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Differential Material Movement in Tall Mass Timber Structures

An Overview of Column Movement Types and How to Address Them

It is a common narrative that tall mass timber buildings are relatively new to the U.S., and wood structures between seven and 24 stories have been built successfully in other countries for more than a decade. However, while there are dozens of timber buildings over eight stories tall worldwide, the suggestion that America is new to these types of projects is fast becoming out of date.

U.S. interest in tall timber buildings, i.e., buildings that exceed height and area limits for wood construction 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, about 10% of the mass timber buildings in design or built in this country exceed the 2018 prescriptive height limits. In 2021 alone, tall projects such as INTRO in Cleveland, Ascent in Milwaukee, 11 E Lenox in Boston, 80M in Washington DC, and Apex Plaza in Charlottesville, VA either started or completed the mass timber portion of construction. 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

Photo: Harbor Bay Real Estate Advisors


INTRO in Cleveland, OH

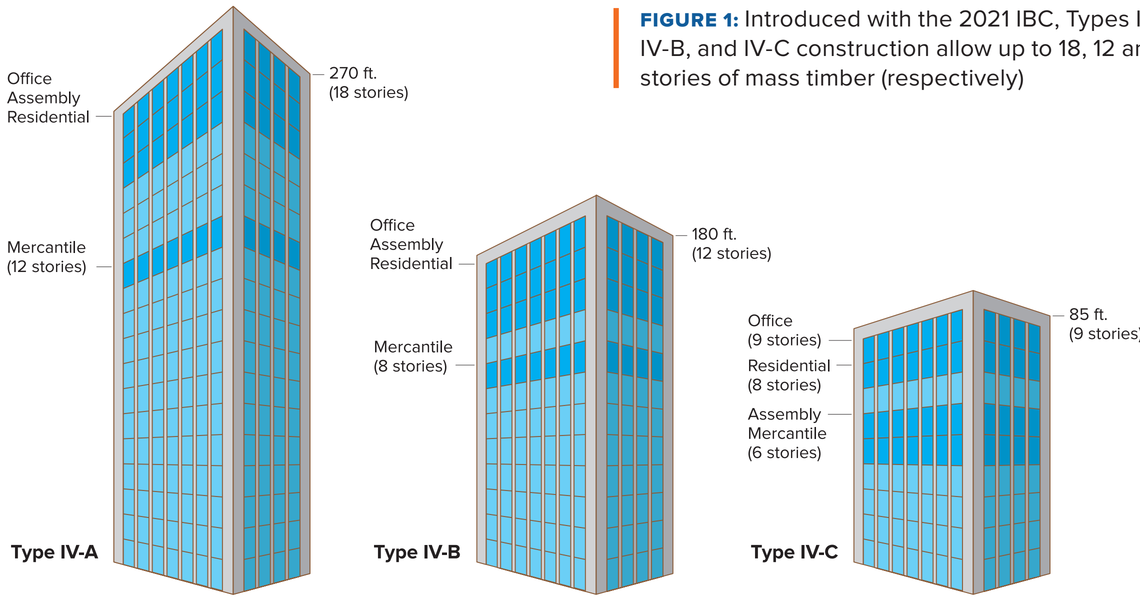


FIGURE 1: Introduced with the 2021 IBC, Types IV-A, IV-B, and IV-C construction allow up to 18, 12 and nine stories of mass timber (respectively)

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.

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-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, column-to-column, beam-to-column, and floor panel-to-column connections 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).

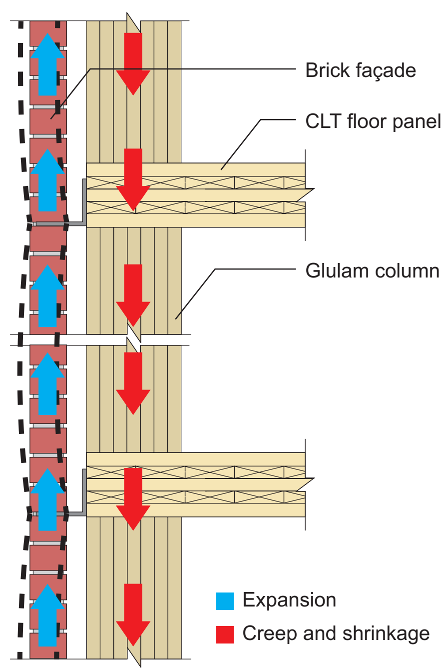


FIGURE 2: Effects of column shortening and panel compression deformation on a brick façade

Photo: WoodWorks

Example column and beam connection at 80M in Washington DC, designed by Hickok Cole

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

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 in the following sections. 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 +/- 1/8-in. of the specified width, and actual panel length be within +/- 1/4-in. of the specified length. Glulam columns up to 20 ft long must have an actual length within +/- 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.

Quantifying Vertical Movement

Column Axial Shortening

Axial forces on any structural column, be it timber, steel or concrete, cause shortening of the member. Using the principles of mechanics of materials, the axial shortening of a column is calculated with the equation:

$$\Delta_{as} = PL/(A\mathrm{E})$$

Where:

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

- Axial load of 45,000 lbs (20,000 lbs dead load, 25,000 lbs live load, duration of load factor = 1.0)
- Assume an 8-3/4-in. x 9-in. Douglas-fir glulam column, layup combination 2
- Column length = 15 feet
- $\mathrm{F'_c}$ = 1,950 psi
- E = 1,600,000 psi

$\Delta_{as} = PL/A\mathrm{E}$ = (45,000)(15*12)/((8.75*9)(1,600,000)) = 0.06 in.

This value is the anticipated column axial shortening, not accounting for the long-term effects of creep. Although not applicable to this design example, many columns resist dead loads, floor live loads, roof live loads, snow loads, etc. The load combinations of ASCE 7 should be used when determining the appropriate axial load for column shortening calculations.

A variable that can impact column axial shortening is the fire-resistance rating (FRR) of the column, which can impact cross-sectional area. Depending on the construction type used, a mass timber column could have a required FRR of between 0 and 3 hours; taller mass timber buildings (Type IV-A, IV-B or IV-C) usually require a 2- or 3-hour rating. The timber column itself can provide some or all of the FRR in an exposed or protected condition. The inherent size and properties of the cross section are used to demonstrate that charring of the outer surface of the wood takes place during fire exposure, while protecting the inner surface of the wood, allowing it to retain its structural integrity. A nominal char rate of 1.5-in. per hour of fire exposure is commonly assumed for glulam columns per NDS section 16.2.1.1. However, additional factors must be accounted for in the final char calculations as noted in Chapter 16 of the NDS. For additional information on the fire-resistive design of exposed mass timber elements, see the WoodWorks publication, *Fire Design of Mass Timber Members*.[1]

Exposed timber columns that require a 2- or 3-hour FRR will usually need to be oversized—i.e., increased in cross section beyond the minimum size required if only resisting gravity loads. It is this oversizing for fire purposes that can impact axial shortening calculations. For example, it is possible that an exposed glulam column in a Type III-B building would be subject to an axial load of 45,000 lbs, as would an exposed glulam column in a Type IV-B building. Construction Type III-B does not require an FRR for columns, while Type IV-B requires a 2-hour FRR for columns. This will likely result in a larger column for the Type IV-B building, despite resisting the same axial load. Since the load is constant in this example, but the cross section is larger for the Type IV-B building, the column axial shortening would be less in the IV-B building; using the *PL/(AE)* equation, *A* is increased and all other variables remain the same; therefore Δ_{as} is reduced.

Photo: David Barber, ARUP

Glulam column pre (left) and post (right) 2-hour fire test

Column Axial Shortening Including Creep Effects

When initially axially loaded, a wood column deforms elastically. As the load is maintained over time, additional deformations occur—this is called creep. 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). Since this is not explicitly covered in the NDS, engineering judgement is required. Chapter 5 of the Wood Handbook states that "relative creep at low stress levels is similar in bending, tension, or compression parallel to grain," providing one possible option for justifying the use of NDS Section 3.5 creep equation and values when evaluating long-term column axial 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 (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 (in.)
- Δ_{ST} = deformation due to short-term loading (in.)

For the column in the above example, the 20,000 lbs axial dead load on the column is the long-term load, and the 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)(0.06)(20,000/45,000)
+ (0.06)(25,000/45,000) = 0.07 in.

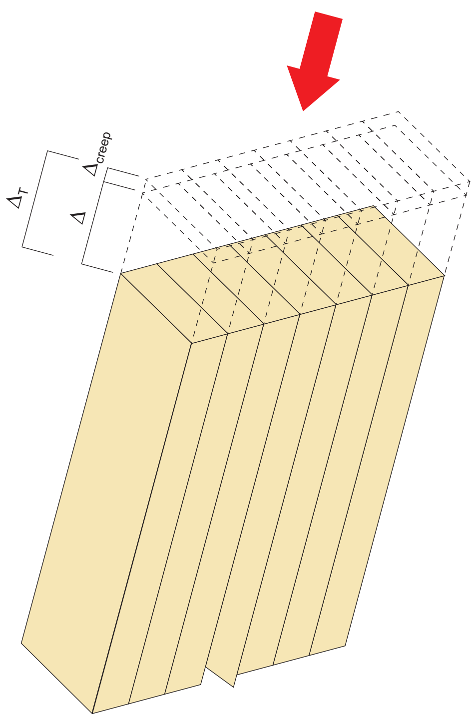


FIGURE 3: Shortening of glulam columns

Rate of Creep

According to Chapter 5 of the Wood Handbook, "creep occurs at even very low stresses, and it will continue over a period of years." The Wood Handbook also notes the role that moisture within a wood member and relative temperature and humidity within a space have on the creep rate and magnitude. "Ordinary climatic variations in temperature and humidity will cause creep to increase. An increase of about 28°C (50°F) in temperature can cause a two- to threefold increase in creep. Green wood may creep four to six times the initial deformation as it dries under load." As noted, the time-dependent creep factors included in Section 3.5 of the NDS assume dry service conditions. Where other conditions exist, the engineer should consider the effects of these external factors when calculating anticipated column deformations. See Chapter 5 of the Wood Handbook for additional information on factors that influence creep rates and magnitudes.

Shrinkage

Wood is hygroscopic, meaning it can absorb and release moisture. As this occurs, it also has the potential to change dimensionally.

Wood shrinkage occurs primarily perpendicular to grain, meaning that shrinkage effects on a timber column are much more significant in the width and depth of the column than its length. This is due to the cellular composition of wood products. In a glulam column, typically composed of 2x products oriented in parallel, moisture can be present in two forms: (1) free water in cell cavities, and (2) bound water in cell walls.

Wood's Cellular Composition

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 (see Figure 4). 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.

Photo: USDA Forest Service Agricultural Handbook

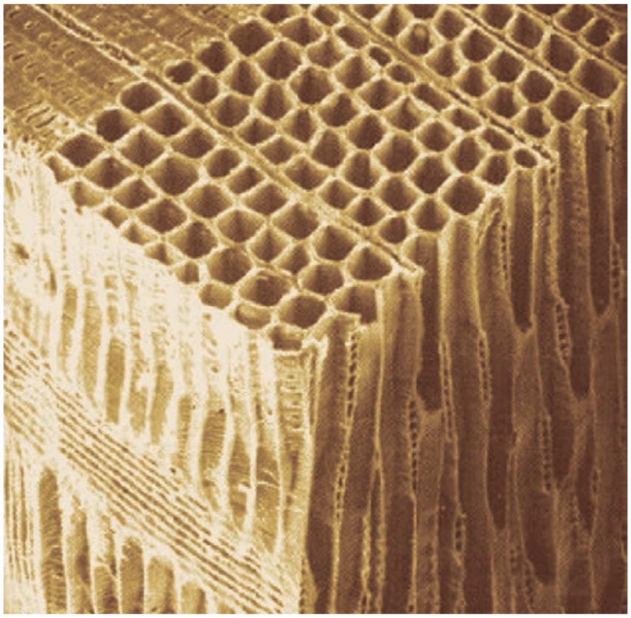


FIGURE 4: Southern yellow pine cellular makeup

Wood Shrinkage Influencers

Typically, in low- to mid-rise wood-frame construction, longitudinal shrinkage is negligible, meaning that shrinkage effects on lengths of wall studs and columns are assumed to be non-existent. However, in taller mass timber buildings, it is prudent to include longitudinal shrinkage effects when calculating overall vertical movement.

The three variables that influence the magnitude of shrinkage in mass timber members are:

1. Installed MC
2. In-service MC
3. Length or depth of the member under consideration (typically length of columns, depth of beams)

For mass timber products such as glulam columns, the MC at the time of manufacture is specified in the product standard. ANSI A190.1 requires that the lumber elements used in glulam members have a maximum moisture content of 16% at the time of bonding. PRG 320 requires that the lumber elements used in CLT panels have a moisture content of 12% +/- 3% at the time of manufacturing. However, mass timber products do not necessarily maintain these MCs over the course of a project's pre-construction life (transport and storage), nor do they necessarily stay at that same MC for the duration of construction. It is possible for the pre-construction or construction-phase MC of mass timber members to rise to 20% or higher if they are not protected well. The MC can also vary across the depth or thickness of a mass timber member, and is higher near surfaces directly exposed to moisture. Proper protection of the products, both when stockpiled on site and after installation, is critical to long-term performance and minimization of moisture effects including shrinkage. See WoodWorks' *U.S. Mass Timber Construction Manual*[2] for a discussion of ways to avoid moisture accumulation during construction.

EMC is a function of temperature and relative humidity and is a dynamic equilibrium, meaning it can change throughout the year with climate changes. Knowing both the installed MC and the EMC of the mass timber members allows for the calculation of anticipated shrinkage. For additional information on these topics, see the WoodWorks publication, *Accommodating Shrinkage in Multi-Story Wood-Frame Structures.*[3]

Quantifying Wood Shrinkage

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 doing this would be to assume an average longitudinal column shrinkage of 0.15% from 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 inch of column length per % of MC change. Similarly, the Canadian Wood Council's *Wood Design Manual* notes a longitudinal shrinkage coefficient of 0.00005. The example calculations in this document use a longitudinal shrinkage coefficient of 0.000054.

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

Column Length:
$\Delta_{shrinkage}$ = (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 per each % of MC change.

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, an 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:

$\Delta_{shrinkage}$ = (24 in.)(0.0025)(19-12) = 0.42 in.

Beam width:

$\Delta_{shrinkage}$ = (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 inches 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 (see Figure 5). 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 0.42 in. per level, in addition to approximately 0.12 in. of panel thickness shrinkage, assuming a 6-7/8-in. deep panel. The total shrinkage per floor due only to beam and panel shrinkage is 0.54-in.

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 (see Figure 6). Detailing strategies involve either notching the column to allow the beam to bear on a shelf or creating a 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.

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]

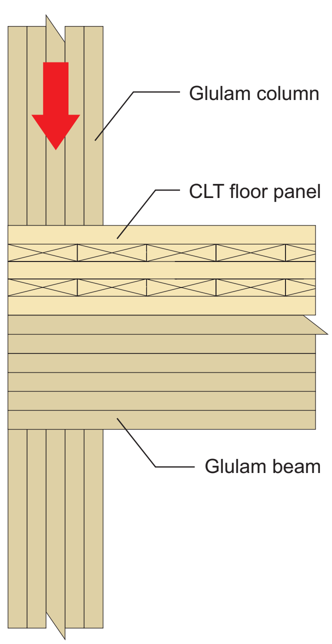


FIGURE 5: Example column and beam connection; beam bears directly on column with beam shrinkage accumulation sub-optimal

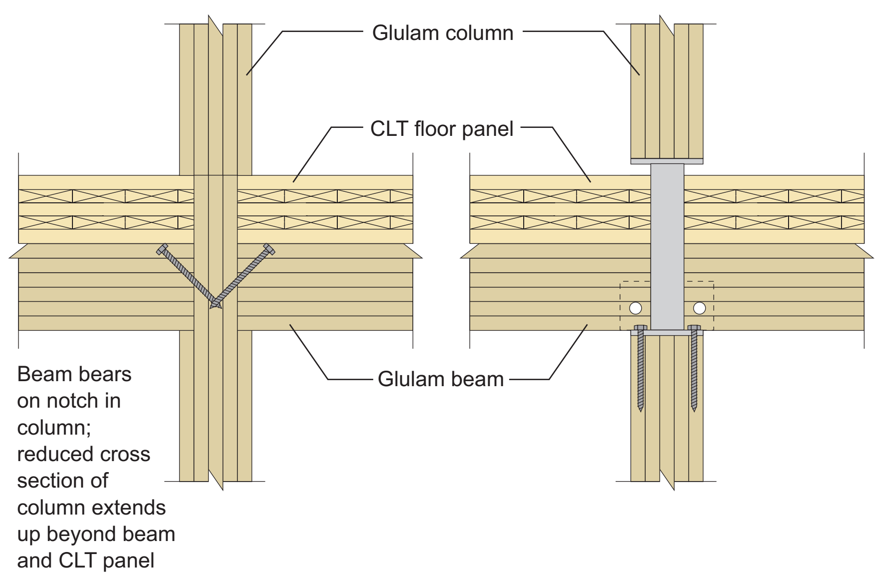


FIGURE 6: Example column and beam connections, with beam shrinkage isolated from cumulative building shrinkage

Perpendicular-to-Grain Crushing of Beams and Floor Panels

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 400 to 800 psi. Even when keeping actual perpendicular-to-grain stresses at or below allowable levels, some crushing does occur. The magnitude of crushing is non-linear as shown in Figure 7.

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 0.02 in. and crushing at 100% of allowable perpendicular-to-grain stress is 0.04 in.

Assume the column in this design example bears on top of an 8-3/4-in. wide x 24-in. deep glulam beam. $F'_{c,perp}$ = 650 psi. The perpendicular-to-grain stress on top of the beam is:

$F_{c,perp}$ = 45,000 lbs/(8.75)(9) = 571 psi

And the resulting crushing is:

Stress ratio = 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.

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 since the bearing condition shown in Figure 5 occurs at both the top and bottom of the beam, essentially doubling the cumulative beam crushing. Any additional load carried by the beam would also need to be accounted for at the bottom of beam to top of column crushing calculation, but that is neglected here for simplicity. This results in a net beam crushing at each level of:

$\Delta_{crushing}$ = (0.03)(2) = 0.06 in.

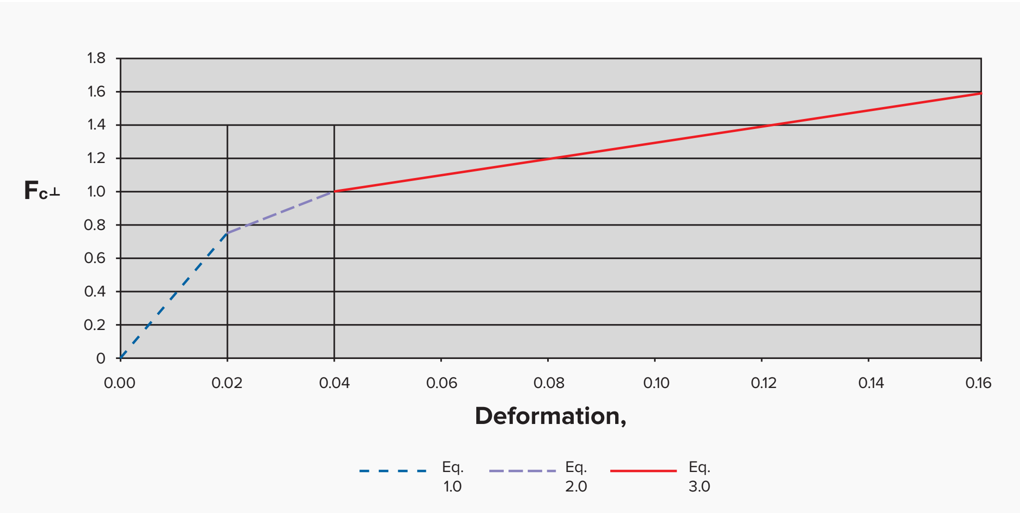


FIGURE 7: $F_{c\perp}$ load deformation curve
SDPWS Commentary Example C4.3.4-2 and SDPWS Commentary Reference 67

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

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

Where:

Δ = deformation, in.

$f_{c\perp}$ = induced stress, psi

$F_{c\perp 0.04\text{ in.}} = F_{c\perp}$ = reference design value at 0.04 in. deformation, psi ($F_{c\perp}$)

$F_{c\perp 0.02\text{ in.}}$ = reference design value at 0.02 in deformation, psi (0.73 $F_{c\perp}$)

Similar to the discussion in the *Quantifying Wood Shrinkage* section, 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 in the section, *Detailing Options to Minimize Shrinkage and Crushing*.

In addition to localized crushing at the top and bottom of the beam where the column above bears on the top of the beam and the beam bears on the column below, the engineer may also want to look at elastic shortening effects of the beam depth. One method is to assume that localized crushing is isolated in the top and bottom 2 in. of the beam depth, with elastic shortening occurring in the remaining core beam depth. When doing this analysis, the *PL/(AE)* equation is used, assuming that *P* is the applied load, *L* is the remaining core beam depth (total beam depth minus 2-in. each top and bottom), *A* is the area of the column bearing on the beam (influenced area of the beam core may be increased 2-in. each direction, not to exceed beam edges) and *E* is *E* of the beam divided by 30. The *E*/30 term is an estimate derived from ASTM D2555 for clear wood. For the beam and column example above, this would result in a beam core depth shortening of:

$PL/(AE) = (45{,}000)(24-2-2)/((8.75)(9+2+2)(1{,}600{,}000/30))$
$= 0.15$ in.

This would be in addition to the 0.03 in. localized crushing of the beam depth top and bottom. Since these equations are not codified, engineering judgment is necessary when determining their use, applicability and adjustment factors. Note that this beam depth shortening is not included in the summing calculations below but the engineer may choose to include them.

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 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 8.

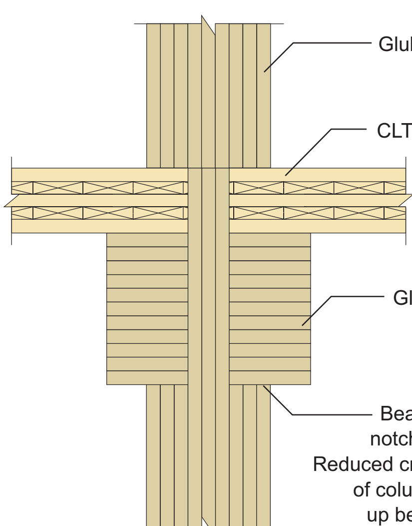


FIGURE 8: Double beam system straddling timber column

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 +/- 1/16-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 (1/16-in. per floor could be an assumption for this settlement amount) while others choose to ignore it.

Net Vertical Column Movement

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:

$\Delta_{column} = 0.07 + 0.42 + 0.07 + 0.06 + 0.06 = 0.68$ 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:

$\Delta_{column} = 0.07 + 0 + 0.07 + 0 + 0.06 = 0.2$ 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 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 in the section, *Detailing Options to Minimize Shrinkage and Crushing*.

Differential Movement

The previous 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 following sections. 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.

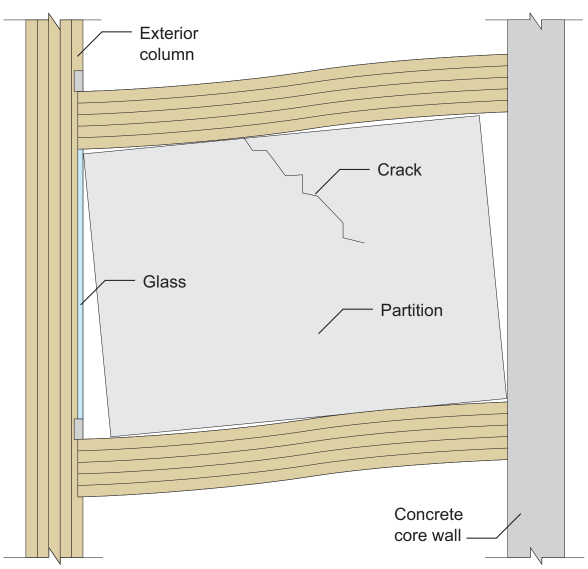


FIGURE 9: Effects of structure shortening on a glazed façade if differential movement is not accounted for in design and detailing

Effective Strategies and Detailing to Minimize and Accommodate Movement

As highlighted in the shrinkage and crushing discussion, the types of details chosen at beam, column and panel interfaces will have a significant impact on the resulting vertical movement of the timber structure. However, keeping the transportation and construction-phase moisture content of the timber elements as low as possible through proper protection can also minimize vertical movement.

Detailing Options to Minimize Shrinkage and Crushing

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 details like the one 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 1/16-in.-thick steel shim plates at the column-to-column connections on three strategic levels (8, 12, and 16).

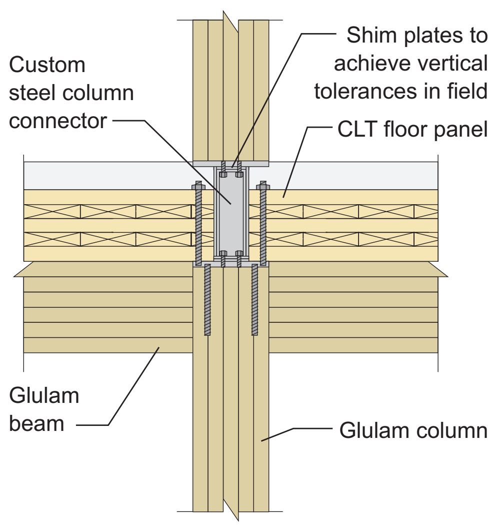


FIGURE 10: Column-to-column connection details, with vertical load path isolated from beams and panels

Detailing Options to Accommodate Differential Movement

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 11. A steel embed plate was cast with the concrete core wall, oversized relative to the steel ledger angle to which it was later attached.

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.

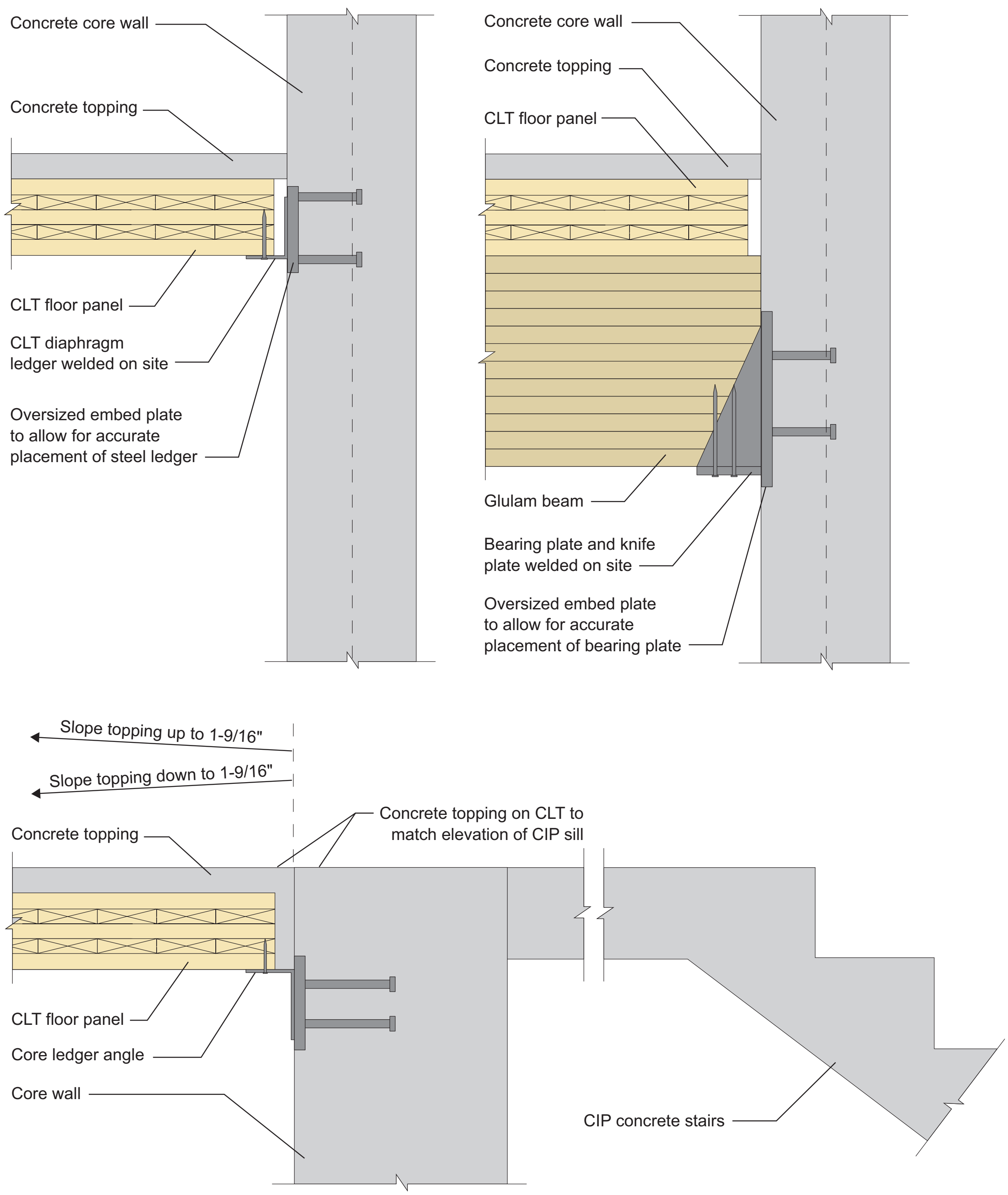


FIGURE 11: Options for accommodating differential movement at timber-to-concrete walls
If steel connections require an FRR, additional protection may be necessary.

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.

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.

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 impacts 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*.

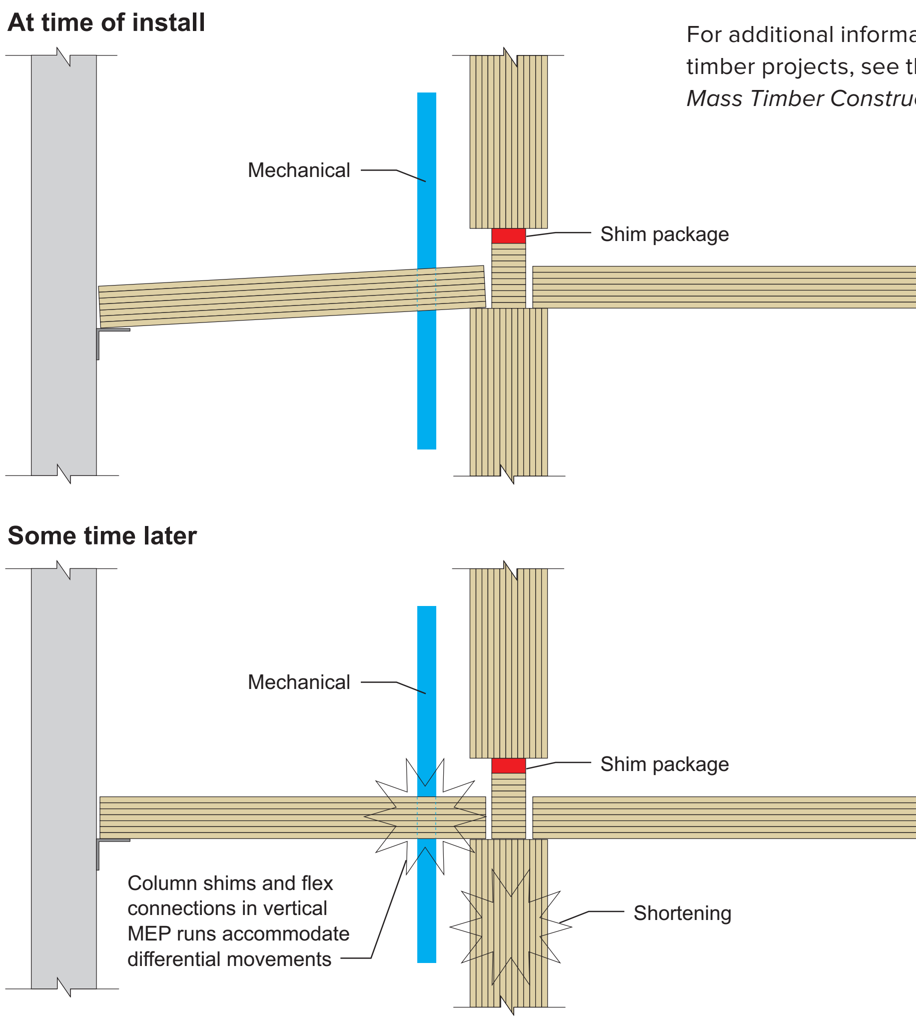


FIGURE 12: Potential negative impacts of vertical movements on vertical MEP runs

Impacts of Different Structural Systems

Concrete

Concrete columns and walls are susceptible to elastic shortening, shrinkage strain caused by drying, and creep strain induced by sustained loading. Sequence and timing of construction will influence the amount of creep strain in the concrete elements, which can be cast with these effects in mind.

Concrete shear walls are sized to handle lateral demands and potentially large inelastic drifts. These components will likely not have significant compressive stresses under typical gravity load situations and will see less elastic shortening than concrete gravity columns. With a standard building layout, deformations due to shrinkage and creep may approach two-thirds of the total shortening effect in concrete shear walls. The American Concrete Institute (ACI) Committee 209 is focused on creep and shrinkage effects in concrete and has authored a handful of design guides and papers that provide further information about how to calculate these axial shortening effects (e.g., ACI PRC-209.2-08 and ACI PRC-209-92).

Structural Steel

Steel is relatively dimensionally stable and does not deform significantly from creep effects. This means that nearly all the shortening will be in the form of elastic shortening. Steel columns that are part of the lateral force-resisting system will likely be controlled by lateral demands, resulting in lower stresses under gravity load effects. This will result in low elastic shortening effects of the steel lateral columns compared to adjacent gravity members.

Where axial shortening effects are significant, steel columns may be fabricated with expected elastic shortening in mind; however, computed values often overestimate elastic shortening due to stiffness contributions from elements not typically included in structural models (e.g., partitions, exterior cladding, secondary components). Elevation datums used for steel lateral components can also vary slightly from timber components to account for creep and shrinkage effects of the timber columns. Accurately calculating overall axial shortening effects is difficult.

In general, elastic shortening and creep effects are proportional to the magnitude of the axial load on the column. Columns that carry higher gravity loads than adjacent columns, such as columns supporting transfer beams or columns with higher tributary area, should be handled with care to avoid areas of increased column shortening and thus differential shortening between adjacent columns. Exterior and edge columns will likely have lower compressive forces than interior columns and pose a similar problem. Maintaining similar design criteria for all columns will help mitigate this differential effect. When lateral cores are utilized, differential shortening between timber columns and adjacent steel or concrete cores can be mitigated by having long spans between the differing materials.

Mass Timber Bearing Walls

Sometimes referred to as a honeycomb structural system, an all-mass timber framing option used on several international tall timber projects consists of mass timber bearing walls supporting mass timber floor panels. The considerations for shortening and shrinkage for mass timber bearing walls are similar to those for mass timber columns, although the magnitude of anticipated vertical movement will likely be lower. Also, the type of mass timber bearing wall panel will have some impact on overall movement. For example, bearing walls with all laminations oriented vertically (i.e., NLT and DLT wall panels) will experience some longitudinal shrinkage and shortening. Due to the continuous nature of these systems and their uniformly supported loads, vertical movements would be expected to be low. For systems such as CLT, vertical movement is typically restrained by horizontally oriented laminations, making for a more dimensionally stable wall panel.

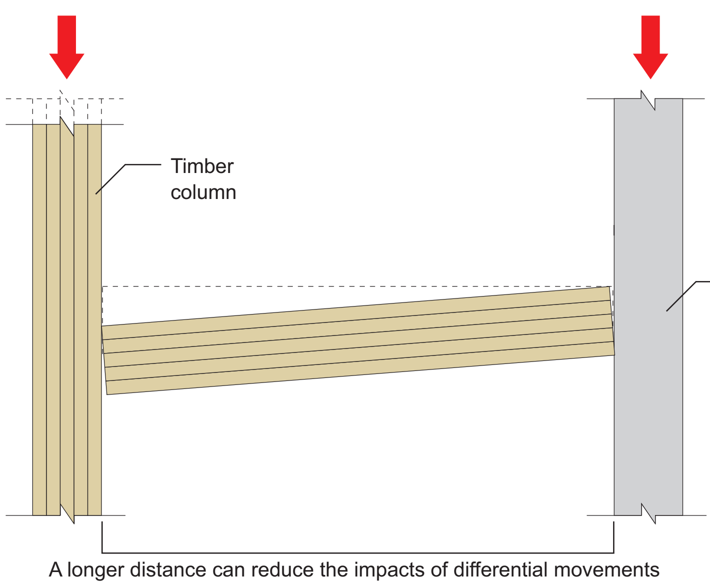


FIGURE 13: A longer span between the timber column and concrete core can lessen negative effects of differential movements between core and adjacent timber structure.

Light Wood-Frame Bearing Walls

Although not used on tall projects, some low- and mid-rise mass timber projects have utilized a hybrid structural system consisting of light wood-frame walls supporting mass timber floor panels. The wood walls act as both bearing walls and shear walls, supporting the gravity and lateral loads transferred from the mass timber floor panels. When considering vertical movement in this structural system, most of the shrinkage zone is located at the wall top and bottom plates. As noted, longitudinal wood shrinkage is considerably smaller than cross-grain shrinkage. As such, shrinkage of the length of the wood studs is commonly assumed to be negligible in a four- or five-story wood building, while the shrinkage of the wall top and bottom plates should be taken into account.

Photo: KL&A Engineers and Builders

Example mass timber and light wood-frame hybrid project

If all mass timber floor panels in the building are supported on light wood-frame bearing walls, structural differential movement would not usually be a concern as all walls would in theory shrink and settle uniformly. However, the cumulative effect of building shrinkage should still be considered, particularly its effects on MEP, finishes, exterior facades, etc. For additional information on the shrinkage of light wood-frame wall systems, see the WoodWorks publication, *Accommodating Shrinkage in Multi-Story Wood-Frame Structures*.

Non-structural Components

Axial shortening can also influence non-structural components such as partitions and cladding systems. Non-structural systems supported between individual stories can be damaged from differential shortening either between adjacent columns on a story (racking), or from total shortening of a story (crushing). Appropriate consideration and detailing to accommodate both types of movement are recommended.

Site Verification and Structural 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 behavior 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 behavior, draw conclusions about the current state of fatigue, and forecast changes over time.

Modern technology allows for precise observation and analysis of a structure, both during construction and over its lifetime. Different types of sensors can be used concurrently to capture many parameters. For example, bridges are a common target of structural health monitoring. Bridges may have sensors that measure local wind and weather effects, traffic, elongation of prestressing and stay cables, and condition of the main deck or abutments. The owner and design team will decide the quantity, locations, and type of sensors based on the project budget, goals, and construction type. They will also determine how often data will be gathered, analyzed, and acted on. Economic considerations will likely dictate many of these decisions.

Sensors that measure parameters such as internal pressures, strains, crack propagation, and change in inclination may be embedded within concrete elements. They can also be attached to the face of members, which allows the sensor to be applied after construction is complete. This may be beneficial depending on the construction type. All sensors will be networked to a central device, like a small computer, which aggregates the data.

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 behaviors 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.

String pots are simple devices that can be used in confined spaces, offer different mounting options, can be routed around barriers, and are compact and cost effective. Measurements from string pots can be used to more accurately determine floor datums and compensate for axial shortening with realistic, observed values.

Other sensors can be used in conjunction with string pots to capture a larger picture of the behavior of the building after construction. Temperature and moisture sensors are two common devices used to monitor overall structural health of mass timber buildings.

Structural health monitoring can provide valuable data, but also increases the cost of the structure. Some site verification means may be covered by the contractor to ensure the level of accuracy required on specific projects. In other cases, the owner may be willing to take on the additional costs. Research and education grants may also be a funding option, which was the case for Brock Commons Tallwood House.

Beyond the cost of acquiring and installing the sensors, there are costs to maintain the sensors and process sthe data. Care should be taken to ensure that central data acquisition hardware is protected from the elements while remaining accessible. A long-term plan should also be implemented to ensure the cost of health monitoring is realized in the form of actionable data for the building owner.

Case Study – Brock Commons Tallwood House

Comparison of calculated vs. actual differential movement

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.

Project Overview, Source & Magnitude of Potential Differential Movement

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 four 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 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.

Tolerances

Due to the larger tolerances in concrete construction when compared to mass timber construction, details at the interface of these materials were carefully designed to allow for adequate adjustability (vertically and horizontally).

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 +/- 1/16-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.

Code references for vertical construction tolerances are outlined in Table 1. Designers of Brock Commons referenced equivalent Canadian codes when analyzing the impact of expected tolerances for each material.

Vertical Movements

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

- Column shrinkage: 0.43-in.
- Column elastic shortening (short term loading): 1-in.
- Column shortening (creep): 0.47-in.
- Concrete core shrinkage: 0.47-in.
- Concrete core elastic shortening (short term loading): 0.08-in.
- Concrete core shortening (creep): 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 as shown in Figure 11

TABLE 1: Vertical construction tolerances

	Cast-in-Place Concrete	Structural Steel	Glulam
U.S. standard	ACI 117-10	AISC 303-16 AWS D1.1	ANSI A190.1
Mitigation	Tighten specs at some locations	Tighten specs	Tighten specs
Magnitude	5/16" Floor	25/64" Connector	25/64" Column length

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.

On-Site Adjustments

Based on discussions with the design and construction team, most of the shortening and joint settlement was mitigated by adding a series of 1/16-in.-thick steel shim plates at the column-to-column connections on three strategic levels (8, 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.

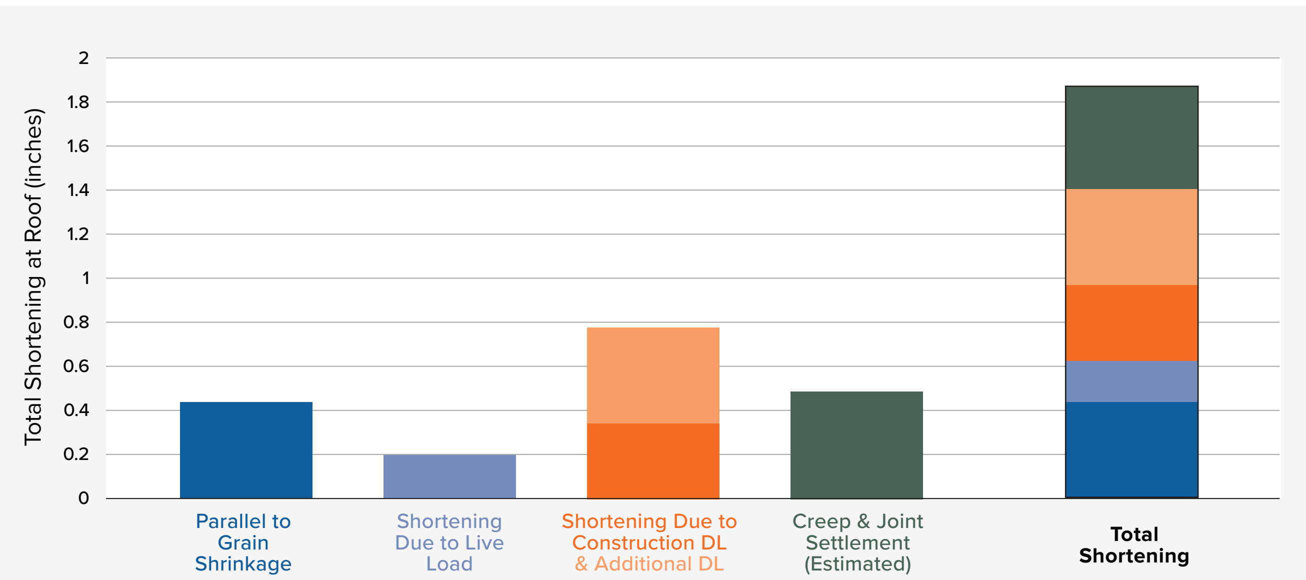


FIGURE 14: Total roof vertical shortening of the glulam columns

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.

On-Site Moisture Mitigation

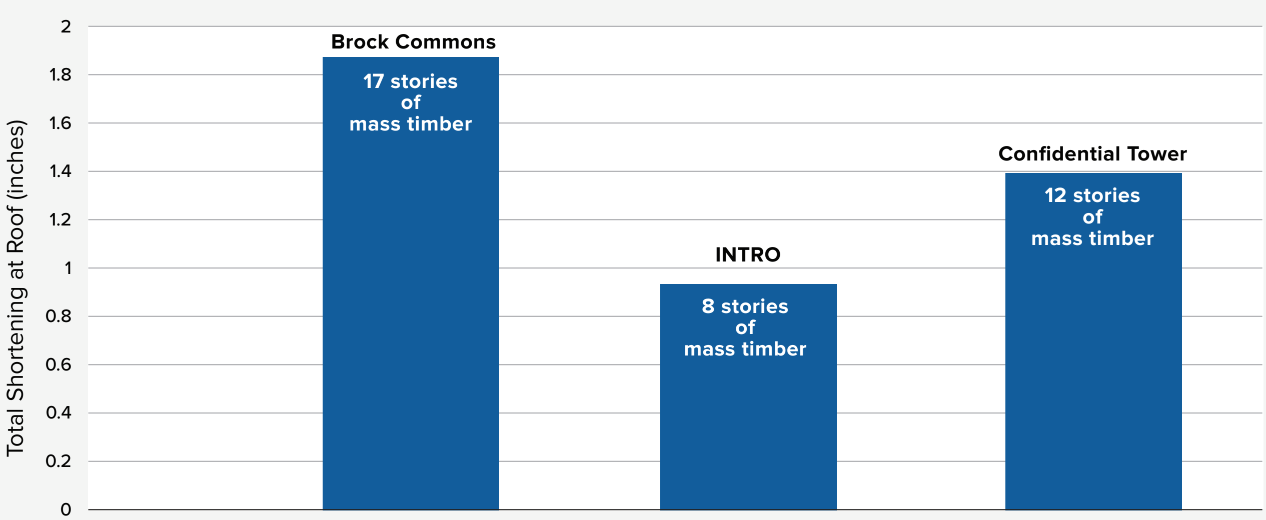
The design and construction team also defined a moisture management plan that limited exposure to weather and water accumulation. This plan relied on the following:

- 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

Comparisons

Since the completion of Brock Commons, an analysis of mass timber projects in design and under construction has been carried out. Figure 15 compares three residential mass timber buildings—Brock Commons, INTRO, Cleveland, and a confidential 12-story mass timber tower—and the total expected cumulative shortening of their columns evaluated at the roof. Values are categorized based on the encapsulation/exposure to fire, grid dimensions, story height, and type of structural system as these parameters have the greatest impact on column shortening.

Column shortening is typically a lesser concern for columns designed to incorporate a wood char protection layer for fire design, as these designs result in a larger cross section for the same design load than an encapsulated column, or a column not subjected to fire (PL/AE). Because INTRO has fewer stories and exposed columns where Brock commons has fully encapsulated columns with the 2-hour FFR achieved by gypsum only, this project should have less than half of Brock Commons' shortening value. This is not reflected in Figure 15 because INTRO also has a larger grid as well as event spaces and a rooftop pool with heavy design loads.



FFR & Exposure	2 hrs - Fully encapsulated	2 hrs - Exposed	2 hrs - Partially encapsulated
Grid	13' x 9'	20' x 22' average	10' x 12'
Structural system	Point-supported CLT	CLT on glulam beams	10' x 12'
Main story height	9'-2"	11'-5"	9'-8"

FIGURE 15: Total calculated vertical shortening of the glulam columns of three residential buildings

Validation of Estimated Timber Shortening Based on Field Recorded Data

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.

Validation of Timber Moisture Variation

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 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%.

The data that is relevant to column differential movement is the variation between maximum moisture content when the product is cut to size (16% for glulam) and the lower bound of in-service moisture content, typically around 7% MC. It is the engineer's responsibility to gather appropriate MC data for site-specific conditions. Note that in some conditions where the seasonal MC variation of interior timber columns can vary greatly, more investigation should be carried out.

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.

Validation of Shortening

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 5/64-in. and 5/32-in. per column between levels two and seven, and 0.01-in. to 0.04-in. per column between level seven and the roof. Based on this, cumulative column shortening can be assumed to be 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 1.89-in. of total shortening compared to 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.

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.

WoodWorks – Wood Products Council provides education and free technical support related to the design, engineering and construction of commercial and multi-family wood buildings in the U.S. A non-profit organization staffed with architects, structural engineers and construction experts, WoodWorks has the knowledge to assist with all aspects of wood building design. If you are experiencing challenges related to the design of a mass timber, light-frame or hybrid building, contact us at www.woodworks.org/project-assistance or email help@woodworks.org. Visit our website at www.woodworks.org.

End Notes

[1] *Fire Design of Mass Timber Members*, WoodWorks, www.woodworks.org/resources/fire-design-of-mass-timber-members-code-applications-construction-types-and-fire-ratings/

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