Mass Timber Connections Index: Optimal Connection Considerations

Erin Kinder, PE and Greg Kingsley, PhD, PE • KL&A Engineers & Builders

This paper is a companion piece to the Index of Mass Timber Connections, available on the WoodWorks website ***here****.*

The popularity of mass timber structures continues to grow throughout the United States as owners, developers, architects and contractors embrace the environmental benefits, aesthetics and increased construction speed of this innovative building type. As the number of structures increases, there is a heightened desire for detailed analysis of the cost drivers. It is generally understood that greater wood volume equates to increased cost, and it is therefore important to reduce member sizes as much as possible. It is also recognized that the cost of connections in a mass timber structure can significantly affect the overall project cost; however, because mass timber connection design must consider not only structural design but also aesthetics, fire-rating requirements, constructability, accommodations for shrinkage and swelling, and moisture protection, finding the optimal solution can be challenging. To assist designers in this effort, WoodWorks has published a simple index highlighting the spectrum of available structural and architectural mass timber connections. The intent is to facilitate the selection of cost-optimal connection types while balancing other important considerations. This paper focuses on the structural connections, addressing each of these considerations to inform users of the basis and intent of the index.

Connection Classes

To organize the index, structural connections were grouped into three categories or 'Connection Classes' that share common attributes regarding cost, constructability and fire rating. These classes are defined and illustrated in Table 1 as Class 1, Class 2 and Class 3. Class 1 connections require only mass timber elements and structural fasteners. Class 2 connections are custom steel fabricated elements, made up of components such as plates and angles, and include structural fasteners. Class 3 connections are prefabricated proprietary connectors available from suppliers such as Simpson Strong-Tie, Rothoblaas, MiTek and others. Class 3 connections are often backed by supporting tests for strength and fire rating.

Photo: JC Buck

Platte Fifteen
LOCATION: Denver, Colorado
OWNER: Crescent Real Estate LLC
ARCHITECT: Oz Architecture
STRUCTURAL ENGINEER: KL&A Engineers & Builders

In general, Class 1 connections are the least expensive and simplest to install, but they may not always meet other project constraints. Class 2 and 3 connections are generally more costly; however, Class 3 connections may be most appropriate when hidden connections are desired, or if fire-resistance ratings are important.

TABLE 1: Connection Classes

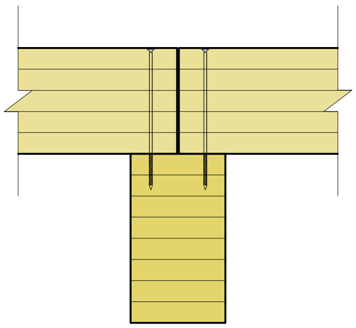
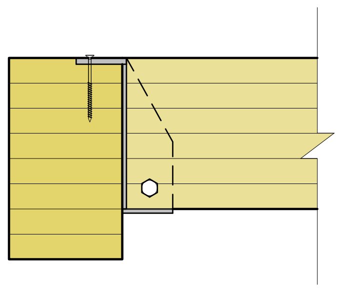
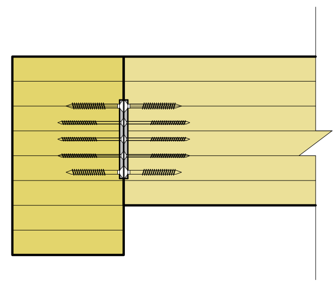
Connection class	**Class 1**	**Class 2**	**Class 3**
Class description	Requires only mass timber elements and fasteners	Utilizes steel fabricated elements, with components such as angles and plates, and includes fasteners	Prefabricated proprietary connectors
Connection example			
	Beam Bears on Girder*	Beam Bears on Steel Bearing Seat with Knife Plate*	Beam Connected to Girder with Proprietary Concealed Connector*

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

Mass Timber Connection Structural Basics

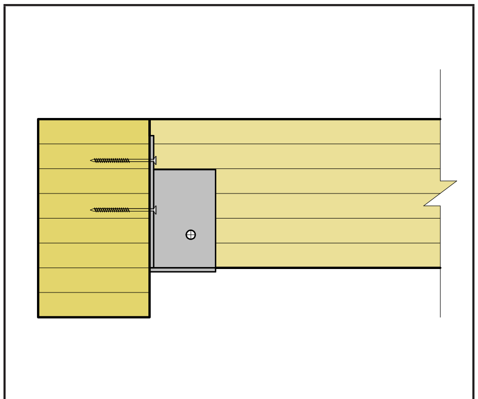
The design of mass timber connections should of course be based on well-established principles of structural mechanics. Minimum requirements and guidelines are standardized in a variety of sources, including but not limited to the following:

- International Building Code (IBC), International Code Council
- Minimum Design Loads and Associated Criteria for Buildings and Other Structures (ASCE/SEI 7), American Society of Civil Engineers
- *National Design Specification® (NDS®) for Wood Construction*, American Wood Council
- *APA EWS T300 – Glulam Connection Details Construction Guide*, APA – The Engineered Wood Association
- *Steel Construction Manual*, American Institute of Steel Construction (AISC)

For a typical mass timber connection, structural design considerations can include checking the parallel and/or perpendicular-to-grain capacity of the wood members, determining the type, size and quantity of fasteners, and any design checks required for the steel, concrete or masonry components of the connection. For example, for the connection shown in Figure 1, the supported beam at the right would be checked for perpendicular-to-grain bearing where it is supported by the steel bucket connection. The steel bucket would be designed in accordance with procedures outlined in the *Steel Construction Manual*, with the bolt connecting the beam to the steel bucket providing positive connectivity and located in accordance with APA EWS T300 guidelines to accommodate wood shrinkage over time. The screws into the girder would then be selected based on shear and withdrawal requirements, either calculated according to the NDS for wood screws or from capacities provided by the screw manufacturer for proprietary screws.

The load-carrying capacity of a connection will be based on material strength, bearing area, fastener type, size and length, and other factors. While load-carrying capacity of the connection is an important consideration, it is not the only factor. Because of this, each section of the index includes a variety of connection options. The final selection will depend on structural requirements, as well as those related to constructability and performance.

FIGURE 1:



Beam Bears on Steel Bearing Seat with Side Plates (Bucket)*

Table 8 in the* ***Index*

Connection Constructability and Performance

In addition to the structural capacity of the connection, several other important considerations must be accounted for in mass timber connection design, including aesthetics, construction tolerances, ease of construction, moisture and shrinkage concerns, fire rating and inspection requirements, and cost. These considerations are discussed in detail in the following sections.

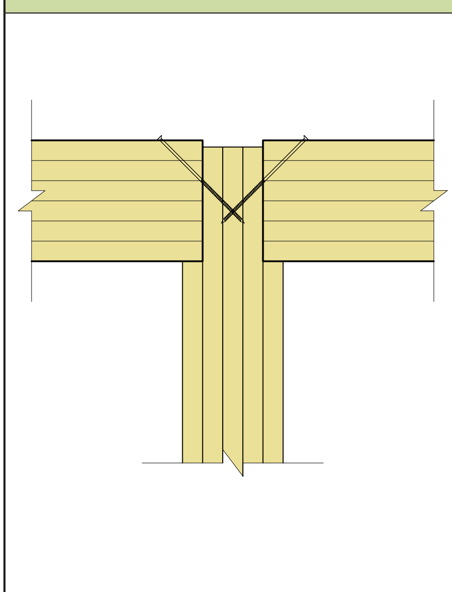
Aesthetics

One appealing aspect of mass timber construction is the potential to leave the wood structure exposed. The appearance of connections can then become an important driver guiding the design. The desired aesthetics for each project, architect and owner will vary. Sometimes it will be desirable to provide a seamless looking connection, where none of the hardware or fasteners are visible. In other cases, expressing the structural components of the connection will be preferred. In these cases, the surface treatment of the metal hardware is also an important consideration for aesthetics.

For example, Figures 2A and 2B show the connection of two beams to a column, one with modern screws in a concealed installation, and the other with an exposed cast metal connector common in early 20th century mill buildings. In most scenarios, either connection is a viable structural option, but the two connections have significantly different appearances and potentially different stiffnesses, though each may be adequate for the design loads.

FIGURE 2A:

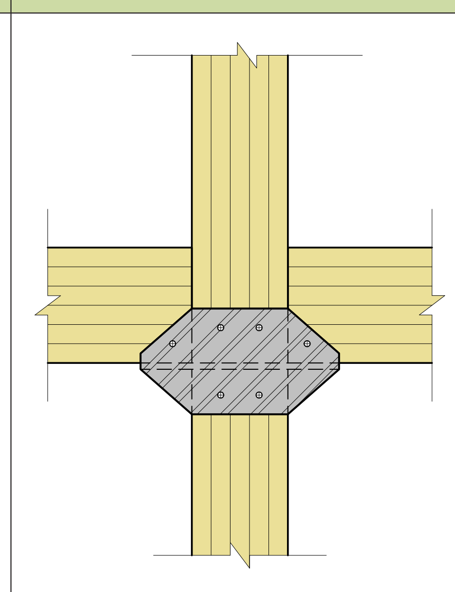
Connection Components Concealed



Multiple Beams Bear on Column at Notches*

FIGURE 2B:

Connection Components Visible



Multiple Beams Bear on Column Collar*

Table 9 in the* ***Index*

TABLE 2: Tolerance Solutions

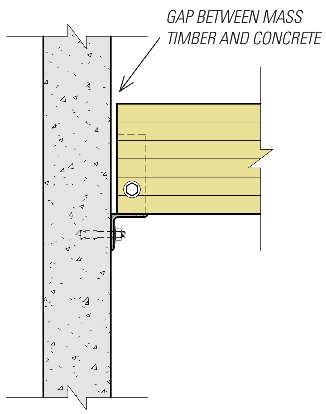
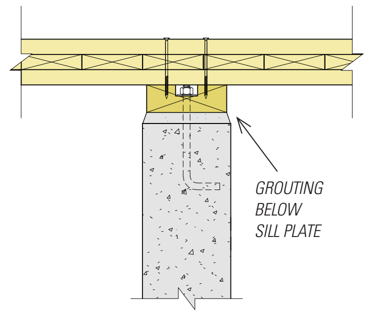
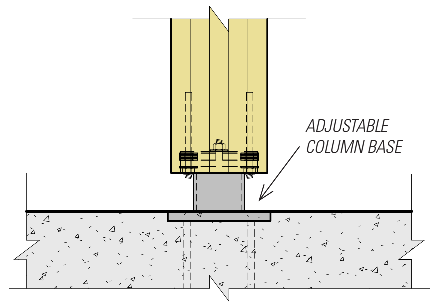
Solution	**Gap Between Mass Timber Beam and Concrete Wall**	**Grouting Below Sill Plate at Mass Timber Panel to Concrete Wall**	**Adjustable Column Base at Mass Timber Column to Concrete**
Connection example			
	Beam Perpendicular to Wall Connected to Face of Wall*	Panel Bears at Top of Wall**	Column Bears on Concrete with Adjustable Standoff Base***

Table 11 in the* ***Index* ***Table 5 in the* ***Index*** ****Table 15 in the* ***Index***

Construction Tolerances

Mass timber is often fabricated with exceptionally tight tolerances for overall size, as well as size and locations of holes, notches and any other alterations, and can be constructed to within as little as +/- 1/16-in. of the specified dimensions. While this is extremely beneficial when connecting mass timber members to each other, it presents a challenge when attaching mass timber elements to other materials with allowable tolerances that may be much larger. To maximize constructability, it is essential to consider these different tolerances during design and not in the field. For example, the connections in Table 2 show three scenarios with possible solutions to address the different tolerances between concrete and timber: allowing for a gap between members of differing materials, specifying grout as a means of adjusting elevations, and providing built-in adjustability in the connection itself. While these are relatively straightforward to incorporate during the design phase, fixes in the field can be much more involved, time-consuming and costly.

Constructability

Mass timber construction can largely be compared to a construction kit. The pieces are precisely fabricated off site and delivered to the site ready to be fit together. There are, of course, strategies and designs that can make the construction kit analogy more or less applicable. Where mass timber interfaces with other materials like concrete and steel, the system should be designed to accommodate construction tolerances, including the effects of less precisely constructed parts of a building (e.g., foundations). It is also essential to have conversations with the contractor and wood supplier prior to construction, or even better, during the design phase, to discuss sequencing and other aspects of construction that can be influenced by design decisions.

The contractor may have preferred suppliers, sequencing (balloon versus platform framing), equipment height and/or weight limitations, as well as preferred connection details and fastener types based on prior experience with mass timber structures. The builder's comfort with these aspects of the project can affect their ability to control risk and therefore cost.

Mass timber construction has not been standardized in the same way as steel or light wood-frame construction, and it is therefore important to work with the supplier when possible to determine optimal building and connection geometries. A mass timber supplier may have preferred connection details, cut, notch and skew limitations, or preferred fastener types, for example. Suppliers will also have varying levels of manufacturing and fabrication (e.g., computer numerical control, or CNC) capabilities that can influence preferred and feasible detailing. Suppliers have a wealth of knowledge regarding potential connections and early collaboration can lead to alternate designs that are beneficial to the project. As a simple example, the supplier may be able to suggest connections that minimize handling of large pieces either in the shop or on site to minimize cost.

Contractor and supplier preferences can have a large impact on both the construction schedule and overall project costs. Due to supplier or contractor constraints, a connection that appears to be more expensive may in fact be the economical choice for a specific project.

Moisture & Shrinkage

Wood is by nature a porous material, making it susceptible to natural environmental conditions and moisture fluctuations that are site dependent. When the moisture content in wood increases, the member swells. When the moisture content decreases, it shrinks. Both swelling and shrinkage are a natural part of wood structural behavior, but either can cause damage if not properly addressed in design and construction.

For example, in the 'Panel Bears on Beam' connection shown in Table 3, swelling of the wood panel could cause the head of the screw to stretch upward, subjecting the screw to unanticipated and potentially large tension stresses. If the wood panel were to shrink, the screw head could then be exposed above the top of the panel and could be a tripping hazard or damage the finishes above the panel. The solution to these problems involves careful selection of screw heads, depth of countersink and thread length, and water management on site.

In the 'Beam Bears at Top of Concrete Column or Wall' connection in Table 3, the bolt that connects the wood member to the knife plate can constrain the member at the connection. If the wood beam were to shrink, there could be delamination and cracking between the plies of the beam as multiple bolts restrict vertical movement of the member. If the beam were to swell, there could be crushing damage of the beam at the base plate and between multiple bolt holes. To account for both shrinkage and swelling in the beam, use of a single bolt as close to the base plate as is practical would be preferable, and the holes in either the beam or steel tab could be vertically slotted or oversized to allow for movement between the bolt and the wood. It should be noted that changes in moisture content can also reduce the lateral design values per NDS Table 11.3.3.

Moisture fluctuations can also be an aesthetic consideration. Moisture infiltration can discolor the wood directly or by contact with unprotected metal connection components, which may not be acceptable for exposed members. The ends of wood members are especially susceptible to moisture infiltration and should be appropriately protected. Keep in mind that concrete itself can be a source of moisture, making moisture an important consideration at all wood-to-concrete connections.

TABLE 3: Shrinkage/Swelling Solutions

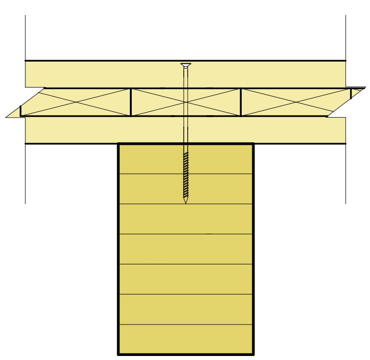
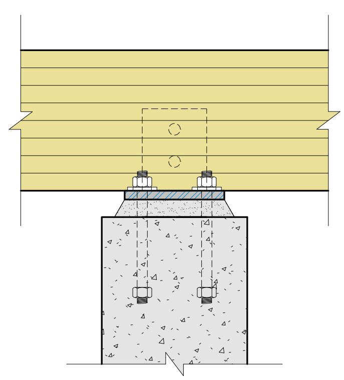
Moisture concern	**Screw Placement**	**Bolt Placement**
Potential solution	Appropriate selection of screw head, depth of countersink and thread length	Use single bolt placed low on beam
Connection example		
	Panel Bears on Beam*	Beam Bears at Top of Column or Wall**

*Table 2 in the **Index**

Table 11 in the **Index

Fire Rating

Mass timber structures may need to meet fire-resistance rating requirements based on the building type, as outlined in the IBC. Mass timber has a recognized inherent fire resistance due to its mass and ability to form a protective char layer during a fire. More information on this phenomenon can be found in the following resources:

- *Technical Report No. 10: Calculating the Fire Resistance of Wood Members and Assemblies*, American Wood Council[i]
- The *CLT Handbook*, FPInnovations[ii]
- *Fire Design of Mass Timber Members: Code Applications, Construction Types and Fire Ratings*, WoodWorks[iii]
- *Demonstrating Fire-Resistance Ratings for Mass Timber Elements in Tall Wood Structures*, WoodWorks[iv]

The inherent fire resistance of mass timber is calculated in accordance with Chapter 16 of the NDS. Where a fire-resistance rating is required, both the members and connections must be fire rated. Both the IBC and NDS require connections of fire resistance-rated members to be protected for the full fire-resistance rating time. The NDS allows the use of wood, gypsum or other approved materials.

Connections that are tested as part of a fire resistance-rated assembly do not require additional protection. Some or all of these strategies will be options for each project, based on the building type as defined in the IBC. A list of fire-rated assemblies can be found in WoodWorks' *Inventory of Fire Resistance-Tested Mass Timber Assemblies & Penetrations*.[v] It is also recommended to work with the local Authority Having Jurisdiction (AHJ) to understand any jurisdiction-specific requirements or interpretations of the code. Unanticipated code interpretations from the AHJ late in the project could have significant cost implications.

Many Class 1 connections (requiring only wood members and fasteners), depending on their size and load requirements, may be inherently fire resistant. Class 2 connections (incorporating custom steel fabricated elements) will often require additional protection to meet fire-rating requirements, and Class 3 connections (proprietary connectors) are typically approved under alternative methods and materials provisions of the building code. Many have fire performance testing data available or may require additional protection. Examples of Class 1, 2 and 3 connections with respect to fire-rating requirements can be seen in Table 4.

TABLE 4: Connection Class in Relation to Fire Rating

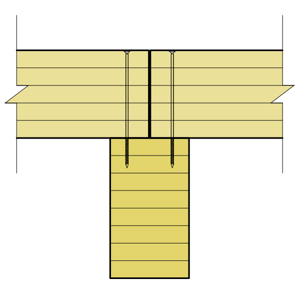
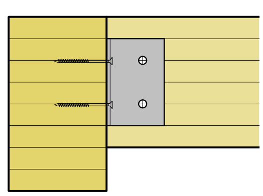
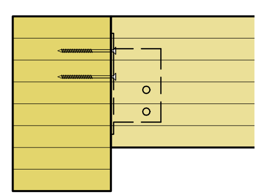
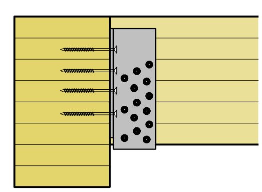
Connection class	**Class 1**	**Class 2**	**Class 3**	**Class 3**
Fire resistance	May be inherently fire resistant according to NDS calculations	Requires additional protection to meet fire-rating requirements	Tested fire-resistance rating (as specified by manufacturer)	Requires additional protection to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

*Table 8 in the **Index**

Inspections

Inspection requirements are currently fairly limited in the 2015 and 2018 IBC for mass timber structures. These have been expanded in the 2021 IBC for Type IV-A, IV-B and IV-C building types. It is likely that, as mass timber construction becomes more common, the building code will define required inspections more explicitly. However, some jurisdictions or specific building occupancies may already necessitate more rigorous inspections, or the engineer of record may think it appropriate to inspect certain connections. Typically, jurisdictions in hazardous wind or seismic regions require more inspections of connections if the mass timber element is part of lateral force-resisting system (LFRS). Potential inspection items include bearing area, fastener type and spacing, steel sizes, and grout and/or embed placement. The inspection strategy will depend on whether the connection and fastener are visible once installed or require in-progress inspection, and whether the connection must be inspected more than once to verify appropriate installation. Depending on the required inspections, it may be advantageous to alter a connection.

Cost Considerations

As can be inferred from above, cost is just one component in selecting the appropriate connection, and each of the above constraints can influence cost in some way. Still, there are several things that can be done to optimize the cost of connections for any given structure. As in many projects, early communication is key. This includes communication with the architect and owner to understand their vision for the completed structure, with the AHJ to understand their interpretation of fire protection and inspection requirements, and with the contractor and suppliers to account for construction and fabrication considerations.

Fastener selection can also play a significant role in connection cost. Depending on the connection, the fastener could be a nail, partially-threaded screw, fully-threaded screw, bolt or dowel. Some timber connections require no metal components at all. Suppliers, fabricators and contractors may have preferred fastener manufacturers and types. However, in general, nails, and specifically nail gun nails, are the least expensive fastener, followed by collated screws, partially-threaded screws, fully-threaded screws, and finally bolts. Nail gun nails are also usually the quickest and easiest to install, while bolts are generally more involved and time consuming. However, depending on the connection, this may not be the case, as it may be impractical to use certain fastener types.

In general, connecting different materials is inherently more expensive—and mass timber construction is no exception. There will likely be a cost increase when attaching mass timber elements to steel, concrete or masonry elements due to the involvement of multiple trades and consideration of differential tolerances. In most mass timber projects, other materials are also used, so careful consideration of the number and detailing of these connections can help mitigate added costs.

Class 1 connections are typically the least expensive and simplest to install. Depending on other requirements, such as aesthetics, fire ratings, inspections, or the ability to use the same connection multiple times on a project, Class 2 or 3 connections may be preferred and provide an overall cost reduction.

Conclusion

Design of mass timber connections is clear if based on the required capacity of the connection and standard mechanics. However, selection of the appropriate connection for a given mass timber structure is less straightforward and requires consideration of aesthetics, moisture, fire rating, inspection requirements, cost and other aspects of the project. Each project will have its own set of constraints, which should be weighed to determine the optimal connection design. The designers will likely find it helpful to coordinate with the contractor and supplier very early in the design phase and/or create a performance specification for more repetitive conditions.

References

[i] https://www.awc.org/pdf/codes-standards/publications/tr/AWC-TR10-1510.pdf

[ii] https://info.thinkwood.com/clt-handbook

[iii] https://www.woodworks.org/wp-content/uploads/Wood_Solution_Paper-Fire-Design-of-Mass-Timber-Members-WoodWorks-Apr-2019.pdf

[iv] https://www.woodworks.org/wp-content/uploads/wood_solution_paper_Fire-Resistance_Mass_Timber_Tall_Wood_TechNote.pdf

[v] https://www.woodworks.org/wp-content/uploads/Inventory-of-Fire-Resistance-Tested-Mass-Timber-Assemblies-Penetrations.pdf

Updated September 1, 2021