World Conference on
Timber Engineering
Oslo 2023

DIFFERENTIAL MATERIAL MOVEMENT IN TALL MASS TIMBER STRUCTURES

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ABSTRACT: As mass timber buildings reach unprecedented heights, not to be overlooked in the design and detailing of these structures is the effects of vertical movements, particularly due to their cumulative. Glulam column shrinkage, joint settlement, and creep can affect vertical mechanical systems, exterior enclosures, and interior partitions, as well as differential create challenges where timber framing systems move relative to other structural systems such as concrete core walls. This paper analyzes the reasons for vertical movement (both short and long term), provides methods of calculating anticipated movement, compares calculated movement to on-site verified movement, highlights detailing options, and discusses vertical movement strategies implemented on tall mass timber projects completed in North America.

KEYWORDS: Creep, Settlement, Shrinkage, Crushing, Movement, Deflection, Columns, Monitoring, High-Rise

1 INTRODUCTION

As the height of mass timber buildings continues to grow, a new set of design and detailing challenges arises, creating the need for new engineering solutions to achieve optimal building construction and performance. One necessary detailing consideration is vertical movement, which includes column shrinkage, joint settlement, and creep.

2 TALL MASS TIMBER

U.S. interest in tall timber buildings, i.e., buildings that exceed height and area limits prescribed in the 2018 and previous versions of the International Building Code (IBC), has steadily increased over the past several years. With the introduction of three new construction types in the 2021 IBC—Types IV-A, IV-B and IV-C, which allow up to 18, 12 and nine stories of mass timber construction respectively—these projects are also getting built. Currently, more than 10% of the mass timber buildings in design or built in this country exceed the 2018 prescriptive height limits. Tall projects such as Heartwood in Seattle, 1510 Webster in Oakland, Ascent in Milwaukee, INTRO in Cleveland, 11 E Lenox in Boston, and 80M in Washington DC are either under construction or completed and occupied. At the time of writing, several others are set to break ground.

As the height of mass timber buildings continues to grow, a new set of design and detailing challenges arises, creating the need for new engineering solutions to achieve optimal building construction and performance. One necessary detailing consideration is vertical movement, which includes column shrinkage, joint settlement, and creep. The main concerns are the impact of deformations on vertical mechanical systems, exterior enclosures, and interior partitions, as well as differential vertical movement of timber framing systems relative to other building features such as concrete core walls and exterior façades. This paper analyzes the reasons for vertical movement (both short and long term), provides methods of calculating anticipated movement, compares calculated movement to on-site verified movement, highlights detailing options, and discusses vertical movement strategies implemented on tall mass timber projects completed in North America.

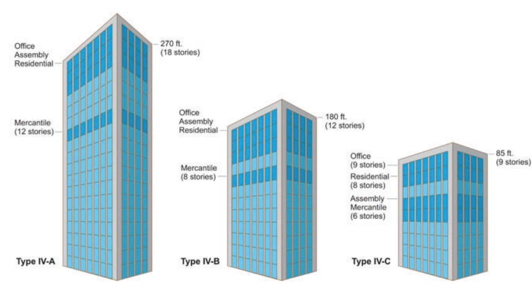

Figure 1: *Introduced with the 2021 IBC, Types IV-A, IV-B, and IV-C construction allow up to 18, 12 and nine stories of mass timber (respectively). Credit: WoodWorks*

3 SOURCES OF VERTICAL MOVEMENT

Vertical movement occurs in all buildings, regardless of height and structural materials used. The key to mitigation is to understand all potential sources of movement, calculate the sum of the ones predicted, and provide connection details that minimize movement and its effects while allowing for field adjustability. Most tall mass timber projects use a structural system of timber beams and columns supporting mass timber floor and roof panels. The columns and beams are usually glue-

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https://doi.org/10.52202/069179-0383

laminated timber (glulam), though structural composite lumber (SCL) can also be used, and options for the panels include cross-laminated timber (CLT), nail-laminated timber (NLT) and dowel-laminated timber (DLT), among others. It is common for the vertical lateral force-resisting systems to be non-wood—e.g., concrete shear walls and steel braced frames. As the primary vertical elements in a tall mass timber building, the timber columns have a significant impact on the net vertical movement of the building. However, the connections of column to column, beam to column and floor panel to column can also play a significant role. Not only should the net vertical movement of the timber columns and connections be considered, so too should the movements of these elements relative to other building systems which may not be moving to the same degree or in the same direction (e.g., timber column movement relative to concrete core wall movement).

The main sources of vertical movement in tall mass timber structures, all of which are addressed in this paper, include:

- Column axial shortening
- Column creep
- Column, beam and panel shrinkage
- Beam and panel crushing perpendicular to grain
- Settlement at connections

Figure 2: *Example column and beam connection at 80M in Washington DC, designed by Hickok Cole*
Credit: WoodWorks

4 BUILDING CODES AND STANDARDS

Applicable building codes and standards vary based on the project's location, the jurisdiction's adopted building code, and any relevant amendments. The following codes and standards commonly apply to tall mass timber buildings.

International Building Code (IBC)
The IBC is a model building code developed by the International Code Council (ICC). Adopted as a base code by most jurisdictions in the U.S., it addresses health and safety concerns for buildings based on prescriptive and performance requirements. This document refers to the 2021 IBC unless otherwise noted.

Chapter 35 of the IBC provides a list of referenced standards, which represent consensus on how a material, product or assembly is to be designed, manufactured, tested or installed to achieve a specified level of performance. Standards that address vertical movement topics are noted below. Additionally, IBC Section 2304.3.3 requires that wood-framed projects greater than three stories include an analysis of the effects of shrinkage. It stipulates that shrinkage in a wood building not have adverse effects on systems such as roof drainage, electrical, mechanical, or other equipment.

National Design Specification® (NDS®) for Wood Construction
Published by the American Wood Council (AWC), the NDS defines the methods to be used in the structural design of wood members and connections. It contains information related to the design of mass timber products including CLT, glulam and SCL. Topics in the NDS that can impact vertical movement include creep and wood crushing when loaded perpendicular to grain.

Product Standards such as ANSI/APA PRG 320 Standard for Performance-Rated Cross-Laminated Timber and ANSI 190.1 Standard for Wood Products – Structural Glued Laminated Timber
Standards for mass timber products typically include dimensional tolerances. For example, PRG 320 requires that the actual width of a CLT panel be within +/- 3.175 mm (1/8-in.) of the specified width, and actual panel length be within +/- 6.35 mm (1/4-in.) of the specified length. Glulam columns up to 6.1 m (20 ft) long must have an actual length within +/- 1.59 mm (1/16-in.) of the specified length. These tolerances can impact vertical movement, particularly at connections.

Note that the abovementioned codes and standards do not contain explicit information on some aspects of vertical movement in tall timber structures. For example, calculations for determining shrinkage in wood members are not detailed in codes and standards, nor is the creep factor for column axial shortening. As such, engineering judgement is necessary and other sources of information are relied on. As with any circumstance requiring the use of engineering judgement, it is the responsibility of the engineer to use the most current information, research, test results, etc. to inform or validate assumptions made. The following sections note several *possible* methods of quantifying vertical movement in tall timber buildings. This information is intended to demonstrate options for quantifying these movements; it is not intended to cover all the options or solutions.

5 QUANTIFYING VERTICAL MOVEMENT

5.1 COLUMN AXIAL SHORTENING

Axial forces on any structural column, be it timber, steel or concrete, cause shortening of the member. Using the

https://doi.org/10.52202/069179-0383

principles of mechanics of materials, the axial shortening of a column is calculated with the equation:
$\Delta_{as} = PL/(AE)$

Where:

- Δ_{as} = column axial shortening (mm or in.)
- not including creep effects
- P = axial load supported by the column (N or lbs)
- L = length of the column (mm or in.)
- A = cross-sectional area of the column (mm^2 or in^2)
- E = modulus of elasticity of the column (kPa or psi)

Following is an example axial column shortening calculation. Note that this is an arbitrary design example and is not related to the actual project examples in the on-site verification information contained in the full document.

- Axial load of 200.2 kN (45,000 lbs) of which 89 kN (20,000 lbs) are dead load, and 111.2 kN (25,000 lbs) are live load, duration of load factor = 1.0
- Assume a 222 mm x 229 mm (8-3/4-in. x 9-in.) Douglas-fir glulam column, layup combination 2
- Column length = 4.6 m (15 feet)
- F'c = 13,445 kPa (1,950 psi)
- E = 11,031,612 kPa (1,600,000 psi)

$\Delta_{as} = PL/AE = (200.2)(4600)/((222*229)(11,031,612/1000^2) = 1.6$ mm
Or $(45,000)(15*12)/((8.75*9)(1,600,000)) = 0.06$ in.

Section 3.5 of the NDS discusses creep effects of long-term loading on deflection of bending members. Although this section of the NDS is directly applicable to bending members, it is not uncommon to also apply creep calculations to axial column deformations (shortening). Equation 3.5-1 in the NDS provides a method of quantifying the deformation effects of long-term loading on bending members.
$\Delta_{as,T} = K_{CR}\,\Delta_{LT} + \Delta_{ST}$, where:

- $\Delta_{as,T}$ = column axial shortening including creep effects (mm or in.)
- K_{CR} = time-dependent deformation creep factor
  - If we assume the creep factor for axial compression is the same as for bending,
- K_{CR} = 1.5 for seasoned timbers, glulam or SCL used in dry service conditions.
- Δ_{LT} = immediate deformation due to long-term loading (mm or in.)
- Δ_{ST} = deformation due to short-term loading (mm or in.)

For the column in the above example, the 89kN (20,000 lbs) axial dead load on the column is the long-term load, and the 111.2 kN (25,000 lbs) axial live load is the short-term load. If one applies this creep deformation equation to axial column shortening, accounting for long-term creep effects, the total anticipated axial column shortening in this example would be:
$\Delta_{as,T} = (1.5)(1.6)(89/200.2) + (1.6)(111.2/200.2) = 1.9$ mm
Or $(1.5)(0.06)(20,000/45,000) + (0.06)(25,000/45,000) = 0.07$ in.

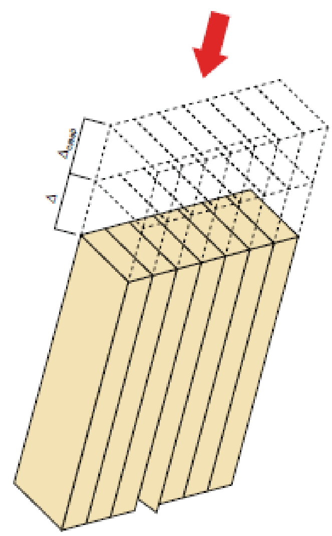

Figure 3: *Shortening of glulam columns*

5.2 SHRINKAGE

Simplistically, wood's cellular structure can be imagined as a bundle of drinking straws held together with a rubber band, with each straw representing a longitudinal cell in the wood. As noted, water can be free water stored in the straw (cell) cavity or bound water absorbed by the straw (cell) walls. At high moisture contents, water exists in both locations. As the wood dries, the free water is released from the cell cavities before the bound water is released from the cell walls. When wood has no free water and yet the cell wall is still saturated, it is said to be at its fiber saturation point (FSP).

The FSP of different species of wood varies but for most common softwoods is around 28-30%. The MC of lumber in service is typically 7-14%, much lower than the FSP. Wood remains dimensionally stable above the FSP, i.e., it doesn't change in dimension with an increase or decrease of moisture as long as it remains above the FSP at all times. This is because the water being absorbed or released is largely free water, not bound water. Once the moisture content drops below the FSP (i.e., bound water is being removed), the wood starts to change dimensionally.

Wood moisture content (MC) is the weight of water in wood as a percentage of the completely dry wood weight. During the life of a tree, its MC can exceed 200%, meaning the total water weight in a given volume of wood makes up two thirds or more of the total weight.

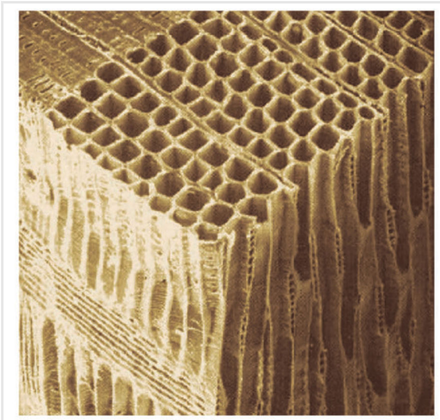

Figure 4: *Southern yellow pine cellular makeup*
Photo: USDA Forest Service Agricultural Handbook

Average shrinkage values from FSP to oven dry are approximately 5% and 7% (radial and tangential shrinkage, respectively), while longitudinal is approximately 0.1% to 0.2% for most species of wood. However, columns in mass timber construction are installed well below the FSP and maintain some residual moisture greater than oven dry. Since only a range of longitudinal shrinkage is provided, the engineer should use engineering judgement when determining the appropriate shrinkage coefficient to use. One method of calculating glulam column longitudinal shrinkage would be to assume an average shrinkage of 0.15% from fiber saturation point (FSP) to oven dry. Assuming that FSP is 28% MC, this allows one to calculate a coefficient of 0.15% / 28 = 0.000054, which equals the amount of longitudinal shrinkage per mm (or inch) of column length per % of MC change.

Using the column from the example earlier in this document, assume a 222 mm x 2229 mm (8-3/4-in. x 9-in.) column, 4.6 m (15 ft) long, with installed MC of 19% and EMC of 12%. Calculated longitudinal column shrinkage is:

$\Delta_{shrinkage}$ = (4600 mm)(0.000054)(19-12) = 1.7 mm
Or (15 ft)(12 in./ft)(0.000054)(19-12) = 0.07 in.

Detailing the column-to-beam connections should also include shrinkage consideration. Cross-grain shrinkage is much more significant than longitudinal shrinkage. A common coefficient used to calculate the cross-grain shrinkage of wood members is 0.0025 in. per inch of cross-sectional dimension for every 1% change in MC. Recall the common range of radial and tangential shrinkage discussed previously, 5% to 7% from FSP to oven dry, and we can see how this 0.0025 coefficient is derived. Assume a worst case of 7% shrinkage and an FSP of 28%, and the cross-grain shrinkage coefficient = 7% / 28 = 0.0025.

For example, a 222 mm x 610 mm (8-3/4-in. x 24-in.) glulam beam with an installed MC of 19% and EMC of 12% would have an anticipated shrinkage of:

Beam Depth: $\Delta_{shrinkage}$ = (610)(0.0025)(19-12) = 10.7 mm
Or (24 in.)(0.0025)(19-12) = 0.42 in.

Beam Width: $\Delta_{shrinkage}$ = (222)(0.0025)(19-12) = 3.9 mm
(8.75 in.)(0.0025)(19-12) = 0.15 in.

If this beam depth shrinkage occurs at each level, the overall effects on a 12- or 18-story mass timber building would be significant, resulting in multiple centimetres of building shrinkage. This is one reason why detailing the beam-to-column connections in multi-story mass timber structures such that beam shrinkage is isolated from impacting the overall building height is a key method of minimizing the impacts of vertical movement.

Consider the relative differences in the following column-to-beam configurations:

Option 1: An upper column bears directly on the mass timber floor panel, which bears directly on the support beam which bears on the lower column. This is essentially a platform-frame detail; because the shrinkage zone per floor is relatively deep (equaling the depth of the floor panel plus depth of the beam), shrinkage per floor is high. In the example above, the shrinkage in the depth of the beam would be approximately 10.7 mm (0.42 in.) per level, in addition to approximately 3 mm (0.12 in.) of panel thickness shrinkage, assuming a 175 mm (6-7/8-in.) deep panel. The total shrinkage per floor due only to beam and panel shrinkage is 13.7 mm (0.54-in.).

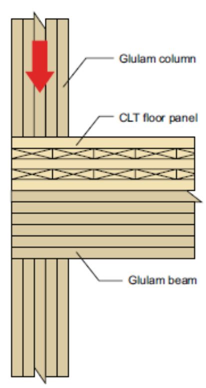

Figure 5: *Example column and beam connection; beam bears directly on column with beam shrinkage accumulation sub-optimal*

Option 2: beams and panels are isolated from the shrinkage zone by connections in which the beams do not bear directly on top of the columns below and similarly, the upper columns do not bear directly on top of the beams or panels. Detailing strategies involve either notching the column to allow the beam to bear on a shelf or creating a

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vertical load path where columns above bear directly on columns below, in some cases involving beam hangers. These options essentially eliminate all cross-grain shrinkage zones.

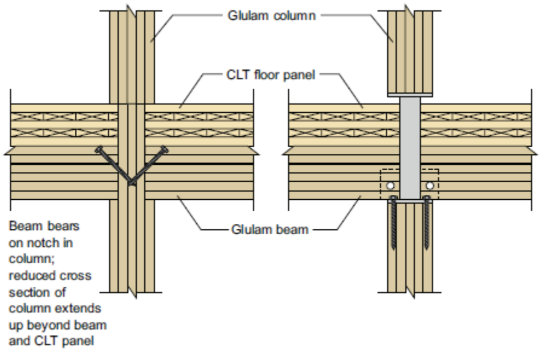

Figure 6: *Example column and beam connections, with beam shrinkage isolated from cumulative building shrinkage*

As the connections in Option 2 illustrate, it is possible (and preferable) to completely isolate beam depth shrinkage from impacting the overall building shrinkage. This is not to say that beam depth shrinkage will not occur—it will. However, keeping the beam depth shrinkage isolated from the continuous vertical load path of the columns minimizes the impacts, which are realized at each individual level without being transferred from one level to the next.

For additional connections and detailing options, browse the WoodWorks CAD/Revit tool and accompanying *Index of Mass Timber Connections* [4].

5.3 PERPENDICULAR-TO-GRAIN CRUSHING

Not only do column, beam and floor panel connection details impact vertical movement because of shrinkage potential, they can add to vertical movement due to crushing of the wood members. When loaded perpendicular to grain, wood members are prone to isolated crushing. NDS Section 3.10.2 provides general guidance on bearing perpendicular to grain, and the NDS Supplement provides allowable perpendicular-to-grain stresses. For softwood species commonly used in mass timber products, the typical range for allowable perpendicular-to-grain stresses is 2758 to 5516 kPa (400 to 800 psi.). Even when keeping actual perpendicular-to-grain stresses at or below allowable levels, some crushing does occur.

For steel-on-wood bearing conditions with the wood member loaded perpendicular to grain, the equations for calculating wood crushing are below. Note that crushing at 73% of allowable perpendicular-to-grain stress is 0.5 mm (0.02 in.) and crushing at 100% of allowable perpendicular-to-grain stress is 1 mm (0.04 in.).

Where: $f_{c\perp} \leq F_{c\perp 0.02\text{ in}}$

$$\Delta = 0.02 \times \left(\frac{f_{c\perp}}{F_{c\perp 0.02\text{ in.}}}\right)$$

Where: $F_{c\perp 0.02\text{ in.}} < f_{c\perp} < F_{c\perp 0.04\text{ in.}}$

$$\Delta = 0.04 - 0.02 \times \frac{1-\left(\frac{f_{c\perp}}{F_{c\perp 0.04\text{ in.}}}\right)}{0.27\text{ in.}}$$

Where: $f_{c\perp} > F_{c\perp 0.04\text{ in.}}$

$$\Delta = 0.04 \times \left(\frac{f_{c\perp}}{F_{c\perp 0.04\text{ in.}}}\right)^3$$

Assume the column in this design example bears on top of a 222 mm x 610 mm (8-3/4-in. wide x 24-in.) deep glulam beam. $F'c_{,perp}$ = 4482 kPa (650 psi.). The perpendicular-to-grain stress on top of the beam is:

$Fc_{,perp}$ = 200.2 kN/(222/1000)(229/1000) = 3940 kPa
Or 45,000 lbs/(8.75)(9) = 571 psi

And the resulting crushing is:
Stress ratio = 3940/4482 = 0.88
Or 571/650 = 0.88. Therefore, use equation 2.0 to calculate crushing:

$\Delta_{crushing}$ = (0.04 - (0.02)((1-(571/650))/0.27)) = 0.03 in. = 0.8 mm

Note that this is the crushing at one of the column-to-beam interfaces (top or bottom of beam surface). The same crushing occurs twice in this instance, essentially doubling the cumulative beam crushing (1.6 mm or 0.06 in total).

Similar to the discussion in the *Quantifying Wood Shrinkage* section above, where beam-to-column connections can be detailed in such a manner as to isolate beams from impacting cumulative building movement, the same is true for beam crushing. By utilizing details where upper columns do not bear directly on top of beams below, and beams do not bear directly on top of columns below, crushing of the wood members is isolated or eliminated and therefore does not contribute to overall building shrinkage. Additional discussion on effective detailing strategies for minimizing shrinkage and crushing effects at beam and column connections is included below.

One place where beams bearing on top of columns may be desired is at cantilevers. When columns are held back from the exterior wall, with the beams and floor panels cantilevering out to support the exterior wall, it might be assumed that the beams need to run directly over the column, which is undesirable from a beam crushing and shrinkage perspective. Rather, a double beam system with

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each beam straddling the column, supported by partial bearing on a notch into the column, would allow the beam cantilever while avoiding cumulative effects of both. An example of this detail is shown in Figure 7.

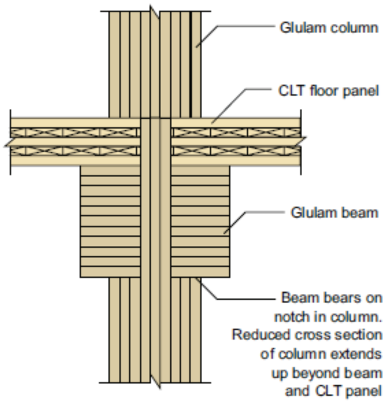

Figure 7: *Double beam system with each beam straddling the column, supported by partial bearing on a notch into the column*

5.4 JOINT SETTLEMENT AT CONNECTIONS

Small amounts of vertical settlement can occur at mass timber connections such as column base and column cap conditions. In addition to mass timber member tolerance allowances (i.e., the length of a column could be +/- 1.6 mm (1/16-in.) of its specified length) the steel hardware at these connections also has tolerance limits that may result in small amounts of settlement. Some engineers include this additional movement in total building shrinkage calculations (1.6 mm or 1/16-in. per floor could be an assumption for this settlement amount) while others choose to ignore it.

6 NET VERTICAL COLUMN MOVEMNT

Summing all of the vertical movements noted above, the net vertical column movement for the design example is calculated as:

$\Delta_{column} = \Delta_{as,T} + \Delta_{shrinkage} + \Delta_{crushing} + \Delta_{settlement}$

Using the detail shown in Figure 5 where the beam **is not** isolated from the shrinkage and crushing zone, the net vertical movement per level is:

Δ_{column} = 1.9 + 10.7 + 1.7 + 1.6 + 1.6 = 17.5 mm
Or 0.07 + 0.42 + 0.07 + 0.06 + 0.06 = 0.68 in.

Using the detail shown in Figure 6 where the beam is isolated from the shrinkage and crushing zone, the net vertical movement per level is:

Δ_{column} = 1.9 + 0 + 1.7 + 0 + 1.6 = 5.2 mm
Or 0.07 + 0 + 0.07 + 0 + 0.06 = 0.2 in.

The difference between the two detailing options is significant, further emphasizing the importance of providing details that isolate beam shrinkage and crushing from the overall building movement. Even when doing so, the net vertical column movement for this example, in a 12-story building, would be approximately 62 mm (2.4 in.). Some of this net vertical movement could be reduced with vertical adjustment in connections via shims or other elements placed during construction. This method is described below.

7 DIFFERENTIAL MOVEMENT

The above sections note the potential sources of vertical movement in mass timber framing systems, particularly columns and connections. In most instances, this vertical movement is a downward movement. It is also important to consider how mass timber framing systems interact with other building materials and building components. Other materials may exhibit significantly different vertical movement characteristics. For instance, some materials:

1. Expand due to moisture or thermal changes (brick veneer, masonry shaft walls)
2. Do not shrink due to moisture change but may move with thermal changes (steel framing, and steel/cast iron/PVC piping)
3. Shrink much less than mass timber (concrete core walls)

It is this differential movement that can create issues with the function and performance of finishes, openings, enclosures, mechanical/electrical/plumbing (MEP) systems, structural connections, and more. One of the primary ways to avoid negative impacts is to limit vertical movements of the timber structure as noted in the sections above, while also using detailing strategies discussed in the sections below. It is also important to monitor differential movement during construction, adjusting as necessary. Construction documents and details that provide guidance on how field adjustments should be made at material interfaces are important pieces of the long-term performance solution.

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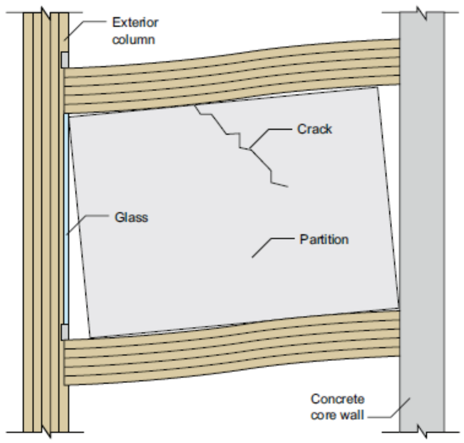

Figure 8: Effects of structure shortening on a glazed façade if differential movement is not accounted for in design and detailing

7.1 EFFECTIVE STRATEGIES AND DETAILING TO MINIMIZE AND ACCOMMODATE MOVEMENT

Several detailing options for beams to columns and columns to columns are shown in Figure 6. Particularly for tall mass timber buildings, where it might be desirable or necessary to make vertical adjustments at the column connections during construction based on real-time feedback (i.e., vertical elevation monitoring), using a detail like the ones in Figure 10 can be effective. In addition to isolating the panels and beams from the shrinkage and crushing zone, these steel connections, which often utilize tube or pipe sections fitted together, can be adjusted by inserting steel shims. For example, the 18-story Brock Commons Tallwood House project discussed later in this document utilized a series of 1.6 mm (1/16-in.)-thick steel shim plates at the column-to-column connections on three strategic levels (8, 12, and 16).

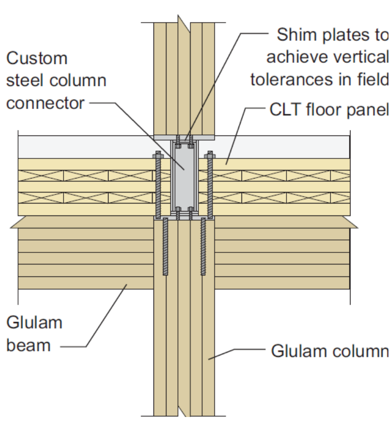

Figure 9: *Column-to-column connection details, with vertical load path isolated from beams and panels*

At connections between different materials, such as a mass timber beam or panel connecting to a concrete core wall, allowances for horizontal and vertical adjustability should be included. One example from the INTRO, Cleveland project is shown in Figure 10. A steel embed plate was cast with the concrete core wall, oversized relative to the steel ledger angle that was later attached to it. The connecting CLT panel was fabricated to allow a small gap between the end of the panel and face of the wall, sized as a function of the tolerance limits for the panel length and wall face location. Vertical adjustability was provided by the oversized embed plate, allowing the steel angle to be field welded to the plate once final elevations were determined (and ideally once some initial shrinkage and settlement had occurred). A similar condition can be used at a beam-to-core wall connection.

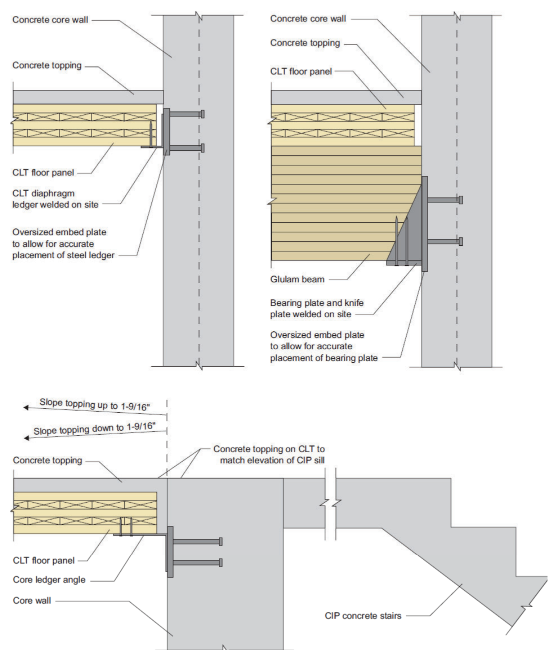

Figure 10: *Options for accommodating differential movement at timber to concrete walls*

Differential movements must also be accounted for in other elements of the building such as vertical MEP runs and exterior wall assemblies. Flex connections within MEP distribution lines (e.g., ductwork, drainage piping, conduit) at each level or every few floors may be prudent. Discussion with the mechanical and electrical engineer is recommended to determine the appropriate steps.

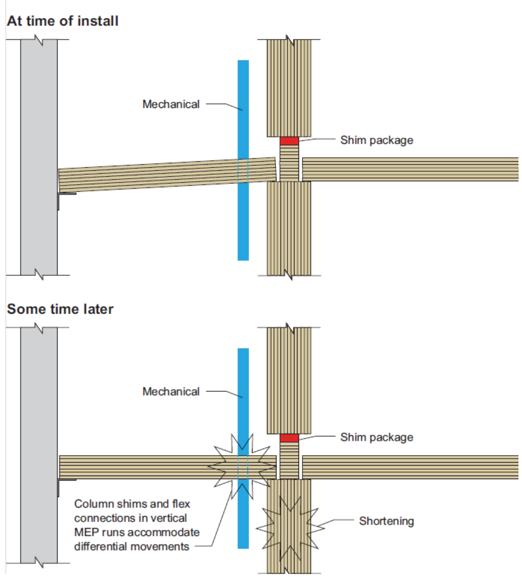

Figure 11: *Potential negative impacts of vertical movements on vertical MEP runs*

Since tall mass timber projects primarily use post-and-beam structural systems, the exterior walls are usually non-load bearing. As such, slip connection details at head of wall conditions not only allow the structure to deflect under gravity loads without loading the walls, but can also function as flex connections that account for vertical differential movements.

7.2 MOISTURE PROTECTION AS A MEANS TO MINIMIZE VERTICAL MOVEMENT

Moisture protection cannot be overemphasized for mass timber, and it is critical that all parties understand the potential effects of moisture on vertical movement potential. It is common on a mass timber project for the architect or engineer, through their specifications, to require a moisture management plan from the contractor. Although on-site material protection is usually considered a means and methods item for the contractor, mass timber is typically both structure and exposed finish. As a result, the design team may have more input on construction moisture management practices than on a non-mass timber project. The design team and owner may choose to require a preconstruction meeting with the contractor to review on-site moisture management techniques.

Key elements of effective construction-phase moisture control in mass timber buildings include:

- Coverings and other means of bulk water deflection/diversion
- Adequate ventilation to promote drying
- Removal of any standing water as soon as possible
- Coatings to protect the mass timber elements, particularly the end grain
- Installation of exterior enclosures in tandem with erection of the timber structure (off-site panelized exterior wall assemblies can aid in this regard)

For additional information on moisture control for mass timber projects, see the WoodWorks publication *U.S. Mass Timber Construction Manual*.

8 SITE VERIFICATION AND HEALTH MONITORING

Structural health monitoring involves the measurement, observation, and analysis of a structure to determine its status over time. These results can be used to determine necessary maintenance, and to ensure intended behaviour of the structure is reflected in the field. Measurements are taken by sensors at regular intervals to provide a numerical history of the structure. The data allows engineers to make observations about the loading and short-term behaviour, draw conclusions about the current state of fatigue, and forecast changes over time.

Once data has been acquired, it must be post-processed to remove noise, normalize variability from environmental effects, and reach meaningful results. Cleansing of data is also important to remove unreliable data, which can result from faulty installation or operation of a sensor.

To monitor short-term and long-term vertical movements in tall mass timber buildings, sensors can be installed throughout the structure to capture specific behaviours of interest. String potentiometers (string pots) can be used to determine vertical movements. These devices use a measuring cable and spring coupled to a spool and rotational sensor. The cable is attached to the point of interest, which will deform relative to the potentiometer. The spring works to maintain tension in the cable, while the sensor determines how much vertical movement has taken place based on the rotation of the spool. String pots can achieve accuracy ±0.0025% of the full scale of the string pot.

8.1 CASE STUDY – BROCK COMMONS TALLWOOD HOUSE

The following is an analysis of one of the first tall mass timber projects in North America to benefit from years of in-service performance feedback and monitoring data.

Located in Vancouver, Canada, Brock Commons Tallwood House is an 18-story hybrid building that includes 17 stories of mass timber construction over a single-story above-grade concrete podium, and two full-height concrete stair cores. The floor system consists of 5-ply CLT panels supported on glulam columns, and the roof is made of prefabricated sections of steel beams and metal decking. As of this writing, the building has five

https://doi.org/10.52202/069179-0383

years of in-service life and has been monitored for vertical movement and moisture content since construction started in 2016.

For the design of a 53 m (174-ft)-tall hybrid building, it was critical to consider differential movement between the timber structure and concrete cores. A specific concern was the potential impact of vertical movement on the mechanical services running through the CLT floor panels adjacent to the concrete cores.

Cumulative differential movement between mass timber members due to fabrication tolerances was minimized by the relatively low probability of occurrence. Glulam columns are typically manufactured with a tolerance of +/- 1.6 mm (1/16-in.) along their height. The probability of having all the shortest members on one side of the panel span and longest on the other is low and was compensated by surveying column datums and using shims as required. Another way to mitigate this risk is to utilize proper truck loading and column identification number tags, such that longer columns are installed above shorter ones and vice-versa.

The following vertical movements for Brock Commons were assessed using structural analysis methods prior to construction and represent cumulative totals at the roof of the building.

- Column shrinkage: 11 mm (0.43-in.)
- Column elastic shortening (short term loading): 25 mm (1-in.)
- Column shortening (creep): 12 mm (0.47-in.)
- Concrete core shrinkage: 12 mm (0.47-in.)
- Concrete core elastic shortening (short term loading): 2 mm (0.08-in.)
- Concrete core shortening (creep): 3 mm (0.12-in.)
- Foundation differential settlement: No critical impact on this project
- Tolerances intra-material: Mitigated by truck sequencing, column marking
- Tolerances extra-material: Interface details between timber and concrete allowing for movement

The anticipated concrete core movement was mainly due to shrinkage, as elastic shortening was negligible. Construction sequencing allowed the design team to minimize this discrepancy because the concrete core was cast in full prior to the erection of timber elements; most of the shortening had already occurred and therefore did not impact the final differential movement between materials.

Based on discussions with the design and construction team, most of the shortening and joint settlement was mitigated by adding a series of 1.6 mm (1/16-in.)-thick steel shim plates at the column-to-column connections on three strategic levels (eight, 12, and 16). The top of the first level column was surveyed and adjusted with leveling nuts at the base to mitigate any differential between columns due to concrete tolerances.

The total shim package thickness varies based on assumed loads and a varying elastic modulus. Due to the general level of uncertainty surrounding these two parameters, only 50% of the calculated values were mitigated, while details were designed to accommodate the other 50% if they were to occur. It is important to maintain this level of flexibility at critical locations so as not to overcompensate for calculated differential movement that does not occur because certain assumptions weren't realized.

The design and construction team also defined a moisture management plan that limited exposure to weather and water accumulation. This plan relied on the following:

- Fast erection pace of one story per week
- Prefabricated enclosure panels installed as soon as each level was built
  - For tall buildings, wall enclosure is a more effective way to reduce exposure to weather than temporary roof enclosure.
- Erection of the timber structure during summer
- Use of sealant and tapes to limit water penetration in the timber
  - With non-edge-glued CLT, this was not sufficient to stop water transfer from the active deck to lower floors; as the CLT panels dried and shrank, some of the lamination lines opened, creating passages for water.
- Use of concrete topping to create an effective water barrier
  - Concrete topping was placed four levels below the active deck, acting as a temporary roof and preventing water transfer to the floors below.
- Fans strategically placed to avoid moisture accumulation

Recording of moisture content across the thickness of CLT panels began at the manufacturing plant, continued through transportation and installation, and is ongoing today. Data showed that panels were kept at a consistent and relatively low moisture content at the factory and during transportation (<19% MC) but that many panels were subject to a large increase on site, especially in the top lamination, exceeding in some cases the fiber saturation point at their surface. Rapid increase and decrease during and after a rain event demonstrated the drying ability of the CLT, such that within a few days the exposed layer was back to an MC below 16%. Data generated from the CLT moisture monitoring was also used to understand the MC of glulam columns.

Throughout construction, strategies were developed to limit water exposure and transfer to lower floors to ensure

https://doi.org/10.52202/069179-0383

that the MC of timber elements could decrease to acceptable ranges as each story was partially enclosed. Once that occurred, the average moisture level during construction was kept below 20%, decreasing to below 15% once the building was complete. After the first two years of use, the MC had settled to between 8% and 15%.

If a proper water management plan is established (and followed), higher moisture content readings during construction should not significantly affect the level of shimming or material interface connections. Real data from Brock Commons confirmed that the variation of moisture content from factory to the project's in-service condition is close to the ranges assumed in the initial column shrinkage calculations.

As part of the Tall Wood Building Demonstration Initiative, Brock Commons benefited from 338 sensors located throughout the structure to measure vertical compression of the timber columns, moisture content, temperature, and humidity. Implemented by SMT Research, instrumentation of the building was deemed important to provide a better understanding of the behavior of tall mass timber structures. This also allowed better tracking of potential issues during construction and a documented comparison of expected vs. actual differential movement.

The timber columns were instrumented to record data for vertical displacement at the first four stories, except for a few columns that were monitored through the roof level. The displacement on the outer columns was about half that of the inner columns, as expected due to the smaller loads. The most recent published shortening record was between 2 mm (5/64-in.) and 4 mm (5/32-in.) per column between levels two and seven, and 0.25 mm (0.01-in.) to 1 mm (0.04-in.) per column between level seven and the roof. Based on this, cumulative column shortening can be assumed to be 22 mm (0.87-in.) total at the roof.

In addition to vertical displacement sensors, the elastic modulus of the lam stock used to manufacture the glulam columns was collected. The average elastic modulus was 20% higher than the design value, which implies 20% less elastic shortening and creep. The values used for elastic modulus, live load, creep, joint settlement, and moisture variation can compel designers to overestimate the total shortening and lead to over-shimming. Engineering judgement and experience in mass timber buildings are important to balance theoretical study. The theoretical study for Brock Commons resulted in 48 mm (1.89-in.) of total shortening compared to 22 mm (0.87-in.) from site monitoring; therefore, the safeguard of shimming up to 50% of the calculated shortening was deemed appropriate for this design. Slight shortening is still expected to occur in the future due to creep.

9 CONCLUSION

The Brock Commons Tallwood House data confirms that it is critical to consider axial column shortening in tall mass timber buildings and that precautions should be taken to address estimated shortening due to the uncertainties that lie within assumptions. It is critical to understand where a designer should allow for flexibility and how to protect other components from structural movements. When properly accounted for, shortening should not negatively affect the construction, use, or long-term performance of the building. Negative impacts can be avoided through a combination of proper detailing and effective moisture management strategies that involve coordination and discussion among all members of the design and construction team.

In addition to regular, on-site observation and movement monitoring, third-party inspections to review movement-accommodating details as installed, and to check items such as shims, will help to ensure that performance matches design intent. To have successful vertical movement performance, proper detailing must lead to proper installation. Education may also be necessary for the building owner, contractor and subcontractors to understand potential issues and how to avoid them. Once fully understood, accommodating vertical movement simply becomes another design criteria.

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