Mass Timber Engineering

Something Old and Something New

By Jim DeStefano, P.E., AIA, F.SEI

Portland Jetport's glulam timber roof structure. Courtesy of Robert Benson Photography.

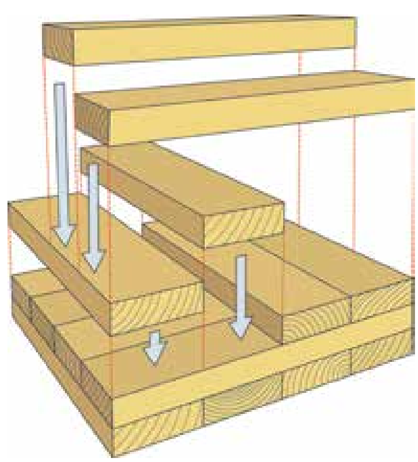
Mass timber is not a new idea, just a new name. Many people have heard the term "mass timber" batted around in the last few years, but not everyone has a clear understanding of what it means. Mass timber used to be referred to as "heavy timber" and the *International Building Code* (IBC) classifies it as Type IV construction.

Mass timber is a type of structure made up of big, fat pieces of wood that, unlike light wood frame construction, burn slowly. Because mass timber structures maintain their integrity during a fire without the need for layers of fire-resistant materials, they are suitable for larger buildings and the IBC recognizes that.

Timber buildings have been built for over 4,000 years – since bronze-age man developed the technology to forge sharp tools that could hew trees into square timbers and fashion mortise and tenon joints. Timber structures were the dominant construction type in Europe, Asia, and North America until 1850 when balloon-frame wood structures began to displace timber construction. By the turn of the 20th century, timber construction was nearly extinct and structural iron construction was becoming commonplace for larger structures.

Following World War II, glulam timber construction became popular for long-span and architecturally exposed applications such as church roofs. At the time, if you wanted a structure that looked like timber, glulam construction was your only choice. That is no longer true.

In the 1970s, traditional timber frame construction experienced a revival. A small, core group of timber craftsmen, mostly located in northern New England, rediscovered and mastered the lost art of crafting timber structures with intricate joints. By the 1990s, timber frame construction had re-entered mainstream construction and was displacing glulam construction for architecturally exposed structures.



CLT panel layup with alternating plies of dimension lumber. Courtesy of WoodWorks.

CLT panels are available up to 10 feet wide and over 60 feet long. Courtesy of WoodWorks.

So, What's New?

Timber panels are new – Cross-Laminated Timber (CLT) and Dowel Laminated Timber (DLT). CLT has been used in Europe since the 1990s but has only been available in North America for a little more than a decade. Today, there are five major manufacturers of CLT in North America and one producer of DLT. The availability of timber panels has stimulated interest and excitement in the architectural community for building with mass timber.

Modern mass timber structures typically consist of a glulam timber frame supporting CLT or DLT floor and roof panels, often with CLT shear walls. This type of construction is extremely versatile and is suitable for both large and small structures – anywhere that an architecturally exposed structure is desired. It does not make much sense to build with timber and then cover it up with sheetrock and hung ceilings. By the way, industry experts continue to express that mass timber construction is also very sustainable, sequesters carbon, and is cost-effective.

CLT, NLT, and DLT

Cross-Laminated Timber has often been described as plywood on steroids. It is made up of alternating plies of dimension lumber that has been planed to approximately $1\frac{3}{8}$-inch thickness. Like plywood, each ply is oriented perpendicular to its adjacent plies. Common CLT layups are 3-ply ($4\frac{1}{8}$-inch), 5-ply ($6\frac{7}{8}$-inch), and 7-ply ($9\frac{5}{8}$-inch). CLT panels are typically 8 feet or 10 feet wide and up to 60 feet long.

The structural design of CLT panels is covered in Chapter 10 of the *National Design Specification® (NDS®) for Wood Construction*. Effective section properties and reference design values can be found in ANSI/APA PRG 320-2018, *Standard for Performance-Rated Cross-Laminated Timber*.

T3 Office Building's Nail Laminated Timber panels on glulam framing. Courtesy of Bergerson Photography.

Mystic Seaport Exhibition Building's glulam timber connections transfer structural loads in bearing with minimal exposed bolts and steel hardware.

Nail-Laminated Timber (NLT) panels are made up of dimension lumber (typically 2x6s) laid side-by-side and spiked together with nails. NLT is not a new thing and has been used infrequently for over a century. The advantage of NLT construction is that it does not require specialized fabricating equipment to manufacture, and it can even be built on-site. The disadvantage is that NLT panels require a significant number of nails that are labor intensive to install and make it impossible to cut the panels with Computer Numerical Control (CNC) equipment without the embedded nails destroying the cutter-head.

Dowel-Laminated Timber panels are the newest alternative. DLT is similar to NLT, except that it contains no nails. Transverse hardwood dowels are used instead of nails to bond the panels. Unlike NLT, DLT panels lend themselves to CNC fabrication.

Reaching for the Sky

High-rise construction has long been the exclusive domain of structural steel and reinforced concrete, but that is starting to change. Mass timber is now a player in the high-rise market. Brock Commons in Vancouver is currently the tallest mass timber building in North America, topping out at 18 stories. In the world of tall buildings, 18 stories may not sound all that impressive, but, for wood construction, it is a big deal.

It is unlikely that mass timber is going to displace structural steel and reinforced concrete for high-rise construction completely, but we will see more tall, mass timber projects and will probably be seeing a lot more mass timber and structural steel hybrids, especially with anticipated changes coming in the 2021 IBC. The 2021 IBC will permit buildings up to 18 stories to be constructed of mass timber.

Getting Connected

Timber engineering is all about the connections. Sizing the timbers and panels is the easy part. Designing timber connections is the challenging part. It has been said that a structure is essentially an assembly of connections that happen to be separated by beams and columns, and that is especially true of timber structures.

18-story Brock Commons. Courtesy of www.naturallywood.com.

Many engineers that are inexperienced with timber engineering will attempt to connect timbers in a fashion similar to structural steel construction, with bulky side plates and lots of bolts. While this approach sometimes works, it is seldom the most practical or efficient way to make a timber connection, and it is rarely the most aesthetically pleasing solution for an exposed structure.

It is smarter to configure connections and connection hardware so that structural loads are transferred primarily in bearing and bolts are only relied on to resist incidental loads.

Timber is an organic material that shrinks and swells seasonally with changes in humidity. Failure to consider timber dimension changes associated with moisture content when designing connections can lead to disappointing (or dangerous) results. Steel gusset plates can restrain dimension change movements resulting in the splitting of the timbers (for more on this, see the February 2004 issue of STRUCTURE).

Fired Up

It is a common misconception that because wood is combustible, wood buildings perform poorly in a fire. While that may be true of light wood frame construction, it is not at all true of mass timber.

Timbers will develop a char layer on the surface when exposed to a flame. The char layer progresses slowly and insulates the wood beneath it from the heat of the fire, permitting the timbers to continue to carry load. When timber structures do eventually fail during a fire, they do not fail suddenly. They typically give firefighters ample warning prior to a collapse by making loud cracking and hissing noises. The exception is, when steel connection hardware is exposed to the fire, the connections will fail suddenly. It is important to protect steel connection hardware either with an intumescent coating or preferably by having all steel hardware embedded inside the timbers where the wood can protect the steel from the fire.

Unlike most other structural systems, the fire-resistance rating of mass timber assemblies or elements is based on a structural analysis rather than on the listed results of an ASTM E119 fire test. Chapter 16 of the NDS has a procedure for calculating the fire-resistance rating. The thickness of the char layer on the timber is stipulated for different time intervals. For instance, if a 1-hour fire rating is required, the NDS stipulates that the char layer on a timber is 1.8-inch-thick after 1 hour of fire exposure. It is then a simple matter of calculating the remaining section properties of a timber with 1.8 inches of wood removed from the exposed perimeter and determining if the reduced section is capable of supporting the applied dead loads with a stress increase to convert allowable stress to ultimate stress. The fire-resistance calculation for a CLT panel is similar, except the stipulated char thicknesses are a little different. A 5-ply CLT is needed if a fire rating is required since there is not much left of a 3-ply CLT if the bottom ply burns away.

Serviceability Considerations

The design of mass timber floor systems is typically not controlled by strength, but by serviceability – principally sound transmission and vibration.

Bare timber floors will readily transmit sound, particularly impact sound associated with footfalls. It is common to install an acoustic mat over the timber floor with a non-composite concrete topping slab or gypcrete topping to address sound transmission.

Floor vibration associated with foot traffic must be evaluated. Designing to an arbitrary static deflection limit such as L/360 or L/480 will not ensure that a floor structure does not feel bouncy, particularly if the floor structure has a period of vibration less than 9.0 Hertz.

Hybridization

Mass timber plays well with other structural materials. Often the right structural solution for a project is not a pure mass timber structure, but a hybrid solution. CLT floor and roof panels with glulam joists, structural steel girders and columns, and a concrete topping slab often make for a very efficient structure. The structural steel elements often require an intumescent coating to achieve a fire resistance comparable to the timber elements.

For the 18-story Brock Commons project, reinforced concrete shear walls resist wind and seismic loads. Mass timber shear walls could have done the job, but for a variety of reasons, it just made more sense to use concrete. There is no shame in not being a purist.

Design or Delegate

It is not uncommon for a Structural Engineer of Record to delegate design responsibility to a specialty timber engineer engaged by the contractor. Sometimes, responsibility for engineering just the timber connections is delegated, but occasionally an engineer will delegate responsibility for engineering the entire timber structure. In such cases, it is best to engage the specialty timber engineer during the design phase of the project. Otherwise, the bidding process can turn into a circus.

So how much of the timber engineering should be performed by the Engineer of Record and how much should be delegated? The answer depends on how much prior experience the engineer has with timber structures. The best advice is for the Engineer of Record to do as much as he is competent to do and delegate only what he is inexperienced at.

Resources

So, where can an engineer turn to get more information on mass timber engineering? The *Timber Frame Engineering Council* (TFEC) is an organization of structural engineers who specialize in timber. The TFEC has produced a library of documents that offer design guidance, including a *Standard for Design of Timber Frame Structures, Code of Standard Practice*, master specifications, and technical bulletins, all of which are available free of charge at **https://bit.ly/2S7H7fp**.

The *CLT Handbook* produced by FPInnovations offers a wealth of practical information.

The *WoodWorks* team is also always willing to offer design assistance and to point engineers and architects in the right direction.▪

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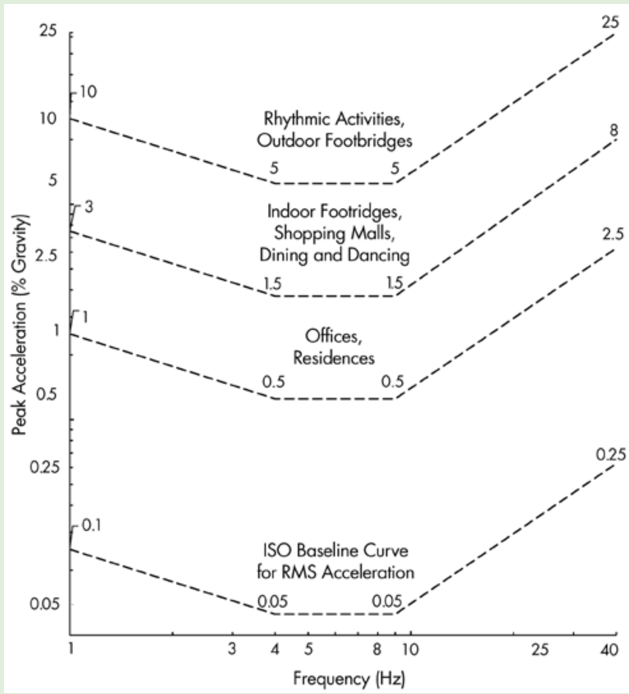
Mass Timber Floor Vibration

By Lucas Epp, P.Eng.

The maximum span of many floor systems is often controlled by limiting occupant perception of vibrations rather than strength or deflection. This is the case for long span concrete and steel floor framing, high-performance, light frame floors, and mass timber floors. The unsettling performance of a bouncy floor is typically caused by resonance between human walking frequencies (1.6-2.0 Hz) and the floor's natural frequency. If the walking pace is a multiple of floor frequency (e.g., walking at 2.0 Hz causing a floor at 6.0 Hz to vibrate), resonance can occur and the resulting accelerations can be disconcerting, particularly in longer-span structures with low damping.

For mass timber floors, rule-of-thumb guidance such as limiting the floor's fundamental frequency to above 8.0 Hz, or limiting the deflection under a unit point load, has been used in an attempt to avoid floors which perform poorly. However, simply limiting the natural frequency of the floor does not guarantee good performance. A better estimate of floor performance is the accelerations, which result from walking activities. These accelerations depend not only on the natural frequency, but also the amount of floor mass being mobilized, the damping in the system, the length of the walking path, and the frequency of occurrence. Human sensitivity to accelerations is a grey area and recommended limits on permissible accelerations for various use cases vary significantly between different guidelines. (*See Figure*)



Recommended peak acceleration tolerance limits for human comfort, after Allen and Murray (1993), Design Criterion for Vibrations Due to Walking.

Guides such as AISC Design Guide 11 (*Vibrations of Steel-Framed Structural Systems Due to Human Activity*, 2016) provide detailed approaches to calculate accelerations on floor plates. There are also several European guides which provide similar guidelines with different calculation approaches.

Calculating accelerations on a given floor plate can be done using finite element software, but this is an involved analysis and simpler guidance is needed to assist in early stage design and scheming.

Current Design Guidance

For mass timber floors, there are various guidelines in North America and Europe which have been developed to determine allowable vibration-controlled spans.

The *CLT Handbook* (FPInnovations, 2013) presents a formula which limits the span based on a combination of deflection under a unit point load and natural frequency. This criterion, however, ignores the contribution of different damping levels, the weight of any superimposed mass (such as concrete topping), and any added flexibility of supporting structure, all significant factors in vibration performance. The *CLT Handbook* formula results in the following maximum spans for typical CLT layups (ANSI/APA PRG 320, 2018):

4⅛-inch-thick, 3-ply CLT – 11 feet to 12 feet

6⅞-inch-thick, 5-ply CLT – 16 feet to 17 feet

9⅝-inch-thick, 7-ply CLT – 20 feet to 21 feet

Concrete topping is often required on mass timber floors to generate sufficient acoustical separation between floors. This topping increases the modal mass (i.e., participating mass that needs to be excited by footfall), directly affecting the accelerations which would be felt on the floor plate.

In Europe, the guidance for mass timber floors in *Eurocode 5* (EN 1995-1-1) states that, for floors with a natural frequency (f) > 8.0 Hz, the deflection under a 225-pound point load should be limited to less than $\frac{1}{16}$ to $\frac{1}{32}$ of an inch. For floors with f < 8.0 Hz, the *Eurocode* recommends calculating accelerations and limiting these to 0.5 to 1.5% gravity.

For early-stage design with panels supported on bearing walls, the *CLT Handbook* formula can be used only as an initial estimate of the maximum vibration-controlled span. For panels spanning onto beams, this formula is unconservative and more detailed acceleration analysis should be undertaken, as the beams contribute significantly to the flexibility of the system.

Currently, there is ongoing research to develop more accurate simplified criteria, as well as a robust guidance document for vibration design of mass timber floors. The *US Mass Timber Floor Vibration Design Guide* will be published by WoodWorks in 2020 and will contain more details on both analysis methods and acceptance criteria.

For further information and design guidance, refer to TFEC Bulletin 2019-14, *Vibration Design of Mass Timber Floor Systems*.

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