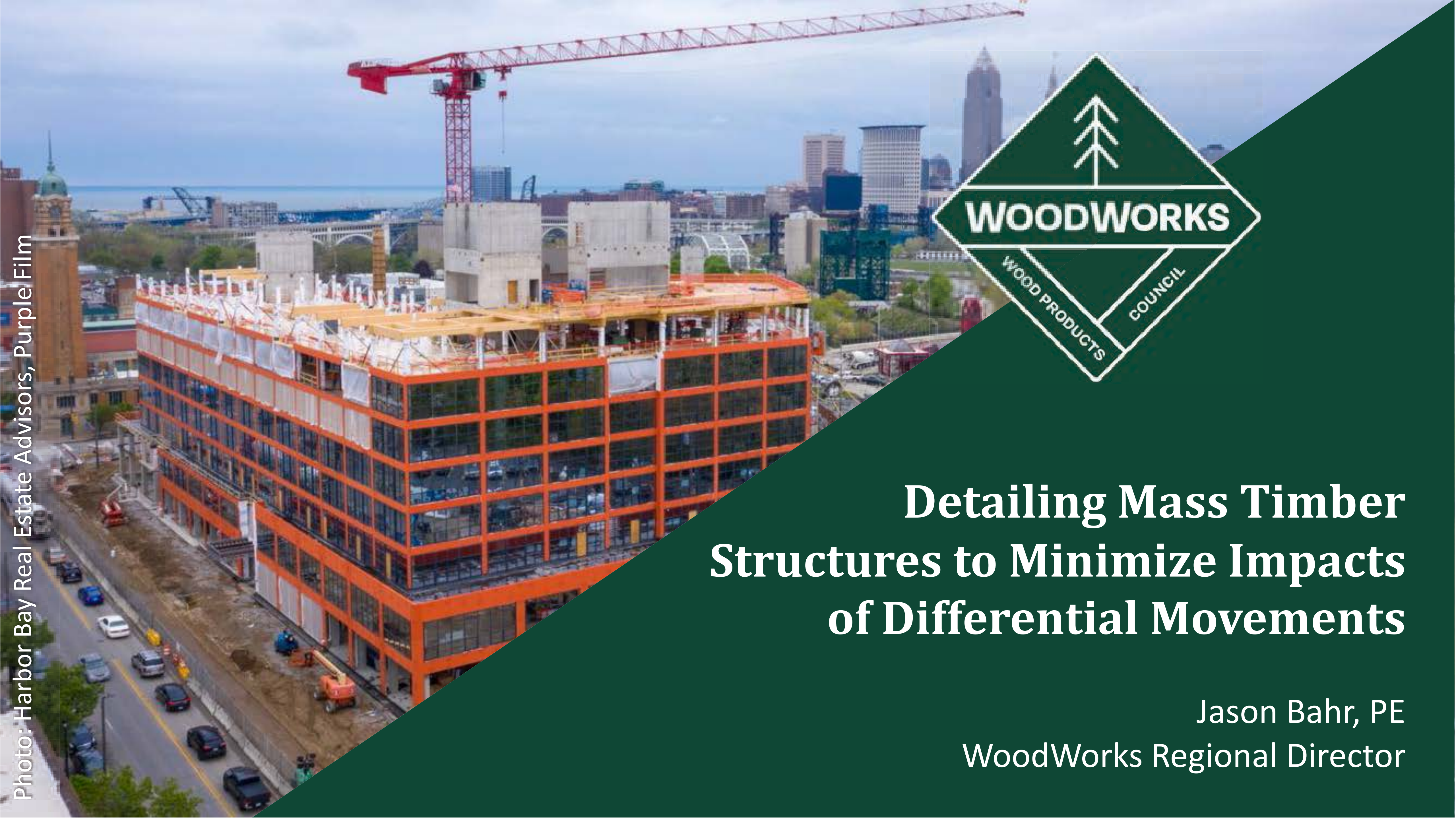

Photo: Harbor Bay Real Estate Advisors, Purple Film

Detailing Mass Timber Structures to Minimize Impacts of Differential Movements

Jason Bahr, PE
WoodWorks Regional Director

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Course Description

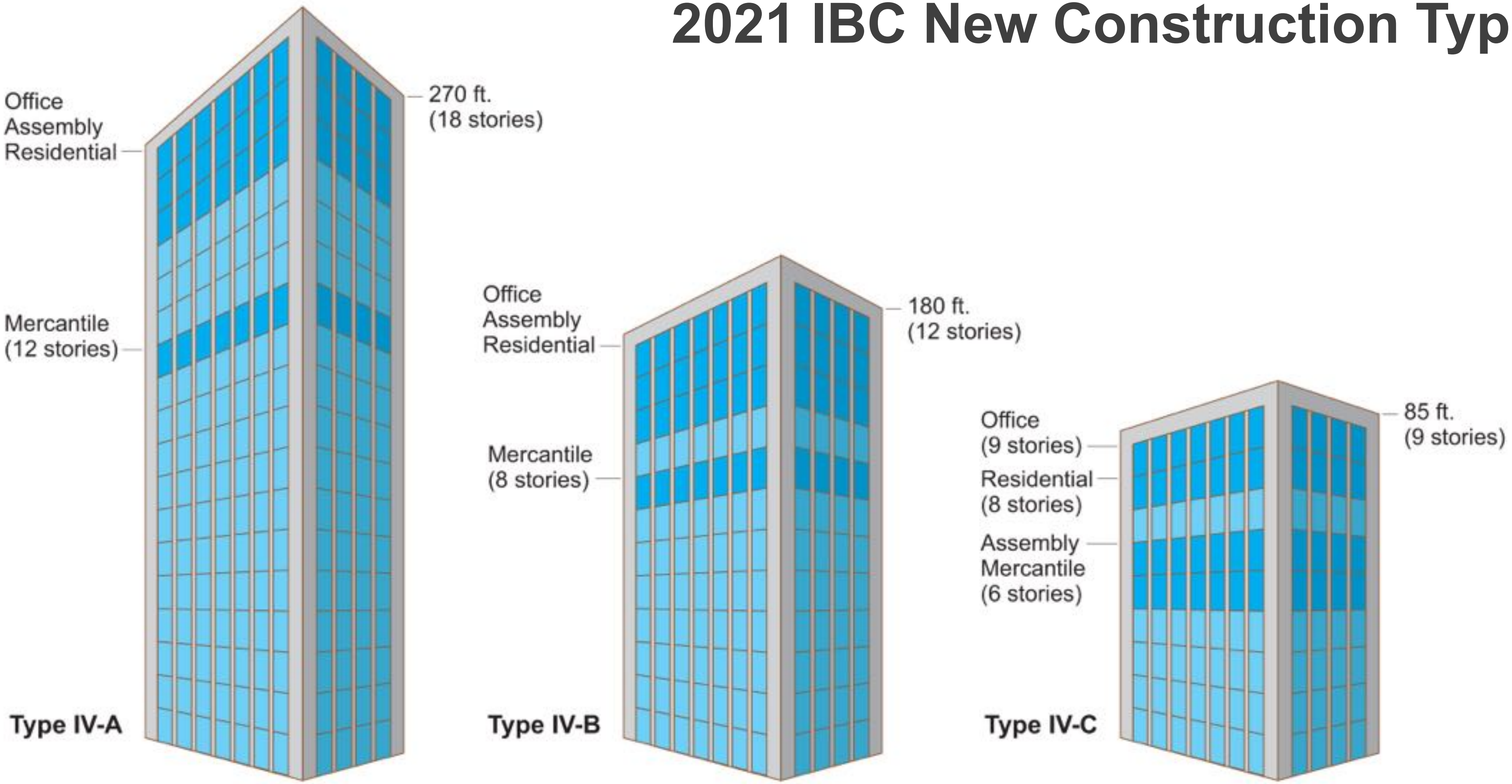
As the height of mass timber buildings continues to grow, so too does the level of design and detailing knowledge required to achieve optimal building construction and performance. A necessary consideration for mass timber buildings of any height is vertical movement—including column shrinkage, joint settlement, and creep—and this is especially important on tall projects. The main concerns are potential impacts on vertical mechanical systems, exterior enclosures, and interior partitions, as well as differential vertical movement of the timber framing systems relative to building elements such as concrete core walls and exterior facades. This presentation will analyze reasons for vertical movement (short and long term), provide methods of calculating anticipated movement such as creep, crushing and shrinkage, highlight detailing options to minimize and accommodate movement, and discuss strategies implemented on mass timber projects completed in North America.

Learning Objectives

1. Discuss how vertical differential movement in mass timber buildings is addressed in the International Building Code and referenced standards.
2. Explore causes of differential vertical material movement in mass timber structures and discuss potential impacts on mechanical, electric, plumbing and fire protection (MEPF) services and architectural finishes.
3. Highlight effective detailing measures to minimize and accommodate vertical movement in mass timber buildings, including connections through floor depths and at attachment points to concrete and steel lateral systems.
4. Review the results of on-site vertical movement monitoring in completed mass timber buildings to assess how these compare with calculated movements, and discuss how adjustments can be made during construction to ensure proper function of fire and life safety components.

Tall Mass Timber: New Opportunities, New Engineering Solutions

2021 IBC New Construction Types



Tall Mass Timber: New Opportunities, New Engineering Solutions

Vertical Movements of Timber Elements, Relative to Other Elements

Photo: H+O Structural Engineering, Kure Creative

Photo: Swinerton

Vertical Movements in Tall Mass Timber: Outline

- **Codes & Referenced Standards**
- **Sources of Vertical Movement**
- **Detailing to Minimize & Accommodate Movements**
- **Calculations vs. On-site Measured Movements**

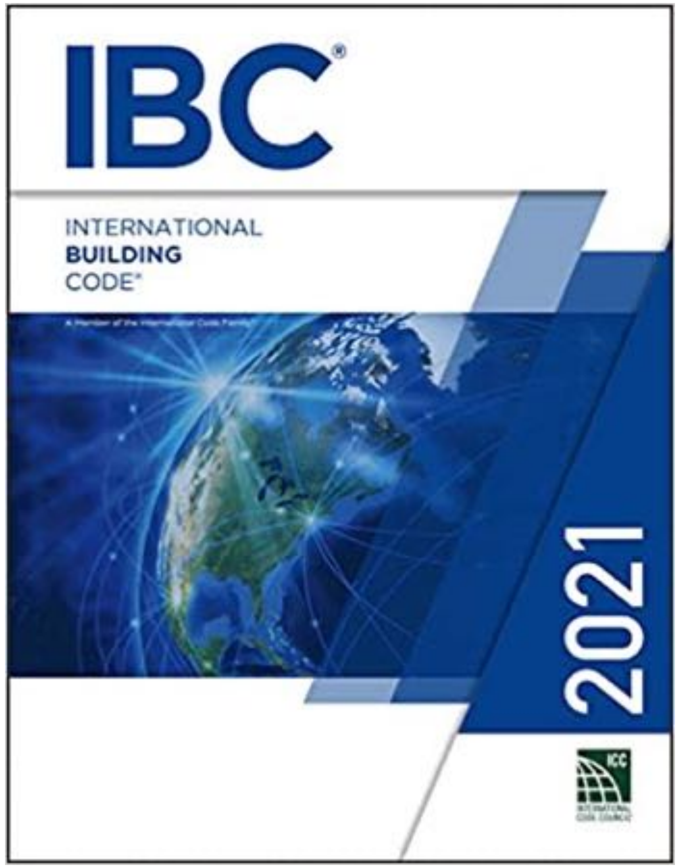
INTRO, Cleveland, OH, Photo: Harbor Bay Real Estate Advisors, Purple Film

Building Codes and Standards

IBC

References Material Standards (NDS) and Product Standards (PRG 320, ANSI 190.1)

IBC 2304.3.3 requires assessment of shrinkage effects on systems such as roof drainage, electrical, mechanical, and other equipment



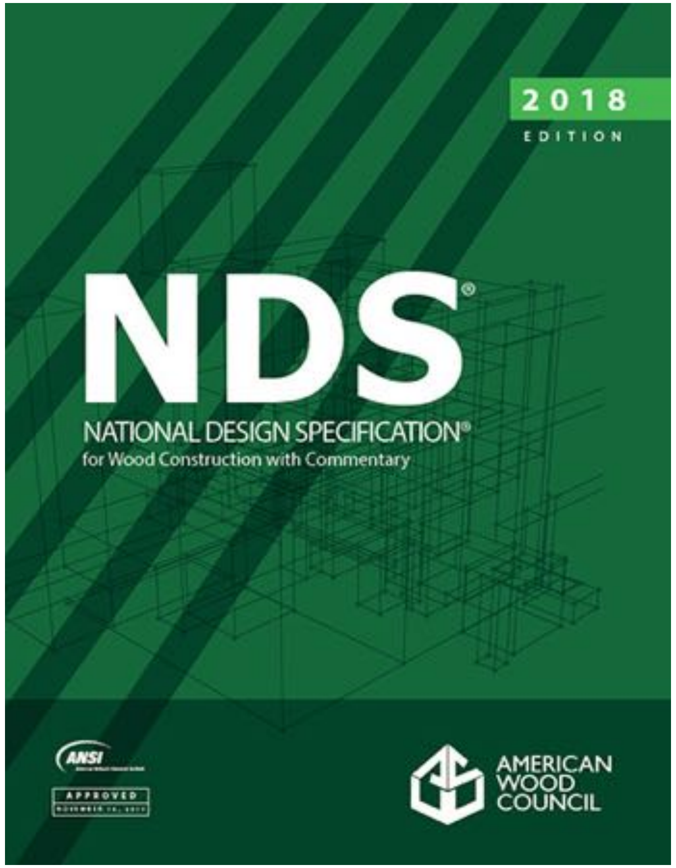
Building Codes and Standards

NDS

Design properties for wood members and connections

Includes properties for calculation of perpendicular to grain loading, resulting in crushing

Creep effects on bending members



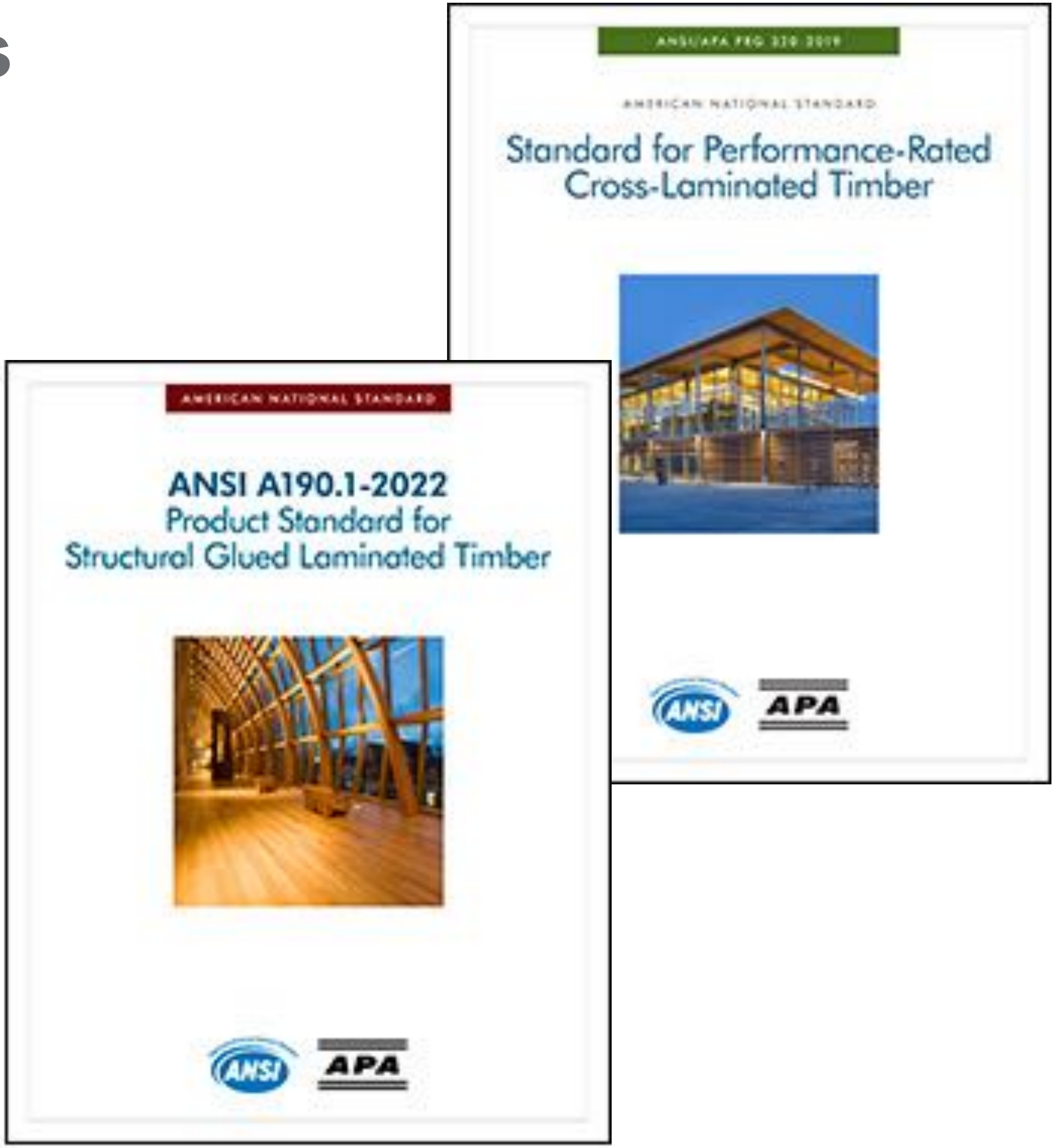
Building Codes and Standards

Mass Timber Product Standards

Product tolerances & MC at time of manufacturing

EG. CLT panel width +/- 1/8”
CLT panel length +/- ¼”
Glulam columns up to 20 ft long +/- 1/16”

ANSI A190.1: lumber used in glulam max MC = 16% at the time of bonding

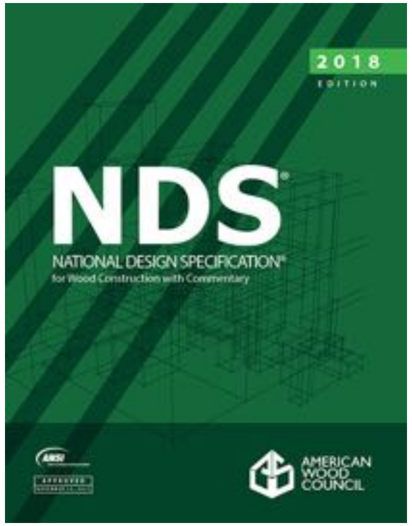


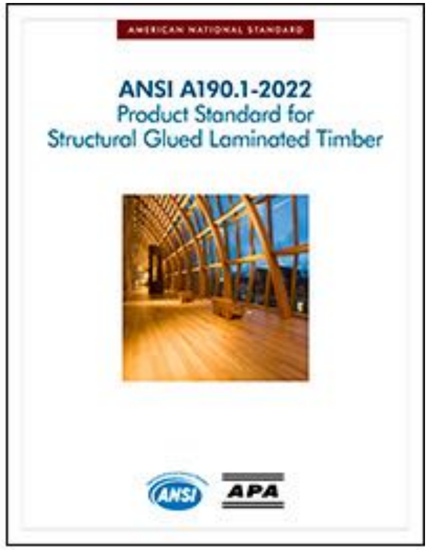
Building Codes and Standards

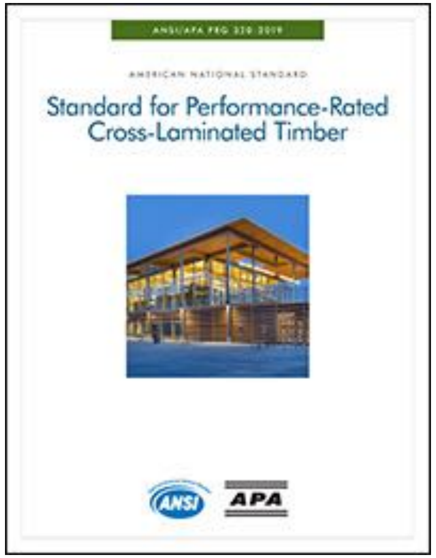
What's not addressed?

- Calculations for shrinkage
- Creep factor for column axial shortening
- Connection settlements

Engineering judgement is necessary. The following information notes several possible methods, it is not intended to cover all options or solutions







Quantifying Vertical Movement

Movement Types

- Column Axial Shortening including Creep
- Column Axial Shrinkage
- Panel & Beam Shrinkage
- Panel & Beam Crushing
- Beam Shortening
- Tolerances & Joint Settlements

Photo: Alex Nye

Quantifying Vertical Movement

Column Axial Shortening

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

Where:

- Δ_{as} = column axial shortening (in.)
- 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)

Photo: WoodWorks

Quantifying Vertical Movement

Column Axial Shortening

Design example:

- 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
- F'_c = 1,950 psi
- E = 1,600,000 psi

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

Photo: WoodWorks

Not accounting for creep effects

Quantifying Vertical Movement

Column Axial Shortening Including Creep Effects

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.)

Quantifying Vertical Movement

Column Axial Shortening Including Creep Effects

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:

$$\Delta_{as,T} = (1.5)(0.06)(20{,}000/45{,}000) + (0.06)(25{,}000/45{,}000) = 0.07 \text{ in.}$$

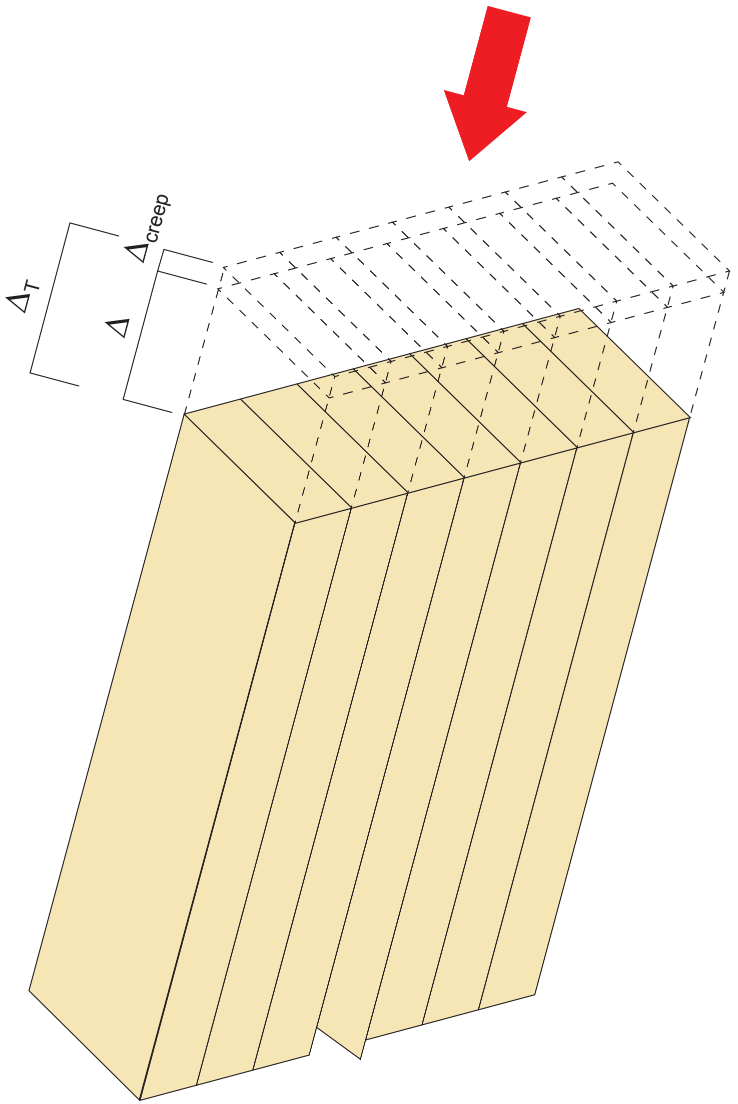
(0.01 in of this total is from creep)

Quantifying Vertical Movement

Column Axial Shortening Including Creep Effects

0.01 in creep
0.06 in non-creep
0.07 in total

Figure 3
Shortening of glulam columns



Quantifying Vertical Movement

Column Axial Shortening

Impact of fire-resistance ratings

$$\Delta_{as} = PL/AE$$

A column that is 'oversized' to provide a FRR will have a larger cross section for the same load, resulting in less axial shortening

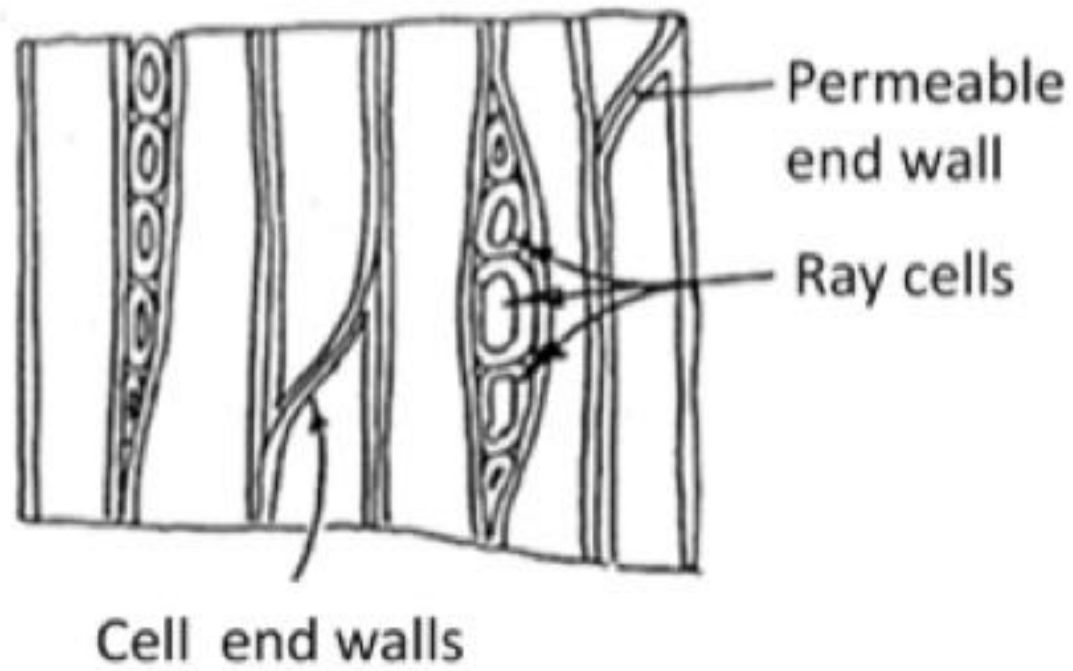
Photo: David Barber, Arup

Quantifying Vertical Movement

Column Axial Shrinkage

Wood is a hygroscopic material

- Has the ability to take on or give off moisture – acclimates to its surrounding conditions



Quantifying Vertical Movement

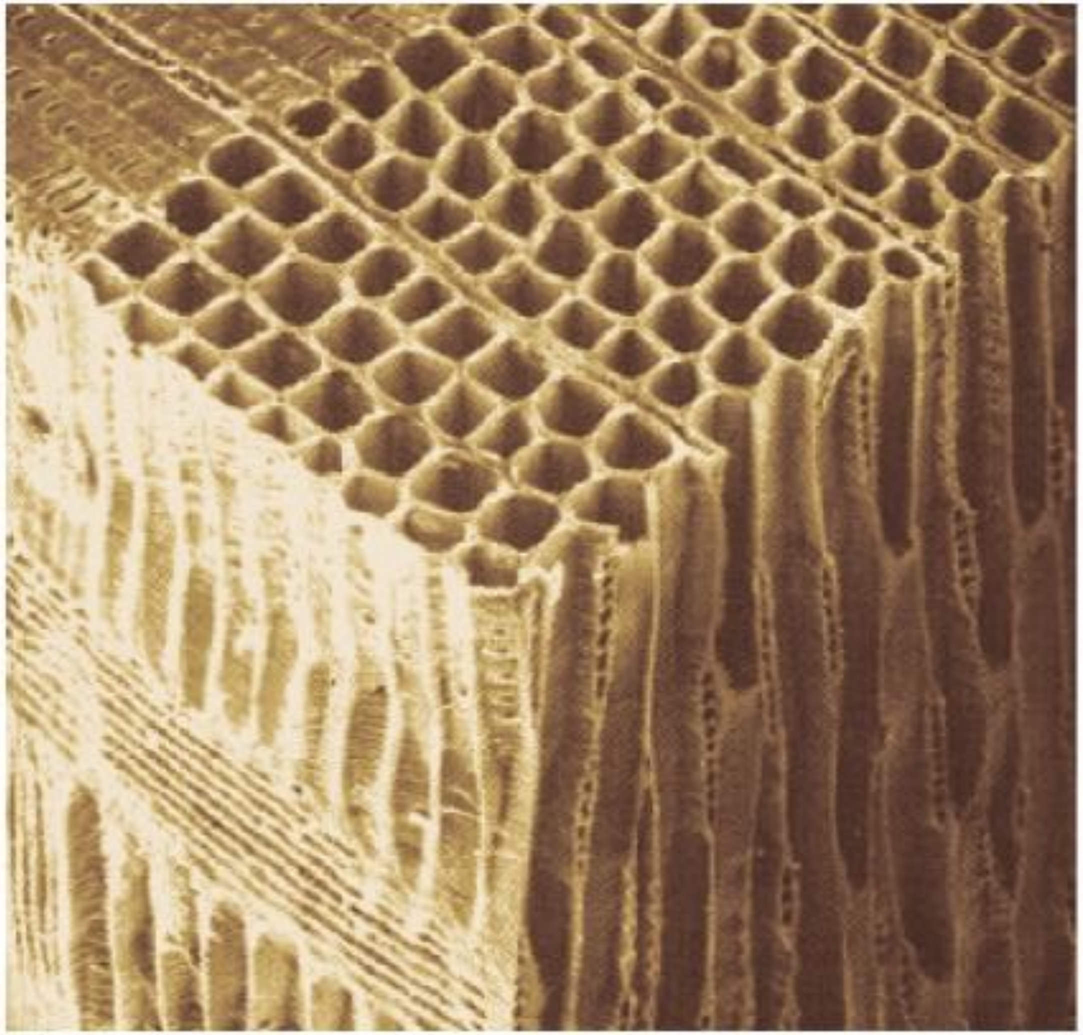
Column Axial Shrinkage

Water exists in wood in two forms:

- Free Water – water in cell cavity
- Bound Water – water bound to cell walls

Fiber Saturation Point (FSP):

- Point at which cell walls are completely saturated but cell cavities are empty (i.e. no free water but still has all its bound water)

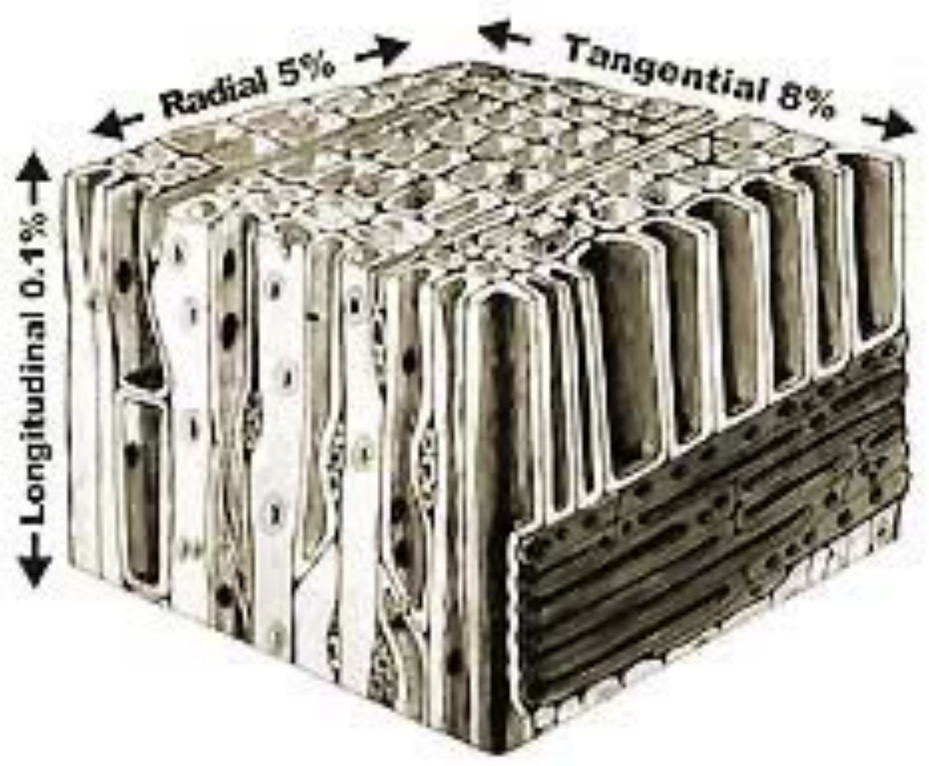


Southern yellow pine cellular makeup

Source: USDA Forest Service Agricultural Handbook (1972)

Quantifying Vertical Movement

Column Axial Shrinkage



When does wood shrink?

- After MC drops below FSP – bound water is removed

Why does wood shrink?

- Loss of moisture bound to cell wall changes thickness of cell wall

Is shrinkage uniform across all dimensions of a piece of lumber?

- No…

Quantifying Vertical Movement

Column Axial Shrinkage

Wood is orthotropic, meaning it behaves differently in its three orthogonal directions: Longitudinal (L), Radial (R), and Tangential (T)

- Longitudinal shrinkage is usually considered negligible in low- and mid-rise wood buildings
- In tall mass timber structures, effects can accumulate, should consider impacts

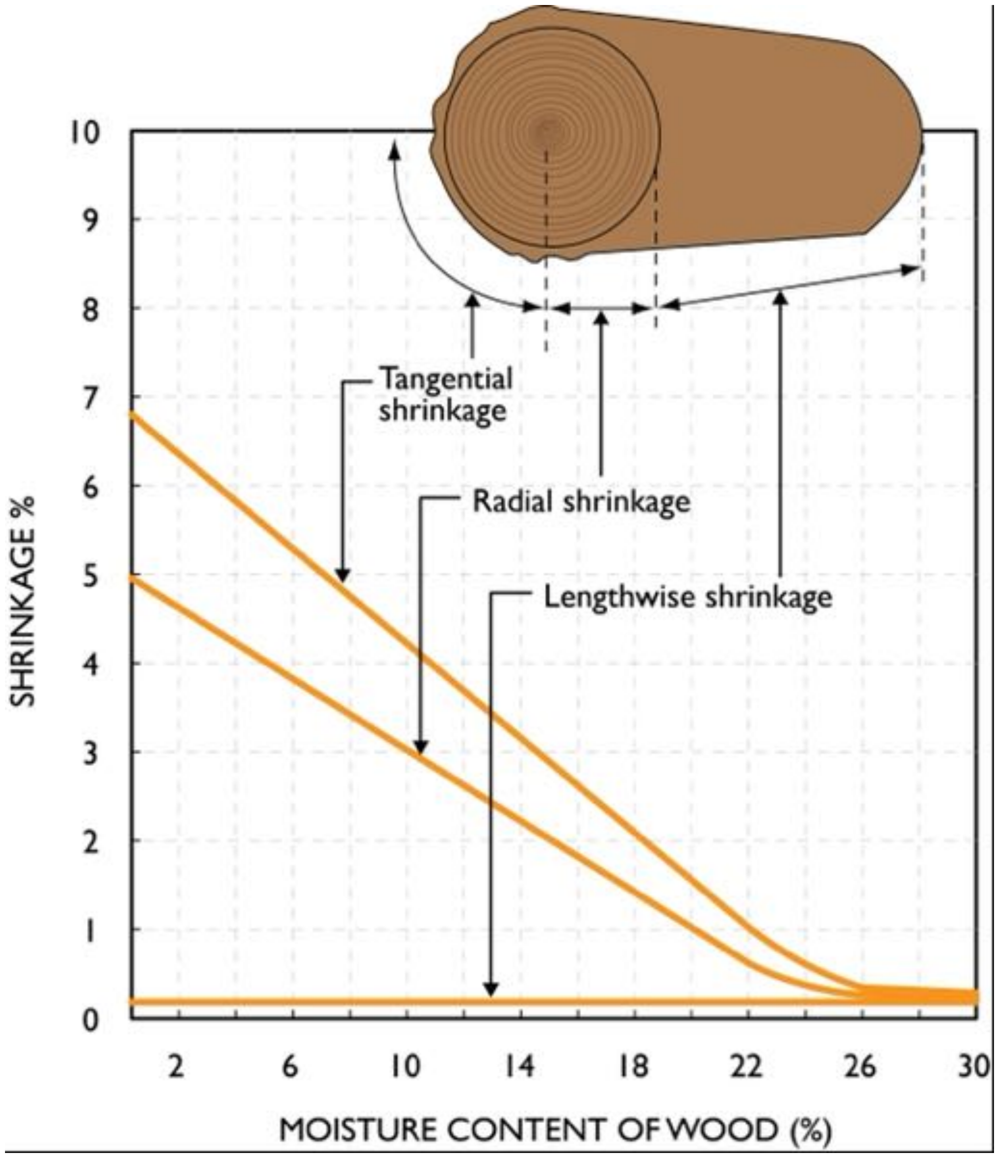


Image: RDH Building Science, Inc.

Quantifying Vertical Movement

Column Axial Shrinkage

Longitudinal shrinkage approximately 0.1% to 0.2%

Assuming an avg. of 0.15%, and a fiber saturation point (FSP) of MC = 28%, this results in a coefficient of longitudinal shrinkage of:

0.0015 / 28 = 0.000054

INTRO, Cleveland, OH, Photo: Harbor Bay Real Estate Advisors, Purple Film

Quantifying Vertical Movement

Column Axial Shrinkage

0.000054 is the amount of longitudinal shrinkage per inch of column length per % of MC change.

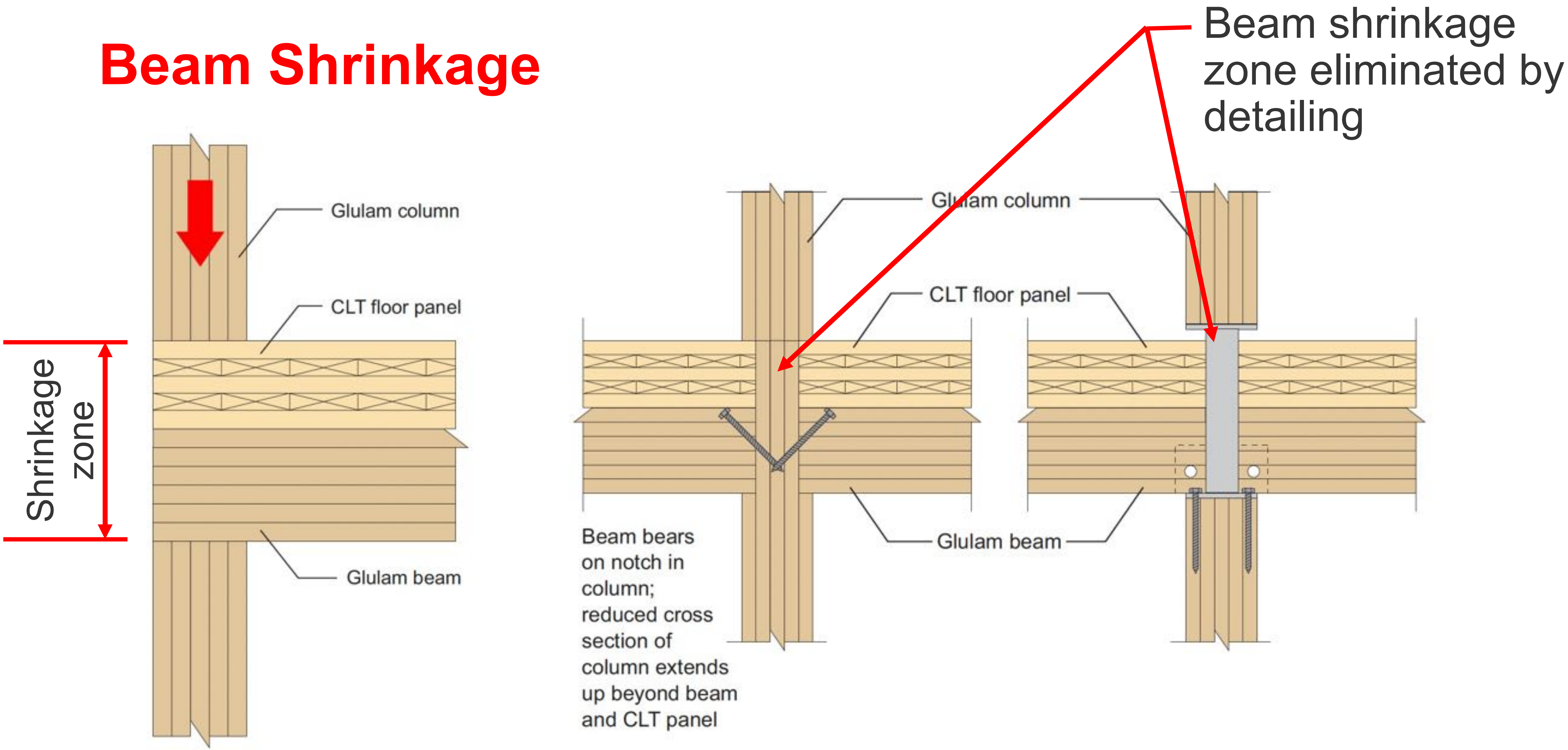
Using the column from the example earlier in this document, assume an 8-3/4-in. x 9-in. column, 15 ft long, with installed MC of 19% and EMC of 12%. Calculated longitudinal column shrinkage is:

Column Length:

$$\Delta_{shrinkage} = (15\text{ ft})(12\text{ in./ft})(0.000054)(19\text{-}12) = 0.07\text{ in.}$$

Quantifying Vertical Movement

Beam Shrinkage



Quantifying Vertical Movement

Beam Shrinkage

Longitudinal shrinkage approximately 0.1% to 0.2%

Radial & Tangential (cross-grain) shrinkage approximately 5% to 7%

Coefficient of cross-grain shrinkage = 0.07 / 28 = 0.0025

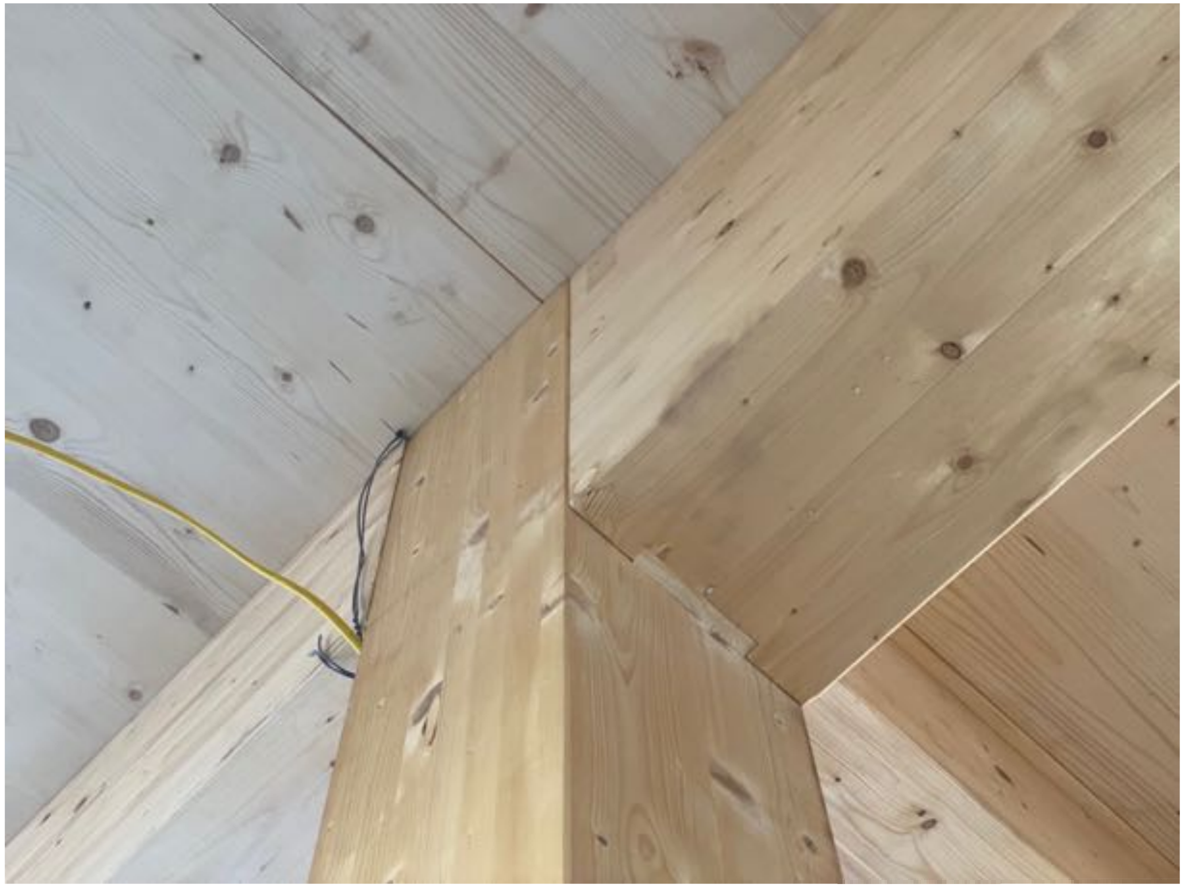


Photo: WoodWorks

Quantifying Vertical Movement

Beam Shrinkage

Beam to column connection not detailed to eliminate shrinkage:

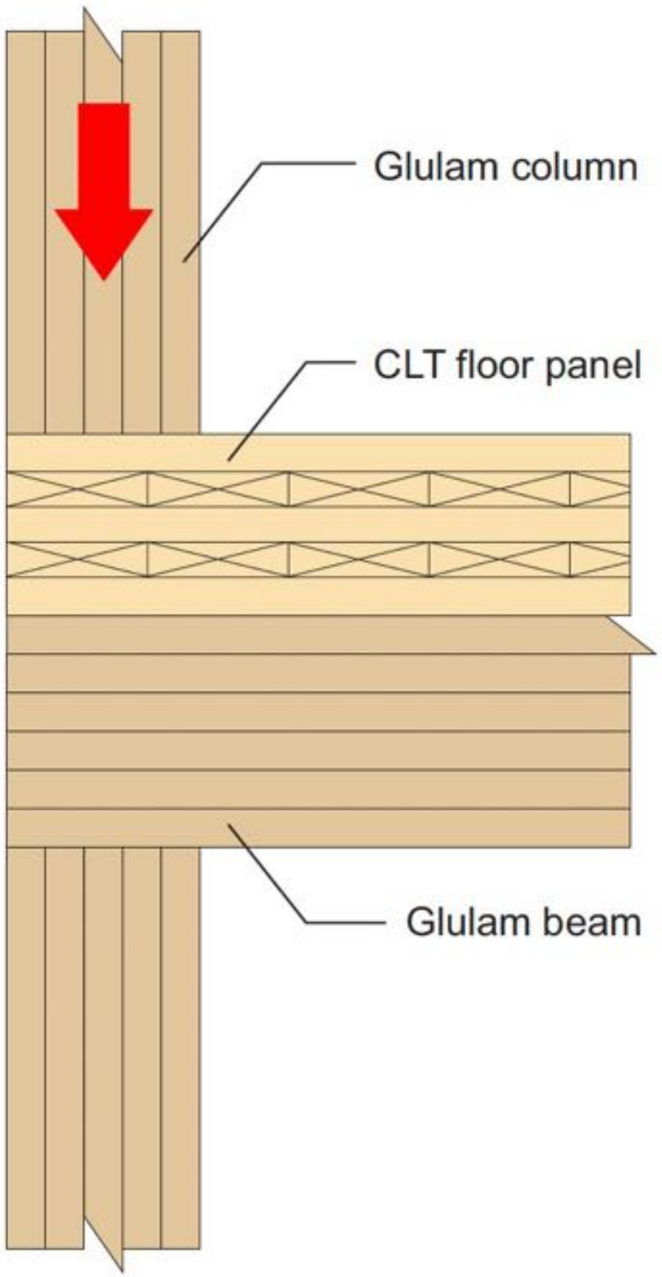
For example, an 8-3/4-in. x 24-in. glulam beam with an installed MC of 19% and EMC of 12% would have an anticipated shrinkage of:

Beam depth:

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

Beam width:

$$\Delta_{shrinkage} = (8.75 \text{ in.})(0.0025)(19\text{-}12) = 0.15 \text{ in.}$$



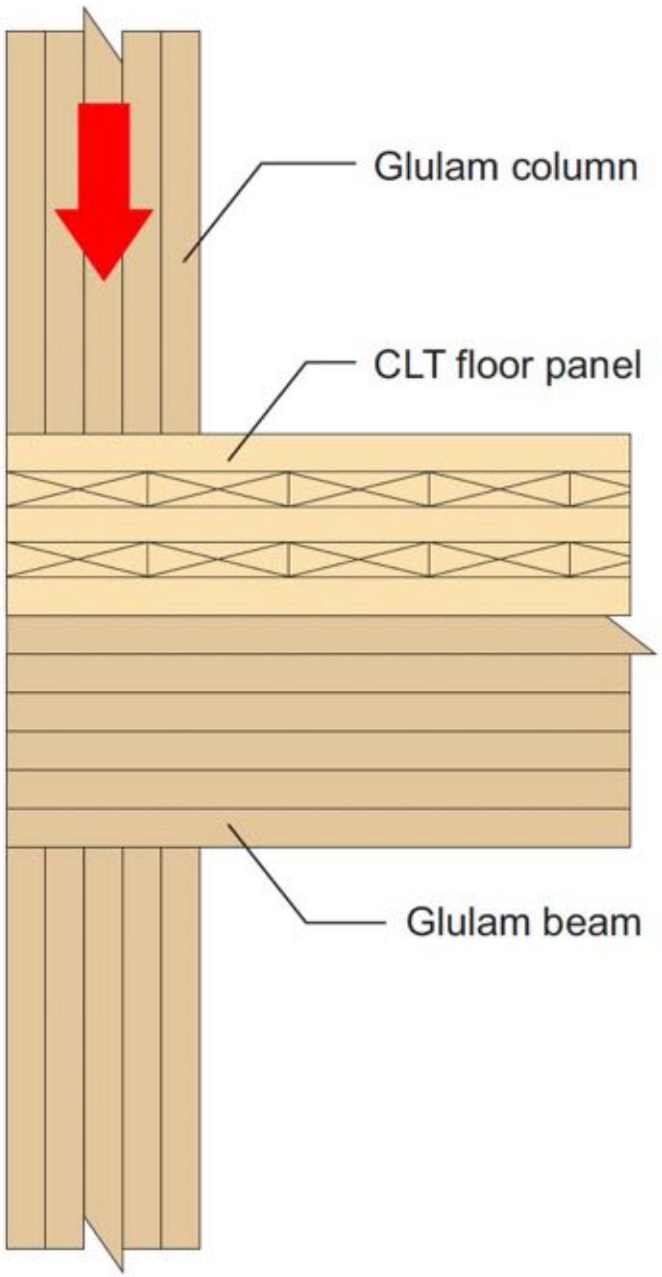
Quantifying Vertical Movement

Panel Shrinkage

Some engineers may also choose to account for panel shrinkage if not isolated from shrinkage zone:

Assume 5-ply mass timber panel, 6-7/8” thick:

$\Delta_{shrinkage}$ = (6.875 in.)(0.0025)(19-12) = 0.12 in.



Quantifying Vertical Movement

Beam & Panel Shrinkage

On-site moisture protection measures directly impact column & beam shrinkage

Recall that one of the variables in the shrinkage equation is installed MC. The lower this is, the closer it will be to equilibrium MC, which results in less shrinkage

Photo: WoodWorks

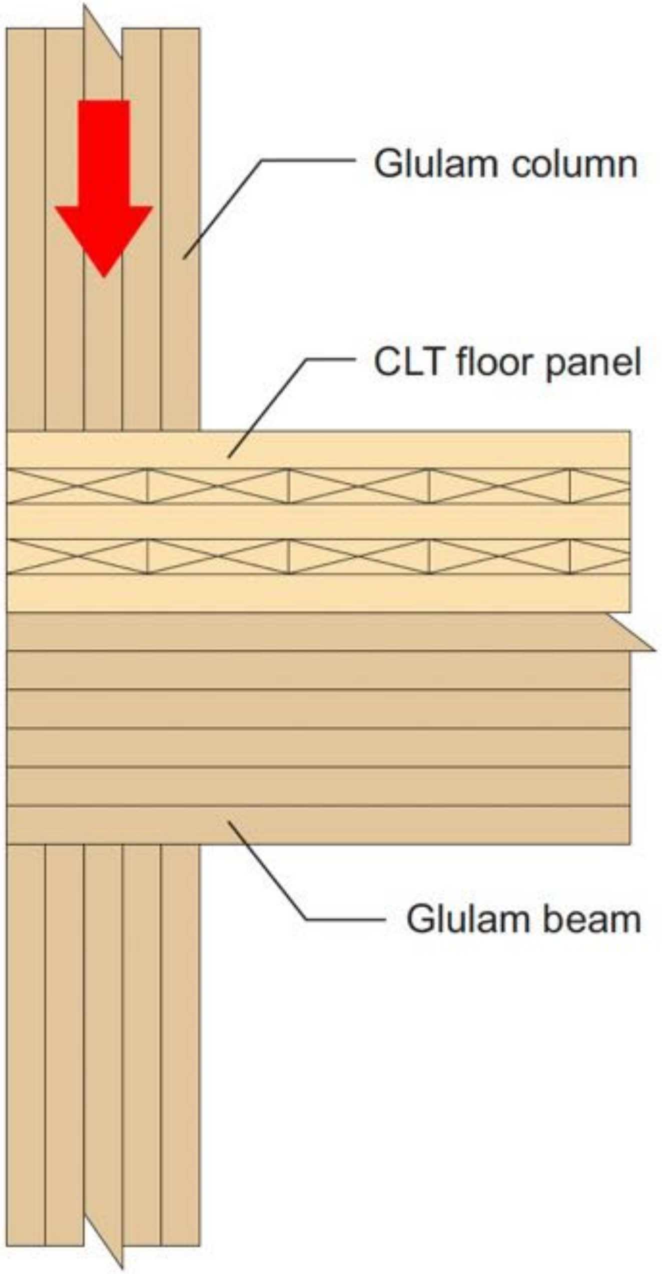
Quantifying Vertical Movement

Beam Crushing

Limiting perp to grain stresses in bearing (eg. column bearing top of beam or panel) results in small amounts of localized crushing

Crushing at 73% of allowable perpendicular-to-grain stress is 0.02 in.

Crushing at 100% of allowable perpendicular-to-grain stress is 0.04 in.



Quantifying Vertical Movement

Beam Crushing

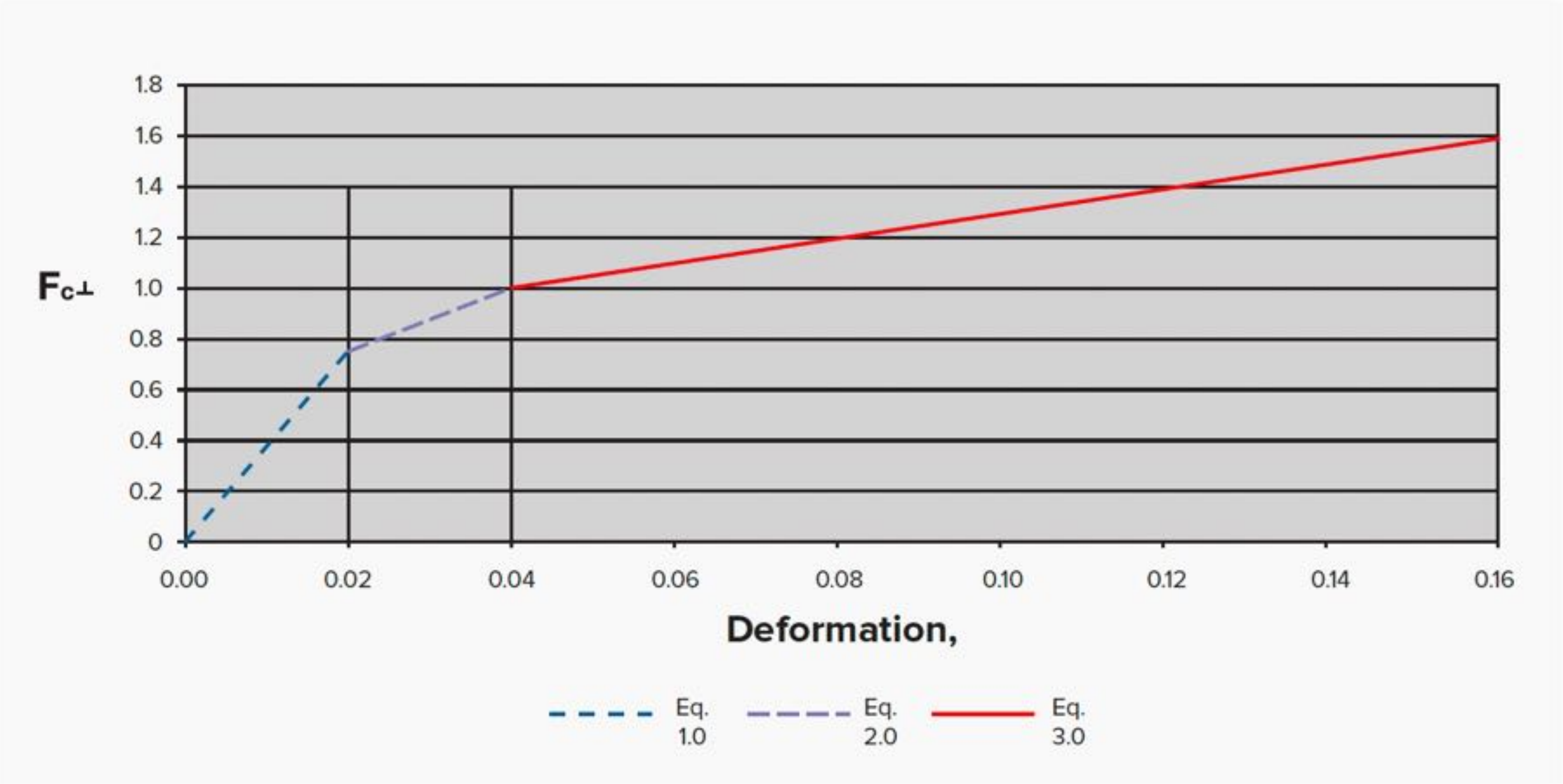


FIGURE 7: Fc⊥ load deformation curve
SDPWS Commentary Example C4.3.4-2 and SDPWS Commentary Reference 67

Quantifying Vertical Movement

Beam Crushing

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 $F_{c\perp}$)

Quantifying Vertical Movement

Beam Crushing

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. ← Per bearing interface

$\Delta_{crushing}$ = (0.03)(2) = 0.06 in. ← 2x bearing interfaces

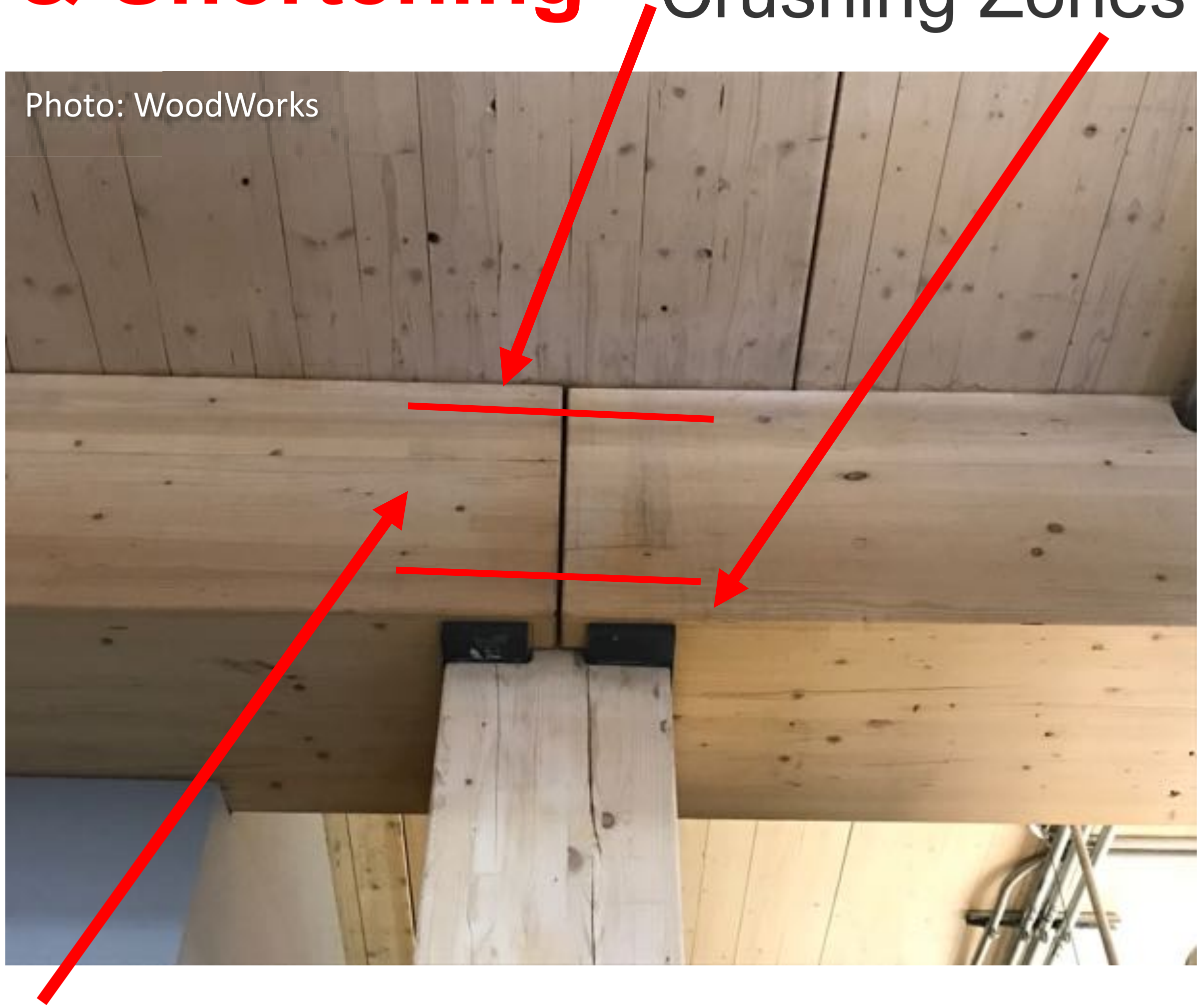
Quantifying Vertical Movement

Beam Shrinkage, Crushing & Shortening

Crushing commonly assumed to occur within 2” of top and bottom of beam

What about the short “column” in between?

Can still be subject to shortening in a similar manner to PL/(AE) of columns



Quantifying Vertical Movement

Beam Shortening

PL/(AE):

- 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)
- E is E of the beam divided by 30
    - E/30 term is an estimate derived from ASTM D2555 for clear wood

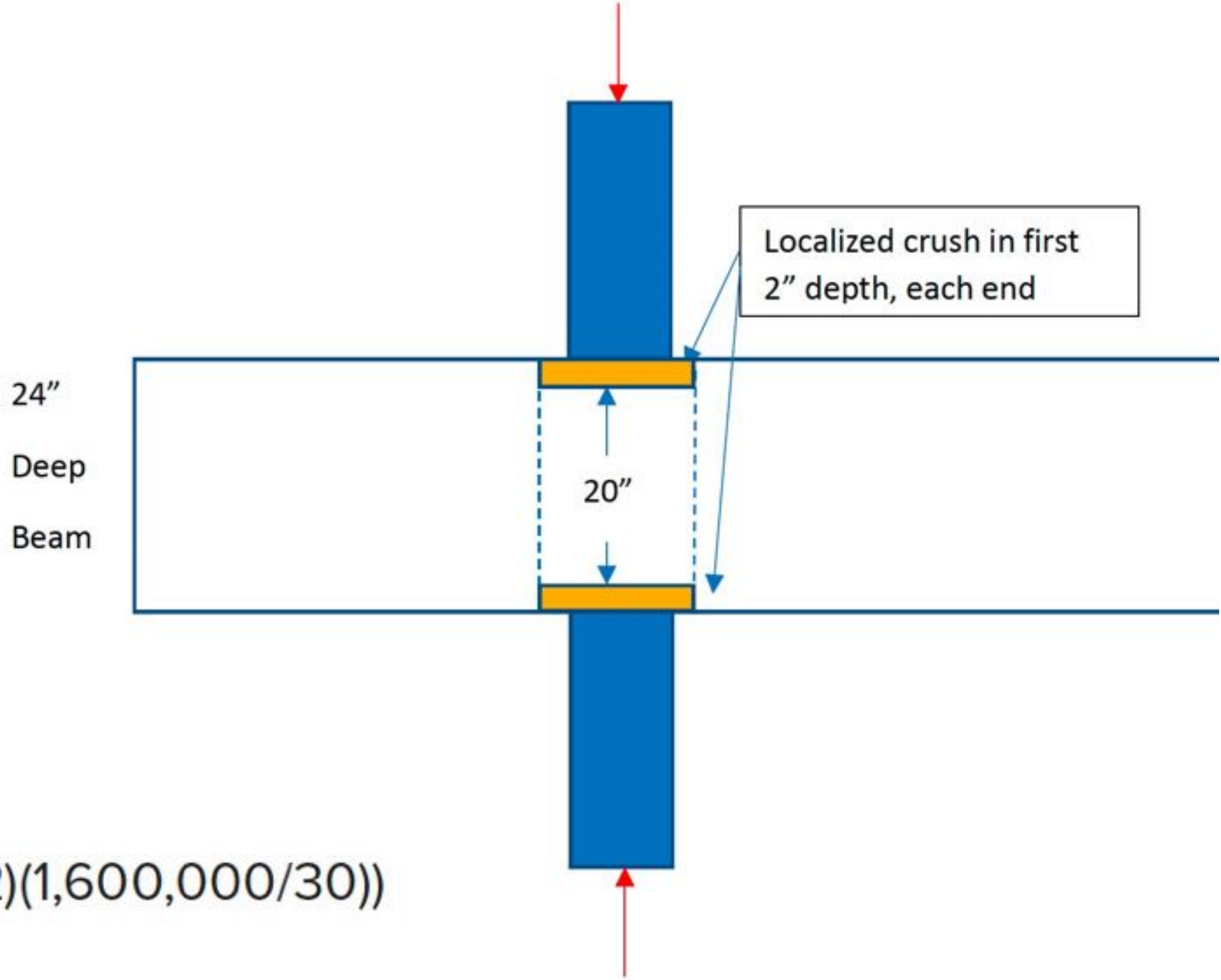
Quantifying Vertical Movement

Beam Shortening

For the beam and column example above, this would result in a beam core depth shortening of:

Column is 8.75”x9”

Beam is 8.75”x24”



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

Quantifying Vertical Movement

Tolerances & Joint Settlements

Material tolerances and small amounts of vertical settlement at connections can result in additional vertical movements

Some engineers include this additional movement in total building shrinkage calculations (1/16-in. per floor for example) while others choose to ignore it

Photo: WoodWorks

Quantifying Vertical Movement

Summing all Vertical Movements

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

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:

$$\Delta_{column} = 0.07 + 0.42 + 0.07 + 0.06 + 0.06 = 0.68 \text{ in.}$$

x 12 story building = 8.2 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:

$$\Delta_{column} = 0.07 + 0 + 0.07 + 0 + 0.06 = 0.2 \text{ in.}$$

x 12 story building = 2.4 in

Vertical Movement in Mass Timber Design Resource

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WoodWorks – Wood Products Council

WOODWORKS

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

INTRO in Cleveland, OH

Free download at woodworks.org

Questions?

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901 East Sixth, Thoughtbarn-Delineate Studio, Leap!Structures, photo Casey Dunn

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