TWO
CNC MACHINE
CIRCULAR SAW

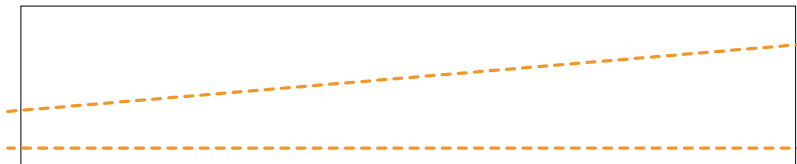


CUT THREE
CNC MACHINE
CIRCULAR SAW

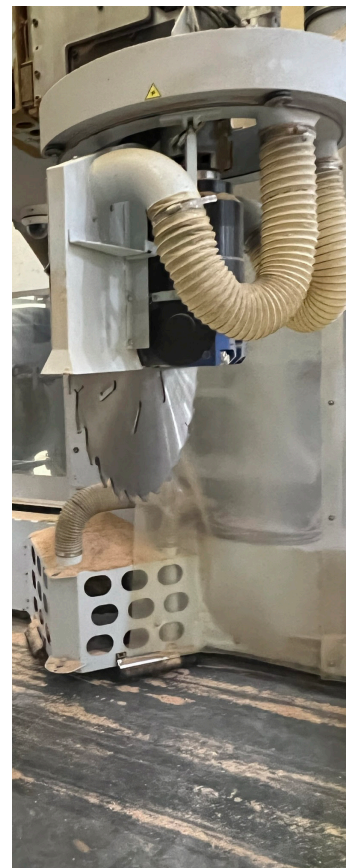
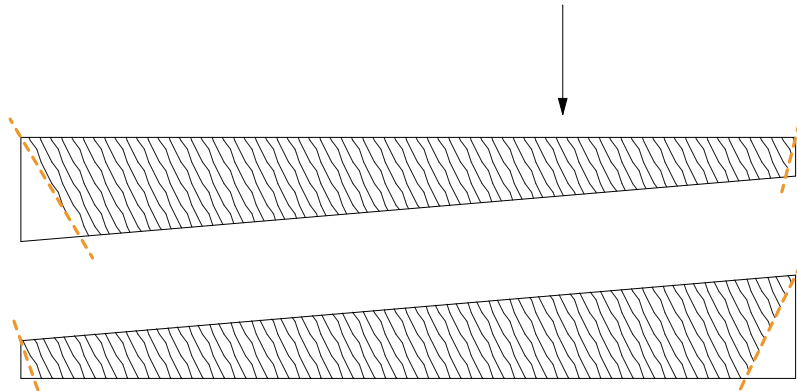


BEAM STEPS

CUT ONE
BEAM MACHINE'S
BAND SAW

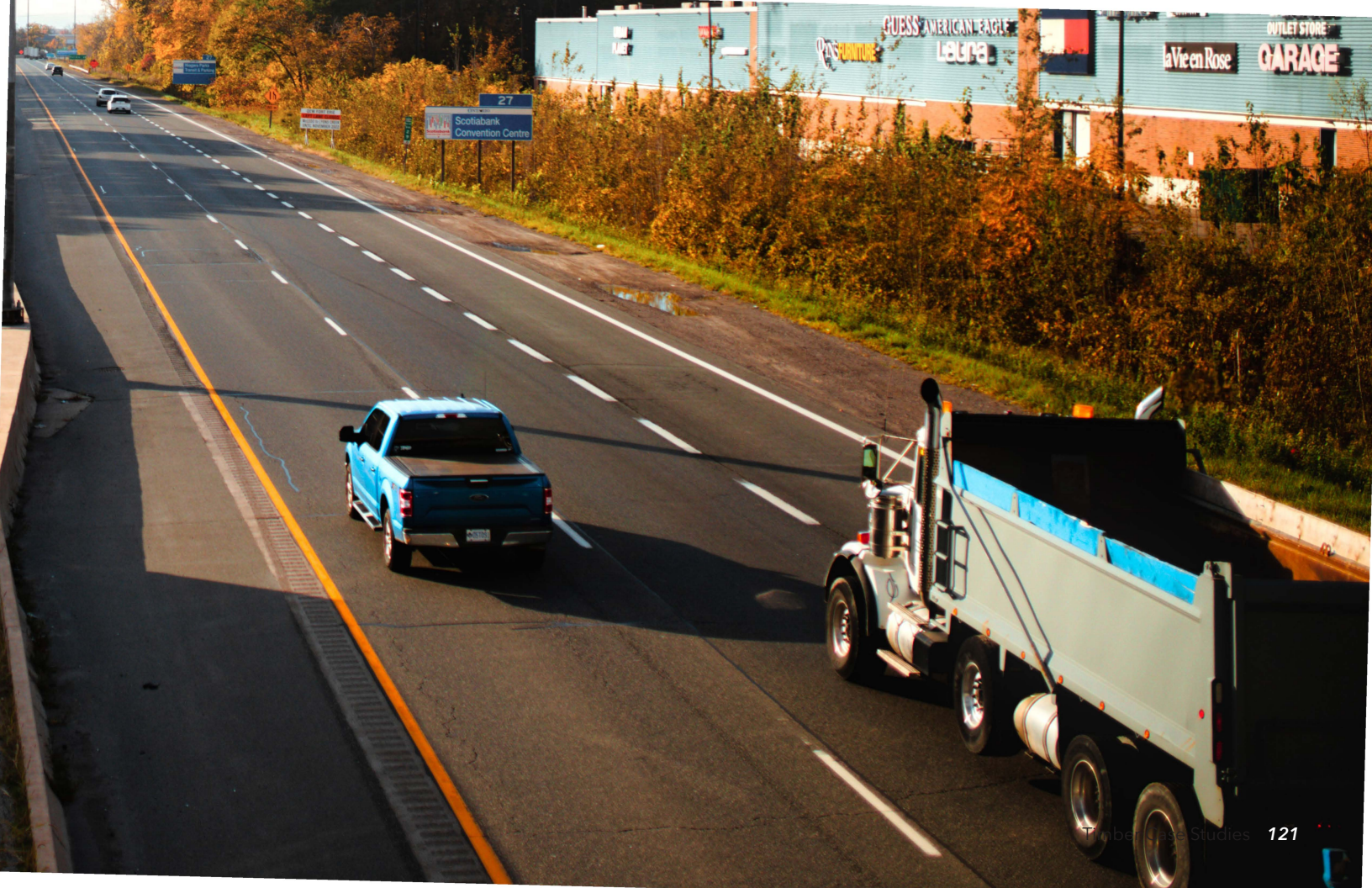


CUT TWO
CNC MACHINE
CIRCULAR SAW



TRANSPORTATION





Transportation Methodology

To figure out how these frame members would be transported from the panel fabrication factory to the job site, I used federal and state truck transport information provided by Modern Building Systems. This company is a market leader in delivering modular construction to the State of Oregon and throughout the west. My assumptions included transporting the frame members on flat bed truck beds rather than rail due to the flexibility that truck transport provides.

I utilized their transportation specifications to understand what the maximum dimensions for transporting these members would be within federal and state highway guidelines. I looked at both guidelines where no additional transportation permits would be required, but my goal was to have these members be able to fit on a truck bed without any additional permits which would add an additional step and cost to transporting a complete building. The summary of the transportation specifications obtained from Modern Building Systems is on the next page.

All of the frames easily fit within these regulations with the connectors attached and would not require special permits to transport of highways.



TRANSPORTATION SPECS

Width :

Federal and State highway regulation limit maximum vehicle cargo width to 8'-0". However, by obtaining highway permits common wide loads range from 12'-0" to 14'-0".



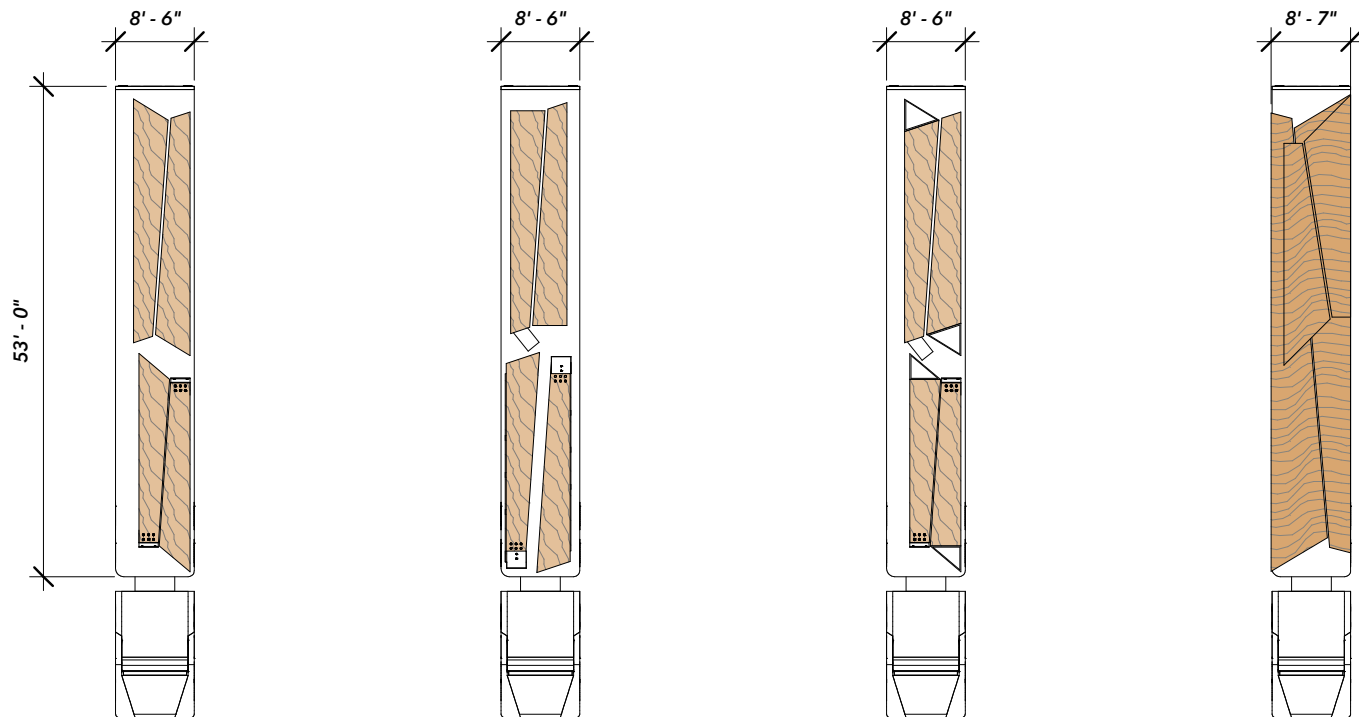
Length :

Federal and State highway regulations limit vehicle cargo lengths up to 64'-0".

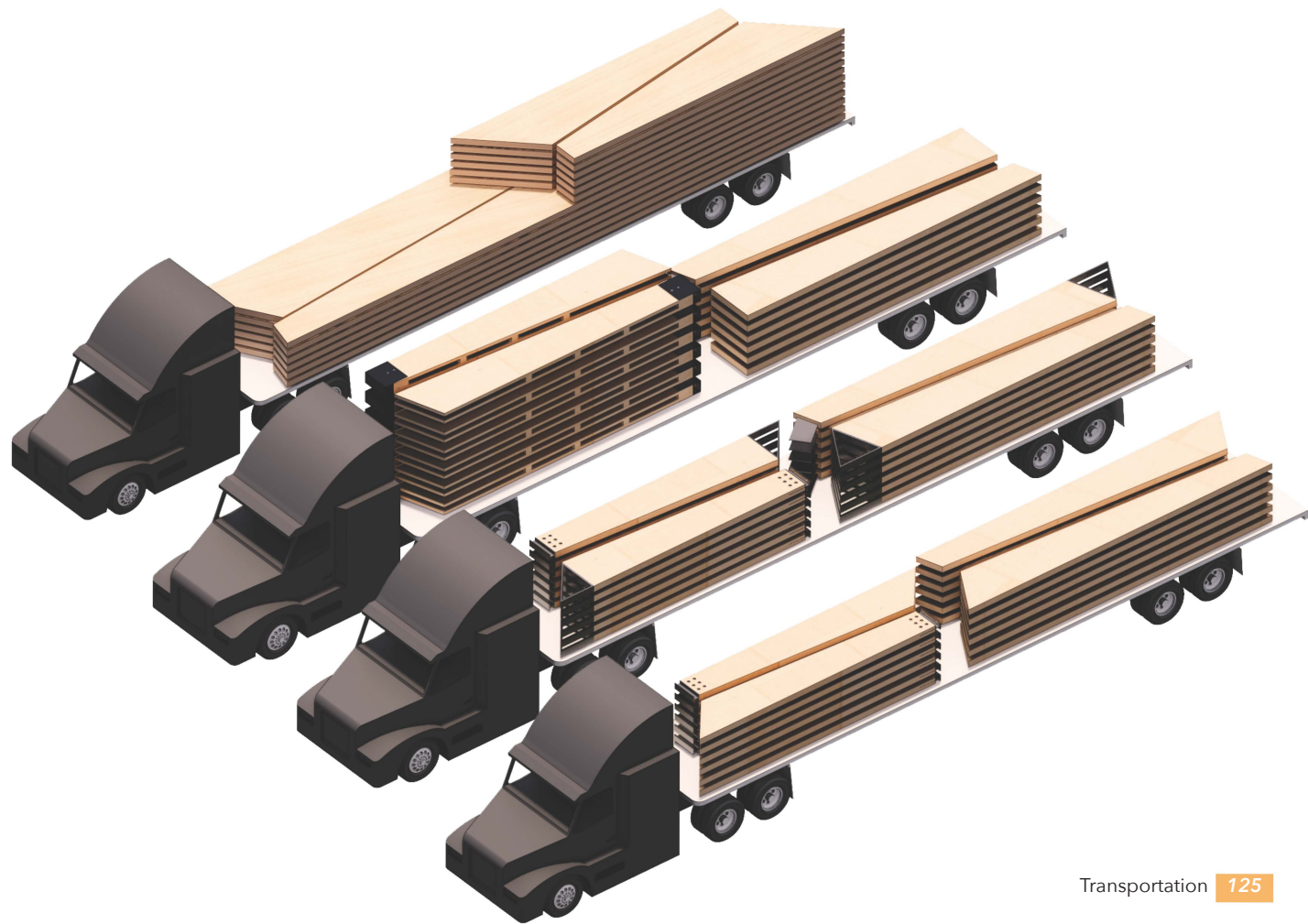
Height :

Federal and State highway regulations limit vehicle cargo height to 14'-0". By obtaining special permits and careful routes, the height can be expanded to 16'-0".

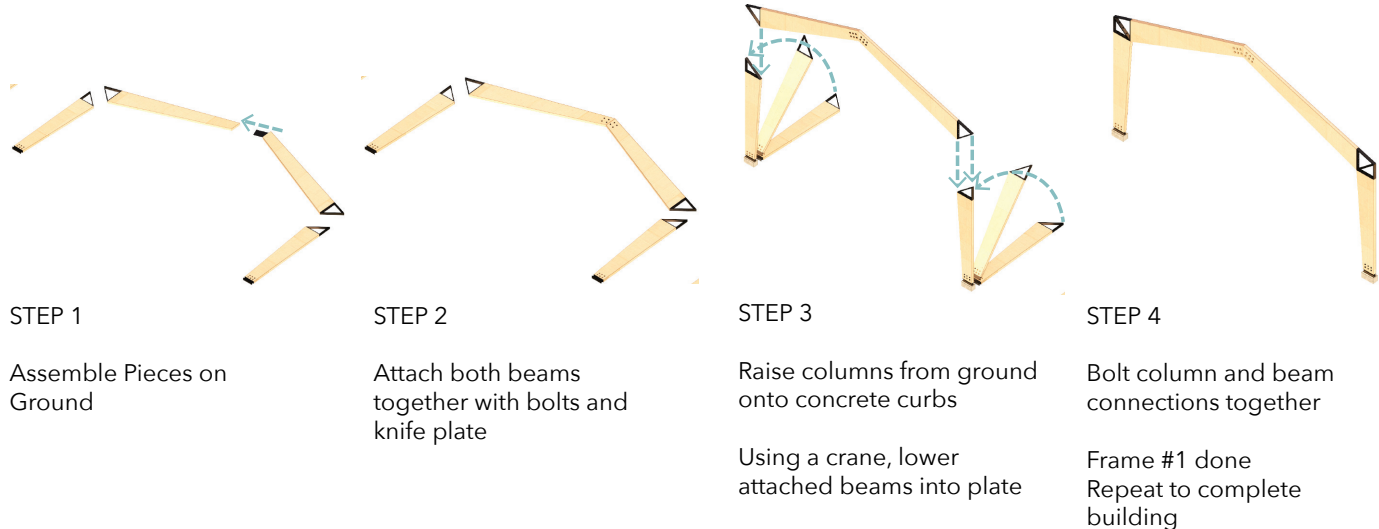




In laying out all the frame members required for a building within the Modern Building Systems summarized guidelines for State and Federal transport on trucks, I found that all members fit on a flat bed semi-truck.



Below is a diagram of one way the open steel connection could be constructed from taking the frame members from the flat bed truck, to be constructed as a frame. The open steel connection has the most pre-fabrication in the factory which limits the work on site once unloaded from the truck.







KIT OF PARTS

Kit of Parts Methodology

To re-iterate, when ordering a pre-engineered metal building, you have the option to additionally order from a range of “kit of parts” including secondary framing, wall cladding, roofing systems, door and window trim, corner and eave trim as well as skylights. The ability to order an entire building enclosure as well as the structural framing including all the bolts, screws and connectors is a signature of this building typology.

In my mass timber alternative, I looked at how we can create a mass timber kit of parts for secondary framing as well as wall cladding and roofing systems in a sustainable way. First, I considered the main types of cladding systems offered by Butler Buildings. Once identifying two cladding systems that they employ, full height panels and foam panels, Then I determined how these systems could be improved from an energy performance and environmental impacts perspective. The cladding assemblies I designed are on the following pages.

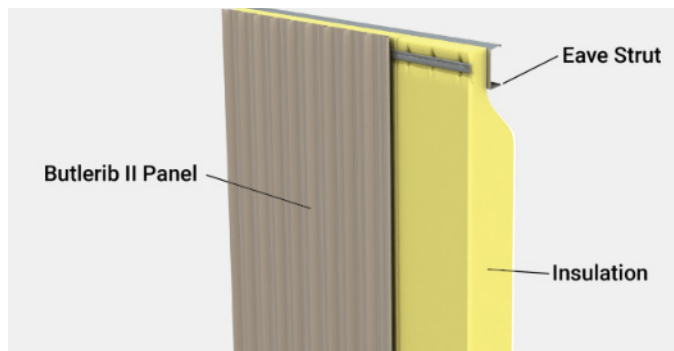


Existing Butler Wall Systems

FULL HEIGHT PANELS

3'-0" wide metal panels span from the base trim to the eave strut. Once the girts have been installed on to the primary frames, a sheet of plastic is laid across girts, a batt insulation follows. A metal stanchion pinches the batt insulation creating a connection point to each steel girt. A metal panel that is 3'-0" wide is attached to the stanchions. The metal exterior cladding is available in different gauges and profiles.

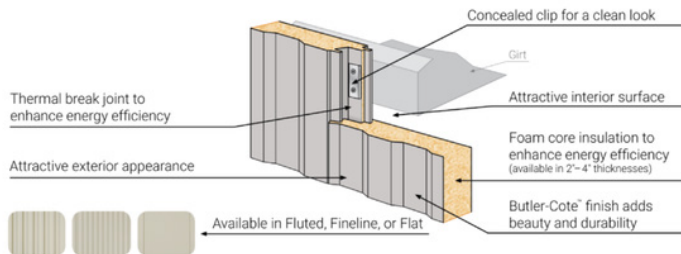
However convenient and inexpensive, this assembly often has durability issues when the sheet of plastic rips, or sags causing the insulation to be exposed.



INSULATED FOAM PANEL

The insulated foam panel is a pre-finished panel which requires less labor in the field. These panels are typically 2'-0" to 3'-0" wide and span from the base trim to the eave. The panels consist of an interior plastic finish, foam core insulation (minimum 2" to 4") and a metal cladding. The panels offer a concealed clip to attach back to the steel girt provided a clean exterior look and to create a thermal break joint for energy efficiency.

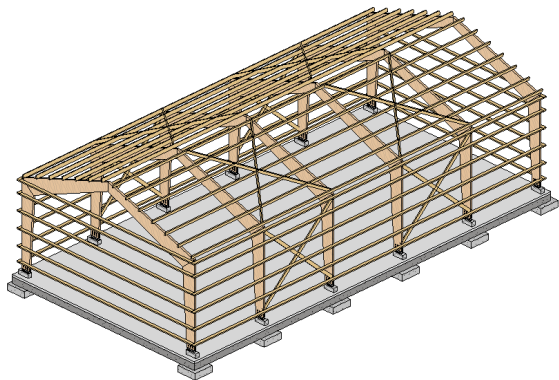
Panel-To-Structure Attachment



Secondary Framing Exploration - Girts

In the butler building typology, steel girts are added across the primary members as secondary framing members.

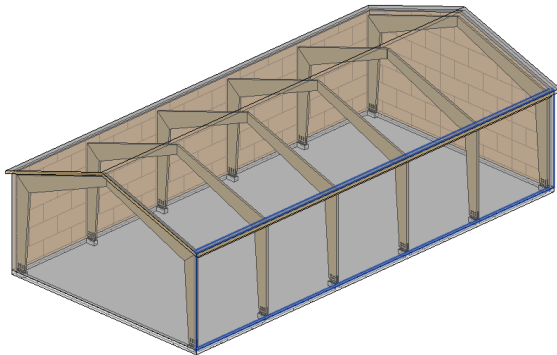
My first exploration of creating a mass timber alternative to secondary framing was to create mass plywood panel girts. The mass plywood girts are 2" x 9" cross section and are spaced 4'-0" on the walls and in the roof. Timber cross bracing is added in two bays in the wall and roof plane.



Secondary Framing Exploration - Mass Plywood

In order to full take advantage of a mass timber cladding system, I investigated using 2" mass plywood panels as the secondary framing.

As advised by my advisor Mikhail Gershfeld, the mass plywood panel as the wall and roof acts as the structural diaphragm for the building. Although calculations from a structural engineer would need to be done to confirm, but the primary frames with mass plywood walls would just be taking gravity load and could be optimized for smaller member sizes.



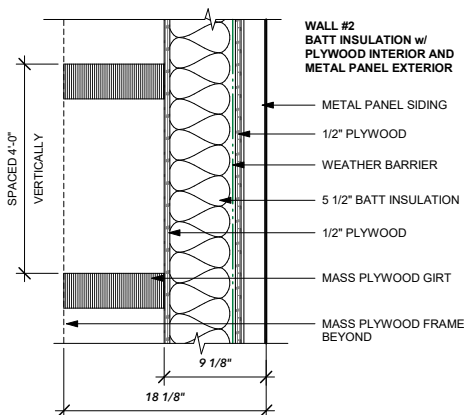
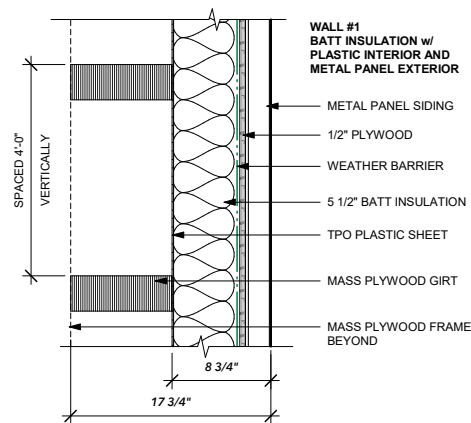
Cladding Exploration

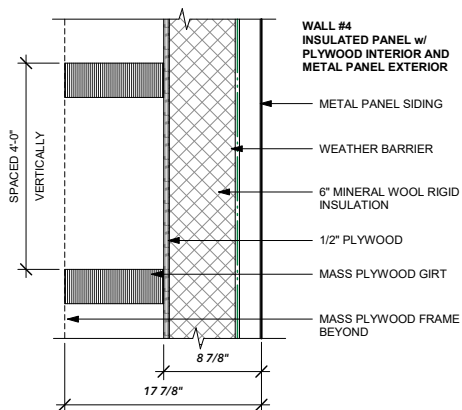
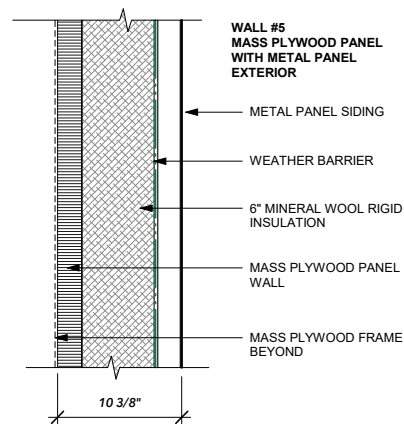
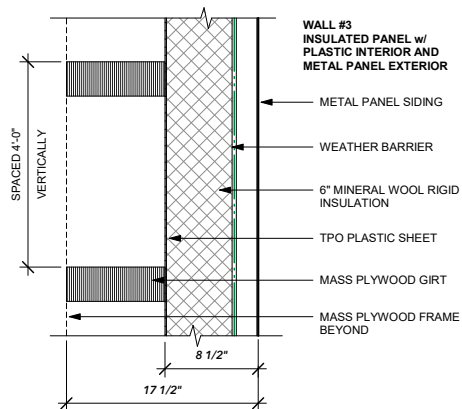
Once the secondary framing systems were developed, five cladding systems were investigated. The differences between the cladding systems come from the insulation type and interior finish.

For the first two cladding systems they use batt insulation, alike the full height panel that is standard for Butler buildings. For the last three cladding systems they use a rigid mineral wool board insulation.

The first and the third cladding systems use a plastic TPO interior finish, alike the Butler building standard finish. The second and the fourth cladding system employ a plywood sheet as a substitute for the interior finish. The fifth cladding system has mass plywood panel as its interior finish.

Across all five cladding systems, all have metal panel siding. Metal panel siding is an industry standard for a durable, lightweight, low cost cladding system.







PART III :
ANALYSIS

The image features a blurred background of a dense green forest. In the foreground, a sharp, detailed pine branch with green needles extends from the right side towards the center. The text "ENVIRONMENTAL ANALYSIS" is overlaid in the lower-left quadrant in a white, bold, sans-serif font.

ENVIRONMENTAL ANALYSIS



Life Cycle Assessment Methodology

In order to quantify the environmental impacts of the different frame systems, life cycle assessments (LCA) is a helpful tool.

Inputs (like material extraction, fabrication and manufacturing) and outputs (such as carbon emissions) are measured over an entire life cycle of a building.

One of the main incentives of creating a mass timber alternative to a pre-engineered metal building is the potential to lower the building emissions and even sequester carbon. The goal with performing life cycle assessments

For this project there are two different methodologies and systems that I used to conduct life cycle assessments:

For the primary structural frame and connection variations both in mass plywood and in steel, the assessments were done through excel calculations drawing from the environmental product declaration (EPD) for each of the materials.

Due to the material complexity of a cladding system containing multiple materials compared to the structural frames which only have two, the cladding system life cycle assessments were completed with the software Tally. Tally is an Autodesk Revit plug-in.



Life cycle of mass timber materials

system boundary includes stages A1-C4

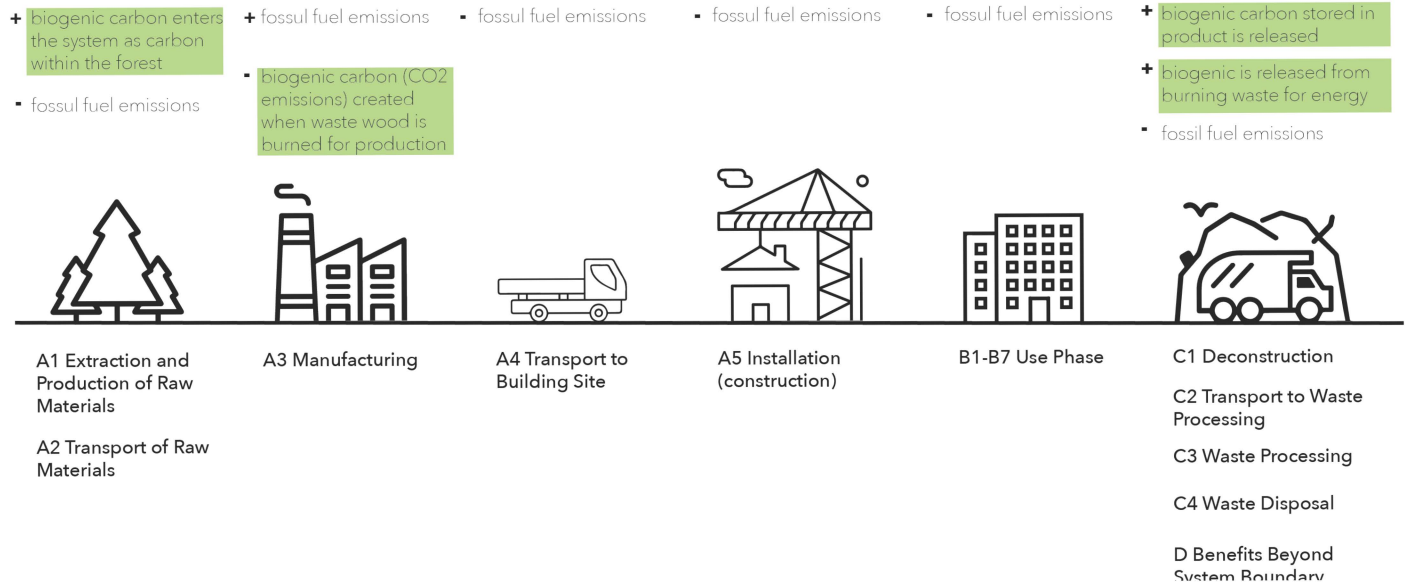


Diagram of system boundary of stages assessed in LCA.

Life Cycle Assessment - Primary Structural System

The life cycle assessments for the primary structural system were completed by calculating the global warming potential from published environmental product declarations for each of the primary materials. The life cycle assessments for the primary structural system has defined system boundaries as are limited to A1-A3. The three materials which EPD's were gathered were mass plywood panels from Freres Engineered Wood, hot rolled pre fabricated steel fasteners from an industry standard EPD, and a pre engineered primary frame members from the metal building manufacturers association. The three EPD's have been included as Appendix 3-5. The steps of calculation are outlined over the next few pages.

The life cycle assessments were calculated for each of the connections that were developed, plywood gusset, open steel connection and dowel connection for each of the span widths. They were separated due to the differing amounts of steel fasteners and mass plywood among the connection types. The next page shows the frame shapes, and a summary of the life cycle assessments among the different connection types. The following pages break down the calculations done to calculate the global warming potential.

The first step in calculating the global warming potential from the EPD data is converting all of the declared units into cubic meters.

The second step was taking the total cubic meter of each material per frame and multiplying it by the EPD functional unit. In the case of the mass plywood, there is a different value for the functional unit depending on the biogenic carbon inventory parameters. In the EPD to calculate the global warming potential accounting for biogenic carbon, values were taken from Table 3: Biogenic carbon Inventory parameters for Mass Ply Panel, and substituting them into a revised Table 2. The calculations are explained on adjacent page.



Table 2 from Freres EPD :

Table 2: LCIA Results Summary for Cradle-to-Gate production of 1 m3 of Mass Ply Panel.

Core Mandatory Impact Indicator			TOTAL	A1	A2	A3
Global warming potential, biogenic ¹	GWP _{BIO}	kg CO2e	259.16	(2,105.83)	0.18	2,364.80
Global warming potential, TRACI 2.1	GWP _{TRACI}	kg CO2e	259.16	199.47	0.18	59.51

Table 3: Biogenic carbon inventory parameters for Mass Ply Panel

Additional Inventory Parameters		A1	A2	A3	A5	C3/C4	Total
		kg CO2e					
Biogenic Carbon Removal from Product	BCRP	(2,305.30)	-	0.00	0.00	0.00	(2,305.30)
Biogenic Carbon Emission from Product	BCEP	0.00	-	958.07	0.00	1,000.62	1,958.69
Biogenic Carbon Removal from Packaging	BCRK	-	-	(0.3712)	0.00	-	(0.3712)
Biogenic Carbon Emission from Packaging	BCEK	-	-	0.00	0.00	-	-
Biogenic Carbon Emission from Combustion of Waste from Renewable Sources Used in Production	BCEW	-	-	346.98	0.00	-	346.98

Biogenic Carbon Inventory Parameters TOTAL : (2,305.30) + 1,304.68 = -1,000.62

Revised Table 2 with revised biogenic carbon inventory parameters:

Core Mandatory Impact Indicator			TOTAL	A1	A2	A3
Global Warming Potential, biogenic	GWP _{bio}	kgCO2eq	(741.46)	(2,105.83)	0.18	1,364.19
Global Warming Potential, TRACI 2.1	GWP _{traci}	kgCO2eq	259.16	199.47	0.18	59.51

Single Tapered Beam

Single Tapered Column

50' - 0" span

20' - 0" bay spacing

Volume of Wood varies
per connection type

Pre-Engineered Frame

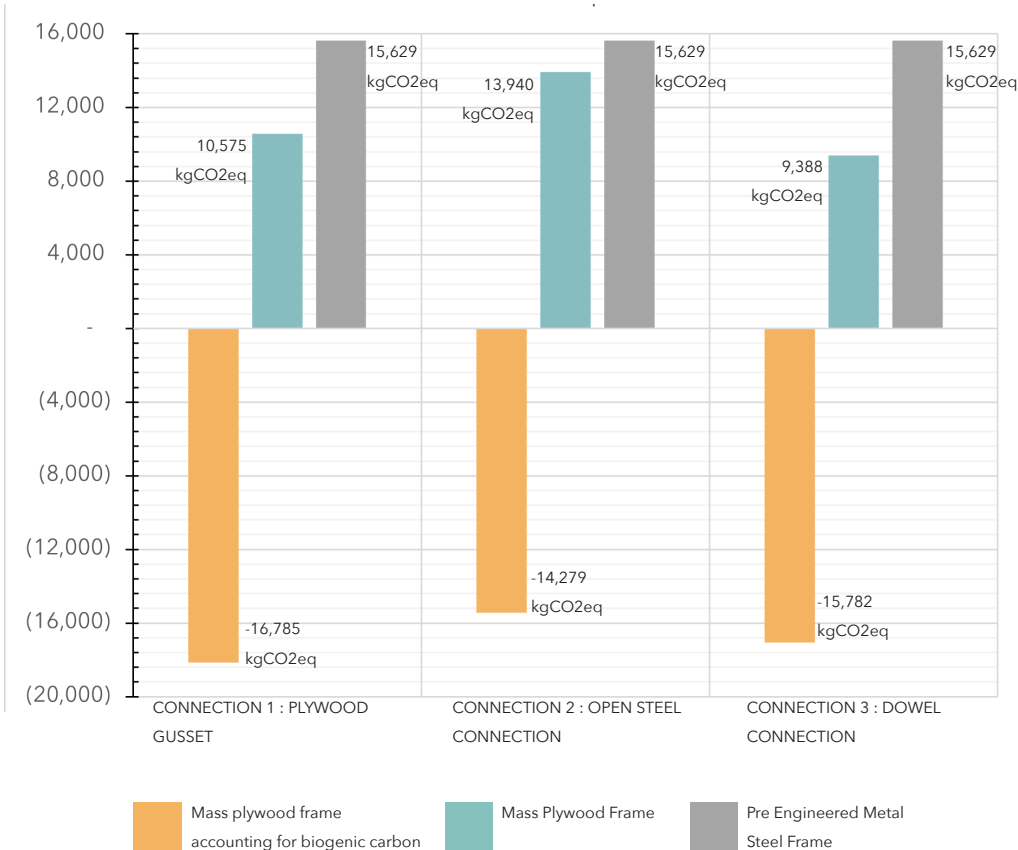
Single Tapered Beam

Single Tapered Column

50' - 0" span

20' - 0" bay spacing

Volume : 8 CF



The assessment from the EPD outputs shows that when accounting for both biogenic carbon and without biogenic carbon, across the three connection types the global warming potential of the mass plywood building is lower in all three scenarios.

Out of the three connections, the steel dowels has the lowest global warming potential when not accounting for biogenic carbon as it has the least amount of steel out of all of the connections.

The plywood gusset has the lowest global warming potential when accounting for biogenic carbon due to the extra plywood required for the connection.

50' - 0 " SPAN || Connection 1 - Plywood Gusset Plate

EPD Exports			
CONVERSION			
Frame Type	Density of Material	Volume of 1 metric ton	Cubic Meters of Material per Frame
Mass Plywood Frame			3.77 m3
Mass Plywood	N/A	N/A	
Steel Fastners	7,800 kg per m3	0.128 m3	
Pre-Engineered Metal Steel Frame	7,833 kg per m3	0.13 m3	0.23 m3

EPD APPLICATION						
	EPD FUNCTIONAL UNIT	GWP per unit (A1-A3)	GWP (biogenic) per unit (A1-A3)	Units per Frame	GWP PER FRAME	GWP (biogenic) PER FRAME
Mass Plywood Frame						
Mass Plywood	1 m3	259.16 kgCO2eq	(741.46) kgCO2eq	3.77	977.79 kgCO2eq	(2,797.46) kgCO2eq
Steel Fastners	1 m3	11,450.40 kgCO2eq	N/A	0.069	784.65 kgCO2eq	N/A
TOTAL					1,762.44 kgCO2eq	(2,797.46) kgCO2eq
Pre-Engineered Metal Steel Frame	1 m3	11,498.84 kgCO2eq	N/A	0.227	2,604.86 kgCO2eq	N/A

COMPARISON		
	EPD	
Wall Exploration Name	Without Biogenic Carbon	With Biogenic Carbon
Mass Plywood Panel Frame	10,574.62 kgCO2eq	(16,784.73) kgCO2eq
Pre-Engineered Metal Steel Frame	15,629.18 kgCO2eq	N/A

50' - 0" SPAN || Connection 2 - Open Steel Connection

EPD Exports			
CONVERSION			
Frame Type	Density of Material	Volume of 1 metric ton	Cubic Meters of Material per Frame
Mass Plywood Frame			
Mass Plywood	N/A	N/A	3.21 m3
Steel Fastners	7,800 kg per m3	0.128 m3	0.13 m3
Pre-Engineered Metal Steel Frame	7,833 kg per m3	0.13 m3	0.23 m3

EPD APPLICATION						
	EPD FUNCTIONAL UNIT	GWP per unit (A1-A3)	GWP (biogenic) per unit (A1-A3)	Units per Frame	GWP PER FRAME	GWP (biogenic) PER FRAME
Mass Plywood Frame						
Mass Plywood	1 m3	259.16 kgCO2eq	(741.46) kgCO2eq	3.21	831.82 kgCO2eq	(2,379.85) kgCO2eq
Steel Fastners	1 m3	11,450.40 kgCO2eq	N/A	0.130	1,491.49 kgCO2eq	N/A
TOTAL					2,323.31 kgCO2eq	(2,379.85) kgCO2eq
Pre-Engineered Metal Steel Frame	1 m3	11,498.84 kgCO2eq	N/A	0.227	2,604.86 kgCO2eq	N/A

COMPARISON		
	EPD	
Wall Exploration Name	Without Biogenic Carbon	With Biogenic Carbon
Mass Plywood Panel Frame	13,939.85 kgCO2eq	(14,279.11) kgCO2eq
Pre-Engineered Metal Steel Frame	15,629.18 kgCO2eq	N/A

50' - 0 " SPAN || Connection 3 - Dowells

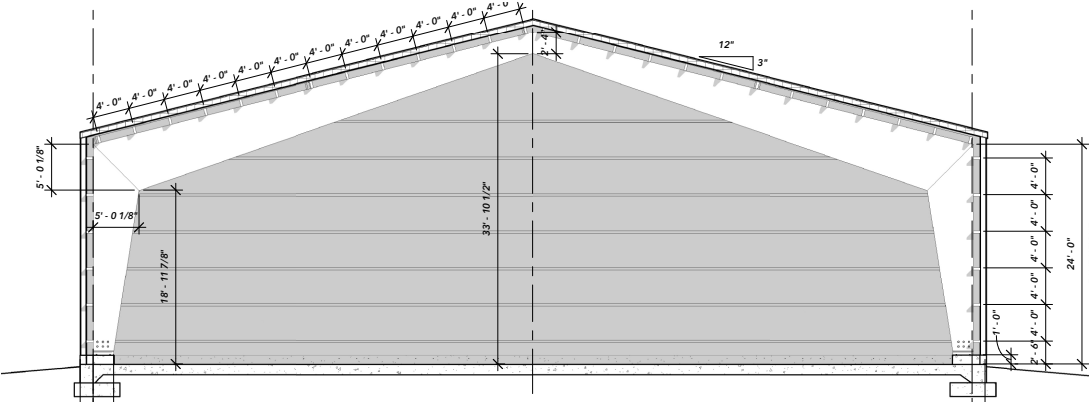
EPD Exports			
CONVERSION			
Frame Type	Density of Material	Volume of 1 metric ton	Cubic Meters of Material per Frame
Mass Plywood Frame			3.55 m3
Mass Plywood	N/A	N/A	
Steel Fastners	7,800 kg per m3	0.128 m3	
Pre-Engineered Metal Steel Frame	7,833 kg per m3	0.13 m3	0.23 m3

EPD APPLICATION						
	EPD FUNCTIONAL UNIT	GWP per unit (A1-A3)	GWP (biogenic) per unit (A1-A3)	Units per Frame	GWP PER FRAME	GWP (biogenic) PER FRAME
Mass Plywood Frame						
Mass Plywood	1 m3	259.16 kgCO2eq	(741.46) kgCO2eq	3.55	919.37 kgCO2eq	(2,630.33) kgCO2eq
Steel Fastners	1 m3	11,450.40 kgCO2eq	N/A	0.056	645.23 kgCO2eq	N/A
TOTAL					1,564.60 kgCO2eq	(2,630.33) kgCO2eq
Pre-Engineered Metal Steel Frame	1 m3	11,498.84 kgCO2eq	N/A	0.227	2,604.86 kgCO2eq	N/A

COMPARISON		
	EPD	
Wall Exploration Name	Without Biogenic Carbon	With Biogenic Carbon
Mass Plywood Panel Frame	9,387.60 kgCO2eq	(15,781.98) kgCO2eq
Pre-Engineered Metal Steel Frame	15,629.18 kgCO2eq	N/A



Life Cycle Assessment - Structural Frames



Mass Timber Frame

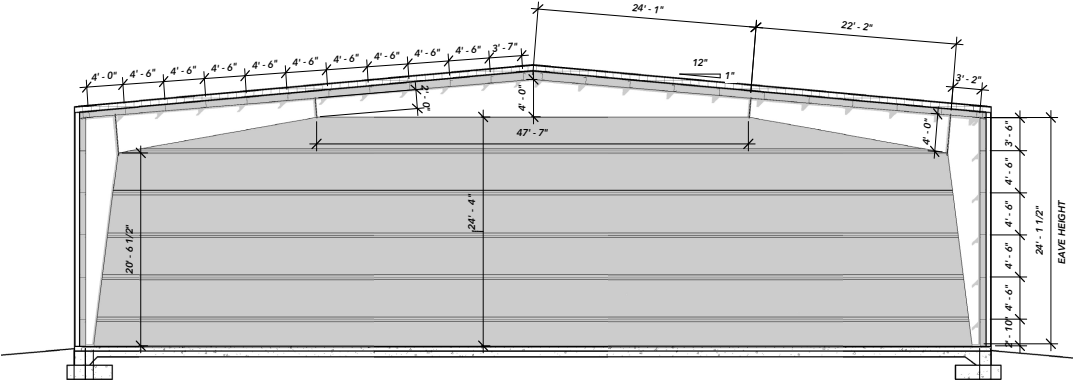
Single Tapered Beam

Single Tapered Column

94' - 0" span

20' - 0" bay spacing

Volume varies per connection type



Pre-Engineered Frame

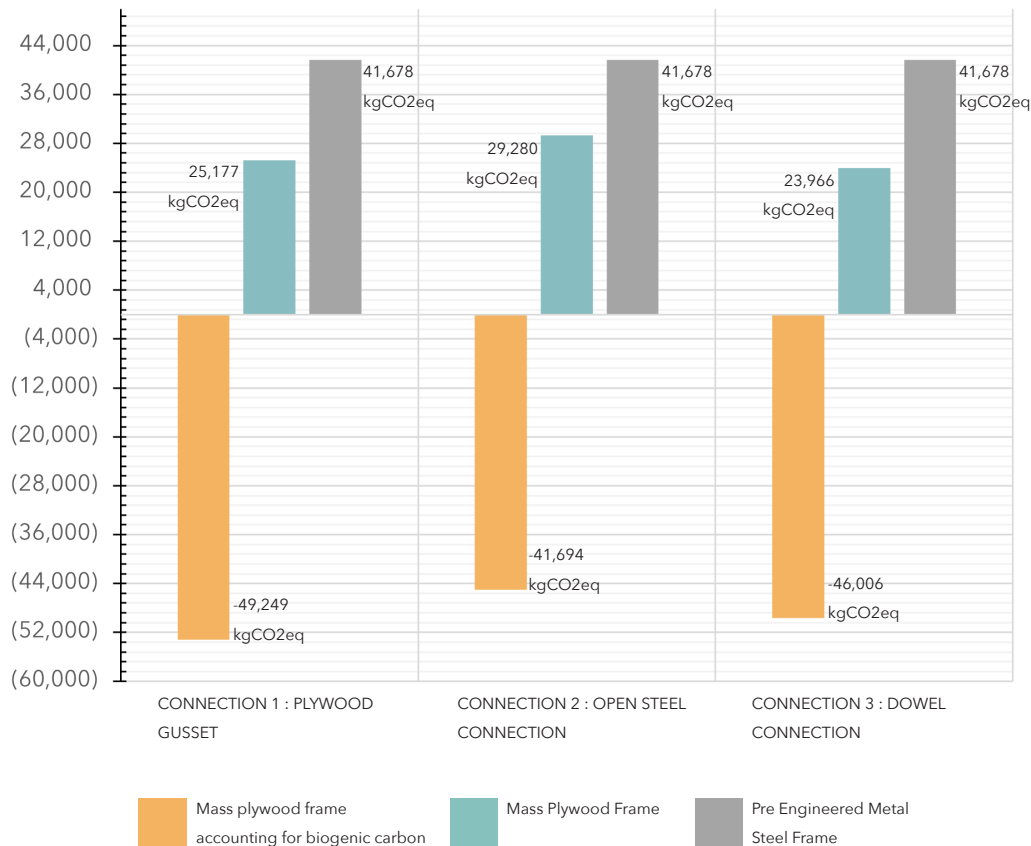
Single Tapered Beam

Single Tapered Column

94' - 0" span

20' - 0" bay spacing

Volume : 16 CF



The assessment from the EPD outputs shows that when accounting for both biogenic carbon and without biogenic carbon, across the three connection types the global warming potential of the mass plywood building is lower in all three scenarios.

Similar to the shorter span, the steel dowels has the lowest global warming potential when not accounting for biogenic carbon as it has the least amount of steel out of all of the connections.

The plywood gusset has the lowest global warming potential when accounting for biogenic carbon due to the extra plywood required for the connection.

94'-0" SPAN || Connection 1 - Plywood Gusset Plate

EPD Exports			
CONVERSION			
Frame Type	Density of Material	Volume of 1 metric ton	Cubic Meters of Material per Frame
Mass Plywood Frame			
Mass Plywood	N/A	N/A	8.30 m3
Steel Fastners	7,800 kg per m3	0.128 m3	0.09 m3
Pre-Engineered Metal Steel Frame	7,833 kg per m3	0.13 m3	0.45 m3

EPD APPLICATION						
	UNIT	GWP per unit (A1-A3)	(A1-A3)	Frame	GWP PER FRAME	FRAME
Mass Plywood Frame						
Mass Plywood	1 m3	259.16 kgCO2eq	(741.46) kgCO2eq	8.30	2,151.73 kgCO2eq	(6,156.12) kgCO2eq
Steel Fastners	1 m3	11,450.40 kgCO2eq	N/A	0.087	995.41 kgCO2eq	N/A
TOTAL					3,147.13 kgCO2eq	(6,156.12) kgCO2eq
Pre-Engineered Metal Steel Frame	1 m3	11,498.84 kgCO2eq	N/A	0.453	5,209.73 kgCO2eq	N/A

COMPARISON		
	EPD	
Wall Exploration Name	Without Biogenic Carbon	With Biogenic Carbon
Mass Plywood Panel Frame	25,177.07 kgCO2eq	(49,248.98) kgCO2eq
Pre-Engineered Metal Steel Frame	41,677.81 kgCO2eq	N/A

94' - 0" SPAN || Connection 2 - Open Steel Connection

EPD Exports			
CONVERSION			
Frame Type	Density of Material	Volume of 1 metric ton	Cubic Meters of Material per Frame
Mass Plywood Frame			
Mass Plywood	N/A	N/A	7.03 m3
Steel Fastners	7,800 kg per m3	0.128 m3	0.16 m3
Pre-Engineered Metal Steel Frame	7,833 kg per m3	0.13 m3	0.45 m3

EPD APPLICATION						
	UNIT	GWP per unit (A1-A3)	(A1-A3)	Frame	GWP PER FRAME	FRAME
Mass Plywood Frame						
Mass Plywood	1 m3	259.16 kgCO2eq	(741.46) kgCO2eq	7.03	1,821.64 kgCO2eq	(5,211.74) kgCO2eq
Steel Fastners	1 m3	11,450.40 kgCO2eq	N/A	0.161	1,838.42 kgCO2eq	N/A
TOTAL					3,660.06 kgCO2eq	(5,211.74) kgCO2eq
Pre-Engineered Metal Steel Frame	1 m3	11,498.84 kgCO2eq	N/A	0.453	5,209.73 kgCO2eq	N/A

COMPARISON		
	EPD	
Wall Exploration Name	Without Biogenic Carbon	With Biogenic Carbon
Mass Plywood Panel Frame	29,280.49 kgCO2eq	(41,693.92) kgCO2eq
Pre-Engineered Metal Steel Frame	41,677.81 kgCO2eq	N/A

94' - 0 " SPAN || Connection 3 - Dowells

EPD Exports			
CONVERSION			
Frame Type	Density of Material	Volume of 1 metric ton	Cubic Meters of Material per Frame
Mass Plywood Frame			
Mass Plywood	N/A	N/A	7.76 m3
Steel Fastners	7,800 kg per m3	0.128 m3	0.09 m3
Pre-Engineered Metal Steel Frame	7,833 kg per m3	0.13 m3	0.45 m3

EPD APPLICATION						
	UNIT	GWP per unit (A1-A3)	(A1-A3)	Frame	GWP PER FRAME	FRAME
Mass Plywood Frame						
Mass Plywood	1 m3	259.16 kgCO2eq	(741.46) kgCO2eq	7.76	2,010.02 kgCO2eq	(5,750.70) kgCO2eq
Steel Fastners	1 m3	11,450.40 kgCO2eq	N/A	0.086	985.68 kgCO2eq	N/A
TOTAL					2,995.70 kgCO2eq	(5,750.70) kgCO2eq
Pre-Engineered Metal Steel Frame	1 m3	11,498.84 kgCO2eq	N/A	0.453	5,209.73 kgCO2eq	N/A

COMPARISON		
	EPD	
Wall Exploration Name	Without Biogenic Carbon	With Biogenic Carbon
Mass Plywood Panel Frame	23,965.60 kgCO2eq	(46,005.58) kgCO2eq
Pre-Engineered Metal Steel Frame	41,677.81 kgCO2eq	N/A

In both building spans and connection types the mass plywood frames have across the board less global warming potential than the steel frame.

In the short span, when not accounting for the impacts of biogenic carbon the mass plywood frames emit 11-40% less carbon emissions than the steel frame. When accounting for the impacts of biogenic carbon, the mass plywood frames emit 191-207% less emission than the steel frame.

The larger difference between pre-engineered frame and mass plywood frame is the larger span. When not accounting for the impacts of biogenic carbon the mass plywood frames emit 30-42% less carbon emissions than the steel frame. When accounting for biogenic carbon, the mass plywood frames emit 200-218% less carbon emissions than the steel frame.

Summary of Global Warming Potential of Primary Structural Members : between frame,connection and material types

Frame and Connection Type		Mass Plywood Frame		Pre Engineered Metal Steel Frame
		With Biogenic Carbon	Without Biogenic Carbon	
50'	Connection 1 - Plywood Gusset	(18,132) kgCO ₂ eq	10,575 kgCO ₂ eq	15,629 kgCO ₂ eq
	Connection 2- Open Connection	(15,425) kgCO ₂ eq	13,940 kgCO ₂ eq	15,629 kgCO ₂ eq
	Connection 3 - Dowells	(17,049) kgCO ₂ eq	9,388 kgCO ₂ eq	15,629 kgCO ₂ eq
94'	Connection 1 - Plywood Gusset	(53,202) kgCO ₂ eq	25,177 kgCO ₂ eq	41,678 kgCO ₂ eq
	Connection 2- Open Connection	(45,040) kgCO ₂ eq	29,280 kgCO ₂ eq	41,678 kgCO ₂ eq
	Connection 3 - Dowells	(49,698) kgCO ₂ eq	23,966 kgCO ₂ eq	41,678 kgCO ₂ eq

Life Cycle Assessment - Cladding

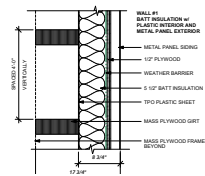
The life cycle assessments for the cladding system were completed with the software Tally. Tally is an Autodesk Revit Plug-in. For this project, I was able to receive a free educational software trail for use. The quantity of materials are taken from Revit and translated into volumes which are computed in their own LCI database (Zuo et al. 2017). Tally creates a methodology report which includes the bill of materials that was user specified, these report have been included as Appendix 6 and 7 . I chose to run the cladding life cycle assesments through Tally instead of calculating through EPD's is the complexity of multiple materials in each cladding system, but also across the whole.

The life cycle assessment of the cladding through Tally was run one accounting for the impact of biogenic carbon and one that discounts the effect of biogenic carbon. Biogenic carbon is the stored carbon in the growth of biomass.

However helpful, there are shortcomings of life cycle assessment software. At the time of this study, the software Tally does not have a published environmental product declaration (EPD) for mass plywood panel in their software. In lieu, laminated veneer lumber was selected as the member to be assessed. Freres Engineered Wood has published an EPD, but it has not been incorporated into the software of Tally.

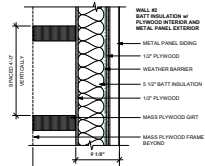
Out of the cladding, the three assemblies, Wall 2, Wall 4 and Wall 5 which all feature plywood as the interior finish had the lowest global warming potential out of the five assemblies. This is likely due to the additional bio-based material in the assemblies. The cladding with TPO plastic as the interior finish and mineral wool insulation had the largest gloval warming potential, 48,661 kgCO₂eq when not accounting for biogenic carbon, and 33,959 kgCO₂eq when accounting for the impacts of biogenic carbon.





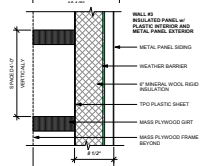
WALL 1

Batt Insulation /
Plastic
Interior



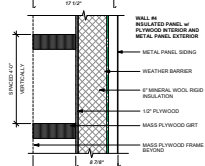
WALL 2

Batt Insulation /
Plywood
Interior



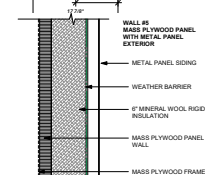
WALL 3

Mineral Wool /
Plastic
Interior



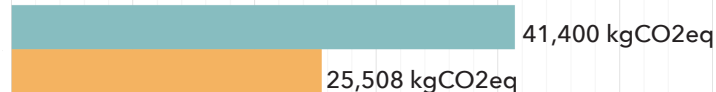
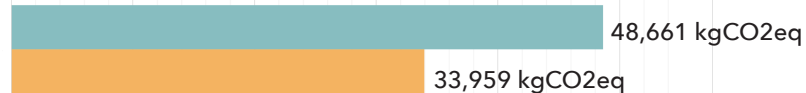
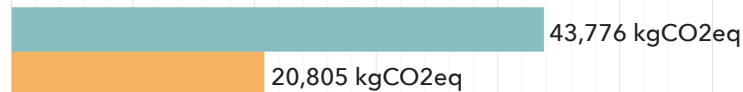
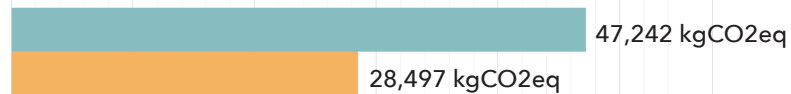
WALL 4

Mineral Wool /
Plywood
Interior



WALL 5

Mineral Wool /
Mass Plywood
Panel



Global warming potential
accounting for biogenic carbon

Global warming
potential





COSTING

Costing Methodology

Regardless of the deciding what building system to build, many of decisions as the structural system come down to the economics.

A common barrier in adoption of new systems is the cost premium that comes along with the innovation. Although the final step in my analysis, the costing analysis of the developed mass plywood frames and the pre-engineered frames was among the most crucial if these frames are to be adopted and utilized in actual built work.

In order to figure out the costing of the pre-engineered frames, I reached out to Chambers Construction the licensed Butler Building manufacturer in our region. Once the final frames that I was concentrating on for refinement were set, I relayed those to Chambers Construction's Butler Sales Manager Logan Zenk for costing estimate. The cost estimate includes just the primary structural frames, and does not include any labor, secondary framing, cladding systems or foundation.

In order to figure out the costing for the mass plywood frames, I was able to obtain a costing bid from December 2020 for a mass plywood building from a construction company in Portland with mass timber expertise. The costing bid was from a similar building system, and therefore was used to calculate costing estimates for the frames developed. From the costing bid, I parsed out the line items including just the primary structure including the connections. As the costing bid was from 2020, a factor of inflation was added to the cost to make them comparable in this study. Although over the last two years there has been volatility in lumber costs from supply chain shortages and rapid inflation, the price of mass plywood has increased from thirty-four dollars per cubic foot to thirty-seven dollars per cubic foot.

Before conducting the costing assessment, my goal was for the mass plywood frames to be within a ten percent premium when compared to a Butler building frame. My





hope was for a developer or a prospective tenant to choose to construct one of these mass plywood frames and be willing to absorb a ten percent premium for an innovative building.

Once the costing exercise compared the Butler Building costing estimate and the mass timber frame estimate, in both the short and the longer span the mass timber was thirty-four percent cheaper. In the shorter fifty-foot span, the mass timber alternative was sixty-five thousand nine hundred dollars less expensive than the Butler building frame. In the longer ninety-four-foot span, the mass timber frames were one hundred and ten thousand dollars less expensive than the Butler building frame.

Even in 2022, the global supply chain and its impact on commodity goods such as steel are constantly in flux. The costing estimates obtained and that are compared in this study reflect a point in time, May 2022.

Acknowledgement :



FRAME #1 COST ESTIMATE
50'-0" SPAN X 100'-0" LONG

Estimates from Cost Bid for MPP Frame Building December 2020				
	Takeoff Quantity	Total Cost / Unit	Total Amount	
FRAME #1 Primary Structure (Frames)				
Knife Plate, Embeds and Through Bolts	9,000 sf	3.5 /sf	\$ 31,500	
Furnish MPP Materials	4,342 sf	19.17 /sf	\$ 83,232	
			\$ 114,732	2020 costing bid
			12%	addition of 12% inflation
			\$ 128,500.00	2022 costing estimate

Butler Building Costing from Chambers Construction, April 2022				
Frame #1 Primary Structure (Frames)			\$ 194,400.00	2022 costing bid

+ \$65,900 (34%)
PREMIUM FOR
BUTLER BUILDING
FRAME



FRAME #2 COST ESTIMATE
94' - 0" SPAN X 100'-0" LONG

Estimates from Cost Bid for MPP Frame Building December 2020				
	Takeoff Quantity	Total Cost / Unit	Total Amount	
FRAME #2 Primary Structure (Frames)				
Knife Plate, Embeds and Through Bolts	15,000 sf	3.5 /sf	\$ 52,500	
Furnish MPP Materials	9,650 sf	19.17 /sf	\$ 185,000	
			\$ 237,500	2020 costing bid
			12%	addition of 12% inflation
			\$ 266,000.00	2022 costing estimate

Butler Building Costing from Chambers Construction, April 2022				
Frame #2 Primary Structure (Frames)			\$ 325,200.00	2022 costing bid

+ \$59,200 (18%)
PREMIUM FOR
BUTLER BUILDING
FRAME







CONCLUSIONS

Costing 167

Conclusions

My goal with this project was to create a viable alternative to pre-engineered metal frame buildings out of mass timber.

Through developing these structural frames, applying them in demonstration buildings, and analyzing them for preliminary structural optimization, environmental analysis and delivering the buildings for less than a Butler Buildings, this project demonstrates that these frame systems are a viable alternative. As these frame building systems cost less (34% less for the 50'-0" span, and 18% less for the 94'-0" span) than Butler Building systems, reduce the global warming potential by two-fold, these newly developed systems outperform my original expectations.

As this study included only preliminary sizing of members, further refinement and structural optimization would need to occur to further reduce the amount of wood fiber in each frame. For example, in the cladding exercise where there are mass plywood walls, the frames could be optimized as the frames are only carrying gravity load as the mass plywood wall is acting as the shear diaphragm. In this study, the frame shapes that were able to be explored were limited due to scope and time, one advantage about the Butler building type is the vast array of frame shapes, spans and member sizes that have been developed. A future area of research is explorations in different frame shapes and frame spans. An additional area of research would be to bring this conceptual framework idea to a panel manufacturer or a pre-engineered metal building manufacturer for further fabrication optimization.



Although formal structural calculations would need to be run to confirm all member sizes, the timber frame design dimensions are an estimate based on publicly available sources, discussions with my structural engineering advisor, Professor Gershfeld, throughout the project and conceptual calculations done by my collaborator, Patrick. In addition, a future area of study would be conducting structural calculations for different design loads that vary with location. The adaptability of these systems to be able to have the flexibility to be placed anywhere will make the frames more adoptable for the building industry. Formal structural calculations would need to be conducted on the three connection types that were developed, and there is the potential for further optimization once analyzed by a structural engineer.

The goal when this project started was to create a mass timber alternative in a building sector where wood is rarely considered. Although more structural optimization can occur, the outcome of this project can demonstrate to designers, construction professionals, and the industrial building industry that mass plywood frames are a feasible system. As more companies are leaning to constructing buildings that have lower environmental impacts, these newly developed systems illustrate a system that performs structurally as well as steel, cost significantly less than the steel buildings and significantly reduces the environmental impact. The hope is that this project can serve as part of a catalyst for industrial buildings considering the use of mass timber structural systems.





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This thesis project would not have been possible without my committee chair, Judith Sheine. Thank you for all of the countless advice and helping me shape this study.

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Thank you to Roger Bates at Tally Inc. for providing an educational license to perform the Life Cycle Assessments.



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