PUBLIC REPORT

New York City Public Schools
Mass Timber Design Feasibility Study

Submitted to:

NYC School Construction Authority
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EXECUTIVE SUMMARY

This study was initiated by the NYC School Construction Authority (SCA) in response to three developments: the growing use of mass timber construction in New York City; increased attention by the building design and construction industry to the role of embodied carbon in greenhouse gas (GHG) emissions accounting; and the enactment of the 2022 NYC Building Code (BC).

Mass timber (MT) is a composite material made up of wood laminations, strands, or veneers connected by adhesive or fasteners. This study focuses on two types of MT made from solid dimensional lumber: glue laminated timber (GLT or glulam), in which the lumber is oriented such that the grain of all layers runs parallel to the longitudinal axis; and cross laminated timber (CLT), in which the lumber is oriented such that the grain of different layers run perpendicular or transverse to each other. CLT, which offers two-way bending strength, has revolutionized the MT building industry since its introduction in 1985.

MT materials can serve as structural columns, beams, and floor and wall panels. The use of MT has several advantages over conventional steel and reinforced concrete construction, including but not limited to: reduced embodied carbon, which refers to the carbon emitted by the extraction, manufacture, transportation, installation, maintenance, and ultimate disposal of a material; lighter weight; the potential to use “structure as finish,” reducing the need for concealing materials; human health benefits from exposure to natural building materials; and reduced on-site construction time, waste, and noise.

These and other advantages have driven a rapid increase in the use of MT construction over the past two decades, particularly for mid-sized (100,000sf and 7 stories or less) residential, commercial, and institutional buildings located near commercial forests in Europe and the Northwest U.S. The past decade has seen larger and taller MT buildings constructed across a much wider market, as well as some mid-sized residential and commercial buildings using a hybrid of GLT and reinforced concrete in New York City. The 2022 NYC Building Code, which explicitly allowed the use of CLT for the first time, has increased the potential for MT construction in the city.

This study provides an overview of the policy and code context for MT construction in NYC; an introduction to primary MT design and construction considerations, and their applicability to SCA new school construction; and a feasibility analysis of two SCA test cases demonstrating what could be constructed under the current code: a 40,510sf, 4-story new school addition with a typical SCA program and layout, and a 4,410sf, 1-story standalone gym building with long spans supporting its roof. The analysis for each building includes a schematic-level structural design, a detailed inventory of structural and non-structural MT elements, and an embodied carbon accounting.

The study concludes that a new SCA school including long-span spaces, using GLT columns and beams, CLT floor and wall panels, and reinforced concrete foundations, stair and elevator cores and shear walls, is currently feasible and would yield benefits including smaller foundations due to lighter weight and an approximately 50% reduction in embodied carbon. Such a project would also face challenges including code constraints on building size and a local construction industry with limited MT experience.

TASK 1: RESEARCH REVIEW AND EXPANSION

POLICY CONTEXT

NYS EO22/2022

Directs state executive agencies to adopt a sustainability and decarbonization program. Among other things, EO22 directs the agencies to reduce the embodied carbon of all new construction and substantial renovation projects, to calculate the total embodied carbon of each such project, and to require bidders to provide environmental product declarations (EPDs) quantifying the embodied carbon in the building materials they propose to use in such projects.

NYC EO23/2022

Requires NYC capital agencies (DDC, DCAS, DEP, DOT, and DPR) to:

- Use best efforts to specify low-carbon concrete in capital projects
- Provide environmental product declarations (EPDs) for steel and concrete used in capital projects
- Use best efforts to employ low-emission vehicles on and off construction sites
- Endeavor to achieve the LEED v4 Life Cycle Analysis (LCA) credit for capital projects required to comply with LL32/2016 (the updated “green public buildings law”)
- Develop embodied carbon reduction action plans by 10/1/2023

While the SCA is neither a NYS executive agency nor a NYC capital agency, the goals of NYS EO22/2022 and NYC EO23/2022 are in alignment with the SCA’s sustainability goals.

- Under the Green Schools Guide, which governs the compliance of SCA capacity projects with LL32/2016 (formerly LL86), these projects are required to provide comparative LCAs for the exterior wall assemblies and roof assemblies under consideration during Pre-Schematic Design.

CODE CONTEXT

2022 New York City Building Code

The 2022 NYC Building Code (2022 NYC BC) adopted the use of cross-laminated timber (CLT) and structural composite lumber (SCL, a category which includes laminated veneer lumber or LVL).

- Based on 2015 International Building Code (2015 IBC).
- Also includes some 2021 IBC requirements related to design requirements, production quality, and safety standards for MT elements.
- Explicitly allows the use of MT in Type IV-HT construction
    - *602.4 Type IV. Type IV construction is that type of construction in which the exterior walls are of noncombustible materials or other materials permitted by Section 602.4.1 or 602.4.2, and the interior building elements are of solid wood, glue-laminated timber, heavy timber (HT), structural composite lumber (SCL), or cross-laminated timber (CLT) without concealed spaces.*
- Implicitly allows the use of MT in Type III-A construction
- *602.3 Type III. Type III construction is that type of construction in which the exterior walls are of noncombustible materials and the interior building elements are of any material permitted by this code.* According to communication received on 11/17/2023 from the Department of Buildings (see *Code Clarifications* section below), “The 2022 NYC BC intends to classify all mass timber

buildings as Type IV" and therefore "the department is seeking to clarify the portion of code that seems to allow Type III mass timber buildings in the upcoming code revision cycle."

Following are key mass timber provisions of 2022 NYC BC:

- Concealed spaces are permitted in Type III construction but not Type IV. Concealed space is defined as enclosed spaces within partitions, walls, floors, roofs, stairs, furring, pipe chases and column enclosures and other similar spaces.
    - *602.4 …interior building elements are of solid wood, glue-laminated timber, heavy timber (HT), structural composite lumber (SCL), or cross-laminated timber (CLT) without concealed spaces. Interior walls and partitions not less than 1-hour fire-resistance rating or heavy timber complying with Section 2304.11.2.2 shall be permitted.*
- Cross-laminated timber (CLT) is permitted in exterior wall assemblies for Type IV construction but not Type III.
    - *602.4 …exterior walls are of noncombustible materials or other materials permitted by Section 602.4.1 or 602.4.2…. Exterior non-bearing walls are permitted to be constructed with cross-laminated timber (CLT) complying with Section 602.4.2 of this code…*
    - *602.4.2 Cross-Laminated Timber In Exterior Walls: Cross-laminated timber (CLT) complying with Section 2303.1.4 shall be permitted within exterior wall assemblies not less than 6 inches (152.4 mm) in thickness with a 2-hour rating or less, provided the exterior surface of the cross-laminated timber (CLT) is protected by one of the following:*
        - *Fire-retardant-treated wood sheathing complying with Section 2303.2 and not less than 15/32 inch (11.9 mm) thick;*
        - *Type X gypsum board not less than 5/8 inch (15.9 mm) thick; or*
        - *A noncombustible material.*
- Primary structural framing, floor framing, and roof framing composed of heavy timber structural members meeting minimum sizes have no required fire resistance time.
- Exterior bearing walls (an uncommon design element for SCA capital projects) have a 2+ hrs required fire resistance time.
- Connections between MT structural elements must have 1-hour fire rating and must be tested or proven by engineering analysis.

Summary of structural MT fire protection differences between 2022 NYC BC and IBC:

- Where 2022 NYC BC is more flexible than IBC:
    - Allows Type IV buildings up to 6/7 stories (compared to 3/4 in IBC 2015)
    - Requires lower fire rating than IV-A, IV-B, and IV-C mass timber buildings elsewhere
- Where 2022 NYC BC is less flexible than IBC:
    - Limits Type IV buildings to maximum height of 85 ft
    - Strictly no use of MT in concealed spaces in Type IV buildings (unlike IBC 2021)
    - Connections must be encapsulated (covered by gypsum or other fire-resistant material) or proven to have required fire rating

Most SCA capacity projects (new schools and additions) are currently filed as Type IIA or IB construction.

2021 International Building Code (IBC)

The 2022 NYC BC is based on IBC 2015 rather than IBC 2021 because the NYC code revision process began in 2015; while the process was delayed by the COVID-19 pandemic, it was too late to incorporate IBC 2021. The main differences between the IBC 2021 and NYC BC 2022 are outlined as follows:

- IBC 2021 permits taller and bigger Type IV construction using mass timber subdivided into various construction types with increased allowable building height and area.
- In IBC 2021, concealed spaces are permitted if combustible surfaces are protected or if the spaces are filled with non-combustible insulation.
- IBC 2021 provides a prescriptive approach to calculate fire resistance for mass timber structures by adding the Fire Resistance Rating of unprotected heavy timber member to protection time of the non-combustible material (IBC 2021 Section 722.7).
- Source at DOB commented that there is no guarantee that IBC 2021 provisions for mass timber will be incorporated in the next NYC Building Code.

Table 1 below compares the construction types most likely to be used for a MT school under 2022 NYC BC and IBC 2021.

Table 1. *Building Code Restrictions for Mass Timber Construction Types Applicable to SCA Schools*

	2022 NYC BC		IBC 2021	
Construction Type	III-A	IV-HT	IV-C	IV-HT
Sprinklers Required	Y	Y	Y	Y
Allowable Height (ft)	85	85	85*	85*
Allowable Stories	5	7	4*	4*
Allowable Area Above-grade (sf)	47,000	51,000	96,625	76,500
Structural Fire Resistance Required	√	X	√	X
CLT Permitted in Exterior Wall Assembly	X	√	√	√
Fire Retardant Treated Wood Permitted in Exterior Wall Assembly	√	√	√	√
Concealed Spaces Permitted	√	X	√	√
Unprotected Mass Timber Permitted in Interior Wall Assembly	√	√	√**	√
Interior Finish Requirements Apply (flame spread and smoke development)	√	X	√	X***

** Allowable number of stories and area under IBC 2021 would be subject to change if adopted by NYC.*
*** Mass timber shafts, elevator hoist ways and stair enclosures must be protected with non-combustible materials.*
**** Interior finish requirements apply to exit stairways, exit ramps and exit passageways.*

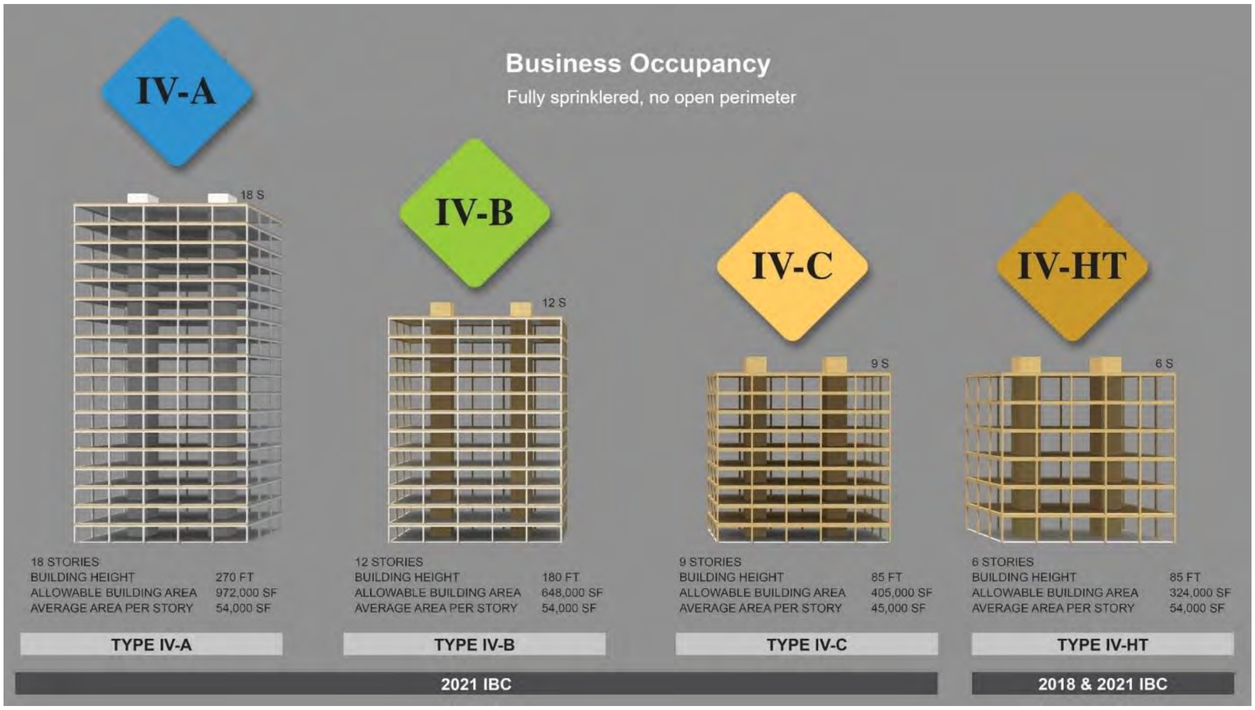


Figure 1. *Mass Timber Construction Types in IBC 2021 (credit: IBC 2021)*

Concealed Spaces

2022 NYC BC defines concealed spaces as "*enclosed spaces within partitions, walls, floors, roofs, stairs, furring, pipe chases and column enclosures and other similar spaces*."

As noted above, 2022 NYC BC allows the use of unprotected MT materials in concealed spaces in Type III construction, but not Type IV.

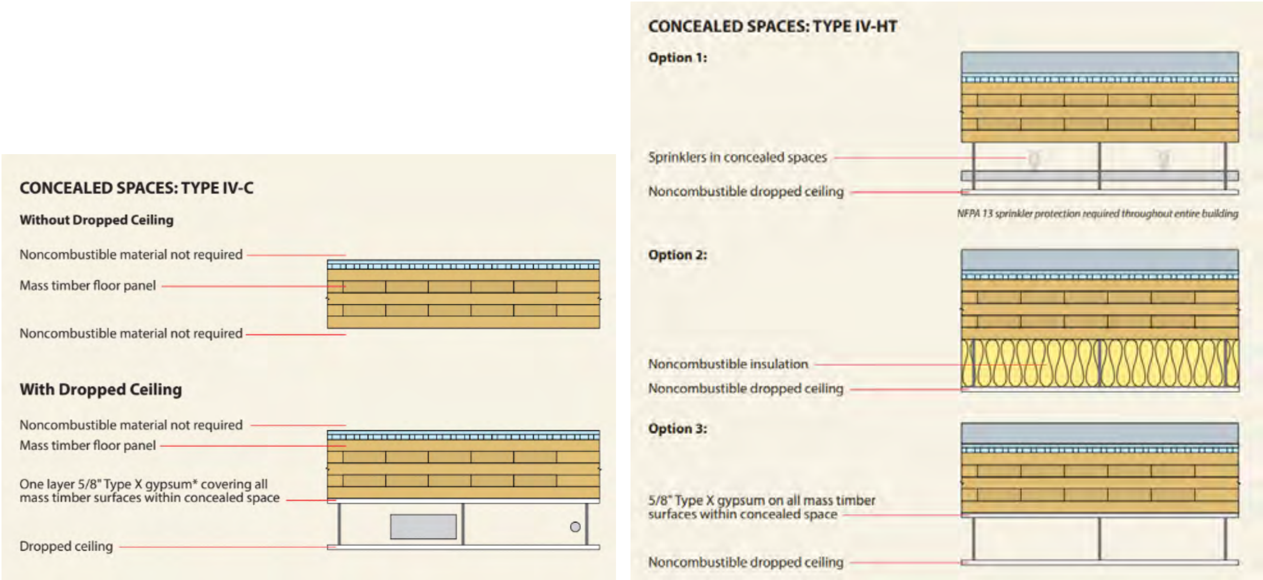


Figure 2. *Fire Protection Options for Concealed Spaces in IBC 2021 (credit: IBC 2021)*

MASS TIMBER DESIGN

Types of Mass Timber

"Mass Timber" = "Engineered Wood" = Composite materials made up of wood laminations, strands, or veneers connected by adhesive or fasteners.

- This study is concerned with mass timber (MT) composed of solid dimensional lumber (in the U.S., typically planed 2x4 or 2x6 lumber).
- Other types of mass timber made of laminated materials, such as MPP (mass plywood panels) or the various types of SCL (structural composite lumber) defined by the NYC Building Code including LVL (laminated veneer lumber), are not the focus of this study.

MT composed of solid dimensional lumber has several advantages over old-fashioned heavy timber, or solid wood elements made from a single tree, including:

- Uniform mechanical properties.
- Improved dimensional stability.
- Greater strength with less material and lower-quality material; defects like scars, cracks, and knots can be deliberately dispersed and staggered to minimize loss of strength.
- Composed of many small pieces of lumber, so large MT elements can be built from small, fast-growing trees that can be replaced in a matter of years rather than decades.

GLT (Glue-Laminated Timber or Glulam)

The lumber in GLT is oriented such that the grain of all layers runs parallel to the longitudinal axis.

- Can be composed of any number of layers, in widths of as little as a single plank.
- Primarily used in beams and columns, but can be used in panels.
- Patented in 1901 (Switzerland).
- Has a long history of use in the U.S. for beams, columns, and floor plates.
- Was permitted for use as a structural material in NYC prior to 2022 BC.

Figure 3. *Glue-Laminated Timber: Diagram (top left, Abed et al., 2022) and Layup (bottom left, SwedishWood.com) Curved, Shaped GLT Beam (right, Western Wood Products)*

CLT (Cross-Laminated Timber)

The lumber in a CLT element is oriented such that the grain of different layers run perpendicular or transverse to each other.

- Typically composed of 3, 5, 7, or 9 layers.
- Primarily used in panels, but can be used in beams and columns.
- Patented in 1985 (France).
- First multi-story building use in 1998 (Austria).
- Explicitly permitted for use as a structural material in NYC for the first time in 2022 BC.

Figure 4. *Cross-Laminated Timber: Diagram (top left, Abed et al., 2022) and Assembly (bottom left, Lulea Institute of Technology); Sample Pieces of 3- and 5-Ply CLT Panels (right, Oregon Department of Forestry)*

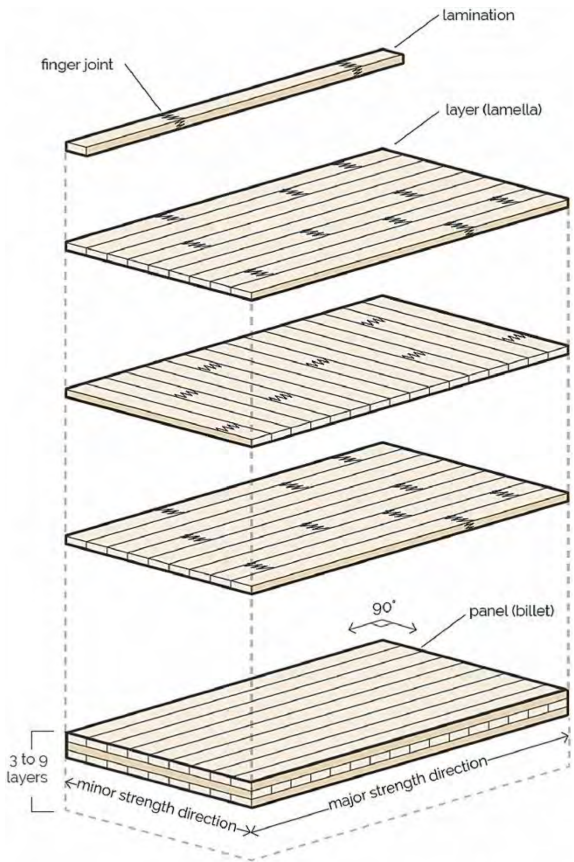
The basic steps in building a CLT or GLT element are the same:

1. Planks (individual pieces of lumber) are kiln-dried to 12% (+/-3%) moisture content.
2. Planks are graded for strength, appearance, etc. (see *Mass Timber Materials* below).
3. Planks are selected and grouped for a specific element.
4. Planks are finger-jointed end-to-end to make longer planks or laminations.
5. Planks are assembled in a layer or lamella, and adhesive is applied.
6. Layers are glued together into elements such as beams, columns, or panels according to a pre-determined arrangement called a layup.
7. The glued element is compressed and cured in a hydraulic or vacuum jig.
8. The stabilized element is trimmed, planed and machined, adding openings or forming ends/edges for connection to other elements in the factory or field.
9. The completed element is sanded and factory finish is applied.
10. The final product is marked for delivery and wrapped for moisture protection.

Key distinguishing characteristics of CLT include:

- The layers are face-bonded, i.e., glued together on the "broad" faces of the planks. Typically there is no glue applied between adjacent planks within a single layer, i.e., on the narrow faces or edges of the planks, unless it is required for enhanced structural performance.

- Primary layers have planks oriented parallel to the major strength direction; transverse layers have planks oriented perpendicular to the major strength direction.
- CLT elements always use primary layers as the outer layers of the element. Inner primary and transverse layers may alternate or be doubled up, but the overall layup is always symmetrical and uses an odd number of layers.
- In floors and beams, the major strength direction is oriented with planks parallel to the longer span. In walls and columns, the major strength direction is oriented with planks up/down.
- To relieve stresses from cupping or twisting once the layers are glued together, the wood grains of the planks on the top and bottom layers may be opposed, and planks may be kerfed (grooved).



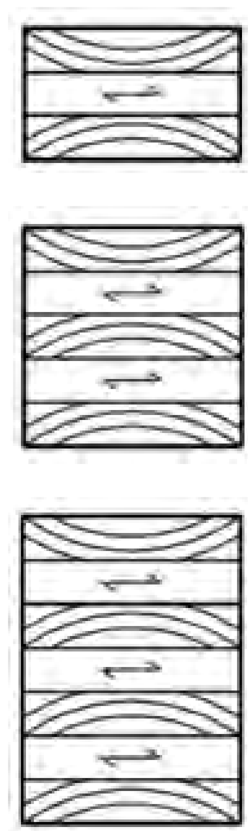


Figure 5. *CLT Element Construction: Typical Floor Panel Construction (left, ThinkWood)*
Simplified Diagrams of Wood Grain in 3-, 5-, and 7-Ply Panels (right, ThinkWood)

Because of its relative novelty and versatility, CLT has been the focus of much recent investment and code development in North America. CLT's advantages include:

- Two-way bending strength (like reinforced concrete slabs), with greater bending strength in the "major" direction (odd-numbered layers, including the top and bottom layer).
- High dimensional stability due to resistance to dimensional shrinkage in both directions.
- Potentially infinite varieties of layups (layering schemes) are available to meet highly specific structural, dimensional, fire resistance, acoustic, and aesthetic requirements.
- Some manufacturers provide material-optimized layups with thinner minor or transverse layers.

- When used in walls, can accommodate door and window openings without reinforcement.
- When used in floors, can accommodate limited penetrations without reinforcement.

Disadvantages of CLT relative to GLT include:
- Cannot span long distances.
- Cannot be used in trusses or curved elements.
- Slight gaps between adjacent planks reduce fire resistance ratings.

NLT and DLT (Nail Laminated Timber and Dowel Laminated Timber)

NLT and DLT are sometimes used when CLT is desired but becomes prohibitive due to supply, cost, or fire rating concerns. NLT and DLT have one-way bending strength only.

Figure 6. *Nail-Laminated Timber: Diagram (top left, Abed et al., 2022); Sample of Prefabricated NLT Panel (bottom left, naturallywood.com); Site-Fabricated NLT Floor Plate (right, StructureCraft)*

NLT is essentially the same as mill decking, the practice of nailing boards together that was common in urban warehouse and factory construction more than 100 years ago.
- Can be site-fabricated or prefabricated.
- Site-fabricated NLT has a rougher appearance, with planks slightly out of plane and visible gaps.
- Difficult to drill or cut through in the field due to the presence of the nails.
- Typically, sheathing is laminated or nailed to one face of a NLT panel to improve its strength.
- Was used in the floor decking of the 7-story, 225,000sf T3 office building in Minneapolis, MN (completed 2016 and framed in GLT) because the lead time for CLT, which was just starting to be produced in the U.S., was too long.

DLT is similar to CLT in that it is prefabricated and factory-machined and has a highly finished appearance, but it does not use adhesive.
- The easiest type of MT frame to disassemble; dowels are simply drilled out.
- All-wood construction has superior acoustical properties to CLT and NLT.
- Panels available in a variety of architectural profiles.
- Currently only 1 fabricator in the U.S.

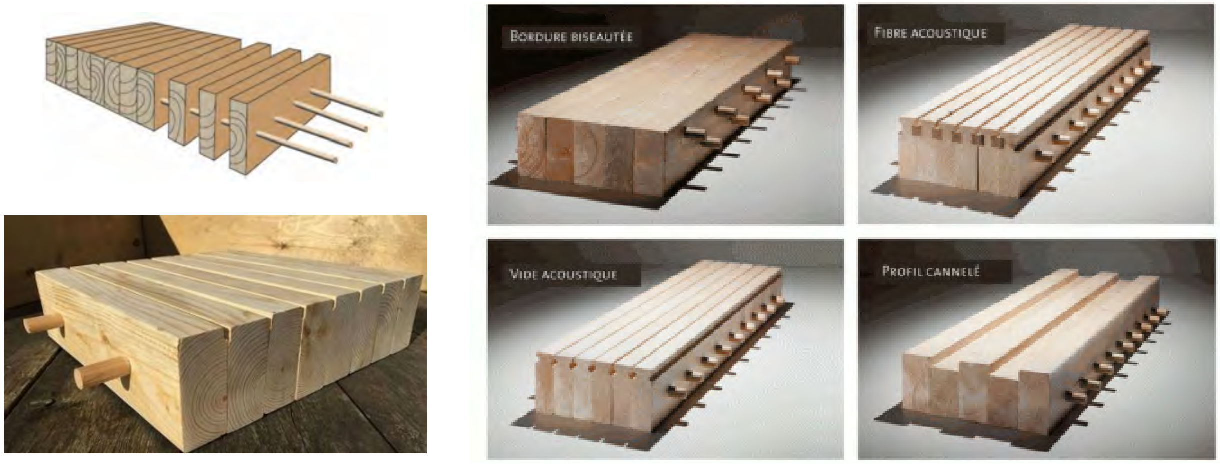


Figure 7. *Dowel-Laminated Timber: Diagram (top left, Abed et al., 2022); Sample of DLT Panel (bottom left, Natural Resources Canada); Options for DLT Panel Profiles (right, StructureCraft)*

Not addressed in this study:

LVL (Laminated Veneer Lumber)

Formed by bonding multiple thin wood veneers.

- Made of dried and graded wood veneers, strands, or flakes.
- Typically used for beams, which can be curved or shaped.
- Prone to warping, splitting, or delamination when exposed to high moisture content or when used in an unventilated area.
- More difficult to nail into due to density of glue and veneer layers.

Figure 8. *Laminated Veneer Lumber (theconstructor.org)*

MPP (Mass Plywood Panels)

A hybrid of CLT and LVL; essentially, CLT panels using plywood instead of dimensional lumber.

- Patented in 2017 by an Oregon plywood and veneer manufacturer.
- Produced in 9-ply, 4’x8’x1” thick panels that can be laminated and scarf jointed into panels thick as 12” and as long as 48’.
- Uses less wood fiber than a comparably strong CLT panel, and can be made from trees as small as 5.5” diameter.

Figure 9. *Mass Plywood Panel (Freres Lumber)*

Mass Timber Materials

Relative to structural steel and concrete design, MT design generally involves more granularity in specification and shop quality control.

- Examples of gradations in MT specification include:
  - Tree species of origin
  - Sawing method (for sawn lumber products)
  - Visual, mechanical, or structural composite grading
  - Layup design (nominal layups are standardized in multiple ways)
  - Appearance grades of finished layups (standardized by ANSI A190.1 into framing, industrial, architectural and premium grades, with architectural or premium grades being used for the exposed and visible surfaces of the layup)
- A “layup” is the layering scheme for a specific MT panel.
  - Theoretically, there are infinite numbers of different possible CLT layups incorporating layers with different tree species, sawing methods, mechanical or structural grading, appearance grading, thicknesses, and orientations.
  - In practice, each manufacturer offers a limited number of CLT layups with some customization. Total CLT panel thicknesses of up to 20” are available. Individual layer thicknesses range from 5/8” to 2”.

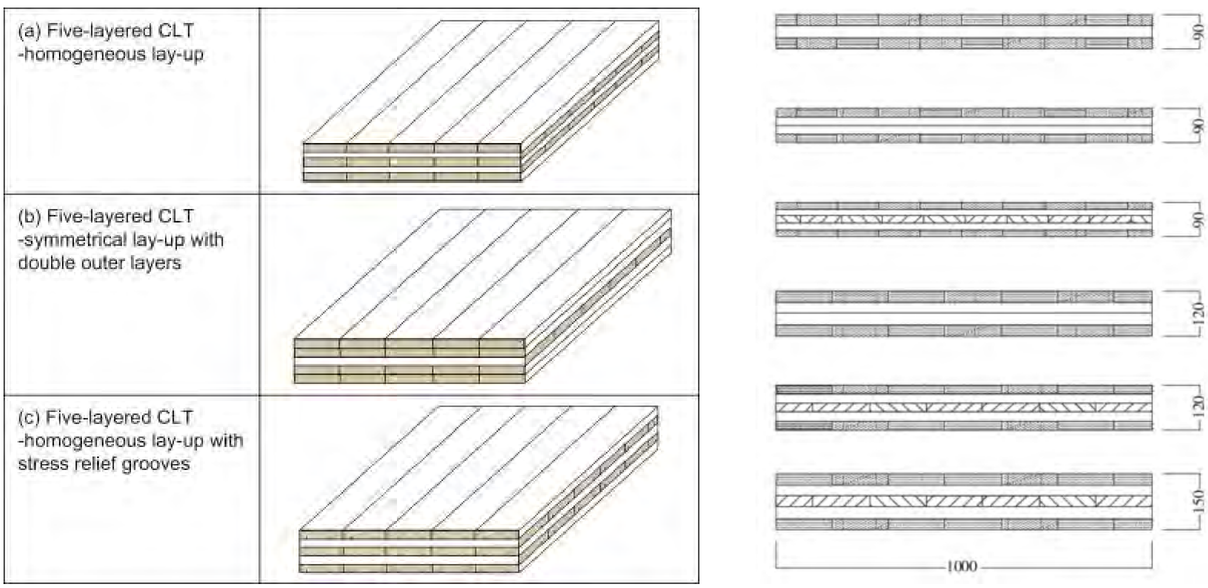


Figure 10. *Examples of Different Types of CLT Layups*
(left, ThinkWood; right, Minoru Okabe et al., Journal of Wood Science, February 2014)

- This increased level of design specificity must be provided by:
  - an architect and/or structural engineer trained in MT design;
  - the manufacturer/fabricator/supplier; or
  - a third party facilitator in conversation with both the design team and the supplier.
- In the case of a design-bid-build project, some specifics can be deferred to the construction phase through the use of manufacturer qualifications and limitations, RFIs, or submittal approvals.

- For example, some MT building structural designers may specify that a GLT beam must be within a given stress class, then leave the final GLT layup (including species, sawing method, and grading) to be determined during the submittal process.
- However, because of the long lead time of MT elements, deferment of design specifics can add risk to a project. (These issues are discussed further in sections below.)

Tree Species

Tree species is a major level of specification in MT element design. When exposed MT elements are an architectural feature, species is also determinative of the element's color.

- Douglas Fir and Southern (Yellow or Loblolly) Pine are typical choices in the United States. Manufacturers in the Northwest U.S. and Southwest Canada typically use Douglas Fir; those in the Southeast U.S. typically use Southern Yellow Pine; those in Eastern Canada typically use Spruce Pine Fir. Manufacturers in all of these locations serve the NYC market.
- Alternative woods can be chosen for specific applications; for example, hardwoods and Alaska Cedar may be favored for "wet service," i.e. exterior use with permanent exposure to moisture. (Note: 2022 NYC BC does not allow exterior exposure of MT construction, so this should not be a factor in species selection for NYC projects.) However, many manufacturers do not offer alternative species, and very few MT assemblies have been tested for fire resistance using species other than Douglas Fir, Southern Yellow Pine, or Spruce Pine Fir.
- Early choice of manufacturer provides structural designers with the assurance that they can select and design around a species that the manufacturer is confident in the availability of; when this is impossible, engineers typically default to typical choices.

Species Group	Symbol	Species that may be included in the group
Alaska Cedar	AC	Alaska Cedar
Douglas Fir-Larch	DF	Douglas Fir, Western Larch
Eastern Spruce	ES	Black Spruce, Red Spruce, White Spruce
Hem-Fir	HF	California Red Fir, Grand Fir, Noble Fir, Pacific Silver Fir, Western Hemlock, White Fir
Port-Orford Cedar	POC	Port-Orford Cedar
Softwood Species	SW	Alpine Fir, Balsam Fir, Black Spruce, Douglas Fir, Douglas Fir South, Engelmann Spruce, Idaho White Pine, Jack Pine, Lodgepole Pine, Mountain Hemlock, Ponderosa Pine, Sugar Pine, Red Spruce, Western Larch, Western Red Cedar, White Spruce
Southern Pine	SP	Loblolly Pine, Longleaf Pine, Shortleaf Pine, Slash Pine
Spruce-Pine-Fir	SPF	Alpine Fir, Balsam Fir, Black Spruce, Engelmann Spruce, Jack Pine, Lodgepole Pine, Norway Pine, Red Spruce, Sitka Spruce, White Spruce

Figure 11. *Suitable Wood Species for Engineered Wood Products (ANSI 117)*

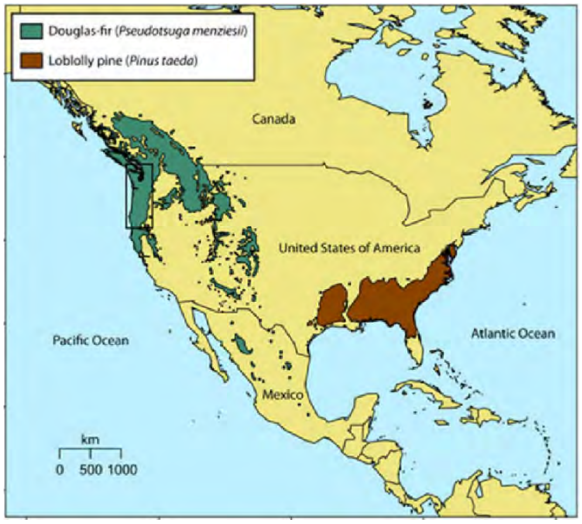


Figure 12. *Distribution of Key MT Tree Species in the U.S. (Andrew Eckert, BMC Proceedings 5, September 2011)*

Adhesives

Structural adhesives used in MT production are required to be:

- Moisture-durable, i.e. resistant to delamination up to 16% moisture content of wood (up to approximately 65% RH and 68F ambient conditions)
- Heat-durable, i.e. resistant to delamination in a fire (typically incorporated into the MT product's certified fire resistance rating)

Types of adhesives used in U.S. CLT production include:

- One-component polyurethane (PUR): also used for GLT; medium curing time; formaldehyde-free and low- or no-VOC; commonly used in Europe and N. America; light-colored.
- Phenolic-based, such as phenol-resorcinol formaldehyde (PRF): also used for GLT; longest curing time; dark-colored.
- Emulsion polymer isocyanate (EPI): also used for wood I-joists; shortest curing time; formaldehyde-free; commonly used in Asia; light-colored.
- Natural adhesives such as soy-based adhesives: formaldehyde- and VOC-free; promising but as yet untested.

Polyurethane adhesives with no or low VOC emissions are widely available in the U.S. and are most likely to be in compliance with NYC SCA Green Schools Guide requirements. (Note: GSG requirements are not strictly applicable to MT. GSG regulates VOC content and emissions for field-applied adhesives; the adhesives used in MT are not field-applied, and are fully cured by the time they are installed. GSG also regulates urea-added formaldehyde in composite wood products; MT may be considered a composite wood, as it contains wood and adhesives.) The use of formaldehyde (PRF) and isocyanate (EPI) adhesives should be avoided due to their higher potential for VOC emissions.

Material Optimization

"Material optimization" here refers to the design goal of meeting code requirements using a minimum amount of a particular material. Because modern MT construction has not yet achieved the maturity of steel or concrete construction, and because of the wide variety in specifications in use, the industry has yet to develop a standardized approach to material optimization.

- MT construction is inherently optimized relative to steel or concrete construction, as it involves highly controlled premanufacturing methods. However, MT construction lacks the standardized components used to facilitate the design of steel or concrete buildings.
- Material optimization for MT buildings means a careful balancing of structural, fire resistance, and acoustical requirements with architectural expression and cost drivers.
    - In some cases, material optimization may dictate the use of thicker MT floor plates with more widely spaced MT beams; in others, it may dictate the opposite.
    - A poorly optimized MT design can eliminate the potential embodied carbon savings of an MT building compared to a steel or concrete building.
- Given that a primary driver behind the adoption of MT is the opportunity to reduce the use of carbon-intensive and nonrenewable resources, manufacturers typically play a critical role in MT material optimization
- In MT structures utilizing CLT floor plates, reducing CLT depth is a primary concern.
    - Slabs make up more of a MT building's structural material volume than beams.
    - Beams make up more of a MT building's structural material volume than columns.
    - However, minimization of CLT depth may not be optimal if it results in an increase in the number and/or complexity of connections between MT elements. Connections can be a primary driver of cost in MT construction.
- CLT depth is impractical to reduce to less than 5-ply (about 7 inches) depth where CLT is left exposed and required to meet a fire resistance rating of 1 hour.
    - With the typical assumption of a 1.5-inch-per-hour char rate, this char can reduce the effective design depth of the CLT, in strength calculations, by up to 2.2-inch-per-hour of fire resistance rating.
    - GLT panels are designed for a uniform effective char rate of 1.8-inch-per-hour.
    - The adhesives used between laminations in a MT panel increase the rate of fire spread across the width and length of the lamination.
- Where CLT floor plates are not exposed or where a fire resistance rating is not required, as in a Type IV building, and where structural spans allow, the use of 3-ply depth (about 5 inches) offers a significant reduction in material volume.
    - Per 2022 NYC BC, CLT floor plates may not be less than 4 inches actual thickness (3 inches nominal thickness for CLT roofs).

		SlabSpan(ft)																
Include charring (T/F)	Y-Grid..	5.00	6.25	6.67	7.50	8.33	8.75	10.00	11.67	12.50	13.33	15.00	17.50	20.00	25.00	30.00	35.00	40.00
False	20	0.58	0.58	0.56	0.59	0.57	0.61	0.58	0.59	0.56	0.72	0.69	0.82	0.89	0.84	0.86	0.87	0.89
	25	0.61	0.61	0.59	0.61	0.59	0.62	0.60	0.60	0.58	0.73	0.70	0.83	0.90	0.95	0.96	0.97	0.99
	30	0.64	0.63	0.62	0.63	0.61	0.65	0.61	0.62	0.59	0.75	0.72	0.84	0.92	0.97			
	35	0.67	0.66	0.64	0.65	0.63	0.67	0.63	0.63	0.61	0.76	0.73	0.85	0.93	0.99			
	40	0.71	0.69	0.67	0.68	0.67	0.70	0.66	0.66	0.64	0.78	0.75	0.87	0.89	1.01			
True	20	0.93	0.92	0.91	0.92	0.90	0.93	0.90	0.91	0.88	0.92	0.89	0.89	0.96	0.92	0.92	0.93	0.95
	25	0.94	0.94	0.92	0.93	0.91	0.93	0.91	0.91	0.89	0.92	0.89	0.89	0.96	1.02	1.02	1.03	1.04
	30	0.97	0.95	0.94	0.94	0.93	0.96	0.92	0.92	0.90	0.93	0.90	0.90	0.98	1.03			
	35	0.99	0.97	0.96	0.97	0.94	0.97	0.94	0.94	0.92	0.94	0.92	0.90	0.98	1.04			
	40	1.02	1.01	0.99	0.99	0.97	1.00	0.95	0.96	0.94	0.96	0.94	0.92	0.94	1.06			

Avg. Total wood vol (ft3/sf)
0.56 – 1.06

Figure 13. *An Example of Material Optimization Calculations for a CLT Floor Plate (USDA, Prototype Mass Timber Office Building Models: Material Quantities, version 2, February 2018)*

Mass Timber Structural System Typologies

Primary structural system "typologies" refer to pre-design decisions about what types of structural elements will provide a building with required resistances to loads imposed by the building program, natural events, and other design considerations.

Post and Beam Structure

This typology is also typical of all-steel construction.

- Best suited for institutional programs where longer spans are required to minimize interior columns, and rooms may need to be repurposed/resized in the future.
- Advantages:
    - With GLT beams, spans of greater than 60-feet are possible, accommodating large open spaces like gyms, auditoriums, and swimming pools as long as the floor-to-floor height allows for deep GLT beams.
    - Most cost-effective for buildings with larger spans, as this minimizes the number of individual MT columns and beams in the project and shortens the construction timeline.
    - Easily accommodates transfers and different MT floor plate thicknesses.
    - Easily understood by steel frame laborers.
- Disadvantages:
    - Typically requires higher floor-to-floor heights than other MT structural typologies.
    - Beams can complicate horizontal MEP distribution.
    - May require more complicated connectors.

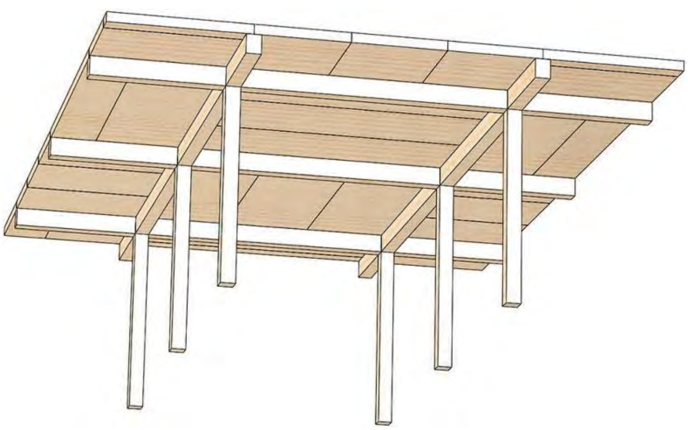



Figure 14. *Post and Beam System*
(left: canadianarchitect.com; right: Joshua Jay Elliot)

Flat Plate (Post and Panel) Structure

This typology is also typical of reinforced concrete construction.

- Best suited for residential programs with limited spans, limited floor-to-floor heights, and a need for a "clean" aesthetic.
- Advantages:
    - Because CLT floor plates are partially two-way (with maximum bending strength in the "major" direction and substantial bending strength in the "minor" direction), they can mimic some of the characteristics of reinforced concrete 2-way slab systems.
    - Can accommodate carefully placed MEP openings without the need for beams.

- Flat plate buildings may still utilize some beams where necessary (i.e. transfers, around large openings, over supports, or under spaces with higher design loads).
- Can reduce floor-to-floor heights below the minimums possible with concrete or steel.

- Disadvantages:
  - Max column spacing limited to CLT fabrication widths: as low as 7.8ft, as high as 14ft.
  - Max CLT bending strength is much lower than that of reinforced concrete.

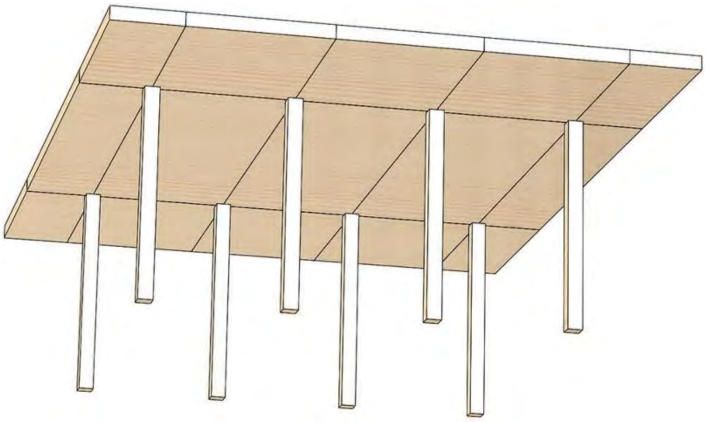



Figure 15. *Flat Plate System*
(left: canadianarchitect.com; right: Acton Ostry Architects)

One MT manufacturer provides the following comparison of post and panel and post and beam structures:

SYSTEM	RECOMMENDED GRID X (beams)	RECOMMENDED GRID Y (purlins/panel)	FIRE RESISTANCE	MEP	ACOUSTICS	VALUE PROPOSITION
POST AND PANEL	8'-10' (2.44 m-3.05 m)	10'-14' (3.05 m-4.27 m)	2 hr encapsulated	Surface Mounted MEP collides with nothing	Requires additional build floor system or dropped ceiling	Quick speed of installation and MEP simple layout fastening
POST-BEAM-PANEL	10'-30' (3.05 m-9.14 m)	15'-40' (4.57 m-12.19 m)	1-2 hr exposed 2+ hr encapsulated	Raised Access Floor Dropped Ceiling Surface Mounted MEP collides with beams in one direction only	Requires additional build floor system or dropped ceiling	Mass timber kits of parts, quick install, amazing performance and aesthetics, cost competitive

Figure 16. *Flat Plate System (StructurLam)*

Cellular (Honeycomb) Structure

This less commonly used typology employs interior MT partitions as load-bearing walls, typically in combination with a limited number of columns and beams or shear walls.

- Best suited for buildings with small, repetitive rooms such as hotels and dorms.
- Interior load-bearing walls are a common choice in residential and single-story buildings, but are not a typical choice in mid-rise institutional applications.
  - Walls offer more compressive capacity than columns, but with non-industrial/mechanical floor loads, this is not a significant benefit until reaching high span lengths.

- Buildings with interior load-bearing walls also can achieve excessive lateral resistance relative to just shear wall cores at stairwells/elevators.
    - CLT panel walls can be fabricated more quickly and assembled more easily than MT columns and beams because of their lower material weight.
- Disadvantages:
    - Room repurposing/resizing with interior load-bearing walls requires structural reanalysis, introduction of new load-bearing elements, and significant construction processes that shore the load-bearing wall elements.
    - It is ineffective and impractical to provide structural transfer girders where supports for load-bearing walls are interrupted.

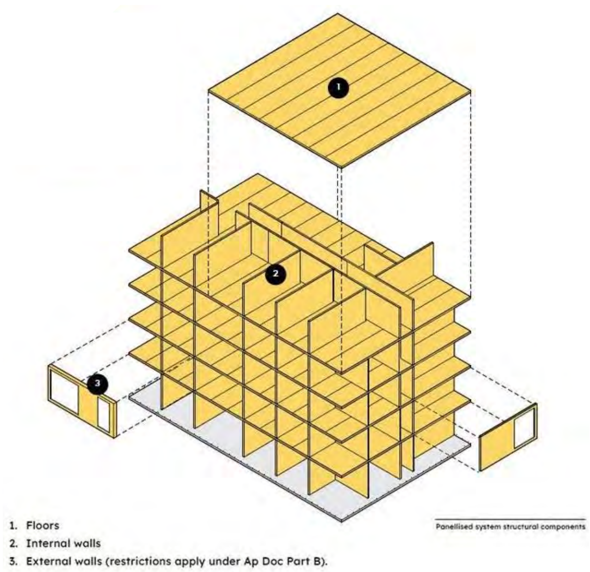


Figure 17. *Cellular (Honeycomb) System*
(left: Waugh Thistleton; right: LendLease)

Long Span Structures

For a given long-span framing arrangement built with MT rather than concrete or steel, the reduced material bending modulus of the MT will always require increasing the depth, reducing the tributary area, increasing the width, or sistering beams.

- Large-depth GLT components are reached by adding additional laminations, while large-width GLT components are accomplished by staggering joints between discrete sawn lumber pieces.
- The basic long-span MT options are GLT deep girders and GLT trusses.
    - GLT trusses are always specialty details that must be worked out with the manufacturer, and will sometimes integrate steel for the web.
    - Deep GLT girders are not typically listed in manufacturers’ product manuals and must be detailed with in cooperation with the manufacturer to determine what their production machinery and processes allow.
- GLT girders may be flat or high-camber (curved).
- GLT trusses are frequently used in large public assembly spaces such as auditoriums.
    - In case studies, public assembly spaces with GLT trusses frequently include a barrel ceiling and thus a “bowstring” truss, evidently for cost efficiency.

- Bowstring trusses will not fit into a repeated rectangular floor plan unless the large-span framing occurs at the roof level, and may require dunnage platforms in order to accommodate rooftop mechanical units.

- GLT trusses cannot match the thinness of the members used in some steel trusses, which may be required for HVAC duct routing, daylight penetration, or visual effect
  - Hybrid MT trusses with steel elements are common.
  - However, GLT girders may be a more dependable design choice for proving code compliance, as exposed steel components must meet FRR requirements.

Figure 18. *Long Span Systems*
Left: Simple deep GLT bents. Right: GLT bowstring truss and barrel roof.
(left: ThinkWood; right: Kate Simonin)

Hybrid Structures

While hybridity generally introduces cost and complexity into a project, many MT structures, and all MT structures in NYC, include steel elements (such as fasteners) and concrete elements (such as foundations).

- Under 2022 NYC BC, concrete or other non-combustible materials must be used where MT is prohibited, such as the exterior walls of Type III buildings.
- Reinforced concrete foundations are typical in mid-rise and high-rise MT structures.
  - High-strength footings are required for the accumulated compression load of institutional column spans.
  - Reinforced concrete is the logical choice for story-height retaining walls (below-grade walls) enclosing subgrade spaces.
- Reinforced concrete shear wall cores are also typical in mid-rise and high-rise MT structures.
  - In 2022 NYC BC Chapter 6 requires fire walls, exit passageways, and shaft enclosures to be comprised of noncombustible materials.
  - Ongoing research has led to increased use of CLT shear walls outside of NYC, including multifamily buildings in upstate NY .
  - The American Wood Council's 2021 Special Design Provisions for Wind and Seismic (SDPWS) addresses CLT lateral systems, but structural engineers who do not commonly work on MT design are not familiar with this standard.
  - CLT lateral systems are not yet reflected in widely used structural design standards such as the American Society of Civil Engineers (ASCE) 7-2016, Minimum Design Loads and

Associated Criteria for Buildings and Other Structures, although CLT lateral system provisions have been proposed for ASCE 7-2022.

- MT buildings 8 stories or higher are more likely to utilize concrete and steel structural elements.
    - o Steel is sometimes expedient in superstructures because of its superior strength per volume, and its isotropic (omnidirectional) strength properties.
    - o Concrete is sometimes expedient in the podia of taller buildings, particular where the lower levels accommodate commercial uses or parking.

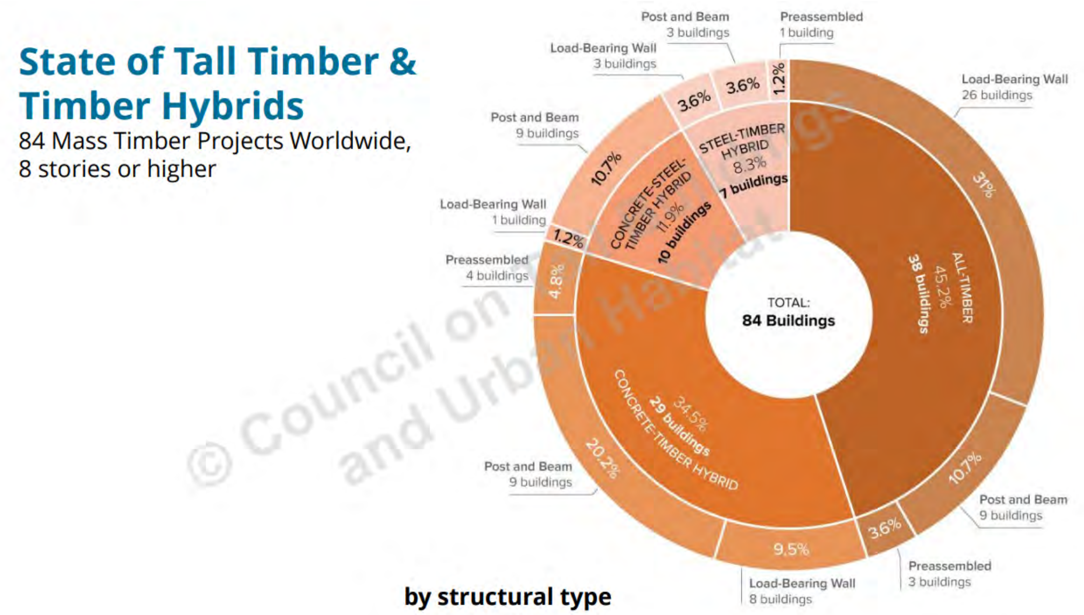


Figure 19. *Mass Timber Projects by Structural Type (Council on Tall Buildings and Urban Habitat)*

Mass Timber Connections

The number and complexity of MT connections can add significantly to the cost of a MT project.

Typologies

Generally, there are three classes of connection design:

- Wood-Wood
    - Low-capacity
    - Easy to construct and inspect
    - May be supplemented by adhesives
    - Often used to spline CLT panels to each other
    - Inherent fire resistance rating is treated somewhat ambiguously by codes

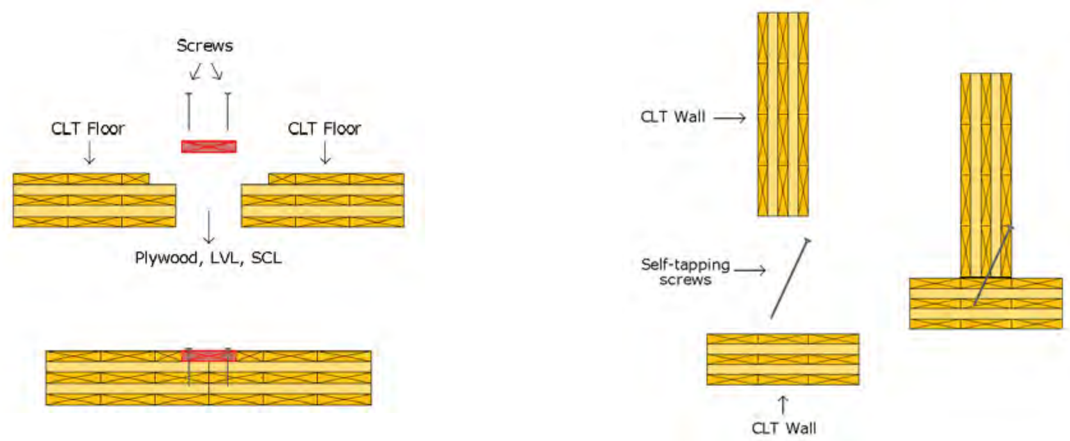


Figure 20. *Examples of Wood-Wood Connections (ThinkWood)*

- Wood-Steel-Wood
    - High-capacity
    - Similar to steel frame connections; composed of common steel shapes or welded plates
    - Always requires fire protection; may be protected by concealment within MT
    - Concealed connections require precise prefabricated profiling using CNC

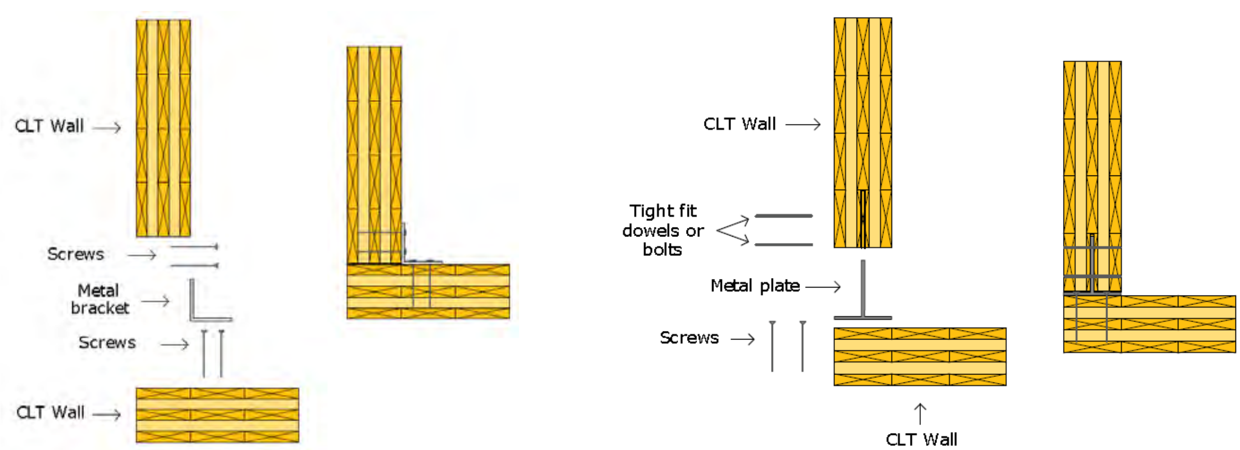


Figure 21. *Examples of Exposed (left) and Concealed (right) Wood-Steel-Wood Connections (ThinkWood)*

- Proprietary connectors (Simpson, Rothoblaas, MiTek, etc.) with fasteners
  - Mostly Wood-Steel-Wood
  - May be used to enhance architectural expression
  - Can solve complicated structural connection problems with a single connector, making assembly faster and easier, using less material
  - Always requires fire protection; usually exposed, but some types may be protected by concealment within MT
  - Concealed connections require precise prefabricated profiling using CNC

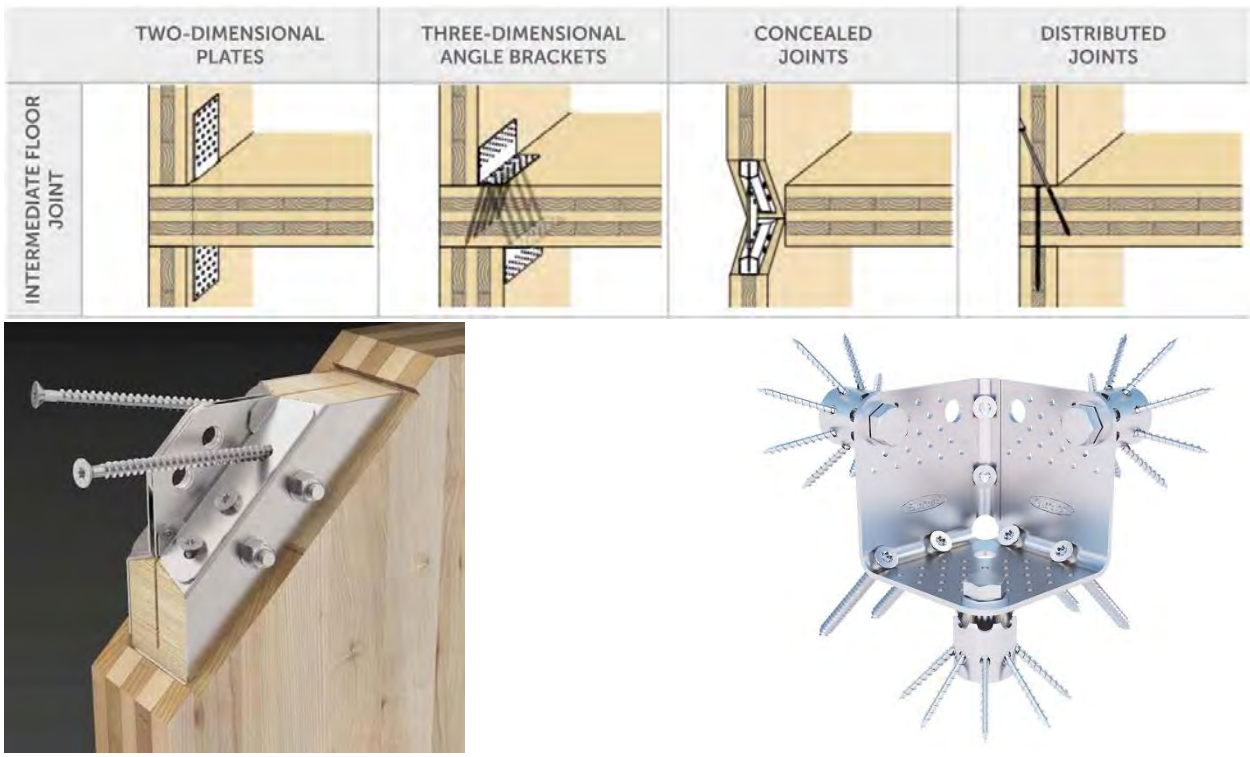


Figure 22. *Proprietary Wood-Steel-Wood Connectors (top and bottom left, Rothoblaas; bottom right, Eurotec)*

Fasteners

Mechanical fasteners used in CLT assemblies may include:

- Wood screws and self-tapping screws: Self-tapping screws are more common, as they do not require pre-drilling.
- Through-bolts and self-drilling dowels: Used where longer fasteners or fewer, thicker fasteners are required; care must be taken when using on panel edges (end grain).
- Nails with grooves or helical threads: Typically used with plates and brackets installed on the surface of CLT panels; cannot be used on panel edges (end grain).
- Wood dowels: Typically used in wood-wood connections only; provide superior acoustical performance and easier disassembly.

Bearing-type fasteners such as split rings and shear plates, which were commonly used in historical heavy timber construction, are not commonly used for CLT.

Fire Resistance Ratings

A common misperception of MT buildings is that they are more vulnerable to fire. However, MT structural components (columns, beams, and slabs) of sufficient thickness will develop an outer charred layer in a fire, protecting the uncharred portion from further damage.

- According to research by Arup, in a 750C fire, char keeps the protected portion of a typical MT structural component at 60C.
- The American Wood Council's *National Design Specification Technical Report 10* (2021, for all MT) and the WoodWorks *CLT Handbook* Chapter 8 (2013, for CLT only) establish how char penetration should be measured (i.e., how much material will be lost to char) and how the strength of charred components should be adjusted for use in structural calculations.
- Char must be measured from all sides of a MT component that will be directly exposed to fire.

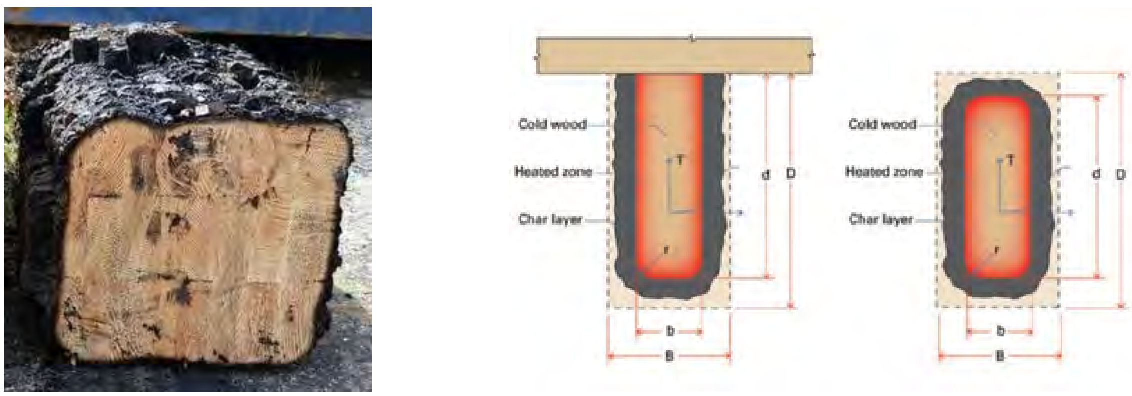


Figure 23. *Charring of MT Structural Members (left: ThinkWood; right: WoodWorks)*

Table 16.2.1A Char Depth and Effective Char Depth (for β_n = 1.5 in./hr.)

Required Fire Resistance (hr.)	Char Depth, a_{char} (in.)	Effective Char Depth, a_{eff} (in.)
1-Hour	1.5	1.8
1½-Hour	2.1	2.5
2-Hour	2.6	3.2

Member Strength	Adjustment Factor, K, for Fire Design
Bending strength	2.85
Beam bucking strength	2.03
Tensile strength	2.85
Compressive strength	2.58
Column buckling strength	2.03
Shear strength	2.75*

Figure 24. *Excerpts from the National Design Specification (American Wood Council)*

MT structures, like steel structures, can also be protected from fire by encapsulation using materials such as gypsum board. However, most MT structures are designed to expose as much wood as possible. Encapsulation negates some of the primary advantages of MT construction, such as aesthetics, biophilic health impacts, and less need for additional finish materials.

<u>Fire retardant treatments cannot be used to achieve MT fire resistance ratings.</u> Fire retardant wood sheathing can be used as a protective material for MT used in exterior walls, but there is no advantage to using such a material instead of gypsum board or other naturally non-combustible materials.

NYC FRR for Mass Timber Structural Members

Mass timber requires unique consideration of fire resistance rating (FRR) in structural design. Structural members must be designed for their charred section strength, i.e., the strength of the uncharred section that remains after charring. SCA capacity projects are typically filed as construction type I-B or II-A.

- Type III-A buildings (see notes under *Code Clarifications* section above): 1-hr fire FRR required for primary structure (raised to 2 hrs. for exterior bearing walls)
- Type III-B buildings (see notes under *Code Clarifications* section above): no FRR required for any elements except exterior bearing walls
- Type IV-HT buildings:
    - o CLT exterior bearing walls are prohibited in the fire district
    - o Non-bearing CLT exterior walls are explicitly permitted
    - o GLT and CLT are considered "heavy timber" elements, as long as they meet minimum dimensional sizes in Table 2304.11
    - o For institutional buildings using MT elements, the member width requirements are the more meaningful determinant of these limits (see table below)

Table 2. *Minimum Dimensions of Heavy Timber Structural Members (2022 NYC Building Code)*

SUPPORTING	HEAVY TIMBER STRUCTURAL ELEMENTS	MINIMUM NOMINAL SOLID SAWN SIZE		MINIMUM GLUED LAMINATED NET SIZE		MINIMIM STRUCTURAL COMPOSITE LUMBER NET SIZE	
		Width, Inch	Depth, Inch	Width, Inch	Depth, Inch	Width, Inch	Depth, Inch
Floor loads only or combined floor and roof loads	Columns; Framed sawn or glued-laminated timber arches that spring from the floor line; Framed timber trusses	8	8	6¾	8¼	7	7½
Roof loads only	Wood beams and girders	6	10	5	10½	5¼	9½
	Columns (roof and ceiling loads); Lower half of: wood-frame or glued-laminated arches that spring from the floor line or from grade	6	8	5	8¼	5¼	7½
	Upper half of: wood-frame or glued-laminated arches that spring from the floor line or from grade	6	6	5	6	5¼	5½
	Framed timber trusses and other roof framing[a]; Framed or glued-laminated arches that spring from the top of walls or wall abutments	4[b]	6	3[b]		3½[b]	5½

NYC FRR for Mass Timber Structural Connections

2022 NYC BC adds new provision *2304.10.8 Connection Fire Resistance*, which is unique and somewhat restrictive compared to requirements for connections between other types of structural materials such as steel or concrete.

- *Wood structural connections, including connectors, fasteners, and portions of wood members included in the connection design, shall be protected from fire exposure for the required fire resistance time. For connections in Type IV construction, the required fire resistance time shall be at minimum one hour or as required for the building element by Table 601 and Section 602.4.*

- Most strictly interpreted, this provision adds a 1-hr FRR requirement to all structural members in Type IV construction (which otherwise does not carry FRR requirements for MT) in so far as they are "included in the connection design".
- Although the provision indicates that only the "portion" included in the connection design must meet the FRR, this is not instructive for structural design.

• *Fire resistance ratings for connections shall be determined by one of the following: 1. Testing in accordance with Section 703.2 where the connection is part of the fire resistance test. 2. Engineering analysis that demonstrates that the temperature rise at any portion of the connection is limited to an average temperature rise of 250°F (139°C), and a maximum temperature rise of 325°F (181°C), for a time corresponding to the required fire resistance rating of the structural element being connected. For the purposes of this analysis, the connection includes connectors, fasteners, and portions of wood members included in the structural design of the connection.*
  - These requirements provide two clearly compliant alternatives for the structural designer: (1) use a connection that has been certified as achieving the required fire rating, or (2) demonstrate by "engineering analysis" the ability of each connection to resist temperature rise (but not accompanying stress) over the FRR time period.
  - Few pre-certified connections exist, and connection design tends to be highly specific to an individual MT project.
  - In NYC, best practices for "engineering analysis" of MT structural connections have not yet been established, and will be developed through ongoing reviews of MT projects by DOB and FDNY.
  - Outside of NYC, structural engineers use the following rule of thumb (reflected in the 2018 National Design Specification (NDS) for Wood Construction, a reference standard of NYC BC): conceal any steel components of the connection with at least 1.5" of wood for each hour of required FRR, based on an assumed wood char rate of 1.5"/hr.
  - In practice, any "engineering analysis" of MT structural connections is likely to be provided by the manufacturer.
  - Steel connectors can also be clad in non-combustible materials such as gypsum wallboard, but this would add complexity and create bulky, ungainly connections, counteracting much of the aesthetic appeal of MT design.

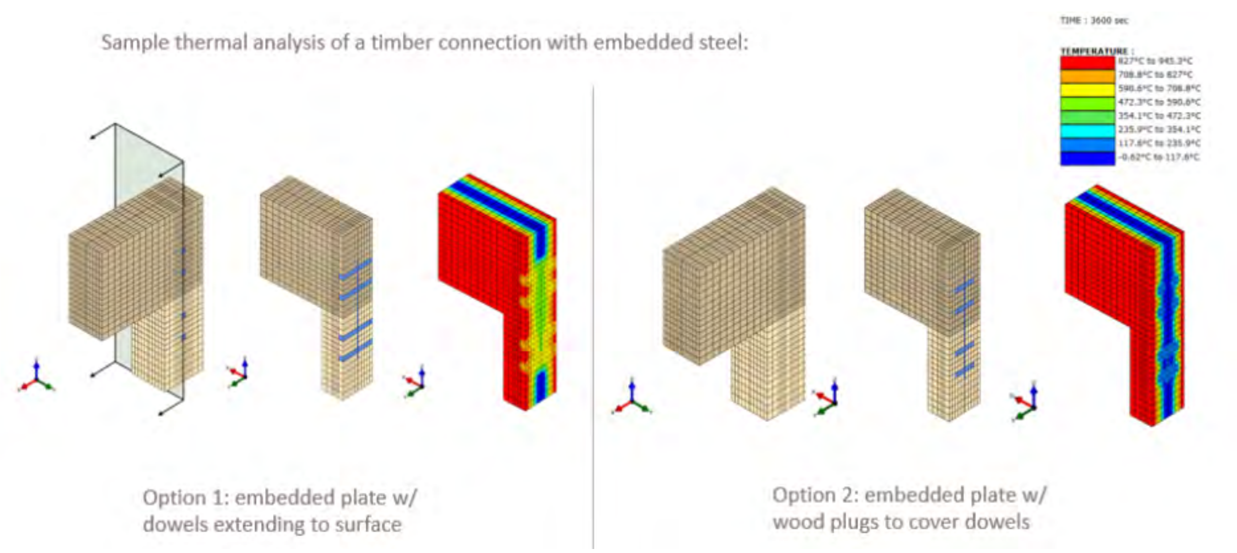


Figure 25. *Example of Finite-Element Fire Analysis for MT Connections (ThinkWood)*

NYC FRR for Mass Timber Assemblies

Per 2022 NYC BC, the fire resistance of assemblies shall be determined based on the fire exposure and acceptance criteria specified in ASTM E 119 or UL 263.

- Currently there are limited options for certified fire-resistance-rated MT assemblies from approved sources, such as UL Certification. WoodWorks maintains and *Inventory of Fire Resistance-Tested Mass Timber Assemblies & Penetrations*.
- MT manufacturers can provide previously certified fire resistance testing reports for their MT products if available. Individual MT manufacturers may have inventories of tested products that are more up-to-date than that provided by WoodWorks.
- Some MT manufacturers are also willing to commission new testing on request if the order is large enough to cover the cost. Manufacturers known to commission testing are noted in the “FRR Testing” column of the Manufacturer Capabilities Table in the *State of the Industry* section of this report (below)
- Alternatively, fire ratings can be calculated up to a 2-hour FRR in accordance with Chapter 16 of *ANSI/AWC National Design Specification for Wood Construction* (NDS).
- Typically, a 5-ply 7” thick CLT panel can achieve a 2-hr FRR.

NYC Requirements for Interior Finishes

Flame spread is the tendency of a material to spread flames during a fire. Smoke development is the tendency of a material to generate smoke during a fire. Per 2022 NYC BC:

- Type IV buildings: no flame spread or smoke development requirements.
- Type III buildings (see notes under *Code Clarifications* section above): interior finishes, including any exposed portion of MT, are required to meet the flame spread performance and smoke development index of Section 803.
- NYC SCA schools with MT may be constructed as either Type III or Type IV. For Type III (see notes under *Code Clarifications* section above), the requirement for schools is Flame Spread Class B; the table below shows that all common MT species fulfill this requirement.

Species	Flame Spread Index	Smoke Developed Index	Flame Spread Class
Douglas-fir	70	80	B
Hem-fir species group	60	70	B
Pine, eastern white	70	110	B
Pine, southern yellow	70	165	B
Spruce, black (4"-thick, 3 layers of cross laminations)	35	55	B

Figure 26. *Flame Spread Values of Common Mass Timber Species (Design for Code Acceptance 1, American Wood Council)*

Mass Timber Building Envelopes

MT components must be kept warm and dry throughout the building's construction and occupancy. This section addresses best practices for building envelope design to manage bulk water and water vapor infiltration, air infiltration, and temperature swings over the life of the building. Best practices to manage moisture during construction are addressed in the *Mass Timber Construction* section below.

Moisture Properties of Mass Timber

MT has a relatively high capacity to store moisture and a relatively slow potential for drying. In other words, MT can retain large amounds of water for extended periods of time.

- Wood swells when it gains moisture and shrinks when it loses moisture, until it reaches equilibrium with environmental relative humidity and temperature conditions.
- Dimensional changes are the greatest across the grain (in the direction of annual growth rings) and usually very small along the grain.
- Moisture can penetrate deep into MT, become trapped within the pore structure of wood, and build up at locations such as prefab panel interfaces, lamination interfaces, splices, exposed end grain, etc.
- When MT retains a large quantity of water over a long period of time, it can cause dimensional changes, creating gaps or checking, as well as increasing risk for microbial growth, decay and corrosion of metal fastener or connectors.
- MT design and construction must ensure that MT elements are sufficiently dry prior to installation or that MT assemblies are designed to facilitate drying. Drying potential depends on the environment; cold weather/high humidity after exposure to water slows down drying.
- Long-term and persistent exposure to moisture is likely to be more problematic to MT than the overall quantity of water. Timely water leak detection and repair is crucial to avoid damage.

Managing Water and Water Vapor Infiltration

Bulk (liquid) water, typically introduced to the building envelope by wind-driven rain, is the most critical load affecting MT construction. However, water vapor infiltration, which often accompanies air infiltration, is likely more common. Absorption rates depends on wood species, grain orientation, and length of exposure.

Best practices to manage both bulk water and water vapor include the following:

- Use a ventilated rainscreen cladding with a cavity and drainage for water control.
- Install a durable, fully adhered roof membrane for long term performance, in accordance with roofing manuals developed by national roofing contractors associations.
- Avoid enclosing MT elements in vapor-impermeable materials, which can trap moisture within MT and limit drying through vapor diffusion.
- Treat areas such as bathrooms, showers, laundry rooms, and foor preparation areas with waterproofing and drainage systems to reduce the exposure of MT floor panels to incidental water.

Managing Air Infiltration

Although MT panels may have low initial air permeability, the interfaces between panels and small spaces or gaps between each lamination may allow for increased passage of air over time due to weathering.

Best practices to manage air infiltration include the following:

- Sheet-based membranes are better than liquid-applied membranes given the potential for gaps or checks in the underlying wood surface to create splits in the membrane.
- Apply fully adhered air barrier membranes directly to wood panels so that the membrane's adhesion to the stiff wood substrate will resist both positive and negative airflow pressures.
- Extend air barrier systems continuously around all MT components, including around soffits, up and over parapets, and across slab edges to ensure continuity at all joints, penetrations and interfaces with other assemblies.
- Air barrier system materials should have the durability and strength to withstand UV exposure, moisture, wind pressure/gusts and trade activities during construction.
- Air barrier systems should be designed to withstand temperature fluctucations, substrate movement, pressure differentials, and environmental exposure over the life cycle of the building.

Managing Thermal Conductivity

MT has relatively low thermal conductivity. CLT has an R-value of around 1.0-1.2 per inch; a 5-ply, 7" CLT panel has a comparable R-value of a 6" metal stud assembly with mineral wool insulation.

Best practices to manage thermal conductivity include the following:

- Locate insulation outboard of wood panels to keep the wood closer to indoor temperature, minimize condensation risk, and limit temperature fluctautions

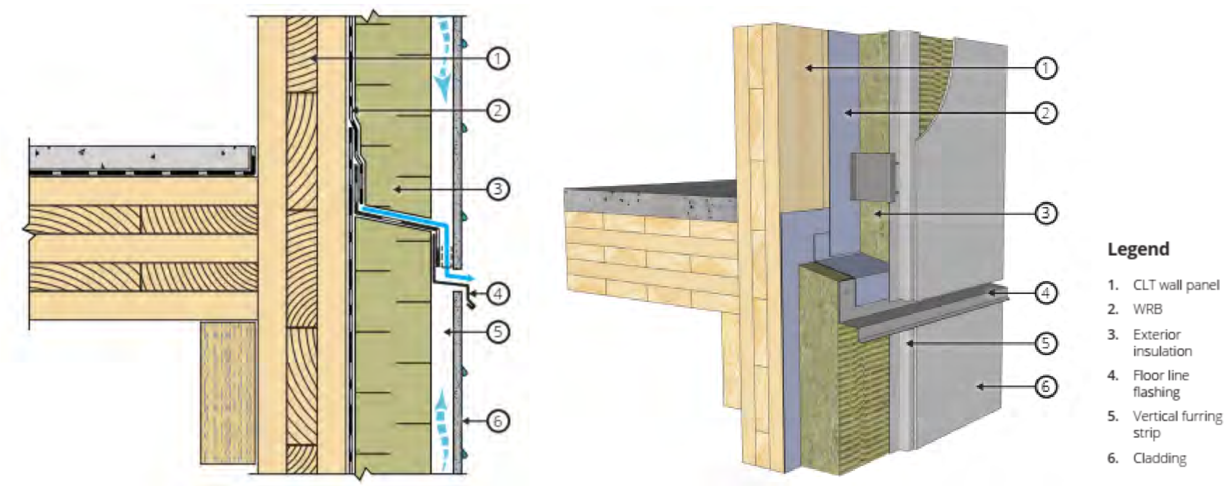


Figure 27. *Details of Typical Exterior Mass Timber (CLT) Wall Assemblies (RDH Building Science)*

Acoustics

Acoustical Properties of MT

When it comes to acoustic value, more mass typically means better noise control. Due its high strength to weight ratio (i.e., less mass), MT is not as good an acoustic insulator as other typical materials such as concrete or metal stud partitions.

- For example, the STC of a 5-ply 6-7/8” CLT floor is 41 while that of 6” concrete slab is 53.
- CLT performs slightly better than other MT products, largely because the cross-orientation of laminations limits sound flanking.

Mass Timber Panel	Thickness	STC Rating	IIC Rating
3-ply CLT wall[4]	3.07"	33	N/A
5-ply CLT wall[4]	6.875"	38	N/A
5-ply CLT floor[5]	5.1875"	39	22
5-ply CLT floor[4]	6.875"	41	25
7-ply CLT floor[4]	9.65"	44	30
2x4 NLT wall[6]	3-1/2" bare NLT 4-1/4" with 3/4" plywood	24 bare NLT 29 with 3/4" plywood	N/A
2x6 NLT wall[6]	5-1/2" bare NLT 6-1/4" with 3/4" plywood	22 bare NLT 31 with 3/4" plywood	N/A
2x6 NLT floor + 1/2" plywood[2]	6" with 1/2" plywood	34	33

Figure 28. *Acoustical Performance of Common MT Panels (ThinkWood)*

There are 3 main ways to improve the acoustic performance of a MT assembly:

1. Add mass such as a poured concrete or gypsum based topping layer, 1-3" thick to increase the mass of the assembly.
2. Add decouplers such as underlayment or mats placed between the MT floor panel and poured topping, or resilient channels placed in wall assemblies.
3. Add sound-absorbing materials such as batt insulation.

Floor Assembly Acoustics

A typical MT floor assembly consists of a CLT panel topped with acoustical components. Typically, these include a surface of leveling concrete or poured gypsum and one or more acoustic mats.

- The topping adds mass to the assembly.
- The acoustic mat serves as a decoupler.
- Typically, this can achieve STC-50 / IIC-50 for typical classroom floors.
- The ceiling side of the CLT panel can be left exposed to the space below.

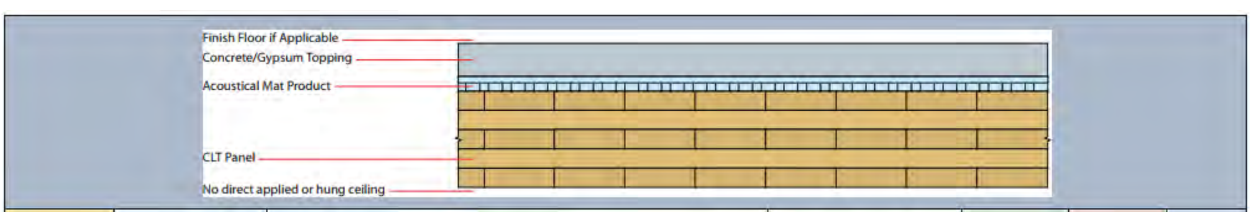


Figure 29. *Typical CLT Floor Assembly with Ceiling Side Exposed (Woodworks)*

Achieving STC-60 / IIC-60 for MT floor assemblies is challenging but not impossible. The following options are explored further in the test case analysis:

- Adding ceiling gypsum board, either directly attached to the underside of the CLT panel or as a dropped ceiling, is a reliable option but comes at the expense of concealing the timber ceiling.
- Adding more concrete topping or increased CLT thickness can improve acoustic performance but comes at the expense of added weight.
- Adding heavy-duty acoustic layers can minimize the contact surface but comes at the expense of added cost and complexity.

Wall Assembly Acoustics

A typical non-bearing MT wall assembly consists of a 3-ply CLT panel with gypsum board and furring on at least on one side.

- A single CLT wall panel assembly with one side of the CLT exposed can generally achieve STC-50-53, which is good for typical corridor walls and classroom walls.
- A double CLT wall panel assembly consisting of two 3-ply CLT panels with sandwiched insulation and one or both sides of the CLT exposed can also achieve STC 50-53 rating. However, this assembly doubles the use of MT material to provide the same acoustic rating as a single CLT panel assembly.

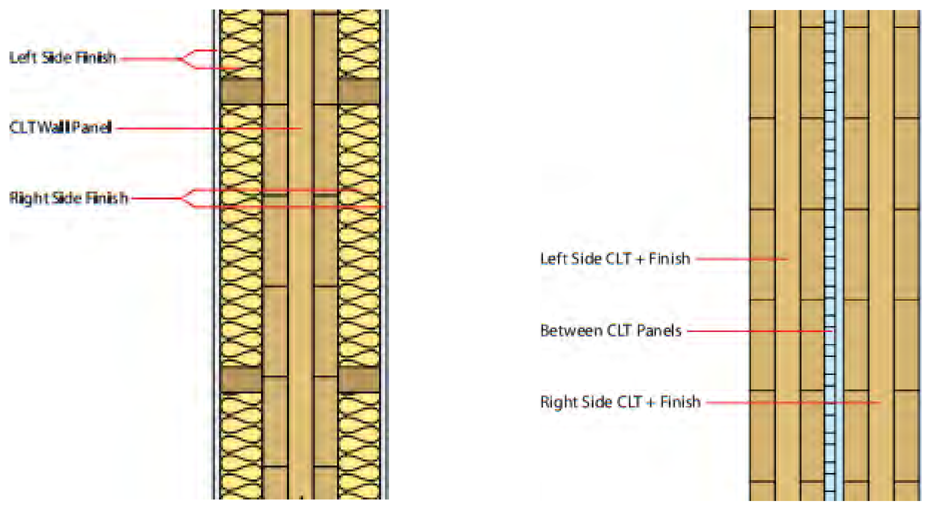


Figure 30. *Acoustical Wall Assemblies with Single and Double CLT Panels (Woodworks)*

Acoustic design of MT wall and floor assemblies must be considered alongside fire resistance ratings as they often go hand in hand.

- In general, an MT wall assembly with a high acoustic rating and FRR requires one or more of the following:
  - Multiple layers of gypsum board
  - Fire blanket or sound attenuation batt insulation
  - Resilient channels
  - Air gaps
- Due to the inherent thickness of the MT, such an assembly is likely to be thicker than its stud wall counterpart, and use more material.
- Acoustic CLT partition walls of STC-60 and 2-hr rated CLT walls are explored further in the test case analysis.

Flanking Acoustics

Sound not only travels through the air from one room to another, but also via indirect paths such as structural elements, walls, floors, ceilings, ducts, or even gaps and cracks.

- Known as flanking noise, this type of sound transfer is unaccounted for in STC ratings.
- MT construction is more susceptible to flanking due to its light weight, even more so with high acoustic rating requirement (STC-60).

MT columns and beams are often left exposed for reasons of aesthetics and material optimization.

- The thickness of these structural members is typically substantial enough to provide an STC rating similar to that of the adjacent wall assembly.
- However, structural elements may contribute to flanking if exposed. For rooms with a high acoustic rating requirement (STC-60), it is recommended that structural elements be covered.

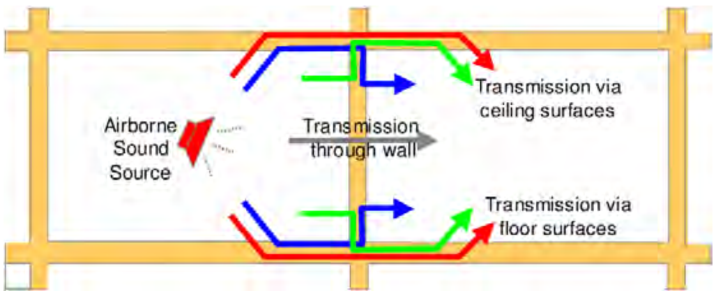


Figure 31. *Acoustical Flanking Diagram (Woodworks)*

Best practices to minimize flanking include:

- Provide breaks and discontinuities in MT structural elements, such as resilient pads between slabs, walls, columns, or beams.

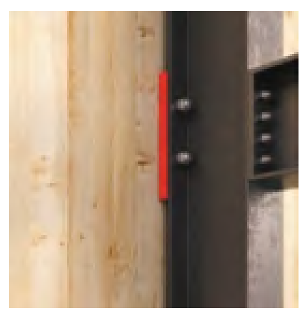


Figure 32. *Resilient Pads for Acoustical Separation Between CLT Beams and CLT Wall (left, Woodworks) and Between Steel Column and CLT Wall (right, Woodworks)*

- Incorporate decoupling elements between MT wall or floor assemblies, such as acoustic mats for floor assemblies or resilient channels for wall assemblies.
- Align MT panel joints with the walls separating spaces in order to avoid having an exposed CLT floor plate spanning between rooms with high acoustic requirements (STC-60+), or consider leaving the panel exposed in one room and covering it in the other.
- Provide proper caulking at all joints.

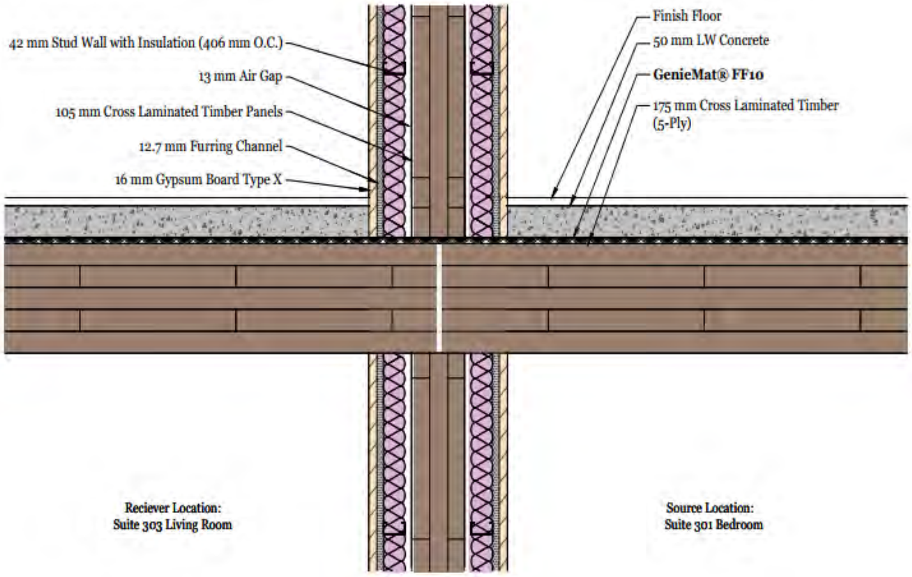


Figure 33. *Typical Floor Detail to Minimize Flanking (Pliteq)*
Note alignment of CLT panel joint with the walls separating living room and bedroom

MEP Integration in Mass Timber Buildings

One design goal of most MT buildings is to expose the MT elements as much as possible in order to maximize:

- Aesthetics
- Health, through biophilic effects of exposure to natural (wood) materials
- Embodied carbon reduction, through the elimination of added finish materials

Thus, the MEP distribution that would otherwise be hidden above the standard dropped acoustical tile or gypsum board ceiling in typical SCA projects may be exposed in an MT building. This would require:

- Early and intensive coordination between trades during design, using highly developed BIM.
- Careful attention to detail by MEP and ceiling trades during construction.
- Incorporation of beam and floor plate penetrations into the MT prefabrication design.
- Simplification and/or reorganization of MEP systems, particularly HVAC ductwork, in order to minimize ductwork sizing and regularize ductwork layouts.
- of ductwork, e.g. using a larger number of smaller AHUs or ERVs instead of the central system in the SCA Standard.

Horizontal MEP Distribution Options

One of three strategies is typically used for horizontal MEP distribution in MT buildings:

- Shallow (or no) beams in corridors
- Stacked beams
- Thickened floor plates

Additional options include the following, all of which are viable in SCA schools using MT:

- Soffits
- Furred walls
- Larger chases (may be possible without adding floor area as use of MT partitions can provide floor area savings – see further discussion below)

Shallow or No Beams in Corridors

MEP items penetrate or (preferably) run below MT beams. This is a viable option for SCA schools.

- Smaller widths of corridors may be spanned by MT floor plates without need for cross beams.
- Shallow beams across the central structural bay (corridor) makes room for mechanical mains.
- Smaller ducts distribute to the rooms on either side of the corridor.

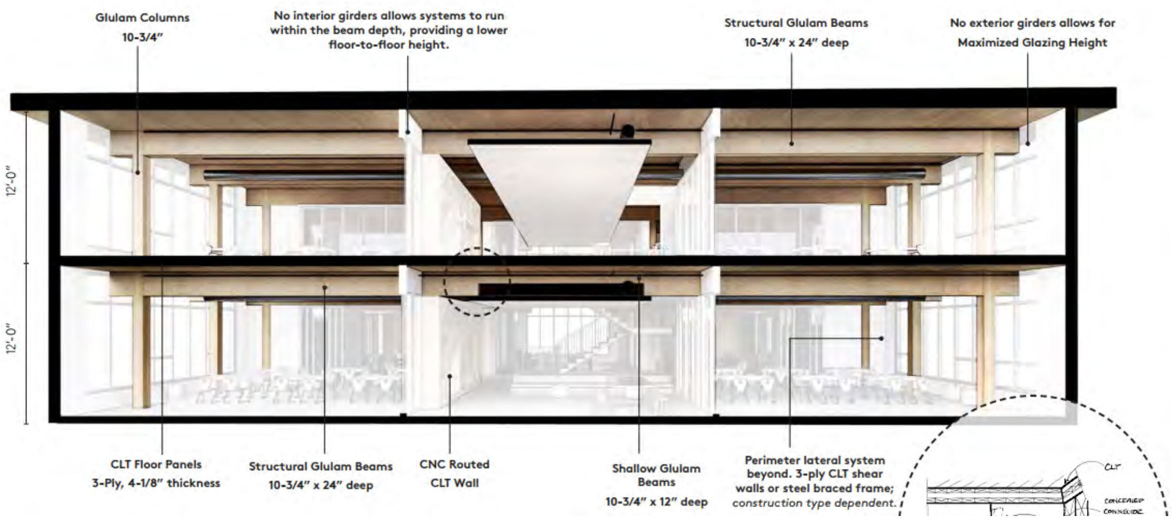


Figure 34. *Building Section Demonstrating Efficiency of a Girder-Less MT System (Craig et al., Mass Timber School Report, Mithun 2022)*

Stacked Beams

Stack cross beams and girders to create openings for MEP components to run through. This is a viable option for SCA schools.

- "Girder" refers to the larger beams supported by the columns. Girders support cross beams.
- "Cross beam" refers to the smaller beams supported by the girders. Cross beams support MT floor plates.

Figure 35. *Stacked Beams at Catalyst, Spokane, WA (left, Michael Green Architecture/Katerra) and Platte 15, Denver, CO (right, OZ Architecture)*

Thickened Floor Plates

Stagger MT floor plates in different planes or use floor plates of different thicknesses and run MEP items above and/or below the resulting channels. This is probably not a viable option for SCA schools, which require larger duct sizes and do not use raised flooring systems.

- Best for conduit and pipes; cannot accommodate ducts larger than 4".
- Best if thicker MT floor plates are already required for structural, FRR, or acoustical reasons.
- Thicker MT floor plates may be specified in order to reduce the number or size of cross beams, minimizing the use of additional material.
- Can be coupled with raised flooring systems for maximum flexibility.

Figure 36. *Thickened Floor Plates at the Wood Innovation Design Center, Prince George, British Columbia (Michael Green Architecture)*

Acoustical Ceiling Treatment Options

As an alternative to or in conjunction with any of the horizontal MEP distribution schemes described above, MT buildings typically use one of the three following ceilings for both acoustical purposes and to conceal or organize horizontal MEP distribution:

- Full or partial acoustical tile ceilings
- Exposed ceilings
- Ceiling “clouds”

Acoustical ceiling treatments are not needed to reduce sound transmission between floors, as that is addressed by adding material to the tops of the MT floor plates (as discussed above).

Acoustical Tile Ceilings

The current SCA Standard calls for a full dropped ATC in core learning spaces, i.e. classrooms. Coupled with a concrete or composite slab, this assembly meets the SCA’s required IIC ratings requirements.

- Dropped ceilings in MT buildings will create concealed spaces, which are not permitted for Type IV-HT construction in the current NYC Building Code.
- While concealed spaces are permitted in Type III-A construction in NYC BC(see notes under *Code Clarifications* section above), these spaces must (see Figure 2 above):
  - Be sprinklered, or
  - Be fully filled with non-combustible insulation, or
  - Fully encapsulate the MT surface with gypsum board.
- Dropped acoustical tile ceilings are a viable option for SCA schools using MT, but would negate some of the advantages of using MT floor plates, such as:
  - Exposing MT materials to view
  - Reducing the amount of additional finish materials
  - Reducing floor-to-floor height

Figure 37. *Dropped Ceilings at Evergreen Charter School, Hempstead, NY (left, Martin Hopp Architects) and Founders Hall, University of Washington, Seattle, WA (right, LMN Architects)*

Exposed Ceilings

A fully open ceiling with visible distribution and end devices is a common choice in Type IV MT construction, as it exposes the bottom face of the MT floor plate to view.

- Ceiling or wall mounted acoustical panels should be provided for sound attenuation and reduced reverberation within the room, but should not obstruct the discharge of the fire sprinklers.
- Exposed ceilings require more careful coordination and layout of MEP distribution and end devices and the use of higher-end materials such as spiral ductwork.
- Conduits and pipes can be recessed into prefabricated grooves in MT panels, but this requires precise design and construction of MEP elements.
- Areas with high concentrations of MEP distribution may have fully obscured MT ceilings.
- Exposed ceilings are a viable option for SCA schools using MT, but may be more suitable for:
    - Offices (limited student access)
    - Back-of-house spaces (no student access)
    - Spaces with higher ceilings

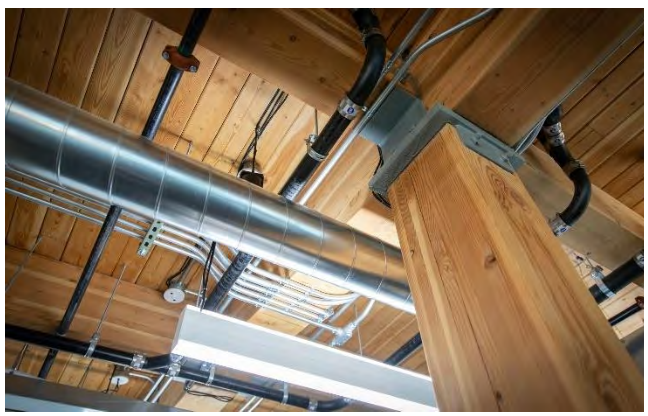


Figure 38. *Exposed MT Ceilings at 38 Davis Office Building, Portland, OR (Ankrom Moisan Architects)*

Ceiling “Clouds”

Prefabricated ceiling clouds are suspended acoustical panels that can integrate HVAC, lighting, A/V, data, sensors and/or fire protection end devices.

- In addition to leaving much of the MT ceiling exposed to view, providing acoustical attenuation, and partially hiding MEP distribution, ceiling clouds neatly organize multiple MEP end devices.
- Sprinklers are required both below and above a cloud ceiling unless it complies with the 2016 NYC Fire Sprinkler Code, which stipulates that the opening widths between clouds must be less than 1 in./ft of ceiling height and that the sum of all openings between clouds should not exceed 20% of the ceiling area of the space.
    - This may seem counterintuitive; the purpose is to increase the aggregate fire resistance provided by the ceiling clouds, creating more of a barrier to flame.
    - Thus, for a 10’ ceiling with sprinkler heads below (or integrated into) the ceiling clouds, the clouds would have to be spaced only 10” apart.
    - This would negate most of the benefits of a cloud ceiling and eliminate the possibility of indirect/direct lighting.
- Ceiling clouds are probably not a viable option for SCA schools using MT unless SCA is open to installing sprinkler heads both above and below (or integrated into) the clouds.

Figure 39. *Ceiling Clouds by Overcast Innovations at UWMilgard Hall, Seattle, WA (left, clouds separate from MEP devices) and Catalyst (right, MEP devices integrated into clouds), Spokane, WA*

Mass Timber Finishes

Wood is subject to a range of factors that can cause biological and physical degradation during its service life. These include humidity, UV exposure, fungus, termites, and exposure to human touch. Protective coatings are critical to ensuring the performance durability of MT components over time, as well as allowing for easy cleanup and maintenance.

In addition, protective coatings enhance and highlight the aesthetic properties of wood.

- The innate characteristics of different wood species may also impact coating decisions.
- Gloss, matte or satin, clear, tinted or opaque looks are available.
- In general, the darker the coat, the better the UV protection.

Timber should not be exposed in areas of high moisture and/or high traffic.

- Rooms such as bathrooms or shower rooms should not have any exposed MT surfaces.
- MT surfaces in corridors, cafeterias and gyms should be covered with impermeable materials such as ceramic tiles on the lower portion of the wall (up to wainscot height or, preferably, the tops of door openings or trim).

Types of Protective Coatings

The traditional stain for surface treatment of wood is oil-based.

- Advantages: Penetrating, water-resistant, durable, easier to maintain and clean.
- Disadvantages: VOCs or petroleum-derived solvents, slow-drying, lacks UV protection, may add an amber hue which can support the growth of mildew.

Water-based finishes are also common.

- Advantages: Fast drying, more environmentally friendly, easier to apply and remove.
- Disadvantages: Does not penetrate as deeply due to rapid evaporation, lacks the performance and durability of oil-based finishes.

Water-borne finishes, composed of modified natural resins suspended in water along with a slow-evaporating solvent such as glycol ether, are a newer product combining the benefits of both water-based and oil-based finishes including:

- Low VOC content and emissions.
- Slow-evaporating solvent softens the protecting coatings on the resin molecules, causing them to bond into one continuous film.
- Unaffected by moisture.
- Resistant to scratches and contamination.
- Successfully used in a number of MT building across N. America including the Earth Systems Sciences Building at the University of British Columbia, Canada and the Hayward Field Stadium in Portland, Oregon.

Application of Protective Coatings

A base primer or undercoat is required for protection of MT elements in transit and during construction, and is factory-applied. It should repel elements while allowing wood to breathe and lose moisture at a controlled rate to reduce checking.

A top finish coat is required for long-term protection of MT elements during occupancy, and can be factory- or site-applied. Application of both base and finish coats in a factory setting, with touch-ups in the field, is becoming a common approach as it provides better quality control.

Proper application is critical for the long-term performance of these coatings. Best practices include:

- Apply product to all six sides of a properly sanded and prepared wood surface.
- Ensure proper dosage (mil thickness) of each coat. Mil thickness should be recorded and kept on file, along with a control sample
- Properly handle the MT on site. Repair any damages and reapply coating.

Maintenance of Protective Coatings

The durability of a MT wood finish depends on many factors, including surface preparation, proper application, exposure to UV and humidity, the color of the finish and quality of wood, etc. Wood finishes also often do not wear out evenly, as.

- More opaque or darker colors provide better protection than a clear system.
- Different sides of an MT element may be exposed to different elements. Areas that are likely to require recoating should be identified during design and coatings should be pre-applied proactively at predetermined time intervals (6 months) as part of regular maintenance.

MASS TIMBER CONSTRUCTION

Prefabrication

MT construction relies much more than conventional steel or concrete construction on custom prefabrication.

- All components – columns, beams, and panels – are built offsite to unique project specifications and tested for quality control by MT manufacturers.
- There are no standardized MT components. Many manufacturers offer their products in standardized sizes, but these do not apply across the industry.
- Each manufacturer uses a different set of suppliers and raw materials, has different prefabrication capabilities, offers a different variety of MT components and finishes, uses different layups, favors different connections, and uses a slightly different design and construction process.
- Some buildings the size of an SCA capacity project will obtain MT components from multiple manufacturers. Most will use materials sourced from multiple suppliers.

Modular Construction

MT construction is a form of modular construction in the sense that large elements such as structural framing, floor and wall panels are delivered ready to assemble like a kit of parts. These elements, particularly exterior walls, may have finishes and fenestration installed.

Fully modular construction using pre-assembled modules with floor, walls, and MEP distribution and devices already installed is also possible with MT.

- These modules can be slotted into a site-built MT or steel structural frame, or stacked up and attached directly to the modules below, above, and adjacent as a kind of cellular structure.
- Fully modular MT construction is best suited to multistory high-density occupancies such as apartments, dormitories, and hotels but can be used for other building types.

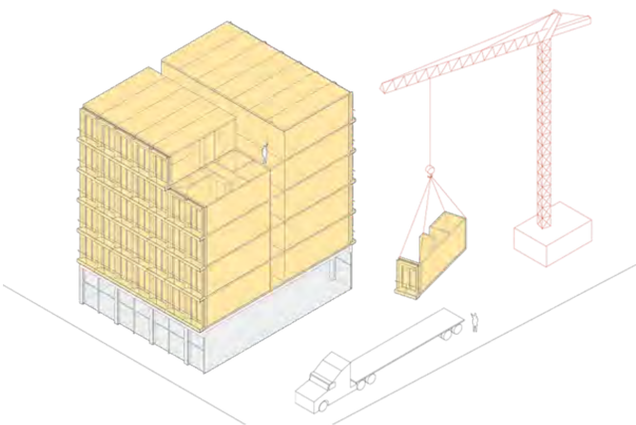


Figure 40. *Fully Modular MT Construction: "Luisenblock" Parliamentary Office Building, Berlin, Germany (left, Sauerbruch Hutton Architects); Residential Modular MT Concept (right, Peter Rose + Partners)*

Early Design Coordination

MT prefabrication requires more intensive design collaboration and decision-making, earlier in the design process, than conventional steel or concrete construction.

- MT components must be carefully fabricated to balance structural, fire resistance, aesthetic, and acoustical requirements.

- Because MT components are often intended to serve as finished surfaces, it is much more difficult to conceal coordination errors.
- Unlike concrete or steel construction, large penetrations of MT panels for ducts and other services cannot be reinforced with additional reinforcement or beams, which may require a different approach to MEP distribution (see *MEP Integration* above).
- Few field modifications other than a limited number of small penetrations, or minor trimming of some components to match field conditions, are required or permissible in MT construction.

It is particularly important to clearly define the engineering scope of work for the project's:

- MT structural design
- Design of connections between MT and steel or concrete elements
- MT detailing and fabrication drawings
- Coordination of MT fabrication drawings with other disciplines (i.e., MEP)

BIM Modeling

MT prefabrication requires a comprehensive BIM model from the design team, typically supplemented by a BIM model from the construction team. Ideally, the manufacturer's BIM model is developed early enough to provide feedback to the design team.

- The manufacturer may rebuild the design team's BIM model using their own software in order to:
  - Facilitate calculations for structure, fire resistance, and material optimization.
  - Assign a unique label to each MT component for tracking through design, fabrication, storage, packing, delivery and assembly.
- The manufacturer's BIM model may also incorporate input from parties such as the construction manager, general contractor, and logistics (delivery and staging) manager.

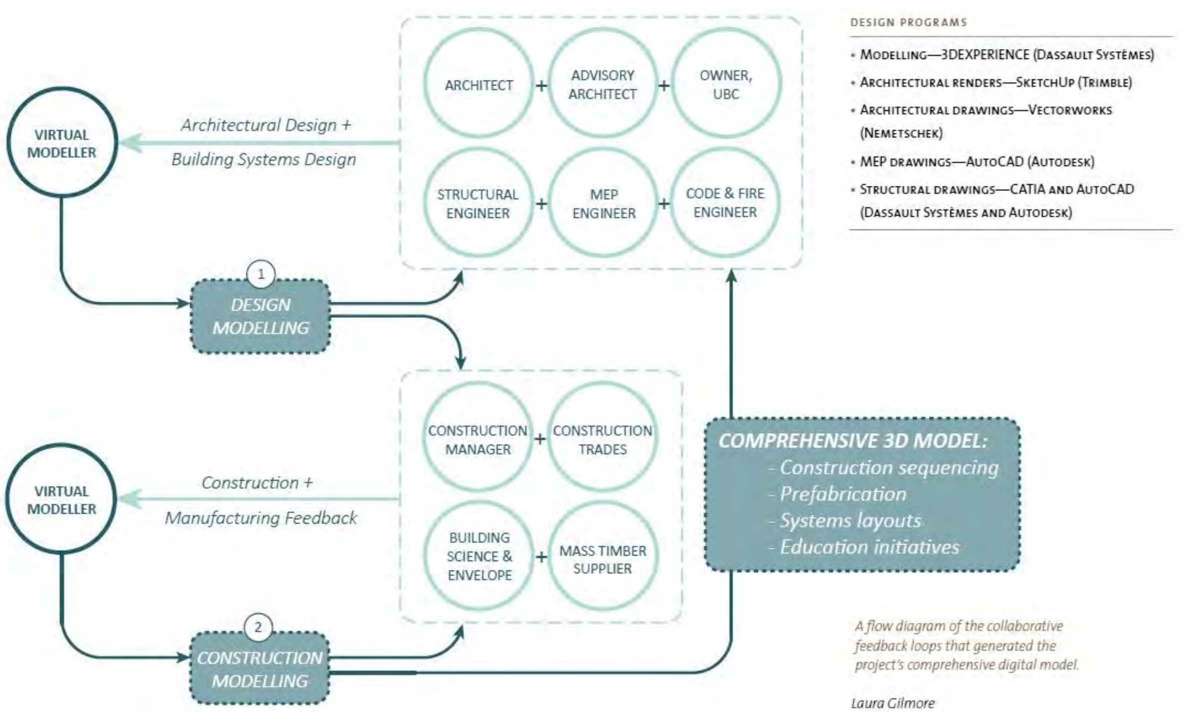


Figure 41. *Manufacturer's BIM Model Provides Feedback to Design Team (Laura Gilmore AIA, published in BIM and Digital Design: A Closer Look at How Mass Timber Goes from Factory to Building Site, Arch Daily)*

Design and Construction Scheduling

Best practices for MT design and construction scheduling include:

Schematic Design

Make the final decision on whether or not to use MT.

- Determine construction classification and initiate discussions with NYC DOB.
- Decide which columns, beams, floor plates, interior walls, exterior walls, shear walls, etc. will be GLT, CLT, or other MT, and which will be concrete or steel.
- Whether concrete or steel can serve as a "fallback" approach if MT does not work out for some or all of the planned elements.

Design Development

Engage potential MT manufacturers starting for input on structural sizing, material optimization, fire resistance, acoustics, and logistics. This requires:

- Determination of which MT elements will be exposed, and which will be concealed.
- Calculation of MT member sizes and panel thicknesses.
- Decisions on connection typologies, materials, and method of concealment.
- Initial coordinated architectural, structural, and MEP BIM model.

During this phase, the team must also choose:

- Species and finish grade of exposed MT materials.
- Construction scheduling goals.
- Where to procure MT material (Pacific Northwest, Southeast U.S., Quebec, Europe).
- Where to fabricate MT elements.
- Which MT finishes will be shop-applied and which will be applied in the field.

50% or 60% Construction Documents

Release the bid package for MT fabrication. This requires:

- Fully coordinated architectural, structural, and MEP BIM model.
- Completed fire resistance calculations.
- Initial buy-in from DOB and FDNY.
- Moisture mitigation plan.

During this phase, the team must also establish:

- Maximum MT sizes for shipping.
- Storage, delivery, and staging parameters.
- Who will install the MT (GC or subcontractor) and whether training is required.
- How the precise tolerances of MT will be accommodated at connections to other materials, particularly the concrete foundation.

100% Construction Documents

Release complete design and MT fabrication drawings as bid addendum.

Lead Times

MT prefabrication requires longer lead times than typical steel or concrete construction due to:

- The precise nature of MT fabrication;
- The need to ship large prefabricated components long distances, unless the project site is located near a manufacturer; and
- Limited capacity of MT manufacturers, particularly in North America.

MT projects that require Forest Stewardship Council (FSC) Certified materials may also have longer lead times due to limited availability. As described in the *Energy/Embodied Carbon Analysis* section below, FSC or similar certification of sustainable forest management practices provides an important guarantee that MT materials can be counted on to sequester the maximum feasible amount of carbon.

The MT designers and manufacturers contacted for this study broadly estimated current lead times for delivery of MT materials to projects in the Northeast U.S. to be around 9 months (from the MT manufacturer's receipt of complete design drawings to delivery), but this will vary extensively depending on the particulars of the project and the selected manufacturer.

- Most manufacturers encourage early design engagement, which does not necessarily require a commitment to use the manufacturer for fabrication, although the recommendations of one manufacturer are not always applicable to another.
- If the manufacturer is not contractually engaged until bid (in a design-bid-build model), additional lead time may need to be factored in to adjust the design drawings to match the manufacturer's sources, capabilities, and process (see *Design-Build vs Design-Bid-Build* below).
- Several European MT manufacturers have larger facilities and more leeway in their production schedules than their North American counterparts, which can yield shorter lead times.
- Smaller and less complex projects will have shorter lead times as they are easier to insert into manufacturers' production schedules.

Figure 42. *Post-Fabrication Storage of MT Panels By Manufacturer (KLH US Holding Corp.)*

Contract Models

Due to the need for early coordination and manufacturer engagement, MT construction is ideally suited to design-build.

- Design-build is not a requirement; MT projects in the Northeastern U.S. have been completed successfully under design-bid-build.
- Design-bid-build projects will benefit from the same reduction in building erection time as design-build projects, but this effect may be negated by a need to revise the design drawings at the beginning of construction (see *Lead Times* below).

Other alternatives to design-bid-build include:

- Construction manager at risk
- Integrated project delivery
- Design assist

Design Assist

In part because of the complexity of the MT design and construction issues described above, and in part because the MT industry is still maturing in North America, the use of design assist is widely used.

- Many levels of design assistance are available, from pre-design through construction. Some of the most common services for projects with a full A/E team include:
  - Design review and recommendations
  - Refinement of the design for MT material and cost optimization
  - Detailing and drafting of MT connections and hardware
  - Identification of suitable MT suppliers, manufacturers, and finishers
  - Transportation, temporary storage, and just-in-time delivery planning
  - Moisture management planning (see *Moisture Management* below)
  - Installation planning and instruction
- Design assist may be provided by MT manufacturers or by a third party hired by the owner, construction manager, or general contractor.
- Design assist by MT manufacturers is generally limited to smaller and/or simpler projects. Larger/more complex projects are likely to need a third party design assist firm.
- Industry associations such as WoodWorks can provide a limited degree of design assistance, particularly during the initial planning stages of a project.

Moisture Management

Moisture Risk

MT is susceptible to moisture risk throughout the construction progress.

- During manufacturing and shipping, sources of moisture may include wetting from rain on unprotected elements during transport or storage.
- During construction, sources of moisture may include rainfall, snowmelt, night sky condensation, and leaks.

It is important to implement measures to avoid excessive wetting of the MT during construction and facilitate drying to bring the moisture level back to normal before occupancy.

- HVAC and humidity control systems are important to keep interior relative humidity between 30-60% when MT building performs best with respect to long term durability.
- The graph below shows a typical moisture cycle for MT components:

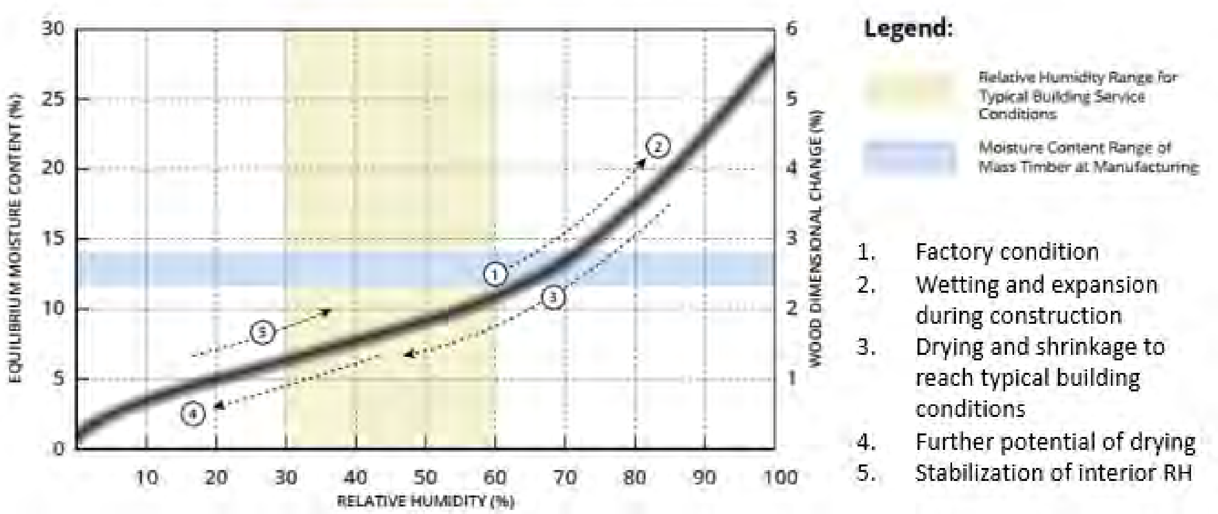


Figure 43. *Generic Sorption Isotherm for Wood Showing the Relationship between the Moisture Content and Dimensional Change of Mass Timber Throughout Construction and Service Life (RDH Building Science)*

Moisture Management Planning

Based on the *Moisture Risk Management Strategies for Mass Timber Buildings by RDH Building Science Inc.* (RDH), there are three steps for moisture management during construction:

- Risk assessment during design;
- Develop a construction phase moisture management plan during design;
- Execute the design and moisture management plan during construction.

Risk Assessment

At the early design, the architect should evaluate the risk for MT assemblies to determine their moisture exposure level and identify solutions for factory or site installed moisture protection membrances and additional assembly design features and detailing needs.

Moisture exposure level is contingent upon the following factors:

- Climate and season – rainfall/snowfall levels and frequency, wind and drying opportunity.
- Water management strategies during construction – presence of roof panel slope, water diversion or deflection, and drains to discharge to the building exterior

- Exposure duration
- Shipping and storage arrangements
- Extent of encapsulation of MT with moisture-sensitive materials for fire protection or insulation

The risk assessment matrix below shows the correlation between the robustness of the protection measures and the moisture exposure level.

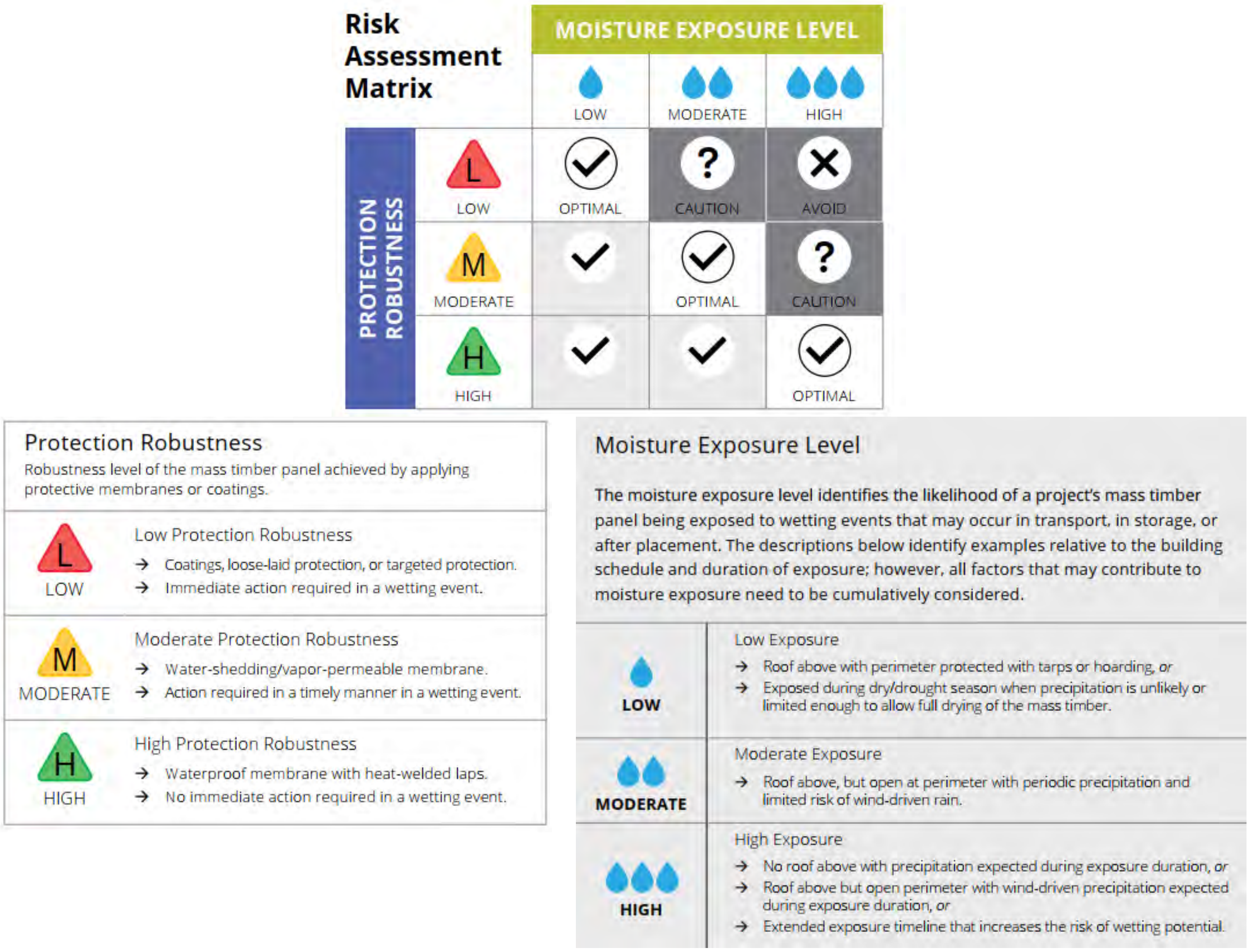


__Figure 44.__ Risk Assessment Matrix Based on Moisture Exposure Level and Protection Robustness (RDH Building Science)

Moisture Management Plan

The contractor should develop a construction phase moisture management plan, from pre-delivery to project completion, to prepare their team for manging construction phase moisture and possible unexpected exposure risks.

- The moisture management plan defines all activities of the construction team to reduce moisture-related risks and may include keeping an active water management team on-site to reduce uptake.
- Early plannning reduces the moisture exposure level with more opportunity to make design and construction phase adjustments due to schedule shifts or project changes.

RDH provides a guideline to establish a construction phase moisture management plan, which includes:

- **Schedule and delivery:** Coordinate delivery, waterproofing and/or roofing subcontractor work to limit moisture exposure/wetting.
    - Just-in-time delivery is recommended to minimize staging needs and moisture exposure risks, with plans to schedule installers (i.e., waterproofing subcontractor or roofing subcontractor) at the time of MT panel installation to ensure moisture protection membrane detailing work is performed alongside or shortly following placement.
    - If on-site storage is needed, provide a dry area under protective wrapping with adequate drainage. Site plan should indicate location of designated material storage area(s) or on-site moisture meter shall be included.
- **Moisture protection:** Identify moisture protection methods at common building details. Examples of such details may include:
    - Panel top and edge coatings (mostly factory-installed)
    - Membranes or acoustic mats (factory or site-installed)
    - Panel edge/joint/penetration treatments
    - Building wrap
- **Water removal:** Provide instructions on when an on-site active water management team will be implemented and methods to remove standing water from un-sloped MT areas using mops, squeegees, and shop vacuums. Drainage plan to identify drainage paths for controlling site water for all floors and roofs shall be included.
- **Checklists:**
    - Weekly checklist: Ongoing moisture management, including weather forecast, review underside of MT panels for leaks and review membranes for damage etc. Measure moisture content of MT daily and weekly, as well as before encapsulation of MT (<16% moisture content).
    - MT delivery acceptance checklist: Minimum number of moisture content readings to be taken at delivery acceptance, and direction on what to do if the MT materials fail to meet the moisture content limit.
    - Pre-and post-pour checklist: Ensure moisture content readings are taken and outline required sequencing prior to pouring concrete and post-pour protection methods.
- **Moisture exposure response:** Outline strategies to dry the MT if the moisture content exceeds recommended limits.
    - Specify resources that will be ready on-site for implementation if needed, e.g. fans, heaters and dehumidifier.
    - The overall depth of the MT and the extent of water intrusion (should it occur) will determine the most effective drying strategy.

Execution and Maintenance

The success of a MT building and its proper operation depends on how dry the MT components were maintained during construction.

- It is important to assign primary responsibility for on-site moisture management.
- During the execution of the design and moisture management plan, the MT components of the building must be monitored and evaluated to assess the effectiveness of the moisture management plan to protect the MT structure.
- It is also critical to control indoor relative humidty and temperature following completion of enclosure, both before and after commissioning of mechanical systems.

- Slow drying of the interior will allow MT to dry to the indoor evinronment while minimizing the risk of checking or cracking.

See Appendix A for an excerpt of a sample moisture management plan from RDH.

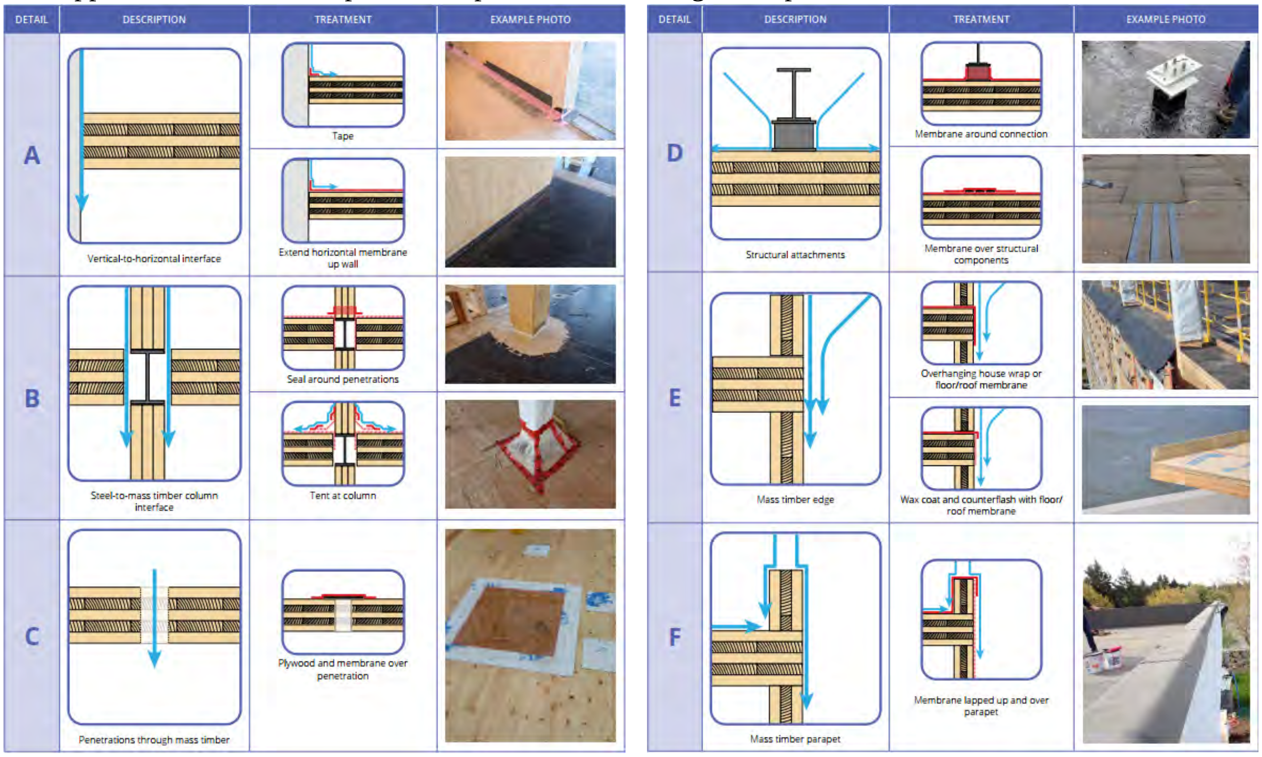


Figure 45. *Examples of On-Site Moisture Protection Details (RDH Building Sciene)*

Moisture Management During Occupancy

The best practice of MT design and construction keep MT components warms and dry throughout the buildings construction and occupancy phases. Sources of moisture during occupancy can include water intrusion through failures of the building enclosure's water control layers at MT assemblies or surrounding assemblies and details. Other sources of occupancy phase moisture include plumbing failures, occupant activities such as bathing and food preparation, appliances that use water, and activation of a fire sprinkler system.

Long-term and persistent exposure to moisture is likely to be more problematic to MT than overall quantity of water. MT can dry out the moisture slowly if wetted. However, without any intervention, moisture can penetrate deep into MT, become trapped within the pore structure of wood, and at locations such as pre-fab panel interfaces, lamination interfaces, splices, exposed end grain etc. Thus, it is critical to detect water leaks early on during maintenance.

The problem with leakage is that it could be difficult to detect until it is too late. It is especially true for roof leaks, where the risks are arguably the greatest. A moisture sensor can be installed to address this concern. It is a non-destructive way of monitoring the integrity of the waterproofing membrane and detecting any deficiencies in the membrane in the roof assembly, which may indicate a leak. Sensors connected with a grid of electrical field tape are installed on top of the waterproof membrane at a 20 feet interval. Using electronic field vector mapping technology, it creates a low voltage field of positively charged electrons. The distribution of the electrons can indicate any paths through the conductive structural element where leakage may take place.

The data collected will be used to generate periodic reports, set alarms for anomalous reading, and can be integrated into the BIS system. It can also inform decisions on deferred maintenance, and guide maintenance managers in a leak investigation and verify leak repair.

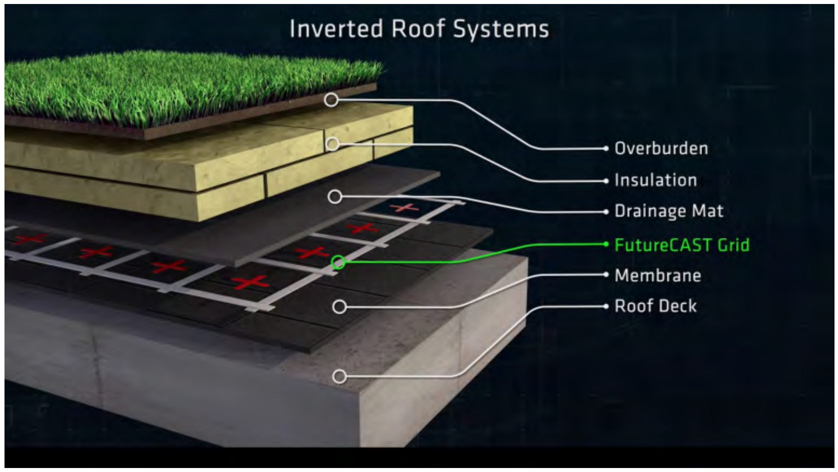


Figure 46. *FutureCast Sensor System*
(Structural Monitoring Technology Research Ltd.)

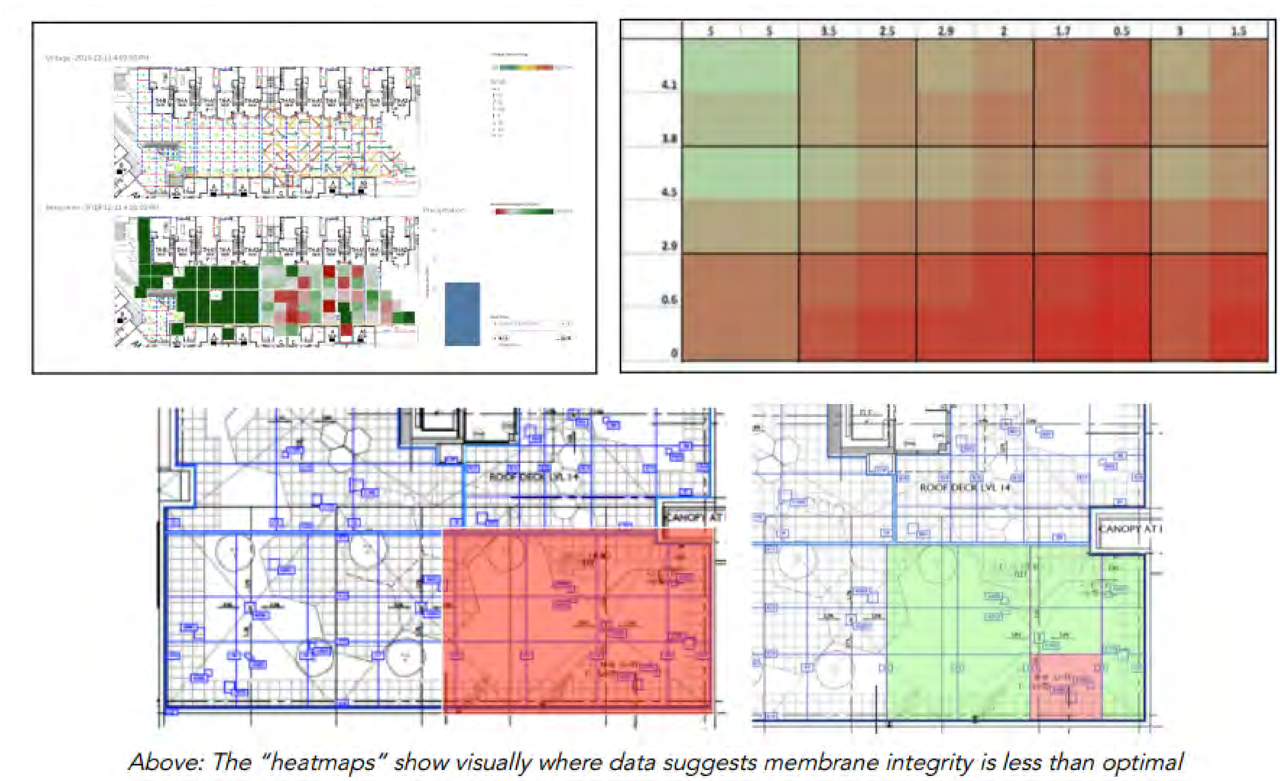


Figure 47. *Sample of Moisture Sensor System Data Collection and Display*
(Structural Monitoring Technology Research Ltd.)

Construction Site Impacts

One of the benefits of MT construction is its typical impact on construction site management. Compared to conventional steel and concrete construction, most MT construction is:

- Faster:
  - 1 week or less per floor (vs 2-3 weeks per floor for CIP concrete)
  - A comparison by Spiritos Properties, a NYC-based developer, estimated 31 person-hours were required to place 1,000sf of MT structural framing, vs. over 50 person-hours for steel and over 100 person-hours for concrete
  - In addition to faster structural frame erection, some MT construction may be designed without need for additional fireproofing or finishes, saving even more time

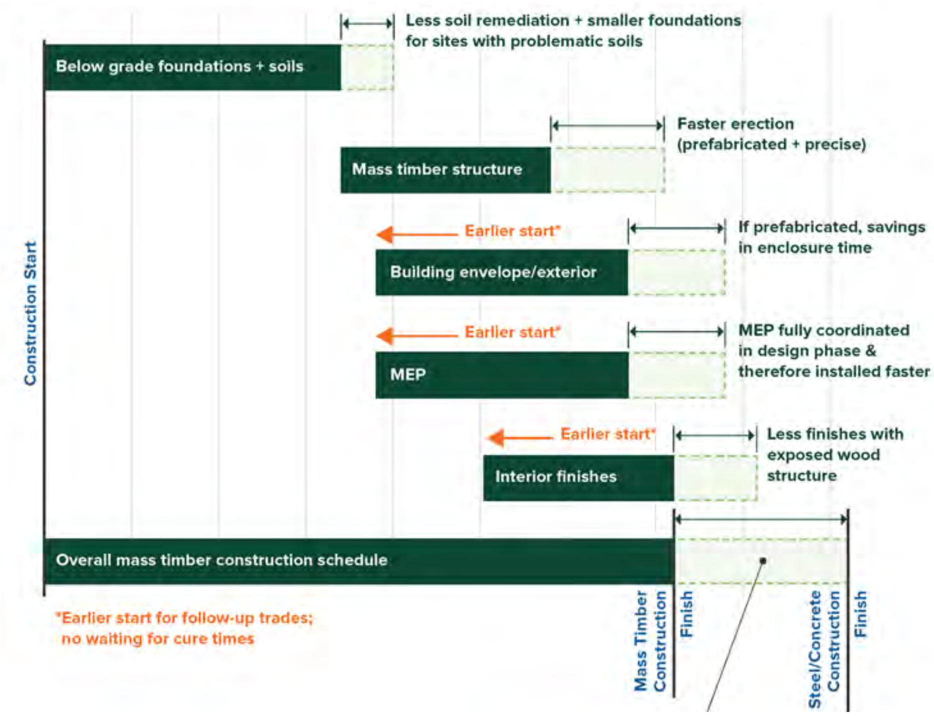


Figure 48. *Opportunities for MT to Reduce Construction Time Up To 25% (WoodWorks)*

- Lower-pollution:
  - Fewer trucks, minimal idling (especially compared to CIP concrete)
  - Reduced temporary electrical load / less need for generators
- Lower-waste:
  - Prefabrication means no off-cuts
  - Fewer finishes means less material on-site overall
  - Less concrete means less waste containment for truck washing
  - MT materials arrive in moisture protection wrap that can be recycled
- Quieter:
  - No welding, grinding, or sawing
  - Minimal hammering (except for projects with wood dowel connectors or onsite construction of NLT panels)
  - Mostly drills/drivers

- Less congested:
    - Superstructure assembly crews typically comprise only 6 to 10 people
    - With some training, can be erected by laborers with experience in CIP concrete, precast concrete, tilt-up, and steel construction
- Convenient: Final prefabricated MT stairs (not applicable in NYC) can be added with each floor – no need for temporary construction stairs/scaffolding

Figure 49. *Typical MT construction (left: naturallywood.com, right: Seagate Structures)*

There are some drawbacks to MT construction site management:

- Moisture management is essential
- Temporary fire protection, such as a standpipe in the elevator core, may be required
- Special care must be taken to avoid marring large MT components that will remain exposed

MT construction site benefits can be maximized by:

- Craning MT components directly from delivery truck/trailer to building (no on-site storage)
- Having a moisture management plan in place before construction begins
- Training crews in MT assembly and correction of finishes

PROCUREMENT AND CONSTRUCTION

State of the Industry in North America

Manufacturer Services

A limited but growing number of A/E firms have the necessary experience to provide complete MT design services.

- Most A/E firms rely on some level of design assistance from the MT manufacturer.
- Many manufacturers provide a wide variety of design services beyond the simple provision of MT components.

In addition to specific design requirements, MT components may also be designed to meet site or transportation limitations. MT manufacturers can include such considerations in their designs.

- A site with limited street access may need smaller or lighter components that can be placed by smaller cranes.
- A site that cannot be reached by a 40-foot trailer may need shorter components that will be spliced together on site.
- A project with high shipping costs may benefit from components optimized to fit a volume or weight limitation.

Some manufacturers provide ready-to-install MT components, while others provide components that may require further modification using CNC (computer numeric control) milling.

- CNC provides more precise tolerances than standard milling can provide.
- CNC is most often used to modify MT elements to accommodate steel connectors, MEP distribution, and openings.

Industry Shortcomings

Although it has grown rapidly, MT is still considered an "immature" industry in North America. As such, it faces the following broadly recognized shortcomings:

- Uneven distribution of manufacturers
    - Mostly located in the Pacific Northwest (Washington, Oregon, and British Columbia) and Quebec, where spruce and Douglas fir forests are concentrated.
    - Growth is expected in the Southeast U.S. (Georgia, Alabama, Arkansas, and South Carolina), where southern pine forests are concentrated.
    - Despite having the most prominent timber industry in the Northeast U.S. and increasing numbers of local MT projects, Maine does not yet have a local MT manufacturing presence, although state-led efforts to attract manufacturers are underway.
- Limited production capacity
    - U.S. manufacturers have been reluctant to expand without certainty of demand, while demand remains limited in part by concerns about production capacity and lead times.
    - The highly publicized 2021 bankruptcy and failure of Katerra, a well-capitalized U.S. construction company that explicitly focused on MT and prefabricated building elements, dampened some investors' enthusiasm for the industry.
    - As a result, some U.S. MT projects have sourced their materials from Europe, where the industry is more well-established, with larger manufacturers and greater production capacity. East Coast MT projects sourced from Europe may end up having transportation

costs, lead times, and transportation carbon footprints similar to or less than those of projects sourced from the Pacific Northwest.

- Lack of warehousing/staging space near major construction markets
  - Outside of the Pacific Northwest, MT projects in the U.S. must ship their materials long distances. However, the fast pace of MT building erection means the materials must be readily on hand. This requires on- or off-site storage, which can be difficult in cities where space is at a premium.
  - Unlike other construction products, MT elements are almost entirely customized, so there is no possibility of warehousing stock elements.
- No standardized sizes for MT components
  - Most MT components are 100% custom-designed for each project.
  - Some manufacturers provides some standard MT sizes, or MT elements with a standard thickness, but these differ from manufacturer to manufacturer due to their equipment capabilities, layup practices, and material sources.
  - The lack of standardization means projects may need to be “locked in” at an early stage to a specific manufacturer or set of manufacturers, as switching manufacturers could require significant design changes.
  - The connections between MT components are even less standardized than the components themselves. This is particularly true for “aesthetic” joints that are exposed to view, which are far more common in MT construction than in steel or concrete buildings.
  - The lack of “stock” components helps inflate the cost of MT design and construction.
- Still developing standard protocols for testing and analyzing MT components
  - While protocols for testing MT components and connections for fire resistance and flame spread have been established, only a limited number MT components, connections, or assemblies have been third-party certified under these protocols.
  - Most North American MT manufacturers have obtained 2-hour fire resistance tests for their CLT and GLT panels of 5 layers or more. However, nearly all testing to date has been facilitated by individual MT manufacturers for their own elements, and therefore cannot be applied to other products.
  - Calculations rather than tests are typically used to establish fire resistance ratings for beams, columns, and connections. While the calculations are relatively straightforward for beams and columns, this is not the case for connections.
  - WoodWorks maintains an inventory of fire-tested MT assemblies.
  - There are some UL-listed assemblies for through-penetration firestops and perimeter fire barrier systems.
- Wide variety of preferences for connections
  - Architects, engineers, manufacturers and prefabricators all have their own preferences for connections (steel vs wood, through-bolts vs screws, hidden vs exposed, etc.)
  - According to Arup, the quantity, variety, and complexity of connections has a greater cost impact on MT construction than the quantity or source of timber material.
  - To help designers better understand the implications of connection design, WoodWorks has created a guide and a CAD/Revit index that groups connections into 4 classes:

Connection Classes in Relation to Fire Rating

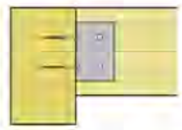
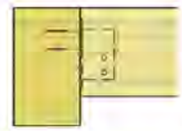
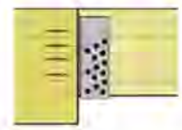
Connection Class	Class 1	Class 2	Class 3	Class 3
Fire Resistance	May be inherently fire resistant according to NDS calculations	Requires additional protection to meet fire-rating requirements	Tested fire-resistance rating (as specified by manufacturer)	Requires additional protection to meet fire-rating requirements
Connection Example				
	Beam Bears on Girder*	Beam Connected to Girder with Steel Angles*	Beam Connected to Girder with Proprietary Concealed Face-Mounted Knife Plate Connector*	Beam Connected to Girder with Proprietary Hanger*

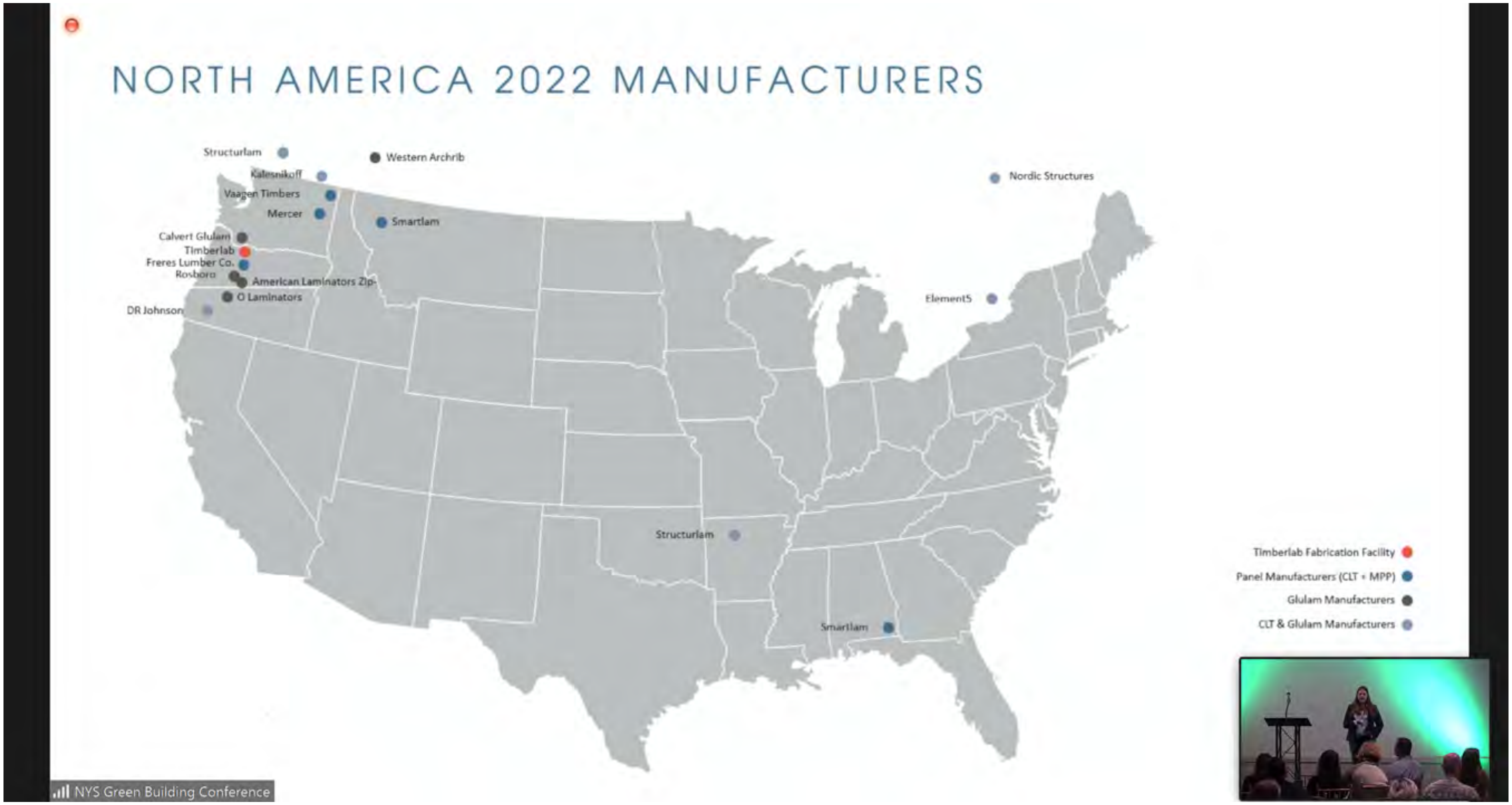
**Table 8 in the WoodWorks Index of Mass Timber Connections*

Figure 50. *Four Classes of Mass Timber Connections (WoodWorks)*

New/Promising Industry Developments

- Growing capacity and experience
- Incorporating reclaimed lumber/castoffs into MT fabrications
- Steel building contractors pivoting to MT (similar skillset)

Manufacturer Locations and Capabilities



Source: Timberlab

Supplier Name	Location[1]	MT Types	FSC[2]	Services	FRR Testing	Website
KLH US Holding Corp	NY	CLT	FSC	3D modeling, CNC fabrication (CLT only)	Yes	https://www.klhusa.com/
South County Post & Beam	RI	heavy timber, GLT		timber framing, flooring, trusses		https://www.scpb.com/
XLAM Dolomiti	Ontario	CLT (made in Italy)		design assist, prefabrication		https://www.xlamdolomiti.it/en
Timber Systems	Ontario	GLT, CLT, NLT		design assist, prefabrication, construction		http://www.timsys.com/
Element Five	Ontario	CLT, GLT, SIP		design assist, prefabrication, construction		https://elementfive.co/
Goodfellow	Quebec	GLT		prefabrication		http://www.goodfellowinc.com/
Structure Fusion	Quebec	GLT, NLT		design assist, prefabrication		https://www.structurefusion.com/en/
Art Massif Structure De Bois	Quebec	GLT		prefabrication		http://www.artmassif.ca/
Nordic Structures	Quebec	CLT, GLT	FSC	design assist, 3D modeling, prefabrication, CNC fabrication, construction, hardware install	Yes	https://www.nordic.ca/
Stark Truss Company	OH	GLT, LVL		prefabrication		https://www.starktruss.com/
TimberLab	SC, OR	CLT, GLT	FSC	design assist, 3D modeling, CNC fabrication, procurement, construction, hardware install		https://timberlab.com/#
Anthony Forest	GA	GLT		prefabrication		info@anthonyforest.com
Boozer Laminated Beam Company	AL	GLT		prefabrication		https://boozerbeam.com/

[1] Some companies have facilities in multiple cities within the same state or province.
[2] Indicates whether the company uses Forest Stewardship Council certified wood in some or all of its products.

Supplier Name	Location[1]	MT Types	FSC[2]	Services	FRR Testing	Website
SmartLam	AL	CLT, GLT		prefabrication		https://www.smartlam.com/
IB X-Lam USA	AL	CLT, GLT		prefabrication		www.smartlam.com
Texas CLT	AR	CLT		prefabrication		http://texasclt.com/
Anthony Forest	AR	GLT		prefabrication		https://www.anthonyforest.com/
Alamco	MN	GLT		design assist		https://alamcowood.com/
Arizona Structural Laminators	AZ	GLT		prefabrication		http://www.azglulam.com/
Gruen-Wald Engineered Laminates	SD	GLT		prefabrication		http://gruen-wald.com/
SmartLam	MT	CLT, GLT (outsourced)	FSC	3D modeling, CNC fabrication (CLT only)	Yes	https://www.smartlam.com/
QB Corporation	ID	GLT		prefabrication, custom finishes		https://qbcorp.com/
Boise Cascade	ID	CLT, GLT, LVL		prefabrication		https://www.bc.com/
Red Built	ID	GLT, LVL, open web trusses		3D modeling		https://www.redbuilt.com/
DRJ Wood Innovations	OR	CLT, GLT	FSC	design assist, 3D modeling, CNC fabrication (CLT), hardware install (outsourced)	Yes	https://www.drjwoodinnovations.com/
Rosboro	OR	GLT		prefabrication		https://rosboro.com/
American Laminators	OR	GLT	FSC	CNC fabrication (limited) (FSC coming soon)		https://www.americanlaminators.com/
Freres Engineered Wood	OR	CLT, LVL		CNC fabrication		https://freresswood.com/

Supplier Name	Location[1]	MT Types	FSC[2]	Services	FRR Testing	Website
Calvert Company	WA	GLT	FSC	prefabrication		http://www.calvertglulam.com/
Shelton Lam and Deck	WA	GLT		prefabrication		https://www.sheltonstructures.com/
Mercer International	WA	CLT		design assist		https://mercerint.com/products-services/mass-timber/
Vaagen Timbers	WA	CLT, GLT		design assist, prefabrication, CNC fabrication, hardware install	Yes	https://vaagentimbers.com/
Seagate Structures	WA	NLT		design assist, 3D modeling, 4D modeling, prefabrication, procurement, installation		https://seagatemasstimber.com/
Western Archrib	Manitoba, Alberta	GLT		cost analysis, design assist, prefabrication, CNC fabrication, connector fabrication, pre-assembly, erection, custom finishes		https://www.westernarchrib.com/
Kalesnikoff	British Columbia	CLT, GLT	FSC	design assist, 3D modeling, prefabrication, CNC fabrication, hardware install	Yes	https://www.kalesnikoff.com/
FraserWood Industries	British Columbia	GLT, NLT		design assist, prefabrication, connector fabrication, hardware install		https://fraserwoodindustries.com/
StructurLam	British Columbia	GLT	FSC	design assist, digital design and engineering, 3D modeling, prefabrication, CNC fabrication	Yes	http://www.structurlam.com/
Stora Enso	Finland	CLT, GLT, LVL	FSC	3D modeling, CNC fabrication		https://www.storaenso.com/en/
Hasslacher Notica Timber	Austria	CLT, GLT, GLT	FSC	3D modeling, CNC fabrication, hardware install		https://www.hasslacher.com/en/from-wood-to-wonders
WIEHAG	Austria	GLT	FSC	3D modeling, CNC fabrication, connector fabrication, hardware install		https://www.wiehag.com/en/

State of the Industry in NYC

Suppliers

Current or completed MT projects in NYC have used a wide variety of MT suppliers in North America and Europe, and some have used multiple suppliers, which is a common practice in the industry. The use of multiple suppliers may allow for a reduced schedule, reduce risk, or provide a mix of specific MT products selected for a project.

According to Martin Hopp Architects (see *Industry Consultations* below), who worked on the Evergreen Charter School in Hempstead Long Island (see *Case Studies* section below), they received MT materials from the following three companies.

KLH

KLH provided the CLT wall elements for the project. KLH fabricated the CLT in Austria. KLH suggests that transportation from Europe to the US is not an issue and is reliable. When materials arrive to the US from Europe, the container is emptied at a transfer shipping yard and then delivered straight to site. KLH recommends projects on the east coast reach out to suppliers early due to the limited supply in the region. KLH claims working in New York is not much different from MT projects in other states, since most projects in the US are relatively new to all stakeholders.

Dinesen

Dinesen provided the flooring and GLT elements for the project. Dinesen fabricates their products in Denmark. The shipping lead time is four weeks from Europe to the US.

South Country Post & Beam

South County Post & Beam provided other GLT materials for the project. They are located in Rhode Island. Organizing transportation from them was easier since they are established within the US.

Contractors and Workforce

There are no NYC-based contractors specializing in MT construction, although several firms that provide MT materials or design assistance have provided specialty MT erection crews for projects in NYC. While a specialized crew can facilitate MT construction, many general contractors – particularly those experienced in structural steel construction – can erect MT buildings with some training.

Cost Multipliers

Higher costs for MT construction in NYC can be expected due to:

- Obtaining DOB approvals
- Lack of contractor experience, which can lead to inflated bids
- Cost of transportation from MT suppliers
- Cost of temporary off-site storage of MT materials

INDUSTRY CONSULTATIONS

WoodWorks

WoodWorks is a nonprofit organization created by the Wood Products Council to provide advocacy, education, and technical guidance for MT projects in the U.S. Key points from discussions with the WoodWorks regional director on March 20, 2023 and March 21, 2023 are summarized below:

- The main change in the 2022 NYC BC is the explicit inclusion of CLT, building height and area limitations have not changed since the previous code edition
- The exclusion of concealed spaces is the biggest drawback of Type IV construction
- The exclusion of CLT for exterior walls is the biggest drawback of Type III construction (see notes under *Code Clarifications* section above)
- There are two methods of proving fire resistance:
    - Using a previously tested assembly
    - Direct calculation
- There is no third-party certification body (such as UL) for fire resistance testing of MT assemblies
- A typical floor-ceiling assembly consists of CLT, an acoustical mat, and a topping
- Acoustical mats are typically rubber or felt wool
- Toppings are typically concrete or gypsum board, gypsum board is sometimes favored because it has lower embodied carbon
- Project teams can expect to save 20-25% in construction time and cost, however, construction cost savings are balanced out by higher material costs

Timberlab

Timberlab is a licensed general contractor specializing in MT design, procurement, fabrication and installation. Timberlab has been involved in several of the most significant MT projects in the U.S., including procuring and managing the fire-resistance testing of the MT materials for the world's tallest hybrid MT structure (as of 2023), the 25-story, 273,000sf multifamily Ascent building in Milwaukee, WI. Key points from discussions with a senior project manager at Timberlab on March 20, 2023 and March 21, 2023 are summarized below:

- Timberlab is one of a few US companies that offers fully integrated MT design and construction oversight, coordinating all aspects of the project related to MT
    - Provides preconstruction or "design assist" including complete structural design or refinement of structural design provided by the design team
    - Acts as broker connecting the client with (a) manufacturers (typically 2 or 3) that can provide the necessary materials and (b) long- and short-distance logistics/delivery companies
    - Provides on-site supervision and/or installation with their own crews
    - Roughly 50% of MT projects in the US hire a "design assist" firm; the rest depend on design firms and construction managers with MT experience
    - Design assist firms should be brought on as early as possible – even during pre-conceptual design – but no later than midpoint of DD
- Timberlab is typically hired by the general contractor or building owner
    - If hired by owner for design assist, typically needs to switch at the beginning of construction to a subcontractor role for the GC due to coordination requirements

    - Unclear how this arrangement would work in a design-bid-build context
- MT requires BIM, for coordination as well as fabrication
    - Timberlab almost always develops a separate BIM model, usually during the second half of DD
    - Timberlab's model then "goes live" and becomes the core model for the team to work with
    - Two levels of modeling: basic, which covers 90% of the design and coordination issues; and advanced, which includes details such as connection designs
- In US, MT is becoming more common for higher education buildings, less so for K-12
- One limiting factor for implementing MT in NYC will likely be logistics associated with construction, including truck lengths and street closures
    - It is best practice to avoid "double handling" MT products as much as possible (i.e., craning products onto site, then onto building; or providing basic assembly at the supplier's shop, then fine detailing at a separate fabrication shop)
    - A drop trailer (a trailer that is left or "dropped" at the site) and storeyard with a short driving distance is a good staging solution
- For NYC projects Timberlab plans to use its own in-house skilled labor, at least initially, and then draw from the local workforce once the company is established there
- For projects on the US East Coast, European CLT fabricators are often more cost-effective
    - European suppliers are larger and less dependent on individual projects, so require less of an up-front deposit to guarantee schedule and lumber pricing
    - Lower production costs offset higher transportation costs
    - European suppliers have more standardized sizing, so it is easier to have multiple bidders
- GLT manufacturing is reasonably well developed in the US and it is easier to find US-based suppliers compared to CLT
    - Timberlab fabricates GLT at a facility in South Carolina
    - South Carolina offers good access to Southeastern US coastal soft pine forests
- Most 5-ply CLT should be 2-hour fire rated, but only certain manufacturers have gone through the testing process, which typically takes 3-5 months
    - Some manufacturers don't want to provide fire testing until they have an order that requires it
    - Fire test stringency is jurisdictionally dependent
- All US MT building require at least some connection between timber and concrete (foundations, slabs on grade, stair/elevator cores, shear walls)
    - Preference is for concrete work to be complete before MT arrives on site
    - Main concern during handoff between concrete and timber trades is larger tolerances for concrete (1-1/2" is typical) vs precision of MT
    - Ideal assembly embeds adjustable connectors in the concrete, but this is not typical practice
    - Coordination between MT and steel is easier

Nordic Structures

Nordic Structures is a MT supplier in Quebec, Canada providing a wide range of CLT slab and wall panels, GLT structural elements, and I-joists. Nordic Structures has a partnership with an FSC-certified black spruce forest in Quebec, but also obtains MT materials from other non-certified suppliers.

Nordic Structures supplied the GLT material for 320 & 360 Wythe Avenue Brooklyn, NY and the CLT material for the Rhode Island School of Design's North Hall (see Case Studies below). Key points from a call with a representative of Nordic Structures on March 14th, 2023, are summarized below:

Nordic's MT elements are fabricated in in its Montreal, Canada facility. MT materials for bigger projects are transported by rail, which requires more careful consideration of timing and scheduling. Materials for smaller projects are transported by truck, which has fewer restrictions. During transportation GLT structural elements are individually wrapped while CLT panels are wrapped together.

Nordic Structures suggested that installation and the building code are the greatest challenges to wider use of MT in NYC. Nordic advised that hybrid MT buildings are more complicated due to the mix of concrete or steel and timber installation. They noted that the carpenters union and steel workers union may disagree on who will work in certain areas and when, causing some delays.

Martin Hopp Architects

Martin Hopp Architects (MHA) is a NYC-based architecture firm with a focus on institutional projects, and designed the MT Evergreen Charter School in Hempstead. Long Island. Key points from a call with a representative of Martin Hopp Architects on March 14th, 2023 are summarized below:

Evergreen, a 4-story, 89,000sf new building designed to accommodate 750 intermediate and high school students, was one of the six winners of the 2022 Mass Timber Competition administered by the U.S. Department of Agriculture and the Softwood Lumber Board. The winners split $2 million in grants to support project development. The project was built under the New York State Building Code.

MHA described some of the challenges that arose when working with MT:

- Getting the correct construction classification; the project began as Type III-D construction but shifted to III-A
- Resolving the thickness of the GLT slab and concrete topping slab
- Coordination of CLT, GLT, and concrete slab and wall penetrations
- How to run conduits along CLT wall panels
- Acoustics

The project includes vertical GLT fins on the façade to help control solar heat gain. MHA did not use GLT or CLT in the exterior wall construction because of the lead time required. The project's received MT materials were obtain from three different companies.

An LCA is being conducted for the project, but was still in development at the time of this call. The project's 2022 Mass Timber Competition entry estimated that the use of MT would all construction to avoid 359 tons of CO_2e emissions.

NADAAA Architects

NADAAA is a Boston-based architecture and urban design firm known for material experimentation, and designed the Rhode Island School of Design's North Hall (see Case Studies below). Key points from emailing with a representative of NADAA on March 15, 2023 are summarized below:

The decision to use MT for the project was made together by the owner, contractor, and design team (architect / structural engineer), as the project used IPD (Integrated Project Delivery). Odeh Engineers, NADAAA's design team partner, are big proponents of CLT. The client, RISD, is an educator of architects and designers and therefore very interested in the raw expression of the building materials.

The following challenges arose when working with MT:

- In-field modification of the CLT decking
- Protecting the CLT during transportation, since the ceilings (the underside of the CLT floor slabs) were to be exposed. If not protected, the contractor would have been required to sand and clean the CLT on site before leaving it as an exposed finish
- To meet high acoustical standards between dorm rooms (STC 50), the floor build-up required LVT (luxury vinyl tile) flooring backed with cork, 2" of gypcrete, and a 1" isolation mat on top of the CLT, a cost not initially accounted for
- The need to isolate the CLT floor slabs from the bathroom tile substrate due to differential expansion rates

The project was classified as Type III-B construction (see notes under *Code Clarifications* section above) due to its concrete podium, so the upper levels were allowed to use CLT under the older (2015) IBC. According to Mr. Chang, cost and scheduling prevented the project from implementing CLT on the exterior. The steel frame was able to be erected much faster than CLT bearing walls would have been, and still allowed the CLT floor slabs to be installed by carpenters.

Arup

Arup is an international engineering consulting firm that has been involved in the design of several MT projects in the U.S. (none in NYC). On June 23, 2023, Arup experts in MT sustainability and construction and MT structural, fire, acoustic, and envelope design hosted the symposium "Mass Timber: A Multidisciplinary View" and answered questions before and after the event.

Construction

- Manufacturers just want to be in the conversation [during design]. It's not like they need to be on the title block [of the construction drawings] to give advice and feedback.
- Design assist services by MT manufacturers are mainly intended for smaller or simpler projects. Larger or complex projects are expected to have a structural engineer who knows MT.
- When it comes to lead times, it's easier to insert smaller projects into the fabrication pipelines of manufacturers. It's a question of volume. European manufacturers have more production capacity because the demand for it is larger and well-established.
- Early design coordination is not optional. Higher upfront costs pay off with far fewer RFIs.
- We have seen construction schedule savings of 20% on MT projects.
- Design-bid-build is possible with MT.

Material Optimization

- Don't hide or cover MT – it needs to be allowed to dry out to the interior of the building.
- The benefits of lighter weight [for MT structures] are real. We had a project in London that had to use MT because there were old tunnels beneath the site that limited the size of the foundations.
- However, light weight is part of what makes MT susceptible to acoustical vibration.

Structural Design

- Most deflection in a MT project happens at the connections, not the floor plates or structural members. Connections, not thickness of MT floor plates, drives the size of MT structural members.
    - Therefore the best way to reduce material costs is to minimize the number and complexity of connections, rather than minimizing the thickness of MT floor plates.
    - Connection design needs to come early in design.
- A steel or reinforced concrete building design can't be "converted" into a MT building design. Grid spacing and member sizing of a MT building will be different if you're looking to optimize material use.
- Stacked MT beams are a good way to accommodate MT distribution.
- The design of MT shear walls has been thoroughly tested in buildings of up to 6 stories.

Fire Resistance

- In a 750C fire, the char that forms on the surface of MT keeps the inner wood at 60C.
- Each exposed side of a MT member will sacrifice some depth to char. For a structure with stacked beams, the girder is exposed on four sides. Its effective structural cross-section must subtract char from all four sides.
- IBC 2021 was the big leap forward for MT, but NYC did not adopt IBC 2021.
    - IBC 2021 allows you to pursue a performance-based path as an alternative to prescriptive code compliance for MT fire resistance.
    - Outside of NYC, Type IV construction is the most common code compliance path for MT.
- NYC allows exterior walls to be made of non-combustible wood, such as fire retardant treated wood or treated CLT, but it must still be covered by non-combustible materials. Intumescent coatings cannot be used with MT.
- The planks in GLT have adhesive on all edges/faces. The planks in CLT only have adhesive on the top and bottom faces, leaving gaps between the plank edges that reduces the fire resistance of CLT relative to GLT.

Sustainability

- It's more important to take care of our forests than to use MT to sequester carbon.
    - Forest processes like decay, soil formation, and new plant growth move orders of magnitude more carbon than anything industrial process like construction will ever do.
    - Sequestration might have an impact in the tens of thousands of MT CO_2e. Natural processes have an impact in the millions.
- Key factors in the effectiveness of carbon sequestration by MT buildings:
    1. Treatment of MT materials at end of building life – re-use or recycling vs. incineration or landfilling – is more important than the decision to use MT in the first place.
    2. A building that uses MT inefficiently will have a carbon footprint equal to or greater than that of a steel or concrete building.
    3. Travel distance of the MT materials from forest to fabricator to site.
- Construction (modules A1-A5 of a whole building life cycle analysis or LCA) comprises 30% of a building's LCA impacts.

Use of MT in Building Envelopes

- Unlike reinforced concrete slab edges, the edges of CLT floor plates can't support much of the weight of the façade.
    - The edge of the floor plate needs to be close to a structural support (a beam).
    - Typically, a CLT exterior wall panel will connect to the beam not at a point but at a section as wide as two feet.
- Exterior MT wall connections to a MT structural frame must be thermally broken in order to prevent condensation which can damage MT materials.
- A panelized MT façade must have carefully detailed joints in the air/vapor barrier in order to allow for movement of the metal connectors while maintaining the integrity of the barrier.
- Exterior MT walls require vertical and horizontal firestopping to prevent fire spread from floor to floor or room to room through the façade.

MT Industry and Costs

- Pricing of MT projects in NYC is highly variable and contingent [on project specifics and on the contractor].
    - We get quotes back [for MT projects in NYC] that are way too high. We think it's because the contractors just aren't familiar with MT yet.
    - [In California] we took a contractor to see a MT fabrication facility so they could better understand the process and the cost came down.
- Volatility in U.S. production capacity – such as the failure of Katerra – has led to some uncertainty in pricing.
- Future expansion of MT manufacturing is expected in the Southeastern U.S., which currently has only one or two facilities.
- It's not clear why there is no MT manufacturing in Maine.

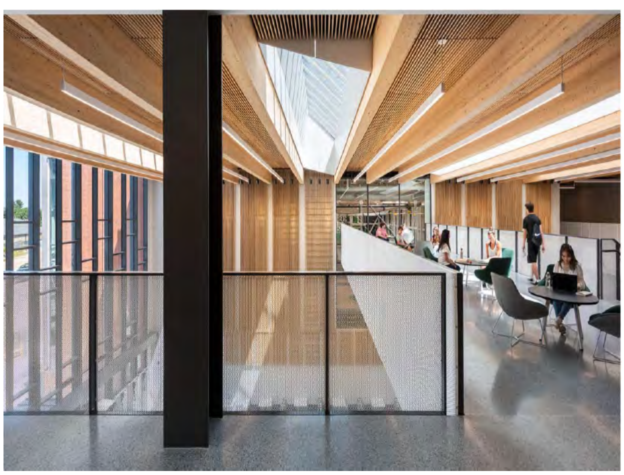
CASE STUDIES

Billerica Memorial High School, Billerica, MA

Perkins + Will / Engineers Design Group / Completed 2020

- Size: 3 stories, 325,000 sf
- Capacity: 1,800 students
- Structural framing: GLT (public wing and commons atrium roofs), steel (academic side)
- Exterior walls: Brick masonry cladding, metal panel cladding
- Cost: $146.7M ($451/sf)

The embodied carbon in the FSC Certified spruce timber structure offsets the equivalent of a typical school bus traveling over 460,000 miles. The project achieved LEED Silver and won a 2022 AIA Award for Architecture.

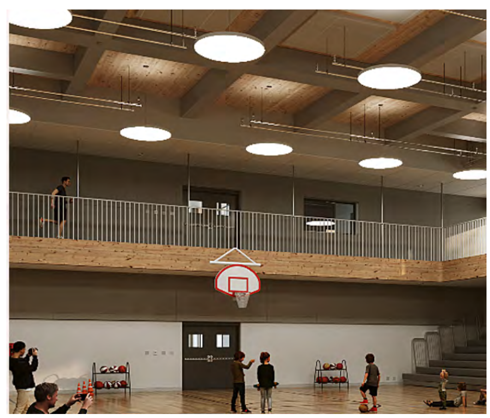


Evergreen Charter School, Hempstead, NY

Martin Hopp Architect / Odeh Engineers / Completion expected 2024

- Construction Type: Began as **III-D** and changed to **III-A**
- Size: 5 stories, 85,000 sf (larger than NYCBC22 max)
- Capacity: 750 K-12
- Structure: Hybrid GLT/concrete
- Exterior walls: Metal panels, GLT fins
- Interiors: CLT partitions, GLT floor plates
- Sources: CLT manufactured by KLH in Austria. GLT manufactured by Dinesen in Denmark. Some GLT manufactured by South County Post & Beam in Rhode Island.
- Cost: $54M ($635/sf) including furnishing

Winner of the Softwood Lumber Board & USDA 2022 Mass Timber Competition (received a portion of $2M in funding to support project development)



John W. Olver Design Building, University of Massachusetts, MA

Leers Weinzapfel Associates / Equilibrium Consulting Inc. / Simpson Gumpertz Heger / Completed 2017

- Construction Type: **IV-HT**
- Size: 4 stories, 87,500 sf
- Capacity: 500 students + 50 faculty
- Structure: Exposed GLT columns and beams, GLT brace frames, CLT shear walls, timber-steel composite trusses, concrete foundation
- Interiors: Timber-concrete floor plates with steel mesh reinforcement, CLT stairs
- Exterior walls: Anodized aluminum panels
- Sources: GLT manufactured by Nordic Structures in Montreal
- Cost: $37M ($423/sf)

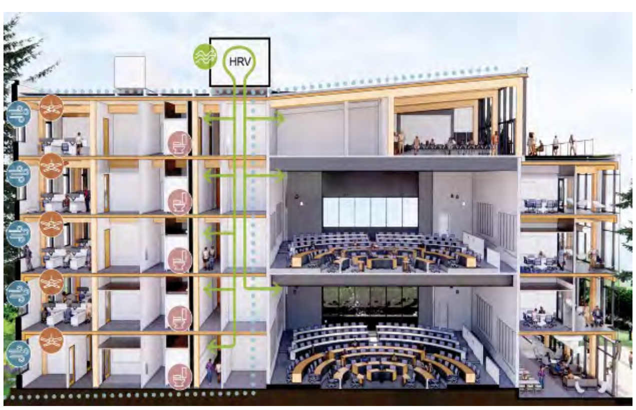
The facility, the first MT structure in the Northeast U.S., used 70,000 cubic feet of wood and saves the equivalent of over 2,500 metric tons of carbon when compared to a traditional energy-intensive steel and concrete building. The project achieved a LEED Gold ranking. An Athena whole building life cycle assessment concluded that the MT construction had significant impacts on the depletion of stratospheric ozone depletion and non-renewable energy resources, reducing them by 10.1% and 14.8% respectively.

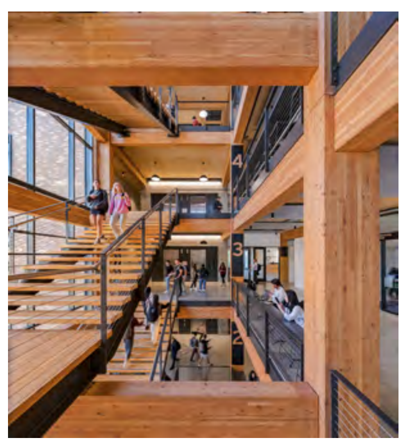
Founders Hall, University of Washington, WA

LMN Architects / Magnusson Klemencic Associates / Completed 2022


- 5 stories, 85,000 sf
- School of Business
- Structure: GLT columns and beams, steel beams at classrooms, reinforced concrete shear walls
- Interiors: CLT floor plates
- Exterior walls: Brick, curtain wall, textured metal cladding
- Sources: CLT and GLT manufactured and fabricated regionally
- Cost: $52.5M ($618/sf)

Founders Hall's MT structure and CLT decking reduce the building's embodied carbon by 58%, with an 85% reduction in operational carbon. The building is projected to achieve a 79% reduction in energy consumption over the first 60 years of its life, and has a site Energy Use Intensity (EUI) of 27 (compared to 40 for a code-compliant school building). Founders Hall will store more than 1,000 tons of CO_2 for the lifetime of the building. The project achieved LEED Gold.





Timber House (670 Union Street), Brooklyn, NY

MESH Architectures / Completed 2022

- Construction Type: **III-A**
- Occupancy: Residential condominiums
- Size: 6 stories, 40,000 sf
- Structure: GLT with reinforced concrete core and shear walls
- Interiors: GLT floor plates (originally approved with CLT flooring, then DOB approval was rescinded)
- Exterior walls: Rain screen on studs, CMU (at lot lines)
- Sources: GLT manufactured by Vaagen Timbers in WA

Timber House is the largest MT building built in New York City to date. The beams are about 20” deep and 30’ long and support the floor plates which run 4’x8’ and measure just under 18” thick. The building was designed with Passive House principles and took 1 week per story to construct.

360/320 Wythe Avenue, Brooklyn, NY

Hansen Architects / Flank / Completed 2023

360 Wythe Ave	320 Wythe Ave
Construction Type: **II-A**	Construction Type: **II-A**
Size: 5 stories, 117,000 sf	Size: 3 stories, 15,000 sf
Occupancy: Mixed-use (B/G retail, 2 stories office, 2 stories residential)	Mixed-use (B/G retail, 2 stories office)

- Structure: GLT, concrete foundation
- Interiors: NLT floor plates
- Exterior walls: Brick independently supported by a secondary structure
- Sources: GLT manufactured by Nordic Structures in Montreal (CA)

The first "brick and beam" buildings to be constructed in New York City in nearly a century. The material is mostly black spruce.

360 Wythe Ave

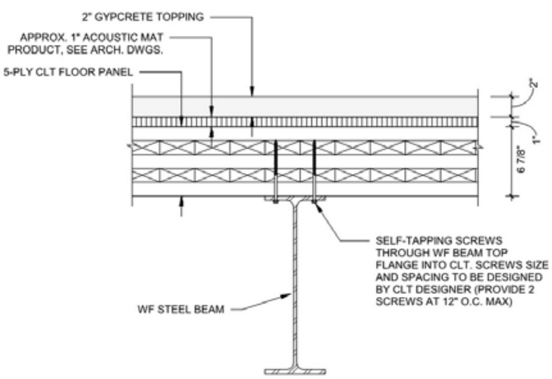
320 Wythe Ave

North Hall, Rhode Island School of Design, RI

NADAA / Odeh Engineers / Completed 2019

- Construction Type: **III-B**
- Size: 6 stories, 40,790 sf
- Occupancy: Student housing
- Structure: Steel columns and beams on concrete podium
- Interiors: CLT floor plates
- Exterior walls: Fiber cement rainscreen
- Sources: CLT manufactured by Nordic Structures in Montreal (CA)
- Cost: $25M ($613/sf) including furnishing

The project is projected to save roughly $16,400 annually by using 27% less energy than a typical code-compliant building (72,794 kWh/year less electricity and 43,000 therms/year less natural gas). GHG emissions will be reduced by 74.3 MTCO2e. The structure was erected in 2 1/2 weeks.



Floor Assembly: E1 CLT – 6 7/8" Thick

Central Utility Space in the Corridors

San Mateo County Office Building, CA

SOM / Completion expected 2023

- Size: 5 stories, 207,000 sf
- Occupancy: Office
- Structure: GLT columns and beams with steel core
- Interiors: CLT floor plates
- Exterior walls: Curtain wall, copper-colored anodized aluminum panels, stone base, precast concrete panels at lot lines
- Sources: GLT and CLT manufactured by Western Wood Structures in Oregon and Canada
- Cost: $182M ($879/sf) including furnishing

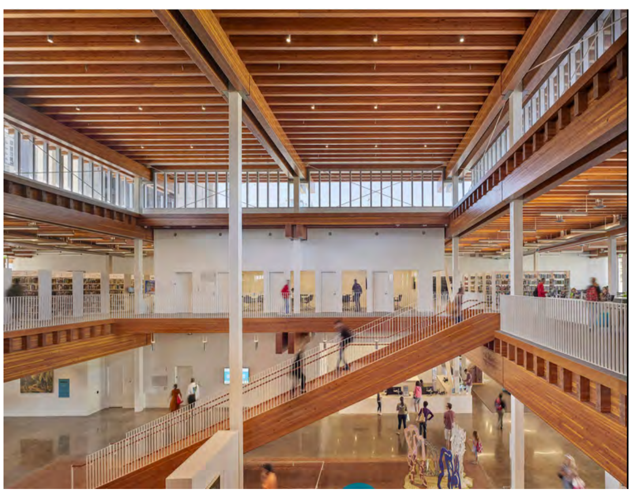
The building, known as COB3, will be one of the first net-zero-energy, ultra-low-carbon civic buildings constructed with MT in the U.S., achieving an 85% reduction in structural embodied carbon. Solar arrays on the roof will offset all of the energy needed for the building’s operations. Passive House design strategies were used. The project is targeting LEED Platinum.

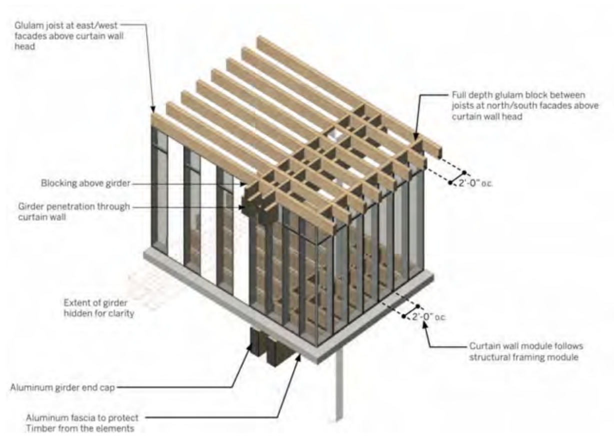
Billie Jean King Library, CA

SOM / Completed 2019

- Construction Type: **IV-HT**
- Size: 3 stories, 96,000 sf
- Occupancy: Library
- Structure: GLT beams and joists, reinforced concrete filled hollow steel columns
- Interiors: CLT floor plates
- Exterior walls: Curtain wall, rain screen, concrete at lot lines
- Sources: CLT and GLT manufactured by DR Johnson in OR
- Cost: $48M ($500/sf) including furnishing

MT comprises 80% of the new library's structural material. The building also features rooftop photovoltaic cells, daylighting strategies, controlled air ventilation systems, and extensive glazing with architectural overhangs for solar protection. The project achieved LEED Platinum.





TASK 2: TEST CASE ANALYSIS

TEST CASE SELECTION

An addition in Queens, which was in design at the time this study was completed, was selected as the test case for this study because it meets the restrictions of NYCBC 2022 Construction Type III-A (maximum 5 stories/85ft, 47,000sf – see notes under *Code Clarifications* section above) and Type IV-HT (maximum 7 stories/85ft, 51,000sf) as well as IBC 2021 Types IV-C and IV-HT. The design also features rectilinear framing with a regular column grid, which streamlined the test case structural MT design process.

Figure 51. *Rendering of Existing School (left) and Addition (right) by STV Inc.*

A free-standing gymnasium in Brooklyn, also in design at the time this study was completed, was selected as a separate test case for long-span roofs because the addition test case does not include a large column-free space such as a gymnasium or auditorium. NYCBC 2022 also allows the roof structure of a Construction Type II building to be composed of MT.

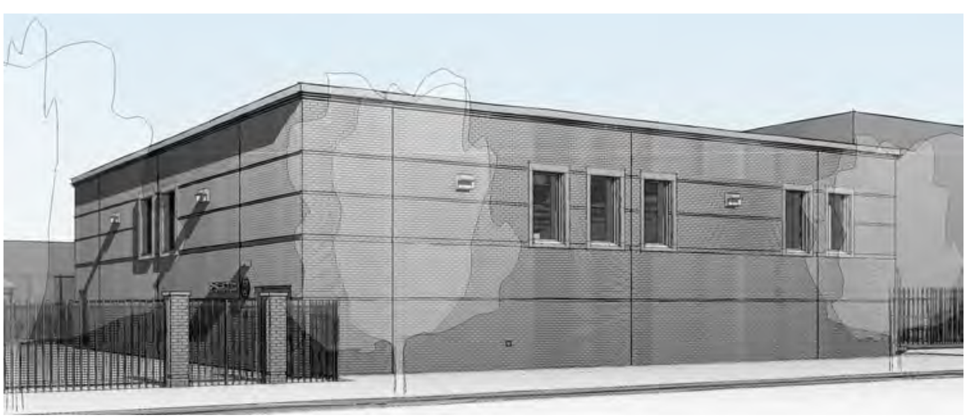


Figure 52. *Rendering of Free-Standing Gymnasium by Purcell Architects*

Most SCA new buildings and additions are larger than 51,000sf and therefore would not be able to comply with NYCBC 2022. It is not clear if or when NYCBC will incorporate the larger maximum building areas of IBC 2021. Rather than speculate, this study chose test cases that could conceivably comply with the current code.

TEST CASE LIMITATIONS

EME's intent in analyzing each test case was to substitute structural elements and partition walls of the existing design with MT elements as much as feasible. EME's philosophy was to make as few changes as possible where these might impact occupant flow and egress, usable floor area, and the MEP systems; in this way, the test case design can be compared with the original building design without any caveats about changing the building occupancy, program, layout, function or size.

It should be noted that in reality, the direct conversion of a fully developed conventional steel or concrete structural design into a MT design is suboptimal. If designed from the beginning as a MT building, the addition might have used a somewhat different structural grid, program layout, and fire safety design in order to optimize the use of MT material (see *Material Optimization* under *Mass Timber Materials* above.

The test case investigates how MT could be used in the building under 2022 NYC BC Type III-A (see notes under *Code Clarifications* section above) as well as Type IV-HT. Under Type IV-HT, CLT can be used in the exterior walls. As noted in the *Code Clarifications* section above, there is some ambiguity in the 2022 NYC BC regarding whether the CLT in an exterior wall must be encapsulated on both sides, or only on the exterior-facing side. In order to further differentiate the two code compliance schemes for the test case, this study uses the assumption that only the exterior-facing side must be encapsulated, and the interior-facing side can be exposed.

This analysis is based on design drawings provided by the SCA.

ADDITION IN QUEENS

Baseline (Existing) Design

Zoning characteristics:

- 40,510 GSF (< 47,000 limit for NYCBC 2022 Type III-A and 51,000 limit for Type IV-HT)
- 4 stories above grade (< 5 story limit for Type III and 7 story limit for Type IV)
- 73' high (< 85' limit for Type III and Type IV)

Architectural characteristics:

- Cellar level extends beyond building footprint, below sidewalk and play yard
- Floorplates 1-4 are identical and connect to existing building at project East facade
- 15'-8' floor-to-floor heights to match existing building (except for 15'-2" cellar)
- Fire rescue rooms: Cellar cafeteria and one room on each of floors 2-4

The existing design has a reinforced concrete structure including:

- Two-way slabs
- Few beams except below roof (to support mechanical dunnage)
- Concrete elevator and stair cores that incorporate shear walls

- Concrete parapets

Building envelope characteristics:

- 4’ high stone water table on concrete knee wall backup
- Insulated precast concrete panels at 1st floor above water table
- Terra cotta rainscreen exterior walls on steel stud backup
- Extensive green roof with 4” growing media

Figure 53. *Addition Site Plan*

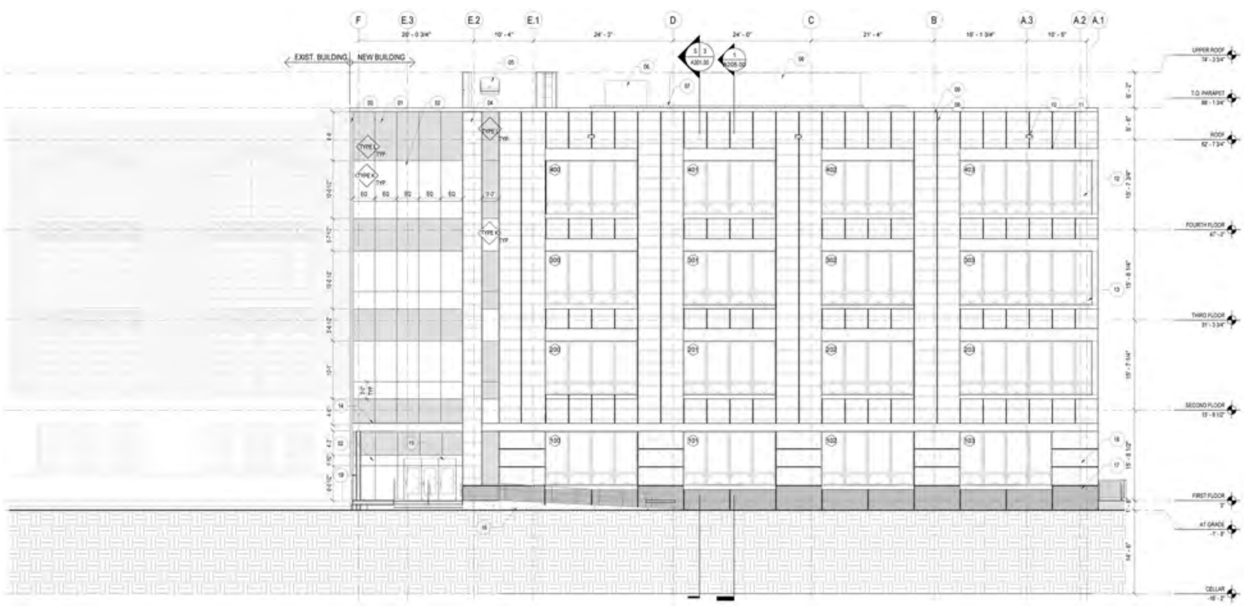


Figure 54. *Addition North Elevation*

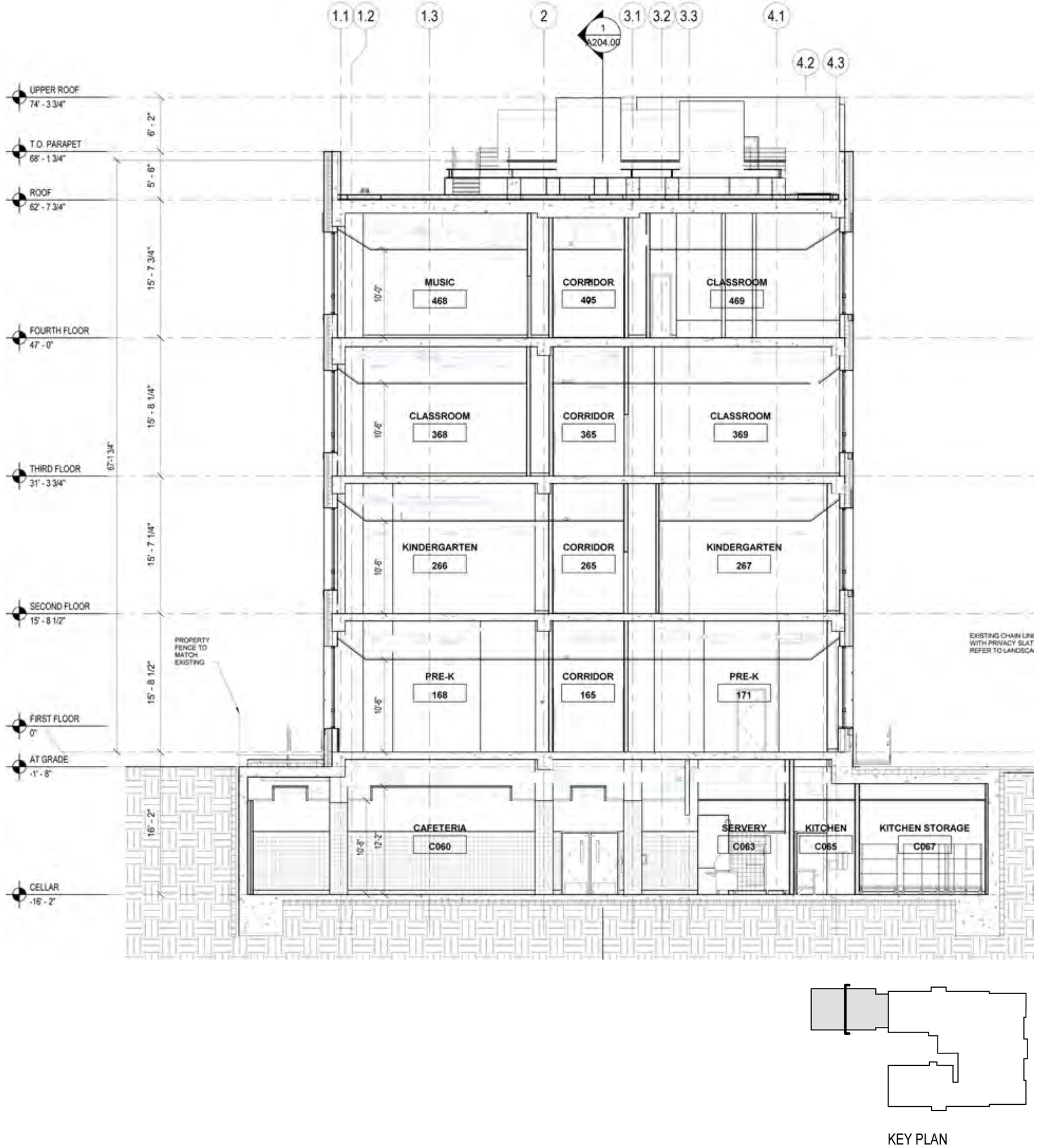


Figure 55. *Addition Section*

Figure 56. *Addition Floor Plans*
(Rooms 060/063, 266, 368, and 468 Are Fire Refuge Areas)

Mass Timber Design Approach

The following diagram illustrates the types and locations of MT components proposed for the test case analysis, including:

- Columns
- Beams
- Floor plates (including roof)
- Exterior walls (Type IV construction only)
- Interior partitions

The following materials remained the same as in the existing design:

- Concrete foundation, slab on grade, and retaining walls
- Concrete knee walls (with stone water table) and decks below sidewalks
- Concrete elevator and stair cores / shear walls
- Steel rooftop mechanical dunnage

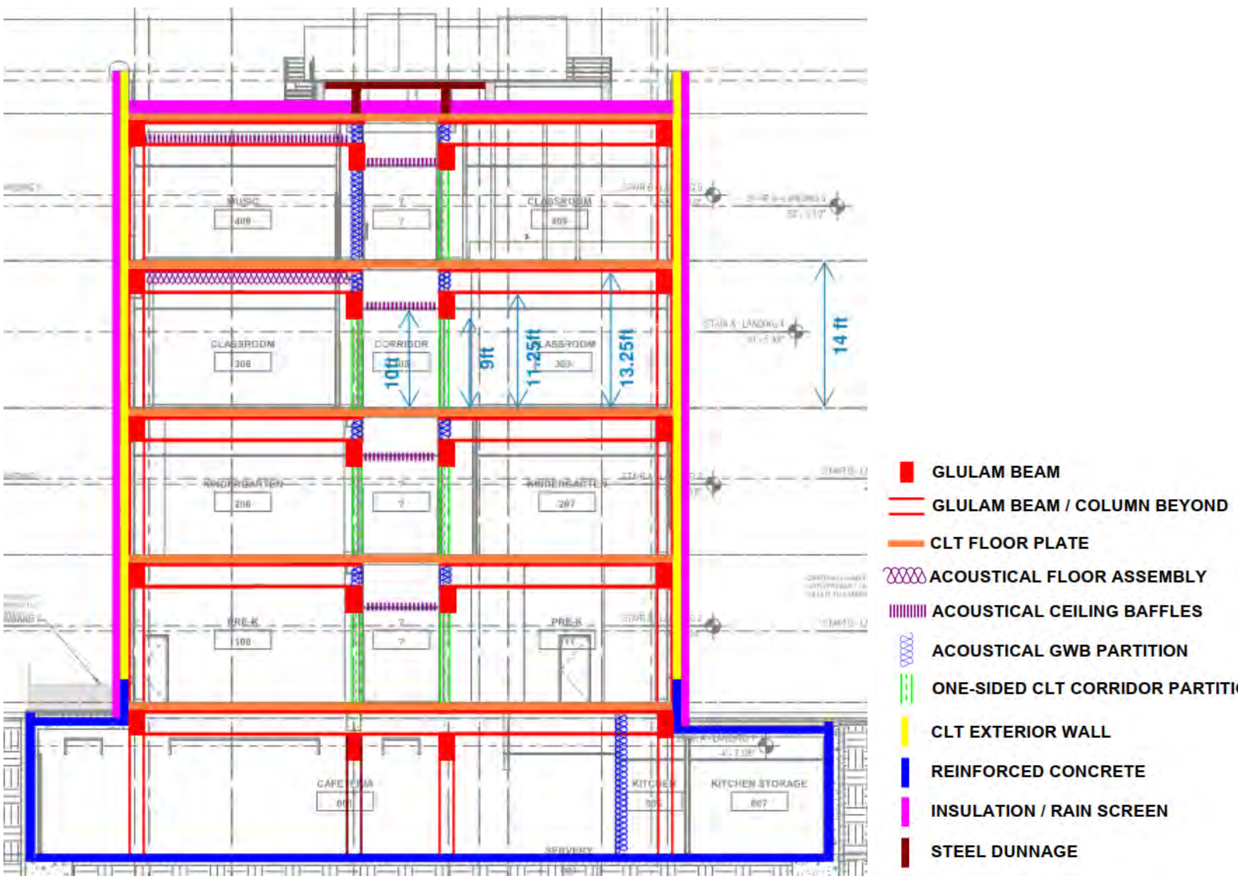


Figure 57. *Section Diagram Showing Proposed Use of MT in Addition*

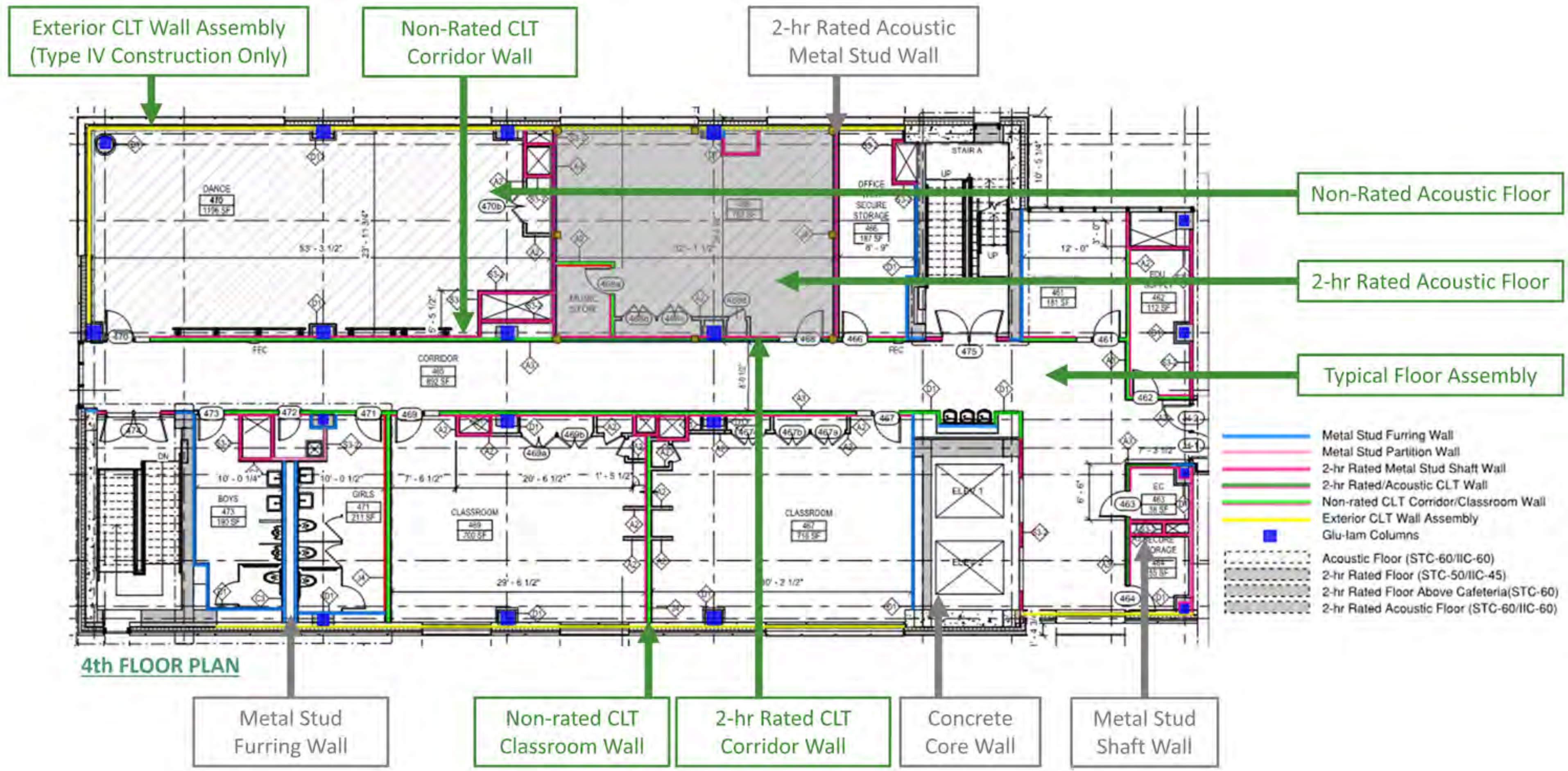


Figure 58. *Plan Diagram Showing Proposed Use of MT in Addition*

Mass Timber Structure

Design of the mass timber ("MT") structure for the addition was performed for two cases: Type III construction and Type IV construction. Under the 2022 edition of the NYC Building Code (NYCBC 2022):

- For Type III construction (see notes under *Code Clarifications* section above): elements in the "Primary structural frame," "Floor construction and associated secondary members," or "Roof construction and associated secondary members" are required to have 1 hour fire resistance rating (see NYCBC 2022 Table 601), and thus the building's CLT structural floors, floor beams, and columns are required to meet this rating requirement.
- For Type IV construction: building structural elements have "HT" fire-resistance rating requirements, which a heavy timber element implicitly satisfies if it exceeds the minimum dimensions of heavy timber structural members in Table 2304.11.

Design of MT elements was in accordance with the NYCBC 2022 edition. The major reference standard for MT structural element design is the ANSI/AWC National Design Specification (NDS), 2018 edition, and its supplement. All MT elements are intended to be acceptable for exposure. In accordance with the NDS 2018, exposed MT structural elements subject to fire resistance requirements must be designed for structural performance during the design fire event.

Chapter 16 of the NDS 2018 determines the depth of effective char that the design fire event removes from the section of an exposed MT element, which differs between GLT and CLT elements. The ANSI/AWC Technical Report No. 10, 'Calculating the Fire Resistance of Wood Members and Assemblies,' provided guidance for NDS 2018 compliant design of structural elements with required fire resistance ratings.

Structural element design was limited to the schematic design of column, beam, and flooring members, each considered to be pin connected at its ends. Load determinations were performed in accordance with the NYCBC 2022 edition, which modifies reference standard ASCE 7-16. Analysis and design considered the ASD load combinations as given in NYCBC 1605.3.1; because allowable stress design was used, structural utilization was considered acceptable when imposed stresses were less than allowable stresses.

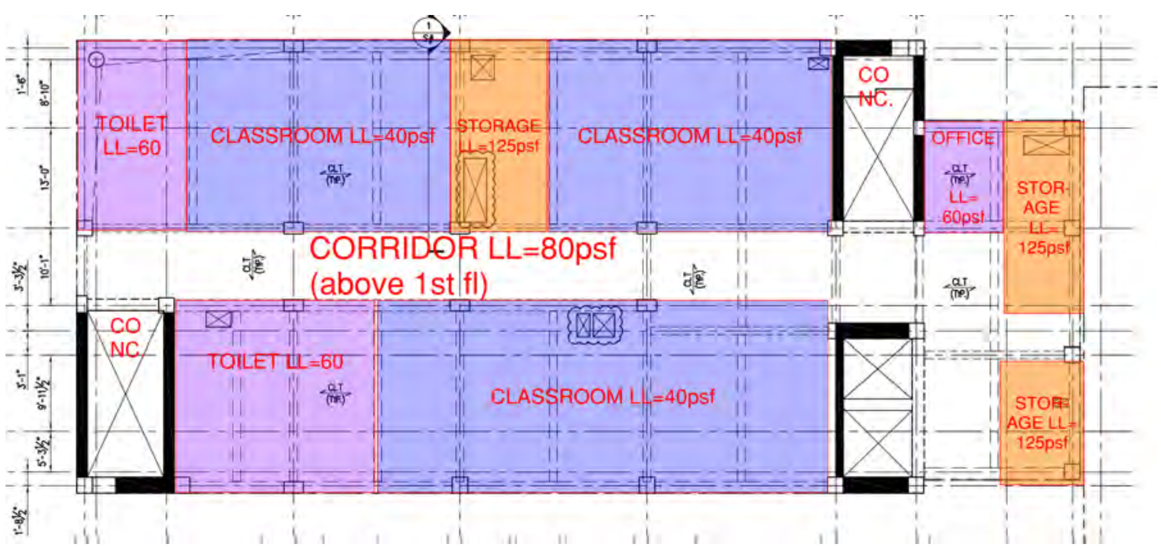


Figure 59. *Live Loads From Reinforced Concrete Design Used to Divide Floor Plans Into "Blocks"*

MT structural element design was based on the geometry of the baseline structural design drawings dated 04/24/2023 (with no revision stamps) by STV Inc.

- The original building uses a two-way reinforced concrete flat slab design with few beams at typical floor levels.
- The column grid of the structure was left with its original spacings, which were often greater than 22 feet but less than 25 feet
- It is suggested by MT design guides, as a rule of thumb, to design around a column grid with spacings close to a multiple of 10 feet.
- In the course of the design case study it was evident that this could have optimized beam efficiency further for most floor levels and spaces.

The MT building structural typology was a “post-and-beam” structure in which structural CLT floors distribute loads to primary and secondary GLT beams, which distribute loads to GLT columns.

- The post-and-beam structural typology was favored for this case study – as opposed to alternative options with load-bearing CLT walls or more frequent columns and fewer beams – because it is the structural typology best suited to the educational program of the building and require the smallest changes to the building architectural plans.
- Adding more columns to facilitate a two-way flat-plate design without beams would disrupt the openness of classroom spaces, using deep CLT panels spanning as long as 20 feet to facilitate two-way flat-plate design would result in an inefficient design, and using load-bearing CLT walls to facilitate a cellular design would restrict the flexibility of the building program and make future room repurposing nearly impossible.

For cross-laminated timber (CLT) flooring design, CLT layups (lamination thickness, species combinations in each lamination, and material properties of the layup) were based on the Structurlam US Technical Design Guide.

- Visually graded spruce-pine-fir CLT layups with uniform 1-3/8” laminations and appearance-grade face layers were selected, but the guide also presented options for layups with thinner minor layers.
- Although CLT manufacturers differ in which species combinations, lamination thicknesses, etc. they include in their typical layups, each detail of the CLT layups selected in design is relatively typical in the North American MT industry.

For GLT beam and column design, beams were based on Structurlam’s EWS 24F-V8 DF layup combinations (balanced layup combinations with Douglas-fir laminations), while the column designs were based on L2 DF properties.

(Structurlam is one of the oldest and largest MT manufacturers in the U.S., and its design guides were more comprehensive and transparent than those of other manufacturers surveyed.)

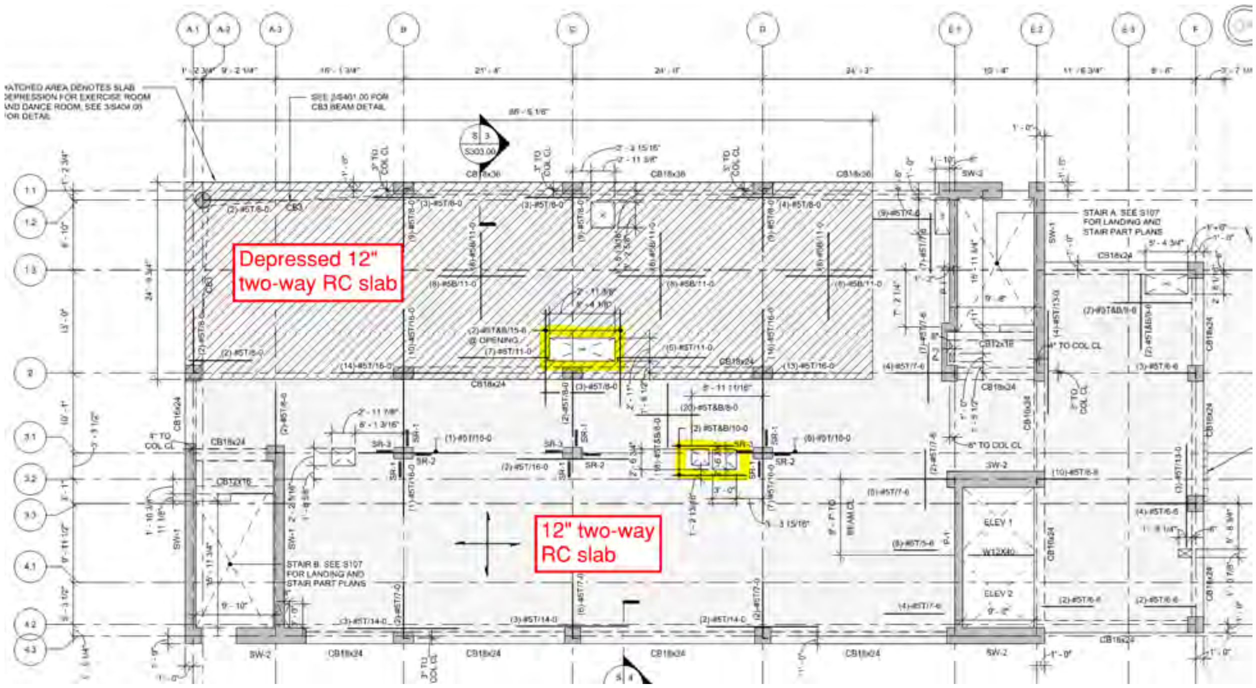


Figure 60. *Reinforced Concrete Structural Design of 4th Floor*

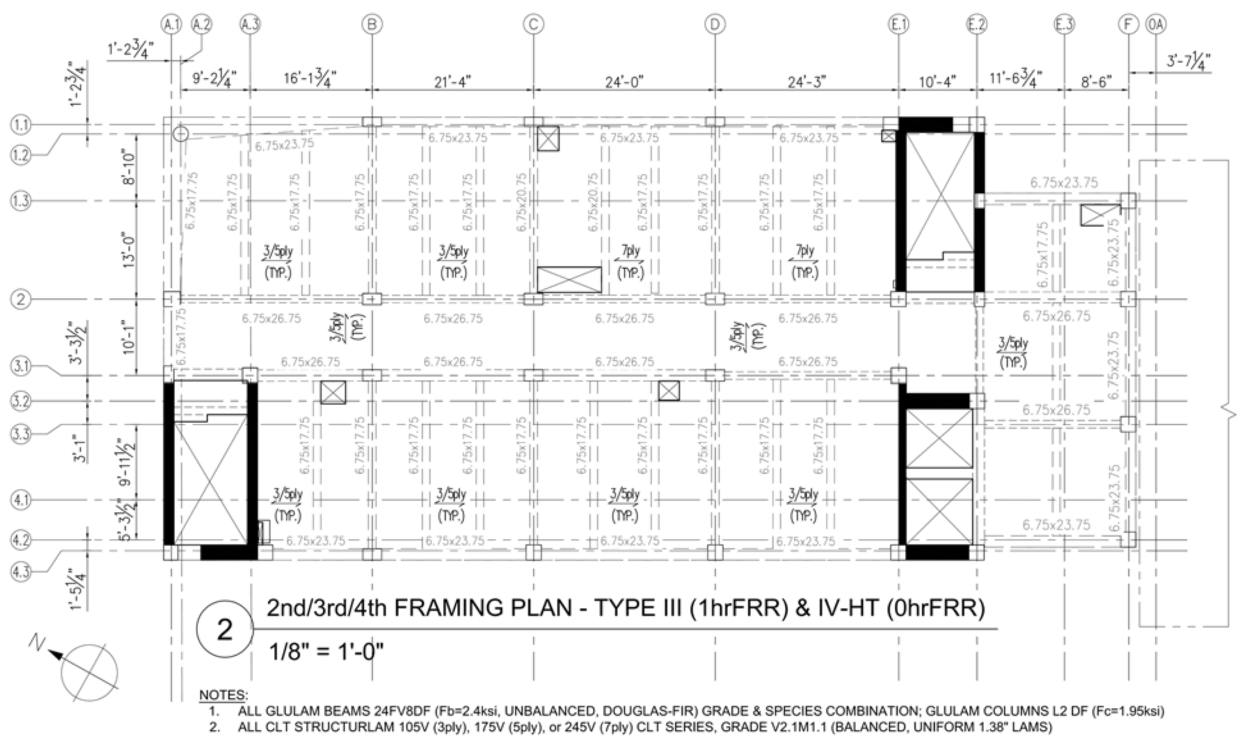


Figure 61. *Mass Timber Structural Design of 4th Floor*

Structural analysis of the MT design yielded the following general results:

- Typical MT columns averaged 19.25”x19.25” columns, smaller than the typical baseline design reinforced concrete columns of 24”x24” or 18”x30”.
- Typical floor plates in the Type IV MT design were 4.14” thick 3-ply CLT. This could have been reduced to 3.43” thick 3-ply CLT in some spaces, but 4.14” was used instead in order to meet acoustical requirements.
- Typical floor plates in the Type III MT design were 6.875” thick 5-ply CLT.
- Floor plates requiring a 2-hr FRR were 9.66” thick 7-ply CLT.

Element design was performed at a schematic level and neglected the consideration of lateral loads (wind or seismic) on the building or connection design. Reinforced concrete shear walls at shafts, elevator hoistway, and stairway enclosures were retained from the original design, providing the lateral resistance system of the building, but also providing vertical supports for some beams and CLT panels.

- It is typical for MT buildings in the United States to use reinforced concrete shear walls as a lateral resistance system, this solution is favorable because the reinforced concretes shear walls function simultaneously to provide noncombustible shafts, elevator hoistways, and stairway enclosures.
- Research is rapidly advancing on cross-laminated timber shear walls – for use with a structural height limit of 65 feet – and this is reflected in the ANSI/AWC 2021 Special Design Provisions for Wind and Seismic (SDPWS) but is not yet reflected in the IBC for municipal building code adoption.

Designs of rooftop dunnage, external concrete elements, and foundation elements were left identical in the MT designs, with the exception that the volumes of the reinforced concrete footings required to resist accumulated building loads were adjusted in proportion to the calculated reduction in building loads.

- This reduction was as high as 49% for some interior columns, yielding significant savings in concrete footing volume.
- The typical reduction was calculated as a 2’ reduction in footing thickness (depth).

Complete structural calculations are provided in the Appendix.

Mass Timber Assemblies

EME analyzed various exterior wall, roof, floor, and interior partition assembly options based on NYCBC 2022 and SCA Standards and compared each with the baseline design in term of material composition, thickness, mass, acoustic performance, and embodied carbon.

The thickness and embodied carbon of the recommended MT assemblies was generally much less than that of the base design assemblies, even more so when LCA Module D (after the building’s useful life ends) is considered. However, there were some exceptions. This information is discussed in detail in the *Energy/Embodied Carbon* section.

Mass Timber Building Enclosure

The following building enclosure details have been identified in the addition:

- Typical exterior wall assembly
- Typical roof assembly
- Typical green roof assembly

Exterior Wall and Parapet Assembly

The exterior partition wall of the MT version of the addition varies based on the construction type.

- In Type III construction, CLT is not permitted to be part of the exterior wall. The exterior wall assembly of the Type III MT design will be the same as the baseline design.
- In Type IV construction, CLT is permitted to be part of the exterior wall. A 5-ply CLT is proposed to substitute for the metal stud wall in the baseline assembly. Both are similar in thickness, while the CLT assembly is double the mass of the metal stud wall.
- It is assumed that the interior side of the CLT wall panel can be exposed, although NYCBC 2022 is somewhat ambiguous on this issue (see *Code Clarifications* section above).
- The terra cotta rain screen, continuous exterior insulation, and air/vapor control layer remain the same in all cases. The CLT wall does not require additional sheathing, so the air/vapor control layer is applied directly to the exterior face of the CLT.

Both the baseline design exterior wall assembly and the CLT exterior wall assembly achieve an effective R value of 30 and STC-50.

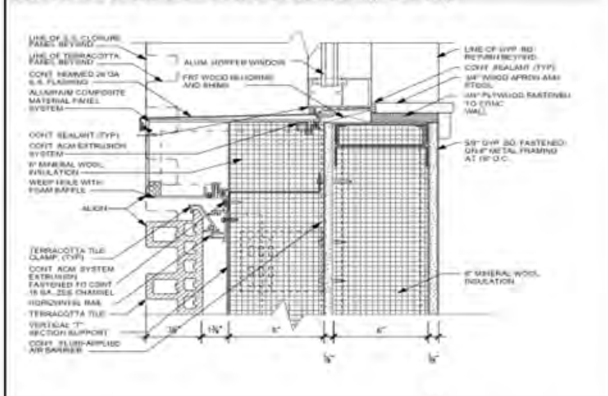
- The total R-value of the metal stud wall with one layer of gypsum board on each side is 7.93, including the R-7.03 6" cavity insulation and steel stud (NYCECC C402.1.4.1).
- The typical R-value of typical North America softwood dimensional lumber is approximately R-1.2 per inch. Therefore, while 3-ply CLT could have been used in the exterior wall assembly, 5-ply CLT is proposed in order to provide the necessary R-value.
- The 6.875" 5-ply CLT panel yields R-8.25, comparable to that of the metal stud wall. With all other elements unchanged, the CLT exterior partition wall can achieve R-30.

In the Type IV construction version of the MT test case, the parapet wall is also constructed with CLT. In the Type III construction version of the MT test case, the parapet wall is an extension of the rain screen and metal stud wall, rather than the baseline concrete parapet, in order to provide comparable R-values.

Thermal bridging is reduced in the CLT exterior assemblies in the Type IV MT design.

- The rain screen support frame is connected to the backup wall by clips with screws. In the baseline design, the screws completely penetrate the exterior GWB sheathing to connect to the backup stud wall every 16" horizontally and 24" vertically. In the Type IV MT design, the backup material of the CLT exterior wall is solid wood with no through-penetrations.
- In both cases, the window can be framed into the insulation layer to reduce thermal bridging. In the baseline design, the window is supported by and screwed through wood blocking into a frame of doubled steel studs. In the Type IV MT design, the window is supported by and screwed into the solid CLT panel.
- In the baseline design, the reinforced concrete parapet is thermal broken with a structural thermal break material connecting the continuous exterior wall insulation to the continuous roof insulation. In the Type IV MT design, the CLT panel provides the thermal break, resulting in a much simpler, lighter assembly.

CONVENTIONAL EXT. WALL ASSEMBLY (TYPE III)



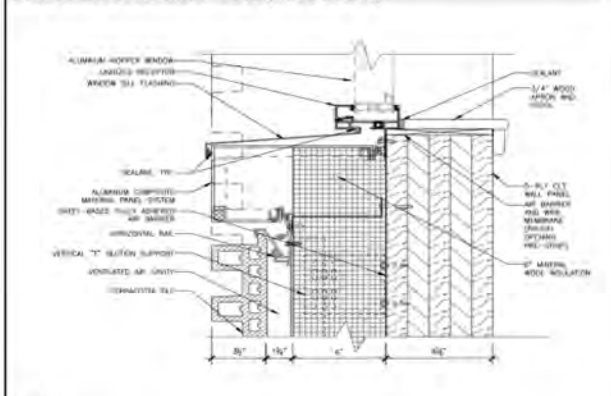
R Value	30
STC	50

Assembly (Left to right)	Thickness (in)	Mass (psf)
Terracotta Clading	3.5000	1.3500
Rainscreen	1.7500	0.0000
WRB*	0.0000	0.0000
Mineral wool insulation	6.0000	2.2000
5/8" Gypsum Board	0.6250	2.2000
6" metal stud wall + insulation	6.0000	2.7955
5/8" Gypsum Board	0.6250	2.2000
Total	**18.5000**	**10.7455**

*Assume weight of WRB negligible

Source: SCA

EXT. WALL ASSEMBLY - CLT (TYPE IV-HT)



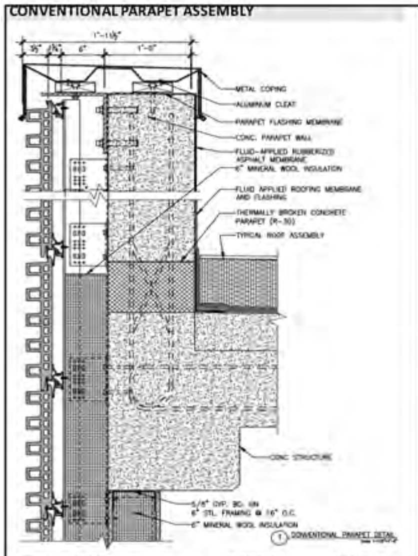
R Value	30
STC	50

Assembly (Left to right)		Thickness (in)	Mass (psf)
Terracotta Clading		3.5000	1.3500
Rainscreen		1.7500	0.0000
WRB		0.0000	0.0000
Mineral wool insulation		6.0000	2.2000
5-ply CLT		6.8750	17.1875
Total		**18.1250**	**20.7375**
	Δ	-0.3750	9.9920

Source: RDH

Figure 62. *Typical Exterior Wall Assembly*

CONVENTIONAL PARAPET ASSEMBLY

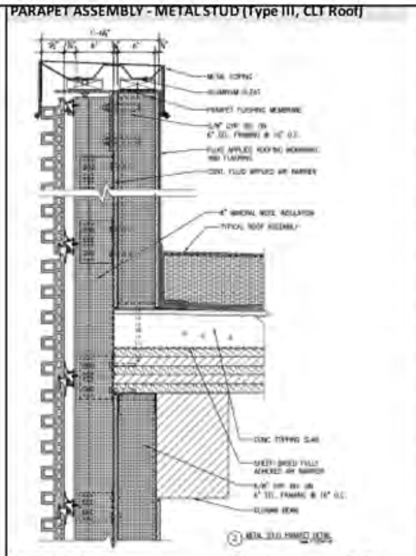


Assembly (Left to right)	Thickness (in)	Mass (psf)
Terracotta Clading	3.5000	1.3500
Rainscreen	1.7500	0.0000
WRB*	0.0000	0.0000
Mineral wool insulation	6.0000	2.2000
Concrete parapet	12.0000	150
Fluid-applied membrane	0.0000	0.0000
Total	**23.2500**	**153.5500**

*Assume weight of WRB negligible

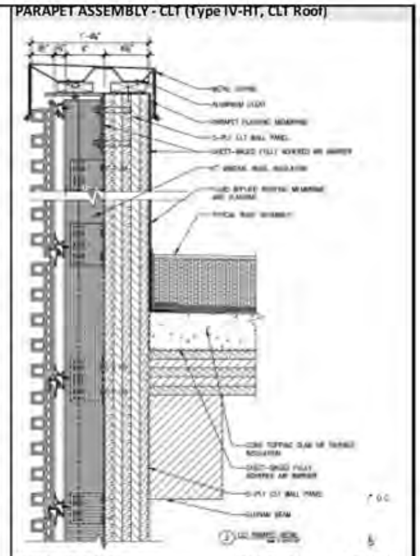
Source: SCA

PARAPET ASSEMBLY - METAL STUD (Type III, CLT Roof)



Assembly (Left to right)		Thickness (in)	Mass (psf)
Terracotta Clading		3.5000	1.3500
Rainscreen		1.7500	0.0000
WRB		0.0000	0.0000
Mineral wool insulation		6.0000	2.2000
5/8" Gypsum Board		0.6250	2.2000
6" metal stud wall + insulation		6.0000	2.7955
5/8" Gypsum Board		0.6250	2.2000
Fluid-applied membrane		0.0000	0.0000
Total		**18.5000**	**10.7455**
	Δ	-4.7500	-142.8045

PARAPET ASSEMBLY - CLT (Type IV-HT, CLT Roof)



Assembly (Left to right)		Thickness (in)	Mass (psf)
Terracotta Clading		3.5000	1.3500
Rainscreen		1.7500	0.0000
WRB		0.0000	0.0000
Mineral wool insulation		6.0000	2.2000
5-ply CLT		6.8750	17.1875
Air barrier		0.0000	0.0000
Fluid-applied membrane		0.0000	0.0000
Total		**18.1250**	**20.7375**
	Δ	-5.1250	-132.8125

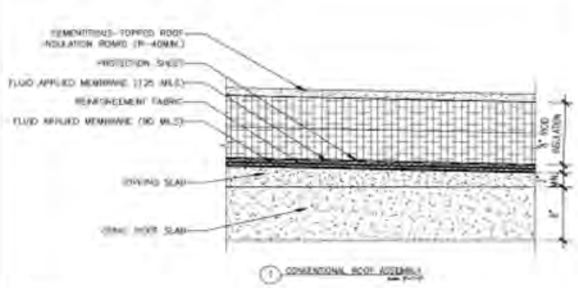
Figure 63. *Typical Parapet Assembly*

Roof Assembly

Concrete screed is used to provide roof pitch for standard SCA projects. The assembly meets the SCA's STC-50 requirement for exterior assemblies.

- The CLT roof assembly is significantly lighter than the conventional concrete slab option.
- The thickness of CLT roof panel varies depending on the construction type and fire resistance rating requirement, as discussed in the *Mass Timber Structure* section above.

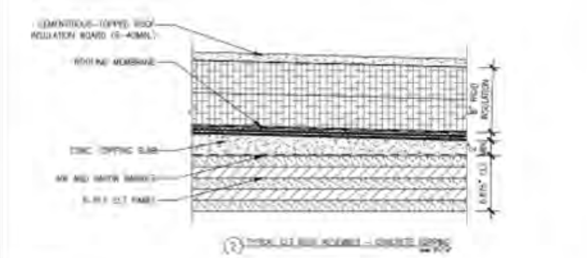
CONVENTIONAL ROOF ASSEMBLY



R Value	40	
STC	50	
Assembly (Top to bottom)	Thickness (in)	Mass (lbs/sf)
Cementitious-topped Insulation	9.0000	7.0000
Roofing membrane	0.5	0
Topping slab	3.5	32.0833
Concrete slab	8	100.0000
Total	**21.0000**	**139.0833**
	Stages A-C	Stages A-D
Embodied carbon (kgCO2eq./sf)	22.3000	22.3000

Source: SCA

ROOF ASSEMBLY - CLT



R Value		40	
STC		50	
Assembly (Top to bottom)		Thickness (in)	Mass (lbs/sf)
Cementitious-topped Insulation		9.0000	7.0000
Roofing membrane		0.5	0
Topping slab		3.5	32.0833
Air and vapor barrier		0.0000	0.0000
5-ply CLT*		6.8750	17.1875
Total		**19.8750**	**56.2708**
	Δ	-1.1250	-82.8125
		Stages A-C	Stages A-D
Embodied carbon (kgCO2eq./sf)		8.5900	4.8100

* Applicable to Typ III Construction. (4.14" 3-ply panel for Typ IV.)

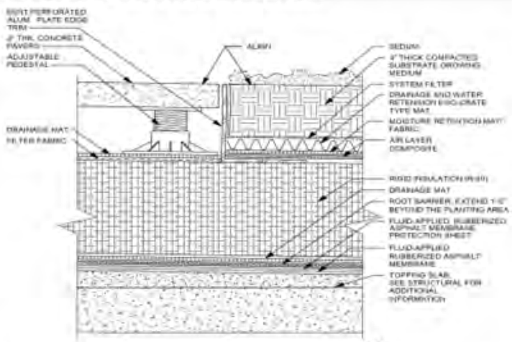
Source: RDH

Figure 64. *Typical Roof Assembly*

The same roof assembly is applicable to the green roof, as the same CLT panel thickness can support the additional load of the green roof and water retention.

- Structural calculations assumed 4" of growing medium with a maximum saturated weight of 67.5 psf.
- Green roof manufacturers recommend installing a stronger (heavy-duty) root barrier for MT structures.

CONVENTIONAL GREEN ROOF ASSEMBLY

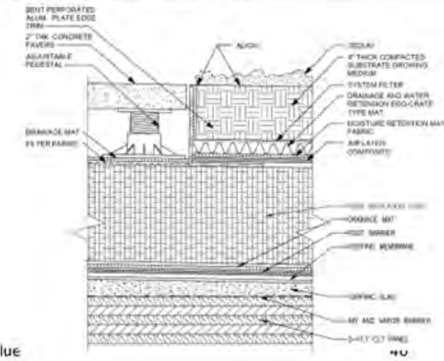


R Value	40
STC	50

Assembly (Top to bottom)	Thickness (in)	Mass (lbs/sf)
Green roof	6.0000	67.5000
Cementitious-topped Insulation	9.0000	7.0000
Roofing membrane	0.5	0
Topping slab	3.5	32.0833
Concrete slab	8	100.0000
Total	**27.0000**	**206.5833**

Source: SCA

GREEN ROOF ASSEMBLY - CLT



R Value	40
STC	50

Assembly (Top to bottom)		Thickness (in)	Mass (psf)
Green roof		6.0000	67.5000
Cementitious-topped Insulation		9.0000	7.0000
Roofing membrane		0.5	0
Topping slab		3.5	32.0833
Air and vapor barrier		0.0000	0.0000
5-ply CLT*		6.8750	17.1875
Total		**25.8750**	**123.7708**
	Δ	-1.1250	-82.8125

* Applicable to Typ III Construction. (4.14" 3-ply panel for Typ IV.)

Source: RDH

Figure 65. *Typical Green Roof Assembly*

Mass Timber Floor Assemblies

The following typical floor assemblies have been identified in the baseline design:

1. Typical floor assembly (1-hr rated for Type III and non-rated for Type IV, STC-50/IIC-45)
2. Floor assembly above cafeteria (2-hr rated, STC-60)
3. Acoustic floor assembly for Dance Room (1-hr rated for Type III and non-rated for Type IV, STC-60/IIC-60)
4. Acoustic floor assembly for Music Room (2-hr rated, STC-60/IIC-60)

See *Mass Timber Design Approach* above for typical locations of these assemblies at the addition.

Between instructional and office spaces and the adjacent spaces listed, provide constructions that, at a minimum, yield the degree of airborne sound isolation listed in the following table:

Adjacent	Airborne Sound Isolation (STC**)	
Classroom	50	
Corridor	45	(Excluding entry doors, which shall achieve STC-35)
Gang Toilets	53	
Music/Dance	60	
Mechanical	60	
Gym	60	
Cafeteria	60	

**Sound Transmission Class per ASTM E413 and ASTM E90

Adjacent Overhead Space	Impact Sound Isolation (IIC*)
Classroom/Office	45
Auditorium	60
Gymnasium/Gymatorium	60
Kitchen/Cafeteria/Cafetorium	50
Mechanical	--
Music/Dance	60

Figure 66. *SCA Standard Acoustic Rating Requirements*

Unlike the baseline design, no dropped acoustical tile ceilings are used in the MT floor assembly options. Dropped ceilings:

- Are not necessary to achieve the required FRR and acoustical ratings related to the transmission of sound from one space to another.
- Would create a concealed space requiring sprinklering, encapsulation of the bottom of the MT floor plates and beams, or filling of the concealed space with non-combustible insulation (see *Fire Resistance Ratings* section above.
- Would conceal the bottom of the MT floor plates and beams from view, thus removing one of the most desirable attributes of MT construction.
- Would add additional layers of material and thus additional weight, embodied carbon, complexity, cost, and construction time, thus removing more of the desirable attributes of MT construction.

In addition to helping prevent sound transmission from one space to another, acoustical tile ceilings also serve to reduce reverberation within a space.

- In the MT floor assembly options below, several options (not shown) are available to serve this purpose without creating concealed spaces, obscuring the MT material from view, or adding significant amounts of material.
- These options are addressed in the *Acoustical Ceiling Treatment Options* section above.

1. Typical Floor Assembly (SCA Requirement: STC-50/IIC-45, 0 or 1-hr rated)

As noted in the *Acoustics* section above, MT floor plates require additional mass and a decoupling layer in order to achieve the SCA's acoustical requirements. The additional mass is similar to that used to level reinforced concrete slabs, but thicker (typically 2"). Leveling is not required for MT floor plates; the additional mass is required solely for acoustical purposes.

There are two common options for adding mass to CLT floor plates:

- Concrete topping, like that used for leveling in conventional construction, is more readily available and affordable.
- "Dry" gypsum or magnesium oxide floor underlayment panels. Dry flooring has the following advantages and disadvantages:

Advantages	Disadvantages
Easier and quicker to install	Relatively new material
Light weight	Less readily available
No curing time needed	Higher cost
No moisture risk	Requires thicker CLT and/or acoustic mat to compensate for its lighter mass
Lower embodied carbon	

EME studied the following options for the typical floor assembly:

Option 1 (STC-53 / IIC-48, recommended): 3-ply or 5-ply CLT + 2" concrete topping + luxury VCT

- Type III construction: 6.875" 5-ply CLT (1-hr FRR)
- Type IV construction: 4.14" 3-ply CLT (non-rated)
- The proposed assembly includes LVT (Luxury Vinyl Tile) floor finish. Thinner, non-luxury VCT will lower the acoustic ratings by 1-2 points, but this assembly is still anticipated to meet SCA requirements for typical floor assemblies.
- Concrete topping provides more mass, which contributes to better acoustics
- Heaviest MT assembly (but still 72% lighter than baseline reinforced concrete assembly)

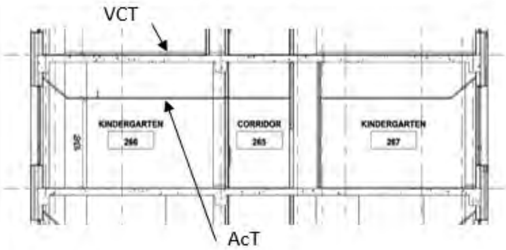
Option 2 (STC-52 / IIC-50): 5-ply CLT + GenieMat FF17 acoustic baffle + 1" gypsum board + GenieMat RST05 acoustic mat + VCT

- Needs a minimum of 6.875" 5-ply CLT to achieve SCA acoustic requirements
- The 5-ply requirement removes the advantage of being able to use 3-ply CLT in Type IV construction, resulting in significantly more material, weight, and embodied carbon.
- Pliteq's GenieMat FF is a thick, resilient recycled rubber baffle with a bottom surface profiled to limit surface contact to 4% of its area
- Pliteq's GenieBoard is a high density fiber gypsum board with tongue and groove edges
- Pliteq's GenieMat RST is a thin, resilient recycled rubber mat
- Thickest MT assembly (but still thinner than baseline reinforced concrete assembly)

Option 3 (STC-52 / IIC-52): 3-ply or 5-ply CLT + Sofix acoustic panel + OSB + VCT

- Type III construction: 5-ply (1-hr FRR)
- Type IV construction: 3-ply (non-rated)
- OSB (oriented strand board) is a widely used, low-cost composite wood product made from pre-consumer wood waste bonded with adhesive under heat and pressure
- Acousti-Tech's Sofix is a 2 feet x 4 feet decoupling panel made from non-woven synthetic fibers and introduces hemispherical cups to reduce contact surface areas between assembly layers to a minimum. This product was installed in a MT residential project in Brooklyn.
- Lightest, thinnest MT assembly

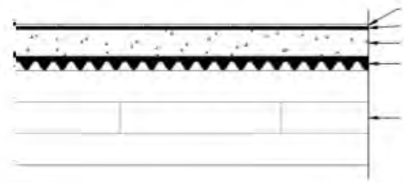
CONVENTIONAL DESIGN - TYPICAL FLOOR ASSEMBLY



STC	50
IIC	45
Fire Rating	2

Assembly (Top to bottom)	Thickness (in)	Weight (psf)
VCT	0.1875	1.3500
Concrete Slab	10	125
Total	**10.1875**	**126.3500**

TYP MT ASSEMBLY - OPTION 1 - CONCRETE TOPPING



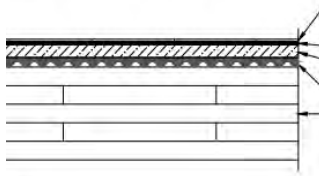
STC	53 *
IIC	48 *
Fire Rating	0 HR (Typ IV)

* Rating based on testing with 4.125" CLT and LVT

Assembly (Top to bottom)	Thickness (in)	Weight (psf)
VCT	0.1875	1.3500
GenieMat RST05	0.1969	1.0000
Concrete Topping	2.0000	20.0000
GenieMat FF25	1.0000	2.2000
3-ply CLT	4.1250	10.3125
Total	**7.5094**	**34.8625**

Source: Pliteq

CLT FLOOR - OPTION 2 - DRY FLOORING + ACOUSTIC M



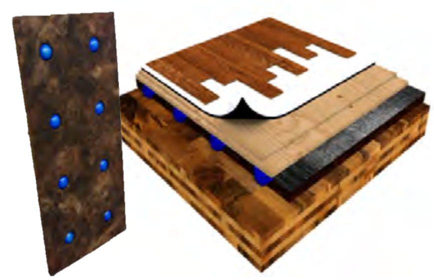
STC	52 *
IIC	50 *
Fire Rating	1

* Baesd on test ing with 6.875" CLT and LVT floor finish

Assembly (Top to bottom)		Thickness (in)	Mass (psf)
VCT		0.1875	1.3500
GenieMat RST05		0.1969	1.0000
Genieboard 302		1.0000	5.9400
GenieMat FF17		0.6667	1.7333
5-ply CLT		6.8750	17.1875
Total		**8.9260**	**27.2108**
	Δ	-1.2615	-99.1392

Source: Pliteq

CLT FLOOR - OPTION 4 - SOFIX PANEL



STC	52
IIC	52
Fire Rating	0

Assembly (Top to bottom)		Thickness (in)	Mass (psf)
VCT		0.1875	1.3500
2 layers of OSB		1.2500	4.5000
Acoustic-TECH SOFIX		1.5000	0.5000
3-ply CLT		4.1250	10.3125
Total		**7.0625**	**16.6625**
	Δ	-3.1250	-109.6875

Source: Acousti-TECH

Figure 67. *Options for Typical Floor Assembly*

2. Floor Assembly Above Cafeteria (SCA Requirement: STC-60, 2-hr rated)

Option 1 (STC-60 / IIC-58, recommended): 9.66” 7-ply CLT + Insonomat membrane + Lead 6 membrane + Sofix acoustic panel + OSB + VCT

- Soprema’s Insonomat is a thick elastomeric bitumen and recycled rubber membrane
- Acousti-Tech’s Lead 6 is a thin membrane made from recycled materials, required to prevent binding between Insonomat below and Sofix above
- Thinnest and lightest assembly

Option 2 (STC-59 / IIC-56): 9.66” 7-ply CLT + GenieMat FF50 acoustic baffle + 3” concrete topping + GenieMat RST02 acoustic mat + VCT

- GenieMat FF50 is a 2” thick, double-layer material
- Heaviest MT assembly (but still 55% lighter than baseline reinforced concrete assembly)

Option 3 (STC-63 / IIC-60): 6.875” 5-ply CLT + GenieMat FF10 acoustic baffle + 2” concrete topping + GenieMat RST02 acoustic mat + VCT, with dropped ceiling below

- CLT thickness can be reduced from 7-ply to 5-ply by providing ceiling with FRR below
- Needs a minimum of 6.875” 5-ply CLT to achieve SCA acoustic requirements
- Dropped ceiling creates a concealed space, requiring encapsulation of the CLT with a second GWB layer
- Thickest MT assembly (but still slightly thinner than baseline reinforced concrete assembly)

3. Dance Room Assembly (SCA Requirement: STC-60/IIC-60, 1-hr rated)
4. Music Room Assembly (SCA Requirement: STC-60/IIC-60, 2-hr rated)

These assemblies are identical in the baseline design, which uses a dropped concrete slab to accommodate the resilient and acoustical materials. The only difference between the spaces is that the Music Room is a fire refuge area requiring a 2-hr FRR, and the Dance Room has a hardwood floor.

Option 1 (STC-60 / IIC-58 / HIIC-74, recommended): Same as Assembly Above Cafeteria Option 1.

- Dance Room: 5-ply CLT (1-hr FRR)
- Music Room: 7-ply CLT (2-hr FRR)
- HIIC ratings cover a wider range of higher frequency sound such as clicks or taps that are more noticeable to human hearing.
- Thinnest and lightest assembly

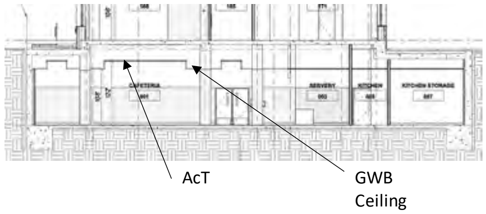
Option 2 (STC-60 / IIC-60): 7-ply CLT + GenieMat FF70 acoustic baffle + 4” concrete topping + plywood with sleepers + VCT (or hardwood)

- Dance Room: 5-ply CLT (1-hr FRR)
- Music Room: 7-ply CLT (2-hr FRR)
- GenieMat FF70 is a 2.75” thick, double-layer material
- Heaviest MT assembly (but still 45% lighter than baseline reinforced concrete assembly)

Option 3 (STC-63 / IIC-60): Same as Assembly Above Cafeteria Option 3.

- Dance Room and Music Room: 5-ply CLT
- Thickest MT assembly (but still slightly thinner than baseline reinforced concrete assembly)

CONVENTIONAL DESIGN - FLOOR ABOVE CAFETERIA

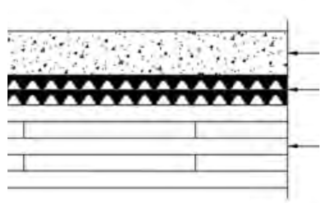


STC	60	
Assembly (Top to bottom)	Thickness (in)	Mass (lbs/sf)
VCT	0.1875	1.3500
Concrete Slab	10	125
Floor Subtotal	10.1875	126.3500
6” Plenum w/ insulation	6.0000	1.2500
7/8” Furring Strip	0.7500	0.3125
5/8” GWB	0.6250	2.2000
Ceiling Subtotal	7.3750	3.7625
Total	**17.5625**	**130.1125**
	Stages A-C	Stages A-D
Embodied carbon (kgCO2eq./sf)	**15.4000**	**15.4000**

CLT FLOOR ABOVE CAFETERIA - OPTION 1

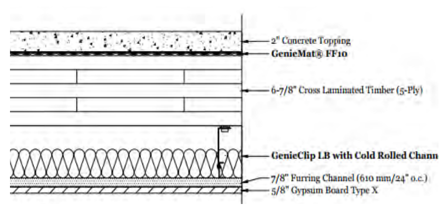
STC	60 *	
IIC	58 *	
Fire Rating	2	
* Baesd on testing with 6" CLT and hardwood floor		
Assembly (Top to bottom)	Thickness (in)	Mass (lbs/sf)
VCT	0.1875	1.3500
2 layers of OSB	1.2500	4.5000
Acoustic-TECH SOFIX	1.5000	0.5000
Lead 6 Floated Underlayment	0.2362	0.2000
Insomomat	0.5906	0.8100
7-ply CLT	9.6600	24.1500
Floor Subtotal	13.4243	31.5100
No ceiling		
Ceiling Subtotal	N/A	N/A
Total	**13.4243**	**31.5100**
Δ	-4.1382	-98.6025
	Stages A-C	Stages A-D
Embodied carbon (kgCO2eq./sf)	**9.5100**	**-0.5900**
Source: Acousti-TECH		

CLT FLOOR ABOVE CAFETERIA - OPTION 2



STC	59	
IIC	56	
Fire Rating	2	
* Baesd on testing with 6" CLT		
Assembly (Top to bottom)	Thickness (in)	Mass (lbs/sf)
VCT	0.1875	1.3500
GenieMat RST02	0.0787	0.4167
3” Concrete topping	3.0000	30.0000
GenieMat@FF50	2.0000	3.0000
7-ply CLT	9.6600	24.1500
Floor Subtotal	14.9262	58.9167
No ceiling		
Ceiling Subtotal	N/A	N/A
Total	**14.9262**	**58.9167**
Δ	-2.6363	-71.1958
Source: Pliteq		

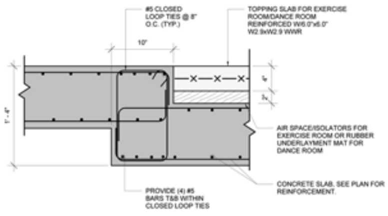
CLT FLOOR ABOVE CAFETERIA - OPTION 3



STC	63	
IIC	60	
Fire Rating	2	
Assembly (Top to bottom)	Thickness (in)	Mass (psf)
VCT	0.1875	1.3500
GenieMat RST02	0.0787	0.4167
Concrete Topping	2.0000	20.0000
GenieMat FF10	0.4000	1.0833
5-ply CLT	6.8750	17.1875
Floor Subtotal	9.5412	40.0375
5/8” GWB	0.6250	2.2000
6” Plenum w/ insulation	6.0000	1.2500
7/8” Furring Strip	0.7500	0.3125
5/8” GWB or Nano CLT	0.6250	2.2000
Ceiling Subtotal	8.0000	5.9625
Total	**17.5412**	**46.0000**
Δ	-0.0213	-84.1125
Source: Pliteq		

Figure 68. *Options for Floor Assembly Above Cafeteria (2-hr FRR)*

CONVENTIONAL DESIGN - DANCE ROOM



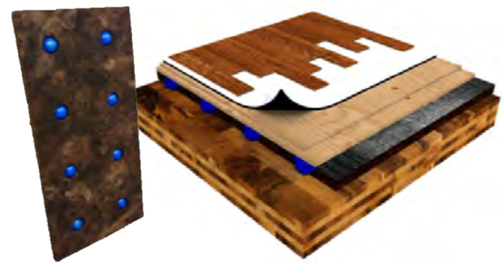
2A: WHERE BEAM IS NOT PRESENT

STC	60	
IIC	60	
Fire Rating	1	

Assembly (Top to bottom)	Thickness (in)	Mass (psf)
Hardwood Floor	0.7441	2.6960
Concrete Slab	4.0000	50.0000
Neoprene Strips	2.0000	
Concrete slab	10.0000	125.0000
Floor Subtotal	16.7441	177.6960
6” Plenum w/ insulation	6.0000	1.2500
7/8” Furring Strip	0.7500	0.3125
5/8” Typ X GWB	0.6250	2.2000
Ceiling Subtotal*	7.3750	3.7625
Total	**24.1191**	**181.4585**

	Stages A-C	Stages A-D
Embodied carbon (kgCO2eq./sf)	**21.0000**	**11.3000**

DANCE ROOM CLT FLOOR - OPTION 1



STC*	60 *	
IIC/HIIC*	58/74 *	
Fire Rating	1	

* Baesd on testing with 6" CLT and hardwood floor

Assembly (Top to bottom)	Thickness (in)	Mass (psf)
Hardwood Floor	0.7441	2.6960
2 layers of OSB	1.2500	4.5000
Acoustic-TECH SOFIX	1.5000	0.5000
Lead 6 Floated Underlayment	0.2362	0.2000
5-ply CLT	6.8750	17.1875
Floor Subtotal	10.6053	25.0835
No ceiling		
Ceiling Subtotal	N/A	N/A
Total	**10.6053**	**25.0835**
Δ	-13.5138	-156.3750

	Stages A-C	Stages A-D
Embodied carbon (kgCO2eq./sf)	**7.3600**	**-9.9100**

Source: Acousti-TECH

DANCE ROOM CLT FLOOR - OPTION 2

GenieMat FF70LDM

- Panels are made with 2" thick Low Dynamic Modulous proprietary Pliteq elastomer embedded in a layer of acoustical insulation
- Natural frequency down to 6 Hz
- Subfloor contact area with the floor is reduced by 96%
- ΔIIC 44 (ASTM E2179)

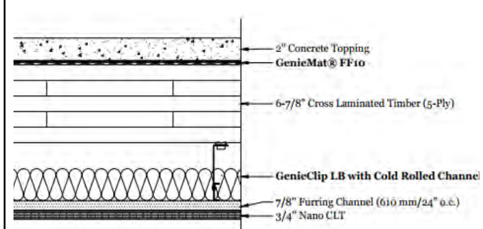
STC	60 *	
IIC	60 *	
Fire Rating	1	

* Baesd on testing with 6.875" CLT and hardwood floor

Assembly (Top to bottom)	Thickness (in)	Mass (psf)
Hardwood Floor	0.7441	2.6960
Plywood w/ sleeper	1.2500	4.5000
Concrete topping	4.0000	40.0000
Geniemat FF70LDM	2.7500	2.4211
5-ply CLT	6.8750	17.1875
Floor Subtotal	14.8750	64.1086
No ceiling		
Ceiling Subtotal	N/A	N/A
Total	**14.8750**	**64.1086**
Δ	-9.2441	-117.3499

Source: Pliteq

DANCE ROOM CLT FLOOR - OPTION 3



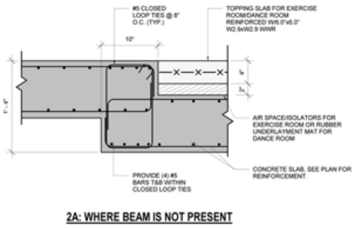
STC	63	
IIC	60	
Fire Rating	1	

Assembly (Top to bottom)	Thickness (in)	Mass (psf)
Hardwood Floor	0.7441	2.6960
GenieMat RST02	0.0787	0.4167
Concrete Topping	2.0000	20.0000
GenieMat FF10	0.4000	1.0833
5-ply CLT	6.8750	17.1875
Floor Subtotal	10.0978	41.3835
5/8” Typ X GWB	0.6250	2.2000
6” Plenum w/ insulation	6.0000	1.2500
7/8” Furring Strip	0.7500	0.3125
5/8” GWB or Nano CLT	0.7500	1.8750
Ceiling Subtotal*	8.1250	5.6375
Total	**18.2228**	**47.0210**
Δ	-5.8963	-134.4375

Source: Pliteq

Figure 69. *Options for Dance Room Floor Assembly*

CONVENTIONAL DESIGN - MUSIC ROOM



STC	60	
IIC	60	
Fire Rating	2	

Assembly (Top to bottom)	Thickness (in)	Mass (psf)
VCT	0.1875	1.3500
Concrete Slab	4.0000	50.0000
Neoprene Strips	2.0000	
Concrete slab	10.0000	125.0000
Floor Subtotal	16.1875	176.3500
6” Plenum w/ insulation	6.0000	1.2500
7/8” Furring Strip	0.7500	0.3125
5/8” Typ X GWB	0.6250	2.2000
Ceiling Subtotal*	7.3750	3.7625
Total	**23.5625**	**180.1125**

MUSIC ROOM CLT FLOOR - OPTION 1

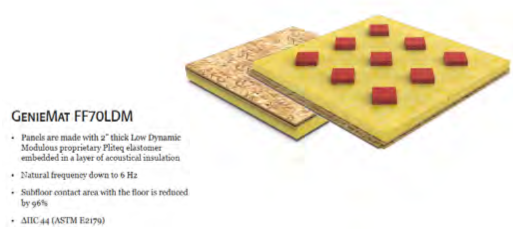
STC*	60	*
IIC/HIIC*	58/74	*
Fire Rating	2	

* Baesd on testing with 6.875" CLT and hardwood floor

Assembly (Top to bottom)	Thickness (in)	Mass (psf)
VCT	0.1875	1.3500
2 layers of OSB	1.2500	4.5000
Acoustic-TECH SOFIX	1.5000	0.5000
Lead 6 Floated Underlayment	0.2362	0.2000
Insomomat	0.5906	0.8100
7-ply CLT	9.6600	24.1500
Floor Subtotal	13.4243	31.5100
No ceiling		
Ceiling Subtotal	N/A	N/A
Total	**13.4243**	**31.5100**
Δ	-10.1382	-148.6025

Source: Acousti-TECH

MUSIC ROOM CLT FLOOR - OPTION 2



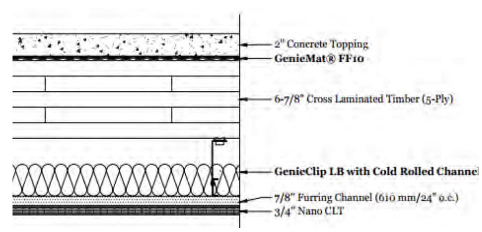
STC	60	*
IIC	60	*
Fire Rating	2	

* Baesd on testing with 6.875" CLT and hardwood floor

Assembly (Top to bottom)	Thickness (in)	Mass (psf)
VCT	0.1875	1.3500
Plywood w/ sleeper	1.2500	4.5000
Concrete topping	4.0000	40.0000
Geniemat FF70LDM	2.7500	2.4211
7-ply CLT	9.6600	24.1500
Floor Subtotal	17.6600	71.0711
No ceiling		
Ceiling Subtotal	N/A	N/A
Total	**17.6600**	**71.0711**
Δ	-5.9025	-109.0414

Source: Pliteq

MUSIC ROOM CLT FLOOR - OPTION 3



STC	63
IIC	60
Fire Rating	1

Assembly (Top to bottom)	Thickness (in)	Mass (psf)
VCT	0.1875	1.3500
GenieMat RST02	0.0787	0.4167
Concrete Topping	2.0000	20.0000
GenieMat FF10	0.4000	1.0833
5-ply CLT	6.8750	17.1875
Floor Subtotal	9.5412	40.0375
5/8” Typ X GWB	0.6250	2.2000
6” Plenum w/ insulation	6.0000	1.2500
7/8” Furring Strip	0.7500	0.3125
5/8” GWB or Nano CLT	0.7500	1.8750
Ceiling Subtotal*	8.1250	5.6375
Total	**17.6662**	**45.6750**
Δ	-5.8963	-134.4375

Source: Pliteq

Figure 70. *Options for Music Room Floor Assembly (2-hr FRR)*

Mass Timber Partition Wall Assemblies

The following typical wall assemblies have been identified in the addition:

1. Typical corridor to classroom partition (STC-45)
2. Typical classroom to classroom partition (STC-50)
3. Typical acoustical partition (STC-60)
4. Typical 2-hr rated partition (STC-50)

All interior partition walls need to be 1-hr rated in Type IV construction, while there is no general FRR requirement for partition walls in Type III construction (see notes under *Code Clarifications* section above). All proposed MT wall assemblies meet the 1-hr FRR requirement based on testing by National Research Council Canada.

See *Mass Timber Design Approach* above for typical locations of these assemblies at the addition.

1. Corridor to Classroom CLT Partition (SCA Requirement: STC-45, 0 or 1-hr rated)

A "one-sided" 3-ply CLT wall, with one side of the CLT exposed and the other clad in 2 layers of GWB with insulated cavity, can meet the acoustic and FRR requirements.

- For the addition, the exposed timber side is proposed for the corridor, with optional ceramic tile wainscot for durability.
- On the classroom side of this partition type, which often incorporates closets and/or restrooms, the GWB cavity wall allows for conduit and pipe runs.
- The one-sided CLT wall is slightly thicker and heavier than the baseline wall.

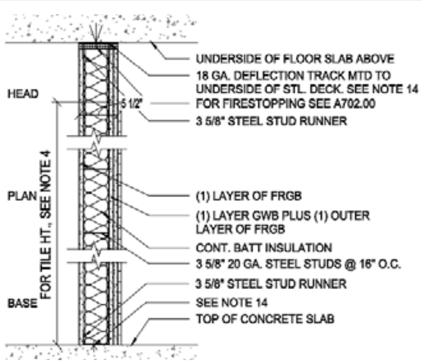
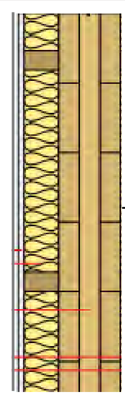
CONVENTIONAL DESIGN - CORRIDOR TO CLASSROOM			CLT CORRIDOR PARTITION		
					
STC	50 *		STC	45	
Fire Rating (hr)	0		Fire Rating (hr)	1 (Req't of IV-HT)	
Assembly (Left to Right)	Thickness (in)	Mass (psf)	Assembly (Left to Right)	Thickness (in)	Mass (psf)
1 layer of GWB	0.6250	2.2000	2 layers of GWB	1.0000	3.2000
Metal stud wall	3.6250	1.3915	Wood Stud @ 24" o.c.	2.0000	0.9467
2 layers of GWB	1.2500	4.4000	3-ply CLT	3.0700	7.6750
Ceramic Tile	0.5000	2.0000	Ceramic Tile	0.5000	2.0000
Total	**6.0000**	**9.9915**	**Total**	**6.5700**	**13.8217**
			Δ	0.5700	3.8302
	Stages A-C	Stages A-D		Stages A-C	Stages A-D
Embodied carbon (kgCO2eq./sf)	**10.5000**	**9.4200**	**Embodied carbon (kgCO2eq./sf)**	**7.2500**	**3.4900**
*SCA Requirement is STC 45.			Source: Woodworks		

Figure 71. *Typical Corridor Partition Assembly*

2. Classroom to Classroom CLT Partition (SCA Requirement: STC-50, 0 or 1-hr rated)

The proposed one-sided CLT partition is identical to the corridor to classroom partition but adds resilient channels to decouple the GWB side from the CLT side.

- The one-sided CLT wall is slightly thinner but heavier than the baseline wall.
- The addition of the resilient channels raises the embodied carbon footprint of the CLT wall slightly above that of the baseline wall, but only if LCA Module D is not considered.
- Assuming that a typical classroom has one corridor to classroom wall, two classroom to classroom walls, and one exterior wall:
    - o The typical classroom will have at least two exposed CLT wall surfaces: one corridor to classroom partition and one of the two classroom to classroom partitions
    - o In Type IV construction, the classroom will have a third exposed CLT wall surface, at the exterior wall
    - o Depending on the arrangement of classroom to classroom partitions, a corner classroom could have three or four exposed CLT wall surfaces

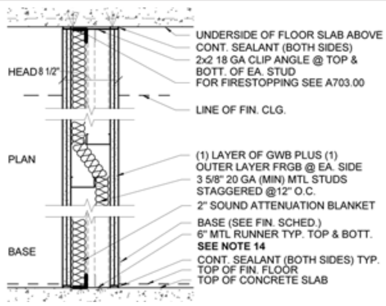
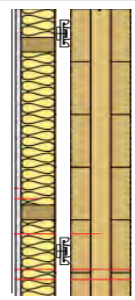
CONVENTIONAL DESIGN - BETWEEN CLASSROOMS			CLT CLASSROOM PARTITION		
					
STC	50		STC	50	
Fire Rating (hr)	0		Fire Rating (hr)	1 (Req't of IV-HT)	
Assembly (Left to Right)	Thickness (in)	Mass (psf)	Assembly (Left to Right)	Thickness (in)	Mass (psf)
2 layer of GWB	1.2500	4.4000	2 layers of GWB	1.0000	3.2000
Staggered metal stud wall	6.0000	1.4387	2" wood stud @ 24" o.c	2.0000	0.7292
2 layers of GWB	1.2500	4.4000	Resilient channel @ 24"o.c.	1.6250	0.2200
			3-ply CLT	3.0700	7.6750
Total Thickness	**8.5000**	**10.2387**	**Total Thickness**	**7.6950**	**11.8242**
			Δ	-0.8050	1.5855
	Stages A-C	Stages A-D		Stages A-C	Stages A-D
Embodied carbon (kgCO2eq./sf)	**7.2400**	**6.1500**	**Embodied carbon (kgCO2eq./sf)**	**7.2500**	**3.4900**
			Source: Woodworks		

Figure 72. *Typical Classroom Partition Assembly*

3. Acoustical CLT Partition (SCA Requirement: STC-60, 0 or 1-hr rated)
4. 2-Hr FRR CLT Partition (SCA Requirement: STC-50, 2-hr rated)

The MT options for these partition types are identical.

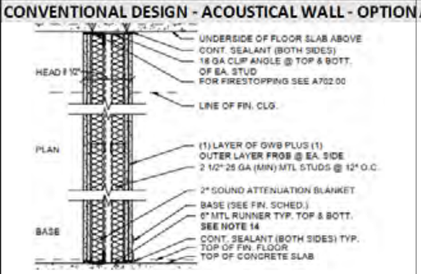
- For the acoustical partition, 5-ply CLT is required for acoustical mass.
- For the 2-hr rated partition, 5-ply CLT is required for fire resistance.
- At THE ADDITION there are some fire rescue areas, such as the Music Room, which require acoustical, 2-hr FRR partitions.

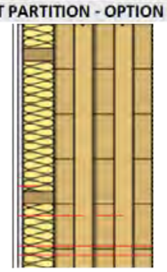
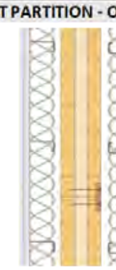
Option 1 (recommended): The baseline (all-GWB) design.

Option 2: Identical to the corridor to classroom partition but with a 6.875” 5-ply CLT panel instead of a 3.07” 3-ply CLT panel.

Option 3: 3-ply CLT is completely encapsulated by 2-layer GWB cavity walls on both sides.

Both MT options are much thicker and heavier than the baseline design, and have higher embodied carbon footprints (again, only if LCA Module D is not considered). Therefore, the baseline design is recommended as both the preferred acoustical and preferred 2-hr FRR partition.



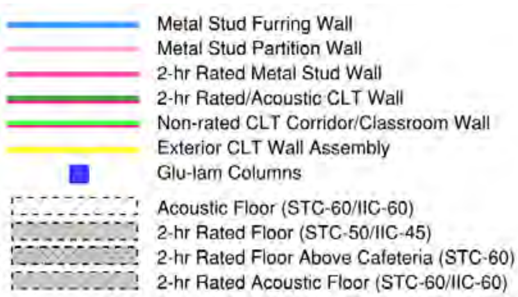
CONVENTIONAL DESIGN - ACOUSTICAL WALL - OPTION			ACOUSTICAL CLT PARTITION - OPTION 2			ACOUSTICAL CLT PARTITION - OPTION 3		
STC	60		STC	59		STC	60	
Fire Rating (hr)	2		Fire Rating (hr)	2		Fire Rating (hr)	2	
Assembly (Left to Right)	Thickness (in)	Mass (lbs/sf)	Assembly (Left to Right)	Thickness (in)	Mass (lbs/sf)	Assembly (Left to Right)	Thickness (in)	Mass (lbs/sf)
2 layers of GWB	1.2500	4.4000	2 layers of GWB	1.0000	3.2000	2 layers of GWB	1.0000	3.2000
Double Metal stud wall	6.0000	1.6372	1.5" wood stud @ 24" o.c	1.5000	0.5469	1.5" furring @16" o.c	1.5000	0.6641
2layers of GWB	1.2500	4.4000	Resilient channel @ 24" o.c.	1.6250	0.2200	Resilient channel @ 24" o.c.	1.6250	0.2200
			5-ply CLT	6.8750	17.1875	3-ply CLT	3.0700	7.6750
						1.5" furring @16" o.c	1.5000	0.6641
						2 layers of GWB	1.0000	3.2000
Total Thickness	8.5000	10.4372	Total Thickness	11.0000	21.1544	Total Thickness	9.6950	15.6231
			Δ	2.5000	10.7172	Δ	1.1950	5.1860
	Stages A-C	Stages A-D		Stages A-C	Stages A-D		Stages A-C	Stages A-D
Embodied carbon (kgCO2eq./sf)	7.6900	6.6000	Embodied carbon (kgCO2eq./sf)	8.5300	1.2900	Embodied carbon (kgCO2eq./sf)	8.0600	4.3000
			Source: Woodworks			Source: Woodworks		

Figure 73. *Options for Typical Acoustical and 2-Hr FRR CLT Partition Assemblies*

Impact of Mass Timber on Occupiable Floor Area

As noted above, both the proposed GLT columns and many of the proposed CLT partitions in the MT version of THE ADDITION are smaller or thinner than their counterparts in the baseline design. Therefore, the conversion to MT results in floor area "savings," i.e., greater occupiable floor area within the same GSF.

The proposed MT floor plans, indicating the wall and floor types, follow. Note the exterior CLT wall assembly shown is for the Type IV construction scenario only.



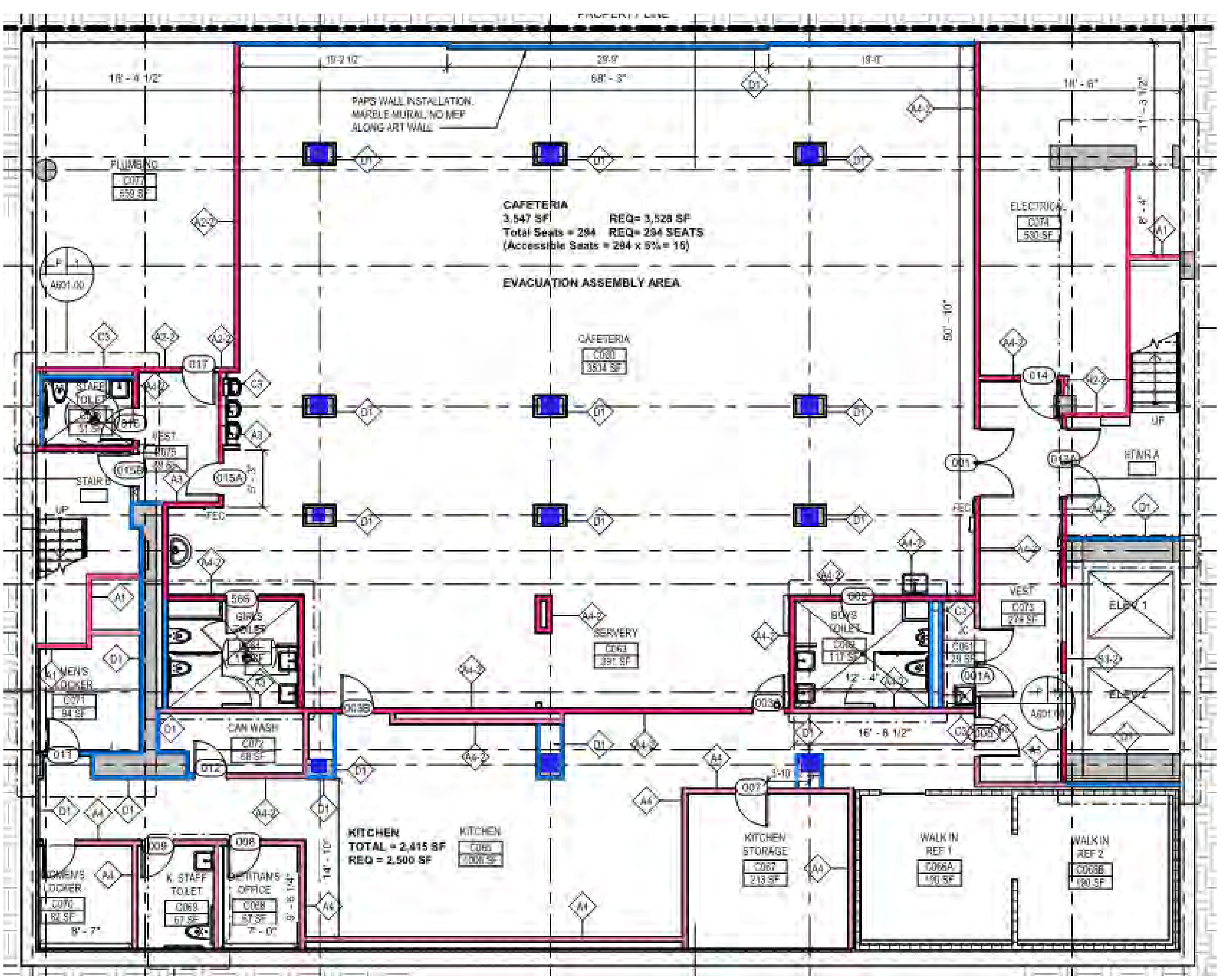


Figure 74. Cellar Floor Plan

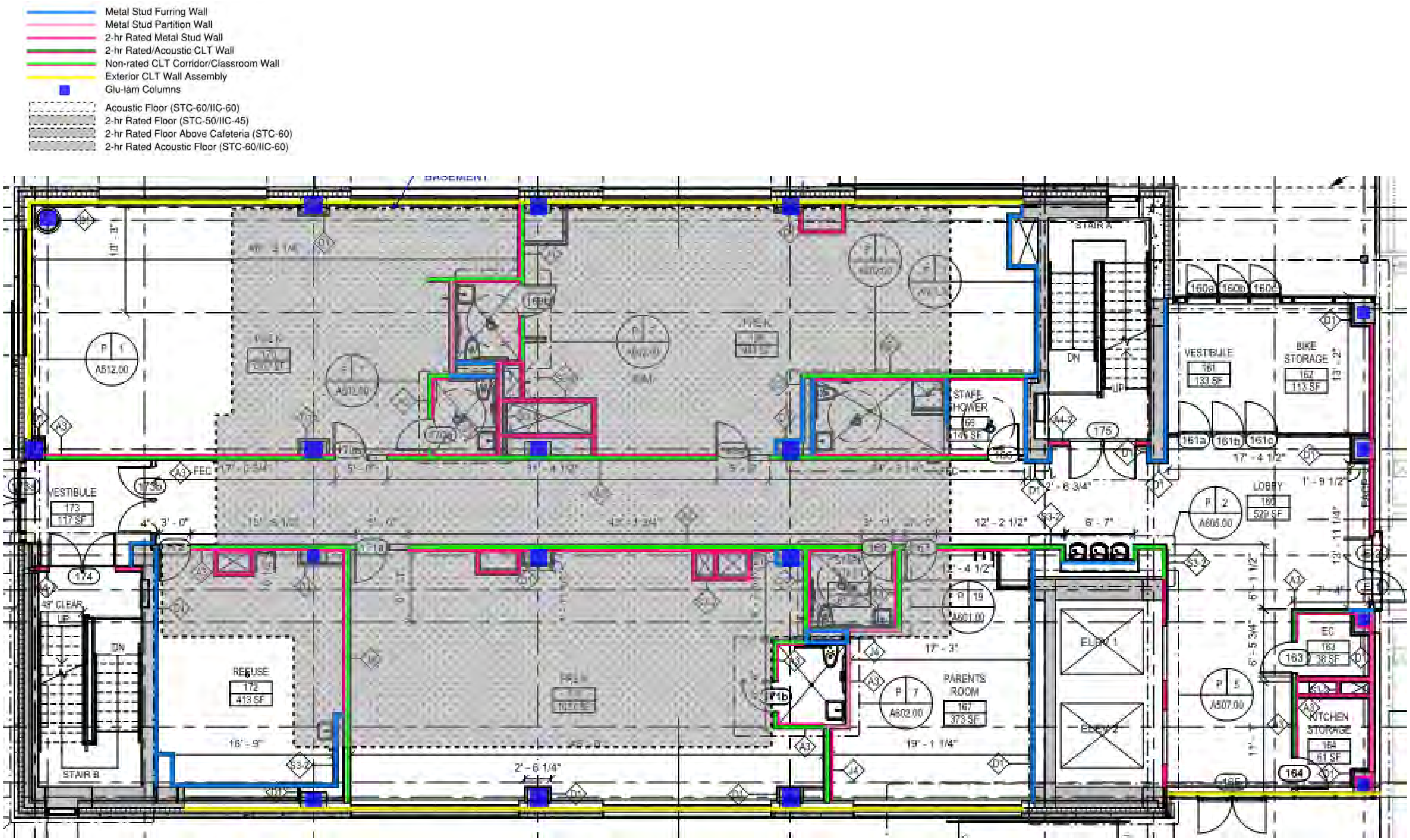


Figure 75. First Floor Plan

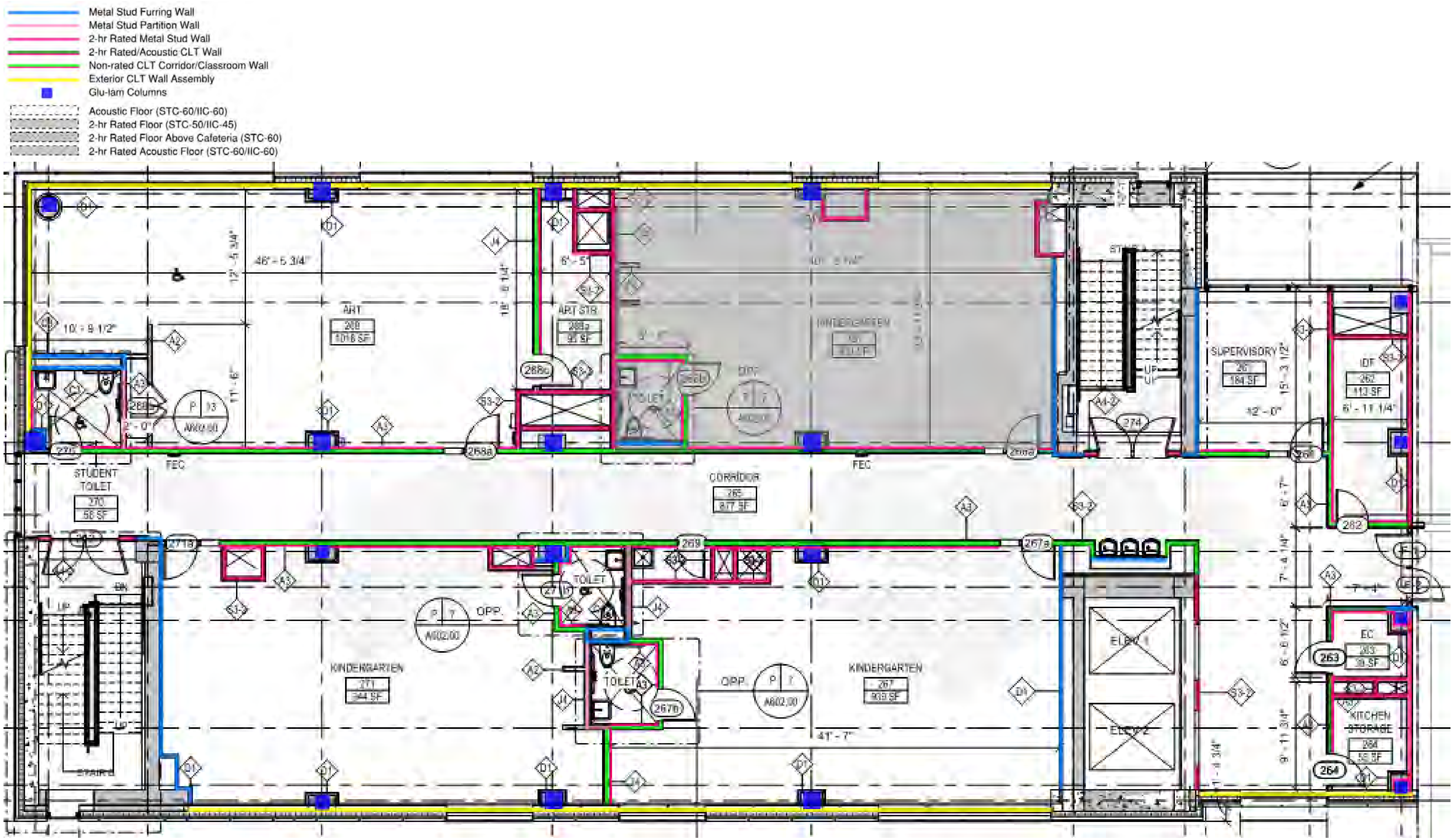


Figure 76. Second Floor Plan

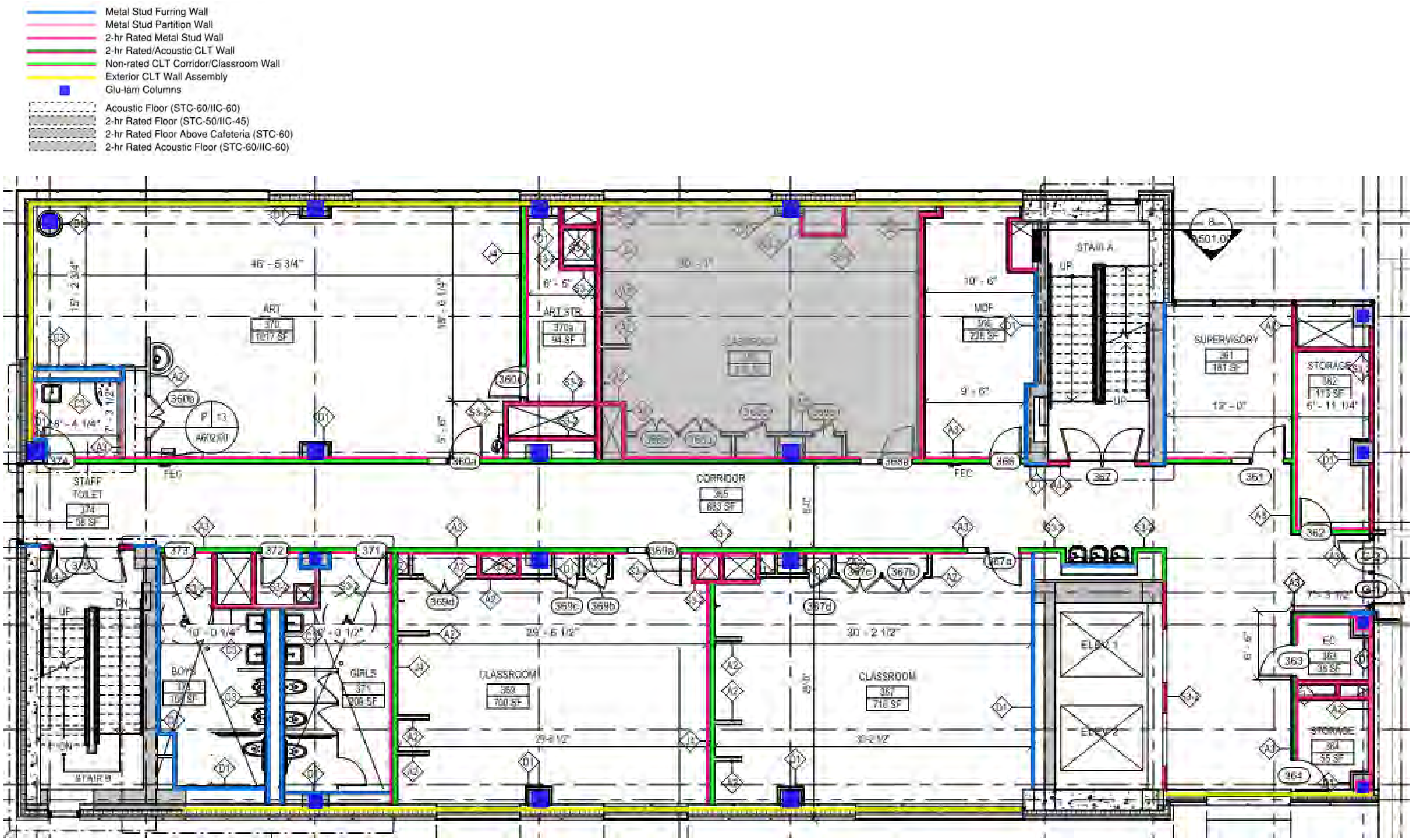


Figure 77. Third Floor Plan

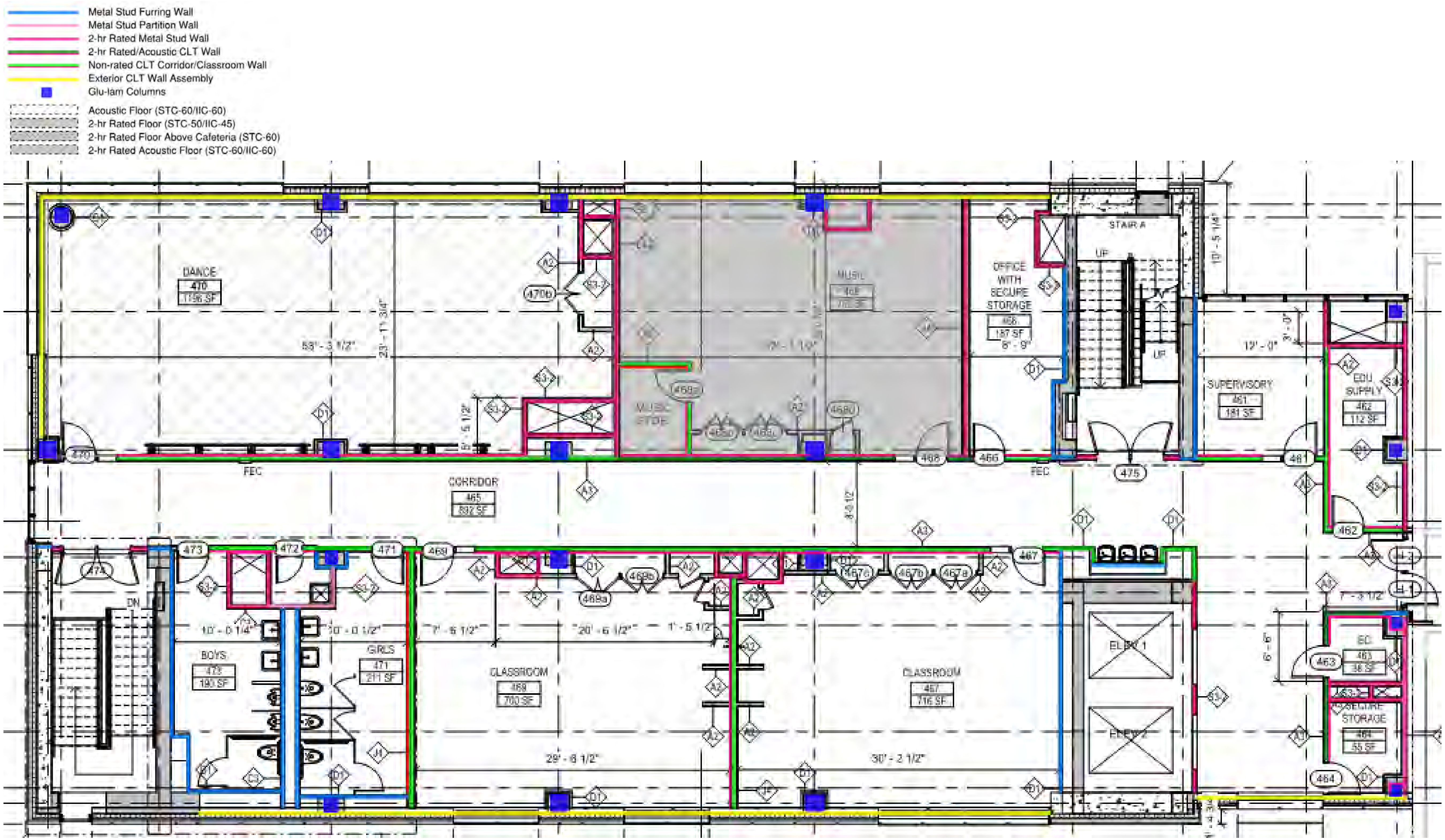


Figure 78. Fourth Floor Plan

The table below shows the total change in Gross Square Feet (GSF) associated with replacing the baseline design's conventional GWB stud walls and reinforced concrete columns with CLT walls and GLT columns throughout the building.

- In the Type III construction scenario, with baseline exterior walls remaining as-is and an increase in some partition thicknesses due to higher FRR requirements, the conversion to MT results in a 0.5% loss of usable GSF due to increased area for building structure, and therefore a 0.5% decrease in usable GSF, without changing the total GSF.
- In the Type IV scenario, with baseline exterior CLT walls and no structural FRR requirements, the conversion to MT results in a 0.7% gain in usable GSF due to decreased area for building structure, and therefore a 0.7% increase in usable GSF, without changing the total GSF.

SPACE SAVINGS DUE TO USE OF MT	**TYPE III-A***	**TYPE IV-HT**
GLT Columns	457.21	457.21
Exterior CLT Walls (Type IV-HT only)		325.50
Typical Classroom CLT Partitions	168.04	168.04
SPACE PENALTY DUE TO USE OF MT		
2-Hr and/or Acoustical CLT Partitions	-829.32	-674.27
TOTAL CHANGE IN USABLE GSF	**-204.06**	**276.49**
Percentage Change (from 40,510 GSF)	**-0.5%**	**0.7%**

*See notes under *Code Clarifications* section above

Table 3. *Space Savings of Mass Timber Construction at Addition*

The following MT elements take up less space than their baseline counterparts:

- Exposed GLT columns vs. baseline reinforced concrete columns with GWB furring
- Classroom-to-classroom CLT partitions vs. baseline GWB stud walls
- Exterior CLT walls vs. baseline exterior stud walls (Type IV-HT construction only)

The following MT elements take up more space than on baseline counterpart:

- 2-hour rated and/or acoustical CLT partitions vs. baseline GWB rated stud walls
- This is one of the reasons why EME recommends the use of the baseline GWB stud wall design for 2-hr FRR and/or acoustical partitions instead of their CLT versions, in both the Type III and Type IV construction scenarios.

MEP Design and Impact of Mass Timber on Floor Height

The typical floor to floor height of a SCA Capacity Project building is 14 feet, as compared to the 15”-8” feet required at THE ADDITION to align with the existing building. The typical flat concrete slab structure and dropped ACT ceiling in the conventional SCA design provide ample space and a great deal of flexibility for MEP ductwork routing:

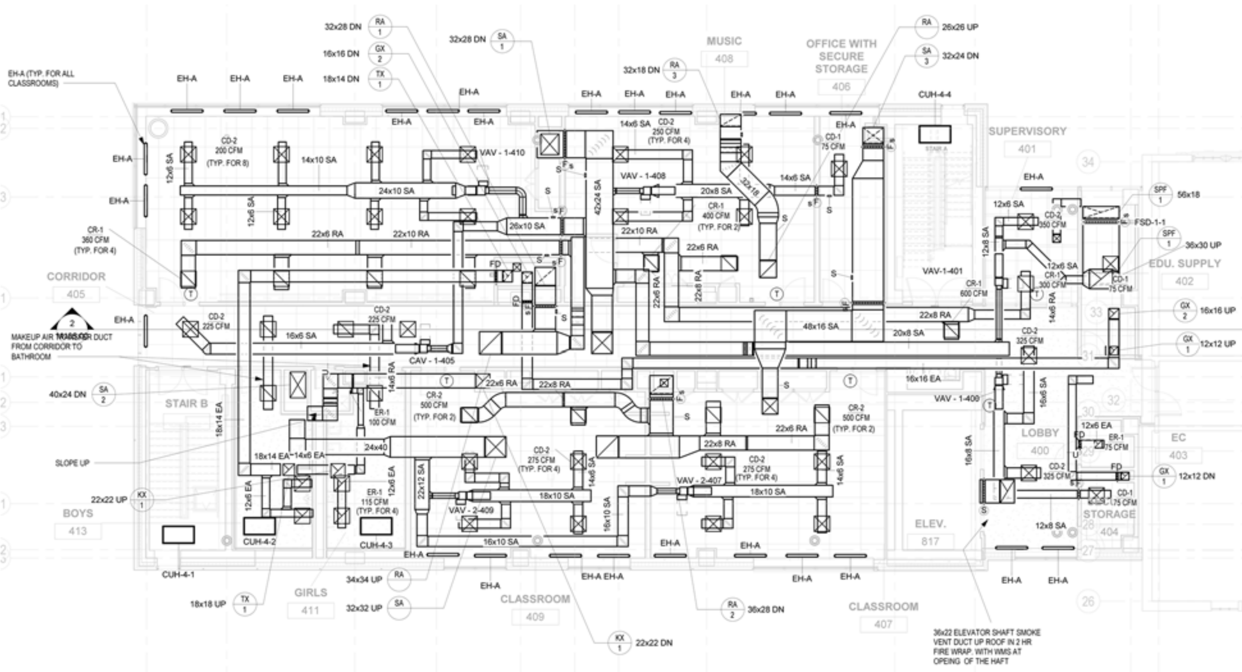


Figure 79. *Baseline 4th Floor HVAC Ductwork Layout*

In the proposed MT post and beam structure, the MEP layout may be exposed and must be more carefully integrated with the structure in order to maximize ceiling heights, minimize beam penetrations, and mitigate the visual impact of building services, requiring more intensive coordination among different design disciplines (see *Prefabrication* section above).

As noted above, the proposed MT design utilizes a “stacked beam” approach, with cross beams sitting atop girders, and girders sitting atop columns.

- The girders run along and parallel to the exterior walls and the tops of the corridor walls, while the cross beams span from exterior girder to corridor girder.
- There is no need for cross beams between the corridor girders, which are only 8 feet apart and can be spanned by CLT panels without reinforcement.

The conceptual HVAC layout of the MT design utilizes the higher, uninterrupted clearance in the corridors for the main trunk lines, with branches to each room crossing over the corridor girders, between the cross beams, and into the rooms.

- Based on a typical 14 foot floor to floor height, the ductwork and sprinkler pipes would branch off into the classrooms with a clearance of approximately 11’-8” feet above the finish floor.
- Terminal air supply and return ducts and registers within each room would pass mounted below the cross beams, with a clearance of 10 feet (the SCA minimum standard) above the finish floor.

- The main vertical duct shafts are located close to the corridor in order to minimize large duct runs within the rooms. This would generally require the rooftop AHUs to be located on or near the central axis of the building.
- Although the actual floor to floor height of THE ADDITION is 15’-8”, the MT design could allow for a floor to floor height of 14’ or less, depending on the ability of the design engineer to balance MT member depth with structural, FRR and acoustical requirements and embodied carbon goals.

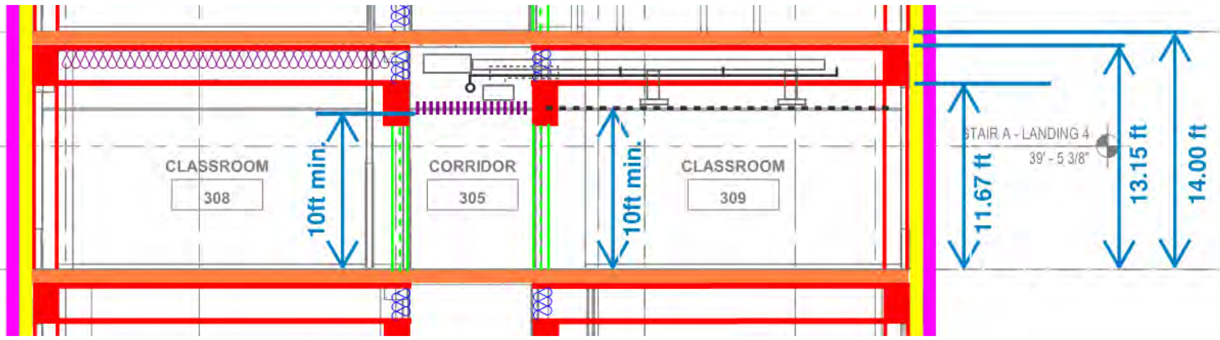


Figure 80. *Conceptual Typical Floor to Floor Section Diagram of MT Design*

Actual clearances below MEP services would depend on the type of additional acoustical elements added to reduce reverberation within spaces.

- The axonometric diagram below shows fully exposed CLT ceilings in the occupied spaces and an acoustical wood slat ceiling baffle in the corridor.
- Options are addressed in the *Renderings* section below and the *Acoustical Ceiling Treatment Options* section above.

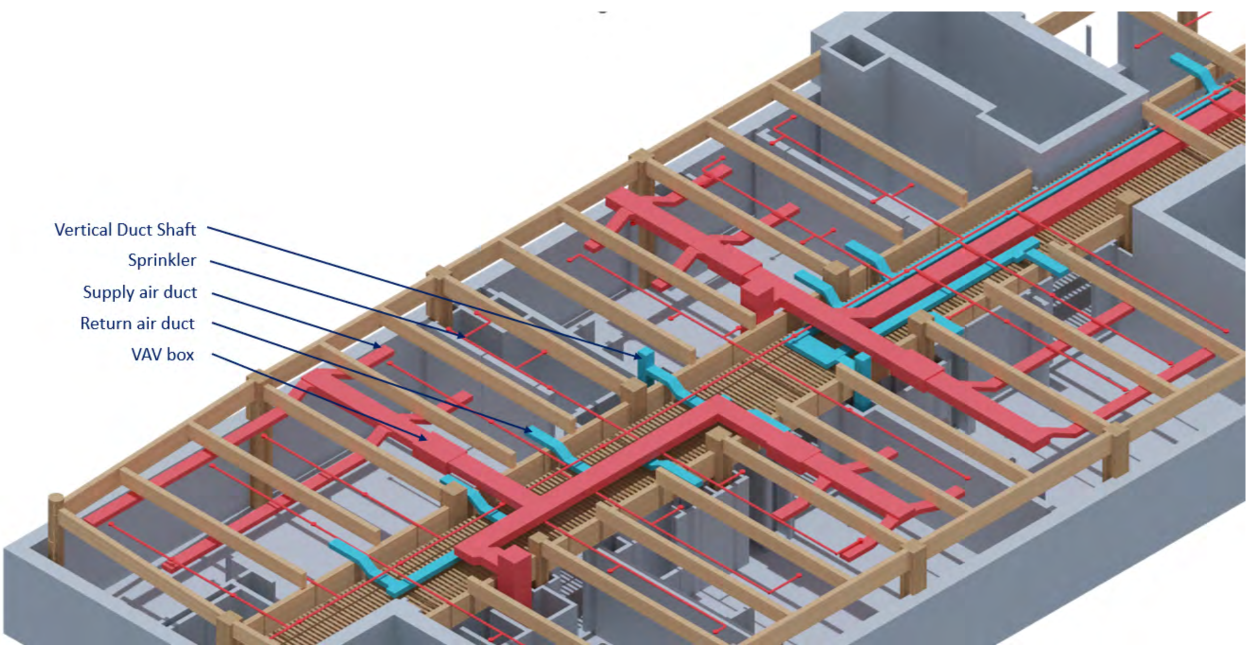


Figure 81. *Conceptual Typical Floor Structural and MEP Layout of MT Design*

Renderings

The following renderings compare the baseline design and the conceptual alternative MT designs of typical spaces at THE ADDITION.

Classroom

The classroom walls vary from exposed CLT to gypsum finishes, depending on the construction type and the orientation of the one-sided CLT classroom-to-classroom wall.

- Note: These renderings represent the dimensions and finishes of typical corner classrooms at THE ADDITION, but not the actual layout, orientation, or fenestration of these spaces.
- Note: In these renderings the one-sided CLT corridor-to-classroom wall is behind the viewer and not shown. This is why the main HVAC duct and the sprinkler pipes reach from behind the viewer, between the cross beams, toward the girder in the exterior wall opposite the viewer.

Renderings of the MT designs are shown for the Type III (see notes under *Code Clarifications* section above) and Type IV construction scenarios.

- One option under each scenario shows the CLT ceiling with all MEP services fully exposed. Vertical acoustic baffles or "blades" are installed at the underside of the CLT to reduce reverberation without obstructing the discharge of the fire sprinklers.
    - This is the recommended design approach as it minimizes cost, construction time, weight, and embodied carbon and fully exposes the CLT ceiling to view.
    - Disadvantages include requirements for higher-quality materials such as spiral ducts (not shown), increased attention to detail during construction, and the need to periodically clean the top surfaces of the exposed service distribution and devices.
- A second option shows suspended acoustic "clouds" integrating the MEP end devices. However, in the design shown, this would require additional sprinklers above the clouds (this is discussed in detail in the *Acoustical Ceiling Treatment Options* section above).
    - Avoiding the additional sprinklers would require reducing the spacing between the clouds to a degree that would start to resemble a fully dropped ACT ceiling.

The original classroom lighting design is shown unchanged in the MT renderings.

Figure 82. *Baseline Conventional Design - Classroom*

Type III Construction (see notes under *Code Clarifications* section above regarding Type III construction)

Figure 83. *Partly Exposed CLT Ceiling with Integrated Ceiling Clouds*

Figure 84. *Fully Exposed CLT Ceiling with Acoustic Baffles*

Type IV Construction (see notes under *Code Clarifications* section above regarding exposed CLT in exterior walls)

Figure 85. *Partly Exposed CLT Ceiling with Integrated Ceiling Clouds*

Figure 86. *Fully Exposed CLT Ceiling with Acoustic Baffles*

Corridor

In the MT design, the typical corridor wall has exposed CLT (the other side of the wall is GWB) with 7 foot high white tile wainscot. The elevator (left) and stair cores (right) have concrete shear walls with tile wainscot and/or painted finishes. An acoustical wood baffle ceiling at 10 feet above finished floor obscures the mechanical equipment in the plenum space, but does not create a concealed space.

Figure 87. *Baseline Conventional Design - Corridor*

Figure 88. *Mass Timber Design – Corridor with Wood Baffle Ceiling*

Cafeteria

In the MT design, the exposed GLT columns are covered with 7 foot high white tile wainscot for protection. The GLT girders and beams are exposed, projecting below the acoustical wood baffle ceilings at 10 feet above finished floor. Unlike in the corridor, the wood baffle ceiling panels in the cafeteria have more widely spaced slats and do not conceal the entire CLT ceiling above. The 2-hr FRR metal stud or concrete cafeteria walls remain unchanged from the baseline (except for the accent color).

Figure 89. *Baseline Conventional Design - Cafeteria*

Figure 90. *Mass Timber Design - Cafeteria with Wood Baffle Ceiling*

FREE-STANDING GYM

Existing Design

The original design of the free-standing gym building in Brooklyn provided in 10/30/2017 building drawings by structural engineering consultant Thornton Thomasetti for Purcell Architects. These drawings were not stamped for construction, and have no noted revisions, but were substantially complete.

The structural typology of the freestanding gym building is a single-story masonry bearing wall structure. The bending members are steel bar joists supporting a composite steel roof deck; a partial, interior mezzanine floor is supported by a one-way concrete slab. This is a typical design choice for single-story buildings, especially with commercial programs, as steel bar joists are material-efficient long-span bending members well-suited for low, non-occupiable roof live loads.

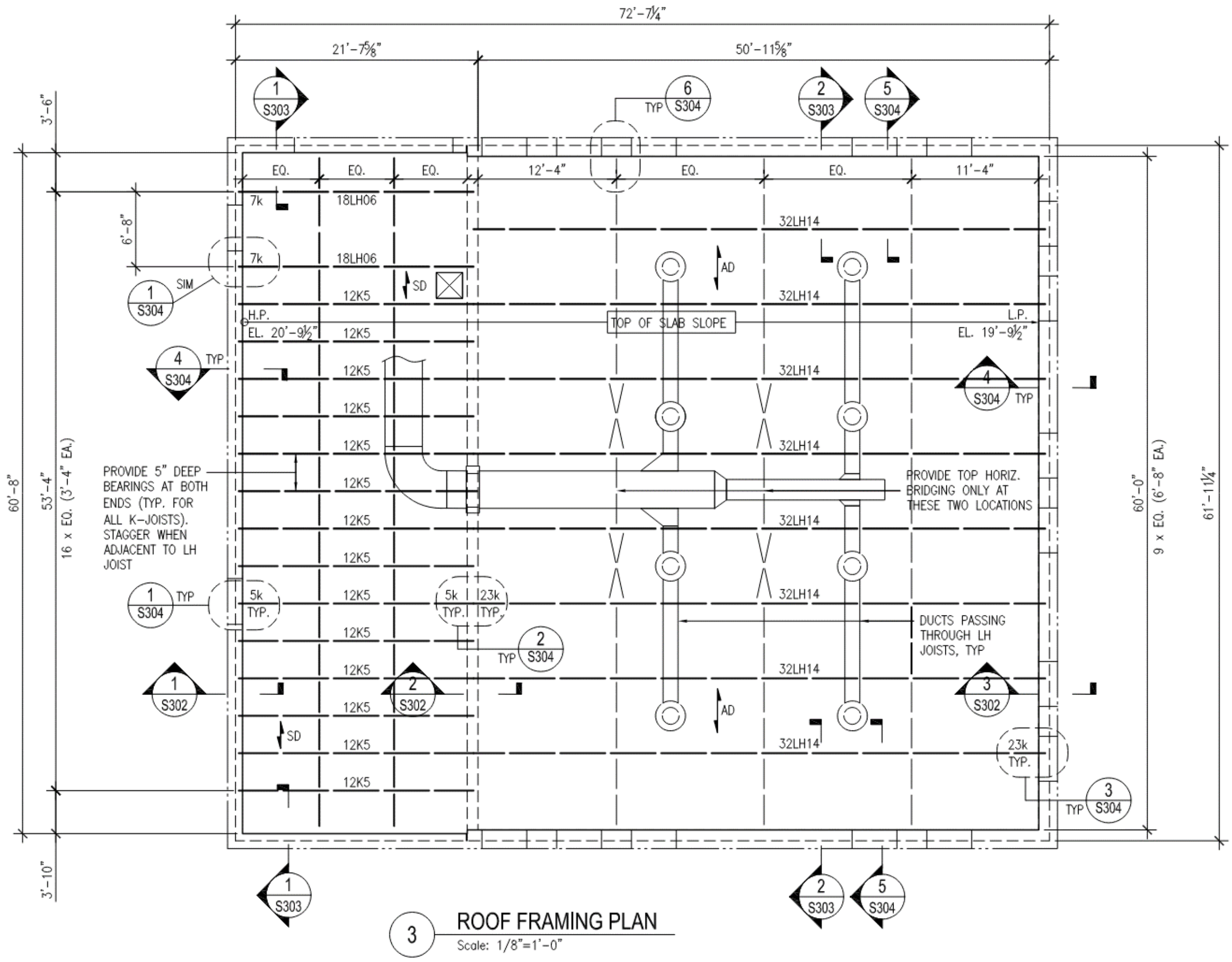


Figure 91. Baseline Structural Roof Framing Plan for Free-Standing Gym

In the baseline plan, “32LH14” bar joists spanning about 51 feet have a 32-inch total depth, while “18LH06” bar joists spanning about 22 feet have an 18-inch total depth. The metal decks with spans labelled “AD” and “SD” are both 4.5” total depth composite concrete-slab-over-metal-deck. Sets of dashed lines indicate 8” and 12” thick CMU bearing walls.

The steel bar joists are supported at each end by “beam pocket” bearing connections into the CMU bearing walls (this will be discussed further in the *Mass Timber Design Approach* section below). The roof deck and the horizontal bar joist bridging are connected at the bearing walls by steel angle brackets anchored into the CMU bearing walls.

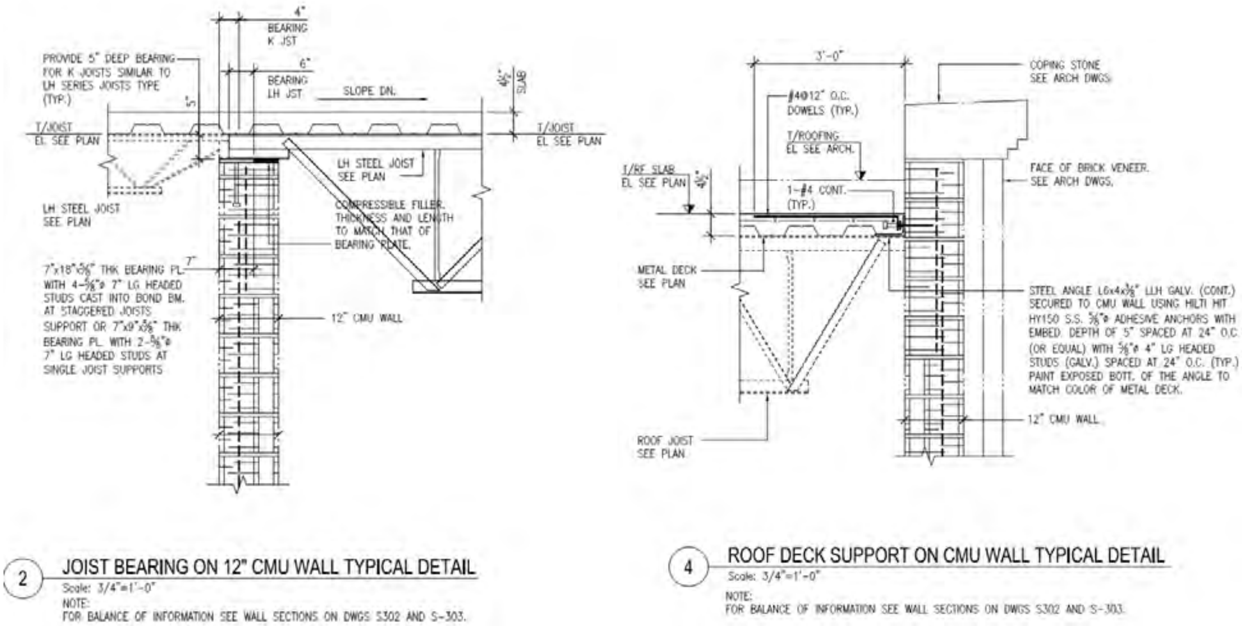


Figure 92. *Baseline Details Depicting Roof Bar Joist End Connections and Slab-on-Metal Deck*

Mass Timber Design Approach

Similarly to the addition test case, EME’s intent in analyzing the free-standing gym test case is to substitute structural elements of the existing roof design with MT elements, in order to compare the size of these elements and how they impact the building detailing.

Unlike the addition test case, only the roof structural elements of the gym were redesigned as MT elements, while leaving the CMU bearing walls, slab-on-grade, and foundation elements as designed.

- The addition test case sought to replace baseline structural and architectural components with MT elements as much as possible (thereby improving the building’s LCA impacts as much as possible), achieving compliance with NYCBC 2022 Type III-A or Type IV-HT construction.
- By comparison, the gym test case sought to replace only the roof, achieving compliance with NYCBC 2022 Type II construction (or even Type I-B construction). Per NYCBC 2022 Table 601: ‘heavy timber shall be allowed where a 1-hour or less fire-resistance rating is required.’

Design of MT elements was in accordance with the NYCBC 2022 edition with reference standard NDS 2018 and supplement. This process is described in the addition test case building discussion above.

Structural element design was limited to the schematic design of new GLT girders and beams and the CLT roof, each considered to be pin connected at its ends where loads transfer from the roof deck to the glulam beams then to the CMU bearing walls.

Element design was performed at a schematic level and neglected the consideration of lateral loads (wind or seismic) on the building, but by virtue of the retention of structural load-bearing CMU walls in the building, it is anticipated that the building lateral system would remain substantially identical.

Load determinations were performed in accordance with the NYCBC 2022 edition, which modifies reference standard ASCE 7-16. Analysis and design considered the ASD load combinations as given in NYCBC 1605.3.1; because allowable stress design was used, structural utilization was considered acceptable when imposed stresses were less than allowable stresses.

- In the proposed gym MT structural design, the superimposed dead loads of the ceiling, hanging basketball backboards, and HVAC ducts were taken from the load table in the original structural drawings, while wind load and snow load were determined according to ASCE 7-16.
- The superimposed dead load from roofing was increased from 17psf in the original drawings to 110psf, representing a fully saturated green roof load, and because of this new superimposed dead load (and the way load duration factors affect NDS 2018 structural design calculations), the ASD Dead + Live load combination controlled the design of the MT roof elements.

Because the gravity load resisting system of the building is only perimeter load-bearing CMU walls and one additional CMU interior wall dividing the 51-by-60-foot building footprint into the gymnasium and support spaces, the building's geometry was left virtually unchanged.

- Long-span girders span the short direction in the gymnasium space, and 10ft of tributary width was taken as a rule-of-thumb for preliminary beam design.
- As discussed in the *Mass Timber Structural Typologies* section above, there are two typical design choices for long-span mass timber elements: deep GLT girders or GLT truss products (parallel GLT girders joined by wood or steel web elements, with steel connections or fasteners).
- Because of the lack of standardization and explicit code acceptance of GLT truss products, deep GLT girders were used as the long-span bending members in the free-standing gym test case design.

For the CLT roof design, CLT layups (lamination thickness, species combinations in each lamination, and material properties of the layup) were based on the Structurlam U.S. Technical Design Guide.

- Visually graded spruce-pine-fir CLT layups with uniform 1-3/8" laminations and appearance-grade face layers were selected, but the guide also presented options for layups with thinner minor layers.
- Although CLT manufacturers differ in which species combinations, lamination thicknesses, etc. they include in their typical layups, each detail of the CLT layups selected in design is relatively typical in the North American MT industry.
- The proposed deep GLT girders and beams were based on Structurlam's EWS 24F-V8 DF layup combinations (balanced layup combinations with Douglas-fir laminations).

Two alternative GLT framing options were evaluated for the building's longest spans:

1. (6) 14.25"x37.25" GLT girders spaced about 7.5 feet apart, and
2. (5) sets of sistered 12.25"x29.75" GLT girders (10 total) spaced about 8.5 feet apart.

Beam sizes were based on Structurlam's materially optimal standard section for long-span GLT girders in framing. In each case, the span between girders was sufficiently low to allow the use of a relatively thin and lightweight 4.38"-thick, 3-ply CLT roof plate.

The roof over the mezzanine space (at the left side of these plans) requires (6) GLT girders spaced about 8.25 feet apart to support the use of a minimally thick CLT floor plate, and the smallest manufacturer-standard GLT section of 6.75"x19.25" supports the CLT panels while spanning about 22 feet.

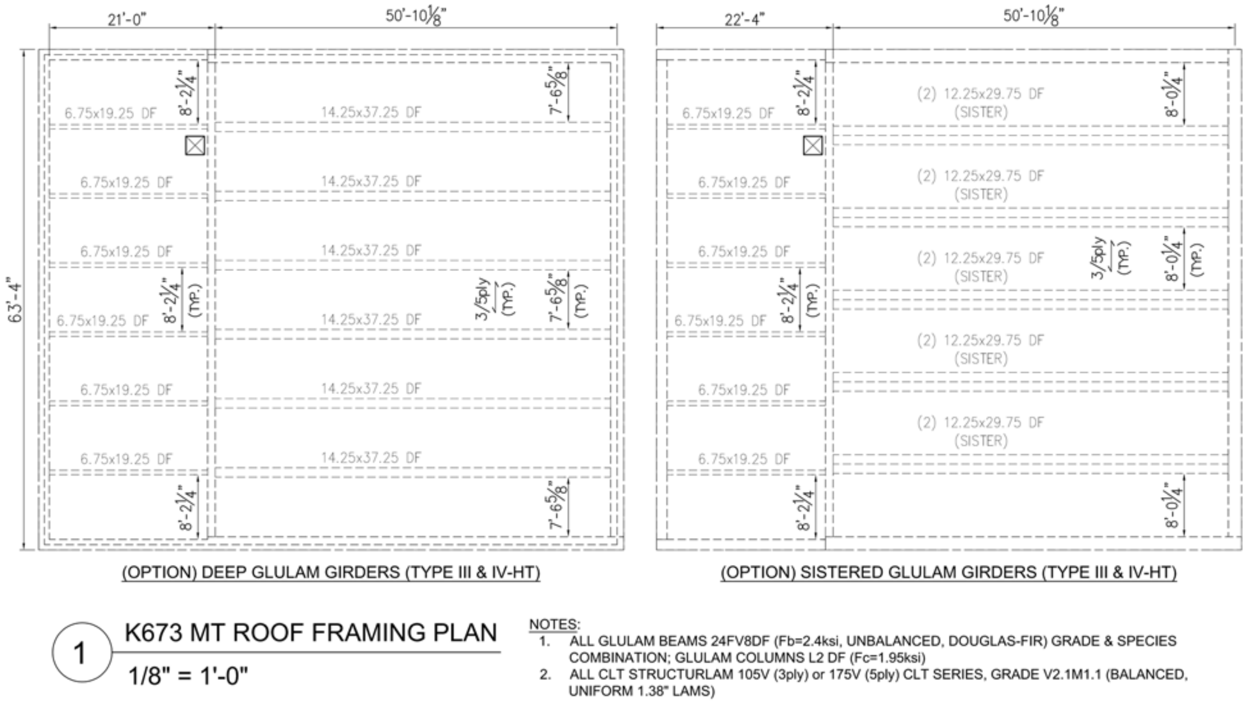


Figure 93. *Two schematic-level framing plans depicting potential roof framing options for the freestanding gym building with GLT beams and CLT roof panels.*

Comparing the two framing options:

- The MT material volume required for the non-sistered GLT girder option (option 1) is 14.5% less than that required for the sistered GLT girder option (option 2), which is advantageous from a cost and LCA point of view.
- The 29.75" depth of the sistered GLT beams (option 2) is less than both the 37.25" non-sistered GLT beams (option 1) and the 32"-deep bar joists used in the baseline design, which is advantageous from an MEP planning point of view:
  - The 14" diameter HVAC ductwork in the baseline design passes through the bar joists. In the baseline design, the total depth of the girders and ducts is 32".
  - In either of the MT design options, the ductwork would have to pass beneath the GLT beams. In option 1, the total depth of the girders and ducts is 51". In option 2, the total depth of the girders and ducts is 43".

In both cases, the GLT girders are considerably heavier than the steel bar joists which they replace.

- However, the total weight of the 3-ply CLT (9psf) roof decks is 81% lighter than that of the baseline design's 4.5" thick composite lightweight concrete slab-on-metal-deck.

- The increased weight of the GLT girders would only affect the girders themselves and the design of the bearing walls and beam pockets, each of which is typically overdesigned in such a one-story masonry bearing wall structure.
- As a result, the total weight of the MT structural roofing elements would be considerably lighter than the baseline design.

Table 4. *Comparison of Total Change in Building Weight Between Gym Baseline Design and MT Roof Design*

<table>
<tr><th>Structural roof element in gym baseline design</th><th>Structural roof element in gym MT design</th><th>Proportional change in weight</th><th>Amount throughout roof plan</th><th>Approximate total change in building weight</th></tr>
<tr><td>4.5”-thick LW concrete slab-on-metal-deck
=48psf</td><td>4.38”-thick 3-ply CLT (105V Grade V2.1M1.1 by Structurlam)
=9 psf</td><td>(-) 81%</td><td>Approx. 4,404 sf</td><td>(-) 177,179 lbs</td></tr>
<tr><td>18LH06
15plf x 2 joists
=30plf total</td><td rowspan="2">6.75”x19.25” DF
31.6plf x 6 beams
=189.6plf total</td><td rowspan="2">(+) 48%</td><td rowspan="2">21’-7 5/8” span</td><td rowspan="2">(+) 1,333 lbs</td></tr>
<tr><td>12K5
7plf x 14 joists
=98plf total</td></tr>
<tr><td rowspan="2">32LH14
33plf x 8 joists
=264plf total</td><td>Option 1
14.25”x37.25” DF
129 plf x 6 girders
= 774plf total</td><td rowspan="2">(+) 193%

OR

(+) 236%</td><td rowspan="2">50’-11 5/8” span</td><td rowspan="2">(+) 25,994 lbs

OR

(+) 31,703 lbs</td></tr>
<tr><td>Option 2
12.25”x29.75” DF
88.6 plf x 10 girders
=886plf total</td></tr>
<tr><td colspan="3" rowspan="2">Total weight savings of gym MT design</td><td>Option 1</td><td>149,852 lbs</td></tr>
<tr><td>Option 2</td><td>144,143 lbs</td></tr>
</table>

The freestanding gym test case demonstrates that long-span GLT members and structural CLT roof elements, together, provide the benefit of reduced structural building weight in comparison to highly efficient steel bar joists and slab-over-metal deck. It is likely that benefits in constructability and environmental impacts similar to those for the addition test case could be demonstrated, although that was beyond the scope of the test case.

The sistered glulam design option (option 2) demonstrates that a long-span mass timber roof structure will not necessarily require an increase in the overall depth of primary bending members compared to steel.

- The bar joists in the original design allowed the building designers to route MEP through the deep bar joists, and so enabling MT building designers to do the same with glulam beam penetrations would facilitate the same level of design streamlining as in the baseline design.
- Future standardization of GLT trusses and their reflection in model building codes will provide structural designers with another viable option.

TASK 3: EMBODIED CARBON ANALYSIS

WHOLE-BUILDING LIFE CYCLE ANALYSIS

ISO 14040, part of a series of international standards that address environmental management, defines a Life Cycle Analysis (LCA) as a “compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.”

- Whole-Building LCA (WBLCA) is a type of LCA specific to buildings
- WBLCA allows for the measurement of construction impacts across several environmental categories over the entire building lifecycle
- ISO 14040 allows for the exclusion from a WBLCA of any material that comprises less than 5% of the total mass of the building

WBLCAs are based on a bill of materials: an accounting of all of the materials that go into a building’s construction, including those used in the construction process and those that become a permanent part of the building itself.

- The usefulness of a WBLCA in measuring environmental impacts is limited by the completeness of its bill of materials
- Most WBLCAs focus on the major structural and envelope components of a building, and exclude interior partitions, finishes, MEP systems, and furnishings, each of which typically comprises less than 5% of the total mass of the building
- For reasons addressed below, this study includes interior partitions and finishes

WBLCA Impact Categories

The most commonly measured impact categories for WBLCAs are:

1. Global warming potential (GWP) through the release of carbon dioxide (CO2), methane CH4), nitrous oxide (NO), and other greenhouse gases (GHGs)
2. Acidification of soils and water through the release of nitrous oxides and sulfur oxides that create acid rain
3. Release of airborne particulates affecting human health (HH), particularly the creation of fine inhalable particles 2.5 micrometers in size and smaller (PM2.5) through forest fires, dust-generating activities like mining or construction, and the burning of fossil fuels
4. Eutrophication of both freshwater and seawater through the release of nitrogen compounds that feed algal blooms, which de-oxygenate water bodies when they die off
5. Stratospheric ozone depletion potential (ODP) through the release of certain types of refrigerants, particularly chlorofluorocarbons (CFCs)
6. Ground level ozone (smog) creation through the release of nitrous oxides and volatile organic compounds
7. Energy consumption from fossil fuels and other non-renewable sources

The SCA Green Schools Guide requires that a WBLCA be performed for the primary building envelope systems during the Integrative Design Process (IDP) prior to Schematic Design.

- This exercise is intended to compare the environmental impacts of different roof systems (currently including reinforced concrete roofs and composite roofs, or concrete on metal deck) and different envelope systems (currently including precast concrete panels, masonry cavity walls, and rain screens on either masonry or steel stud backup)

- All impact measurements are converted into GWP in order to facilitate comparisons
- This comparison is used as one of several factors used to determine the envelope system of each GSG project

Embodied Carbon

"Embodied carbon" refers to the GWP impact of creating, using, and disposing of a building or material. GWP is measured in kilograms of CO_2e (carbon dioxide equivalent) or $kgCO_2e$.

- Embodied carbon is often considered in relation to "operational carbon," which refers to the GWP impact of operating a building's energy- and water-consuming mechanical, electrical, and plumbing systems
- Operational carbon includes both direct GWP through the on-site burning of fossil fuels and indirect GWP through:
  - The on-site use of electricity produced elsewhere by the burning of fossil fuels
  - The on-site use of potable water provided by municipal water systems that use energy to extract, treat, and distribute water
  - The on-site production of wastewater that must be treated by municipal wastewater systems, which use energy and also release methane

As the operational carbon footprints of buildings improve due to increasingly efficient building envelopes and equipment and increasingly carbon-free energy sources, the embodied carbon footprints of buildings are comprising an increasing proportion of these buildings' total GWP.

- A new building's operational carbon footprint can be reduced to zero through the exclusive use of carbon-free energy and water sources and the on-site treatment and reuse of wastewater
- A new building's embodied carbon footprint cannot be reduced to zero – at least, not yet – as even a building composed entirely of reused materials (a feat that is not currently feasible) would require the use of energy to process, transport, install, and maintain those materials

This study is concerned solely with embodied carbon, measured as GWP.

Mass Timber Carbon Sequestration

Carbon sequestration in MT refers to the removal of carbon dioxide from the atmosphere via photosynthesis, and the storage of this carbon within the timber.

- Carbon stored in flora and fauna is referred to as "biogenic carbon"
- In the natural world, most biogenic carbon is eventually released back into the atmosphere through processes such as decomposition or burning; over time, this results in net zero "biogenic carbon flow"
- Fossil fuels are a form of biogenic carbon that was sequestered – buried before it had an opportunity to decompose – over millions of years, and stored underground for millions of years more; this carbon is rapidly released by the burning of fossil fuels for energy
- The natural carbon cycle also includes the non-biogenic storage of carbon in mineral formations such as limestone; this carbon is rapidly released by the process of heating limestone to make the cement used in concrete
- The rapid release of carbon by human activity, which is occurring much faster than any natural carbon uptake process can match, is a net positive carbon flow and is the primary driver of global climate change

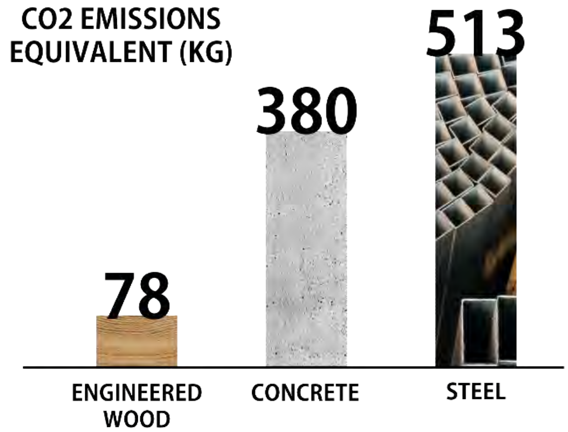


Figure 94. *CO2 Emissions for a beam spanning 7.3m supporting an unfactored load of 14.4 kN/m, as calculated by Athena IE (source: Passive House Accelerator)*

Theoretically, the carbon stored in MT materials can be considered to be permanently sequestered if the materials never decompose and are never burned.

- Permanent carbon sequestration is considered to have a net negative Global Warming Potential because it permanently removes carbon from the atmosphere
- However, the carbon sequestration benefits of MT construction are still being debated by scientists, and more sophisticated analysis is in its early stages
- Current LCA methods do not fully capture many aspects of biogenic MT carbon flows, including broad differences in forestry and manufacturing processes
- For example, MT embodied carbon increases if forestry and milling waste management includes the burning of slash piles (tree branches and leaves) or bark and offcuts, respectively

A 2018 study[3] found that Forest Stewardship Council (FSC) certified forests provide significantly more carbon sequestration per acre than typical state-regulated, privately owned forests by:

- Allowing trees more time to fully develop (60+ years vs. 40+)
- Thinning rather than clearcutting forests
- Protecting ecosystems and water quality
- Minimizing wasteful forestry and milling practices

Currently, the majority of MT material used in the U.S. (like the majority of all wood materials used in the U.S.) is not from FSC certified forests; however, most U.S. MT manufacturers offer the option of using FSC certified wood. Downsides of using MT from FSC certified forests include:

- Reduced timber yield per acre
- Price premium of 5%-15% (carbon markets could help ameliorate this premium)

ISO 21930 provides an international standard for incorporating biogenic carbon flows into Environmental Product Declarations (EPDs) for construction products.

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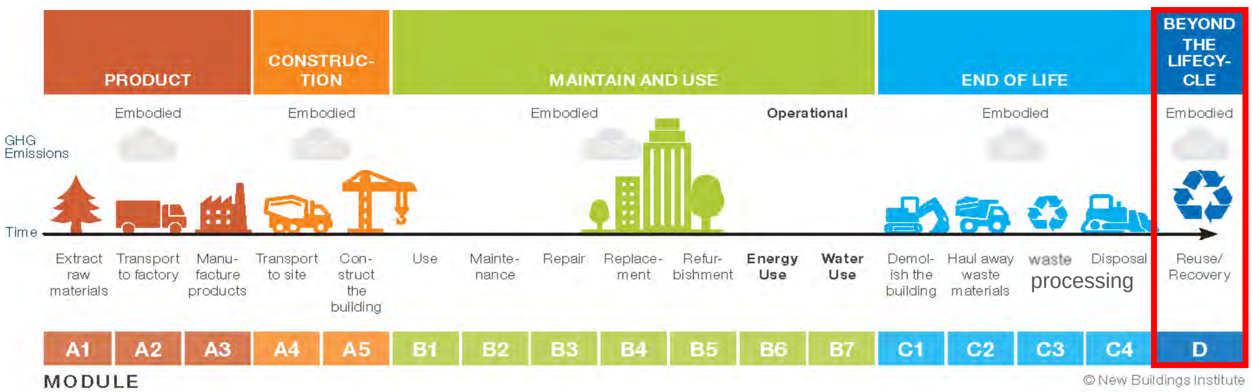
[3] Diaz, Loreno, Ettl, Davies, Tradeoffs in Timber, Carbon, and Cash Flow under Alternative Management Systems for Douglas-Fir in the Pacific Northwest, *Forests* (journal) 2018

- ISO 21930 states that “for wood, biogenic carbon may be characterized with a negative biogenic carbon flow … only when the wood originates from sustainably managed forests”
- Under the definition used by ISO 21930, all U.S. and Canadian lumber is considered to be sourced from sustainably managed forests because the forest carbon stock in each country has been increasing since 1990, when reporting began
- According to the U.S. Department of Agriculture’s Forest Inventory and Analysis Program, U.S. forestland area has been stable for more than 100 years, and the volume of standing inventory in those forests has increased 60% in the past 60 years
- Thus, current LCA standards consider it appropriate to include biogenic carbon in WBLCAs using MT from North America, even if the MT is not FSC certified

WBLCA Stages

A WBLCA divides the building lifecycle into stages, each of which is subdivided into modules:



Stage A

Many LCA studies concern themselves only with building production, or modules A1-A5.

- Modules A1-A3, sometimes called “cradle-to-gate” (i.e. from the source or “cradle” of the materials to the gate leading out of the manufacturing plant), typically comprise a large part of a building’s total WBLCA impact. These modules include:
  - Harvesting or mining of raw materials
  - Transportation of materials to the manufacturing or processing facility
  - The manufacturing or processing itself
- Module A4 measures the impact of the transport of materials and products from the manufacturing or processing facility to the site, and typically constitutes <10% of the total embodied carbon of a structure (source: thestructuralengineer.com).
- Module A5 measures the impact of the construction installation process, and typically constitutes a small percentage of the total embodied carbon of a structure. This includes:
  - A5w: Materials wasted onsite, calculated as a waste factor (WF) of other LCA modules.
  - A5a: Emissions due to site activities such as the operation of construction equipment typically estimated based on studies of similar projects or data from previous projects; 700kg CO_2e per 100,000 lbs of construction material is an average figure that is commonly used for preliminary LCA calculations (source: thestructuralengineer.com).

Stage B

LCA stage B is concerned with building use.

- Modules B1-B5 measure the impact of various aspects of using and maintaining building materials. The following modules are often excluded because they are not well supported by common LCA databases or tools:
  - Module B1 measures the impacts of using the building, but excludes energy and water use; this module is not well supported by data, and there is no professional consensus on a methodology for its measurement
  - Modules B3 and B5 measure the impacts of repairing and refurbishing the building, including the production and transport of materials for repair (generally, to restore something to working condition) and refurbishment (generally, to restore something to its original condition); there is little data available to measure these impacts, which depend on the materials and equipment specific to individual buildings
- Modules B1-B5 are strongly influenced by the service life of the building
- Modules B6-B7 concern the impacts of operating the building via energy and water consumption; as noted above, this study is concerned solely with embodied carbon, and therefore excludes modules B6 and B7 from its WBLCA

Stage C

LCA stage C is concerned with the end of the building's service life. Currently, approximately 10% of waste from building construction and demolition is recycled.* Module C is concerned with the 90% that is sent to landfills or burned in municipal solid waste incineration facilities:

- Module C1 measures the impact of the equipment used in a building's demolition or deconstruction
- Module C2 measures the impact of transporting the demolished materials to landfills or municipal solid waste incineration facilities
- Module C3 measures the impact of processing waste; there is little data available to measure this impact, so it is excluded by common LCA databases or tools
- Module C4 measures the impact of the equipment used in landfills

Together, LCA stages A through C are collectively referred to as "cradle to grave," and make up what is traditionally described as the "system boundary" for the decision-makers involved in the construction, ownership and operation of a building.

* The SCA's Green Schools Guide credit for construction waste management typically captures only the waste generated during new construction.

- About 90% of construction and demolition waste is created by demolition; only 10% is created by the construction process
- Demolition of any existing structures is typically completed under an early "site preparation package" with a separate LLW number that is not included in the Green Schools Guide boundary
- The future demolition of a new SCA building is not considered by the Green Schools Guide credit for construction waste management
- Unlike demolition waste, construction waste such as offcuts, discarded materials, and packaging has a high recycling rate (typically 75% or more in New York City) as these materials are easily separated and not incorporated into the building itself

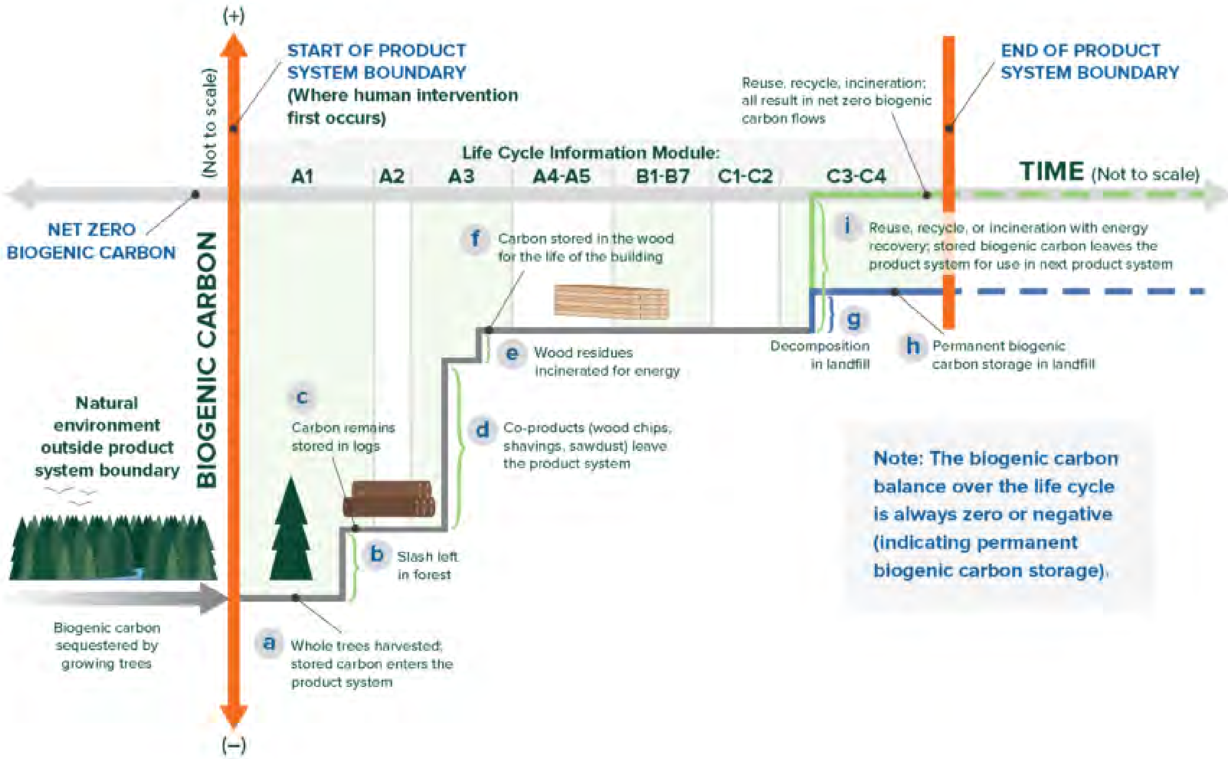


Figure 95. Biogenic Carbon Flows for Wood Products in LCA Stages A-C, per ISO 21930 (WoodWorks)

Stage D

LCA stage D is concerned with what happens to the components of a building after it is demolished or deconstructed, i.e., "beyond the system boundary." LCA stages A through D are collectively referred to as "cradle to cradle." Stage D includes:

- Recovery of materials from building demolition or deconstruction; it is estimated that up to 75% of the materials from building demolition have some residual value
- Reuse or recycling of materials, including reusable materials such as wood flooring, easily recycled materials such as aluminum and steel, and materials such as gypsum board that can be broken down and reconstituted as new building materials
- Down-cycling of materials, including the re-milling of solid wood materials into mulch or composite wood products, or the pulverizing and reuse of materials like concrete, masonry and glass to create coarse aggregates for new concrete, base layers for pavements and slabs on grade, or "alternative daily cover" placed on landfills
- Landfill gas capture or release
    - In aerobic landfills, materials or their leachates are exposed to or injected with air, which stabilizes the materials
    - Most landfills are largely anaerobic, meaning that materials biodegrade in the absence of oxygen and produce methane
    - Methane from anaerobic landfills may leak into the atmosphere (referred to as "fugitive emissions"), be captured and flared or burned (which produces CO2), or be captured, processed, and burned to produce thermal or electrical energy

LCA stage D is an important factor in the measurement of the GWP impacts of MT carbon sequestration.

- If the MT materials are burned (without energy recovery) after the end of the building's life, the carbon is no longer sequestered and the use of MT has a net positive GWP impact
- If the MT materials are landfilled after the end of the building's life, most the carbon is no longer sequestered and the use of MT has a very minor net negative GWP impact
- If the MT materials are indefinitely reused or recycled, either by being disassembled and reassembled into new buildings or by being broken down and used in durable goods such as furniture, the carbon remains sequestered, and has significant net negative GWP impact
- This study considers the GWP impacts of MT carbon sequestration both without stage D (stages A-C only) and with stage D (stages A-D inclusive)
- Assumptions regarding the disposition of the MT materials in stage D are described in the *LCA Tools* section below

Phase	Reuse	Recycling	Incineration	Incineration (with energy recovery)	Landfill
Up to construction	−1100	−1100	−1100	−1100	−1100
Demolition	22	22	22	22	22
Transport	12	12	12	12	12
Re-manufacture	–	10	–	–	–
Re-transport	–	12	–	–	–
Re-construction	45	45	–	–	–
Combustion	–	–	1192	1192	–
Energy recovered	–	–	–	−628	–
Emissions from landfill	–	–	–	–	1013
Total	−1021	−999	126	−502	−53

Figure 96. *Comparison of Biogenic Carbon Flow Accounting for Alternative LCA Stage D Outcomes (source: Darby et al. 2013, A Case Study to Investigate the Life Cycle Carbon Emissions and Carbon Storage Capacity of a CLT Multi-Story Residential Building; markups by TimberLab)*

WBLCA for LEED

The U.S. Green Building Council's building sustainability standard Leadership in Energy and Environmental Design (LEED) for Building Design + Construction (BD+C) version 4.1, which forms the basis for much of the SCA's Green Schools Guide 2019, includes an optional credit for Building Life-cycle Impact Reduction. Performing a WBLCA is one way to achieve this credit. Requirements include:

- The LCA must comply with ISO 14040/14044
- The LCA must be calculated for GWP, ODP, acidification, eutrophication, ozone formation, and depletion of nonrenewable energy resources

- The LCA must find that the proposed building reduce total life cycle impacts by 10 percent compared to a baseline building based on ASHRAE 90.1-2010
    - At least three of the six impact categories must be reduced by at least 10 percent
    - No impact category can increase (worsen) by more than 5 percent
    - Building energy use (a separate measurement) must improve by at least 5 percent
- The LCA must include modules A1-A4, B1-B7, and C1-C4
- The LCA must include the building structure and enclosure
- The LCA must use a building service life of at least 60 years

The SCA Green Schools Guide includes a similar optional credit, but it may only be pursued with SCA permission.

LCA Tools

Spreadsheet Modeling (aka Calculators)

Spreadsheet modeling converts the line items from a bill of materials directly into kgCO2e measurements, which are summed to create a WBLCA.

- Many calculators are limited to GWP or embodied carbon impacts
- A spreadsheet model yields a more simplified analysis than a whole-building model, unless a much more detailed bill of materials is provided
- Assumptions are built into a spreadsheet model, and therefore may be less easy to modify
- However, spreadsheet models are still widely used and accepted by LCA analysts

Commonly used calculators include:

- EPIC, a web-based calculator for early design-stage analysis of embodied carbon
- EC3 (Embodied Carbon in Construction Calculator), a database of Environmental Product Declarations (EPDs) for building materials

Whole-Building Modeling (aka Design Integrated Tools)

Whole-building modeling uses sophisticated 3D building simulations or models.

- The models are either imported from another modeling program such as Revit or generated directly by the LCA software based on inputs and assumptions relating to a building's construction type, use, and size
- Whole-building models tend to cover a wide variety of preset material and construction types as well as the ability to create custom inputs and, sometimes, to modify assumptions, allowing for comparisons across many design options
- "Professional" LCA tools, which are fully customizable and can import data from a wide range of sources, are most commonly used to generate Environmental Product Declaration for individual materials or products, but can also be used for WBLCAs

Commonly used whole-building modeling tools include:

- Athena Impact Estimator (IE), a freestanding software package
- OneClick LCA, a web-based tool that supports BIM integration
- Tally, a Revit plug-in

Professional LCA tools include GaBi, OpenLCA, and SimaPro.

WoodWorks provides a comparison of three WBLCA tools:

	Analysis	Embodied Carbon	Biogenic Carbon	Operational Carbon	Life Cycle Inventory (LCI) Database	Custom Assemblies Possible
LCA Tools that can be used for WBLCA						
Athena Impact Estimator for Buildings (IE4B)	LCA	Yes (A1-C4 + D)	Always included*	Optional	Custom database based on regional North American data	Yes
tallyLCA	LCA	Yes (A1-C4 + D)	Optional*	Optional	Custom database (combination of product specific and industry average)	Yes
One Click LCA	LCA	Yes (A1-C4 + D)	Always calculated, reported separately*	Optional	EPD data from multiple sources	Yes, in some versions

Figure 97. *Comparison of Common WBLCA Tools (source: WoodWorks)*

Jensen, et al. (2021), one of the studies cited in the *Literature Review* section below, provided the following comparison of three WBLCA tools. This study opted to use Tally.

Table 1. Comparison of Whole-Building Life Cycle Assessment tools.

	Athena Impact Estimator (IE)	Tally for Revit	One Click LCA
Type of software	Stand-alone	Plug-in for Revit 2015-2020	Stand-alone and plug-in for Revit
Regionality	North America (limited number of locations)	North America	North America, Europe, Middle East, Asia Pacific, South America
Bill of material (BOM) imports	BOM from AutoCAD File Type: CSV, xml, Excel, tab delimited. Allows manual entries without a model.	BOM from Revit file Tally identifies categories, families and materials. Dynamo imports Excel data into Tally. No manual entries without a model.	Revit, IES-VE, Design Builder, Excel, CSV, gbXML, SketchUp Pro, ArchiCAD, and more. From Revit file, One Click LCA identifies categories, families and materials. Allows manual entries without a model.
BOM additions or modifications	User can add/modify family and material entry at any time in the LCA process within the software.	Changes to a family type, quantity, volume or area need to be completed within Revit and then refreshed in Tally. An accessory material can be added to a family directly in Tally as long as it does not depend on a change of the object's surface area or volume.	User can add/modify family and material entry at any time in the LCA process within the software.
EPD data sources	LCI data developed by Athena and limited EPDs.	Custom thinkstep database	Diverse LCI data sources, One Click generic construction materials database, manufacturer specific EPDs.
EPD accessible during workflow	EPD data cannot be accessed during mapping.	Basic EPD information available (without GWP), but full EPD only available after report is generated.	EPD data always available during mapping and material selection. GWP value visible.
New EPD into database	Request through software developers	Only If developed by thinkstep	After internal review by software developers.
Design comparisons allowed?	Yes. Design options don't need to be modeled.	Yes, but needs Revit design options.	Yes. Design options don't need to be modeled.
Rating systems eligibility	LEED, ILFI's certifications, Green Globes	LEED, ILFI's certifications, Green Globes	LEED, ILFI's certifications, BREEAM, DGNB, and 20+ other global certification schemes.

Figure 98. *Comparison of Common WBLCA Tools (Herrero-Garcia, Technology Architecture + Design Issue 4.2.)*

The SCA used Athena IE to create a prototype WBLCA for a new school, and developed its LCA Impact Assessment Guidelines with Athena IE. According to the Green Schools Guide, "Athena IE provides LCA profiles for many common building assemblies and systems based on regionally specific, ISO 14044-compliant engineering and manufacturing data."

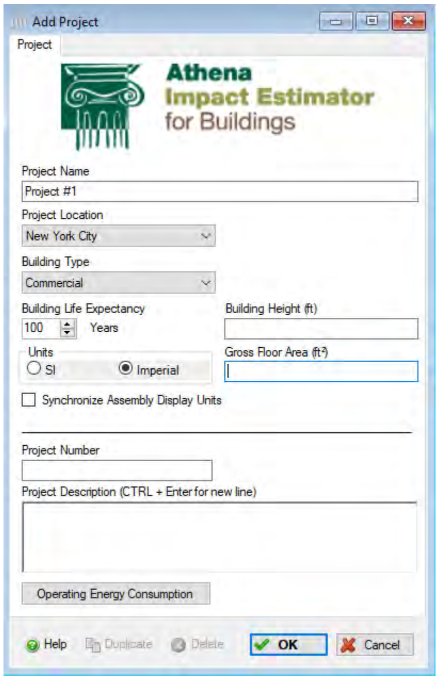


Figure 99. *Athena IE Interface*

This study opted to use Athena IE for its comparative WBLCAs of reinforced concrete and MT versions of a new SCA school. Advantages of Athena IE include:

- Free of charge
- Allows user to either directly specify quantities from bill of materials, or to use automatic calculators based on basic inputs
- Provides regionally-specific North American data
- Includes relatively up-to-date lifecycle impact data for CLT walls, CLT floors, CLT roofs, and GLT beams and columns
- Includes biogenic carbon flows

Athena IE accounts for the biogenic carbon flows of MT materials in WBLCA stage D using the following assumptions:

Figure 100. *Comparison of Common WBLCA Tools (WoodWorks)*

As noted above, the carbon sequestration benefits of MT construction are still being debated by scientists. The following observations may be made of the assumptions used by Athena IE:

- By assuming that only 10% of MT materials are recycled or reused, Athena IE likely underestimates the amount of carbon that is permanently sequestered by MT materials (i.e., underestimates the reduction in embodied carbon or GWP)
- By assuming that only 10% of landfilled MT materials are exposed to aerobic conditions, Athena IE likely overestimates the amount of carbon that is permanently sequestered by storage under anaerobic conditions (i.e., overestimates the reduction in embodied carbon or GWP)
- However, because the widespread use of MT in North American construction is relatively recent, there is not yet enough data on the disposition of MT materials after the end of a building's service life to determine whether these under- and over-estimations balance each other out

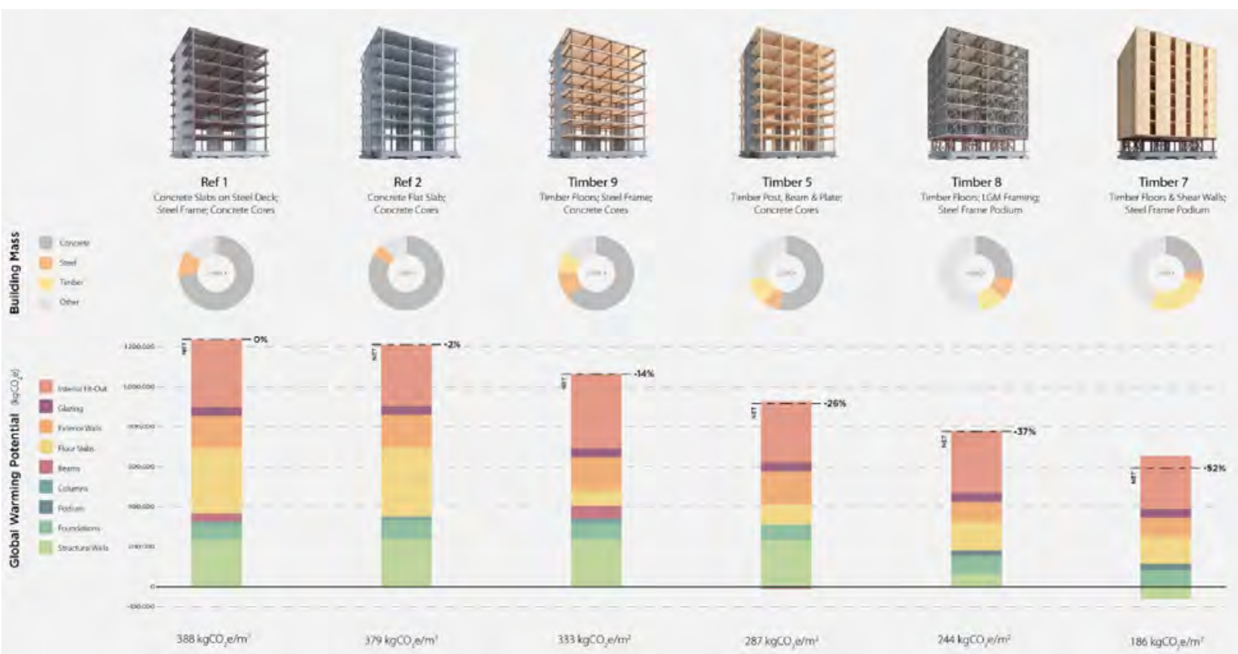
LITERATURE REVIEW

Comparative LCA Studies

Jensen et al. (Buro Happold), 2021
Mass Timber Solutions for Eight Story Mixed-Use Buildings: A Comparative Study of GHG Emissions

General scope: Whole building embodied carbon comparative study of nine MT design options and two typical concrete and steel reference cases for an eight-story mixed-use building
Tool selected: Tally (other tools considered: Athena, GaBi)
Stages studied: A1-A4, B2-B5, C2-C4, D
Location: Average North American travel distances were used
Findings:

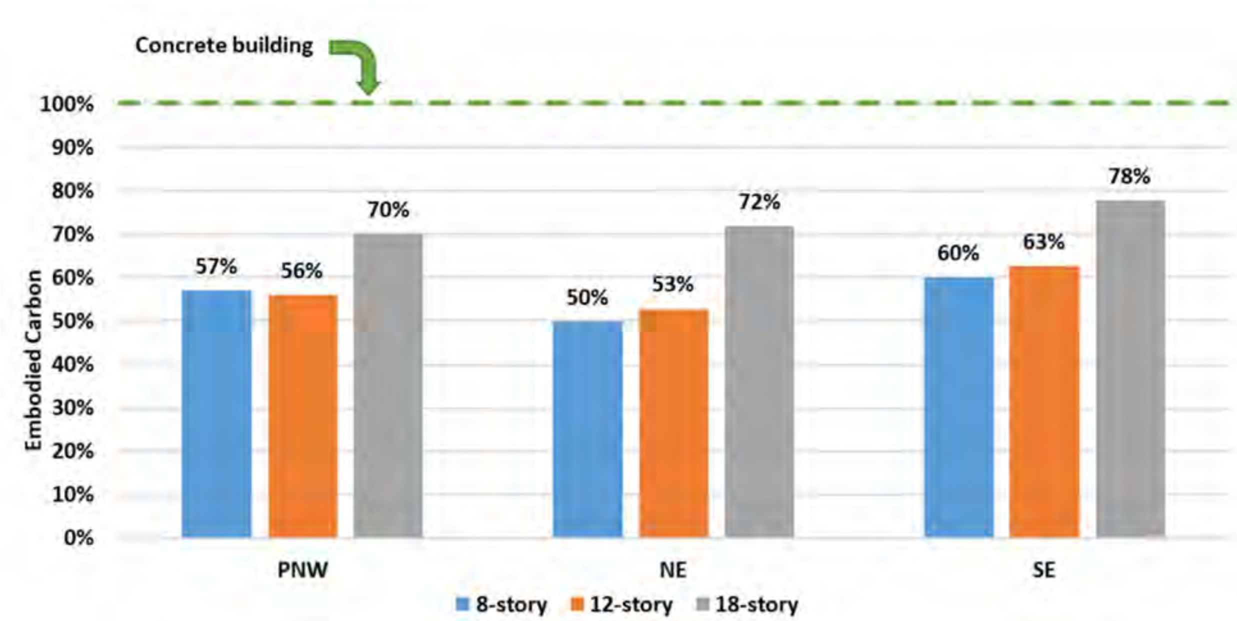
- Nine options (T1-9) reflect a variety of MT structural approaches using 5-ply CLT as a structural slab, varying grid spacing (with spans ranging from approximately 10-20'), altering gravity/lateral systems, and introducing elements of steel to form hybrid systems
- Each variable design option was comprised of the following elements as applicable: columns, beams, foundations, structural walls, floor assemblies, interior walls and fire encapsulation
- The study found that the MT designs varied significantly in environmental impact reduction, ranging between a 14-52% reduction in whole building embodied carbon from the most impactful reference case, and a 31-73% reduction when considering the structural systems alone (i.e. without nonbearing walls, finish materials, etc.)
- Engineering out the concrete core and shear walls and taking a cellular or "honeycomb" approach to the MT structure (T7,T8) led to the most consequential GWP reductions
- Among the options that deployed MT only as slabs, beams and columns (T1-T6), using larger grid spacing and exposing MT members (T5) led to the largest GWP reduction



Puettmann et al., 2021
Comparative LCAs of Conventional and Mass Timber Buildings in Regions with Potential for Mass Timber Penetration

General Scope: Three buildings were designed for the Pacific Northwest, Northeast and Southeast regions in the United States to conform to MT building types with 8, 12, or 18 stories, and compared to typical reinforced concrete reference cases
Tool selected: SimaPro LCA software equipped with the USLCI, EcoInvent, and DATASMART 2019 databases
Stages studied: A1-A5
Location: Seattle (Pacific Northwest), Boston (Northeast), and Atlanta (Southeast)
Findings:

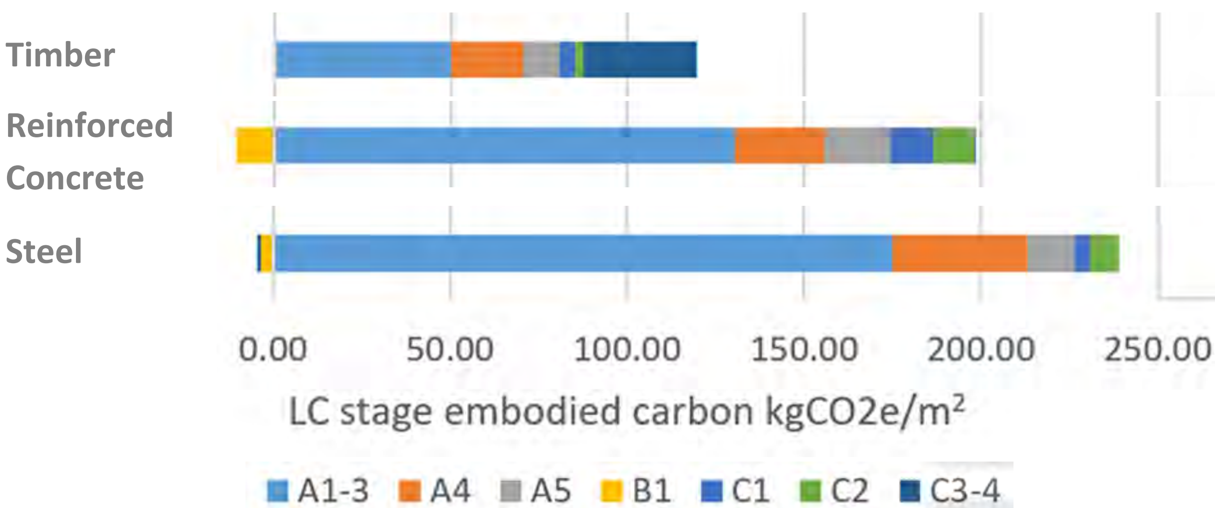
- Three different versions of the MT buildings were based on the wood species endemic to three geographic locations: (1) the Pacific Northwest (Douglas fir and western hemlock), (2) the Northeast (Eastern spruce and white pine), and (3) the Southeast (Southern pine)
- The MT buildings were designed as IBC Type IV-A for 18-story buildings, Type IV-B for 12-story buildings, and Type IV-C for 8–9-story buildings
- The MT building designs were hybrid, with concrete and steel for certain building elements as well as CLT and GLT
- Reporting of embodied carbon was based on the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) evaluation method
- Over all regions and building heights, the MT buildings exhibited a reduction in embodied carbon varying between 22% and 50% compared to the reinforced concrete buildings



Hart et al., 2021
Whole-Life Embodied Carbon in Multistory Buildings – Steel, Concrete and Timber Structures

General Scope: Whole-life embodied carbon (WLEC) emissions of building superstructures using identical frame configurations in steel, reinforced concrete, and engineered timber (MT) frames
Tool selected: SimaPro with GaBi database, proprietary modeling
Stages Studied: A1-A5, B2-B5, C1-C4, D
Location: Embodied carbon coefficients (ECCs) based on UK data (London and Edinburgh)
Findings:

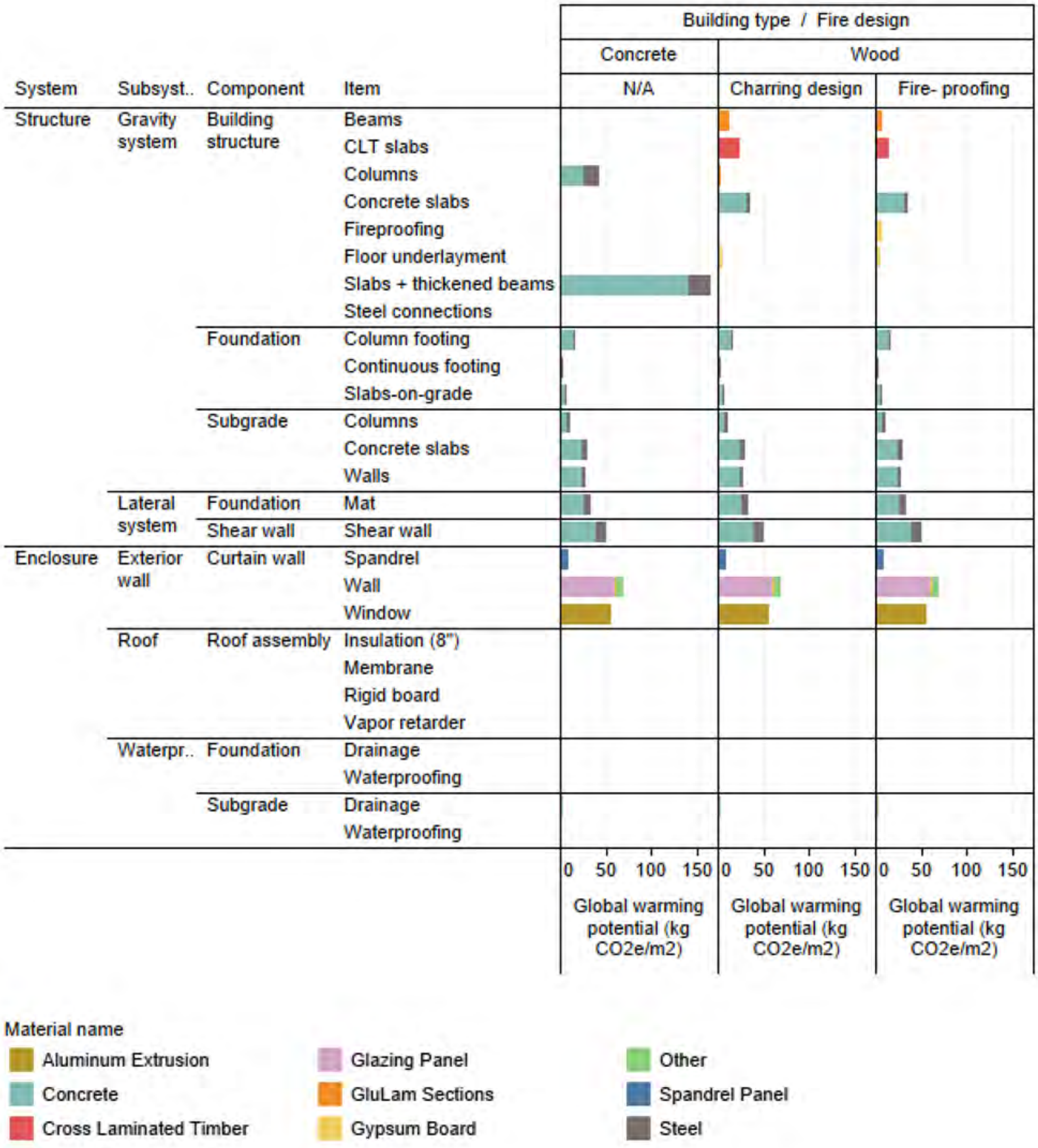
- 381 different frames analyzed – 127 different frame configurations, from 2 to 19 stories
- Embodied carbon coefficients (ECCs) for each material and life cycle stage were represented by probability density functions to capture the uncertainty inherent in life cycle assessment
- For the steel and reinforced concrete structural systems, GHG emissions associated with the production and construction modules (A1-A5) accounted for at least 93% of the WLEC, including 75% (steel) and 70% (reinforced concrete) of the total WLEC for stage A3 alone
- By contrast, for the MT structural system, emissions associated with production and construction (A1-A5) accounted for just 68% of total WLEC, including just 42% of the total WLEC for modules A1-A3
- While timber frames show much lower impacts in the product and construction stages, they can produce higher emissions at the end of life (modules C3-C4, assuming landfilling and decomposition)



Simonen et al., 2019
Environmental Benefits of Using Hybrid CLT Structure in Midrise Non-Residential Construction

General Scope: Cradle-to-gate LCA of 8-story office building superstructures using identical frame configurations in reinforced concrete and hybrid engineered timber (MT) frames
Tool selected: TRACI 2.1
Stages Studied: A1-A5
Location: U.S. Pacific Northwest

- Two fire protection scenarios were considered for the MT building: one with fireproofing provided by gypsum wallboard, and one with fire protection provided by adding thickness to the MT members to allow for charring
- GWP impacts associated with the production stages (A1-A3) were 26.5% less for the MT building
- Embodied carbon savings could be as high as 80% when also factoring in sequestration



Other Findings

- A cradle-to-gate analysis of structural frames for comparably sized buildings by De Wolf et al. (2016) reported that MT versions of the frames had the lowest median GWP value (~200 $kgCO_2e/m^2$) compared to steel and concrete versions (at ~350-380 $kgCO_2e/m^2$)
- A meta-analysis of non-residential whole-building LCA studies by Saade et al. (2019) found that in eight out of eight studies, wood frames achieved lower Global Warming Potential (GWP) than concrete, and in five out of six studies wood was better than steel; the exception was a steel design credited with high optimization and durability
- An assessment of 13 multifamily residential buildings in Germany and Austria by Hafner and Schäfer (2018) found that buildings with MT structures had 9% to 56% lower embodied carbon than comparable buildings with steel or concrete structures
- Research for the UK's Committee on Climate Change by Spear et al. (2019) found embodied carbon savings in the range of 220 to 260 $kgCO_2e/m^2$ (internal area) for the structures of apartment buildings designed with CLT compared to reinforced concrete

OTHER ENVIRONMENTAL IMPACTS OF MT CONSTRUCTION

Biophilic Design

A growing body of research suggests that incorporation of biophilic design into learning spaces can have significant effects on educational outcomes

- Biophilic design emphasizes human connections and adaptations to the natural world, and can encompass anything from flora and fauna to weather
- MT construction provides the biophilic benefit of direct exposure to natural wood materials, impacting sight, smell, and other less easily definable senses
- A study published in *Mass Timber Digest*, July 2022 found:
    - Natural building materials and surfaces featuring exposed wood can have positive neurological impacts
    - Biophilic elements in a classroom setting can reduce stress, boost test scores, and improve indoor comfort for students

Material Weight

The relatively light weight of MT structures (when compared to steel and reinforced concrete buildings designed to support similar loads) significantly reduces overall building weight

- Reduces foundation and ground improvement requirements, thereby saving time, cost, and embodied carbon
- Facilitates building on top of existing structures, thereby allowing existing structures such to be reused and incorporated into higher-density developments

Structure as Finish

The use of MT "structure as finish," – i.e., structural columns, beams, floor and wall plates that do not need to be encapsulated by gypsum board, acoustical tile ceilings, or fire-retardant foam – significantly reduces the need for additional interior finishes

- Because MT is engineered, its surface is smooth and free from the cracks and knots seen in raw wood, and it can be coated to create a surface that can withstand abuse and cleaning
- Unlike many other interior building materials, MT has no or minimal off-gassing of volatile organic compound (VOC) emissions, which translates into better air quality

Design for Deconstruction

Most buildings are currently designed to be demolished, creating piles of debris that are sent to landfills after the most valuable and easily separable materials, such as steel beams, are extracted for recycling. Design for deconstruction makes building materials easier to dismantle, separate, and re-use through strategies such as:

- Minimizing the number of different types of materials
- Minimizing the use of toxic or composite materials
- Using fewer, larger building elements
- Simplifying connections and making them visible or easily accessible
- Using mechanical fasteners instead of sealants and adhesives
- Using modular components or assemblies

ADDITIONTEST CASE LCA SCOPE

System Boundaries

Building/Site Scopes

The material scope of the LCA includes the following assembly groups:

- Foundations
- Columns and beams
- Floor assemblies
- Roof assemblies
- Exterior wall assemblies
- Interior wall assemblies

Because the MT design alternatives to the baseline design did not involve any changes to the site, the LCA does not include site materials.

Material Finishes

Unlike most LCAs, which encompass basic building elements without finishes, this study sought to include interior finishes wherever possible.

- A major benefit of MT construction is the use of "structure as finish"
  - Unlike typical concrete or steel elements, MT columns, beams and floor plates do not need to be protected on all sides by additional finish materials such as GWB
  - An LCA comparison excluding interior finishes would understate the environmental impact reduction of MT construction
- In addition to reducing material volume, weight, thickness, and embodied carbon, the "structure as finish" approach to MT design also maximizes the beneficial biophilic effects of exposure to natural wood (although these benefits, which are proven but somewhat subjective, are not included in LCA impact measurements)

Most WBLCA tools, including Athena, were not created with the intent of comparing buildings with typical interior building finishes to buildings without the need for such finishes.

- Athena makes assumptions about finishes for typical interior partitions
- Athena does not include many finishes in its algorithms for the other assembly groups
- More specifically, Athena's database does not include many of the finish materials recommended in the floor assemblies for the MT designs
- Therefore, EME sought to substitute the nearest equivalent materials in the Athena database for the actual materials recommended for the MT designs
- These equivalencies and the reasoning behind them are discussed in the *Athena LCA Inputs – Material Substitutions* section below

Life Cycle Scope

The LCA follows ISO 21931 and EN 15978 standards, which define the building life-cycle stages and modules including product/construction process stage (A), use stage (B), end-of-life stage (C), and beyond end-of-life stage (D).

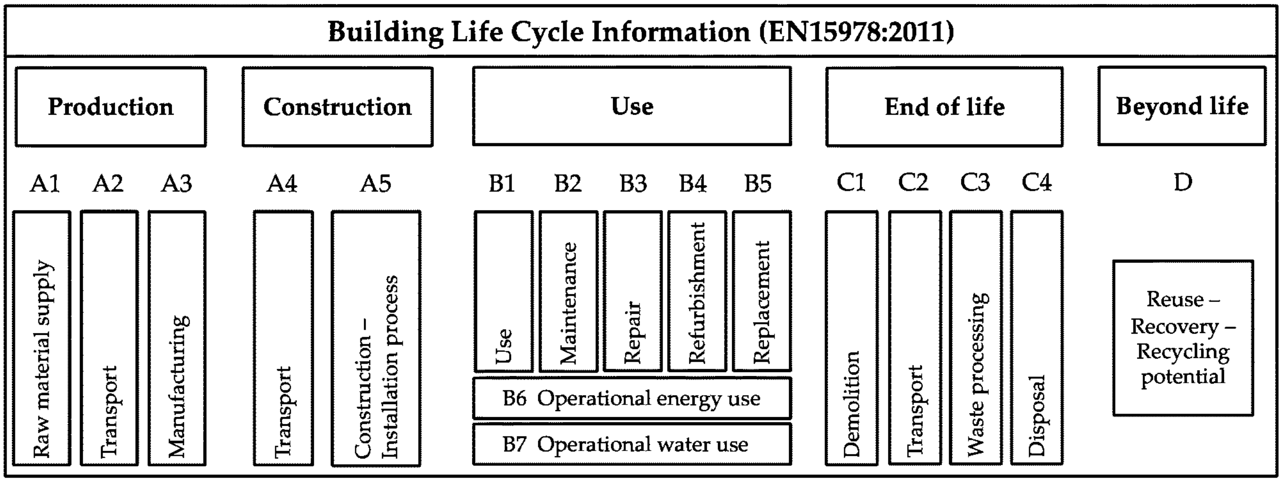


Figure 101. *ISO and EN Life Cycle Stages Classification (EN 15978)*

Information Module	Supports?	Processes Included
A1 Raw material supply	Y	Primary resource harvesting and mining
A2 Transport	Y	All transportation of materials up to manufacturing plant gate
A3 Manufacturing	Y	Manufacture of raw materials into products
A4 Transport	Y	Transportation of materials from manufacturing plant to site.
A5 Construction-installation process	Y	Construction equipment energy use, and A1-A4, C1, C2, C4 effects of construction waste
B1 Installed product in use	N	n/a (currently insufficient consensus in methodology and data for this module to be addressed)
B2 Maintenance	Partial	Painted surfaces are maintained (i.e. repainted), but no annual maintenance aspects are included
B3 Repair	N	n/a (not currently well-supported with data)
B4 Replacement	Y	A1-A5 effects of replacement materials, and C1, C2, C4 effects of replaced materials
B5 Refurbishment	N	n/a (this module applies to known future refurbishment and needs to be addressed on a case-by-case basis if applicable)
B6 Operational energy use	Y	Energy primary extraction, production, delivery, and use
B7 Operational water use	N	n/a
C1 De-construction demolition	Y	Demolition equipment energy use
C2 Transport	Y	Transportation of materials from site to landfill
C3 Waste Processing	N	Most material data does not include waste processing effects, however, the newer metals "avoided burden" methodology data does include waste processing effects, but it is not separated into its own C3 module (see Metal Recycling on page 28)
C4 Disposal	Y	Disposal facility equipment energy use and landfill site effects
D Benefits and loads beyond the system boundary	Y	Carbon sequestration and metals recycling

Figure 102. *Life Cycle Stages Supported By Athena*

LCA Modules Included

See *WBLCA Stages* section above for explanations of excluded modules. Included modules are:

- Production: A1-A5 (entire)
- Use: B2, B4
- End of Life: C1, C2, C4
- Beyond End of Life: D (entire)

Reference Case

- Baseline design: Conventional reinforced concrete building

Proposed Cases

- Type III-A Mass Timber Case
- Type IV-HT Mass Timber Case

The key differences between the Type III and Type IV models are described below:

Assembly Group	Type III	Type IV
Columns and Beams	Larger beams to support thicker CLT floor plates	Smaller beams to support thinner CLT floor plates
Typical Floor Plates	5-ply CLT in typical floor assembly 7-ply CLT in 2-hr rated floors	3-ply CLT in typical floor assembly 7-ply CLT in 2-hr rated floors
Exterior Walls	Terracotta on insulated metal stud backup	Terracotta on 5-ply CLT panel backup

Study Period

Typically, building lifespan in LCA studies ranges from 50 to 100 years. At the request of the SCA, the building lifespan for this study was set to 100 years.

Athena LCA Inputs

Material Substitutions

Specified Material	Assembly Group	Material Composition	Athena Substitute Material
Vinyl Composite Tile (VCT)	Floors	Polyvinyl chloride (PVC) chips, fibers, filler materials	Sika Sarnafil S327 PVC Membrane 80 mil*
Acoustic Ceiling Tile (ACT)	Floors	Mineral fiber	Mineral Wool Batt
GenieMat Acoustical Mats/ Neoprene Flooring Strips	Floors	>90% recycled rubber / synthetic rubber	EPDM membrane 60 mil**
Insonomat Acoustic Membrane	Floors	Elastomeric bitumen and recycled rubber	Asphalt Binder with Ground Rubber Tire
Lead 6 Floated Underlayment	Floors	Recycled non-woven synthetic fibers	Organic Felt #30
Acoustic-TECH SOFIX Acoustical Mat	Floors	80-90% glass mineral wool	Fiberglass Batt
Hardwood Floor	Floors	Wood	Plywood
Granite Panel	Exterior Walls	Granite	Natural Stone
Terracotta Panel	Exterior Walls	Clay-based non-vitreous ceramic material	Clay Tile
Sound Attenuation Blanket	Interior Walls	Fiberglass	Fiberglass Batt
Roof Paver	Roof	Concrete	Inverted Modified Bitumen Roofing System - Polyiso Foam Board Glass Facer
Continuous Extruded Polystyrene Insulation (XPS)	Roof	Extruded polystyrene	Inverted Modified Bitumen Roofing System - Expanded Polystyrene
Fluid-Applied Protected Membrane Roofing System	Roof	Modified Bitumen Membrane 2 ply	Standard Modified Bitumen Membrane 2 ply

* Athena assumes a replacement period of approximately 35 years for this product. We assume that VCT flooring will last the entire building lifespan, thus the total square footage is reduced proportionally.
**Athena assumes a replacement period of approximately 15 years for this product. We assume that this product will last the entire building lifespan as part of a floor assembly, thus the total square footage is reduced proportionally.

Foundations

Material (reinforced concrete) volume reductions due to the reduced building weight of the MT designs were calculated according to the following reduction factors for specific footing types:

- F-1 43.4%
- F-2 49.5%
- F-B 25.0%
- All other footings remained the same

Columns and Beams

Columns and beam inputs were based on measured material volumes taken from the baseline design drawings and MT schematic design drawings.

- Baseline columns: Concrete and rebar volume calculated rigorously for one typical column and multiplied by total number of columns
- Baseline beams: Concrete and rebar volume calculated rigorously for all beams.
- MT columns and beams: GLT volume calculated rigorously for all columns and beams

Floor Assemblies

Floor assemblies modeled:

- Typical floor
- Floor above Cafeteria
- Music room floor
- Dance room floor
- 2-hr rated floor

Athena's algorithm determines the thickness of CLT floor slabs based on the supported span length. The selected span length in Athena was used to modulate the CLT floor thickness for each proposed CLT floor assembly in the MT designs. The following span lengths were used:

- 10 ft was used to approximate 3-ply CLT
- 15 ft was used to approximate 5-ply and thin (6.875") 7-ply CLT
- 20 ft was used to approximate thick (9.66") 7-ply CLT

Exterior Wall Assemblies

Exterior wall types modeled:

- Baseline Design: Rainscreen with terracotta tile on stud wall (precast panel at 1st floor above knee wall/water table was generalized as terracotta rainscreen)
- Baseline and MT Designs: Concrete knee wall with granite panel
- Type III MT Design (see notes under *Code Clarifications* section above): Same as baseline
- Type IV MT Design: CLT exterior wall with CLT exposed to interior (see notes under *Code Clarifications* section above)

Interior Wall Assemblies

Interior wall assembly types modeled:

- CLT non-rated partition wall
- CLT 2-hr rated partition wall
- GWB non-rated metal stud partition wall (A2)
- GWB 2-hr rated metal stud partition wall (A4-2)

- GWB non-rated metal furring partition wall (D1)
- GWB acoustical metal stud partition wall (J4)

Paint: A gallon of paint typically covers from 350 to 400sf. A factor of 1 gallon/375 sf was chosen.

Ceramic Tile: Used in corridors of baseline design only. Not used in MT designs per SCA instruction, although recommended.

Concrete Cores / Shear Walls

Shear walls and retaining will remain the same between the conventional and MT models. Shear walls include: Stair A, Stair B, Elevator Shaft

Roofs

The "Inverted Modified Bitumen Roof System" in Athena was used to approximate the standard SCA roof assembly

Extra Materials

All extra materials have been attributed to their respective assembly group, thus, the "Extra Materials" assembly group will be empty when viewing Athena results

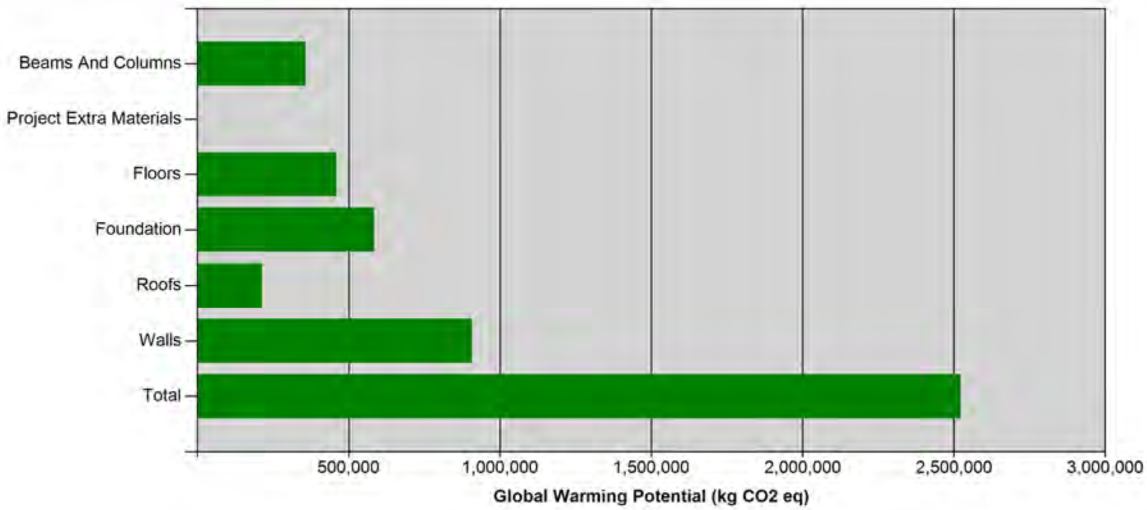
Individual Assembly Embodied Carbon Results

The table below presents a direct comparison of each conventional and MT assembly used to support the WBLCA. The embodied carbon impact of each individual assembly is presented on a per-square-foot basis in units of carbon dioxide equivalents.

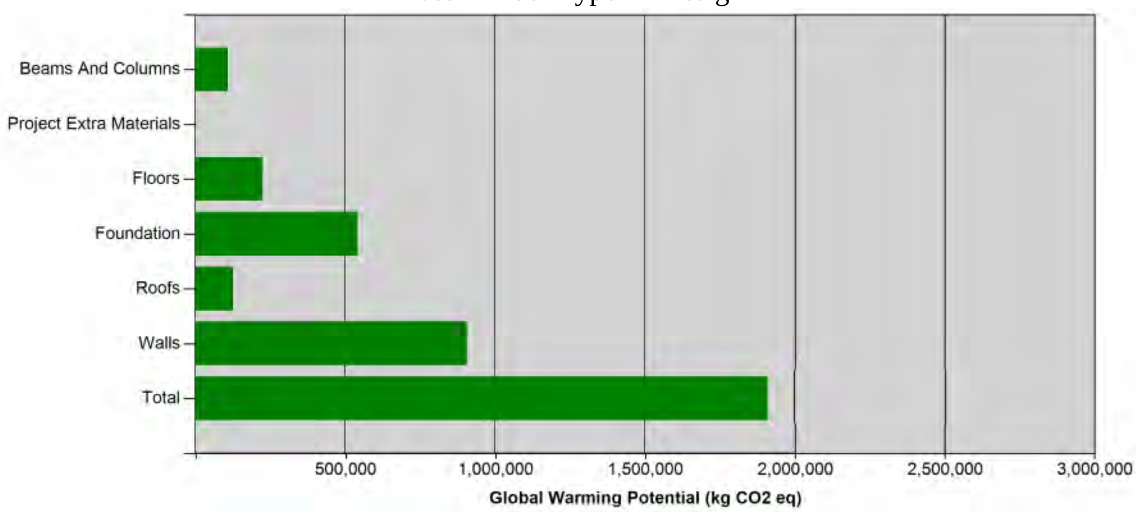
	Conventional Design (kg CO2 eq. per square foot)		Mass Timber Design (kg CO2 eq. per square foot)	
	Stages A - C	**Stages A - D**	**Stages A - C**	**Stages A - D**
Wall Assemblies				
Corridor to Classroom Wall	10.5	9.42	7.25	3.49
Classroom to Classroom Wall	7.24	6.15	7.25	3.49
Music/Dance Room Wall	7.69	6.60	8.06	4.30
2-Hour Fire-Rated Wall	7.67	6.58	8.53	1.29
Floor Assemblies				
Typical Floor	12.9	12.9	5.1	1.3
Cafeteria Floor	14.1	14.1	7.15	-2.95
Music Room Floor	19.1	19.1	7.15	-2.95
Dance Room Floor	18.6	18.2	5.65	-2.24
Roof Assemblies				
Typical Roof	22.3	22.3	8.59	4.81
Exterior Wall Assemblies				
Exterior Wall	12.6	11.1	5.56	-0.73

Whole Building Embodied Carbon Results (LCA Stages A-C Only)

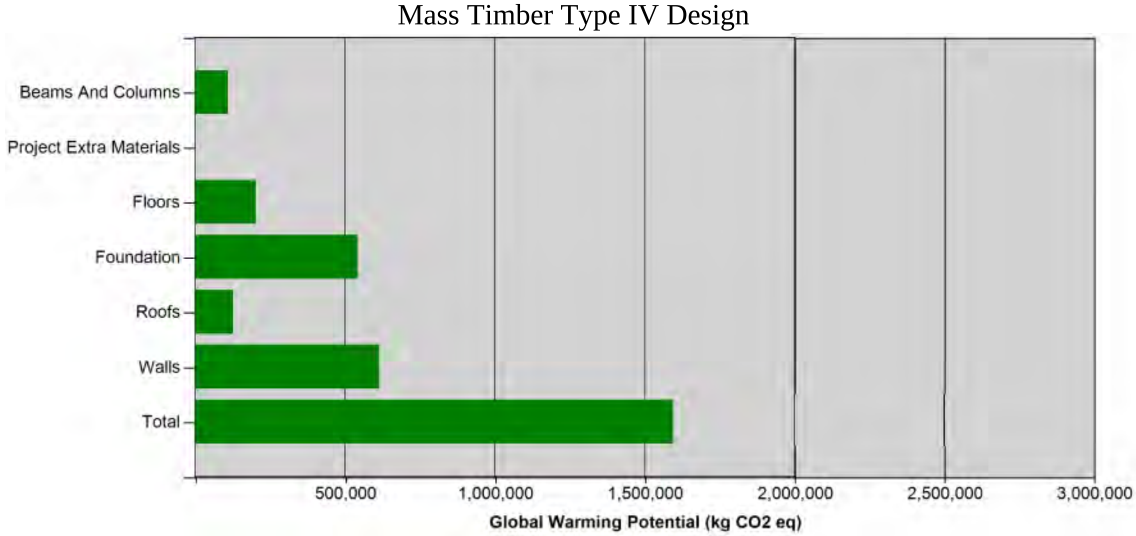
Conventional Design



Mass Timber Type III Design



Mass Timber Type IV Design



Conventional Design

Assembly Group	Unit	Total
Beams And Columns	kg CO2 eq	3.58E+05
Floors	kg CO2 eq	4.60E+05
Foundation	kg CO2 eq	5.85E+05
Project Extra Materials	kg CO2 eq	0.00E+00
Roofs	kg CO2 eq	2.13E+05
Walls	kg CO2 eq	9.07E+05
Total	**kg CO2 eq**	**2.52E+06**

Mass Timber Type III Design

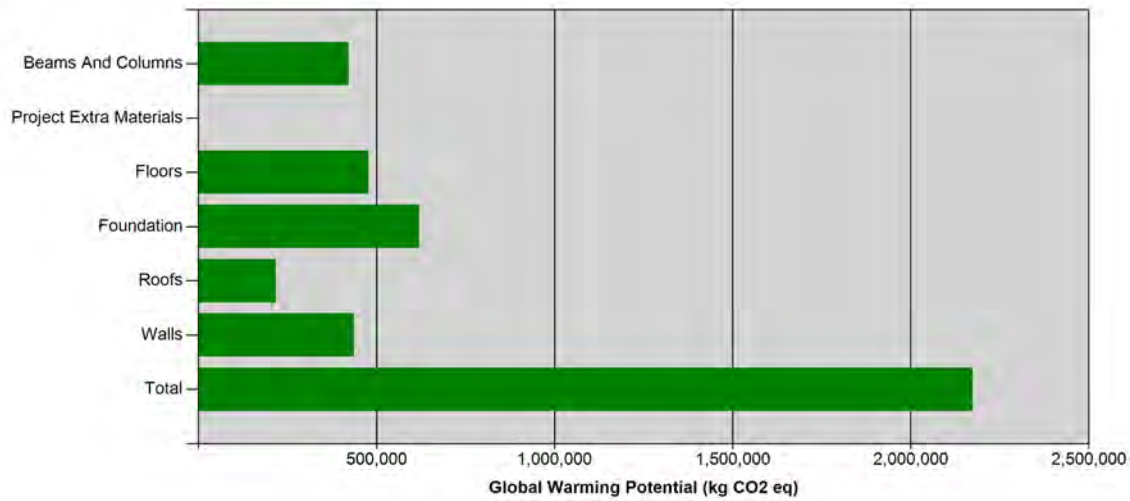
Assembly Group	Unit	Total
Beams And Columns	kg CO2 eq	1.10E+05
Floors	kg CO2 eq	2.25E+05
Foundation	kg CO2 eq	5.42E+05
Project Extra Materials	kg CO2 eq	0.00E+00
Roofs	kg CO2 eq	1.26E+05
Walls	kg CO2 eq	9.07E+05
Total	**kg CO2 eq**	**1.91E+06**

Mass Timber Type IV Design

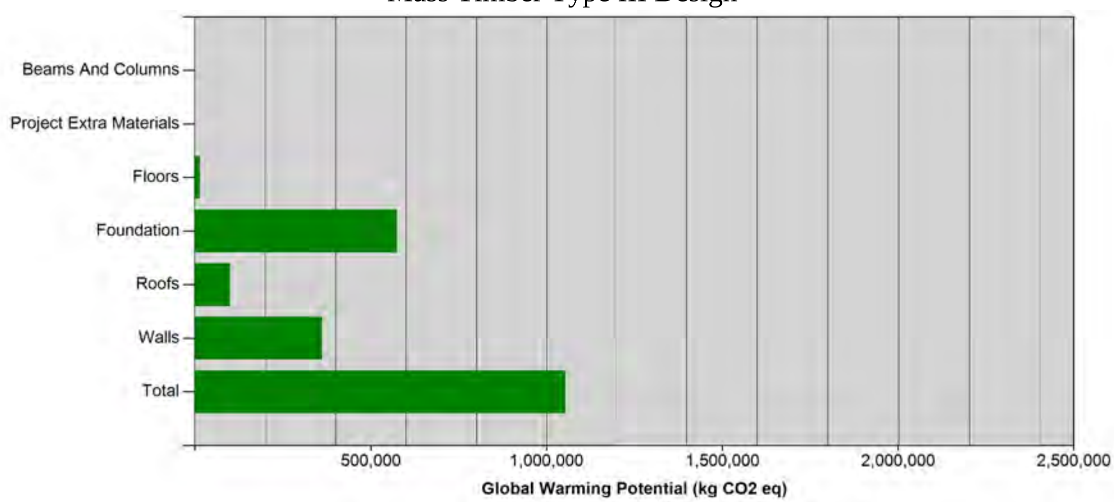
Assembly Group	Unit	Total
Beams And Columns	kg CO2 eq	1.10E+05
Floors	kg CO2 eq	2.02E+05
Foundation	kg CO2 eq	5.42E+05
Project Extra Materials	kg CO2 eq	0.00E+00
Roofs	kg CO2 eq	1.26E+05
Walls	kg CO2 eq	6.14E+05
Total	**kg CO2 eq**	**1.59E+06**

Whole Building Embodied Carbon Results (LCA Stages A-D)

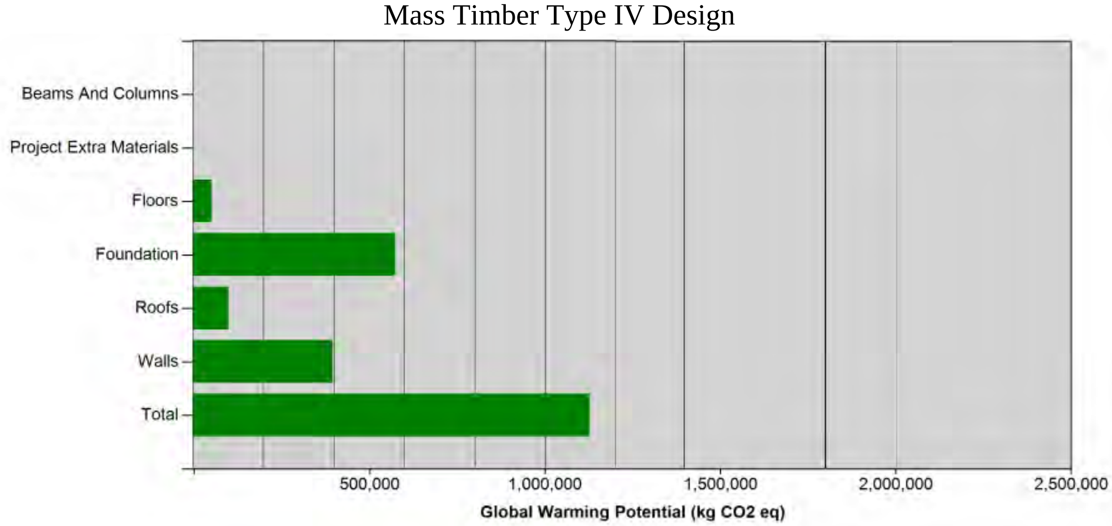
Conventional Design



Mass Timber Type III Design



Mass Timber Type IV Design



Conventional Design

Assembly Group	Unit	Total
Beams And Columns	kg CO2 eq	4.22E+05
Floors	kg CO2 eq	4.77E+05
Foundation	kg CO2 eq	6.20E+05
Project Extra Materials	kg CO2 eq	0.00E+00
Roofs	kg CO2 eq	2.17E+05
Walls	kg CO2 eq	4.37E+05
Total	**kg CO2 eq**	**2.17E+06**

Mass Timber Type III Design

Assembly Group	Unit	Total
Beams And Columns	kg CO2 eq	8.21E+02
Floors	kg CO2 eq	1.50E+04
Foundation	kg CO2 eq	5.74E+05
Project Extra Materials	kg CO2 eq	0.00E+00
Roofs	kg CO2 eq	1.01E+05
Walls	kg CO2 eq	3.62E+05
Total	**kg CO2 eq**	**1.05E+06**

Mass Timber Type IV Design

Assembly Group	Unit	Total
Beams And Columns	kg CO2 eq	8.21E+02
Floors	kg CO2 eq	5.31E+04
Foundation	kg CO2 eq	5.74E+05
Project Extra Materials	kg CO2 eq	0.00E+00
Roofs	kg CO2 eq	1.01E+05
Walls	kg CO2 eq	3.96E+05
Total	**kg CO2 eq**	**1.12E+06**

Discussion

Both the Type III and Type IV MT test case designs yielded significant embodied carbon savings (measured as Global Warming Potential) versus the conventional reinforced concrete design.

In the WBLCAs that excluded Stage D, the Type III MT test case design yielded an embodied carbon savings of 24.2% versus the conventional design, while the Type IV MT test case design yielded an embodied carbon savings of 37.0%.

In the WBLCAs that included Stage D, the Type III MT test case design yielded an embodied carbon savings of 51.6% versus the conventional design, while the Type IV MT test case design yielded an embodied carbon savings of 48.4%.

The increased savings indicated by the WBLCAs that included Stage D were expected, as they included some permanent carbon sequestration in MT materials that are either reused/recycled or landfilled in anaerobic conditions (see *Mass Timber Carbon Sequestration* section above). This result also points to the importance of designing MT buildings for easy disassembly and carefully managing the disassembled materials in order to maximize their embodied carbon savings potential.

In all cases, the most significant source of embodied carbon savings was the MT columns and beams. This was expected, as columns and beams represented the largest volume of MT material in the test cases. In the WBLCAs that excluded Stage D, the next largest source of savings was the MT walls. This explains why the Type IV MT test case, which included MT interior and exterior walls, yielded more embodied carbon savings than the Type III MT test case, which included MT interior walls only.

In the WBLCAs that included Stage D, the next largest source of savings after the MT columns and beams was the MT roofs. This is because Athena IE assumed a nearly 100% recycling rate for the steel studs in the interior and exterior walls of the conventional and Type III test cases, and the interior walls of the Type IV test case. Due to this assumption, the Type IV test case, in which the exterior wall steel studs were replaced with MT, yielded less embodied carbons savings overall than the Type III test case.

These findings of embodied carbon savings of up to 50% for MT construction versus reinforced concrete construction, using Athena IE’s highly conservative estimates of MT reuse/recycling rates, are generally consistent with similar studies of mid-sized commercial and residential buildings in the U.S.

APPENDIX A: TEST CASE STRUCTURAL CALCULATIONS

Section explanation: This sheet repeats a simple design process across different CLT floor design cases throughout the Q095 test model. Cells are shaded green if they are manually selected inputs for the particular design case. The design follows NDS 2018 code as a reference standard of NYCBC 2022 edition, an allowable stress design method with many material-specific factors (that do not differ between design cases here) and procsriptive considerations of the expected long-term deflection behavior of CLT members.

CLT Design case	Use	Design span [ft]	Trial CLT (Structurlam)	Grade [Vlook]	Self-weight [Vlook] [psf]	Temp. factor F	LL	TDL	LL+DL [psf]	simple span Mmax=wL^2/8 [lbs*ft/ft]
1	Classroom	9	87V	V2.1	7.5	<100	40	37.5	77.5	784.69
		FbSeff,0 (lbs*ft/ft strip)	Eieff,0 (*e6, psi/ft)	Gaeff,0 (*e6 plf)	Mallow (lbs*ft/ft strip)	Vallowq (plf)			C_D =	1
	Prefactored section prop.	1444	55.8	0.5	1443.7	1271.3				
	Factored section prop.	1444	55.8	0.5	1443.7	1271.3				
		simple span delta_max	delta_allow=L/240 [in.]	Fixity	K_S	EI_app [*e6, psi/ft]	NDS 10.4.1 Deflection	NDS 3.5.2 LT Deflection	LT Defl. Allowable	Both Defl modes OK?
		0.205	0.45	Pinned	11.5	50.269	0.228	0.304	0.54	OK
									excess Mn capacity:	45.66

CLT Design case	Use	Design span [ft]	Trial CLT (Structurlam)	Grade [Vlook]	Self-weight [Vlook] [psf]	Temp. factor F	LL	TDL	LL+DL [psf]	simple span Mmax=wL^2/8 [lbs*ft/ft]
2	Office	9	87V	V2.1	7.5	<100	50	37.5	87.5	885.94
		FbSeff,0 (lbs*ft/ft strip)	Eieff,0 (*e6, psi/ft)	Gaeff,0 (*e6 plf)	Mallow (lbs*ft/ft strip)	Vallowq (plf)			C_D =	1
	Prefactored section prop.	1444	55.8	0.5	1443.7	1271.3				
	Factored section prop.	1444	55.8	0.5	1443.7	1271.3				
		simple span delta_max	delta_allow=L/240 [in.]	Fixity	K_S	EI_app [*e6, psi/ft]	NDS 10.4.1 Deflection	NDS 3.5.2 LT Deflection	LT Defl. Allowable	Both Defl modes OK?
		0.231	0.45	Pinned	11.5	50.269	0.257	0.331	0.54	OK
									excess Mn capacity:	38.65

CLT Design case	Use	Design span [ft]	Trial CLT (Structurlam)	Grade [Vlook]	Self-weight [Vlook] [psf]	Temp. factor F	LL	TDL	LL+DL [psf]	simple span Mmax=wL^2/8 [lbs*ft/ft]
3	General storage	9	105V	V2.1M1.1	9	<100	125	29	154	1559.25
		FbSeff,0 (lbs*ft/ft strip)	Eieff,0 (*e6, psi/ft)	Gaeff,0 (*e6 plf)	Mallow (lbs*ft/ft strip)	Vallowq (plf)			C_D =	1
	Prefactored section prop.	2042	95.4	0.5	2042.4	1607.6				
	Factored section prop.	2042	95.4	0.5	2042.4	1607.6				
		simple span delta_max	delta_allow=L/240 [in.]	Fixity	K_S	EI_app [*e6, psi/ft]	NDS 10.4.1 Deflection	NDS 3.5.2 LT Deflection	LT Defl. Allowable	Both Defl modes OK?
		0.238	0.45	Pinned	11.5	80.295	0.283	0.283	0.54	OK
									excess Mn capacity:	23.64

CLT Design case	Use	Design span [ft]	Trial CLT (Structurlam)	Grade [Vlook]	Self-weight [Vlook] [psf]	Temp. factor F	LL	TDL	LL+DL [psf]	simple span Mmax=wL^2/8 [lbs*ft/ft]
4	Toilet	9	87V	V2.1	7.5	<100	60	35.5	95.5	966.94
		FbSeff,0 (lbs*ft/ft strip)	Eieff,0 (*e6, psi/ft)	Gaeff,0 (*e6 plf)	Mallow (lbs*ft/ft strip)	Vallowq (plf)			C_D =	1
	Prefactored section prop.	1444	55.8	0.5	1443.7	1271.3				
	Factored section prop.	1444	55.8	0.5	1443.7	1271.3				
		simple span delta_max	delta_allow=L/240 [in.]	Fixity	K_S	EI_app [*e6, psi/ft]	NDS 10.4.1 Deflection	NDS 3.5.2 LT Deflection	LT Defl. Allowable	Both Defl modes OK?
		0.253	0.45	Pinned	11.5	50.269	0.280	0.347	0.54	OK
									excess Mn capacity:	33.04

CLT Design case	Use	Design span [ft]	Trial CLT (Structurlam)	Grade [Vlook]	Self-weight [Vlook] [psf]	Temp. factor F	LL	TDL	LL+DL [psf]	simple span Mmax=wL^2/8 [lbs*ft/ft]
5	Corridor (above 1st fl)	9	87V	V2.1	7.5	<100	75	37.5	112.5	1139.06
		FbSeff,0 (lbs*ft/ft strip)	Eieff,0 (*e6, psi/ft)	Gaeff,0 (*e6 plf)	Mallow (lbs*ft/ft strip)	Vallowq (plf)			C_D =	1
	Prefactored section prop.	1444	55.8	0.5	1443.7	1271.3				
	Factored section prop.	1444	55.8	0.5	1443.7	1271.3				
		simple span delta_max	delta_allow=L/240 [in.]	Fixity	K_S	EI_app [*e6, psi/ft]	NDS 10.4.1 Deflection	NDS 3.5.2 LT Deflection	LT Defl. Allowable	Both Defl modes OK?
		0.298	0.45	Pinned	11.5	50.269	0.330	0.397	0.54	OK
									excess Mn capacity:	21.12

CLT Design case	Use	Design span [ft]	Trial CLT (Structurlam)	Grade [Vlook]	Self-weight [Vlook] [psf]	Temp. factor F	LL	TDL	LL+DL [psf]	simple span Mmax=wL^2/8 [lbs*ft/ft]
6	Corridor (1st fl)	9	87V	V2.1	7.5	<100	100	37.5	137.5	1392.19
		FbSeff,0 (lbs*ft/ft strip)	Eieff,0 (*e6, psi/ft)	Gaeff,0 (*e6 plf)	Mallow (lbs*ft/ft strip)	Vallowq (plf)			C_D =	1
	Prefactored section prop.	1444	55.8	0.5	1443.7	1271.3				
	Factored section prop.	1444	55.8	0.5	1443.7	1271.3				
		simple span delta_max	delta_allow=L/240 [in.]	Fixity	K_S	EI_app [*e6, psi/ft]	NDS 10.4.1 Deflection	NDS 3.5.2 LT Deflection	LT Defl. Allowable	Both Defl modes OK?
		0.364	0.45	Pinned	11.5	50.269	0.404	0.463	0.54	OK
									excess Mn capacity:	3.59

CLT Design case	Use	Design span [ft]	Trial CLT (Structurlam)	Grade [Vlook]	Self-weight [Vlook] [psf]	Temp. factor F	LL	TDL	LL+DL [psf]	simple span Mmax=wL^2/8 [lbs*ft/ft]
7	M/E Equipment Space	9	87V	V2.1	7.5	<100	75	37.5	112.5	1139.06
		FbSeff,0 (lbs*ft/ft strip)	Eieff,0 (*e6, psi/ft)	Gaeff,0 (*e6 plf)	Mallow (lbs*ft/ft strip)	Vallowq (plf)			C_D =	1
	Prefactored section prop.	1444	55.8	0.5	1443.7	1271.3				
	Factored section prop.	1444	55.8	0.5	1443.7	1271.3				
		simple span delta_max	delta_allow=L/240 [in.]	Fixity	K_S	EI_app [*e6, psi/ft]	NDS 10.4.1 Deflection	NDS 3.5.2 LT Deflection	LT Defl. Allowable	Both Defl modes OK?
		0.298	0.45	Pinned	11.5	50.269	0.330	0.397	0.54	OK
									excess Mn capacity:	21.12

CLT Design case	Use	Design span [ft]	Trial CLT (Structurlam)	Grade [Vlook]	Self-weight [Vlook] [psf]	Temp. factor F	LL	TDL	LL+DL [psf]	simple span Mmax=wL^2/8 [lbs*ft/ft]
8	Boiler Room	9	105V	V2.1M1.1	9	<100	150	39	189	1913.63
		FbSeff,0 (lbs*ft/ft strip)	Eieff,0 (*e6, psi/ft)	Gaeff,0 (*e6 plf)	Mallow (lbs*ft/ft strip)	Vallowq (plf)			C_D =	1
	Prefactored section prop.	2042	95.4	0.5	2042.4	1607.6				
	Factored section prop.	2042	95.4	0.5	2042.4	1607.6				
		simple span delta_max	delta_allow=L/240 [in.]	Fixity	K_S	EI_app [*e6, psi/ft]	NDS 10.4.1 Deflection	NDS 3.5.2 LT Deflection	LT Defl. Allowable	Both Defl modes OK?
		0.292	0.45	Pinned	11.5	80.295	0.347	0.353	0.54	OK
									excess Mn capacity:	6.29

CLT Design case	Use	Design span [ft]	Trial CLT (Structurlam)	Grade [Vlook]	Self-weight [Vlook] [psf]	Temp. factor F	LL	TDL	LL+DL [psf]	simple span Mmax=wL^2/8 [lbs*ft/ft]
8	Computer storage	9	105V	V2.1M1.1	9	<100	150	39	189	1913.63
		FbSeff,0 (lbs*ft/ft strip)	Eieff,0 (*e6, psi/ft)	Gaeff,0 (*e6 plf)	Mallow (lbs*ft/ft strip)	Vallowq (plf)			C_D =	1
	Prefactored section prop.	2042	95.4	0.5	2042.4	1607.6				
	Factored section prop.	2042	95.4	0.5	2042.4	1607.6				
		simple span delta_max	delta_allow=L/240 [in.]	Fixity	K_S	EI_app [*e6, psi/ft]	NDS 10.4.1 Deflection	NDS 3.5.2 LT Deflection	LT Defl. Allowable	Both Defl modes OK?
		0.292	0.45	Pinned	11.5	80.295	0.347	0.353	0.54	OK
									excess Mn capacity:	6.29

CLT Design case	Use	Design span [ft]	Trial CLT (Structurlam)	Grade [Vlook]	Self-weight [Vlook] [psf]	Temp. factor F	LL	TDL	LL+DL [psf]	simple span Mmax=wL^2/8 [lbs*ft/ft]
9	Kitchen	9	105V	V2.1M1.1	9	<100	150	9	159	1609.88
		FbSeff,0 (lbs*ft/ft strip)	Eieff,0 (*e6, psi/ft)	Gaeff,0 (*e6 plf)	Mallow (lbs*ft/ft strip)	Vallowq (plf)			C_D =	1
	Prefactored section prop.	2042	95.4	0.5	2042.4	1607.6				
	Factored section prop.	2042	95.4	0.5	2042.4	1607.6				
		simple span delta_max	delta_allow=L/240 [in.]	Fixity	K_S	EI_app [*e6, psi/ft]	NDS 10.4.1 Deflection	NDS 3.5.2 LT Deflection	LT Defl. Allowable	Both Defl modes OK?
		0.246	0.45	Pinned	11.5	80.295	0.292	0.260	0.54	OK
									excess Mn capacity:	21.16

CLT Design case	Use	Design span [ft]	Trial CLT (Structurlam)	Grade [Vlook]	Self-weight [Vlook] [psf]	Temp. factor F	LL	TDL	Roof: Qa/C_D [psf]	simple span Mmax=wL^2/8 [lbs*ft/ft]
10	Green roof	9	87V	V2.1	7.5	<100	0	57.5	80	810.00

		FbSeff,0 (lbs*ft/ft strip)	Eieff,0 (*e6, psi/ft)	Gaeff,0 (*e6 plf)	Mallow (lbs*ft/ft strip)	Vallowq (plf)			C_D =	1.0
	Prefactored section prop.	1444	55.8	0.5	1443.7	1271.3				
	Factored section prop.	1444	55.8	0.5	1443.7	1271.3				
		simple span delta_max	delta_allow=L/240 [in.]	Fixity	K_S	EI_app [*e6, psi/ft]	NDS 10.4.1 Deflection	NDS 3.5.2 LT Deflection	LT Defl. Allowable	Both Defl modes OK?
		0.212	0.45	Pinned	11.5	50.269	0.235	0.304	0.54	OK
									excess Mn capacity:	43.91

CLT Design case	Use	Design span [ft]	Trial CLT (Structurlam)	Grade [Vlook]	Self-weight [Vlook] [psf]	Temp. factor F	LL	TDL	Roof: Qa/C_D [psf]	simple span Mmax=wL^2/8 [lbs*ft/ft]
11	Green roof (corner)	9	87V	V2.1	7.5	<100	0	57.5	80	810.00
		FbSeff,0 (lbs*ft/ft strip)	Eieff,0 (*e6, psi/ft)	Gaeff,0 (*e6 plf)	Mallow (lbs*ft/ft strip)	Vallowq (plf)			C_D =	1.0
	Prefactored section prop.	1444	55.8	0.5	1443.7	1271.3				
	Factored section prop.	1444	55.8	0.5	1443.7	1271.3				
		simple span delta_max	delta_allow=L/240 [in.]	Fixity	K_S	EI_app [*e6, psi/ft]	NDS 10.4.1 Deflection	NDS 3.5.2 LT Deflection	LT Defl. Allowable	Both Defl modes OK?
		0.212	0.45	Pinned	11.5	50.269	0.235	0.304	0.54	OK
									excess Mn capacity:	43.91

CLT Design case	Use	Design span [ft]	Trial CLT (Structurlam)	Grade [Vlook]	Self-weight [Vlook] [psf]	Temp. factor F	LL	TDL	Roof: Qa/C_D [psf]	simple span Mmax=wL^2/8 [lbs*ft/ft]
12	Roof	9	105V	V2.1M1.1	9	<100	0	119	140	1417.50
		FbSeff,0 (lbs*ft/ft strip)	Eieff,0 (*e6, psi/ft)	Gaeff,0 (*e6 plf)	Mallow (lbs*ft/ft strip)	Vallowq (plf)			C_D =	1.0
	Prefactored section prop.	2042	95.4	0.5	2042.4	1607.6				
	Factored section prop.	2042	95.4	0.5	2042.4	1607.6				
		simple span delta_max	delta_allow=L/240 [in.]	Fixity	K_S	EI_app [*e6, psi/ft]	NDS 10.4.1 Deflection	NDS 3.5.2 LT Deflection	LT Defl. Allowable	Both Defl modes OK?
		0.217	0.45	Pinned	11.5	80.295	0.257	0.368	0.54	OK
									excess Mn capacity:	30.58

CLT Design case	Use	Design span [ft]	Trial CLT (Structurlam)	Grade [Vlook]	Self-weight [Vlook] [psf]	Temp. factor F	LL	TDL	Roof: Qa/C_D [psf]	simple span Mmax=wL^2/8 [lbs*ft/ft]
13	Roof (corner)	9	105V	V2.1M1.1	9	<100	0	119	140	1417.50
		FbSeff,0 (lbs*ft/ft strip)	Eieff,0 (*e6, psi/ft)	Gaeff,0 (*e6 plf)	Mallow (lbs*ft/ft strip)	Vallowq (plf)			C_D =	1.0
	Prefactored section prop.	2042	95.4	0.5	2042.4	1607.6				
	Factored section prop.	2042	95.4	0.5	2042.4	1607.6				
		simple span delta_max	delta_allow=L/240 [in.]	Fixity	K_S	EI_app [*e6, psi/ft]	NDS 10.4.1 Deflection	NDS 3.5.2 LT Deflection	LT Defl. Allowable	Both Defl modes OK?
		0.217	0.45	Pinned	11.5	80.295	0.257	0.368	0.54	OK
									excess Mn capacity:	30.58

CLT Design case	Use	Design span [ft]	Trial CLT (Structurlam)	Grade [Vlook]	Self-weight [Vlook] [psf]	Temp. factor F	LL	TDL	LL+DL [psf]	simple span Mmax=wL^2/8 [lbs*ft/ft]
14	Exercise room	9	105V	V2.1M1.1	9	<100	100	69	169	1711.13
		FbSeff,0 (lbs*ft/ft strip)	Eieff,0 (*e6, psi/ft)	Gaeff,0 (*e6 plf)	Mallow (lbs*ft/ft strip)	Vallowq (plf)			C_D =	1
	Prefactored section prop.	2042	95.4	0.5	2042.4	1607.6				
	Factored section prop.	2042	95.4	0.5	2042.4	1607.6				
		simple span delta_max	delta_allow=L/240 [in.]	Fixity	K_S	EI_app [*e6, psi/ft]	NDS 10.4.1 Deflection	NDS 3.5.2 LT Deflection	LT Defl. Allowable	Both Defl modes OK?
		0.262	0.45	Pinned	11.5	80.295	0.311	0.368	0.54	OK
									excess Mn capacity:	16.20

CLT Design case	Use	Design span [ft]	Trial CLT (Structurlam)	Grade [Vlook]	Self-weight [Vlook] [psf]	Temp. factor F	LL	TDL	LL+DL [psf]	simple span Mmax=wL^2/8 [lbs*ft/ft]
15	Music room	9	105V	V2.1M1.1	9	<100	100	69	169	1711.13
		FbSeff,0 (lbs*ft/ft strip)	Eieff,0 (*e6, psi/ft)	Gaeff,0 (*e6 plf)	Mallow (lbs*ft/ft strip)	Vallowq (plf)			C_D =	1
	Prefactored section prop.	2042	95.4	0.5	2042.4	1607.6				
	Factored section prop.	2042	95.4	0.5	2042.4	1607.6				

		simple span delta_max	delta_allow=L/240 [in.]	Fixity	K_S	EI_app [*e6, psi/ft]	NDS 10.4.1 Deflection	NDS 3.5.2 LT Deflection	LT Defl. Allowable	Both Defl modes OK?
		0.262	0.45	Pinned	11.5	80.295	0.311	0.368	0.54	OK
									excess Mn capacity:	16.20

Section explanation: This sheet repeats a simple design process across glulam beam design cases at the 1st floor of the Q095 test model. Cells are shaded green if they are manually selected inputs for the particular design case. The design follows NDS 2018 code as a reference standard of NYCBC 2022 edition, including the consideration of load duration factors and volume factors, but is otherwise a simple beam calculation repeated for differing spans and design loads. This sheet designs for beams in a Type IV building, where no fire rating is required for "heavy timber" members, but a 2-hr fire rating is required when adjacent to spaces serving as fire refuge.

2 HR FRR (cafeteria)

BEAM DESIGN #: 1, typical classroom beams (N-S)

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Classroom	24.000	8.083	70	1	24FV8DF	8.5 x 23.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (**2hr** FRR charred section)
565.833	49.100	44275.200	6790.000	10.000	0.876	1.000
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D	2hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]	2hrFRR Shear Resistance V'_s,fr/C_D			
140026.808	35669.000	84249.349	20966.138			
0hrFRR Moment Check	0hrFRR Shear Check	2hrFRR Moment Check	2hrFRR Shear Check			
OK	OK	OK	OK			

2 HR FRR (cafeteria)

BEAM DESIGN #: 2, N-S beams taking bathroom loads

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Toilet	24.000	8.083	88	1	24FV8DF	8.5 x 23.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (**2hr** FRR charred section)
711.333	49.100	54751.200	8536.000	10.000	0.876	1.000
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D	2hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]	2hrFRR Shear Resistance V'_s,fr/C_D			
140026.808	35669.000	84249.349	20966.138			
0hrFRR Moment Check	0hrFRR Shear Check	2hrFRR Moment Check	2hrFRR Shear Check			
OK	OK	OK	OK			

2 HR FRR (cafeteria)

BEAM DESIGN #: 3, N-S beams taking storage loads

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
General storage	24.000	8.083	145.000	1.000	24FV8DF	8.5 x 25.25
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (**2hr** FRR charred section)
1172.083	52.200	88148.400	14065.000	10.000	0.871	1.000
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D	2hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]	2hrFRR Shear Resistance V'_s,fr/C_D			
157301.988	37912.667	96997.399	22496.513			
0hrFRR Moment Check	0hrFRR Shear Check	2hrFRR Moment Check	2hrFRR Shear Check			
OK	OK	OK	OK			

2 HR FRR (cafeteria)

BEAM DESIGN #: 4, shorter corridor low beams with large tributary area

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Corridor (1st fl)	21.250	16.750	130.000	1.000	24FV8DF	10.25 x 26.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (**2hr** FRR charred section)
2177.500	66.600	126668.926	23135.938	10.000	0.860	0.985
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D	2hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]	2hrFRR Shear Resistance V'_s,fr/C_D			
210286.852	48442.000	199827.209	44049.294			
0hrFRR Moment Check	0hrFRR Shear Check	2hrFRR Moment Check	2hrFRR Shear Check			
OK	OK	OK	OK			

2 HR FRR (cafeteria)

BEAM DESIGN #: 4.2, longer corridor low beams with large tributary area

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Corridor (1st fl)	24.000	16.750	130.000	1.000	24FV8DF	10.25 x 26.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (**2hr** FRR charred section)
2177.500	66.600	161575.200	26130.000	10.000	0.850	0.973
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D	2hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]	2hrFRR Shear Resistance V'_s,fr/C_D			
207743.234	48442.000	197410.110	44049.294			
0hrFRR Moment Check	0hrFRR Shear Check	2hrFRR Moment Check	2hrFRR Shear Check			
OK	OK	OK	OK			

2 HR FRR (cafeteria)

BEAM DESIGN #: 5, corridor strap beams

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Corridor (1st fl)	8.750	8.083	130.000	1.000	24FV8DF	8.5 x 23.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (**2hr** FRR charred section)
1050.833	49.100	10526.706	4597.396	10.000	0.969	1.000
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D	2hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]	2hrFRR Shear Resistance V'_s,fr/C_D			
154892.899	35669.000	84249.349	20966.138			
0hrFRR Moment Check	0hrFRR Shear Check	2hrFRR Moment Check	2hrFRR Shear Check			
OK	OK	OK	OK			

BEAM DESIGN #: 5, corridor strap beams

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Corridor (1st fl)	8.750	8.083	130.000	1.000	24FV8DF	6.75 x 17.75

0 HR FRR

W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	
1050.833	29.100	10335.299	4597.396	10.000	1.000	
Design Moment Resistance M'a/C_D [lbs*ft]	**Design Shear Resistance V'_s/C_D**					
70880.000	21164.667					
0hrFRR Moment Check	**0hrFRR Shear Check**					
OK	OK					

2 HR FRR (cafeteria)

BEAM DESIGN #: 6, corridor loadbearing beam

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Corridor (1st fl)	12.500	8.083	130.000	1.000	24FV8DF	8.5 x 23.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (**2hr** FRR charred section)
1050.833	49.100	21483.073	6567.708	10.000	0.935	1.000
Design Moment Resistance M'a/C_D [lbs*ft]	**Design Shear Resistance V'_s/C_D**	**2hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]**	**2hrFRR Shear Resistance V'_s,fr/C_D**			
149465.621	35669.000	84249.349	20966.138			
0hrFRR Moment Check	**0hrFRR Shear Check**	**2hrFRR Moment Check**	**2hrFRR Shear Check**			
OK	OK	OK	OK			

0 HR FRR

BEAM DESIGN #: 6, corridor loadbearing beam

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Corridor (1st fl)	12.500	8.083	130.000	1.000	24FV8DF	6.75 x 17.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	
1050.833	29.100	21092.448	6567.708	10.000	0.985	
Design Moment Resistance M'a/C_D [lbs*ft]	**Design Shear Resistance V'_s/C_D**					
69838.023	21164.667					
0hrFRR Moment Check	**0hrFRR Shear Check**					
OK	OK					

2 HR FRR (cafeteria)

BEAM DESIGN #: 7, shorter spandrels

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Classroom	21.000	11.000	70.000	1.000	24FV8DF	8.5 x 23.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (**2hr** FRR charred section)
770.000	349.100	61690.388	8085.000	10.000	0.888	1.000
Design Moment Resistance M'a/C_D [lbs*ft]	**Design Shear Resistance V'_s/C_D**	**2hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]**	**2hrFRR Shear Resistance V'_s,fr/C_D**			
141909.145	35669.000	84249.349	20966.138			
0hrFRR Moment Check	**0hrFRR Shear Check**	**2hrFRR Moment Check**	**2hrFRR Shear Check**			
OK	OK	OK	OK			

2 HR FRR (cafeteria)

BEAM DESIGN #: 8, longest spandrels

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Classroom	24.000	11.000	70.000	1.000	24FV8DF	8.5 x 23.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (**2hr** FRR charred section)
770.000	349.100	80575.200	9240.000	10.000	0.876	1.000
Design Moment Resistance M'a/C_D [lbs*ft]	**Design Shear Resistance V'_s/C_D**	**2hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]**	**2hrFRR Shear Resistance V'_s,fr/C_D**			
140026.808	35669.000	84249.349	20966.138			
0hrFRR Moment Check	**0hrFRR Shear Check**	**2hrFRR Moment Check**	**2hrFRR Shear Check**			
OK	OK	OK	OK			

0 HR FRR

BEAM DESIGN #: 8, longest spandrels

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Classroom	24.000	11.000	70.000	1.000	24FV8DF	6.75 x 20.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	
770.000	334.000	79488.000	9240.000	10.000	0.909	
Design Moment Resistance M'a/C_D [lbs*ft]	**Design Shear Resistance V'_s/C_D**					
88042.073	24751.000					
0hrFRR Moment Check	**0hrFRR Shear Check**					
OK	OK					

Section explanation: This sheet repeats a simple design process across glulam beam design cases at the 1st floor of the Q095 test model. This sheet designs for beams in a Type III building, where a 1-hr fire rating is required for structural members, and a 2-hr fire rating is required when adjacent to spaces serving as fire refuge.

2 HR FRR (cafeteria)

BEAM DESIGN #: 1, typical classroom beams (N-S)

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Classroom	24.000	8.083	70.000	1.000	24FV8DF	8.5 x 23.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (**2hr** FRR charred section)
565.833	49.100	44275.200	6790.000	10.000	0.876	1.000
Design Moment Resistance M'a/C_D [lbs*ft]	**Design Shear Resistance V'_s/C_D**	**2hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]**	**2hrFRR Shear Resistance V'_s,fr/C_D**			
140026.808	35669.000	84249.349	52253.804			
0hrFRR Moment Check	**0hrFRR Shear Check**	**2hrFRR Moment Check**	**2hrFRR Shear Check**			
OK	OK	OK	OK			

2 HR FRR (cafeteria)

BEAM DESIGN #: 2, N-S beams taking bathroom loads

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	Trial GL layup	Trial GL dimensions (dropdown)
Toilet	24.000	8.083	88.000	1.000	24FV8DF	8.5 x 23.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (**2hr** FRR charred section)
711.333	49.100	54751.200	8536.000	10.000	0.876	1.000
Design Moment Resistance M'a/C_D [lbs*ft]	**Design Shear Resistance V'_s/C_D**	**2hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]**	**2hrFRR Shear Resistance V'_s,fr/C_D**			
140026.808	35669.000	84249.349	52253.804			
0hrFRR Moment Check	**0hrFRR Shear Check**	**2hrFRR Moment Check**	**2hrFRR Shear Check**			
OK	OK	OK	OK			

2 HR FRR (cafeteria)

BEAM DESIGN #: 3, N-S beams taking storage loads

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
General storage	24.000	8.083	145.000	1.000	24FV8DF	8.5 x 25.25
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (**2hr** FRR charred section)
1172.083	52.200	88148.400	14065.000	10.000	0.871	1.000
Design Moment Resistance M'a/C_D [lbs*ft]	**Design Shear Resistance V'_s/C_D**	**2hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]**	**2hrFRR Shear Resistance V'_s,fr/C_D**			
157301.988	37912.667	96997.399	55824.679			
0hrFRR Moment Check	**0hrFRR Shear Check**	**2hrFRR Moment Check**	**2hrFRR Shear Check**			
OK	OK	OK	OK			

2 HR FRR (cafeteria)

BEAM DESIGN #: 4, shorter corridor low beams with large tributary area

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Corridor (1st fl)	21.250	16.750	130.000	1.000	24FV8DF	10.25 x 26.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (**2hr** FRR charred section)
2177.500	66.600	126668.926	23135.938	10.000	0.860	0.985
Design Moment Resistance M'a/C_D [lbs*ft]	**Design Shear Resistance V'_s/C_D**	**2hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]**	**2hrFRR Shear Resistance V'_s,fr/C_D**			
210286.852	48442.000	199827.209	80608.252			
0hrFRR Moment Check	**0hrFRR Shear Check**	**2hrFRR Moment Check**	**2hrFRR Shear Check**			
OK	OK	OK	OK			

2 HR FRR (cafeteria)

BEAM DESIGN #: 4.2, longer corridor low beams with large tributary area

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Corridor (1st fl)	24.000	16.750	130.000	1.000	24FV8DF	10.25 x 26.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (**2hr** FRR charred section)
2177.500	66.600	161575.200	26130.000	10.000	0.850	0.973
Design Moment Resistance M'a/C_D [lbs*ft]	**Design Shear Resistance V'_s/C_D**	**2hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]**	**2hrFRR Shear Resistance V'_s,fr/C_D**			
207743.234	48442.000	197410.110	80608.252			
0hrFRR Moment Check	**0hrFRR Shear Check**	**2hrFRR Moment Check**	**2hrFRR Shear Check**			
OK	OK	OK	OK			

2 HR FRR (cafeteria)

BEAM DESIGN #: 5, corridor strap beams

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Corridor (1st fl)	8.750	8.083	130.000	1.000	24FV8DF	8.5 x 23.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (**2hr** FRR charred section)
1050.833	49.100	10526.706	4597.396	10.000	0.969	1.000
Design Moment Resistance M'a/C_D [lbs*ft]	**Design Shear Resistance V'_s/C_D**	**2hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]**	**2hrFRR Shear Resistance V'_s,fr/C_D**			
154892.899	35669.000	84249.349	52253.804			
0hrFRR Moment Check	**0hrFRR Shear Check**	**2hrFRR Moment Check**	**2hrFRR Shear Check**			
OK	OK	OK	OK			

BEAM DESIGN #: 5, corridor strap beams

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Corridor (1st fl)	8.750	8.083	130.000	1.000	24FV8DF	6.75 x 17.75

1 HR FR

W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (1hr FRR charred section)
1050.833	329.100	13206.393	4597.396	10.000	1.000	1.000
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D	1hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]	1hrFRR Shear Resistance V'_s,fr/C_D			
70880.000	21164.667	76129.948	24409.481			
0hrFRR Moment Check	0hrFRR Shear Check	1hrFRR Moment Check	1hrFRR Shear Check			
OK	OK	OK	OK			

2 HR FRR (cafeteria)

BEAM DESIGN #: 6, corridor loadbearing beam						
Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Corridor (1st fl)	12.500	8.083	130.000	1.000	24FV8DF	8.5 x 23.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (**2hr** FRR charred section)
1050.833	49.100	21483.073	6567.708	10.000	0.935	1.000
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D	2hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]	2hrFRR Shear Resistance V'_s,fr/C_D			
149465.621	35669.000	84249.349	52253.804			
0hrFRR Moment Check	0hrFRR Shear Check	2hrFRR Moment Check	2hrFRR Shear Check			
OK	OK	OK	OK			

1 HR FRR

BEAM DESIGN #: 6, corridor loadbearing beam						
Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Corridor (1st fl)	12.500	8.083	130.000	1.000	24FV8DF	6.75 x 17.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (1hr FRR charred section)
1050.833	329.100	26951.823	6567.708	10.000	0.985	1.000
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D	1hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]	1hrFRR Shear Resistance V'_s,fr/C_D			
69838.023	21164.667	76129.948	24409.481			
0hrFRR Moment Check	0hrFRR Shear Check	1hrFRR Moment Check	1hrFRR Shear Check			
OK	OK	OK	OK			

2 HR FRR (cafeteria)

BEAM DESIGN #: 7, shorter spandrels						
Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Classroom	21.000	11.000	70.000	1.000	24FV8DF	8.5 x 23.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (**2hr** FRR charred section)
770.000	349.100	61690.388	8085.000	10.000	0.888	1.000
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D	2hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]	2hrFRR Shear Resistance V'_s,fr/C_D			
141909.145	35669.000	84249.349	52253.804			
0hrFRR Moment Check	0hrFRR Shear Check	2hrFRR Moment Check	2hrFRR Shear Check			
OK	OK	OK	OK			

2 HR FRR (cafeteria)

BEAM DESIGN #: 8, longest spandrels						
Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Classroom	24.000	11.000	70.000	1.000	24FV8DF	8.5 x 23.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (**2hr** FRR charred section)
770.000	349.100	80575.200	9240.000	10.000	0.876	1.000
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D	2hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]	2hrFRR Shear Resistance V'_s,fr/C_D			
140026.808	35669.000	84249.349	52253.804			
0hrFRR Moment Check	0hrFRR Shear Check	2hrFRR Moment Check	2hrFRR Shear Check			
OK	OK	OK	OK			

1 HR FRR

BEAM DESIGN #: 8, longest spandrels						
Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Classroom	24.000	11.000	70.000	1.000	24FV8DF	6.75 x 25.25
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (1hr FRR charred section)
770.000	341.400	80020.800	9240.000	10.000	0.891	0.969
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D	1hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]	1hrFRR Shear Resistance V'_s,fr/C_D			
127838.783	30104.000	159427.351	35887.294			
0hrFRR Moment Check	0hrFRR Shear Check	1hrFRR Moment Check	1hrFRR Shear Check			
OK	OK	OK	OK			

Section explanation: This sheet repeats a simple design process across glulam beam design cases at the 2nd/3rd/4th floors of the Q095 test model. This sheet designs for beams in a Type IV building, where no fire rating is required for "heavy timber" members, but a 2-hr fire rating is required when adjacent to spaces serving as fire refuge.

0 HR FRR

BEAM DESIGN #: 1, typical classroom beams (N-S)

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Classroom	24.000	8.083	70	1	24FV8DF	6.75 x 17.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	
565.833	29.100	42835.200	6790.000	10.000	0.923	
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D					
65427.724	21164.667					
0hrFRR Moment Check	0hrFRR Shear Check					
OK	OK					

0 HR FRR

BEAM DESIGN #: 2, N-S beams taking bathroom loads

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	Trial GL layup	Trial GL dimensions (dropdown)
Toilet	24.000	8.083	88	1	24FV8DF	6.75 x 17.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	
711.333	29.100	53311.200	8536.000	10.000	0.923	
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D					
65427.724	21164.667					
0hrFRR Moment Check	0hrFRR Shear Check					
OK	OK					

0 HR FRR

BEAM DESIGN #: 3, N-S beams taking storage loads

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
General storage	24.000	8.083	145	1	24FV8DF	6.75 x 20.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	
1172.083	34.000	86838.000	14065.000	10.000	0.909	
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D					
88042.073	24751.000					
0hrFRR Moment Check	0hrFRR Shear Check					
OK	OK					

0 HR FRR

BEAM DESIGN #: 4, shorter corridor low beams with large tributary area

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Corridor (above 1st fl)	21.250	16.750	105	1	24FV8DF	6.75 x 26.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	
1758.750	43.900	101751.143	18686.719	10.000	0.897	
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D					
144389.851	31906.000					
0hrFRR Moment Check	0hrFRR Shear Check					
OK	OK					

0 HR FRR

BEAM DESIGN #: 4.2, longer corridor low beams with large tributary area

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Corridor (above 1st fl)	24.000	16.750	105	1	24FV8DF	6.75 x 26.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	
1758.750	43.900	129790.800	21105.000	10.000	0.886	
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D					
142643.320	31906.000					
0hrFRR Moment Check	0hrFRR Shear Check					
OK	OK					

0 HR FRR

BEAM DESIGN #: 5, corridor strap beams

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Corridor (above 1st fl)	8.750	8.083	105	1	24FV8DF	6.75 x 17.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	
848.750	29.100	8401.299	3713.281	10.000	1.000	
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D					
70880.000	21164.667					
0hrFRR Moment Check	0hrFRR Shear Check					
OK	OK					

BEAM DESIGN #: 6, corridor loadbearing beam

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Corridor (above 1st fl)	12.500	8.083	105	1	24FV8DF	6.75 x 17.75

0 HR FR

W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	
848.750	29.100	17145.508	5304.688	10.000	0.985	
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D					
69838.023	21164.667					
0hrFRR Moment Check	0hrFRR Shear Check					
OK	OK					

0 HR FRR

BEAM DESIGN #: 7, storage room N-S beam

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
General storage	11.500	10.000	145	1	24FV8DF	6.75 x 17.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	
1450.000	29.100	24451.372	8337.500	10.000	0.994	
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D					
70422.778	21164.667					
0hrFRR Moment Check	0hrFRR Shear Check					
OK	OK					

0 HR FRR

BEAM DESIGN #: 7.2, longer storage room N-S beam

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
General storage	15.500	10.000	145	1	24FV8DF	6.75 x 17.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	
1450.000	29.100	44419.222	11237.500	10.000	0.964	
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D					
68351.770	21164.667					
0hrFRR Moment Check	0hrFRR Shear Check					
OK	OK					

0 HR FRR

BEAM DESIGN #: 8, shorter spandrels

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
General storage	21.000	11.000	145	1	24FV8DF	6.75 x 23.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	
1595.000	339.000	106611.750	16747.500	10.000	0.909	
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D					
115324.302	28319.667					
0hrFRR Moment Check	0hrFRR Shear Check					
OK	OK					

0 HR FRR

BEAM DESIGN #: 9, longest spandrels

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Classroom	24.000	11.000	70.000	1.000	24FV8DF	6.75 x 23.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	
770.000	339.000	79848.000	9240.000	10.000	0.897	
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D					
113794.597	28319.667					
0hrFRR Moment Check	0hrFRR Shear Check					
OK	OK					

Section explanation: This sheet repeats a simple design process across glulam beam design cases at the 2nd/3rd/4th floors of the Q095 test model. This sheet designs for beams in a Type III building, where a 1-hr fire rating is required for structural members.

1 HR FRR

BEAM DESIGN #: 1, typical classroom beams (N-S)

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Classroom	24.000	8.083	70	1	24FV8DF	6.75 x 17.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (1hr FRR charred section)
565.833	29.100	42835.200	6790.000	10.000	0.923	1.000
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D	1hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]	1hrFRR Shear Resistance V'_s,fr/C_D			
65427.724	21164.667	76129.948	24409.481			
0hrFRR Moment Check	0hrFRR Shear Check	1hrFRR Moment Check	1hrFRR Shear Check			
OK	OK	OK	OK			

1 HR FRR

BEAM DESIGN #: 2, N-S beams taking bathroom loads

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	Trial GL layup	Trial GL dimensions (dropdown)
Toilet	24.000	8.083	88	1	24FV8DF	6.75 x 17.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (1hr FRR charred section)
711.333	29.100	53311.200	8536.000	10.000	0.923	1.000
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D	1hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]	1hrFRR Shear Resistance V'_s,fr/C_D			
65427.724	21164.667	76129.948	24409.481			
0hrFRR Moment Check	0hrFRR Shear Check	1hrFRR Moment Check	1hrFRR Shear Check			
OK	OK	OK	OK			

1 HR FRR

BEAM DESIGN #: 3, N-S beams taking storage loads

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
General storage	24.000	8.083	145	1	24FV8DF	6.75 x 20.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (1hr FRR charred section)
1172.083	34.000	86838.000	14065.000	10.000	0.909	0.990
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D	1hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]	1hrFRR Shear Resistance V'_s,fr/C_D			
88042.073	24751.000	106352.800	29000.606			
0hrFRR Moment Check	0hrFRR Shear Check	1hrFRR Moment Check	1hrFRR Shear Check			
OK	OK	OK	OK			

1 HR FRR

BEAM DESIGN #: 4, shorter corridor low beams with large tributary area

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Corridor (above 1st fl)	21.250	16.750	105	1	24FV8DF	6.75 x 26.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (1hr FRR charred section)
1758.750	43.900	101751.143	18686.719	10.000	0.897	0.975
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D	1hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]	1hrFRR Shear Resistance V'_s,fr/C_D			
144389.851	31906.000	181556.038	38182.856			
0hrFRR Moment Check	0hrFRR Shear Check	1hrFRR Moment Check	1hrFRR Shear Check			
OK	OK	OK	OK			

1 HR FRR

BEAM DESIGN #: 4.2, longer corridor low beams with large tributary area

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Corridor (above 1st fl)	24.000	16.750	105	1	24FV8DF	6.75 x 26.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (1hr FRR charred section)
1758.750	43.900	129790.800	21105.000	10.000	0.886	0.963
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D	1hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]	1hrFRR Shear Resistance V'_s,fr/C_D			
142643.320	31906.000	179359.946	38182.856			
0hrFRR Moment Check	0hrFRR Shear Check	1hrFRR Moment Check	1hrFRR Shear Check			
OK	OK	OK	OK			

BEAM DESIGN #: 5, corridor strap beams

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions

1 HR FRR

Corridor (above 1st fl)	8.750	8.083	105	1	24FV8DF	6.75 x 17.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (1hr FRR charred section)
848.750	29.100	8401.299	3713.281	10.000	1.000	1.000
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D	1hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]	1hrFRR Shear Resistance V'_s,fr/C_D			
70880.000	21164.667	76129.948	8876.175			
0hrFRR Moment Check	0hrFRR Shear Check	1hrFRR Moment Check	1hrFRR Shear Check			
OK	OK	OK	OK			

1 HR FRR

BEAM DESIGN #: 6, corridor loadbearing beam

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Corridor (above 1st fl)	12.500	8.083	105	1	24FV8DF	6.75 x 17.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (1hr FRR charred section)
848.750	29.100	17145.508	5304.688	10.000	0.985	1.000
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D	1hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]	1hrFRR Shear Resistance V'_s,fr/C_D			
69838.023	21164.667	76129.948	24409.481			
0hrFRR Moment Check	0hrFRR Shear Check	1hrFRR Moment Check	1hrFRR Shear Check			
OK	OK	OK	OK			

1 HR FRR

BEAM DESIGN #: 7, storage room N-S beam

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
General storage	11.500	10.000	145	1	24FV8DF	6.75 x 17.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (1hr FRR charred section)
1450.000	29.100	24451.372	8337.500	10.000	0.994	1.000
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D	1hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]	1hrFRR Shear Resistance V'_s,fr/C_D			
70422.778	21164.667	76129.948	24409.481			
0hrFRR Moment Check	0hrFRR Shear Check	1hrFRR Moment Check	1hrFRR Shear Check			
OK	OK	OK	OK			

1 HR FRR

BEAM DESIGN #: 7.2, longer storage room N-S beam

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
General storage	15.500	10.000	145	1	24FV8DF	6.75 x 17.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (1hr FRR charred section)
1450.000	29.100	44419.222	11237.500	10.000	0.964	1.000
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D	1hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]	1hrFRR Shear Resistance V'_s,fr/C_D			
68351.770	21164.667	76129.948	24409.481			
0hrFRR Moment Check	0hrFRR Shear Check	1hrFRR Moment Check	1hrFRR Shear Check			
OK	OK	OK	OK			

1 HR FRR

BEAM DESIGN #: 8, shorter spandrels

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
General storage	21.000	11.000	145	1	24FV8DF	6.75 x 23.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (1hr FRR charred section)
1595.000	339.000	106611.750	16747.500	10.000	0.909	0.988
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D	1hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]	1hrFRR Shear Resistance V'_s,fr/C_D			
115324.302	28319.667	142500.442	33591.731			
0hrFRR Moment Check	0hrFRR Shear Check	1hrFRR Moment Check	1hrFRR Shear Check			
OK	OK	OK	OK			

1 HR FRR

BEAM DESIGN #: 9, longest spandrels

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Classroom	24.000	11.000	70	1	24FV8DF	6.75 x 23.75
W_a [plf]	Surplus linear load W [plf]	Simple max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (1hr FRR charred section)
770.000	339.000	79848	9240	10	0.897	0.975
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D	1hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]	1hrFRR Shear Resistance V'_s,fr/C_D			
113794.597	28319.667	140610.2619	33591.73125			
0hrFRR Moment Check	0hrFRR Shear Check	1hrFRR Moment Check	1hrFRR Shear Check			

	OK	OK	OK	OK			

Section explanation: This sheet repeats a simple design process across glulam beam design cases at the roof level of the Q095 test model. This sheet designs for beams in a Type IV building, where no fire rating is required for "heavy timber" members. At this roof level, beams all receive the same roof-live and superimposed dead loads, but differ by the application of heavy mechanical dunnage point loads, which are factored in using simple beam equations.

0 HR FRR

BEAM DESIGN #: 1

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Roof	24.000	8.083	140	1.0	24FV8DF	6.75 x 23.75
W_a [plf]	Surplus linear load W [plf]	Max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	
1131.667	39.000	84288.000	13580.000	10.000	0.897	
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D					
113794.597	28319.667					
0hrFRR Moment Check	0hrFRR Shear Check					
OK	OK					

0 HR FRR

BEAM DESIGN #: 1.2

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	Trial GL layup	Trial GL dimensions (dropdown)
Toilet	24.000	4.000	88	1	24FV8DF	8.5 x 28.25
W_a [plf]	Surplus linear load W [plf]	Max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	
352.000	58.400	185548.800	4224.000	10.000	0.861	
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D					
194707.892	42417.667					
0hrFRR Moment Check	0hrFRR Shear Check					
OK	OK					

0 HR FRR

BEAM DESIGN #: 1.3

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
General storage	24.000	8.083	145	1	24FV8DF	8.5 x 26.75
W_a [plf]	Surplus linear load W [plf]	Max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	
1172.083	55.300	161217.375	14065.000	10.000	0.866	
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D					
175530.863	40174.000					
0hrFRR Moment Check	0hrFRR Shear Check					
OK	OK					

0 HR FRR

BEAM DESIGN #: 2

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Roof	21.250	16.750	140	1.0	24FV8DF	6.75 x 26.75
W_a [plf]	Surplus linear load W [plf]	Max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	
2345.000	43.900	134842.207	24915.625	10.000	0.897	
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D					
144389.851	31906.000					
0hrFRR Moment Check	0hrFRR Shear Check					
OK	OK					

0 HR FRR

BEAM DESIGN #: 2.2

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Roof	24.000	16.750	140	1.0	24FV8DF	8.5 x 26.75
W_a [plf]	Surplus linear load W [plf]	Max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	
2345.000	55.300	172821.600	28140.000	10.000	0.866	

0 HR FRR

Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D					
175530.863	40174.000					
0hrFRR Moment Check	0hrFRR Shear Check					
OK	OK					

0 HR FRR

BEAM DESIGN #: 3

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Roof	8.750	8.083	140	1.0	24FV8DF	6.75 x 17.75
W_a [plf]	Surplus linear load W [plf]	Max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	
1131.667	29.100	11108.900	4951.042	10.000	1.000	
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D					
70880.000	21164.667					
0hrFRR Moment Check	0hrFRR Shear Check					
OK	OK					

0 HR FRR

BEAM DESIGN #: 3.2

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Roof	12.500	8.083	140	1.0	24FV8DF	6.75 x 17.75
W_a [plf]	Surplus linear load W [plf]	Max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	
1131.667	29.100	31108.724	7072.917	10.000	0.985	
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D					
69838.023	21164.667					
0hrFRR Moment Check	0hrFRR Shear Check					
OK	OK					

0 HR FRR

BEAM DESIGN #: 4

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Roof	15.500	10.000	140	1.0	24FV8DF	6.75 x 17.75
W_a [plf]	Surplus linear load W [plf]	Max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	
1400.000	29.100	42917.659	10850.000	10.000	0.964	
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D					
68351.770	21164.667					
0hrFRR Moment Check	0hrFRR Shear Check					
OK	OK					

0 HR FRR

BEAM DESIGN #: 5

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Roof	23.000	12.000	140	1.0	24FV8DF	8.5 x 23.75
W_a [plf]	Surplus linear load W [plf]	Max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	
1680.000	349.100	134174.238	19320.000	10.000	0.880	
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D					
140624.027	35669.000					
0hrFRR Moment Check	0hrFRR Shear Check					
OK	OK					

Section explanation: This sheet repeats a simple design process across glulam beam design cases at the roof level of the Q095 test model.This sheet designs for beams in a Type III building, where a 1-hr fire rating is required for structural members. At this roof level, beams all receive the same roof-live and superimposed dead loads, but differ by the application of heavy mechanical dunnage point loads, which are factored in using simple beam equations.

1 HR FRR

BEAM DESIGN #: 1						
Case	**Span [ft]**	**Trib. width. [ft]**	**Controlling Q_a/C_D [psf]**	**C_D**	GL layup	Glulam dimensions
Roof	24	8.083	140	1.0	**24FV8DF**	**6.75 x 23.75**
W_a [plf]	Surplus linear load W [plf]	Max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (1hr FRR charred section)
1131.666667	39	84288	13580	10	0.897	0.975
Design Moment Resistance M'a/C_D [lbs*ft]	**Design Shear Resistance V'_s/C_D**	**1hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]**	**1hrFRR Shear Resistance V'_s,fr/C_D**			
113794.5969	28319.66667	140610.2619	33591.73125			
0hrFRR Moment Check	**0hrFRR Shear Check**	**1hrFRR Moment Check**	**1hrFRR Shear Check**			
OK	OK	OK	OK			

1 HR FRR

BEAM DESIGN #: 1.2						
Case	**Span [ft]**	**Trib. width. [ft]**	**Controlling Q_a/C_D [psf]**	**C_D**	Trial GL layup	Glulam dimensions
Toilet	24	4.000	88	1	**24FV8DF**	**8.5 x 28.25**
W_a [plf]	Surplus linear load W [plf]	Max moment Ma (lbs*ft)	**Simple max shear Ra (lbs)**	**Wood species coefficient 'x'**	**Volume factor C_v (uncharred section)**	**Volume factor C_v (1hr FRR charred section)**
352	58.4	185548.8	4224	10	0.861	0.916
Design Moment Resistance M'a/C_D [lbs*ft]	**Design Shear Resistance V'_s/C_D**	**1hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]**	**1hrFRR Shear Resistance V'_s,fr/C_D**			
194707.8924	42418	298261.4874	62966.42917			
0hrFRR Moment Check	**0hrFRR Shear Check**	**1hrFRR Moment Check**	**1hrFRR Shear Check**			
OK	OK	OK	OK			

1 HR FRR

BEAM DESIGN #: 1.3						
Case	**Span [ft]**	**Trib. width. [ft]**	**Controlling Q_a/C_D [psf]**	**C_D**	GL layup	Glulam dimensions
General storage	24	8.083	145	1	**24FV8DF**	**8.5 x 26.75**
W_a [plf]	Surplus linear load W [plf]	Max moment Ma (lbs*ft)	**Simple max shear Ra (lbs)**	**Wood species coefficient 'x'**	**Volume factor C_v (uncharred section)**	**Volume factor C_v (1hr FRR charred section)**
1172.083333	55.3	161217.375	14065	10	0.866	0.921
Design Moment Resistance M'a/C_D [lbs*ft]	**Design Shear Resistance V'_s/C_D**	**1hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]**	**1hrFRR Shear Resistance V'_s,fr/C_D**			
175530.8629	40174	266945.3985	59395.55417			
0hrFRR Moment Check	**0hrFRR Shear Check**	**1hrFRR Moment Check**	**1hrFRR Shear Check**			
OK	OK	OK	OK			

1 HR FRR

BEAM DESIGN #: 2						
Case	**Span [ft]**	**Trib. width. [ft]**	**Controlling Q_a/C_D [psf]**	**C_D**	GL layup	Glulam dimensions
Roof	21.25	16.750	140	1.0	**24FV8DF**	**6.75 x 26.75**
W_a [plf]	Surplus linear load W [plf]	Max moment Ma (lbs*ft)	**Simple max shear Ra (lbs)**	**Wood species coefficient 'x'**	**Volume factor C_v (uncharred section)**	**Volume factor C_v (1hr FRR charred section)**
2345	43.9	134842.207	24915.625	10	0.897	0.975
Design Moment Resistance M'a/C_D [lbs*ft]	**Design Shear Resistance V'_s/C_D**	**1hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]**	**1hrFRR Shear Resistance V'_s,fr/C_D**			
144389.8508	31906	181556.0378	38182.85625			
0hrFRR Moment Check	**0hrFRR Shear Check**	**1hrFRR Moment Check**	**1hrFRR Shear Check**			
OK	OK	OK	OK			

1 HR FRR

BEAM DESIGN #: 2.2						
Case	**Span [ft]**	**Trib. width. [ft]**	**Controlling Q_a/C_D [psf]**	**C_D**	GL layup	Glulam dimensions
Roof	24	16.750	140	1.0	**24FV8DF**	**8.5 x 26.75**
W_a [plf]	Surplus linear load W [plf]	Max moment Ma (lbs*ft)	**Simple max shear Ra (lbs)**	**Wood species coefficient 'x'**	**Volume factor C_v (uncharred section)**	**Volume factor C_v (1hr FRR charred section)**
2345	55.3	172821.6	28140	10	0.866	0.921
Design Moment Resistance M'a/C_D [lbs*ft]	**Design Shear Resistance V'_s/C_D**	**1hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]**	**1hrFRR Shear Resistance V'_s,fr/C_D**			
175530.8629	40174	266945.3985	59395.55417			
0hrFRR Moment Check	**0hrFRR Shear Check**	**1hrFRR Moment Check**	**1hrFRR Shear Check**			
OK	OK	OK	OK			

HR FRR

BEAM DESIGN #: 3						
Case	**Span [ft]**	**Trib. width. [ft]**	**Controlling Q_a/C_D [psf]**	**C_D**	GL layup	Glulam dimensions
Roof	8.75	8.083	140	1.0	**24FV8DF**	**6.75 x 17.75**
W_a [plf]	Surplus linear load W [plf]	Max moment Ma (lbs*ft)	**Simple max shear Ra (lbs)**	**Wood species coefficient 'x'**	**Volume factor C_v (uncharred section)**	**Volume factor C_v (1hr FRR charred section)**

1131.666667	29.1	11108.89974	4951.041667	10	1.000	1.000
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D	1hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]	1hrFRR Shear Resistance V'_s,fr/C_D			
70880	21164.66667	76129.94813	24409.48125			
0hrFRR Moment Check	0hrFRR Shear Check	1hrFRR Moment Check	1hrFRR Shear Check			
OK	OK	OK	OK			

1 HR FRR

BEAM DESIGN #: 3.2

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Roof	12.5	8.083	140	1.0	24FV8DF	6.75 x 17.75
W_a [plf]	Surplus linear load W [plf]	Max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (1hr FRR charred section)
1131.666667	29.1	31108.72396	7072.916667	10	0.985	1.000
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D	1hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]	1hrFRR Shear Resistance V'_s,fr/C_D			
69838.02282	21164.66667	76129.94813	24409.48125			
0hrFRR Moment Check	0hrFRR Shear Check	1hrFRR Moment Check	1hrFRR Shear Check			
OK	OK	OK	OK			

1 HR FRR

BEAM DESIGN #: 4

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Roof	15.5	10.000	140	1.0	24FV8DF	6.75 x 17.75
W_a [plf]	Surplus linear load W [plf]	Max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (1hr FRR charred section)
1400	29.1	42917.65938	10850	10	0.964	1.000
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D	1hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]	1hrFRR Shear Resistance V'_s,fr/C_D			
68351.77028	21164.66667	76129.94813	24409.48125			
0hrFRR Moment Check	0hrFRR Shear Check	1hrFRR Moment Check	1hrFRR Shear Check			
OK	OK	OK	OK			

1 HR FRR

BEAM DESIGN #: 5

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Roof	23	12.000	140	1.0	24FV8DF	8.5 x 23.75
W_a [plf]	Surplus linear load W [plf]	Max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (1hr FRR charred section)
1680	349.1	134174.2375	19320	10	0.880	0.937
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D	1hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]	1hrFRR Shear Resistance V'_s,fr/C_D			
140624.0268	35669	210165.9385	52253.80417			
0hrFRR Moment Check	0hrFRR Shear Check	1hrFRR Moment Check	1hrFRR Shear Check			
OK	OK	OK	OK			

Section explanation: This sheet repeats a simple design process for columns based on their simple compressive strength throughout the Q095 test model, then tabulates the volumes of materials used in the Q095 test model. This design process is simplified in that it was deemed expedient to replicate the design decision which the designers of the actual Q095 made in having column section sizes uniform between all floor levels (rather than increasing section size as compressive loads accumulate moving down the stories of the building). The design follows NDS 2018 code as a reference standard of NYCBC 2022 edition. Some original concrete sections are unaltered in the Q095 test case because those columns are integral with the building's concrete cores, which are retained in the test case model for their fire safety and lateral resistance roles. The tables are labeled for the Type III and Type IV design cases, but very few of the mass timber columns' compressive strengths are governed by their charred section's ultimate strength in the Type III design, and so the few column sections which differ are highlighted.

Type III columns (1hr FRR)

column schedule order	column grid #	Q095 conc. section	vertical reinforcement bars	stirrup bars	vertical reinf. volume [yd^3/ft]	stirrup volume [yd^3/ft]	accumulated reaction	final section	F'_c,f 1hr charred [kips]	column height [ft]	timber section area [in^2]	timber volume [yd^3]	concrete volume [yd^3]	reinforcement volume [yd^3]
1	A.1/2	24 x 24	(12)#9	#5 @ 12 loops, (4) #5@12 internal	0.0030839	0.001300831	615	19.25 x 19.25	1754.309	75.47916667	370.5625	7.193865406	-	-
2	A.1/3.1	30 x 16	(10)#9	#5 @ 12 loops, (2) #5@12 internal	0.002569917	0.000451678	479	-	-	75.47916667	-	-	9.318	0.22806743
3	A.1/4.3	24 x 24	(12)#9		0.0030839	0.001300831	385	14.75 x 14.75	473.48	75.47916667	217.5625	4.223620421	-	-
4	1.2/1.2	24 round	(8)#11		0.003212698		554	16.25 x 16.25	685.925	75.47916667	264.0625	5.126341936	-	-
5	A.3/3.1	26 x 24	(12)#9		0.0030839	0.001409234	561	19.25 x 19.25	1754.309	75.47916667	370.5625	7.193865406	-	-
6	A.3/4.3	24 x 24	(12)#9	#5 @ 12 loops, (4) #5@12 internal	0.0030839	0.001300831	444	-	-	75.47916667	-	-	11.182	0.330955893
7	B/1.1	30 x 18	(10)#9		0.002569917		674	19.25 x 19.25	1754.309	75.47916667	370.5625	7.193865406	-	-
8	B/2	30 x 18	(10)#9		0.002569917		660	19.25 x 19.25	1754.309	75.47916667	370.5625	7.193865406	-	-
9	B/3.1	30 x 18	(10)#9		0.002569917		440	14.75 x 14.75	473.48	75.47916667	217.5625	4.223620421	-	-
10	B/4.3	30 x 18	(10)#9		0.002569917		451	16.25 x 16.25	685.925	75.47916667	264.0625	5.126341936	-	-
11	C/1.1	30 x 18	(10)#9		0.002569917		666	19.25 x 19.25	1754.309	75.47916667	370.5625	7.193865406	-	-
12	C/2	30 x 18	(10)#9		0.002569917		712	19.25 x 19.25	1754.309	75.47916667	370.5625	7.193865406	-	-
13	C/3.1	30 x 18	(12)#9		0.0030839		567	19.25 x 19.25	1754.309	75.47916667	370.5625	7.193865406	-	-
14	C/4.3	24 x 24	(12)#9		0.0030839	0.001300831	665	19.25 x 19.25	1754.309	75.47916667	370.5625	7.193865406	-	-
15	D/1.1	30 x 18	(10)#9		0.002569917		620	19.25 x 19.25	1754.309	75.47916667	370.5625	7.193865406	-	-
16	D/2	30 x 18	(10)#9		0.002569917		715	19.25 x 19.25	1754.309	75.47916667	370.5625	7.193865406	-	-
17	D/3.1	30 x 18	(10)#9		0.002569917		562	19.25 x 19.25	1754.309	75.47916667	370.5625	7.193865406	-	-
18	D/4.3	24 x 24	(12)#9		0.0030839	0.001300831	652	19.25 x 19.25	1754.309	75.47916667	370.5625	7.193865406	-	-
19	E.1/1.1	24 x 24	(12)#9	#5 @ 12 loops, (4) #5@12 internal	0.0030839	0.001300831	621	-	-	75.47916667	-	-	11.182	0.330955893
20	E.1/2	24 x 24	(12)#9		0.0030839	0.001300831	758	19.25 x 19.25	1754.309	75.47916667	370.5625	7.193865406	-	-
21	E.1/3.2	24 x 24	(12)#9	#5 @ 12 loops, (4) #5@12 internal	0.0030839	0.001300831	635	-	-	75.47916667	-	-	11.182	0.330955893
22	E.1/4.3	24 x 24	(12)#9	#5 @ 12 loops, (4) #5@12 internal	0.0030839	0.001300831	601	-	-	75.47916667	-	-	11.182	0.330955893
23	E.2/1.1	24 x 24	(12)#9	#5 @ 12 loops, (4) #5@12 internal	0.0030839	0.001300831	390	-	-	75.47916667	-	-	11.182	0.330955893
24	E.2/1.3	16 x 24	(10)#9	#5@12" loops, no internal	0.002569917	0.000144537	478	-	-	75.47916667	-	-	7.455	0.204884702
25	E.2/2	16 x 24	(10)#9	#5@12" loops, no internal	0.002569917	0.000144537	593	-	-	75.47916667	-	-	7.455	0.204884702
26	E.2/3.2	24 x 24	(12)#9	#5 @ 12 loops, (4) #5@12 internal	0.0030839	0.001300831	679	-	-	75.47916667	-	-	11.182	0.330955893
27	E.2/4.3	24 x 24	(12)#9	#5 @ 12 loops, (4) #5@12 internal	0.0030839	0.001300831	529	-	-	75.47916667	-	-	11.182	0.330955893
28	F/1.3	24 x 24	(12)#9		0.0030839	0.001300831	260	13.25 x 13.25	297.499	64.3125	175.5625	2.904028622	-	-
29	F/2	24 x 24	(12)#9		0.0030839	0.001300831	329	14.75 x 14.75	473.48	64.3125	217.5625	3.598762418	-	-
30	F/3.3	24 x 24	(12)#9		0.0030839	0.001300831	341	14.75 x 14.75	473.48	64.3125	217.5625	3.598762418	-	-
31	F/4.2	24 x 24	(12)#9		0.0030839	0.001300831	280	13.25 x 13.25	297.499	64.3125	175.5625	2.904028622	-	-
											Total volume (yd^3)	**125.226**	**102.503**	**2.955**

Type IV columns (0hr FRR)

column schedule order	column grid #	Q095 conc. section	vertical reinforcement bars	stirrup bars	vertical reinf. volume	stirrup volume	accumulated reaction	final section	F'_c,f 0hr charred [kips]	column height [ft]	timber section area [in^2]	timber volume [yd^3]	concrete volume [yd^3]	reinforcement volume [yd^3]
1	A.1/2	24 x 24	(12)#9	#5 @ 12 loops, (4) #5@12 internal	0.0030839	0.001300831	615	19.25 x 19.25	797.7	75.47916667	370.5625	7.193865406	-	-
2	A.1/3.1	30 x 16	(10)#9	#5 @ 12 loops, (2) #5@12 internal	0.002569917	0.000451678	479	-	-	75.47916667	-	-	9.318	0.22806743
3	A.1/4.3	24 x 24	(12)#9		0.0030839	0.001300831	385	14.75 x 14.75	447.164	75.47916667	217.5625	4.223620421	-	-
4	1.2/1.2	24 round	(8)#11		0.003212698		554	16.25 x 16.25	554.932	75.47916667	264.0625	5.126341936	-	-
5	A.3/3.1	26 x 24	(12)#9		0.0030839	0.001409234	561	19.25 x 19.25	797.7	75.47916667	370.5625	7.193865406	-	-
6	A.3/4.3	24 x 24	(12)#9	#5 @ 12 loops, (4) #5@12 internal	0.0030839	0.001300831	444	-	-	75.47916667	-	-	11.182	0.330955893
7	B/1.1	30 x 18	(10)#9		0.002569917		674	19.25 x 19.25	797.7	75.47916667	370.5625	7.193865406	-	-
8	B/2	30 x 18	(10)#9		0.002569917		660	19.25 x 19.25	797.7	75.47916667	370.5625	7.193865406	-	-
9	B/3.1	30 x 18	(10)#9		0.002569917		440	14.75 x 14.75	447.164	75.47916667	217.5625	4.223620421	-	-
10	B/4.3	30 x 18	(10)#9		0.002569917		451	16.25 x 16.25	554.932	75.47916667	264.0625	5.126341936	-	-
11	C/1.1	30 x 18	(10)#9		0.002569917		666	19.25 x 19.25	797.7	75.47916667	370.5625	7.193865406	-	-
12	C/2	30 x 18	(10)#9		0.002569917		712	19.25 x 19.25	797.7	75.47916667	370.5625	7.193865406	-	-
13	C/3.1	30 x 18	(12)#9		0.0030839		567	19.25 x 19.25	797.7	75.47916667	370.5625	7.193865406	-	-
14	C/4.3	24 x 24	(12)#9		0.0030839	0.001300831	665	19.25 x 19.25	797.7	75.47916667	370.5625	7.193865406	-	-
15	D/1.1	30 x 18	(10)#9		0.002569917		620	19.25 x 19.25	797.7	75.47916667	370.5625	7.193865406	-	-
16	D/2	30 x 18	(10)#9		0.002569917		715	19.25 x 19.25	797.7	75.47916667	370.5625	7.193865406	-	-
17	D/3.1	30 x 18	(10)#9		0.002569917		562	19.25 x 19.25	797.7	75.47916667	370.5625	7.193865406	-	-
18	D/4.3	24 x 24	(12)#9		0.0030839	0.001300831	652	19.25 x 19.25	797.7	75.47916667	370.5625	7.193865406	-	-
19	E.1/1.1	24 x 24	(12)#9	#5 @ 12 loops, (4) #5@12 internal	0.0030839	0.001300831	621	-	-	75.47916667	-	-	11.182	0.330955893
20	E.1/2	24 x 24	(12)#9		0.0030839	0.001300831	758	19.25 x 19.25	1754.309	75.47916667	370.5625	7.193865406	-	-
21	E.1/3.2	24 x 24	(12)#9	#5 @ 12 loops, (4) #5@12 internal	0.0030839	0.001300831	635	-	-	75.47916667	-	-	11.182	0.330955893
22	E.1/4.3	24 x 24	(12)#9	#5 @ 12 loops, (4) #5@12 internal	0.0030839	0.001300831	601	-	-	75.47916667	-	-	11.182	0.330955893
23	E.2/1.1	24 x 24	(12)#9	#5 @ 12 loops, (4) #5@12 internal	0.0030839	0.001300831	390	-	-	75.47916667	-	-	11.182	0.330955893

24	E.2/1.3	16 x 24	(10)#9	#5@12" loops, no internal	0.002569917	0.000144537	478	-	-	75.47916667	-	-	7.455	0.204884702
25	E.2/2	16 x 24	(10)#9	#5@12" loops, no internal	0.002569917	0.000144537	593	-	-	75.47916667	-	-	7.455	0.204884702
26	E.2/3.2	24 x 24	(12)#9	#5 @ 12 loops, (4) #5@12 internal	0.0030839	0.001300831	679	-	-	75.47916667	-	-	11.182	0.330955893
27	E.2/4.3	24 x 24	(12)#9	#5 @ 12 loops, (4) #5@12 internal	0.0030839	0.001300831	529	-	-	75.47916667	-	-	11.182	0.330955893
28	F/1.3	24 x 24	(12)#9		0.0030839	0.001300831	260	13.25 x 13.25	347.637	64.3125	175.5625	2.904028622	-	-
29	F/2	24 x 24	(12)#9		0.0030839	0.001300831	329	13.25 x 13.25	347.637	64.3125	175.5625	2.904028622	-	-
30	F/3.3	24 x 24	(12)#9		0.0030839	0.001300831	341	13.25 x 13.25	347.637	64.3125	175.5625	2.904028622	-	-
31	F/4.2	24 x 24	(12)#9		0.0030839	0.001300831	280	13.25 x 13.25	347.637	64.3125	175.5625	2.904028622	-	-
											Total volume (yd^3)	**123.836**	**102.503**	**2.955**

Section explanation: This sheet repeats a simple design process across different CLT floor design cases throughout the small K673 freestanding gym test case, identically to the CLT floor design sheet for the Q095 model. There are simply two one-way, simple span design cases in the K673 test case, under identical roof loads consisting of roof live load and a relatively extreme superimposed dead load that represents a blue-green roof (as opposed to the lighter superimposed dead loads on the actual K673 building).

CLT Design case	Use	Design span [ft]	Trial CLT (Structurlam)	Grade [Vlook]	Self-weight [Vlook] [psf]	Temp. factor F	LL	TDL	LL+DL [psf]	simple span Mmax=wL^2/8 [lbs*ft/ft]
1a	Roof	8.573	105V	V2.1M1.1	9	<100	40	119	159	1460.71
		FbSeff,0 (lbs*ft/ft strip)	Eieff,0 (*e6, psi/ft)	Gaeff,0 (*e6 plf)	Mallow (lbs*ft/ft strip)	Vallowq (plf)			C_D =	1.0
	Prefactored section prop.	2042	95.4	0.5	2042.4	1607.6				
	Factored section prop.	2042	95.4	0.5	2042.4	1607.6				
		simple span delta_max	delta_allow=L/240 [in.]	Fixity	K_S	EI_app [*e6, psi/ft]	NDS 10.4.1 Deflection	NDS 3.5.2 LT Deflection	LT Defl. Allowable	Both Defl modes OK?
		0.203	0.428645833	Pinned	11.5	79.018	0.245	0.354	0.514375	OK
									excess Mn capacity:	28.47

CLT Design case	Use	Design span [ft]	Trial CLT (Structurlam)	Grade [Vlook]	Self-weight [Vlook] [psf]	Temp. factor F	LL	TDL	LL+DL [psf]	simple span Mmax=wL^2/8 [lbs*ft/ft]
1b	Roof	6.667	105V	V2.1M1.1	9	<100	40	119	159	883.42
		FbSeff,0 (lbs*ft/ft strip)	Eieff,0 (*e6, psi/ft)	Gaeff,0 (*e6 plf)	Mallow (lbs*ft/ft strip)	Vallowq (plf)			C_D =	1.0
	Prefactored section prop.	2042	95.4	0.5	2042.4	1607.6				
	Factored section prop.	2042	95.4	0.5	2042.4	1607.6				
		simple span delta_max	delta_allow=L/240 [in.]	Fixity	K_S	EI_app [*e6, psi/ft]	NDS 10.4.1 Deflection	NDS 3.5.2 LT Deflection	LT Defl. Allowable	Both Defl modes OK?
		0.074	0.33335	Pinned	11.5	71.045	0.099	0.130	0.40002	OK
									excess Mn capacity:	56.74

Section explanation: This sheet repeats a simple design process for two glulam beam spans at the roof of the K673 freestanding gym test model. Cells are shaded green if they are manually selected inputs for the particular design case. The design follows NDS 2018 code as a reference standard of NYCBC 2022 edition, including the consideration of load duration factors and volume factors, but is otherwise a simple beam calculation repeated for differing spans and design loads. This sheet designs for beams in a Type IV building, where no fire rating is required for "heavy timber" members.

0 HR FRR

BEAM DESIGN #: 1; (50'11.625"span)

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	GL layup	Glulam dimensions
Roof	51	8.573	150	1.0	24FV8DF	14.25 x 37.25
W_a [plf]	Surplus linear load W [plf]	Max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	
1285.9375	129	460031.5547	32791.40625	10	0.738	
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D					
486194.029	93774.66667					
0hrFRR Moment Check	0hrFRR Shear Check					
OK	OK					

0 HR FRR

BEAM DESIGN #: 2; (20'7.625"span)

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	Trial GL layup	Trial GL dimensions (dropdown)
Roof	21	8.573	150	1.0	24FV8DF	6.75 x 19.25
W_a [plf]	Surplus linear load W [plf]	Max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	
1285.9375	31.6	72629.25469	13502.34375	10	0.928	
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D					
77370.59767	22949					
0hrFRR Moment Check	0hrFRR Shear Check					
OK	OK					

Section explanation: This sheet repeats a simple design process for two glulam beam spans at the roof of the K673 freestanding gym test model. Cells are shaded green if they are manually selected inputs for the particular design case. The design follows NDS 2018 code as a reference standard of NYCBC 2022 edition, including the consideration of load duration factors and volume factors, but is otherwise a simple beam calculation repeated for differing spans and design loads. This sheet designs for beams in a Type III building, where a 1hr fire resistance rating is required for roof structural elements.

1 HR FRR

BEAM DESIGN #: 1; (50'11.625"span)

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	Trial GL layup	Trial GL dimensions (dropdown)
Roof	51	8.573	150	1.0	24FV8DF	14.25 x 37.25
W_a [plf]	Surplus linear load W [plf]	Max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (1hr FRR charred section)
1285.9375	129	460031.5547	32791.40625	10	0.738	0.763
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D	1hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]	1hrFRR Shear Resistance V'_s,fr/C_D			
486194.029	93774.66667	970424.0047	183422.7313			
0hrFRR Moment Check	0hrFRR Shear Check	1hrFRR Moment Check	1hrFRR Shear Check			
OK	OK	OK	OK			

1 HR FRR

BEAM DESIGN #: 2; (20'7.625"span)

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	Trial GL layup	Trial GL dimensions (dropdown)
Roof	21	8.573	150	1.0	24FV8DF	6.75 x 19.25
W_a [plf]	Surplus linear load W [plf]	Max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (1hr FRR charred section)
1285.9375	31.6	72629.25469	13502.34375	10	0.928	1.000
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D	1hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]	1hrFRR Shear Resistance V'_s,fr/C_D			
77370.59767	22949	91122.37313	26705.04375			
0hrFRR Moment Check	0hrFRR Shear Check	1hrFRR Moment Check	1hrFRR Shear Check			
OK	OK	OK	OK			

1 HR FRR

BEAM DESIGN #: 1.2; (50'11.625"span, sistered)

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	Trial GL layup	Trial GL dimensions (dropdown)
Roof	51	5.000	150	1.0	24FV8DF	12.25 x 29.75
W_a [plf]	Surplus linear load W [plf]	Max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (1hr FRR charred section)
750	88.6	272649.825	19125	10	0.766	0.798
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D	1hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]	1hrFRR Shear Resistance V'_s,fr/C_D			
276807.7631	64377.33333	512290.1064	117458.7104			
0hrFRR Moment Check	0hrFRR Shear Check	1hrFRR Moment Check	1hrFRR Shear Check			
OK	OK	OK	OK			

1 HR FRR

BEAM DESIGN #: 2.2; (20'7.625"span)

Case	Span [ft]	Trib. width. [ft]	Controlling Q_a/C_D [psf]	C_D	Trial GL layup	Trial GL dimensions (dropdown)
Roof	21	10.000	150	1.0	24FV8DF	8.5 x 23.75
W_a [plf]	Surplus linear load W [plf]	Max moment Ma (lbs*ft)	Simple max shear Ra (lbs)	Wood species coefficient 'x'	Volume factor C_v (uncharred section)	Volume factor C_v (1hr FRR charred section)
1500	49.1	85394.1375	15750	10	0.888	0.946
Design Moment Resistance M'a/C_D [lbs*ft]	Design Shear Resistance V'_s/C_D	1hrFRR Moment Resistance M'a_fr/C_D [lbs*ft]	1hrFRR Shear Resistance V'_s,fr/C_D			
141909.1452	35669	212086.5784	52253.80417			
0hrFRR Moment Check	0hrFRR Shear Check	1hrFRR Moment Check	1hrFRR Shear Check			
OK	OK	OK	OK			

APPENDIX B: BILL OF MATERIALS CALCULATIONS

CONVENTIONAL

Footings

Footing Mark	Count	Depth (ft)	Width X (ft)	Length Y (ft)	Reinforcement (X-Dir)	Reinforcement (Y-Dir)	Reinf. Type	Weight per foot (lb/ft)	Rebar Weight (lb)	Volume (yd3)	Rebar (lbs/yd3)	Athena Selection (lbs/yd3)
F-1	7	4	10	10	14	14	#8	2.67	747.6	14.8	50.5	118
F-2	3	4	10	20	28	56	#8	2.67	3738.0	29.6	126.2	118
F-3	2	4	5	98	24	24	#9	3.4	8404.8	72.6	115.8	118
F-4	1	4	12	60	26	120	#10	4.303	32324.1	106.7	303.0	169
F-A	1	5	25	86.7	68	232	#10	4.303	93834.1	401.2	233.9	169
F-B	1	5	27	46	72	124	#10	4.303	32909.3	230.0	143.1	143

Slab on Grade

Length (ft)	109
Width (ft)	87
Depth (in)	8

Mass Timber foundations reduction factors:

F-1	43.4%
F-2	49.5%
F-B	25.0%

MASS TIMBER

Footings

Footing Mark	Count	Depth (ft)	Width X (ft)	Length Y (ft)	Reinforcement (X-Dir)	Reinforcement (Y-Dir)	Reinf. Type	Weight per foot (lb/ft)	Rebar Weight (lb)	Volume (yd3)	Rebar (lbs/yd3)	Athena Selection (lbs/yd3)
F-1	7	2.264	10	10	14	14	#8	2.67	747.6	8.4	89.2	118
F-2	3	2.02	10	20	28	56	#8	2.67	3738.0	15.0	249.8	118
F-3	2	4	5	98	24	24	#9	3.4	8404.8	72.6	115.8	118
F-4	1	4	12	60	26	120	#10	4.303	32324.1	106.7	303.0	169
F-A	1	5	25	86.7	68	232	#10	4.303	93834.1	401.2	233.9	169
F-B	1	3.75	27	46	72	124	#10	4.303	32909.3	172.5	190.8	143

Slab on Grade

Length (ft)	109
Width (ft)	87
Depth (in)	8

	CONVENTIONAL		
Specified Material	*Athena*		
Concrete Beams + Columns	Concrete 5000 psi (EXTRA MATERIALS)	589.5	yd^3
Concrete Beams + Columns	Rebar, Rod, Light Sections (EXTRA MATERIALS)	144.3	tons (short)

	MASS TIMBER TYPE IV		
Specified Material	*Athena*		
Glulam Beams	Glulam (EXTRA MATERIALS)	6,033.7	ft^3
Glulam Columns	Glulam (EXTRA MATERIALS)	3,229.6	ft^3
Concrete Columns	Concrete 5000 psi (EXTRA MATERIALS)	104.4	yd^3
Concrete Columns	Rebar, Rod, Light Sections (EXTRA MATERIALS)	21.7	tons (short)

	MASS TIMBER TYPE III		
Specified Material	*Athena*		
Glulam Beams	Glulam (EXTRA MATERIALS)	6,048.9	ft^3
Glulam Columns	Glulam (EXTRA MATERIALS)	3,267.1	ft^3
Concrete Columns	Concrete 5000 psi (EXTRA MATERIALS)	104.4	yd^3
Concrete Columns	Rebar, Rod, Light Sections (EXTRA MATERIALS)	21.7	tons (short)

Columns & Beams

Floors

CONVENTIONAL

Cellar Floor

Area (sf)	9,425
Vinyl Composite Tile (0.1875")	Sika Sarnafil S327 PVC Membrane 80 mil (EXTRA MATERIALS)

Cafeteria Ceiling (Under Exterior)

Area (sf)	2,938
Specified Material	*Athena*
14" Concrete Slab	5000 psi concrete (EXTRA MATERIALS) - 127 yd3

Typical/ 2-Hr Rated Floor

Area (sf)	24,681
Span (ft)	24
Live Load (psf)	75
Specified Material	*Athena*
Vinyl Composite Tile	Sika Sarnafil S327 PVC Membrane 80 mil (EXTRA MATERIALS)
12" Concrete Slab	Concrete Suspended Slab - 5000 psi concrete
ACT	Roofs – Insulation – Mineral Wool Batt R11-15

Music/Dance Floor

Area (sf)	2,040
Span (ft)	24
Live Load (psf)	50
Specified Material	*Athena*
Vinyl Composite Tile	Sika Sarnafil S327 PVC Membrane 80 mil (EXTRA MATERIALS)
4" Concrete Slab	Concrete Suspended Slab - 5000 psi concrete
Neoprene Strips	EPDM Membrane (Black, 60 mil) (EXTRA MATERIALS)
10" Concrete Slab	Concrete Suspended Slab - 5000 psi concrete
6" Plenum with Isulation	Roofs – Insulation – Mineral Wool Batt R11-15 (152.4 mm)
5/8" Type X GWB	5/8" Type X GWB

Cafeteria Ceiling (Under First Floor)

Area (sf)	3,339
Span (ft)	24
Live Load (psf)	75
Vinyl Composite Tile	Sika Sarnafil S327 PVC Membrane 80 mil (EXTRA MATERIALS)
10" Concrete Slab	Concrete Suspended Slab - 5000 psi concrete
6" Plenum with Isulation	Roofs – Insulation – Mineral Wool Batt R11-15 (152.4 mm)
5/8" Type X GWB	5/8" Type X GWB
ACT	Roofs – Insulation – Mineral Wool Batt R11-15

EXTRA MATERIALS TOTALS

Sika Sarnafil S327 PVC Membrane 80 mil (sf)	13,683.0
EPDM membrane 60 mil (sf)	303.0
Concrete 5000 psi (yd3)	127

MASS TIMBER TYPE IV

Cellar Floor

Area (sf)	9,425
Vinyl Composite Tile (0.1875")	Sika Sarnafil S327 PVC Membrane 80 mil (EXTRA MATERIALS)

Cafeteria Ceiling (Under Exterior)

Area (sf)	2,938
Specified Material	*Athena*
14" Concrete Slab	5000 psi concrete (EXTRA MATERIALS) - 127 yd3

Typical Floor

Area (sf)	23,008
Span (ft)	10
Live Load (psf)	75
Specified Material	*Athena*
Vinyl Composite Tile (0.1875")	Sika Sarnafil S327 PVC Membrane 80 mil (EXTRA MATERIALS)
GenieMat RST05 (0.1969")	EPDM membrane 60 mil (sf) (EXTRA MATERIALS)
2" Concrete Topping	Concrete Topping (3000 psi)
GenieMat FF25 (1")	EPDM membrane 60 mil (sf) (EXTRA MATERIALS)
3-Ply CLT (4.125")	CLT

Music Room Floor

Area (sf)	765
Span (ft)	20
Live Load (psf)	50
Specified Material	*Athena*
Vinyl Composite Tile (0.1875")	Sika Sarnafil S327 PVC Membrane 80 mil (EXTRA MATERIALS)
2 layers of OSB (1.25")	3x Oriented Strand Board (EXTRA MATERIALS)
Acoustic-TECH SOFIX (1.5")	Fibreglass Batt (38 mm)
Lead 6 Floated Underlayment (0.236")	Organic Felt #30 (EXTRA MATERIALS)
Insonomat (0.59")	Asphalt Binder with Ground Rubber Tire (EXTRA MATERIALS)
7-Ply CLT (9.66")	CLT

Dance Room Floor

Area (sf)	1,275
Span (ft)	15
Live Load (psf)	50
Specified Material	*Athena*
Hardwood Floor (0.744")	Plywood (EXTRA MATERIALS)
2 layers of OSB (1.25")	3x Oriented Strand Board (EXTRA MATERIALS)
Acoustic-TECH SOFIX (1.5")	Fibreglass Batt (38 mm)
Lead 6 Floated Underlayment (0.236")	Organic Felt #30 (EXTRA MATERIALS)
7-Ply CLT (6.875")	CLT

Cafeteria Ceiling (Under First Floor)

Area (sf)	3,339
Span (ft)	20
Live Load (psf)	75
Vinyl Composite Tile	Sika Sarnafil S327 PVC Membrane 80 mil (EXTRA MATERIALS)
2 layers of OSB (1.25")	3x Oriented Strand Board (EXTRA MATERIALS)
Acoustic-TECH SOFIX (1.5")	Fibreglass Batt (38 mm)
Lead 6 Floated Underlayment (0.236")	Organic Felt #30 (EXTRA MATERIALS)
Insonomat (0.59")	Asphalt Binder with Ground Rubber Tire (EXTRA MATERIALS)
7-Ply CLT (9.66")	CLT

2-Hr Rated Floor

Area (sf)	1,673
Span (ft)	20
Live Load (psf)	75
Specified Material	*Athena*
Vinyl Composite Tile (0.1875")	Sika Sarnafil S327 PVC Membrane 80 mil
GenieMat RST05 (0.1969")	EPDM membrane 60 mil (sf)
2" Concrete Topping	Concrete Topping (3000 psi)
GenieMat FF25 (1")	EPDM membrane 60 mil (sf)
7-Ply CLT (9.66")	CLT

EXTRA MATERIALS TOTALS

Oriented Strand Board (msf)	16.1
Felt (100sf)	54
Asphalt Binder with Ground Rubber Tire (US tons)	14.1
Plywood (msf)	1.3
Concrete 5000 psi (yd3)	127
Sika Sarnafil S327 PVC Membrane 80 mil (sf)	13,241.2
EPDM membrane 60 mil (sf)	7,331.4

MASS TIMBER TYPE III

Cellar Floor

Area (sf)	9,425
Vinyl Composite Tile (0.1875")	Sika Sarnafil S327 PVC Membrane 80 mil (EXTRA MATERIALS)

Cafeteria Ceiling (Under Exterior)

Area (sf)	2,938
Specified Material	*Athena*
14" Concrete Slab	5000 psi concrete (EXTRA MATERIALS) - 127 yd3

Typical Floor

Area (sf)	23,008
Span (ft)	15
Live Load (psf)	75
Specified Material	*Athena*
Vinyl Composite Tile (0.1875")	Sika Sarnafil S327 PVC Membrane 80 mil (EXTRA MATERIALS)
GenieMat RST05 (0.1969")	EPDM membrane 60 mil (sf) (EXTRA MATERIALS)
2" Concrete Topping	Concrete Topping (3000 psi)
GenieMat FF25 (1")	EPDM membrane 60 mil (sf) (EXTRA MATERIALS)
5-Ply CLT	CLT

Music Room Floor

Area (sf)	765
Span (ft)	20
Live Load (psf)	50
Specified Material	*Athena*
Vinyl Composite Tile (0.1875")	Sika Sarnafil S327 PVC Membrane 80 mil (EXTRA MATERIALS)
2 layers of OSB (1.25")	3x Oriented Strand Board (EXTRA MATERIALS)
Acoustic-TECH SOFIX (1.5")	Fibreglass Batt (38 mm)
Lead 6 Floated Underlayment (0.236")	Organic Felt #30 (EXTRA MATERIALS)
Insonomat (0.59")	Asphalt Binder with Ground Rubber Tire (EXTRA MATERIALS)
7-Ply CLT (9.66")	CLT

Dance Room Floor

Area (sf)	1,275
Span (ft)	15
Live Load (psf)	50
Specified Material	*Athena*
Hardwood Floor (0.744")	Plywood (EXTRA MATERIALS)
2 layers of OSB (1.25")	3x Oriented Strand Board (EXTRA MATERIALS)
Acoustic-TECH SOFIX (1.5")	Fibreglass Batt (38 mm)
Lead 6 Floated Underlayment (0.236")	Organic Felt #30 (EXTRA MATERIALS)
7-Ply CLT (6.875")	CLT

Cafeteria Ceiling (Under First Floor)

Area (sf)	3,339
Span (ft)	20
Live Load (psf)	75
Vinyl Composite Tile	Sika Sarnafil S327 PVC Membrane 80 mil (EXTRA MATERIALS)
2 layers of OSB (1.25")	3x Oriented Strand Board (EXTRA MATERIALS)
Acoustic-TECH SOFIX (1.5")	Fibreglass Batt (38 mm)
Lead 6 Floated Underlayment (0.236")	Organic Felt #30 (EXTRA MATERIALS)
Insonomat (0.59")	Asphalt Binder with Ground Rubber Tire (EXTRA MATERIALS)
7-Ply CLT (9.66")	CLT

2-Hr Rated Floor

Area (sf)	1,673
Span (ft)	20
Live Load (psf)	75
Specified Material	*Athena*
Vinyl Composite Tile (0.1875")	Sika Sarnafil S327 PVC Membrane 80 mil
GenieMat RST05 (0.1969")	EPDM membrane 60 mil (sf)
2" Concrete Topping	Concrete Topping (3000 psi)
GenieMat FF25 (1")	EPDM membrane 60 mil (sf)
7-Ply CLT (9.66")	CLT

EXTRA MATERIALS TOTALS

OSB (msf)	16.1
Felt (100sf)	54
Asphalt Binder with Ground Rubber Tire (US tons)	14.1
Plywood (msf)	1.3
Concrete 5000 psi (yd3)	127
Sika Sarnafil S327 PVC Membrane 80 mil (sf)	13,241.2
EPDM membrane 60 mil (sf)	7,331.4

Exterior Walls

CONVENTIONAL

Knee Wall w/ Granite Panel

Height: 4', Length: 272.28', Area: 1089 SF

Specified Material	*Athena*
4'' Granite Panel	Natural Stone
6'' Mineral Wool Insulation	Mineral Wool Batt R20 (152.4 mm)
Air Barrier	Air Barrier
6" Concrete Knee Wall	8" Cast-In-Place Concrete 5000 psi
2" Mineral Wool Batt	Mineral Wool Batt R11-15 (50.8 mm)
1 Layer GWB	5/8" GWB
Furring (2.5" studs)	3 5/8" 25 GA Steel Studs @ 24" OC

Rainscreen w/ Terracotta Tile on Stud Wall

Height: 58.6', Length: 368.34', Area: 21,585 SF

Specified Material	*Athena*
1.5" Terracotta Panel	Clay Tile (EXTRA MATERIALS) 21,585 sf
6'' Mineral Wool Insulation	Mineral Wool Batt R20 (152.4 mm)
Air Barrier	Air Barrier
5/8" Exterior Gyp Board	5/8" Glass Matt Gypsum
6'' Mineral Wool Insulation	Mineral Wool Batt R20 (152.4 mm)
6" Metal Stud	6" Metal Stud
5/8" GWB	5/8" GWB

MASS TIMBER TYPE IV

Knee Wall w/ Granite Panel

Height: 4', Length: 272.28', Area: 1089 SF

Specified Material	*Athena*
4'' Granite Panel	Natural Stone
6'' Mineral Wool Insulation	Mineral Wool Batt R20 (152.4 mm)
Air Barrier	Air Barrier
6" Concrete Knee Wall	8" Cast-In-Place Concrete 5000 psi
2" Mineral Wool Batt	Mineral Wool Batt R11-15 (50.8 mm)
1 Layer GWB	5/8" GWB
Furring (2.5" studs)	3 5/8" 25 GA Steel Studs @ 24" OC

CLT Exterior Wall

Height: 58.6', Length: 368.34', Area: 21,585 SF

Specified Material	*Athena*
1.5" Terracotta Panel	Clay Tile (EXTRA MATERIALS) 21,585 sf
6'' Mineral Wool Insulation	Mineral Wool Batt R20 (EXTRA MATERIALS) 129,510 sf
Air Barrier	Air Barrier (EXTRA MATERIALS) 21,585 sf
5-ply CLT	6.875-in CLT (EXTRA MATERIALS) 12,366.4 ft3

Interior Walls

CONVENTIONAL

A2 - Metal Stud Partition - Non Rated *Area:* 21,893

Specified Material	*Athena*
3 5/8" 20 GA Steel Studs @ 16" OC	3 5/8" 20 GA Steel Studs @ 16" OC
3 5/8" Batt Insulation	Mineral Wool Batt R11-15 (92 mm)
2 Layers FRGB	2 x Gypsum Fire Rated Type 5/8"

A4-2 - Metal Stud Partition - 2Hr Rated *Area:* 15,727

Specified Material	*Athena*
3 5/8" 20 GA Steel Studs @ 16" OC	3 5/8" 20 GA Steel Studs @ 16" OC
3 5/8" Batt Insulation	Mineral Wool Batt R11-15 (92 mm)
2 Layers GWB	Gypsum Regular 5/8"
2 Outer Layers of FRGB	Gypsum Fire Rated Type 5/8"

D1 -Furring Partition - Non Rated *Area:* 15,291

Specified Material	*Athena*
2 1/2" 20 GA Steel Studs @ 16" OC	3 5/8" 25 GA Steel Studs @ 16" OC
2 1/2" Batt Insulation	Mineral Wool Batt R11-15 (63.5 mm)
1 Layer FRGB	Gypsum Fire Rated Type 5/8"

J4 - Metal Stud Partition - Acoustic *Area:* 4,999

Specified Material	*Athena*
3 5/8" 20 GA Steel Studs @ 16" OC	3 5/8" 20 GA Steel Studs @ 16" OC
3 5/8" Batt Insulation	Mineral Wool Batt R11-15 (92 mm)
2" Sound Attenuation Blanket	Fibreglass Batt R11-15 (50.8 mm)
2 Layer GWB	2 x Gypsum Regular 5/8"
2 Outer Layer of FRGB	2 x Gypsum Fire Rated Type 5/8"

Note: Assume 16 ft floor height, divide area by 16 ft to get length

MASS TIMBER

CLT Non-Rated Partition Wall *Area:* 16,456

Specified Material	*Athena*
3-Ply CLT (3.07")	CLT (EXTRA MATERIALS)
2" Steel Studs @ 24" OC	3 5/8" 25 GA Steel Studs @ 24" OC
2" Batt Insulation	Mineral Wool Batt R11-15 (51 mm)
1 Layer GWB	Gypsum Regular 5/8"
1 Outer Layer of FRGB	Gypsum Fire Rated Type 5/8"

CLT 2Hr Rated Partition Wall *Area:* 5,326

Specified Material	*Athena*
5-Ply CLT (6.875")	CLT (EXTRA MATERIALS)
2" Steel Studs @ 24" OC	3 5/8" 25 GA Steel Studs @ 24" OC
2" Batt Insulation	Mineral Wool Batt R11-15 (51 mm)
1 Layer GWB	Gypsum Regular 5/8"
1 Outer Layer of FRGB	Gypsum Fire Rated Type 5/8"

A2 - Metal Stud Partition - Non Rated *Area:* 7,415

Specified Material	*Athena*
3 5/8" 20 GA Steel Studs @ 16" OC	3 5/8" 20 GA Steel Studs @ 16" OC
3 5/8" Batt Insulation	Mineral Wool Batt R11-15 (92 mm)
2 Layers FRGB	2 x Gypsum Fire Rated Type 5/8"

A4-2 - Metal Stud Partition - 2Hr Rated *Area:* 12,099

Specified Material	*Athena*
3 5/8" 20 GA Steel Studs @ 16" OC	3 5/8" 20 GA Steel Studs @ 16" OC
3 5/8" Batt Insulation	Mineral Wool Batt R11-15 (92 mm)
2 Layers GWB	2 x Gypsum Regular 5/8"
2 Outer Layers of FRGB	2 x Gypsum Fire Rated Type 5/8"

D1 - Furring Partition - Non Rated *Area:* 8,457

Specified Material	*Athena*
2 1/2" 20 GA Steel Studs @ 16" OC	3 5/8" 25 GA Steel Studs @ 16" OC
2 1/2" Batt Insulation	Mineral Wool Batt R11-15 (63.5 mm)
1 Layer FRGB	Gypsum Fire Rated Type 5/8"

J4 - Metal Stud Partition - Acoustic *Area:* 1,324

Specified Material	*Athena*
3 5/8" 20 GA Steel Studs @ 16" OC	3 5/8" 20 GA Steel Studs @ 16" OC
3 5/8" Batt Insulation	Mineral Wool Batt R11-15 (92 mm)
2" Sound Attenuation Blanket	Fibreglass Batt R11-15 (50.8 mm)
2 Layer GWB	2 x Gypsum Regular 5/8"

CONVENTIONAL & MASS TIMBER

Shear Walls

Height: 78.8', Length: 189.1'

Specified Material	*Athena*
Concrete Shear Wall	Cast-In-Place Concrete Wall, 5000 psi, #6 reinf., 12"

Retaining Walls

Height: 16.2', Length: 407.8'

Specified Material	*Athena*
Concrete Shear Wall	Cast-In-Place Concrete Wall, 5000 psi, #6 reinf., 12"

STAIR A	Length (ft)
1' Walls	44.6
2' Walls	8.6

STAIR B	Length (ft)
1' Walls	55.8
2' Walls	10.2

ELEVATOR	Length (ft)
1' Walls	17.8
2' Walls	16.6

RETAINING WALLS	Length (ft)
RW-1 (16")	226
RW-2 (12")	106.48

	Length (ft)
TOTAL LENGTH OF 1' WALLS	189.1
	Height (ft)
Height (Cellar to Roof)	78.8

	Length (ft)
TOTAL LENGTH OF 1' WALLS	407.8
	Height (ft)
Height (Cellar to Grade)	16.2

CONVENTIONAL	
Roof Assembly	**Area = 7,511 sf Span = 24 ft**
Specified Material	*Athena*
12" two way concrete slab reinf. With #5@12" OC T&B each way	5000 psi concrete
2" Concrete Paver	Mod. Bit. (Inv)-Polyiso Foam Board Glass Facer (50.8 mm)
8" Continuous Insulation XPS (R-38)	Mod. Bit. (Inv)-Expanded Polystyrene (203.2 mm)
Fluid-Applied Protected Membrane Roofing System*	Standard Modified Bitumen Membrane 2 ply
Sloped concrete topping slab (2" min, 6" max, 1/8" per foot slope)	Concrete 5000 psi (EXTRA MATERIALS) 92.7 yd3

MASS TIMBER	
Roof Assembly	**Area = 7,511 sf Span = 10 ft**
Specified Material	*Athena*
2" Concrete Paver	Mod. Bit. (Inv)-Polyiso Foam Board Glass Facer (50.8 mm)
8" Continuous Insulation XPS (R-38)	Mod. Bit. (Inv)-Expanded Polystyrene (203.2 mm)
Fluid-Applied Protected Membrane Roofing System*	Standard Modified Bitumen Membrane 2 ply
Sloped concrete topping slab (2" min, 6" max, 1/8" per foot slope)	Concrete 5000 psi (EXTRA MATERIALS) 92.7 yd3
5-Ply CLT (4.125")	CLT

*monolithic liquid mebrane (surface conditioner, fluid applied membrane (90 mils), reinforcement fabric, fluid appried membrane (125 mils), protection sheet

Wall Extra Materials

CONVENTIONAL	
Paint	Area (sf)
Partition walls (double-sided)	115,821
Exterior walls	22,674
Gallons Required	369
Clay Tile	Area (sf)
Corridor walls	13,000

MASS TIMBER	
Paint	Area (sf)
Partition walls (double-sided)	58,590
CLT partition walls (single-sided)	21,782
Exterior walls	22,674
Gallons Required	275

Athena		
Concrete 5000 psi (EXTRA MATERIALS)	589.5	yd^3
Rebar, Rod, Light Sections (EXTRA MATERIALS)	144.3	tons (short)

COLUMNS

Floor	# Columns	Column Height (ft)	Volume (ft^3) concrete	Total volume (ft^3) steel
Cellar	27	15.2	1589.5	48.5
1st Floor	31	17.4	2090.7	63.8
2nd Floor	31	15.6	1877.7	57.3
3rd Floor	31	15.7	1887.7	57.6
4th Floor	31	15.6	1882.7	57.4
		TOTAL (ft3)	9328.3	284.5
		TOTAL (yd3)	345.5	-
		TOTAL (ton)	-	69.7

24"x24" Typical Column	Rebar	# bars	Reinf. Type	Reinforcement Weight per foot (lb/ft)	Total Volume (ft^3) concrete per ft length of column	Total Volume (ft^3) steel per ft length of column
	vertical reinf.	12	#9	3.4	3.9	0.11837
	horizontal reinf.	4 @12"	#5	1.043		

FIRST FLOOR BEAMS

BEAM DIMENSIONS						LONGITUDINAL REINFORCEMENT				HORIZONTAL REINFORCEMENT						
BEAM SCHEDULE	Count	Total length (ft)	DEPTH (IN.)	WIDTH (IN.)	Volume (ft^3) concrete	TOP REINF.	Volume (ft^3) steel per f length of beam	BOTTOM REINF.	Volume (ft^3) steel per f length of beam	STIRRUPS	length of steel per stirrup [ft]	Volume (ft^3) steel per ft length of beam	FACE BARS (1/2 EACH FACE)	Volume (ft^3 steel per ft length of	Total Volume (ft^3) steel per ft length of beam	Total volume (ft^3) steel
CB18x24	4	59.1	24	18	169.6	(10) #8 BARS	0.054	(10) #8 BARS	0.054	(2L) #5 @ 9"	7.333	0.021			0.130	7.671
CB16x24			24	16		(6) #9 BARS	0.062	(4) #9 BARS	0.028	(2L) #5 @ 9"	7.000	0.020			0.110	0.000
CB24x48	2	7.9	48	24	60.9	(12) #9 BARS	0.083	(12) #9 BARS	0.083	(2L) #5 @ 6"	12.333	0.053	(8) #9 BARS	0.069	0.288	2.279
CB18x36			36	18		(10) #9 BARS	0.069	(10) #9 BARS	0.069	(2L) #5 @ 6"	9.333	0.040	(2) #9 BARS	0.014	0.192	0.000
CB18x34	5	104.0	34	18	420.7	(12) #9 BARS	0.083	(12) #9 BARS	0.083	(2L) #5 @ 6"	9.000	0.038			0.205	21.304
CB18x18			18	18		(8) #9 BARS	0.056	(8) #8 BARS	0.044	(2L) #5 @ 9"	6.333	0.018			0.117	0.000
CB12x16	2	20.8	16	12	27.4	(4) #6 BARS	0.005	(4) #6 BARS	0.005	(2L)#4 @ 12	4.750	0.006			0.017	0.362
CB18x43	4	74.3	43	18	381.6	(12) #9 BARS	0.083	(12) #9 BARS	0.083	(2L) #5 @ 6"	10.500	0.045	(4) #9 BARS	0.028	0.239	17.757
				TOTAL (ft3)	1060.2										**TOTAL (ft3)**	49.4
				TOTAL (yd3)	39.3										**TOTAL (ton)**	12.1

SECOND/THIRD/FOURTH FLOOR BEAMS

BEAM DIMENSIONS						LONGITUDINAL REINFORCEMENT				HORIZONTAL REINFORCEMENT						
BEAM SCHEDULE	Count	Total length (ft)	DEPTH (IN.)	WIDTH (IN.)	Volume (ft^3) concrete	TOP REINF.	Volume (ft^3) steel per f length of beam	BOTTOM REINF.	Volume (ft^3) steel per f length of beam	STIRRUPS	length of steel per stirrup [ft]	Volume (ft^3) steel per ft length of beam	FACE BARS (1/2 EACH FACE)	Volume (ft^3 steel per ft length of beam	Total Volume (ft^3) steel per ft length of beam	Total volume (ft^3) steel
CB18x24	15	251.3	24	18	721.3	(10) #8 BARS	0.054	(10) #8 BARS	0.054	(2L) #5 @ 9"	7.333	0.021			0.130	32.617
CB16x24	2	25.6	24	16	65.4	(6) #9 BARS	0.062	(4) #9 BARS	0.028	(2L) #5 @ 9"	7.000	0.020			0.110	2.818
CB24x48			48	24		(12) #9 BARS	0.083	(12) #9 BARS	0.083	(2L) #5 @ 6"	12.333	0.053	(8) #9 BARS	0.069	0.288	0.000
CB18x36	1	18.1	36	18	78.0	(10) #9 BARS	0.069	(10) #9 BARS	0.069	(2L) #5 @ 6"	9.333	0.040	(2) #9 BARS	0.014	0.192	3.482
CB18x34	2	43.0	34	18	173.9	(12) #9 BARS	0.083	(12) #9 BARS	0.083	(2L) #5 @ 6"	9.000	0.038			0.205	8.808
CB18x18			18	18		(8) #9 BARS	0.056	(8) #8 BARS	0.044	(2L) #5 @ 9"	6.333	0.018			0.117	0.000
CB12x16	2	20.8	16	12	27.4	(4) #6 BARS	0.005	(4) #6 BARS	0.005	(2L)#4 @ 12	4.750	0.006			0.017	0.362
CB18x43			43	18		(12) #9 BARS	0.083	(12) #9 BARS	0.083	(2L) #5 @ 6"	10.500	0.045	(4) #9 BARS	0.028	0.239	0.000
				TOTAL (ft3)	1066.0										**TOTAL (ft3)**	48.1
				TOTAL (yd3)	39.5										**TOTAL (ton)**	11.8

ROOF BEAMS

BEAM DIMENSIONS						LONGITUDINAL REINFORCEMENT				HORIZONTAL REINFORCEMENT						
BEAM SCHEDULE	Count	Total length (ft)	DEPTH (IN.)	WIDTH (IN.)	Volume (ft^3) concrete	TOP REINF.	Volume (ft^3) steel per f length of beam	BOTTOM REINF.	Volume (ft^3) steel per f length of beam	STIRRUPS	length of steel per stirrup [ft]	Volume (ft^3) steel per ft length of beam	FACE BARS (1/2 EACH FACE)	Volume (ft^3 steel per ft length of beam	Total Volume (ft^3) steel per ft length of beam	Total volume (ft^3) steel
CB18x24	21	382.0	24	18	1096.4	(10) #8 BARS	0.054	(10) #8 BARS	0.054	(2L) #5 @ 9"	7.333	0.021			0.130	49.581
CB16x24	2	28.1	24	16	71.8	(6) #9 BARS	0.062	(4) #9 BARS	0.028	(2L) #5 @ 9"	7.000	0.020			0.110	3.093
CB24x48	2	7.9	48	24	60.9	(12) #9 BARS	0.083	(12) #9 BARS	0.083	(2L) #5 @ 6"	12.333	0.053	(8) #9 BARS	0.069	0.288	2.279
CB18x36	4	68.9	36	18	296.8	(10) #9 BARS	0.069	(10) #9 BARS	0.069	(2L) #5 @ 6"	9.333	0.040	(2) #9 BARS	0.014	0.192	13.255
CB18x34	2	43.0	34	18	173.9	(12) #9 BARS	0.083	(12) #9 BARS	0.083	(2L) #5 @ 6"	9.000	0.038			0.205	8.808
CB18x18	13	288.8	18	18	616.0	(8) #9 BARS	0.056	(8) #8 BARS	0.044	(2L) #5 @ 9"	6.333	0.018			0.117	33.812
CB12x16	1	10.3	16	12	13.6	(4) #6 BARS	0.005	(4) #6 BARS	0.005	(2L)#4 @ 12	4.750	0.006			0.017	0.179
CB18x43			43	18		(12) #9 BARS	0.083	(12) #9 BARS	0.083	(2L) #5 @ 6"	10.500	0.045	(4) #9 BARS	0.028	0.239	0.000
				TOTAL (ft3)	2329.5										**TOTAL (ft3)**	111.0
				TOTAL (yd3)	86.3										**TOTAL (ton)**	27.2