Mitigating Shrinkage and Differential Movement in Wood Construction

Presented by:
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Course Description

In wood-frame buildings of three or more stories, cumulative shrinkage can be significant and have an impact on the function and performance of finishes, openings, mechanical/electrical/plumbing (MEP) systems, and structural connections. However, as more designers look to wood-frame construction to improve the cost and sustainability of their mid-rise projects, many have learned that accommodating wood shrinkage is actually very straightforward. This presentation will describe procedures for estimating wood shrinkage and provide detailing options that minimize its effects on building performance.

Learning Objectives

1. Discuss the cellular structure of wood in order to understand how moisture and wood interact, and identify the paths that moisture typically travels.

2. Explain methods of calculating expected shrinkage in multi-story wood-frame buildings.

3. Highlight best practice details for accommodating wood shrinkage and differential material movement at conditions such as opening sills, MEP lines and shaft wall connections.

4. Review considerations and solutions associated with shrinkage effects on structural connections.

Shrinkage Design Topics - Agenda

1. Wood Science
2. Shrinkage Calculations
3. Minimizing Shrinkage
4. Differential Movement
5. Structural Connections
6. Balconies and Decks

Shrinkage Resource

Code provisions, detailing options, calculations and more for accommodating differential material movement in wood structures

Free resource at woodworks.org

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Accommodating Shrinkage in Multi-Story Wood-Frame Structures

Richard McLain, MS, PE, SE, Technical Director, WoodWorks • Doug Steimle, PE, Principal, Schaefer

In wood-frame buildings of three or more stories, cumulative shrinkage can be significant and have an impact on the function and performance of finishes, openings, mechanical/electrical/plumbing (MEP) systems, and structural connections. However, as more designers look to wood-frame construction to improve the cost and sustainability of their mid-rise projects, many have learned that accommodating wood shrinkage is actually very straightforward.

Wood is hygroscopic, meaning it has the ability to absorb and release moisture. As this occurs, it also has the potential to change dimensionally. Knowing how and where wood shrinks and swells helps designers detail their buildings to minimize related effects.

Wood shrinkage occurs perpendicular to grain, meaning that a solid sawn wood stud or floor joist will shrink in its cross-section dimensions (width and depth). Longitudinal shrinkage is negligible, meaning the length of a stud or floor joist will essentially remain unchanged. In multi-story buildings, wood shrinkage is therefore concentrated at the wall plates, floor and roof joists, and rim boards. Depending on the materials and details used at floor-to-wall and roof-to-wall intersections, shrinkage in light-frame wood construction can range from 0.05 inches to 0.5 inches per level.

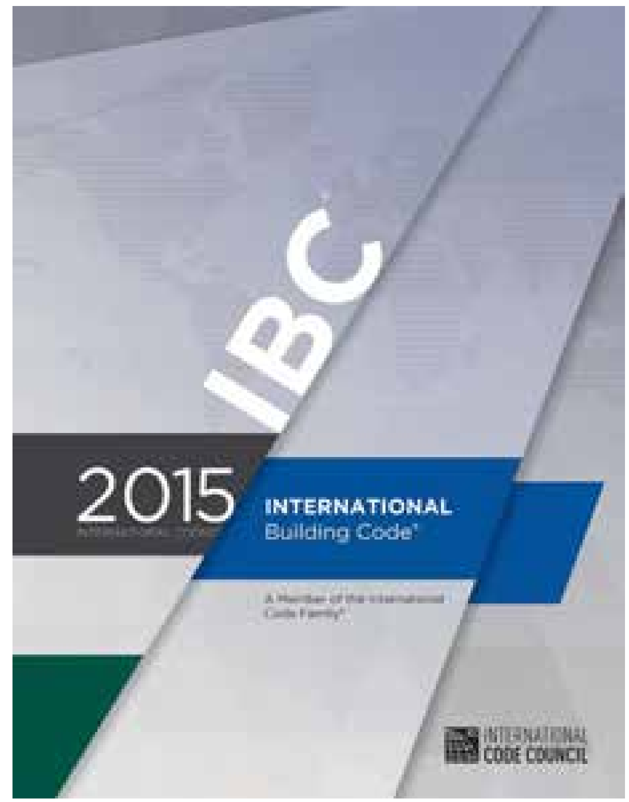
This publication will describe procedures for estimating wood shrinkage and provide detailing options that minimize its effects on building performance.

The Brooklyn Riverside
Jacksonville, Florida
Architect: Dwell Design Studio
Structural Engineer: M2 Structural Engineering

a longitudinal cell in the wood. Water can be free water stored in the straw cavity or bound water absorbed by the straw 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

Shrinkage Code Requirements

2304.3.3 Shrinkage. Wood walls and bearing partitions shall not support more than two floors and a roof unless an analysis satisfactory to the building official shows that **shrinkage of the wood framing will not have adverse effects on the structure or any plumbing, electrical or mechanical systems, or other equipment installed** therein due to excessive shrinkage or differential movements caused by shrinkage. The analysis shall also show that the roof drainage system and the foregoing systems or equipment will not be adversely affected or, as an alternative, such systems shall be designed to accommodate the differential shrinkage or movements.



Shrinkage Design Considerations

Image: Schaefer

Shrinkage Design Considerations

Designing and detailing to accommodate shrinkage is a design criteria but it doesn’t need to be difficult

With proper calculations, detailing & an understanding of how and why wood shrinks, it simply becomes a very approachable design topic


Why Does
Wood Shrink?

Wood Science



Key Terms

Dry lumber – Lumber of less than nominal 5-inch thickness which has been seasoned or dried to a maximum moisture content of 19 percent

Equilibrium moisture content (EMC) – The moisture content at which wood neither gains nor loses moisture when surrounded by air at a given relative humidity and temperature

Green lumber – Lumber of less than nominal 5-inch thickness which has a moisture content in excess of 19 percent or, for lumber of nominal 5-inch or greater thickness (timbers), as defined in accordance with applicable lumber grading rules

Heat treated (HT) – Lumber or other wood product that has been heated in a closed chamber, with or without moisture content reduction, until it achieves a minimum core temperature of 132.8°F for a minimum of 30 minutes

Kiln dried (KD) – Lumber that has been seasoned in a chamber to a predetermined moisture content by applying heat

Moisture content (MC) – The weight of the water in a piece of lumber expressed in a percentage of the weight of the piece after being oven dried.

Fiber saturation point (FSP) – The point in drying wood at which all free moisture has been removed from the cell itself while the cell wall remains saturated with absorbed moisture

Example lumber grade stamps

Grade Stamp Markings:

S-GRN: surfaced green

S-DRY: surfaced dry

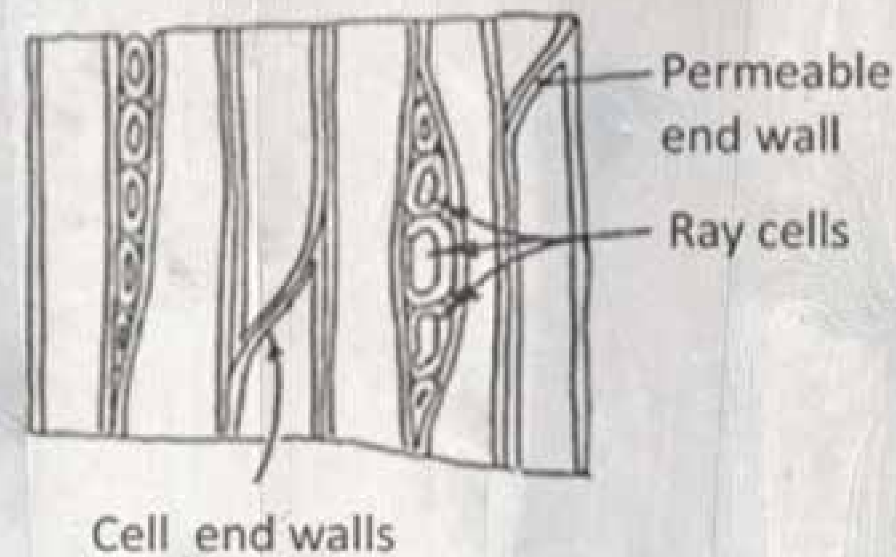
KD: kiln dried

HT: heat treated

Wood Science – Cellular Makeup

Wood is a hygroscopic material

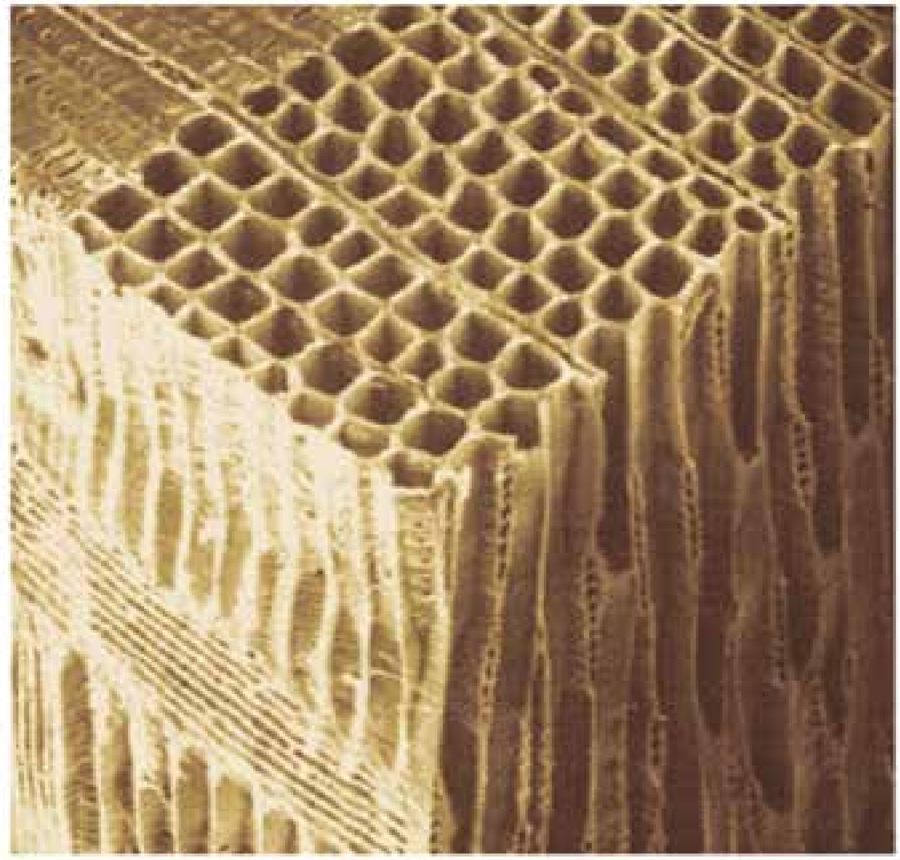
- Has the ability to take on or give off moisture – acclimates to its surrounding conditions



Wood Science – Moisture in Wood

Water exists in wood in two forms:

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



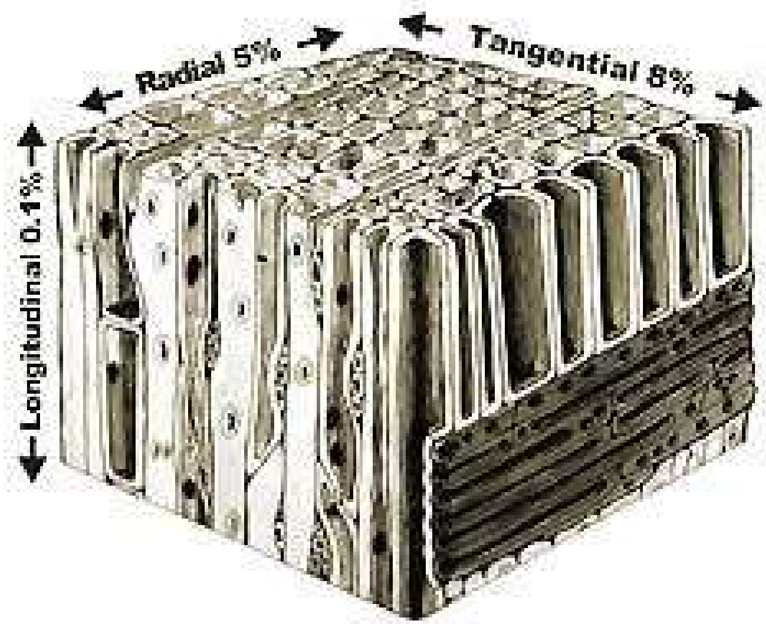
Southern yellow pine cellular makeup

Source: USDA Forest Service Agricultural Handbook (1972)

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)

Wood Science - 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

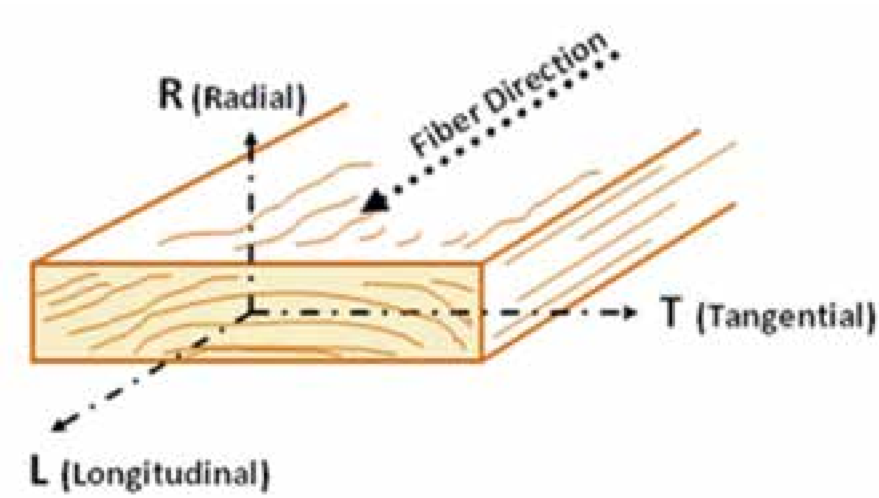
Is shrinkage uniform across all dimensions of a piece of lumber?

- No…

Wood Science

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

- Longitudinal shrinkage is negligible
- Can assume avg. of radial & tangential or assume all tangential



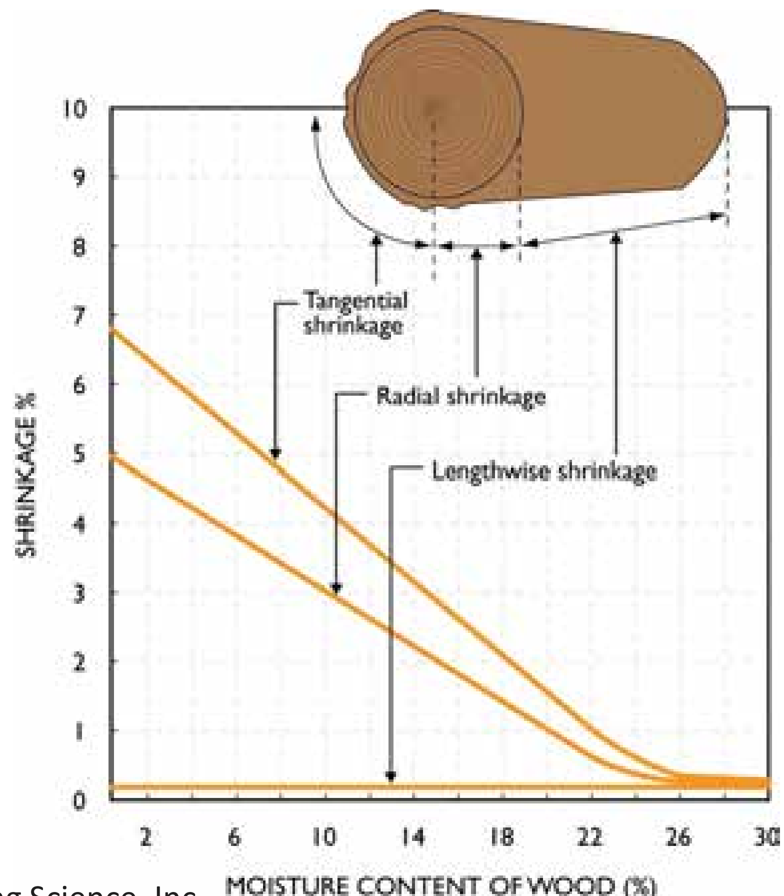


Image: RDH Building Science, Inc.

Wood Science - Moisture Content

Fiber Saturation Point is generally around MC 30%

$$MC = \frac{W_{wet} - W_{dry}}{W_{dry}} * 100\%$$

Where:

MC = Moisture Content

W_{wet} = current weight of wood

W_{dry} = oven dry weight of wood

Wood Science - Moisture Content

Shrinkage will continue to occur linearly from FSP until the wood's equilibrium moisture content (EMC) has been reached.

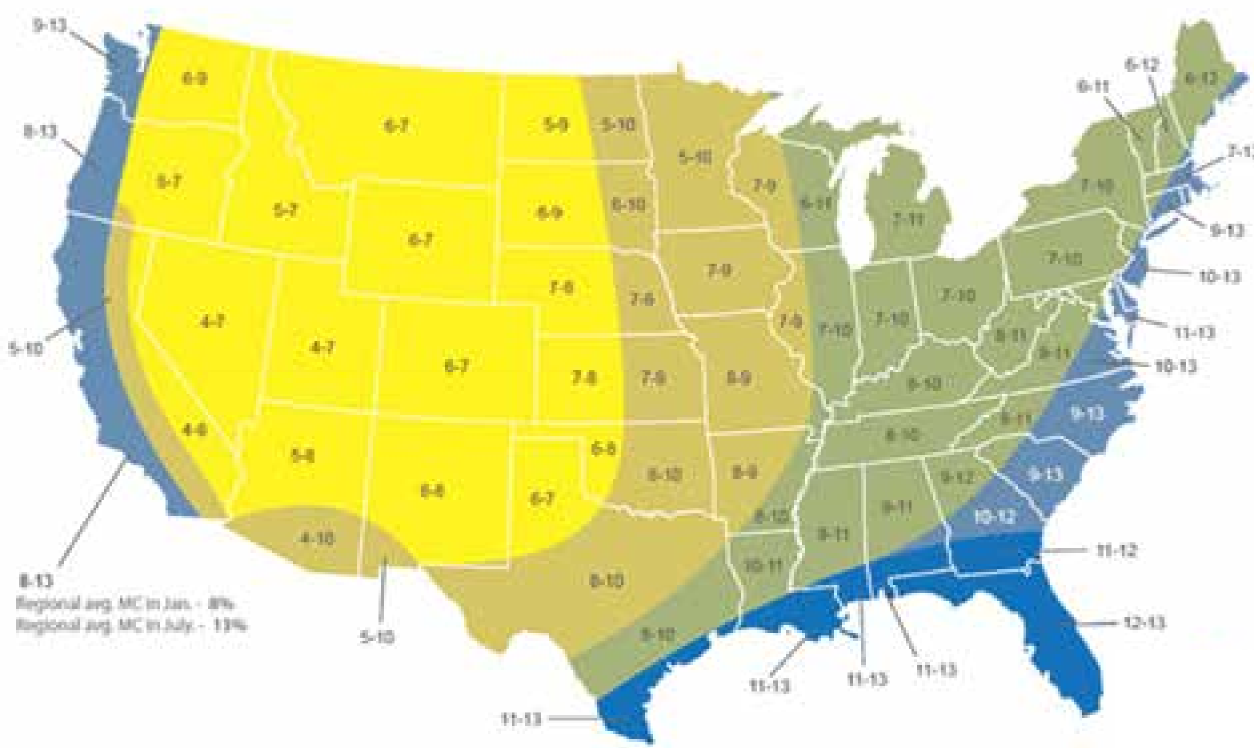
- Function of temperature & relative humidity

Moisture Content of Wood at Various Temperatures and Relative Humidity														
Temperature (F)														
60	4.6	5.4	6.2	7.0	7.8	8.6	9.4	10.2	11.1	12.1	13.3	14.6	16.2	18.2
70	4.5	5.4	6.2	6.9	7.7	8.5	9.2	10.1	11.0	12.0	13.1	14.4	16.0	17.9
80	4.4	5.3	6.1	6.8	7.6	8.3	9.1	9.9	10.8	11.7	12.9	14.2	15.7	17.7
	20	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**
Relative Humidity (percent)														

Source: Wood Handbook, USDA Forest Service

Wood Science - Moisture Content

EMC is the point at which the wood is neither gaining nor losing moisture. However, this is a dynamic equilibrium and can vary throughout the year



Wood Science - Moisture Content

USDA Forest Products Lab's Wood Handbook a useful resource for EMC and other shrinkage related data

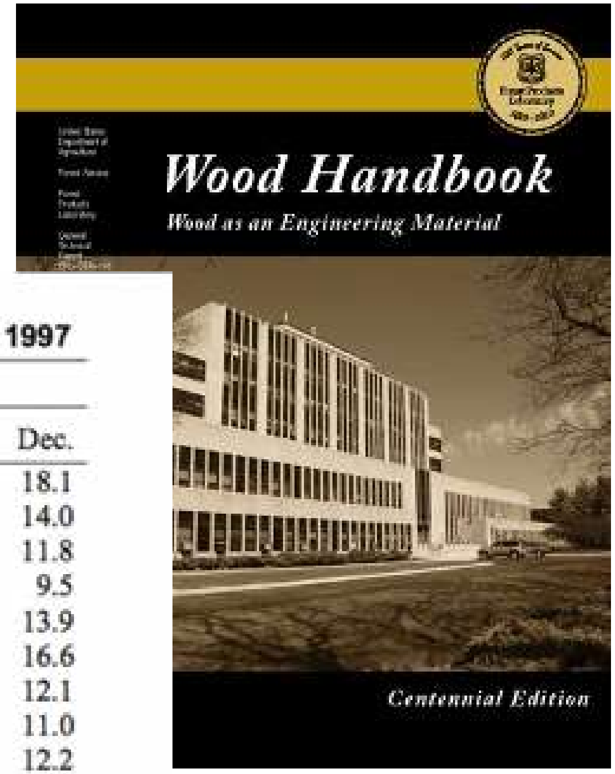


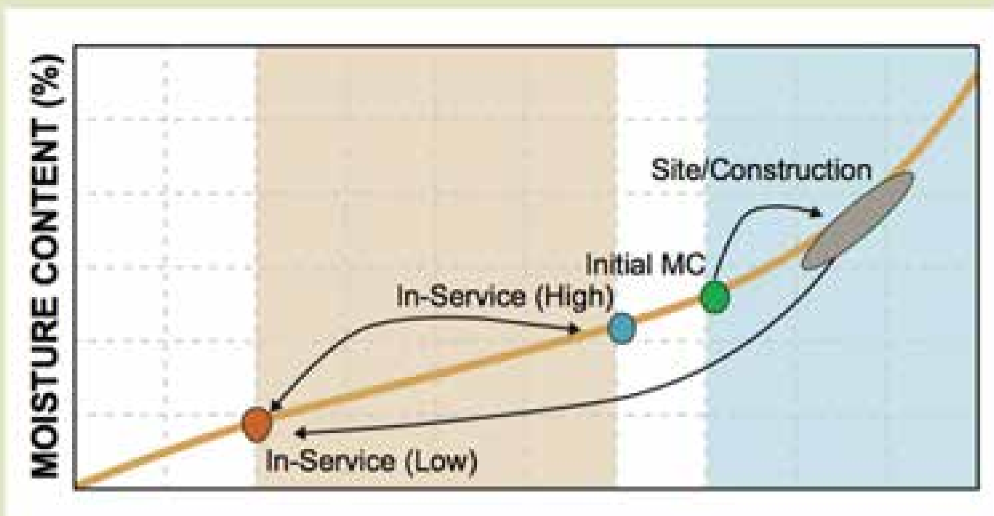
Table 13–1. Equilibrium moisture content for outside conditions in several U.S. locations prior to 1997

		Equilibrium moisture content[a] (%)											
State	City	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
AK	Juneau	16.5	16.0	15.1	13.9	13.6	13.9	15.1	16.5	18.1	18.0	17.7	18.1
AL	Mobile	13.8	13.1	13.3	13.3	13.4	13.3	14.2	14.4	13.9	13.0	13.7	14.0
AZ	Flagstaff	11.8	11.4	10.8	9.3	8.8	7.5	9.7	11.1	10.3	10.1	10.8	11.8
AZ	Phoenix	9.4	8.4	7.9	6.1	5.1	4.6	6.2	6.9	6.9	7.0	8.2	9.5
AR	Little Rock	13.8	13.2	12.8	13.1	13.7	13.1	13.3	13.5	13.9	13.1	13.5	13.9
CA	Fresno	16.4	14.1	12.6	10.6	9.1	8.2	7.8	8.4	9.2	10.3	13.4	16.6
CA	Los Angeles	12.2	13.0	13.8	13.8	14.4	14.8	15.0	15.1	14.5	13.8	12.4	12.1
CO	Denver	10.7	10.5	10.2	9.6	10.2	9.6	9.4	9.6	9.5	9.5	11.0	11.0
DC	Washington	11.8	11.5	11.3	11.1	11.6	11.7	11.7	12.3	12.6	12.5	12.2	12.2
FL	Miami	13.5	13.1	12.8	12.3	12.7	14.0	13.7	14.1	14.5	13.5	13.9	13.4
GA	Atlanta	13.3	12.3	12.0	11.8	12.5	13.0	13.8	14.2	13.9	13.0	12.9	13.2
HI	Honolulu	13.3	12.8	11.9	11.3	10.8	10.6	10.6	10.7	10.8	11.3	12.1	12.9
ID	Boise	15.2	13.5	11.1	10.0	9.7	9.0	7.3	7.3	8.4	10.0	13.3	15.2

Wood Science - Moisture Content

Not only can wood's MC vary during a year, it can vary much more drastically during construction

FIGURE 2:
Moisture content range



Source: RDH Building Science Inc.

Shrinkage Calculations

Three variables influence amount of shrinkage:

- Installed moisture content (MC)
- In-service equilibrium moisture content (EMC)
- Cumulative thickness of cross-grain wood contributing to shrinkage

Wood species has relatively little impact since most species used in commercial construction have similar shrinkage properties.

Shrinkage Calculations

Initial or Installed moisture content (MC)

- Typically specified by Structural EoR
- 19% max MC is common
- Green or 15% max MC also available in select markets
- Important to keep in mind this is the MC when it is manufactured
- MC at time of finish install can be much higher or lower

Shrinkage Calculations

Product	Moisture Content
Lumber – S-Dry	19% or less
Lumber – S-Green	Usually over 19%
Panel products (OSB, plywood)	4-8%
I-Joists	4-16%

$M_i = 19\%$

$M_i = 28\%$

Shrinkage Calculations – Construction Moisture

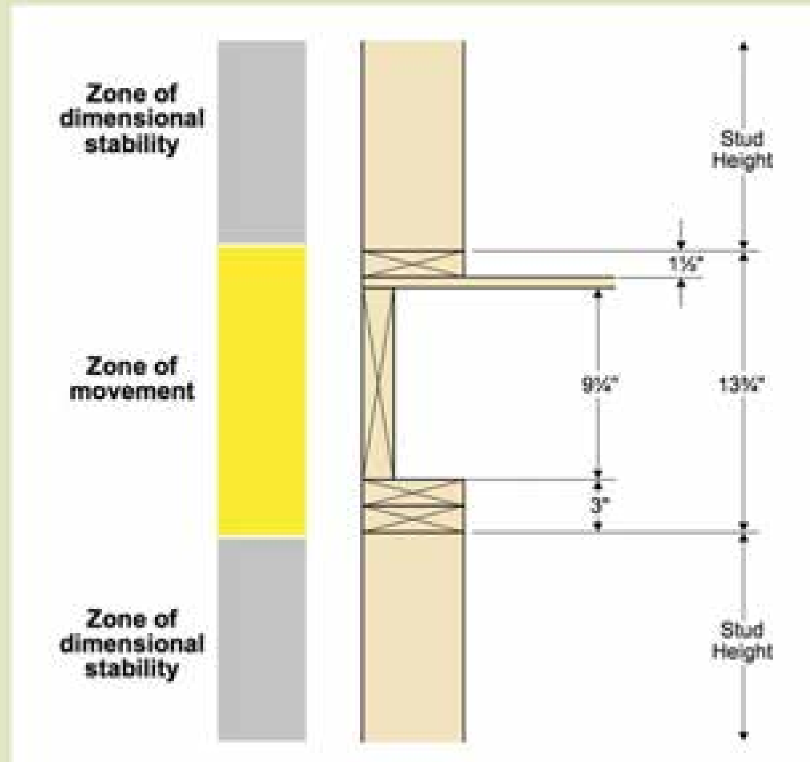
1. Minimize storage of material on site where rain and standing water can increase moisture content.
2. Keep unused framing material covered
3. Inspect pre-built wall panels prior to installation for proper material and quality of mechanical fasteners.
4. “Dry-in” the structure as quickly as possible.
5. Immediately remove any standing water from floor framing after rain showers.
6. Ensure that installed lumber MC is lowered to 19% or calculated max MC before installing finishes & insulation

Shrinkage Calculations – Cross Grain Wood

Shrinkage occurs in cross-grain, but not longitudinal, wood dimensions

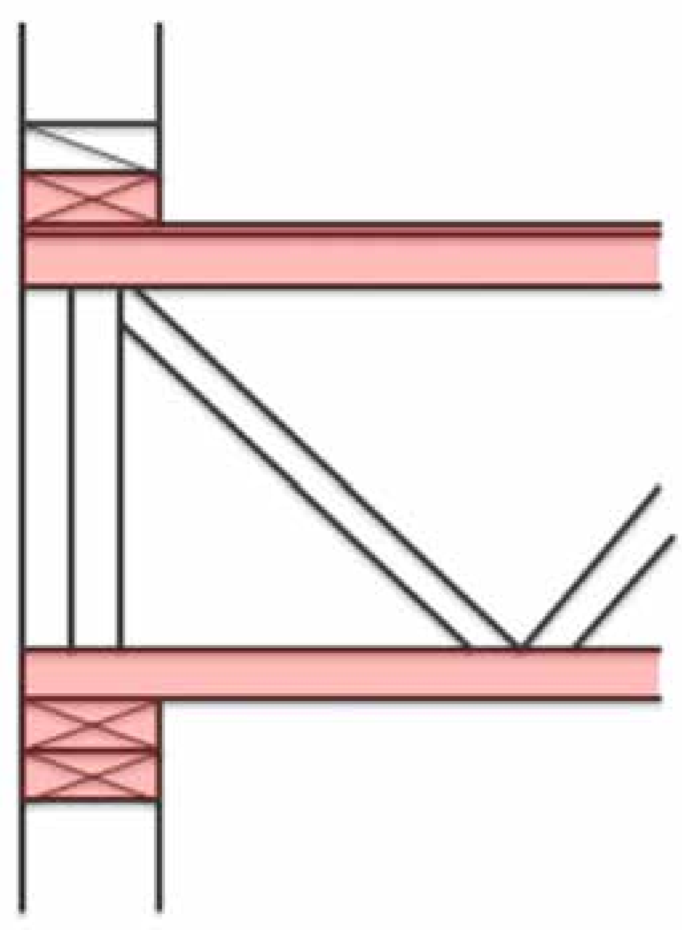
- Primarily in horizontal members
- Wall plates
- Floor/rim joists
- Engineering judgement required when determining what to include in shrinkage zone
- Should Sheathing, I-Joists, Trusses, other products manufactured with low MC be included?

FIGURE 5:
Shrinkage zone in platform-framed detail



Shrinkage Calculations – Cross Grain Wood

In parallel chord trusses, only chords contribute to shrinkage, vertical and diagonal webs don’t



Shrinkage Calculations – Cross Grain Wood

Be aware of cumulative shrinkage

Shrinkage Calculations – Running the Numbers

Species Specific Method:

$$S = C*D_i*(M_F-M_i)$$

Table 13-5. Dimensional change coefficients (C_R, radial; C_T, tangential) for shrinking or welling within moisture content limits of 6% to 14%

Softwood Species	Dimensional change coefficient[a] C_R	C_T
Baldcypress	0.00130	0.00216
Cedar, yellow-	0.00095	0.00208
Cedar, Atlantic white-	0.00099	0.00187
Cedar, Eastern Red	0.00106	0.00162

Wood Handbook: www.fpl.fs.fed.us

S = shrinkage (in inches)

D_i = initial dimension (shrinkage zone)

$C = C_T$ / C_R= dimension change coefficient, tangential/radial direction

C_T = 0.00263 for Douglas Fir-Larch

C_T = 0.00245 for Hem-Fir

C_T = 0.00234 for Spruce-Pine-Fir

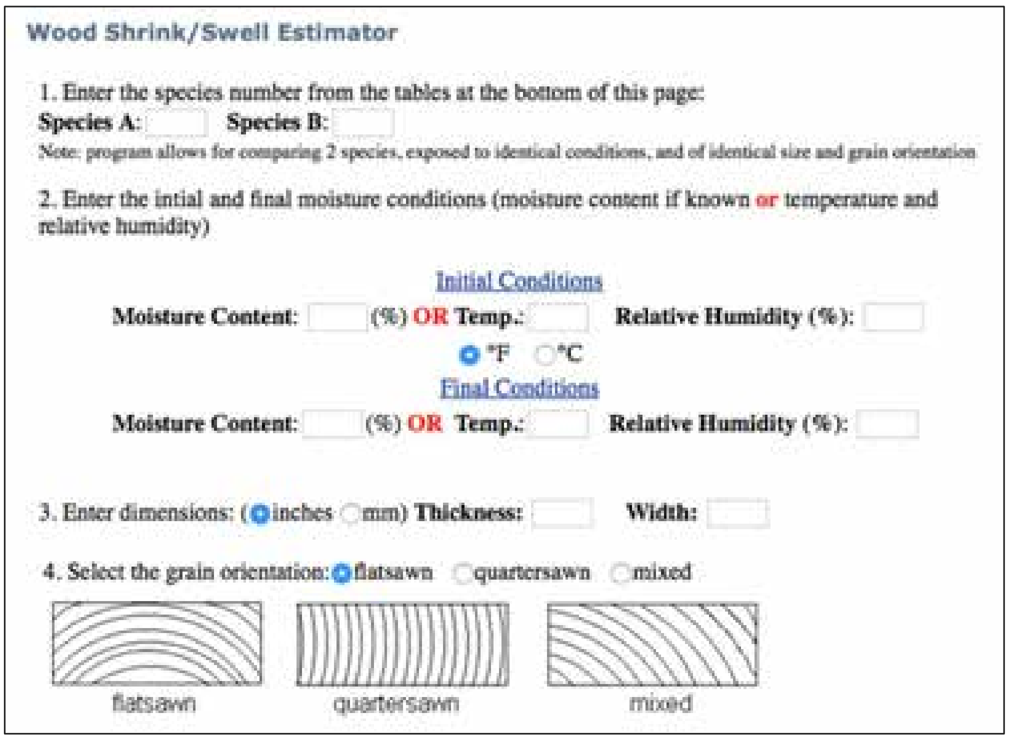
C_T = 0.00263 for Southern Pine

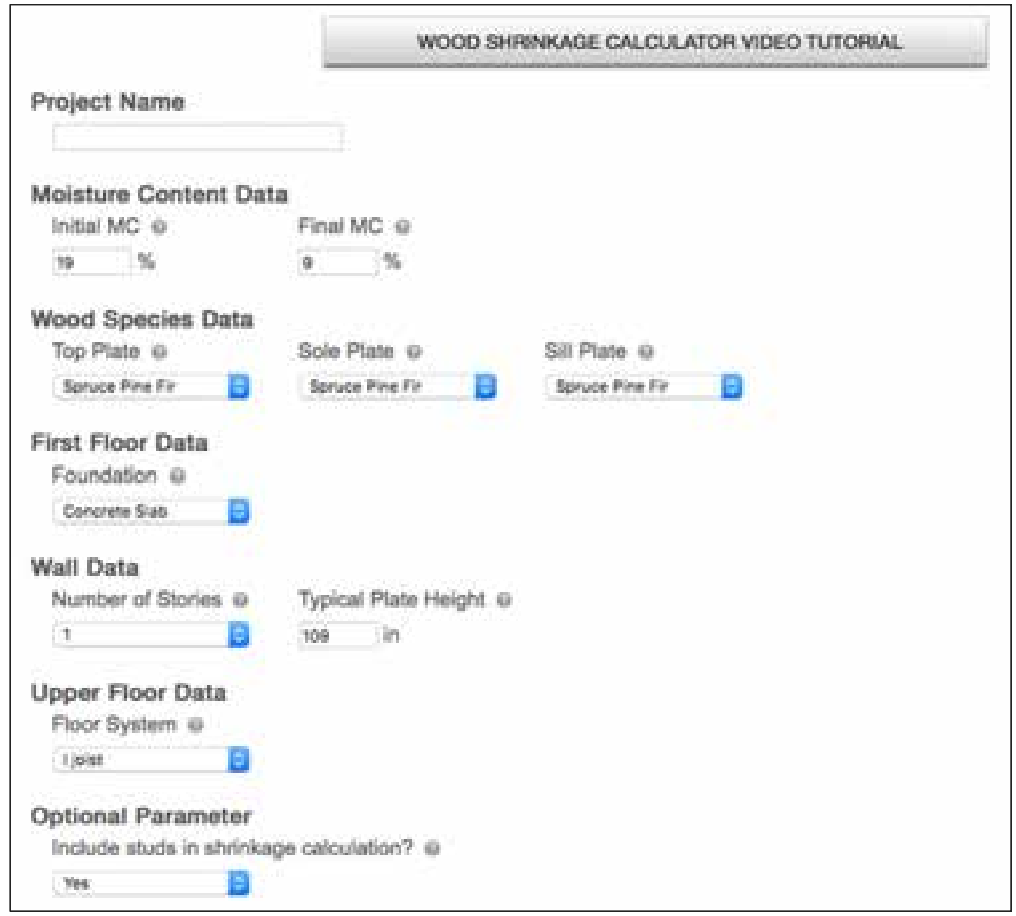
M_F = final moisture content (percent)

M_i = initial moisture content (percent)

Shrinkage Calculations

Several free shrinkage calculators available online





Sources: Oregon State University & Simpson Strongtie

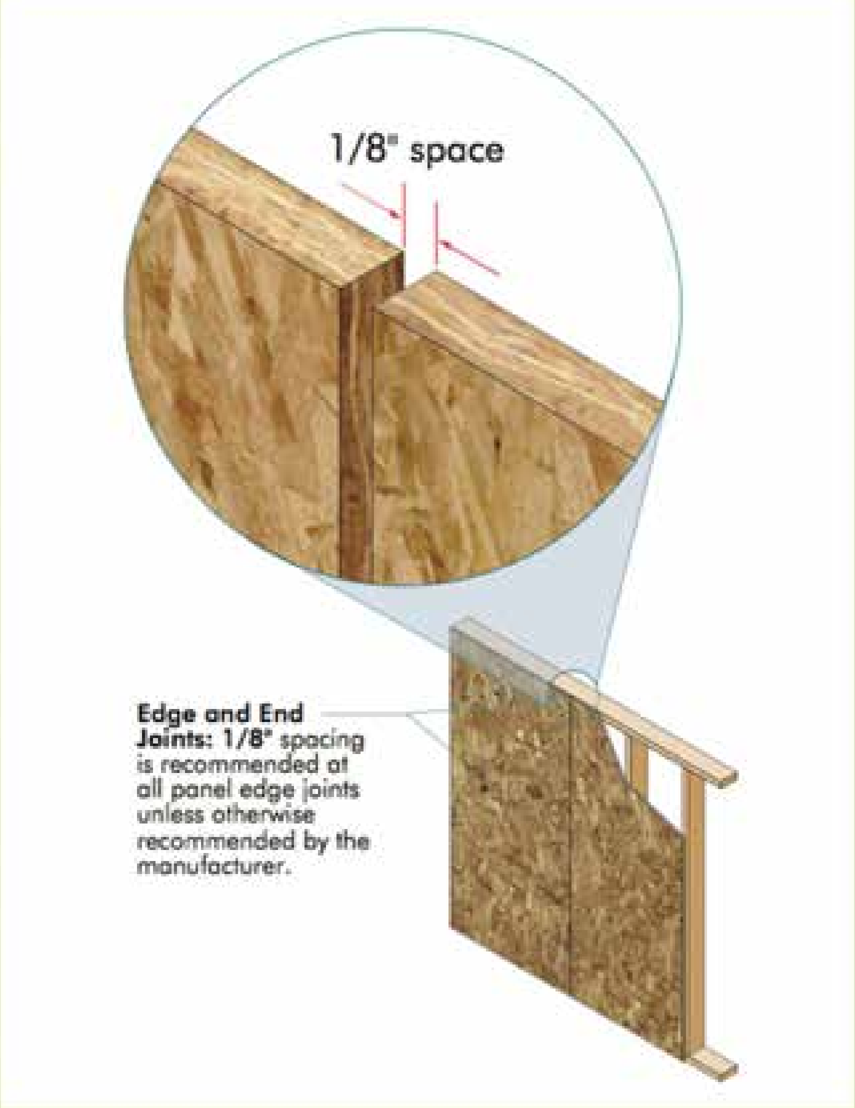
Shrinkage Calculations – The Opposite Effect

Moisture content increase has the opposite effect – expansion of wood members occurs

Primarily a concern in large plane surfaces (floors, roofs & walls) covered with panel sheathing or decking

APA recommends 1/8” gap at all sheathing end & edge joints

See APA U425 – *Technical Note: Temporary Expansion Joints for Large Buildings* for further information



Source: APA – The Engineered Wood Association

Minimizing Shrinkage

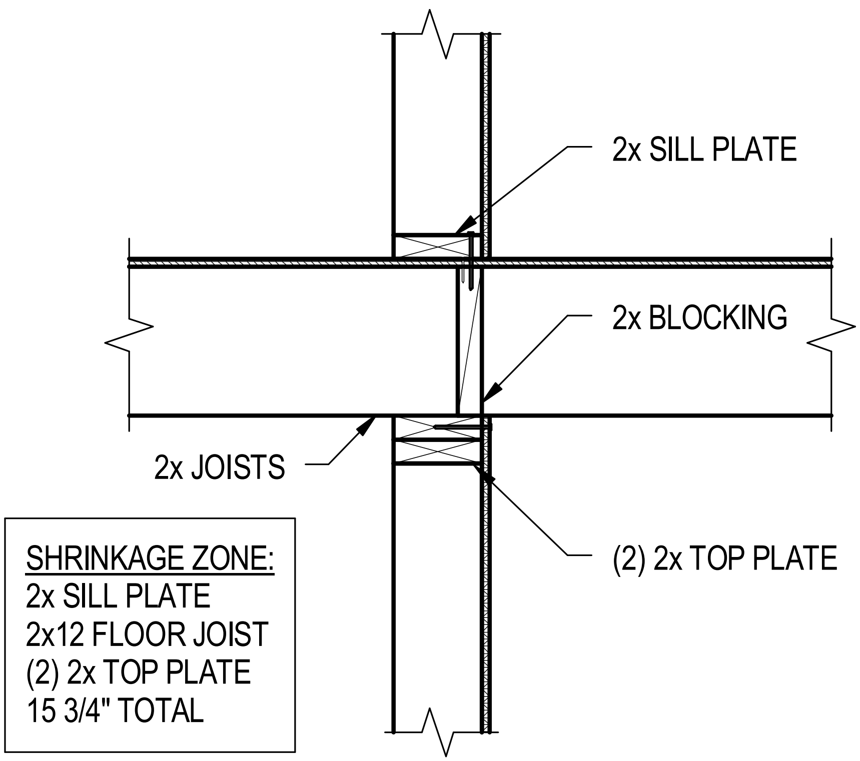
Recalling the three variables that influence amount of shrinkage:

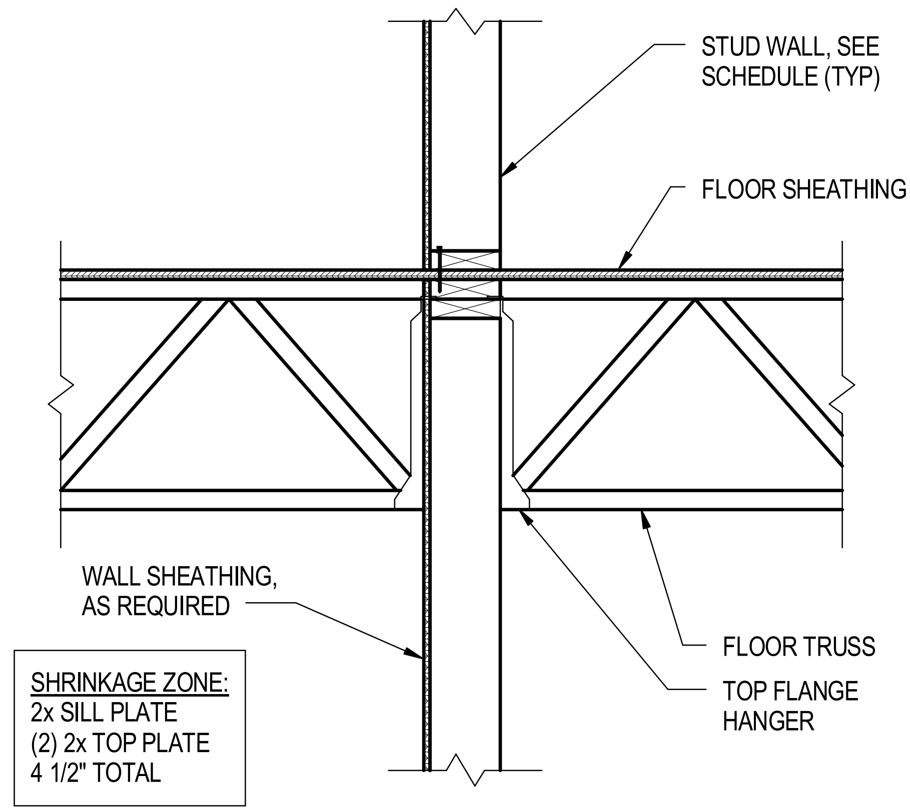
- Installed moisture content (MC)
- In-service equilibrium moisture content (EMC)
- Cumulative thickness of cross-grain wood contributing to shrinkage

As designers, we can impact 2 of these 3 variables

Our specifications and details, hand in hand with on-site protection measures and proper installation, can greatly minimize the magnitude and effects of shrinkage

Minimizing Shrinkage – Detailing





Images: Schaefer

Minimizing Shrinkage – Detailing

Platform Detail:
15.75” Shrinkage Zone
19% MC Initial
12% EMC

S = (0.0025)(15.75”)(12-19) = **0.28”**

5-story building: **1.4” total**

Semi-Balloon Detail:
4.5” Shrinkage Zone
19% MC Initial
12% EMC

S = (0.0025)(4.5”)(12-19) = **0.08”**

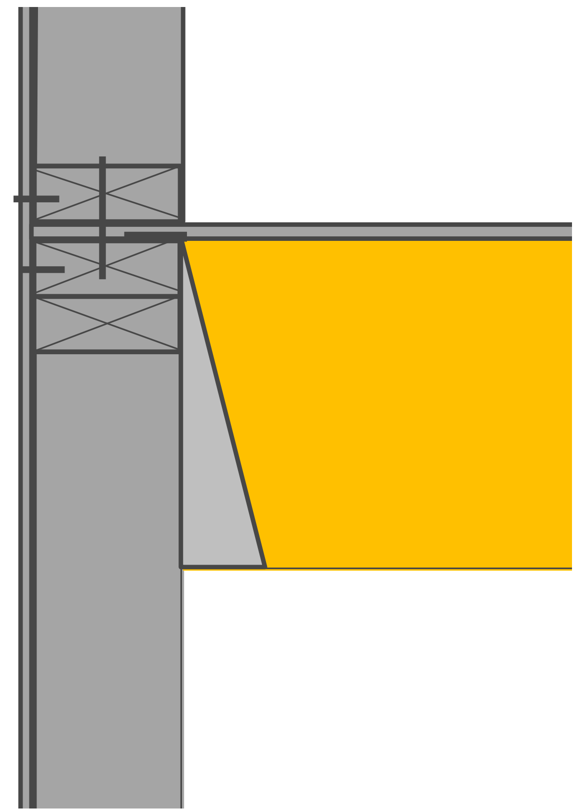
5-story building: **0.4” total**

Minimizing Shrinkage - Detailing

Semi-balloon framing:

- Incorporates floor framing hanging from top plates
- Floor framing/rim joist doesn't contribute to shrinkage

Non-standard stud lengths and increased hardware requirements should be considered



Minimizing Shrinkage – Detailing

The same concepts apply to post & beam wood-frame structures

Photo: Alex Schreyer

Photo: Marcus Kauffman

Minimizing Shrinkage – Detailing

Photos: StructureCraft

Differential Movement

Need to consider differential movement between wood frame elements and other materials that…

- Expand due to moisture or thermal changes
- Do not change with moisture but do change with thermal fluctuations
- Shrink much less than wood




Differential Movement

Wood Framing & Veneer:

- Veneer Type Transitions
- Openings (Sill, Head, Jambs)

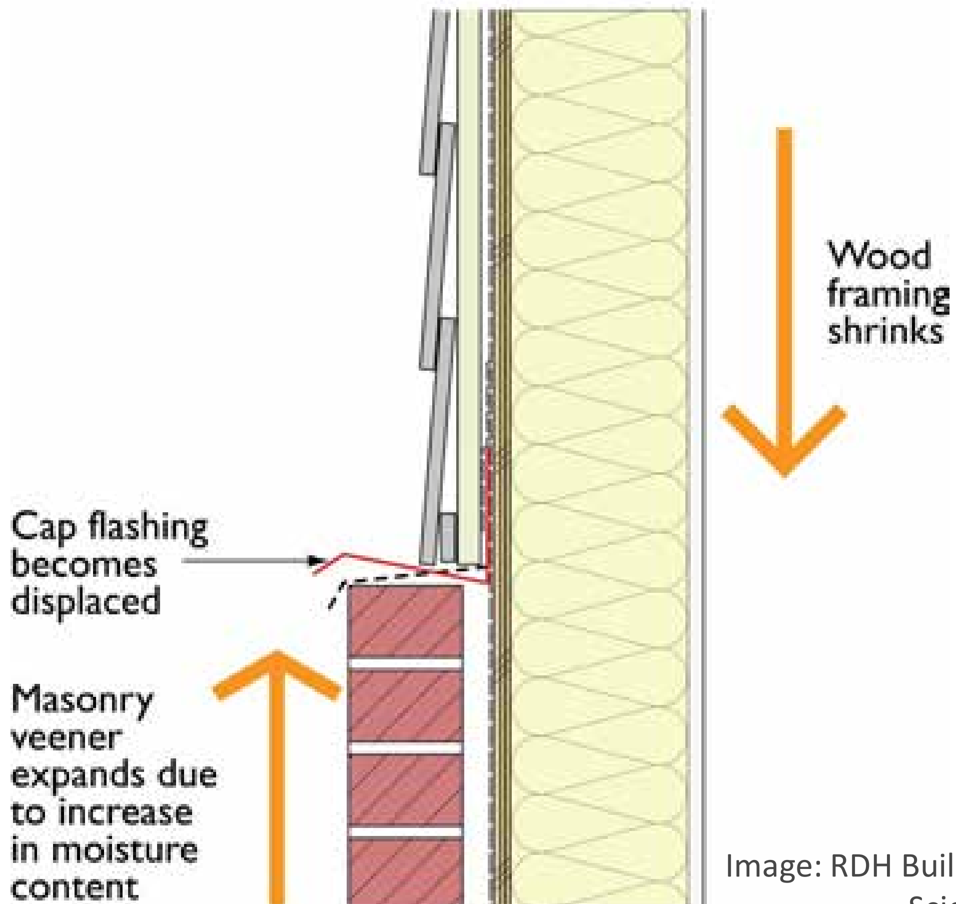


Image: RDH Building Science

Differential Movement – Veneer Transition

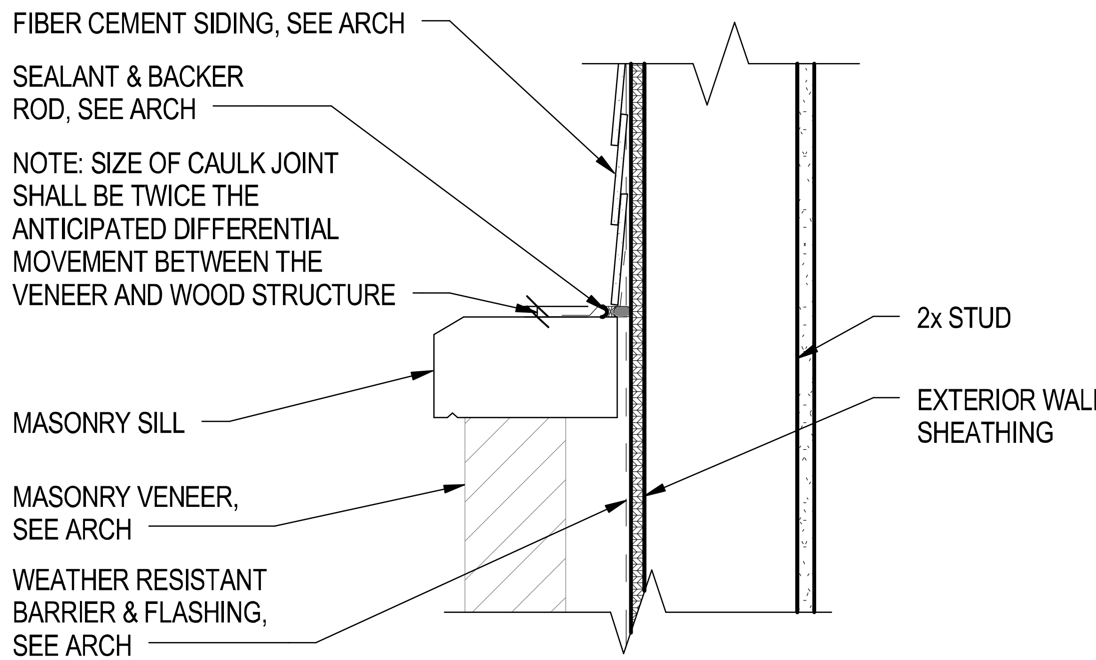
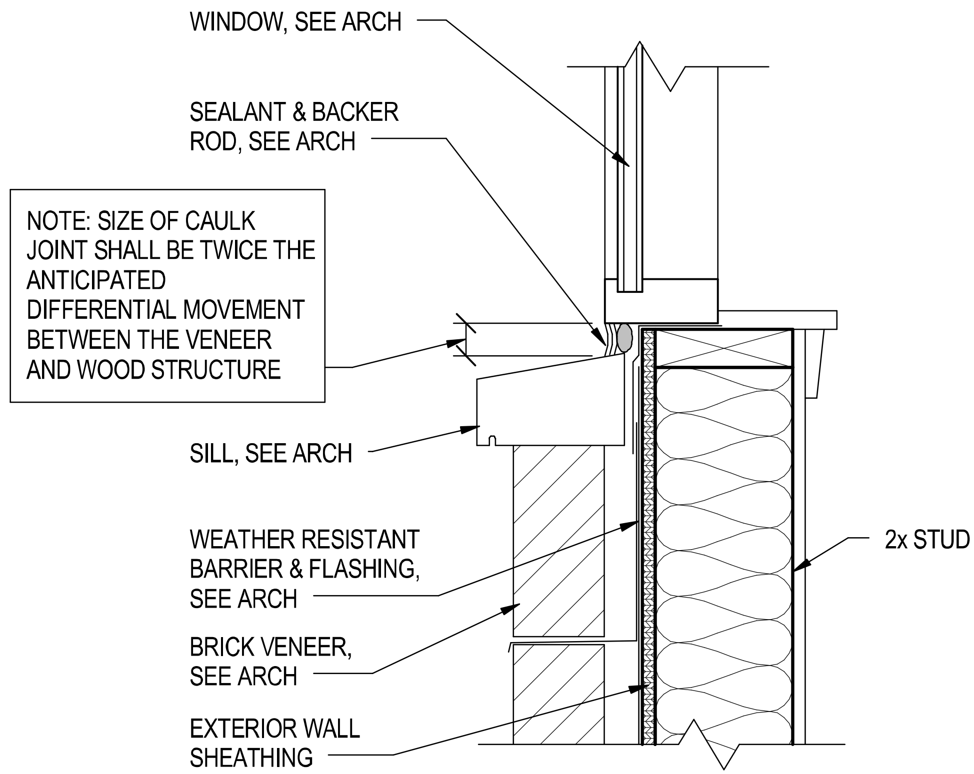


Image: Schaefer

Differential Movement – Veneer Opening



Images: Schaefer

Differential Movement – Veneer Opening

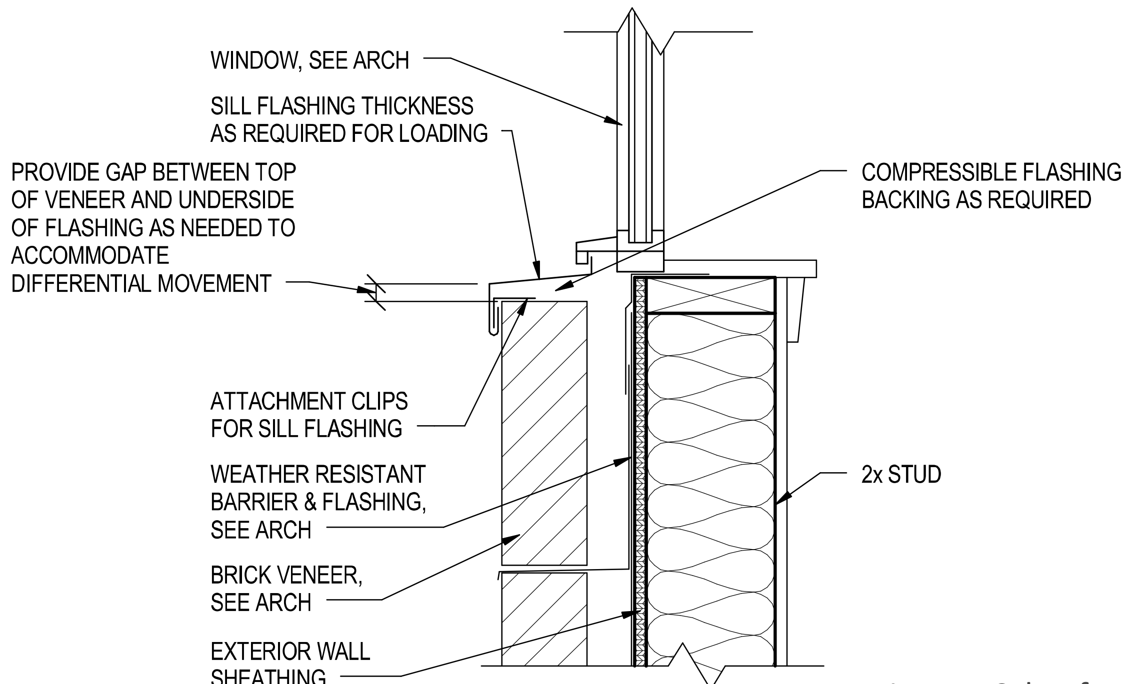


Image: Schaefer

Differential Movement – Veneer Opening

Image: RDH Building Science

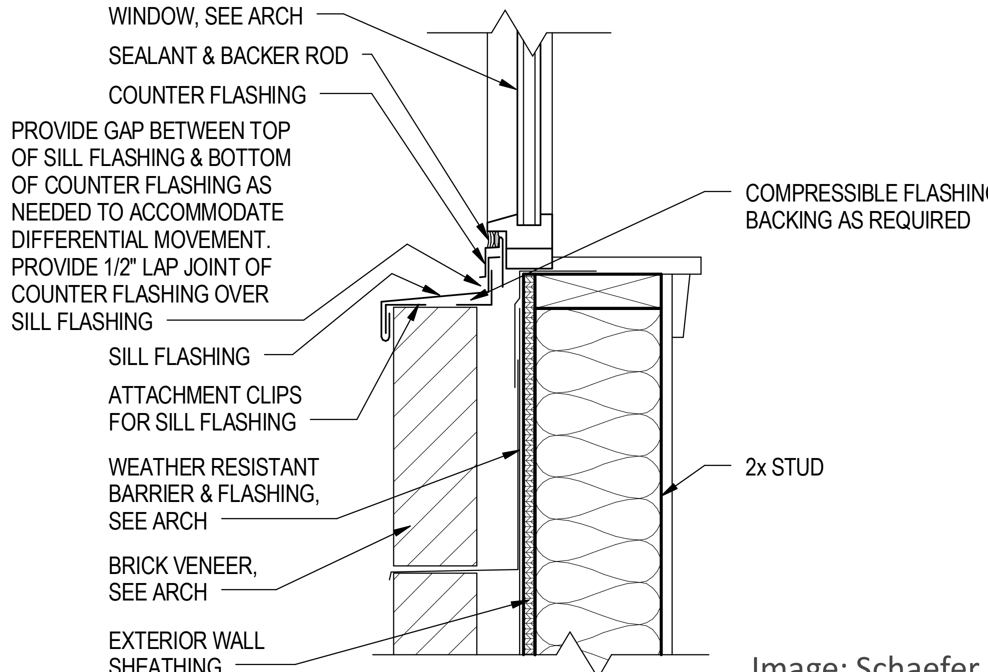


Image: Schaefer

Brick Veneer Resource

Code provisions, detailing options, and more for accommodating multiple stories of brick veneer on wood structures

Free resource at woodworks.org

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Options for Brick Veneer on Mid-Rise Wood-Frame Buildings

With growing interest in taller wood-frame buildings—many with five stories of wood on podiums and with wood-frame mezzanines—there has also been interest in the use of brick veneer at greater heights.

The 2015 *International Building Code*[1] (IBC), Table 504.3, allows building heights up to 65 ft (19.8 m) for un-sprinklered Type III-A wood-frame buildings and up to 85 ft (25.9 m) if approved NFPA 13 sprinklers are used. For Type V-A wood-frame buildings, those heights can be 50 and 70 ft (15.2 and 21.3 m), respectively.

For designers interested in brick veneer as an exterior finish, some publications and design guides reference using steel studs and non-combustible supports. However, there are in fact code-compliant methods for using brick veneer over the entire height of a mid-rise wood-frame structure. Options include a prescriptive approach for the use of brick veneer up to 30 ft (9.14 m) in height and an alternative design approach for its use above 30 ft.

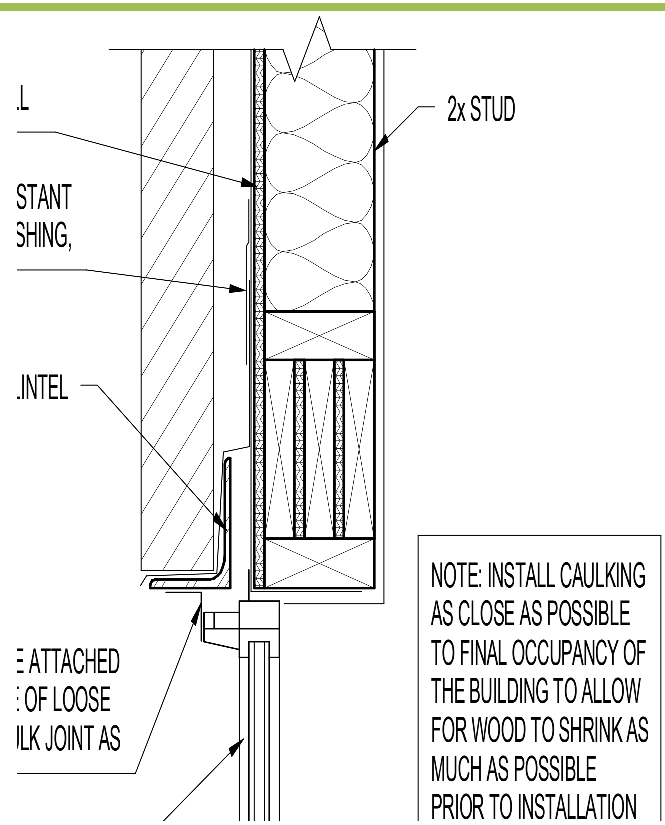
A recent publication by the Brick Industry Association[2] gives direct guidance for the application of brick veneer on wood backing above the 30-ft prescriptive height limit. As this paper explains, one approach is to stack the brick veneer at full height off the foundation without shelf angles or intermediate support by the wood framing. Another is to support the brick veneer off shelf angles that are attached to the wood framing at desired intervals. Both of these approaches require the use of Section 12.2.1, *Alternative design of anchored masonry veneer* in the masonry code.[3]

Prescriptive requirements

The masonry code prescriptive height limitations for brick veneer on wood construction allow veneer up to 30 ft (9.14 m) above the veneer support, which could be interpreted as a foundation or an alternate location of support. This is based on Section 12.2.2.3.1.2, which states:

12.2.2.3.1.2
Anchored veneer with a backing of wood framing shall not exceed 30 ft (9.14 m), or 38 ft (11.58 m) at a gable, in height above the location where the veneer is supported.

Differential Movement – Veneer Opening



Images: Schaefer

Differential Movement – Veneer Opening

- Consider installing caulking at openings as late as possible to allow differential movement to occur
- Differential movement can cause shearing cracks in caulk
- Periodic inspection and re-caulking may be warranted

Image: Schaefer

Differential Movement – Masonry Walls

Differential Movement – Masonry Walls

Mixing masonry walls with wood floor framing can create several issues:

- Differential shrinkage between wood and masonry needs to be considered
- Best practices include seismically isolating masonry shaft walls, only tie wood floor to masonry shaft if/where required (i.e. at elevator door threshold)

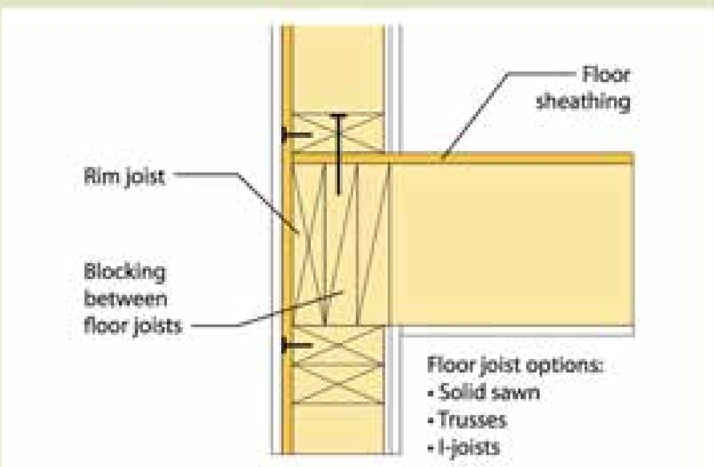
Other considerations:

- Masonry shaft walls often become part of building's lateral force resisting system
- This increases seismic forces and adds mass
- Difference in stiffness between wood & masonry shear walls may need to be considered

Shaft Wall Resource

For these reasons, many are finding value in switching to wood-frame shaft walls

FIGURE 15:
Example wood-frame shaft wall detail



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Shaft Wall Solutions
For Wood-Frame Buildings

Wood shaft walls can reduce costs and shorten the construction schedule.

It is fairly common for light wood-frame commercial and multi-family buildings to include shaft walls made from other materials. However, with the heavy use of wood structure in mid-rise construction, many designers and contractors have come to realize that wood-frame shaft walls are in fact a code-compliant means of reducing cost and shortening construction schedule.

A shaft is defined in Section 202 of the 2012 International Building Code (IBC) as "*an enclosed space extending through one or more stories of a building, connecting vertical openings in successive floors, or floors and roof.*" Therefore, shaft enclosure requirements apply to stairs, elevators, and MEP chases in multi-story buildings. While these applications might be similar in their fire design requirements, they often have different construction constraints and scenarios where assemblies and detailing may also differ.

This paper provides an overview of design considerations, requirements, and options for wood-frame shaft walls under the 2012 IBC. While some of the IBC-referenced section numbers may be different in different editions, none of the main shaft wall provisions have been modified in the 2015 IBC.

Differential Movement – Masonry Walls

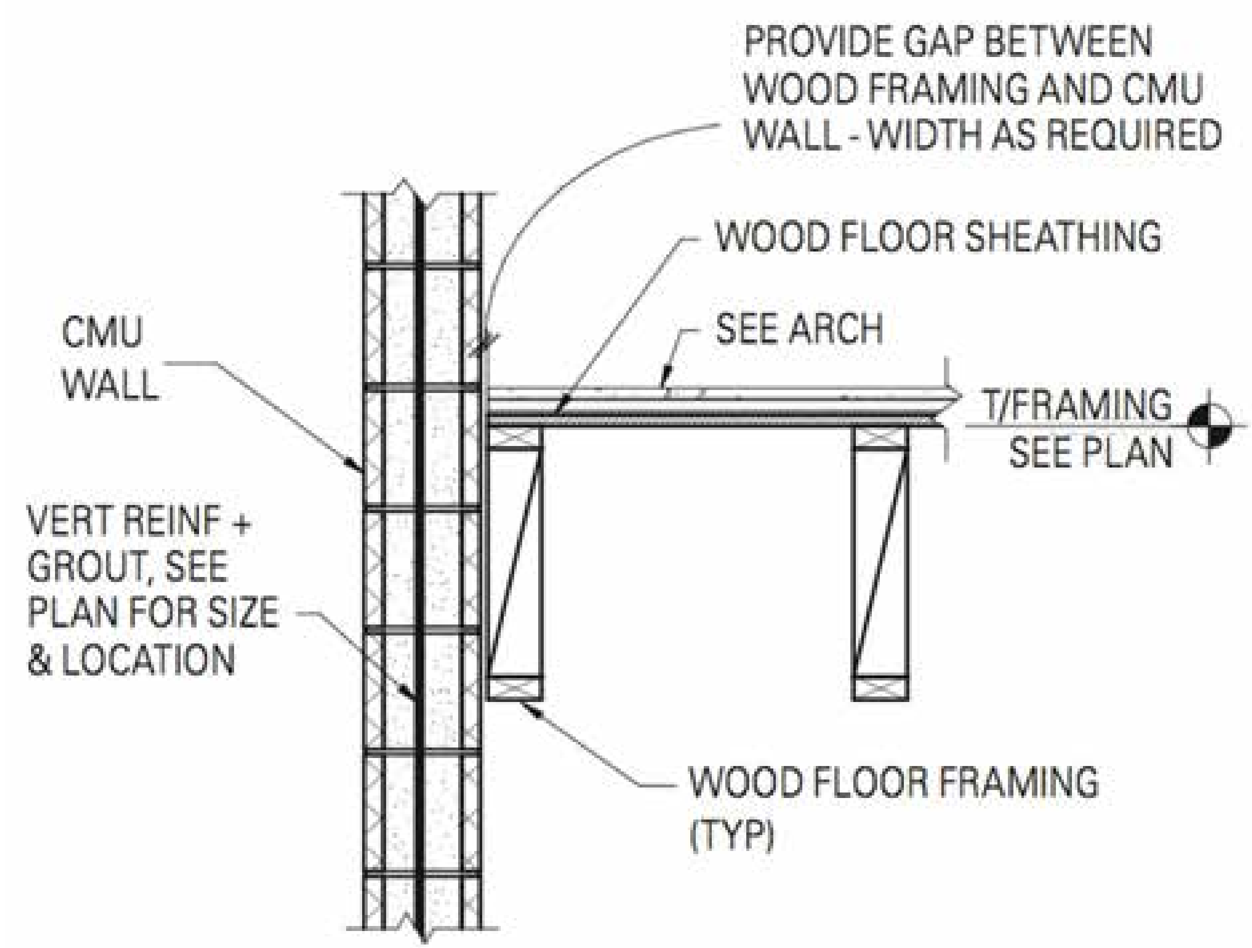
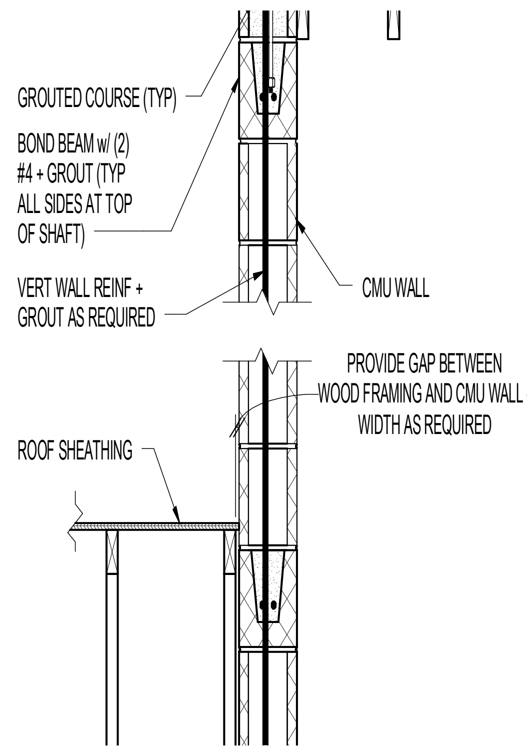


Image: Schaefer

Differential Movement – Masonry Walls

Consider accumulated differential movement effects on:

- Roofing/flashing
- Finishes at roof intersection



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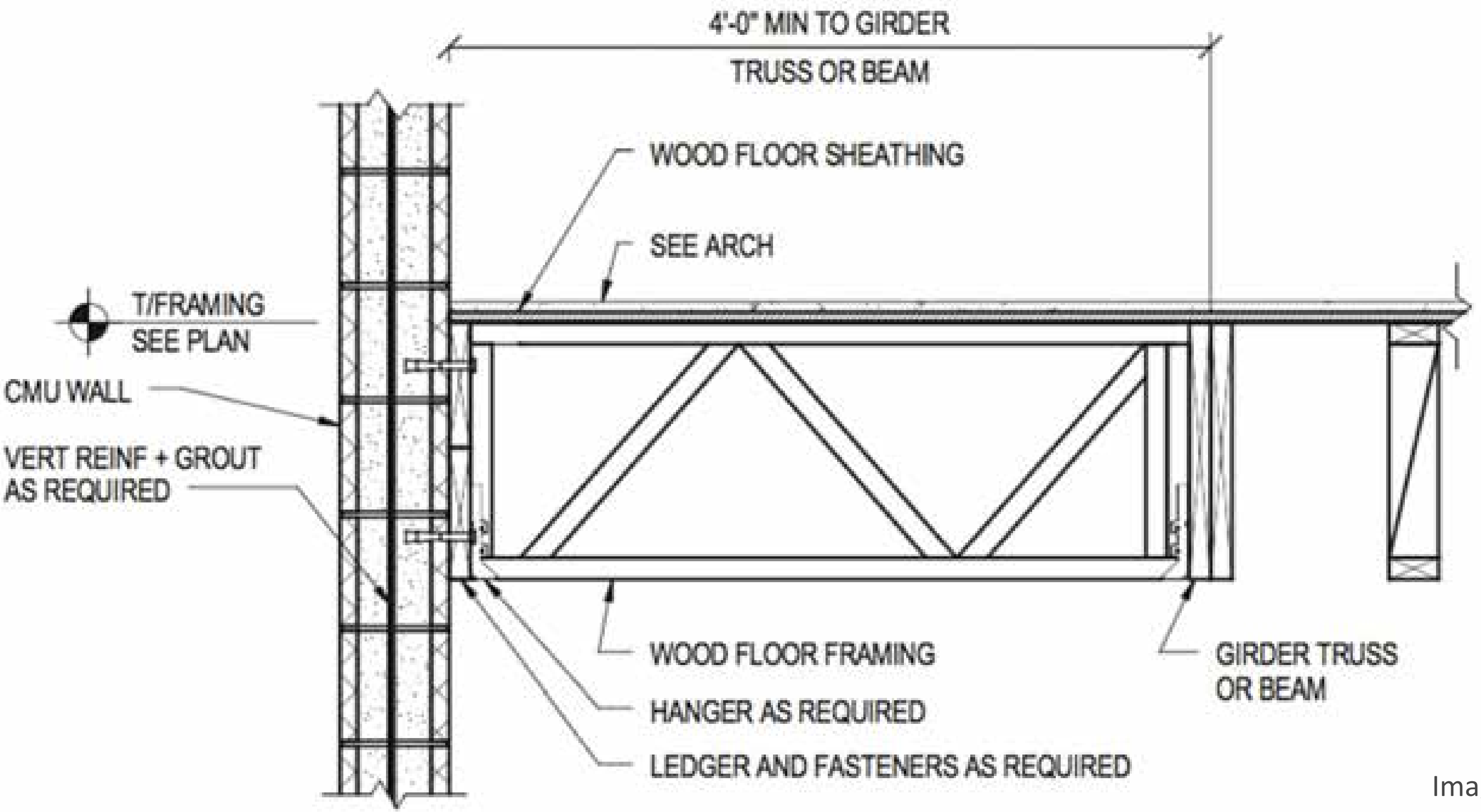
Differential Movement – Masonry Walls



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Differential Movement – Masonry Walls

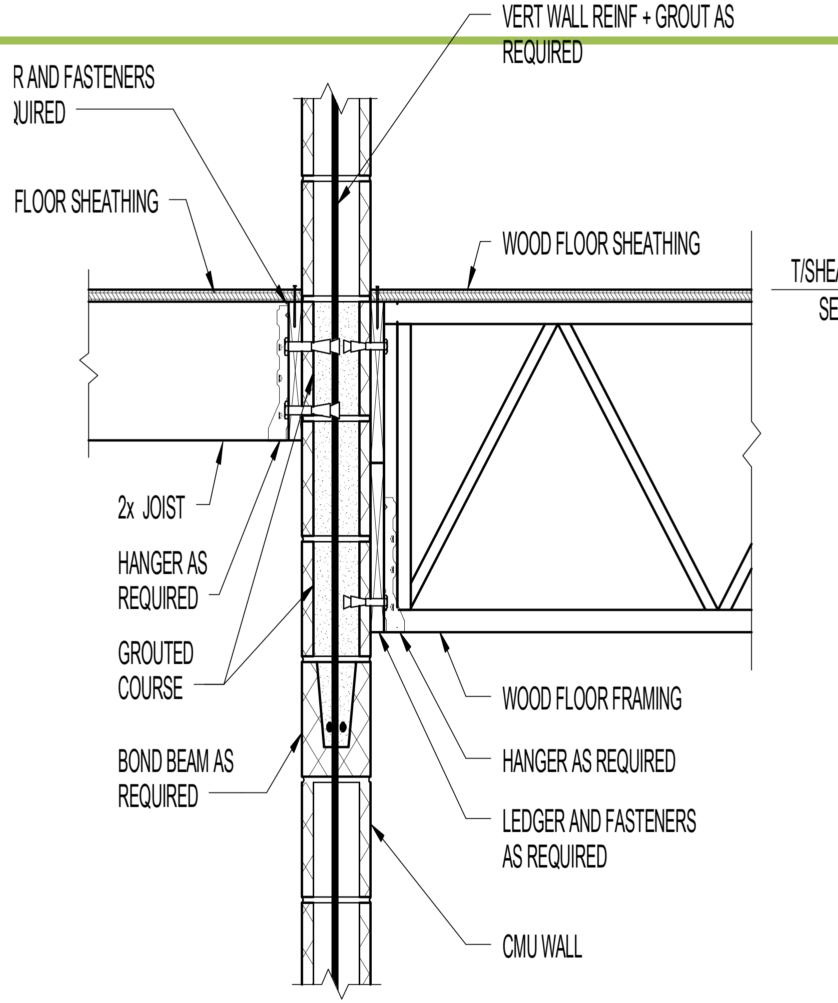


Image: Schaefer

Differential Movement

At multi-story architectural finish applications, such as atriums and shafts, may need to consider shrinkage or differential movement effects

Differential Movement - MEP

MEP main runs often start at base or top of structure, extend throughout height, with horizontal tees at each floor.

Horizontal tees often installed in wood stud partitions

Differential Movement - MEP

Wood framing shrinks, vertical MEP runs remain stationary or expand with thermal fluctuations

Differential movement should be allowed for

Helpful to wait as late as possible after wood framing is erected to install MEP

Note anticipated wood shrinkage at each level on construction documents – MEP contractor should provide methods of accommodating

Differential Movement - MEP

- Vertically slotted holes in studs allow differential movement
- Verify structural adequacy of studs

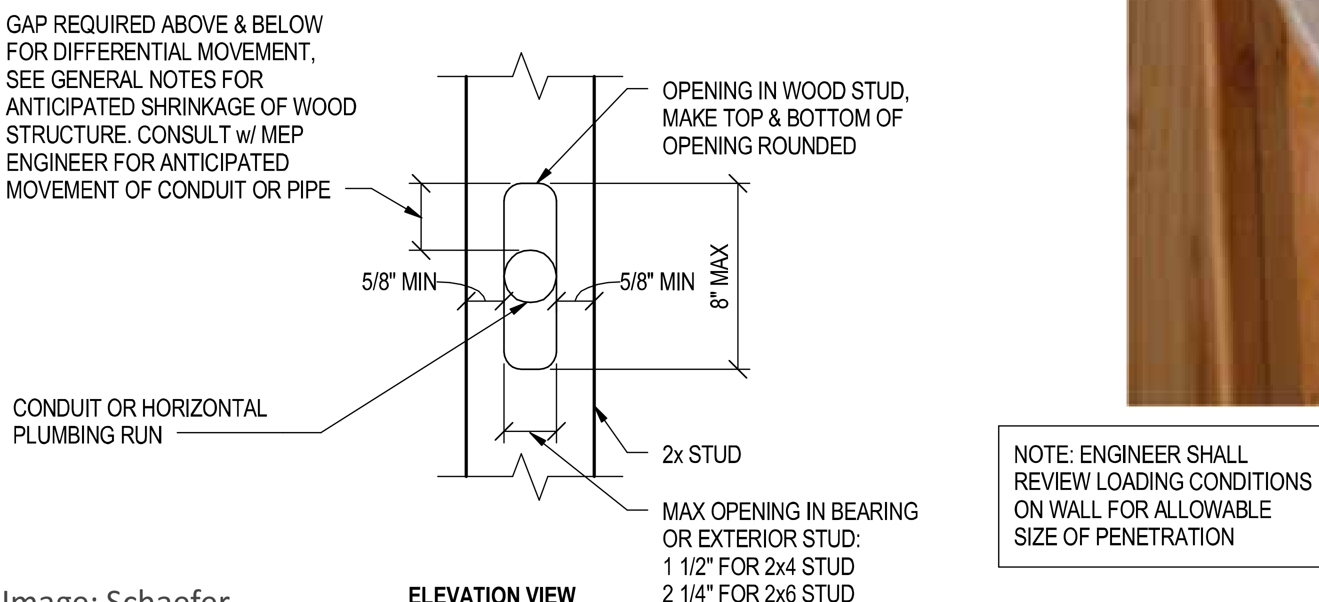


Image: Schaefer

Image: Louisiana-Pacific Corporation

Oval cutout options for Horizontal Pipe

Differential Movement - MEP

A variety of expansion or slip joint connectors are available – allow vertical MEP runs to move with the wood structure

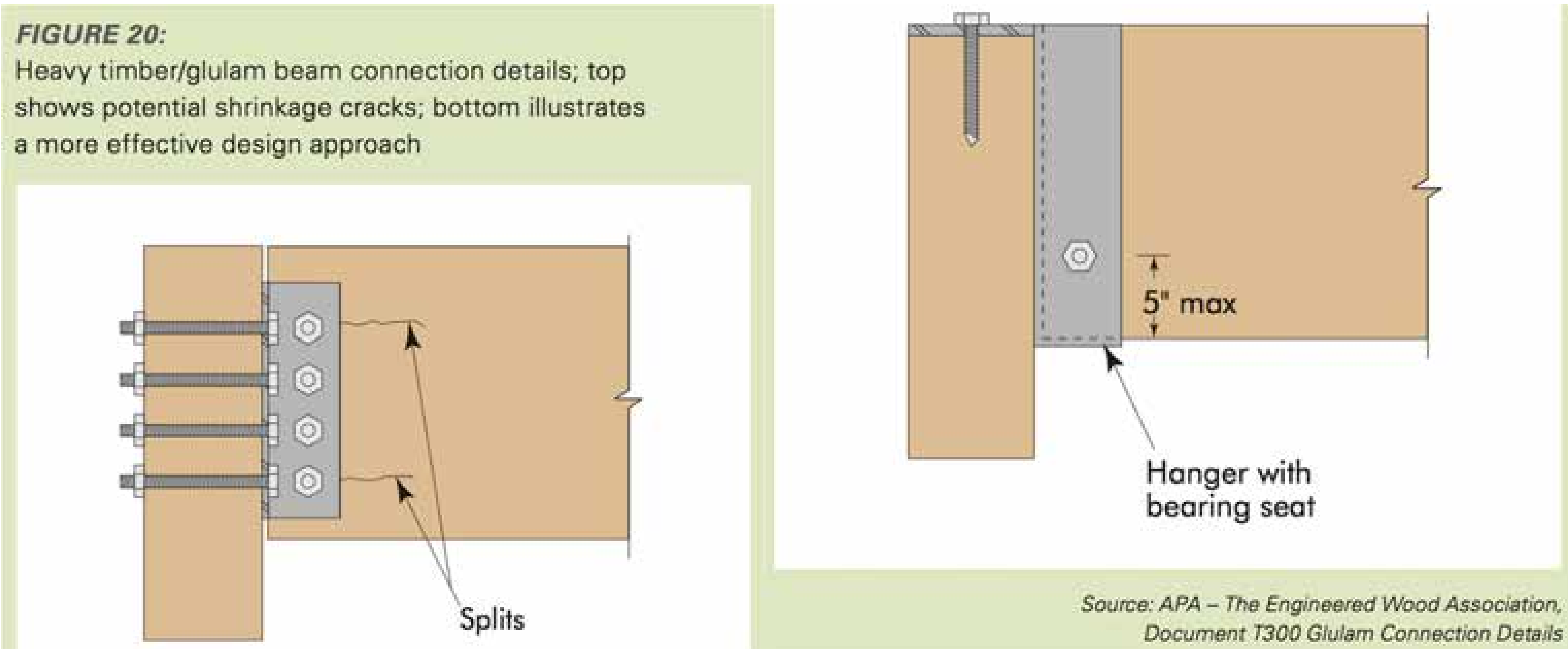
Vertical Stacks – Compensation Devices Installed

Structural Connections - Beams

Due to cross grain shrinkage, consider effects of shrinkage at connections, especially bolted connections

Avoid restraining shrinkage – can result in shear cracking/splitting

Structural Connections - Beams

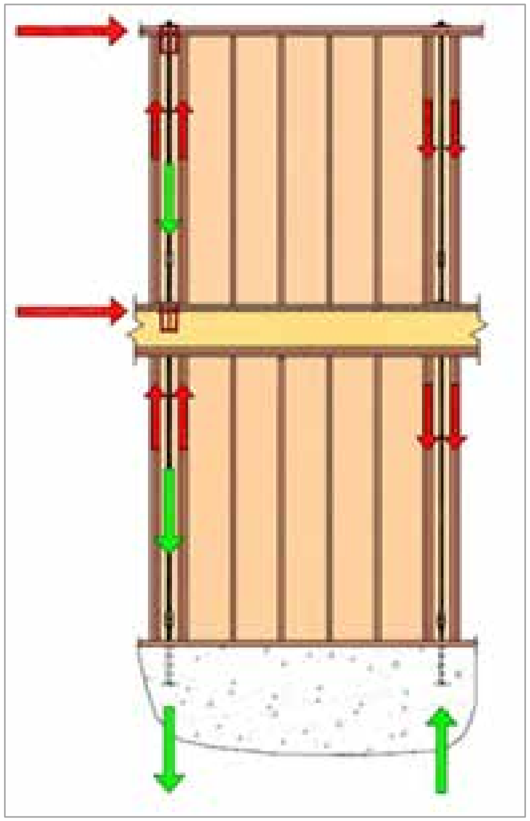


Structural Connections – Uplift & Overturning

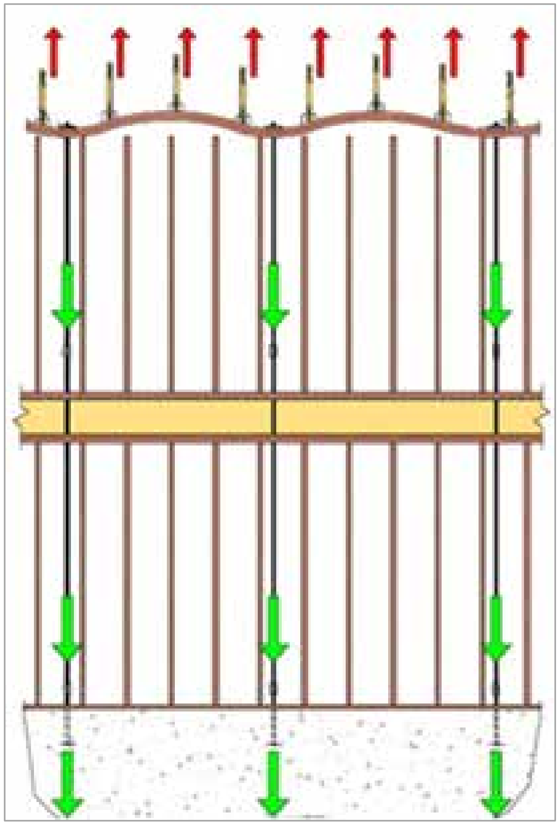
- Wind and seismic forces generate uplift and overturning forces on structures

- Methods of resisting these forces should take shrinkage into account, detail to mitigate its effects

Structural Connections – Uplift & Overturning



Shear Wall Overturning Resistance



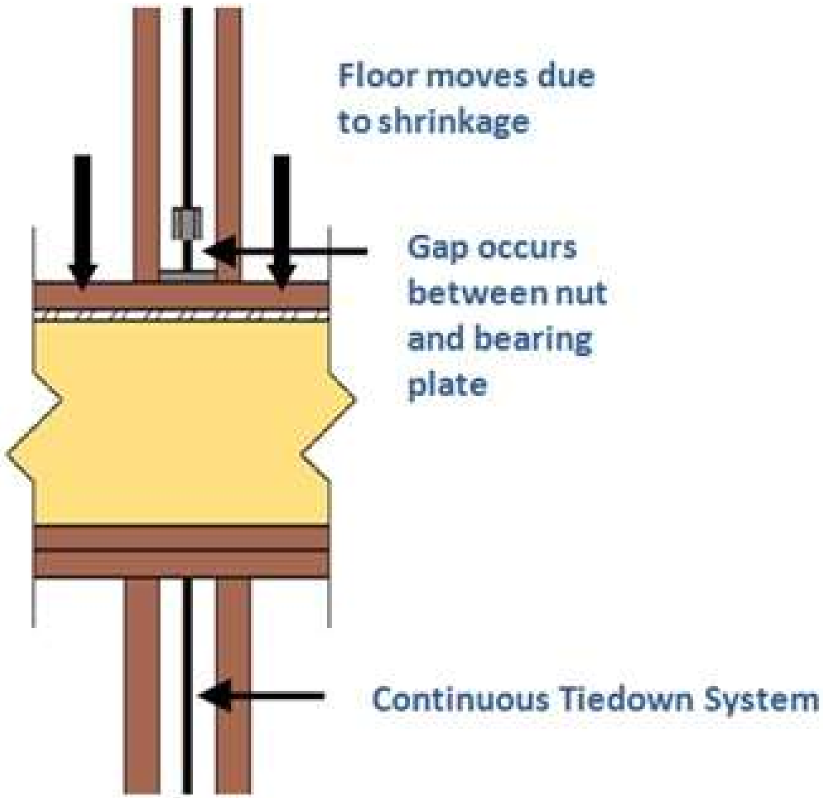
Uplift Resistance

Images: Simpson Strongtie

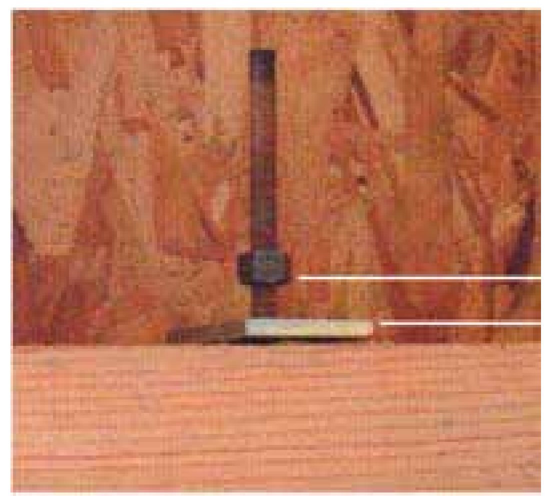
Structural Connections – Uplift & Overturning

Image: Simpson Strongtie

Structural Connections – Uplift & Overturning



Threaded Rod nuts would require re-tightening after shrinkage has occurred – difficult to do as finishes will likely already be installed



Structural Connections – Uplift & Overturning

- Products available that allow building shrinkage while keeping threaded rods engaged in tension
- Shrinkage compensation device or take up device

Images: Simpson Strongtie & CLP

Structural Connections – Uplift & Overturning

Uplift connections spanning through floor

Image: Simpson Strongtie

Balconies & Decks

- Exterior balconies & decks may be supported with columns
- As wood building shrinks, backslope in deck can be created
- Detailing of balcony bearing conditions, slope of balcony and differential shrinkage zones should take this into account

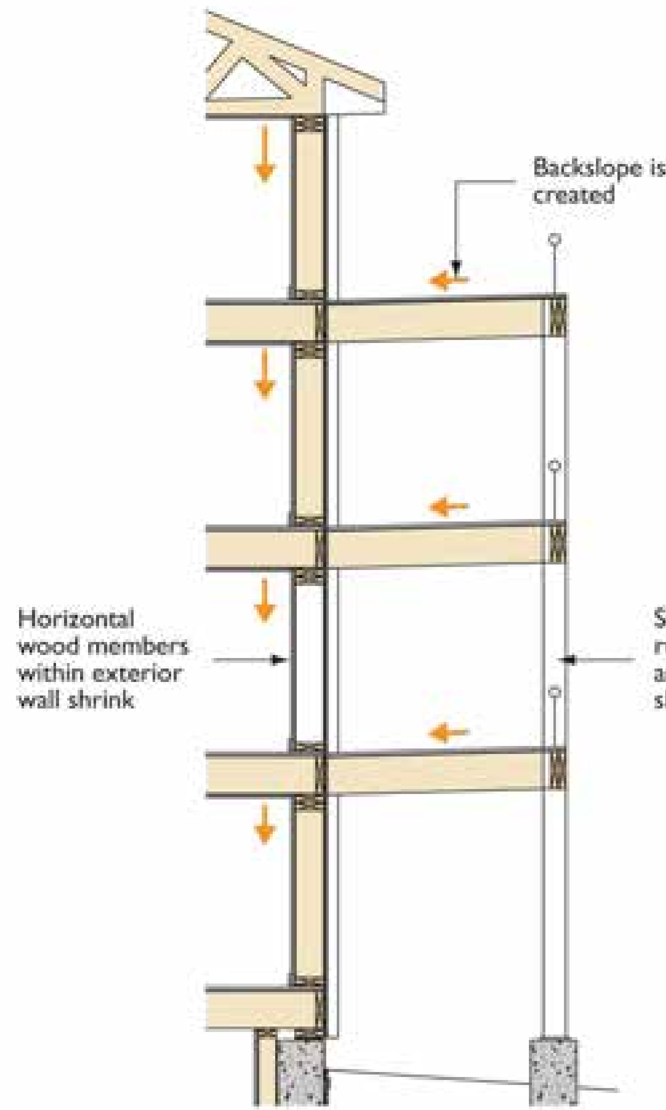


Image: RDH Building Science

Balconies & Decks

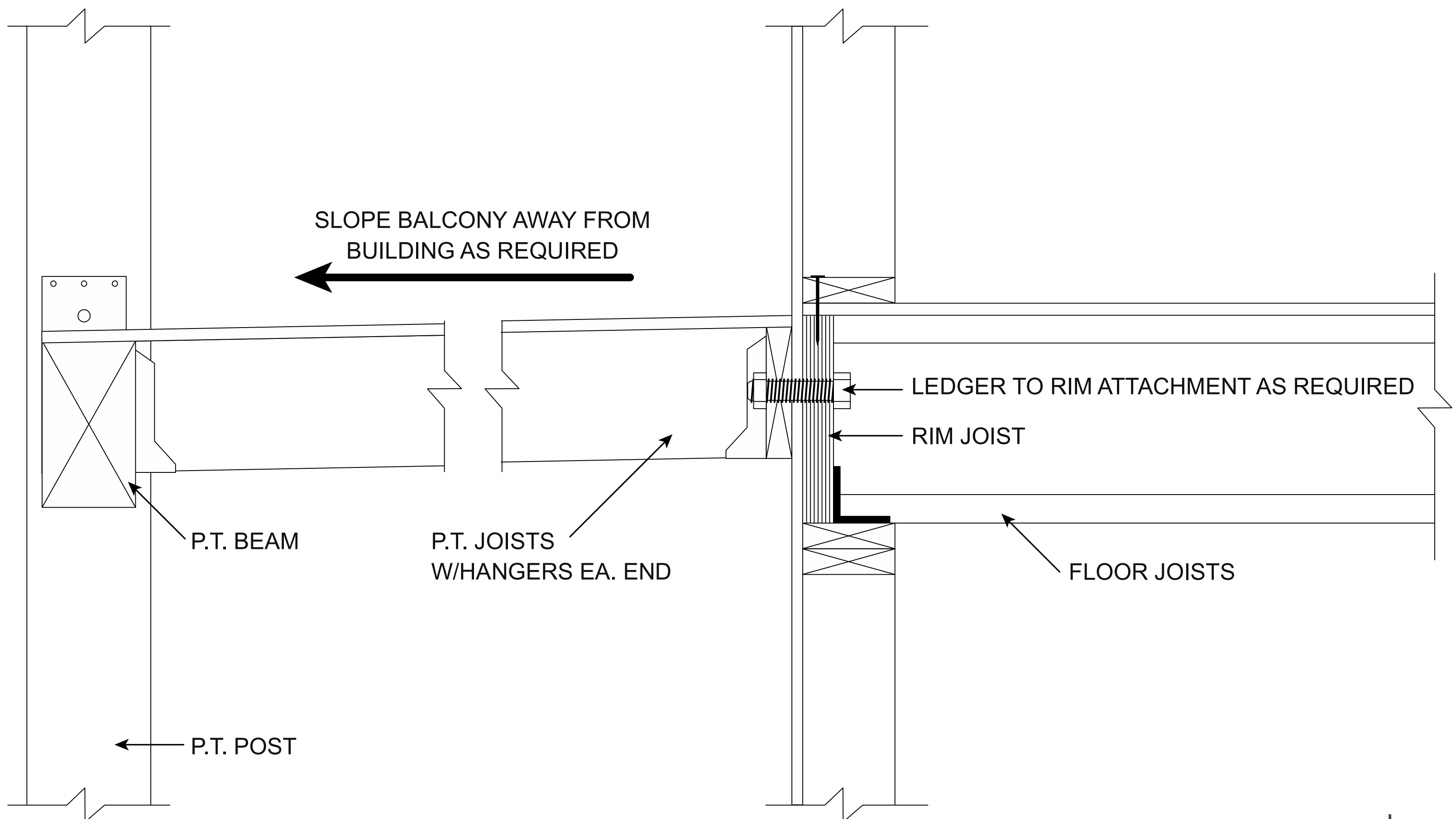


Image: Zeno Martin

Balconies & Decks

Possible Solutions:

- Cantilever Balcony
- Install row of columns just outboard of exterior building wall with same bearing conditions at both edges of deck
- Install enough initial slope in deck such that after building shrinkage, positive slope (away from building) still exists – verify slope adequacy with applicable codes
- Match exterior wall shrinkage zone with shrinkage zone at exterior edge of deck

10 Minute Break!

Jason Bahr, PE
Regional Director – KS, MO, OK and AR
Jason.bahr@woodworks.org
913-732-0075


Photo: Harbor Bay Real Estate Advisors, Purple Film

Differential Material Movement in Tall Mass Timber Structures

Jason Bahr, PE
Regional Director – KS, MO, OK and AR

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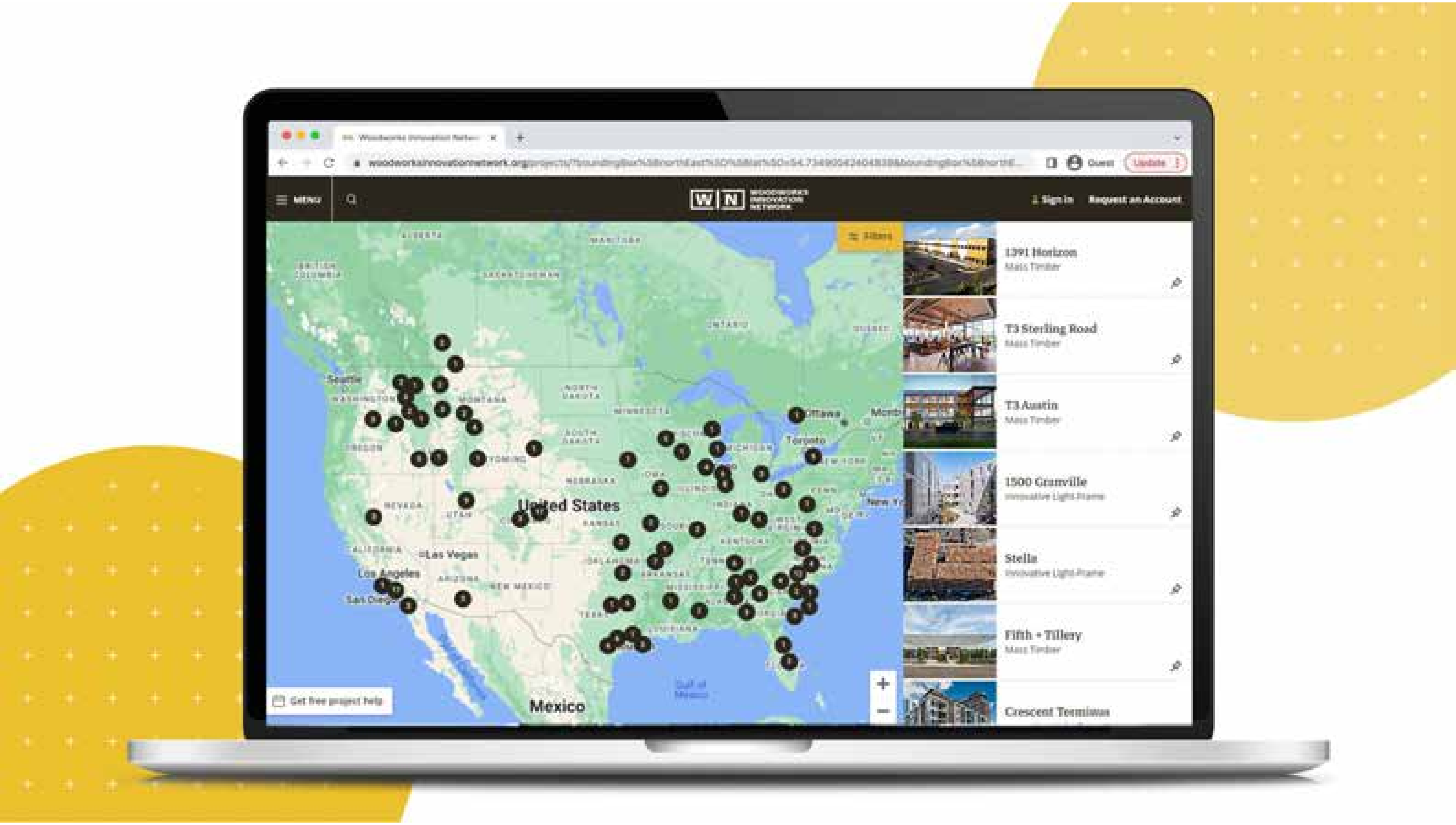
photo Mike Sinclair



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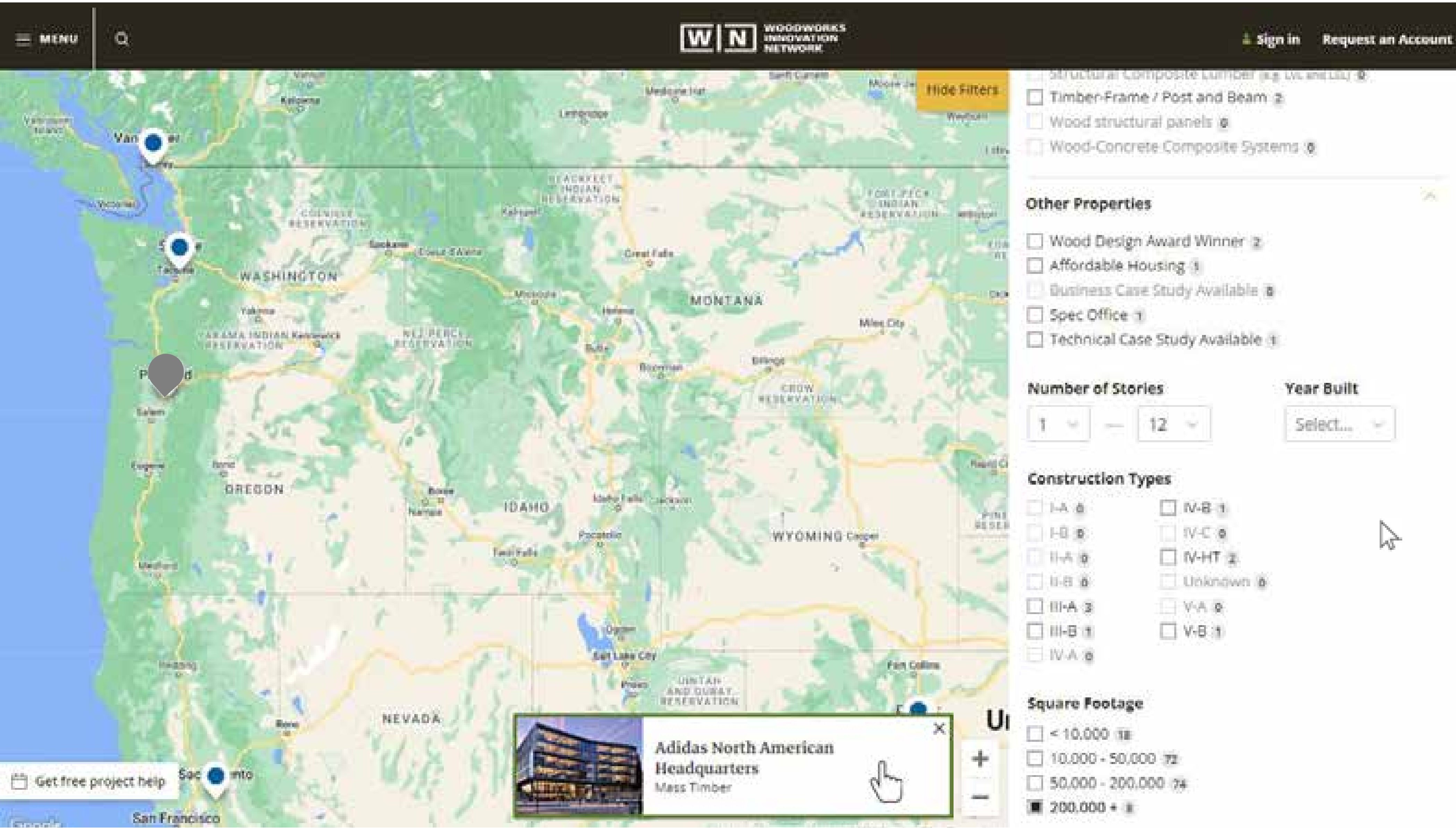
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V-A 0
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Square Footage
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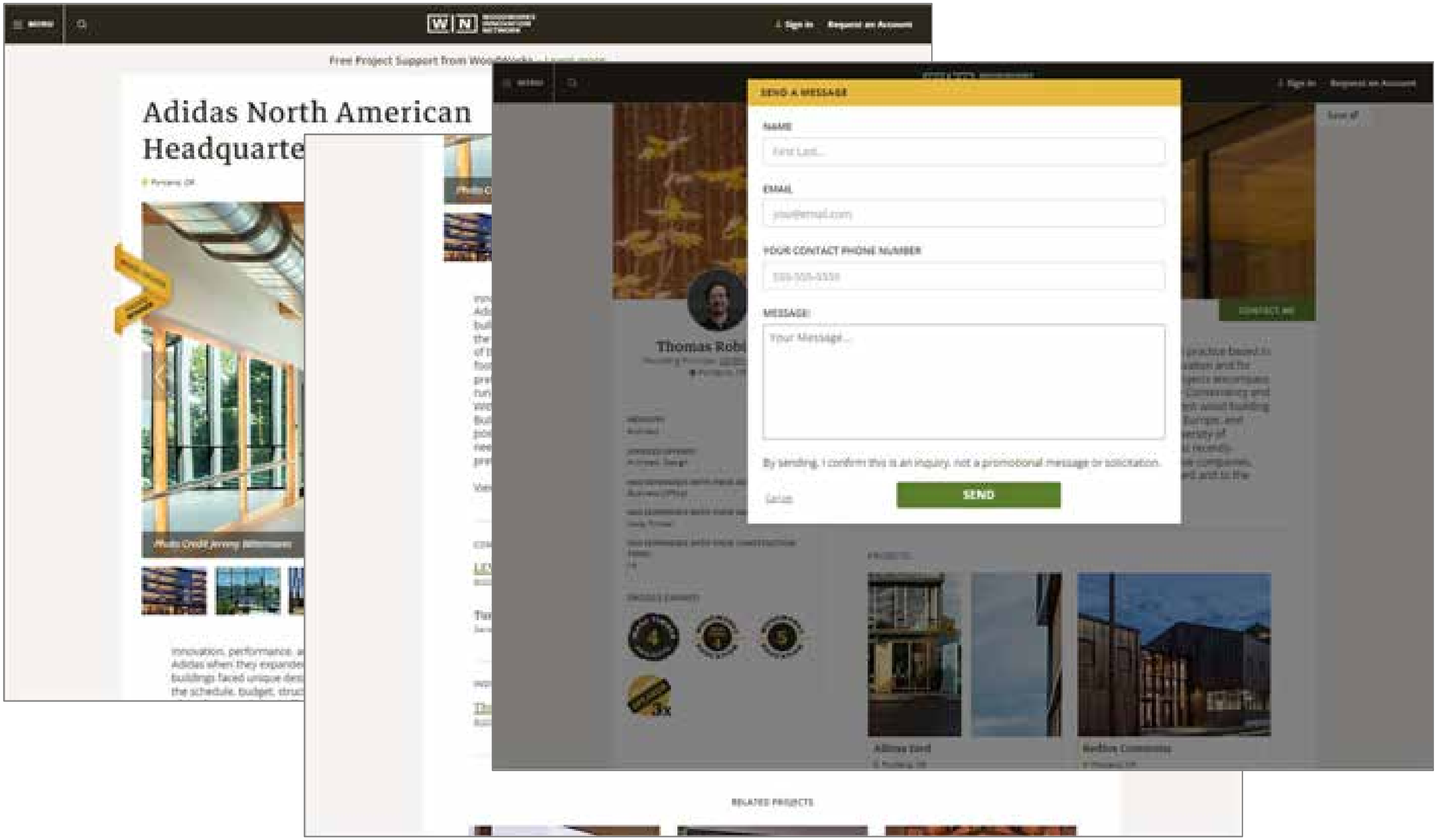

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Course Description

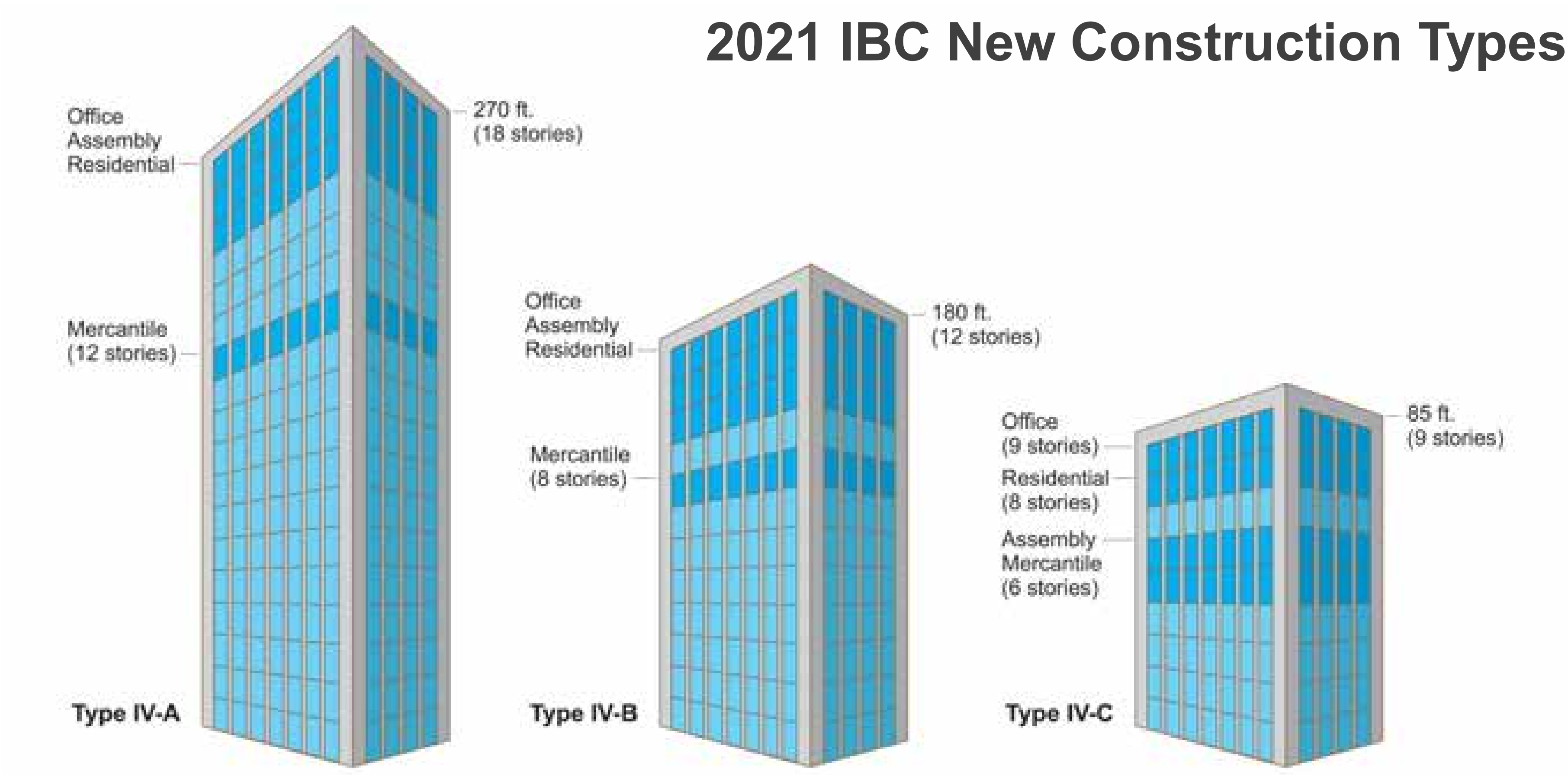
As the height of mass timber buildings continues to grow, so too does the level of design and detailing knowledge required to achieve optimal building construction and performance. One necessary consideration for tall mass timber buildings is vertical movement—including column shrinkage, joint settlement and creep. 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, highlight detailing options to minimize and accommodate movement, and discuss strategies implemented on tall 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 tall 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 to concrete egress components.
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

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

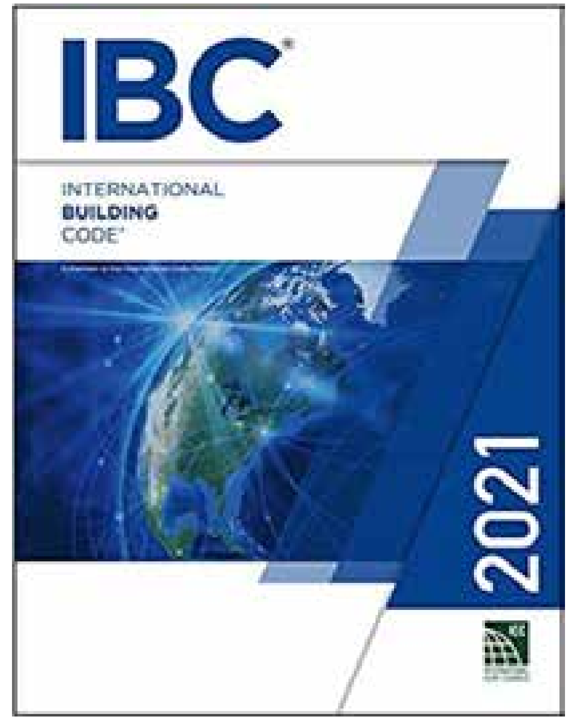
INTRO, Cleveland, OH, Photo: Harbor Bay Real Estate Advisors, Purple Film

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



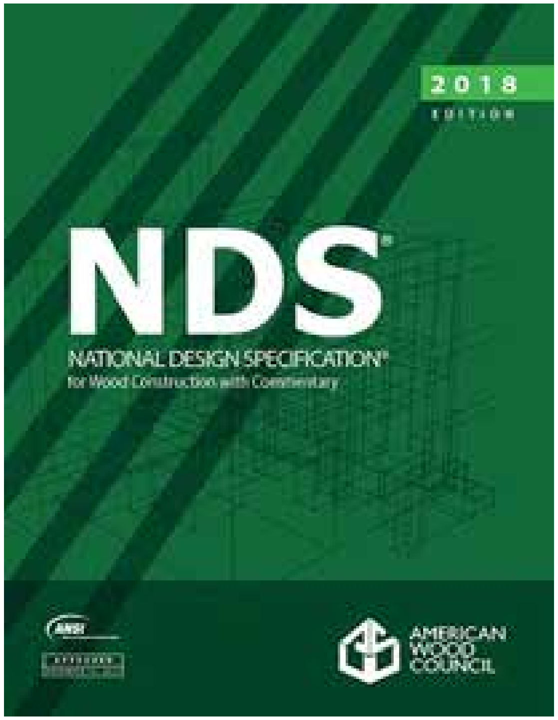
Building Codes and Standards

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



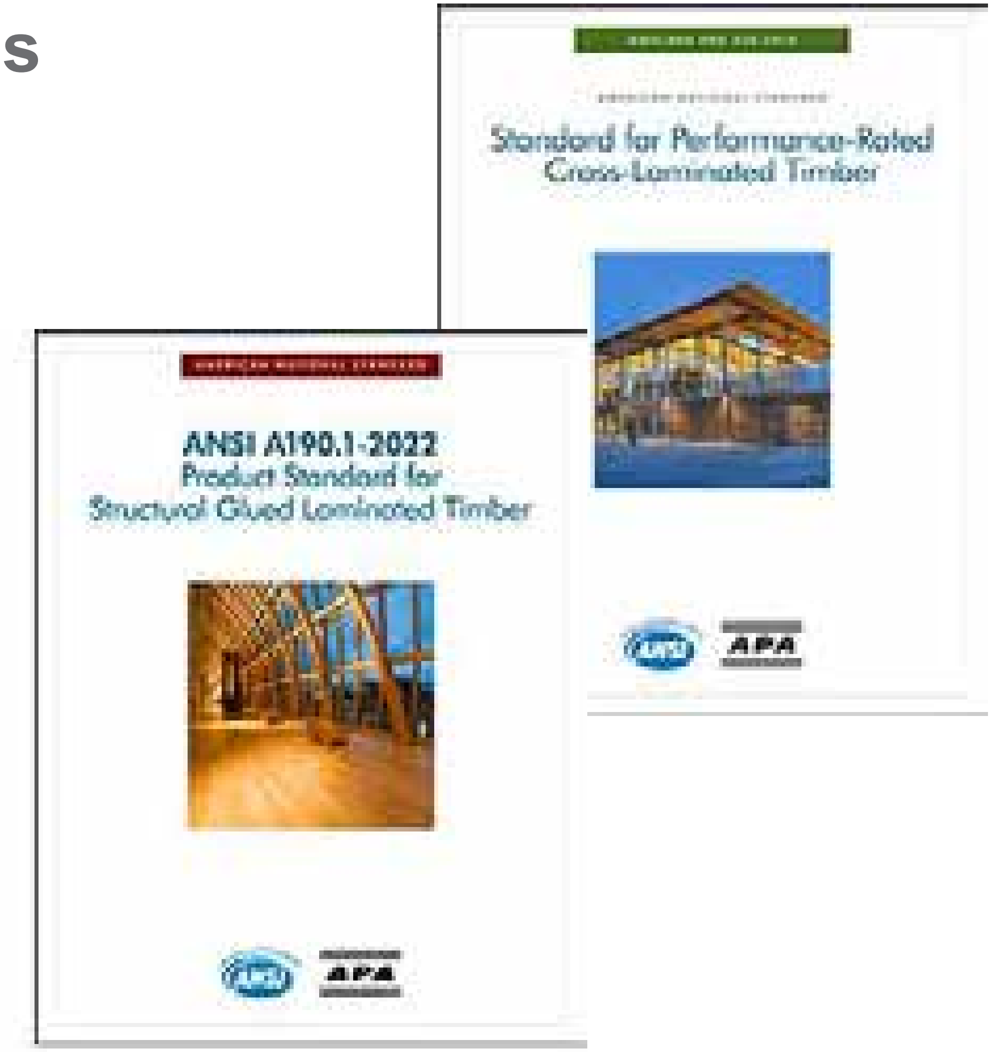
Building Codes and Standards

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

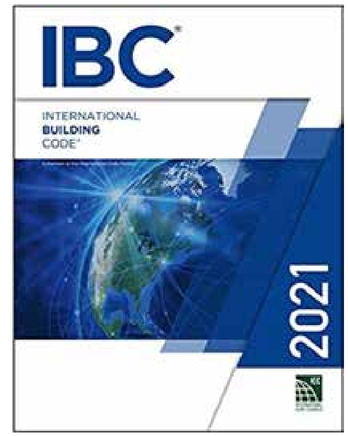


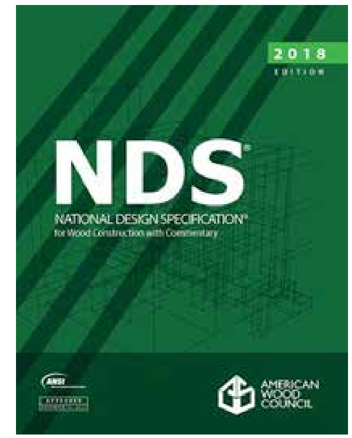
Building Codes and Standards

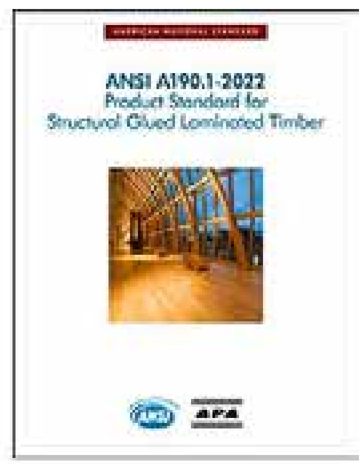
What's not addressed?

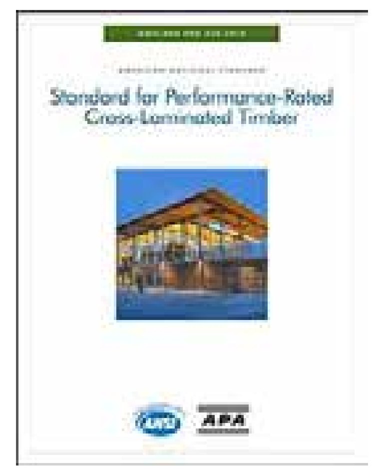
- Calculations for shrinkage
- Creep factor for column axial shortening
- Connection settlements

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

$\Delta_{as} = PL/AE$

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:

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

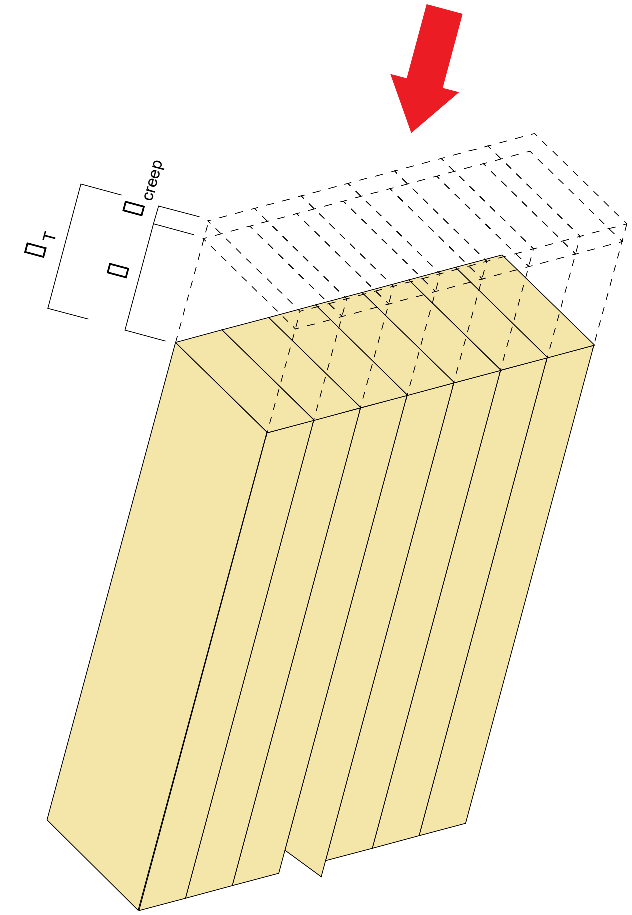
(0.01 in of this total is from creep)

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

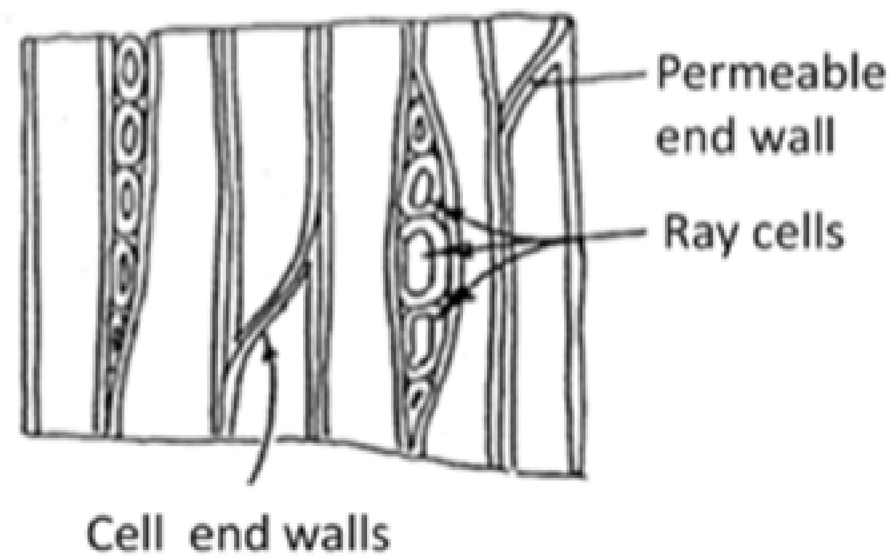
Photo: David Barber, Arup

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

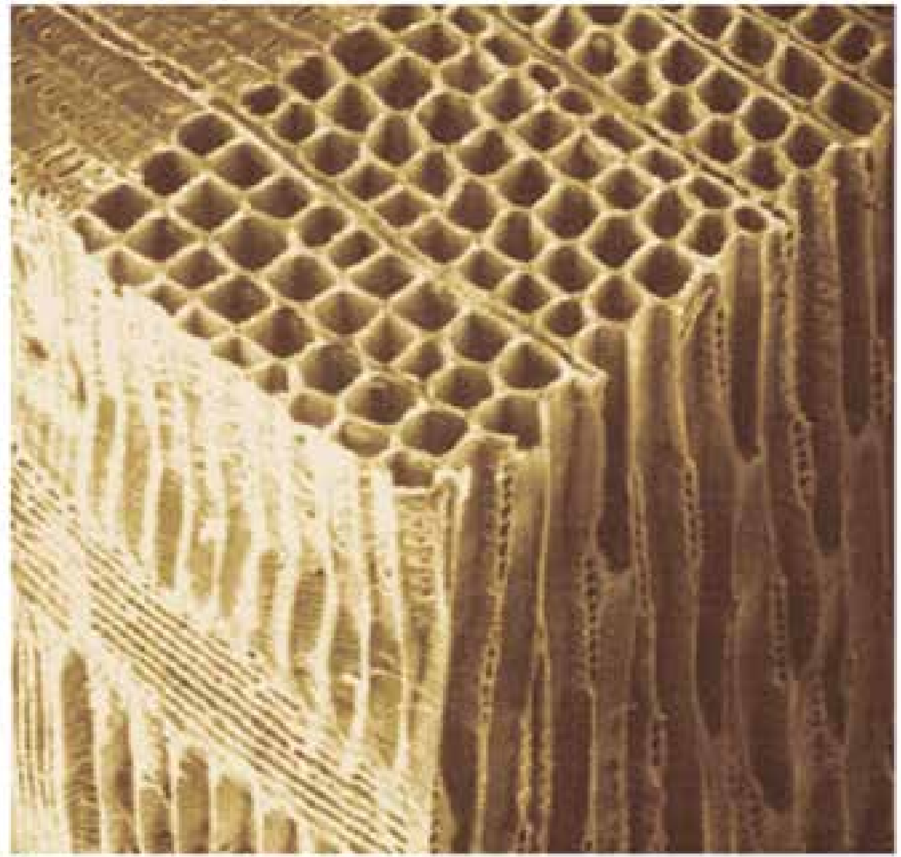
Column Axial Shrinkage

Water exists in wood in two forms:

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

<u>Fiber Saturation Point (FSP)</u>:

- 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)

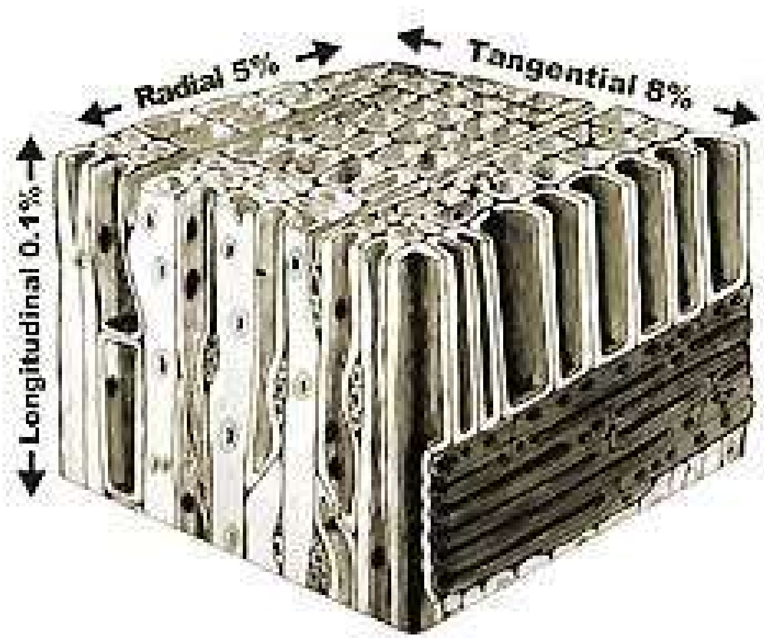


Southern yellow pine cellular makeup

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

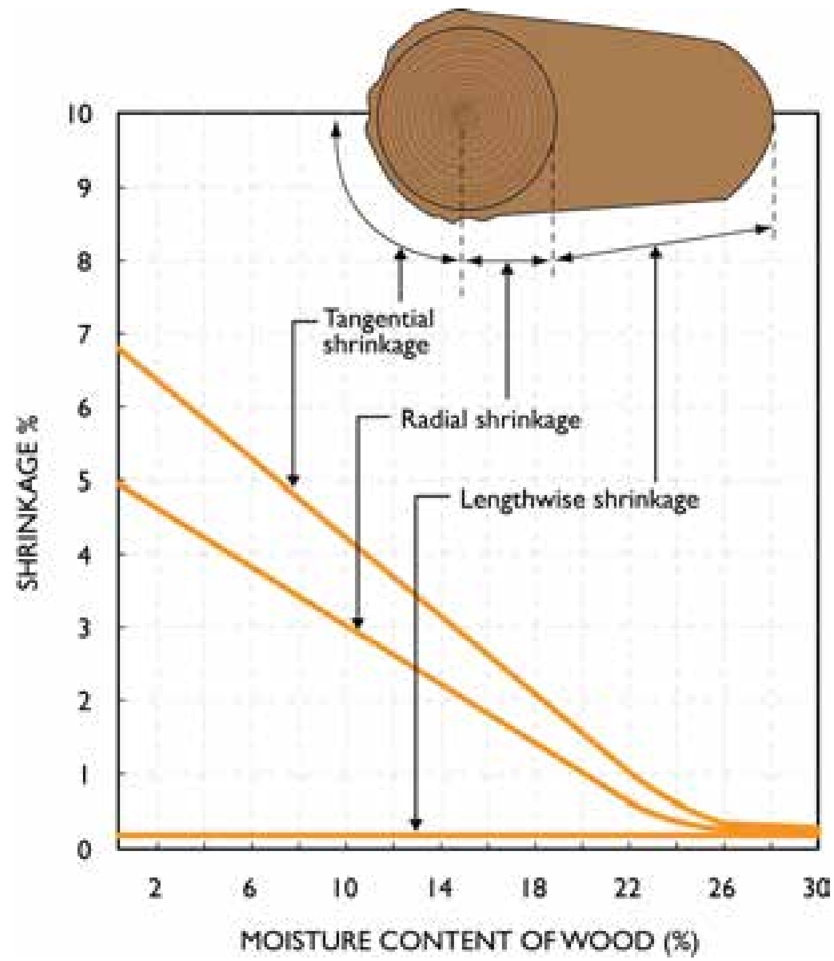


Image: RDH Building Science, Inc.

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

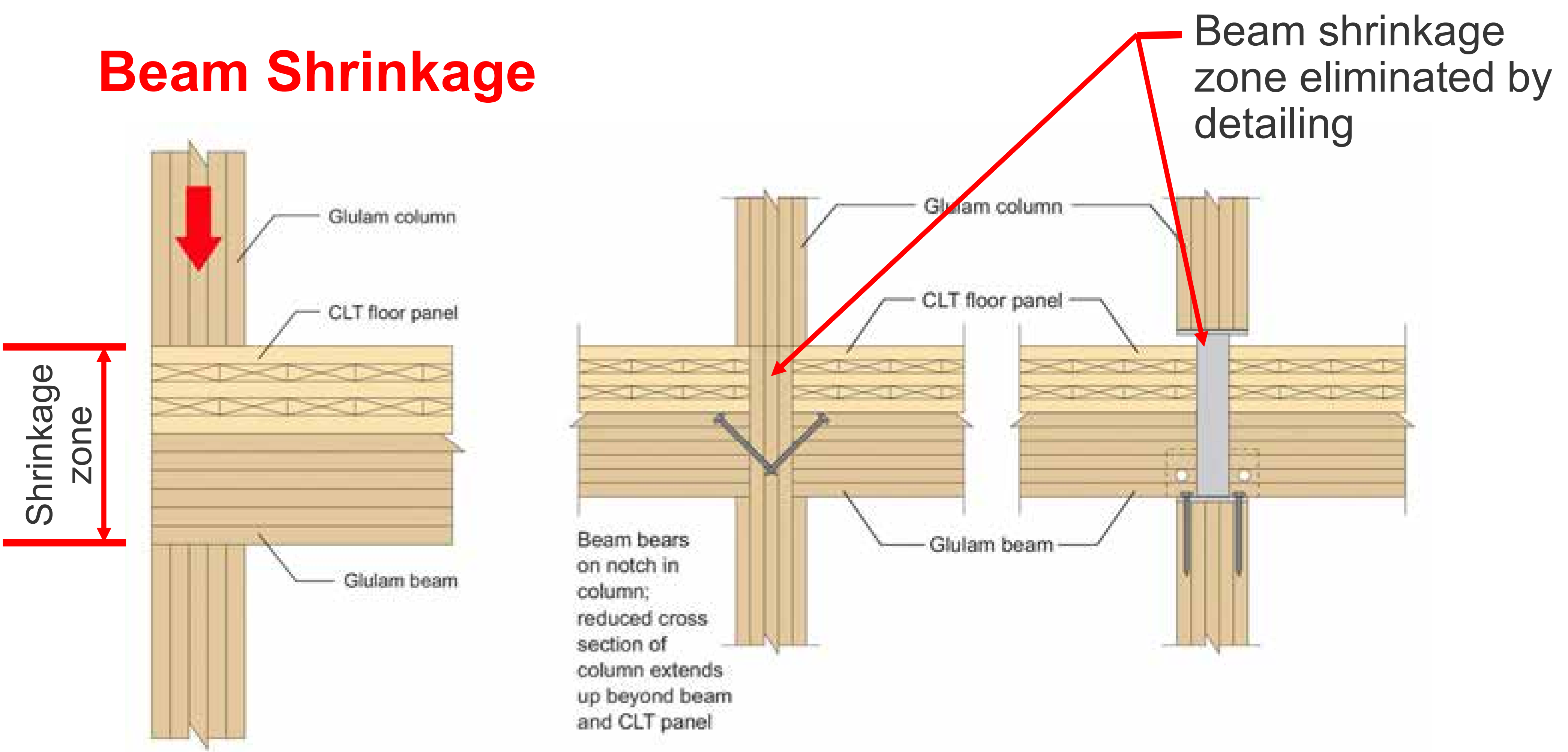
0.000054 is the amount of longitudinal shrinkage per inch of column length per % of MC change.

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



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 <u>not detailed to eliminate shrinkage</u>:

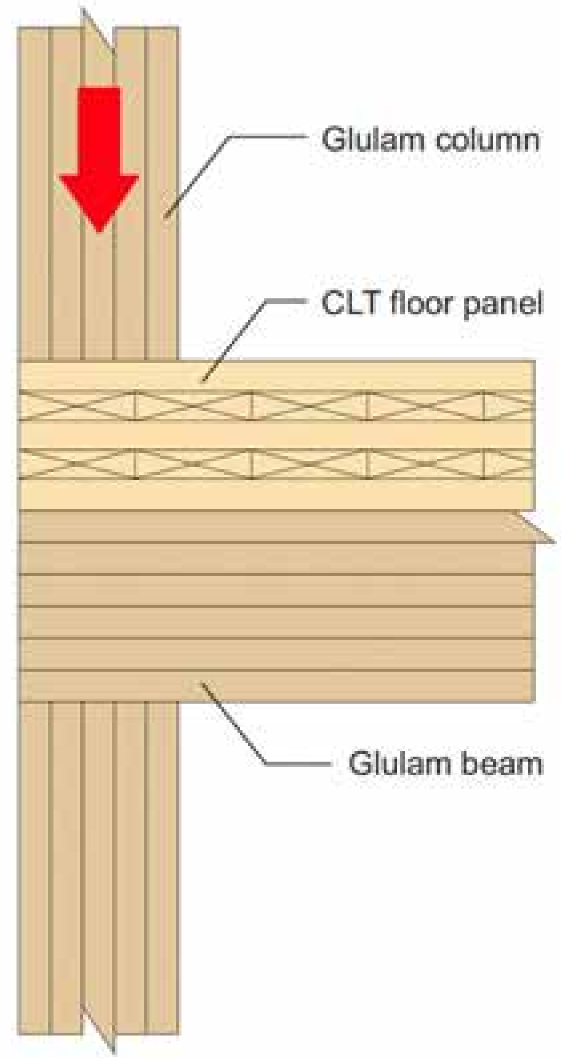
For example, an 8-3/4-in. x 24-in. glulam beam with an installed MC of 19% and EMC of 12% would have an anticipated shrinkage of:

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.



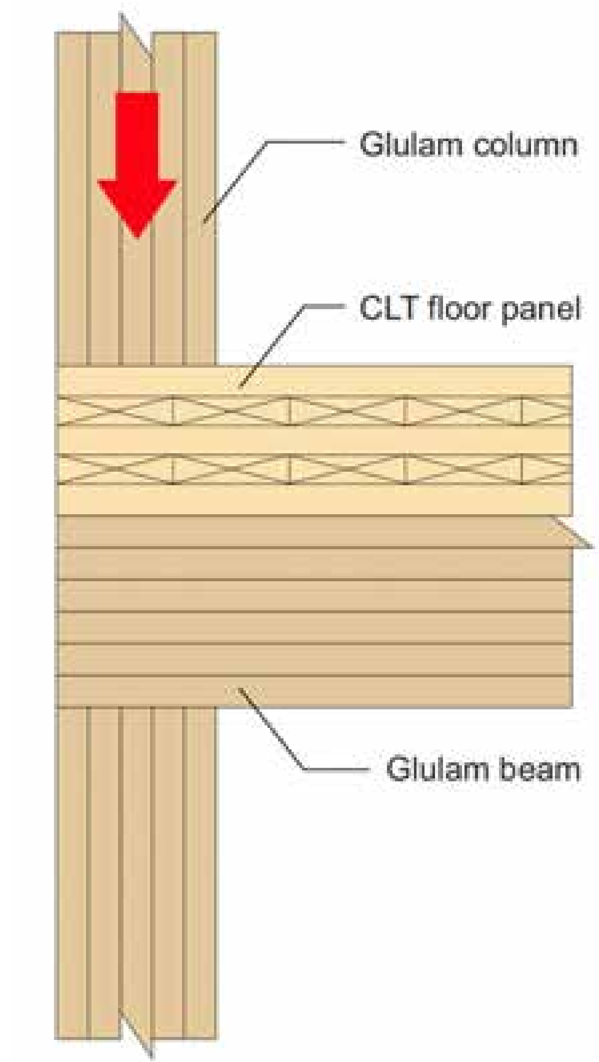
Quantifying Vertical Movement

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

On-Site Moisture Protection Strategies to Minimize Column, Beam & Panel Shrinkage

- Plan Early
- Risk Evaluation
- Develop Construction
- Phase Plan
- Execute the Design and Moisture Management Plan
- Monitor

RDH Moisture Management Guide 1st Ed

Material Environmental Exposure and Moisture Management

Enroute
Onsite
Post-Install
Other Material

Photo: Swinerton

Photo: Alex Schreyer

Quantifying Vertical Movement

On-Site Moisture Protection Strategies to Minimize Column, Beam & Panel Shrinkage

Quantifying Vertical Movement

On-Site Moisture Protection Strategies to Minimize Column, Beam & Panel Shrinkage

On Site Considerations

Quantifying Vertical Movement

On-Site Moisture Protection Strategies to Minimize Column, Beam & Panel Shrinkage

Quantifying Vertical Movement

Faster timber & enclosure install aids in minimizing moisture increase

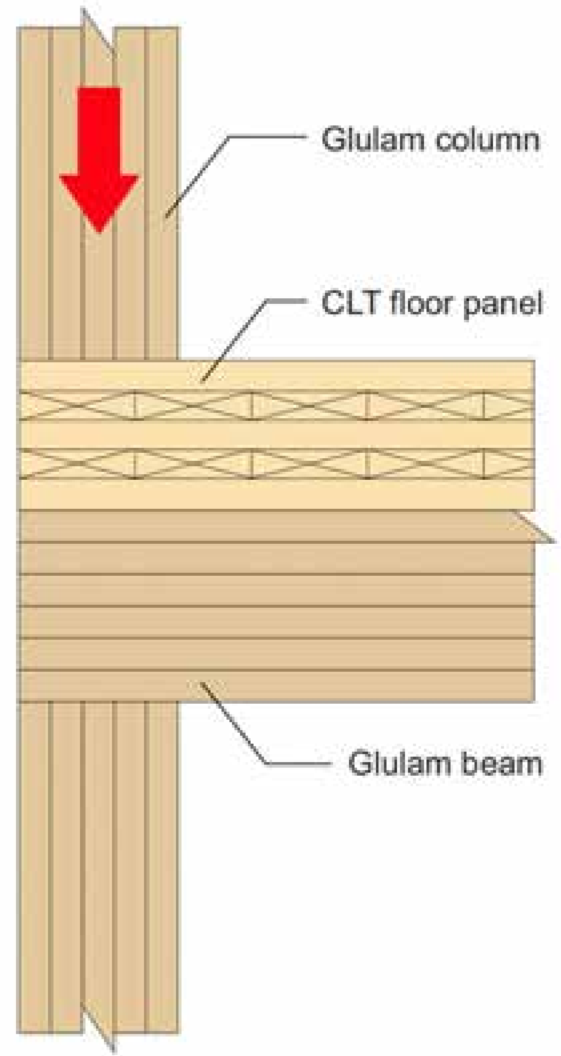
Quantifying Vertical Movement

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

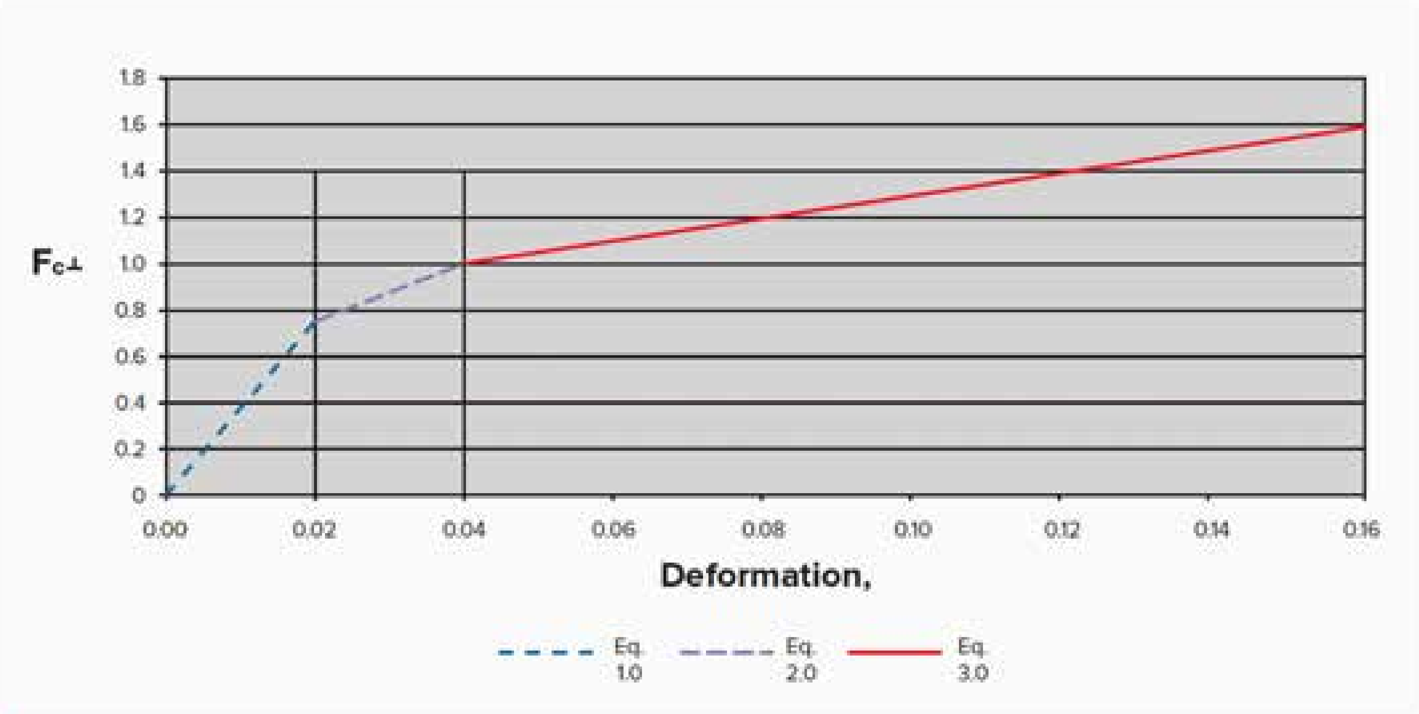


FIGURE 7: Fc⊥ load deformation curve
SDPWS Commentary Example C4.3.4-2 and SDPWS Commentary Reference 67

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

Crushing Zones

Shortening Zone

Quantifying Vertical Movement

Beam Shortening

PL/(AE):

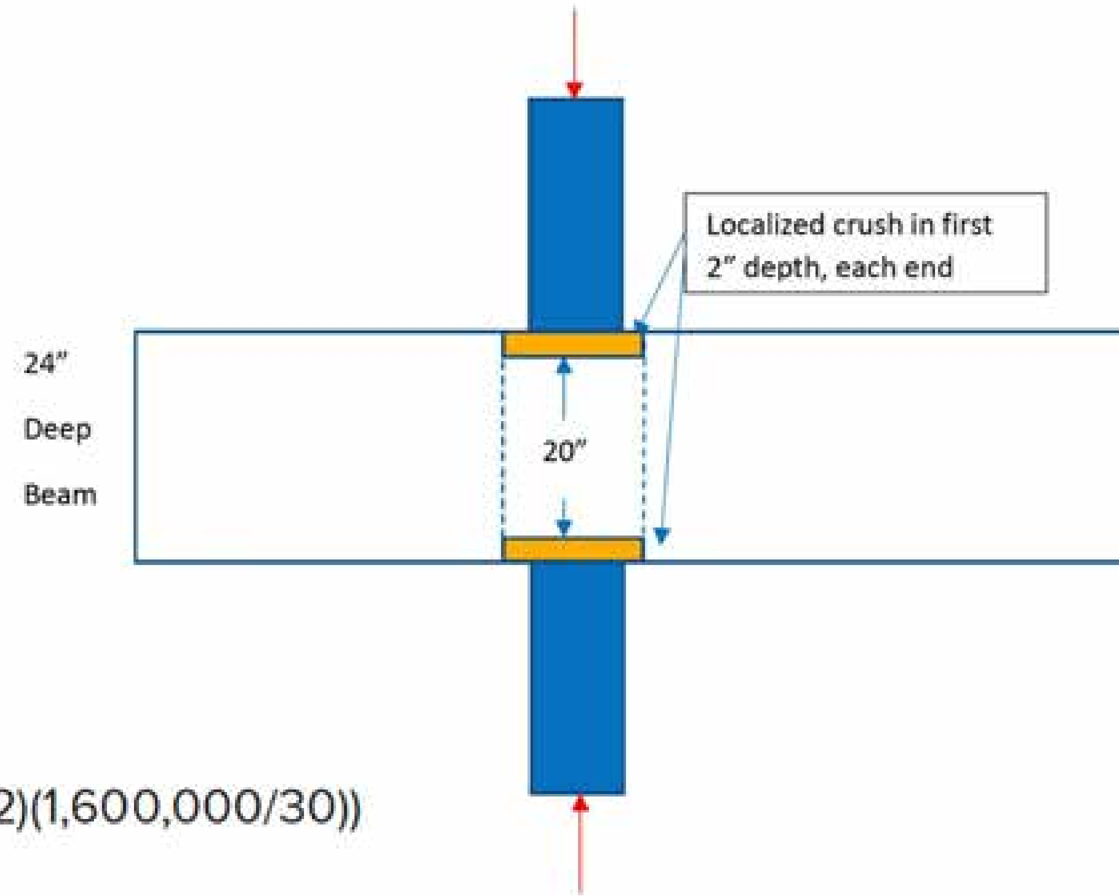
- P is the applied load
- L is the remaining core beam depth (total beam depth minus 2-in. each top and bottom)
- A is the area of the column bearing on the beam (influenced area of the beam core may be increased 2-in. each direction, not to exceed beam edges)
- E is E of the beam divided by 30
  - E/30 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 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:

Δ_{column} = 0.07 + 0.42 + 0.07 + 0.06 + 0.06 = 0.68 in. x 12 story building = 8.2 in

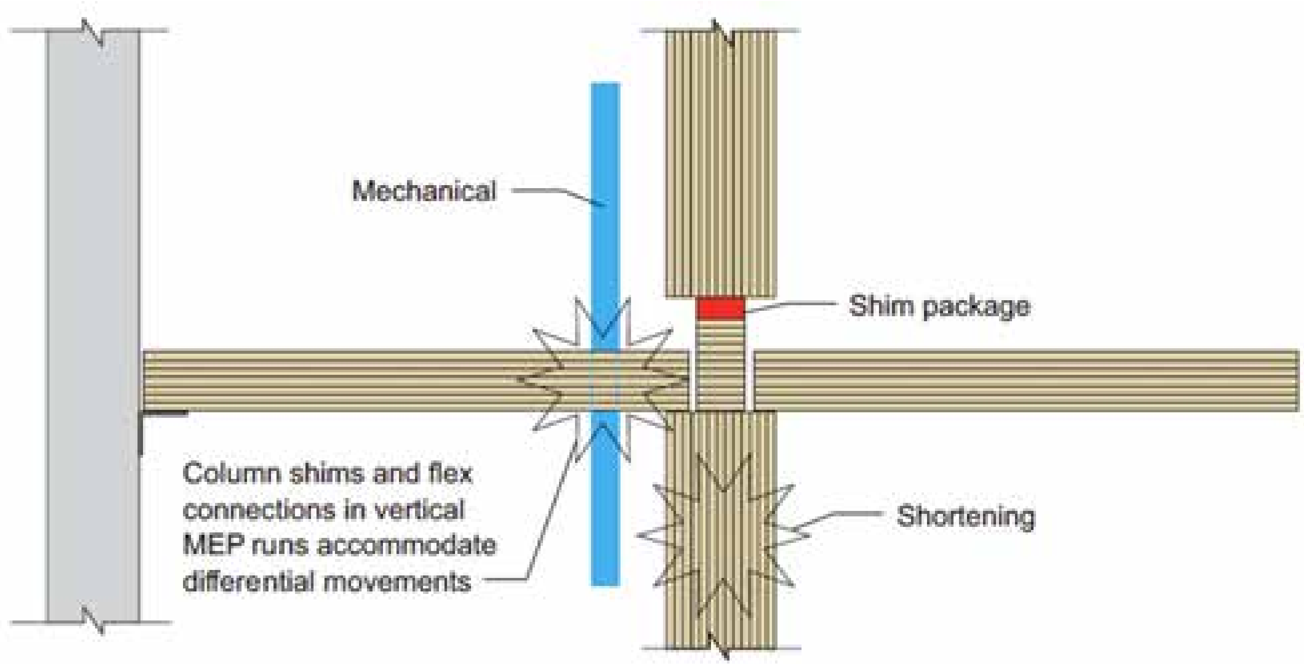
Using the detail shown in Figure 6 where the beam **is** isolated from the shrinkage and crushing zone, the net vertical movement per level is:

Δ_{column} = 0.07 + 0 + 0.07 + 0 + 0.06 = 0.2 in. x 12 story building = 2.4 in

Minimizing Vertical Movement

Now we know how to calculate anticipated movements:

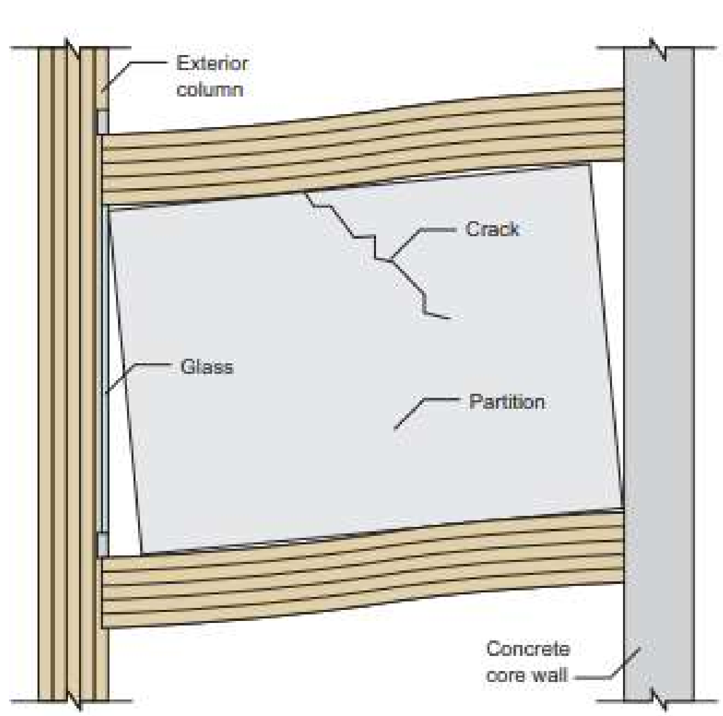
- What do those movements affect?
- It isn't necessarily the vertical movements alone that can cause issues, it is the differential movements than can

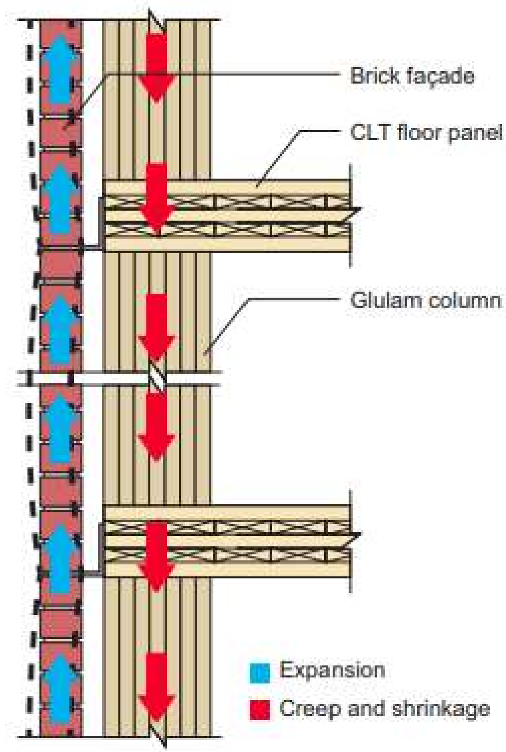


Minimizing Vertical Movement

Impact of Differential Vertical Movements on Non-Structural Components

- Interior Partitions
- Exterior Cladding
- Mechanical Equipment
- Roof Drainage

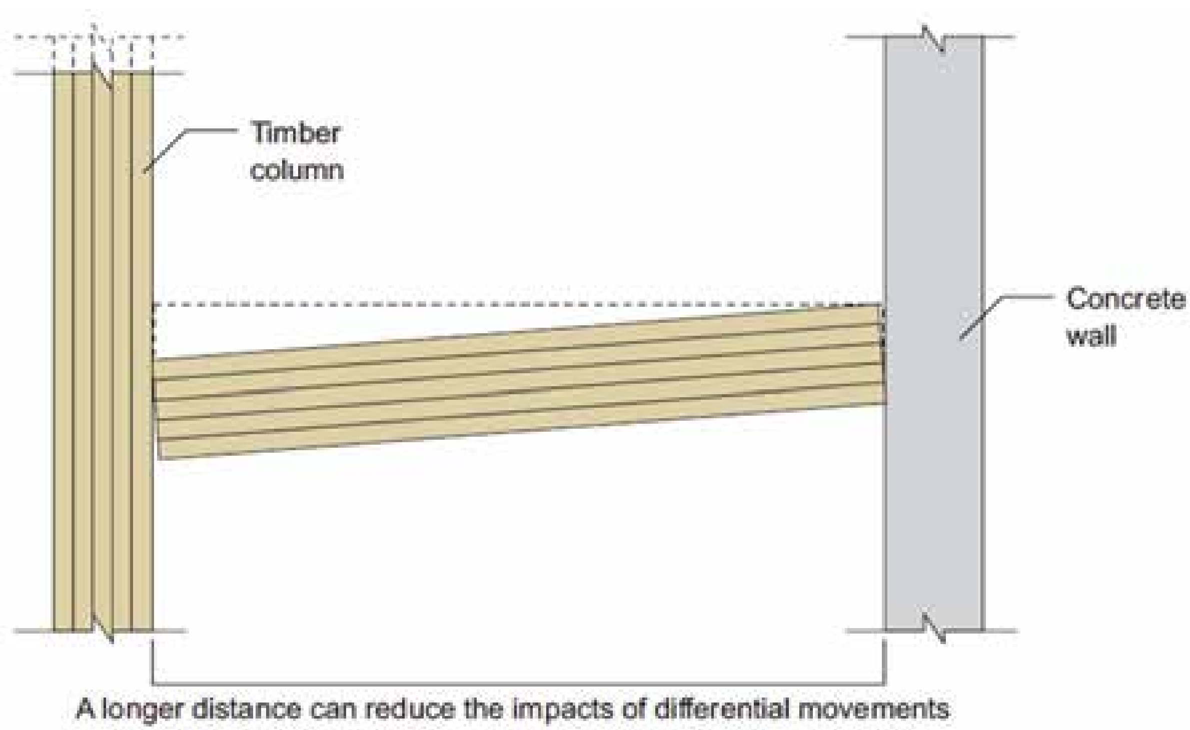




Minimizing Vertical Movement

Impact of Differential Vertical Movements on Structural Components

- Connections to concrete cores, steel braced frames
- Differential gravity support (eg. mix of beams & bearing walls)

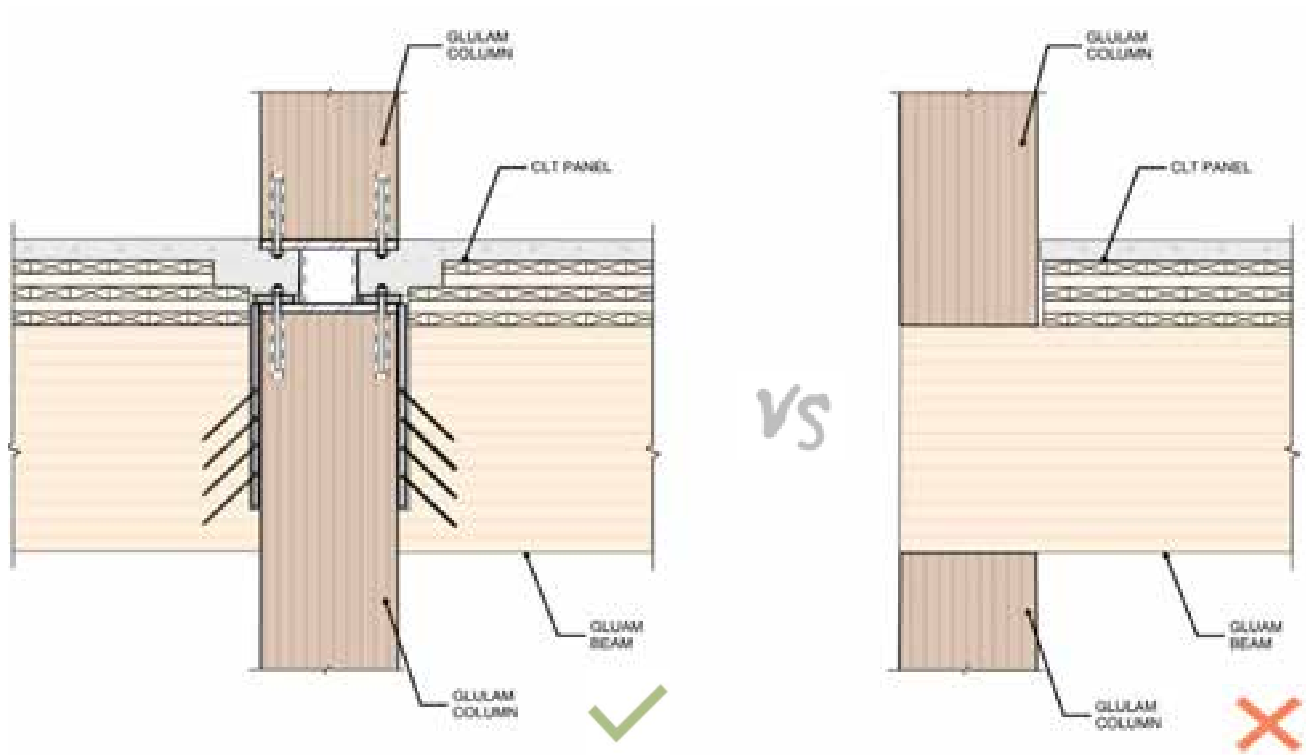


Minimizing Vertical Movement

Beam to beam, beam to column and column to column connections are key in minimizing vertical movements

Minimize movements by:

Isolating perp-to-grain shrinkage & crushing

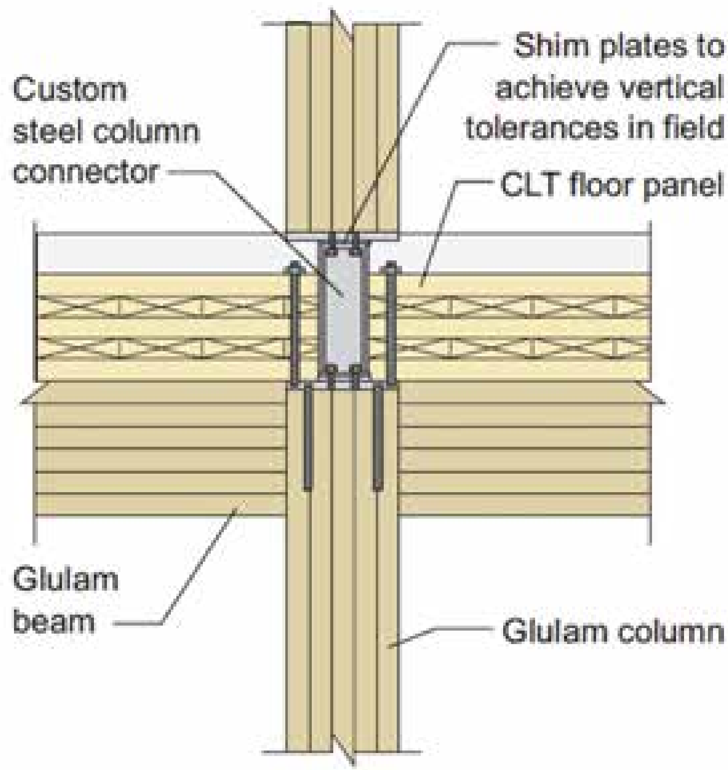


Minimizing Vertical Movement

Beam to beam, beam to column and column to column connections are key in minimizing vertical movements

Minimize movements by:

Shimming column connections

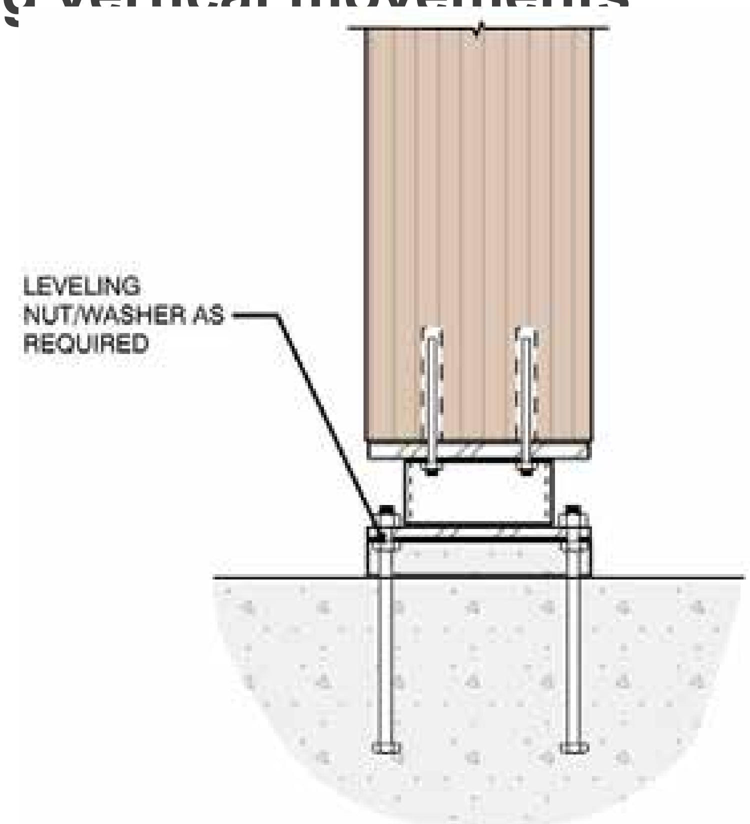


Minimizing Vertical Movement

Beam to beam, beam to column and column to column connections are key in minimizing vertical movements

Minimize movements by:

Adjustments at base with leveling nuts & grout

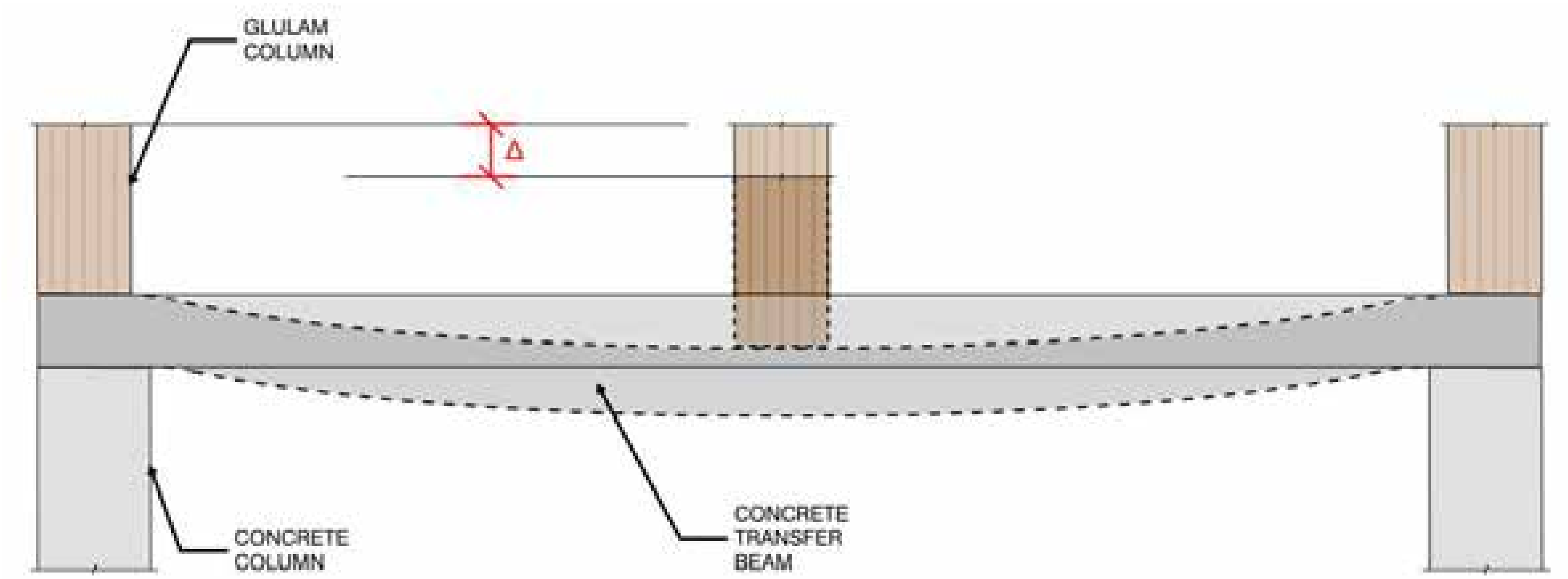


Minimizing Vertical Movement

Consider differential stiffness & deflections of supports

Minimize movements by:

Providing equivalent support stiffnesses or connection details that accommodate differential deflections



Minimizing Vertical Movement

Consider differential movements of supports

Timber vs. Non-Timber Supports

Minimizing Vertical Movement

Consider differential movements of supports

Different Types & Stiffnesses of Timber Supports

Photo: Lendlease

Photo: Kalesnikoff

Accommodating Vertical Movement

Once details and strategies have been implemented which minimize movements, focus on accommodation of movements

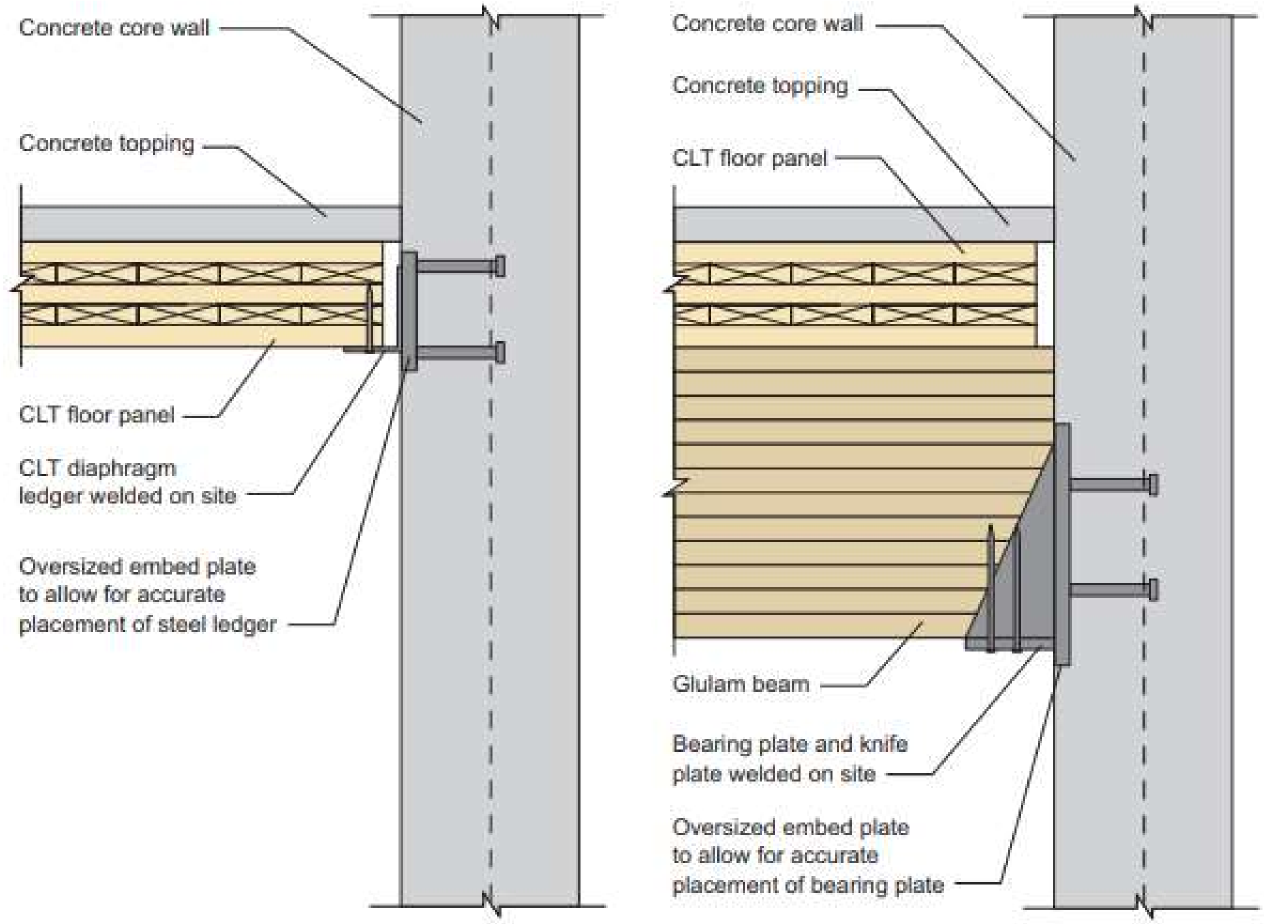
Credit: LeMessurier

Credit: Marcus Kauffman

Accommodating Vertical Movement

Accommodate movement at timber to concrete cores

Example: embedded, oversized steel plate in concrete. Steel angle field welded to plate once final elevations are determined (and ideally once some initial shrinkage and settlement has occurred)



Accommodating Vertical Movement

Accommodating Vertical Movement

Beyond structural connections, consider movement impacts on MEPF services. Flex/compression connections

Accommodating Vertical Movement

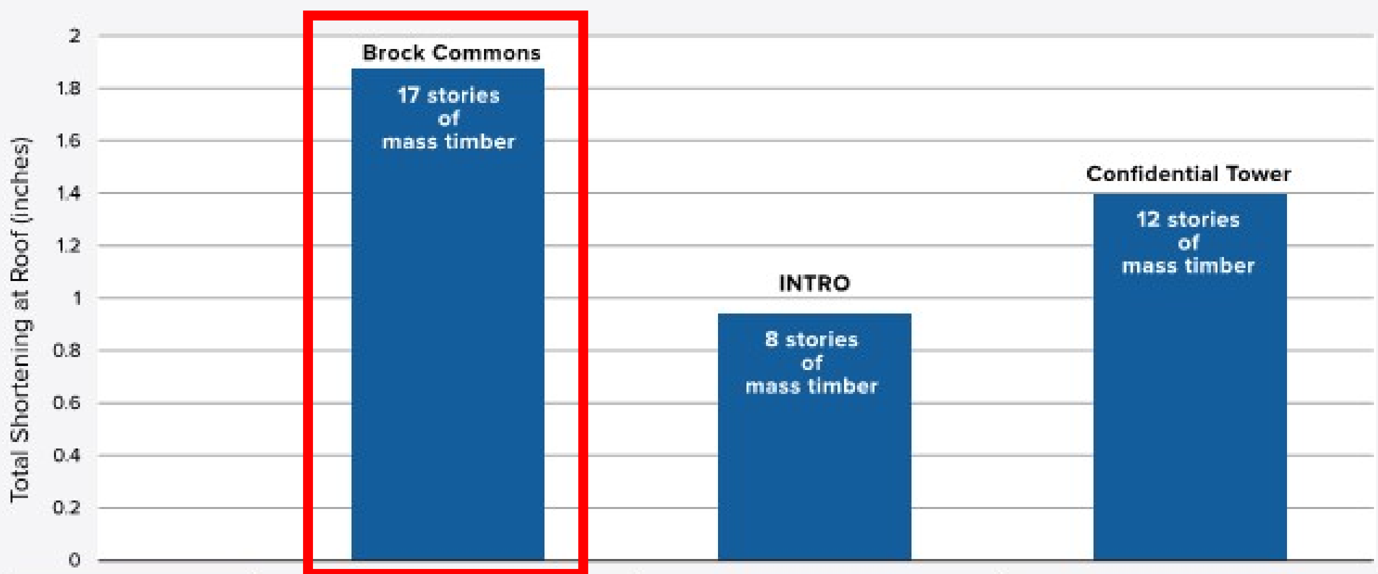
Also consider other continuous non-bearing elements such as exterior walls, shafts. Include deflection tracks, control joints


Credit: naturally Wood

Calculated vs. Actual Vertical Movement

Calculations may overestimate actual movements on site

Examples of calculated vertical movement for several North American tall timber projects:



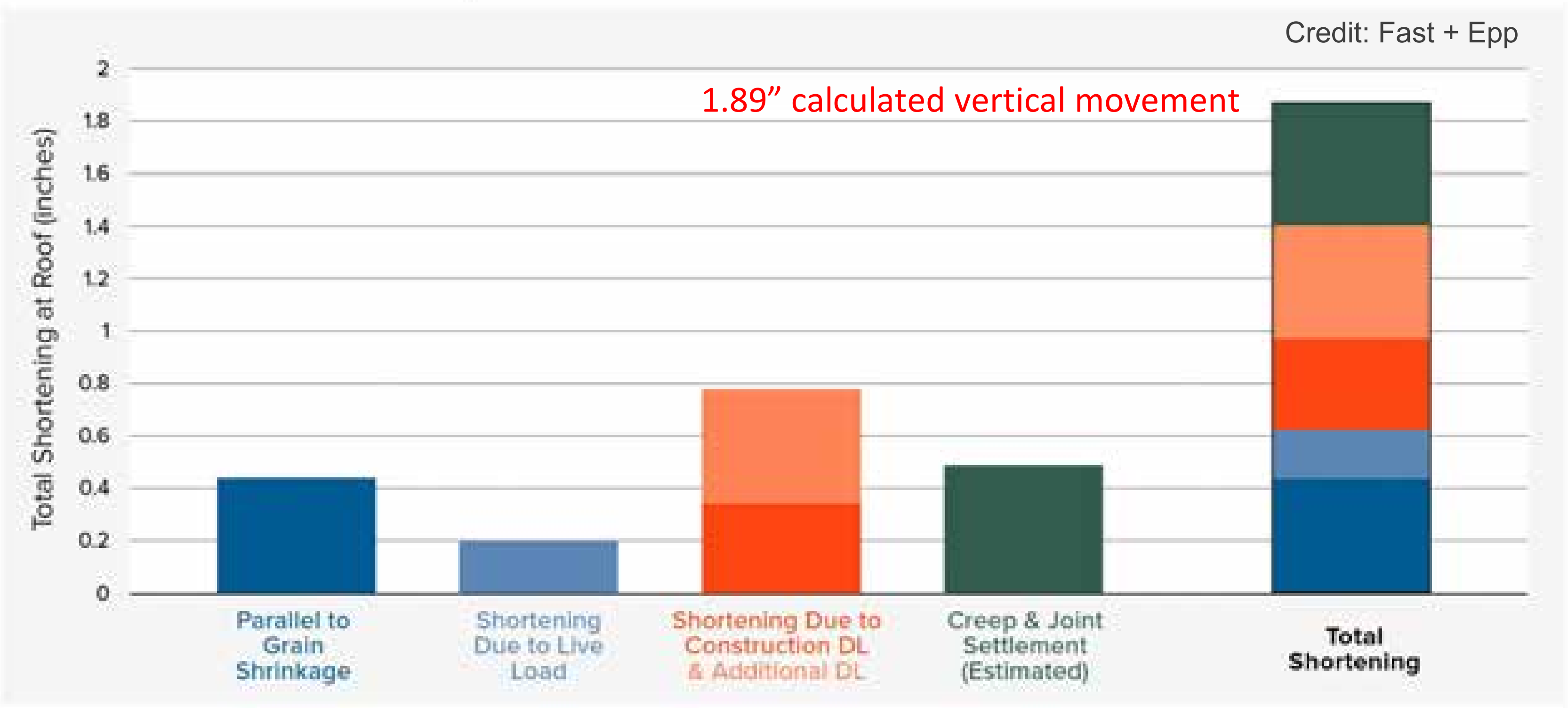
FFR & Exposure	2 hrs - Fully encapsulated	2 hrs - Exposed	2 hrs - Partially encapsulated
Grid	13' x 9'	20' x 22' average	10' x 12'
Structural system	Point-supported CLT	CLT on glulam beams	10' x 12'
Main story height	9'-2"	11'-5"	9'-8"

Credit: Fast + Epp

Calculated vs. Actual Vertical Movement

Calculations may overestimate actual movements on site

Calculated vertical movement at Brock Commons: 18 story (17 over 1) mass timber residence hall in Vancouver, BC.

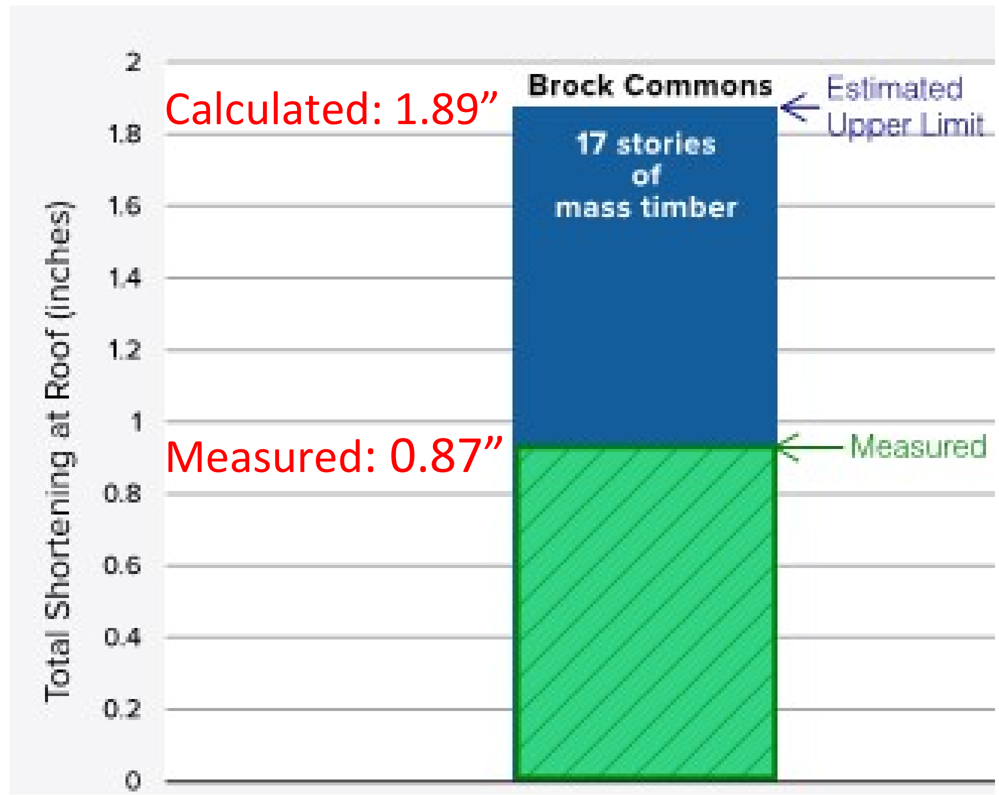


Calculated vs. Actual Vertical Movement

Calculations may overestimate actual movements on site

Brock Commons: Measured movements were ~50% of calculated movements

Values used for elastic modulus, live load, creep, joint settlement, and moisture variation among others 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.

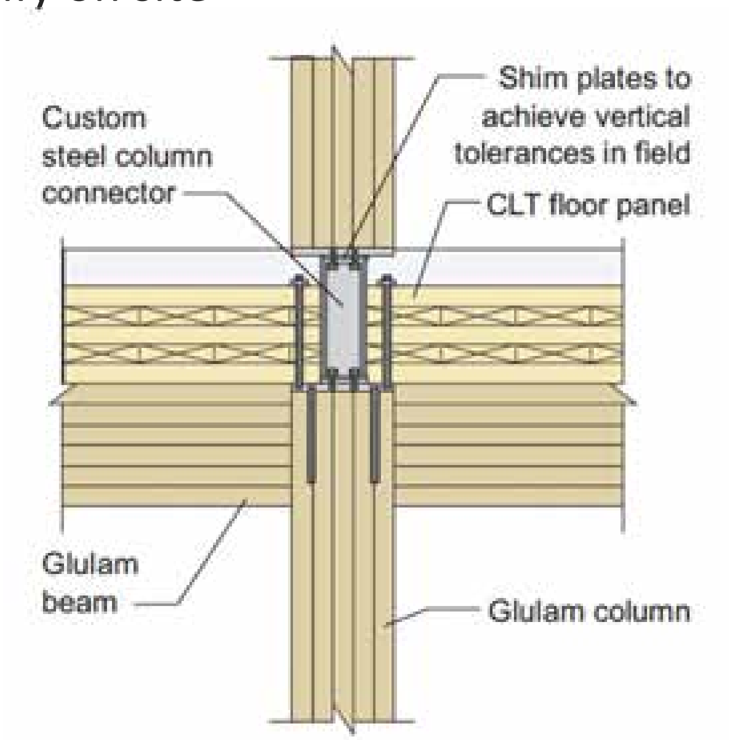


Credit: Fast + Epp

Calculated vs. Actual Vertical Movement

Calculations may overestimate actual movements on site

Takeaways: calculations are important in setting detailing conditions, but don't overshim. Verify on site



Conclusions

- Critical to consider axial column shortening and other vertical movements in tall mass timber buildings
- Precautions should be taken to address estimated shortening due to the uncertainties that lie within assumptions
- Know impacts of movements on structural connections & non-structural components

Photo: H+O Structural Engineering, Kure Creative

Conclusions

- 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
- Involve all members of the design and construction team in understanding vertical movements

Photo: WoodWorks

Conclusions

- On site observations and inspections help to ensure that performance matches design intent
- Proper detailing must lead to proper installation
- Once fully understood, accommodating vertical movement simply becomes another design criteria

Vertical Movement in Mass Timber Design Resource


WOODWORKS

Differential Material Movement in Tall Mass Timber Structures

An Overview of Column Movement Types and How to Address Them

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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