WOOD STRUCTURES

Instructional Material Complementing FEMA 451, *Design Examples*

Timber Structures 13 - 1

Interior of the Old Faithful Inn, Yellowstone National Park, taken by author S. Pryor. Note heavy post and beam construction. Will discuss again later.

Note that this topic, while complete, does not specifically utilize the examples in Chapter 10 of FEMA 451, *NEHRP Recommended Provisions: Design Examples*. The instructor/student should carefully review Chapter 10 of FEMA 451 for additional information on the seismic resistant design of wood structures.

Objectives of Topic

Understanding of:

- **Basic wood behavior**
- **Typical framing methods**
- **Main types of lateral force resisting systems**
- **Expected response under lateral loads**
- **Sources of strength, ductility and energy dissipation**
- **Basic shear wall construction methods**
- **Shear wall component behavior**
- **Analysis methods**
- **Code requirements**

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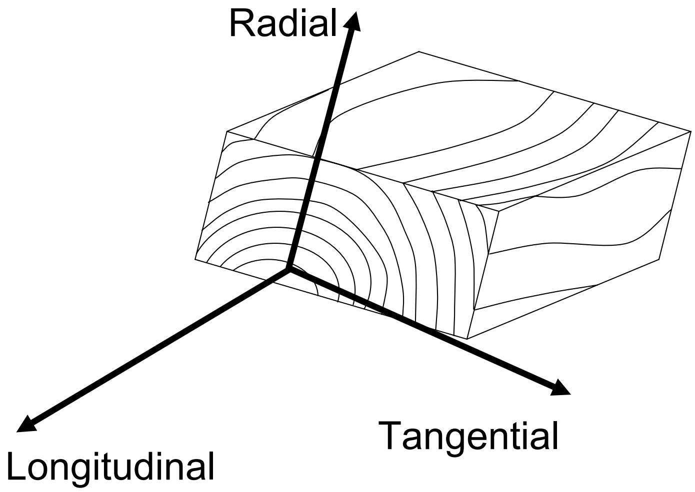
Instructional Material Complementing FEMA 451, *Design Examples* Timber Structures 13 - 2

Self explanatory.

Basic Wood Material Properties



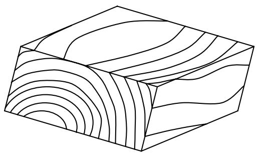
Wood is orthotropic

- **Varies with moisture content**
- **Main strength axis is longitudinal - parallel to grain**
- **Unique, independent, mechanical properties in 3 different directions**
- **Radial and tangential are "perpendicular" to the grain – substantially weaker**

Wood is a very complex organic building material. Nevertheless, it has been used successfully throughout the history of mankind for everything from structures to ships to planes to weaponry.

Mention that naturally occurring “strength reducing characteristics” such as knots, shakes, and splits will contribute the actual strength of lumber.

Basic Wood Material Properties



"Timber is as different from wood as concrete is from cement."

– Madsen, Structural Behaviour of Timber

Concept of "wood" as "clear wood": design properties used to be derived from clear wood with adjustments for a range of "strength reducing characteristics."

- **Concept of "timber" as the useful engineering and construction material: "In-grade" testing (used now) determines engineering properties for a specific grade of timber based on full-scale tests of timber, a mixture of clear wood and strength reducing characteristics.**

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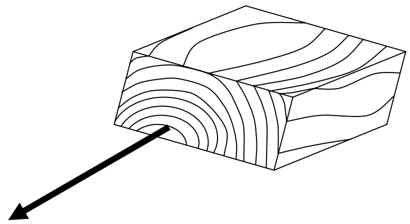
Borg Madsen's distinction is a good one. The understanding of how timber behaves must address the natural occurrence of strength reducing characteristics.

Basic Wood Material Properties



Longitudinal

Sample DFL longitudinal design properties:

- **Modulus of elasticity: 1,800,000 psi**
- **Tension (parallel to grain): 1,575 psi**
- **Bending: 2,100 psi**
- **Compression (parallel to grain): 1875 psi**

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DFL: Douglas Fir-Larch

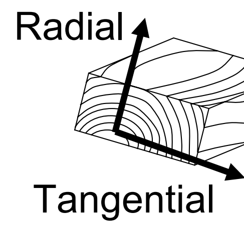
This slide and the next are intended to provide a feel for general level of design allowable stresses (ASD) unless where noted otherwise. LRFD could be used, but ASD is still predominant in the design community.

Discuss how bending > tension because for tension entire cross section is stressed, which means tension strength reducing characteristics will be found/encountered, whereas for bending, max stresses are at the outer edges of the board and grading rules take into account the size and location of strength reducing characteristics and how they would affect bending.

Basic Wood Material Properties

Sample DFL perpendicular to grain design properties:

- **Modulus of elasticity: 45,000 psi (2.5 ~ 5 % of $E_{||}$!)**
- **Tension (perpendicular to grain): 180 to 350 psi <u>FAILURE</u> stresses. Timber is extremely weak for this stress condition. It should be avoided if at all possible, and mechanically reinforced if not avoidable.**
- **Compression (perpendicular to grain): 625 psi. Note that this is derived from a serviceability limit state of ~ 0.04" permanent deformation under stress in contact situations. This is the most "ductile" basic wood property.**



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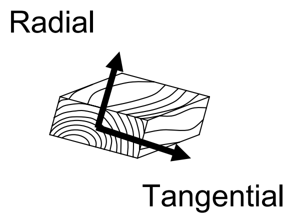
Intended to provide a feel for general level of design allowable stresses and to emphasize the weakness of wood stressed perpendicular to grain. In commercial lumber, tension perpendicular is very low and designs must not rely on this type of action.

Note how miners have long taken advantage of the ductile nature of compression perpendicular to grain in shoring up mine shafts.

Basic Wood Material Properties



Shrinkage

- Wood will shrink with changes in moisture content.
- This is most pronounced in the radial and tangential directions (perpendicular to grain).
- May need to be addressed in the LFRS.

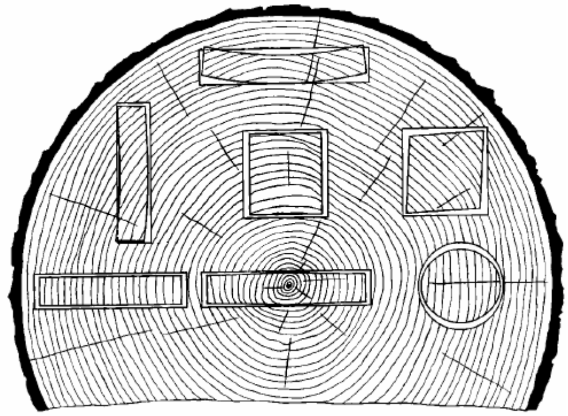


Figure 3–3. Characteristic shrinkage and distortion of flat, square, and round pieces as affected by direction of growth rings. Tangential shrinkage is about twice as great as radial.

(Wood Handbook, p. 58)

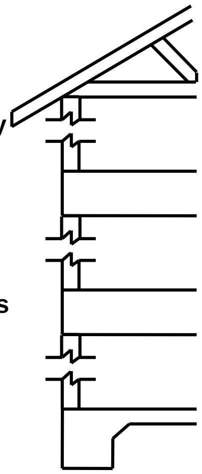
For most designs shrinkage in the longitudinal direction can be ignored. However, that may not be the case for perpendicular to grain shrinkage. Accumulated effects in the boundary chords of shear walls can degrade the performance of the shear wall system and may need to be addressed with shrinkage compensating devices. While tangential ~ 2x radial, for design purposes. this is ignored as one won't know that the orientation will be in service.

Figure is 3-3 from the *Wood Handbook*.

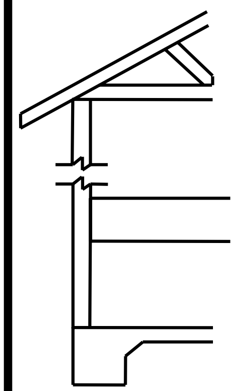
Wood Structure Construction Methods: Gravity

Platform

- Walls are interrupted by floor "platforms."
- Floors support walls.
- Most common type of light-frame construction today.
- Economical but creates discontinuity in the load path.
- Metal connectors essential for complete load path.



Balloon



- Walls feature foundation to roof framing members.
- Floors supported by ledgers on walls or lapped with studs.
- Not very common today.

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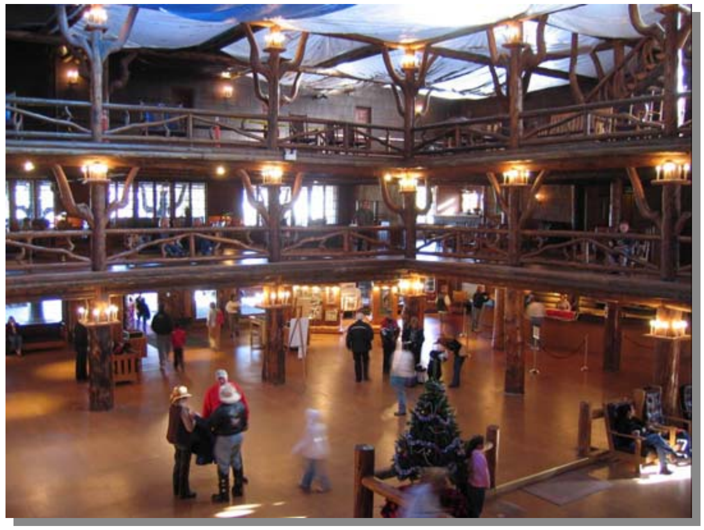
Self explanatory. Note the accumulation potential of shrinkage perpendicular to grain in each floor over the height of the structure.

Wood Structure Construction Methods: Gravity

Post and Beam

- **Space frame for gravity loads.**
- **Moment continuity at joint typically only if member is continuous through joint.**
- **Lateral resistance through vertical diaphragms or braced frames.**
- **Knee braces as seen here for lateral have no code design procedure for seismic.**

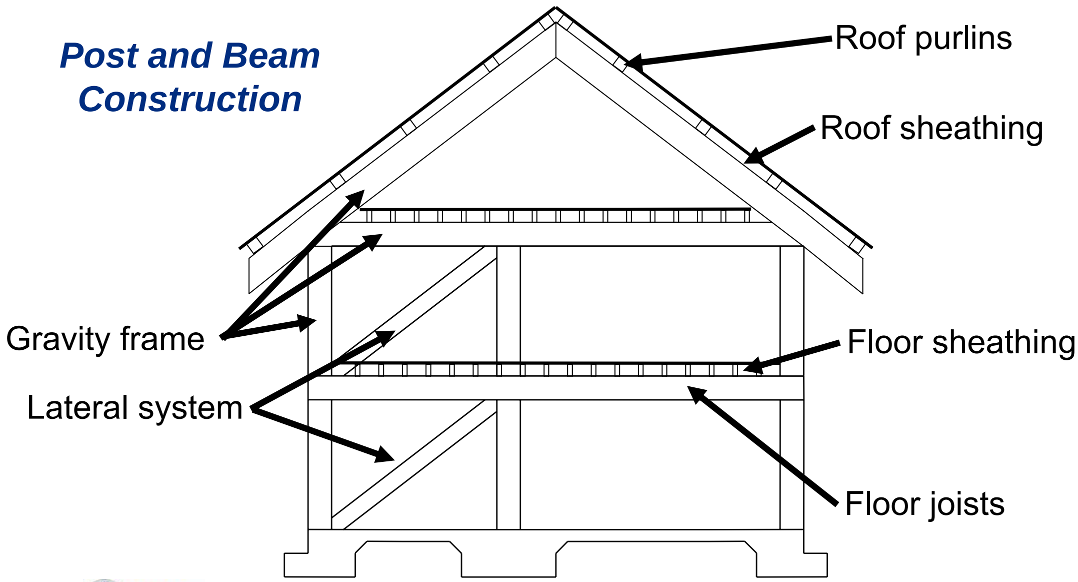


Six story main lobby Old Faithful Inn, Yellowstone, undergoing renovation work in 2005. Built in winter of 1903-1904, it withstood a major 7.5 earthquake in 1959.

The Old Faithful Inn wasn't "designed" for seismic but the designers and builders provided a structure that suffered only minor damage in the 1959 earthquake. Lateral resistance of this structure is a combination of wood moment frame action due to the knee braces at the post/beam connection (note eccentricity in the braces under axial forces due to architectural curvature of the braces, in every brace) and diaphragm action in the roof/walls. Some beam/column connections in the very top of the lobby, which supported a "crows nest" platform where a small orchestra would play and entertain guests, were damaged and so that practice was stopped. Here it is being repaired and strengthened (summer 2005).

Wood Structure Construction Methods: Gravity

Post and Beam Construction



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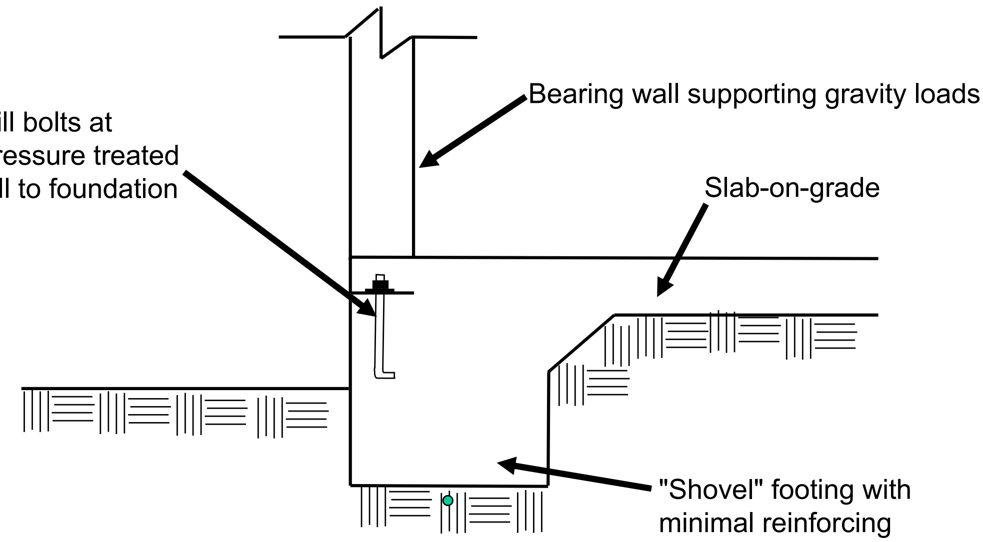
Timber Structures 13 - 10

For the most part. this slide is self explanatory. Emphasize that the lateral system typically will not support gravity load, and while braced frame action is shown here, it could also be vertical diaphragms (stud walls with nailed wood structural panel sheathing). Note that 1997 UBC had seismic design provisions for heavy timber braced frames but none are included in NEHRP or IBC provisions. Because the LFRS doesn’t support gravity loads, it is in a different category when it comes to the *R* factor used to determine lateral demand. Also, spread footings are more likely to support the concentrated loads from the columns as compared to platform style construction.

Typical Light-Frame Foundation: Slab-On-Grade



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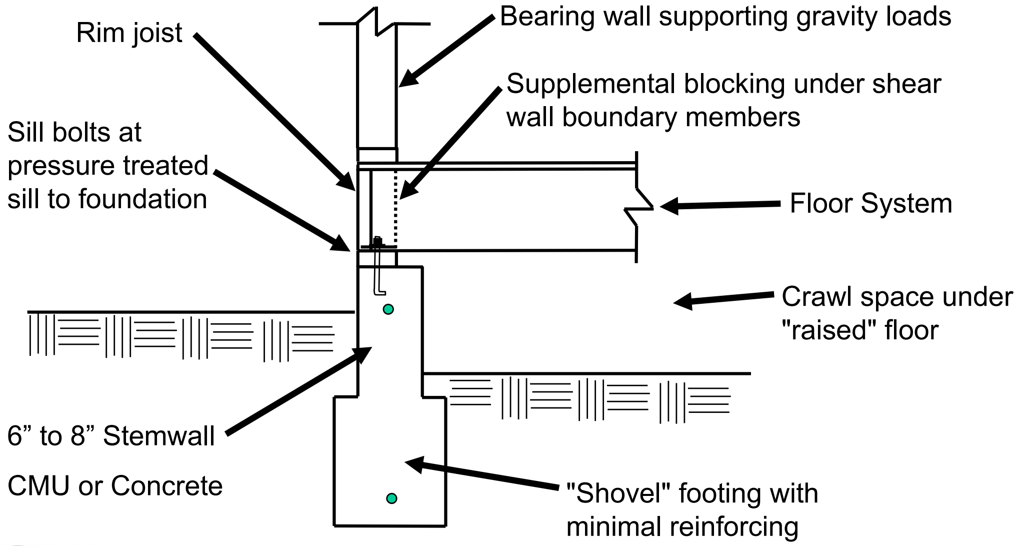
Self explanatory. Note that relatively little engineering goes into the footings for the most part.

Typical Light-Frame Foundation: Raised Floor



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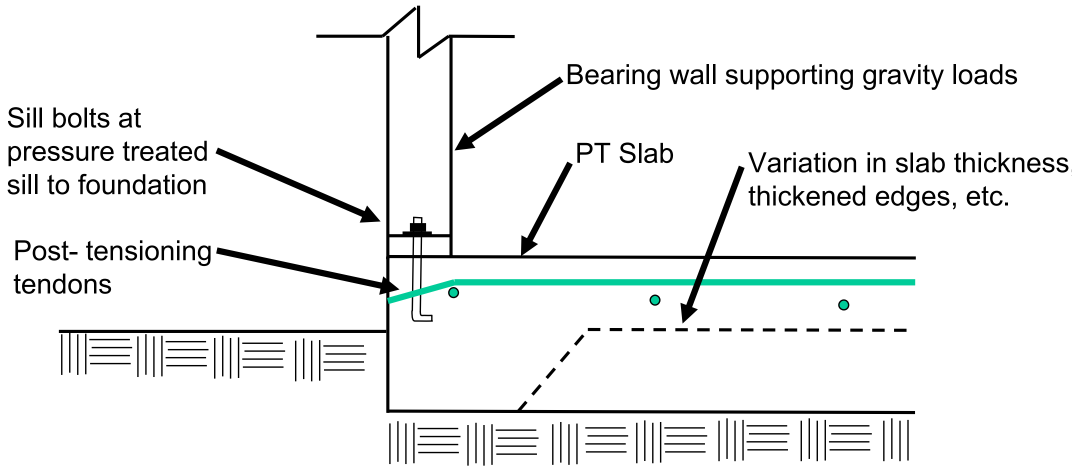
As before, not much attention beyond code reinforcing minimums for the foundation. Shear wall boundary members can create large overturning compression forces that require supplemental blocking to prevent excess deformations through elastic compression of the floors (recall that the MOE of wood perpendicular to grain is 2.5% to 5% of the MOE of wood parallel to the grain. These same issues need to be considered at upper level floors in platform style construction.

Again, note that for uplift forces coming through the walls, careful attention needs to be placed on the load path and ensuring that it is continuous. More on this later.

Typical Light-Frame Foundation: Post Tensioning



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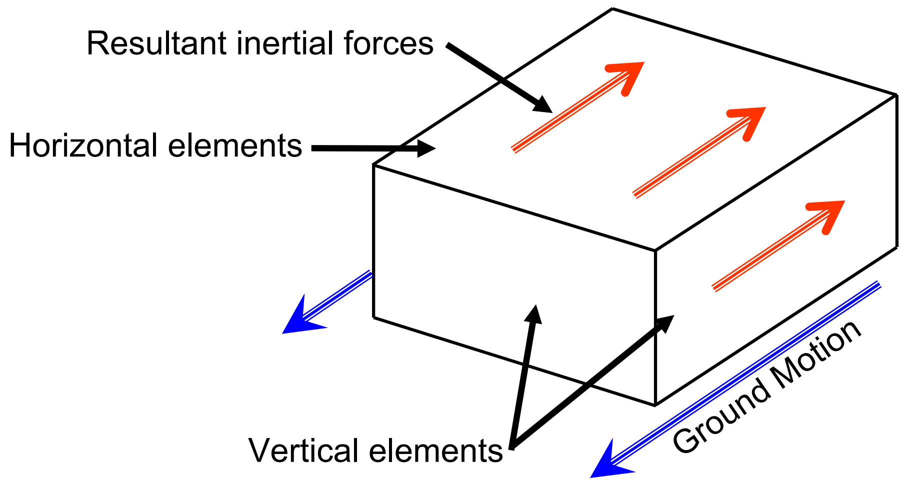
This type of footing common in areas with expansive soil. Slab thickness may be increased in areas of concentrated load from either gravity or overturning. Also may be increased as needed for embedment of anchors to resist uplift (from overturning usually).

Wood Structure Construction Methods: Lateral



- The basic approach to the lateral design of wood structures is the same as for other structures.

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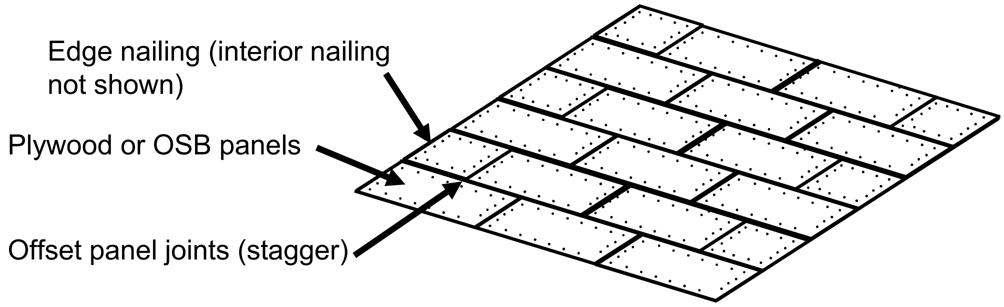
Slide emphasizes that basic design principles apply to wood structures. Horizontal and vertical elements of resistance need to be identified and designed. In the case of prescriptive or nonengineered light-frame structures, this is accomplished through required construction and detailing provisions of the building code.

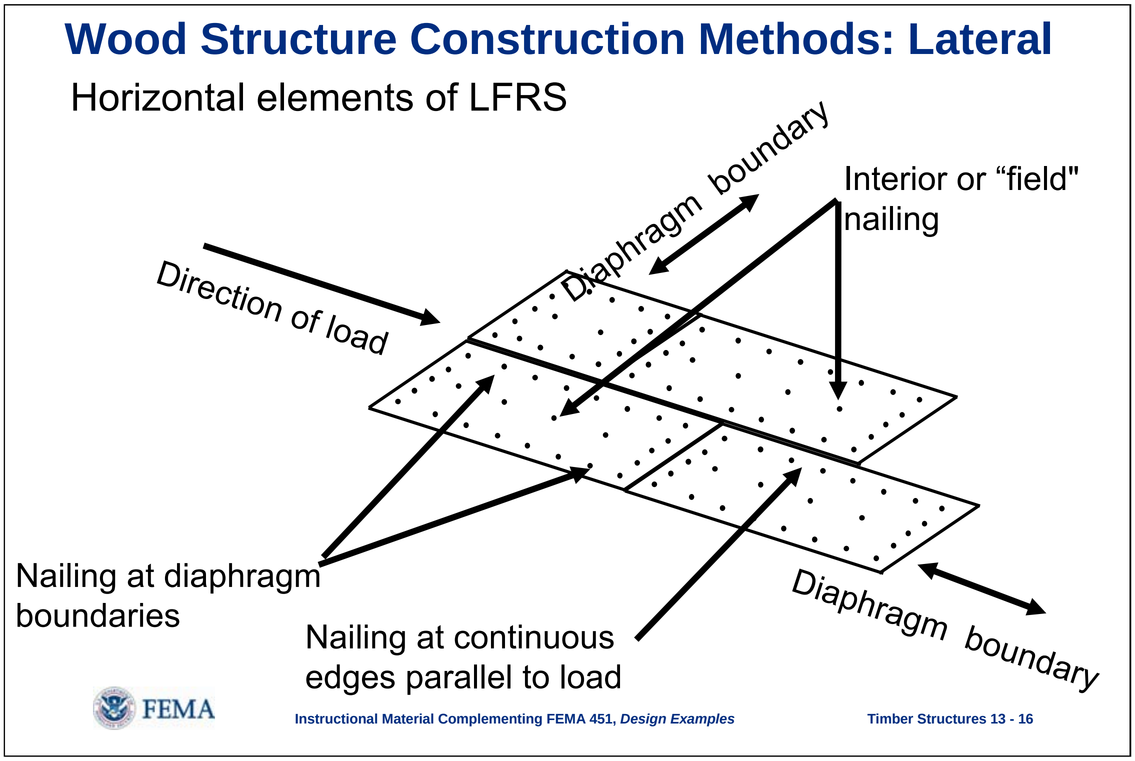
Wood Structure Construction Methods: Lateral

Horizontal elements of LFRS



- **Most structures rely on some form of nailed wood structural panels to act as diaphragms for the horizontal elements of the LFRS (plywood or oriented strand board – OSB).**
- **Capacity of diaphragm varies with sheathing grade and thickness, nail type and size, framing member size and species, geometric layout of the sheathing (stagger), direction of load relative to the stagger, and whether or not there is blocking behind every joint to ensure shear continuity across panel edges.**

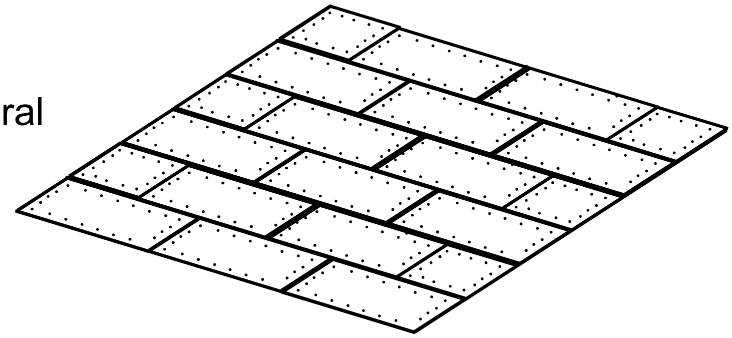
While other types of wood diaphragms are available (single our double diagonal boards, for instance) nailed wood structural is by far the most common.



Additional detail to show difference between nailing at diaphragm boundaries and nailing at continuous panel edges that are parallel to the direction of load.

Wood Structure Construction Methods: Lateral

Horizontal element: nailed wood structural panel diaphragm



- **The building code has tables of diaphragm design capacity (at either ASD or LRFD resistance levels) relative to all of the factors mentioned above.**

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The previous slide mentions a dizzying array of variables that impact design capacity. Here we see that it's not really that bad since someone's figured it all out and tabularized it in the code. Also mention that while inelastic action in the diaphragm may be present, it is not expected, and some construction techniques will minimize the opportunity for inelastic response anyway (more on this later).

Wood Structure Construction Methods: Lateral

Vertical element: nailed wood structural panel diaphragm

- **Shear capacities for vertical plywood/OSB diaphragms are also given in the codes, with similar variables impacting their strength.**
- **Heavy timber braced frames (1997 UBC) and singly or doubly diagonal sheathed walls are also allowed, but rare.**

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Most vertical elements in wood structures really are vertical diaphragms. Vertical trusses, in the form of heavy timber braced frames as shown on the slide of post and beam construction, are also allowed by code. However, heavy timber braced frames are as common as heavy timber structures. Note the holdowns in the wall corners providing overturning restraint. Results of the testing in the right hand picture show nail pull through as the failure mode.

Note that prescriptive construction will rely heavily on the strength of gypsum wallboard and exterior finishes, such as stucco, to provide strength to the overall system for seismic resistance, and this is not explicitly addressed by the prescriptive provisions. Rather, it is provided by default if following the requirements.

Wood Structure LFRS Design Methods: Engineered

- If a structures does not meet the code requirements for "prescriptive" or "conventional" construction, it must be "engineered."
- As in other engineered structures, wood structures are only limited by the application of good design practices applied through principles of mechanics (and story height limitations in the code).
- A dedicated system of horizontal and vertical elements, along with complete connectivity, must be designed and detailed.

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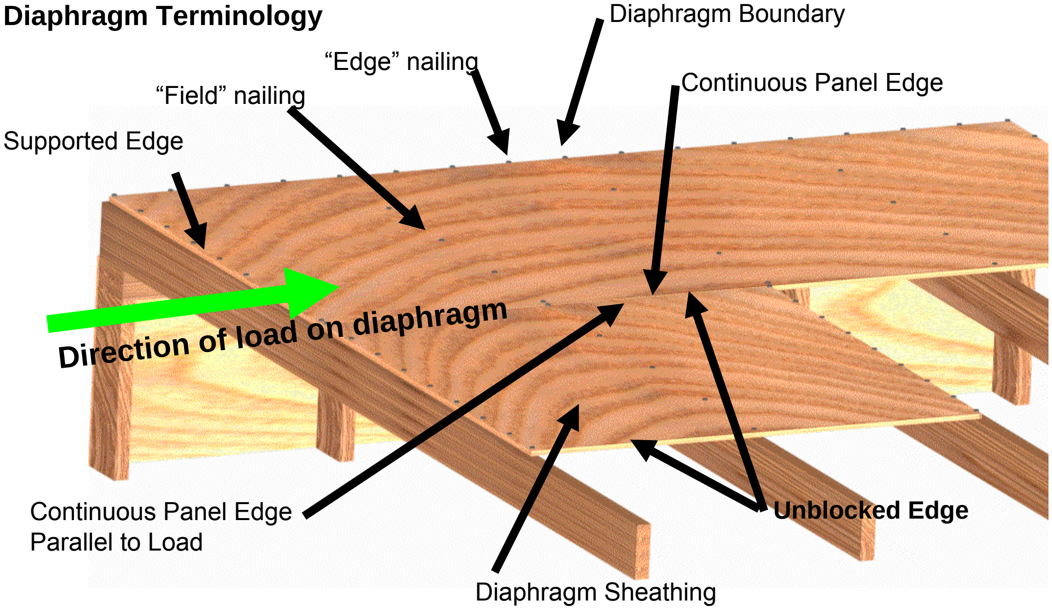
Emphasize the importance of engineering in "engineered" wood structures, developing the "complete load path". The structural load path for lateral forces is complex in wood structures. A system of diaphragms and shear walls, connected through drag struts and shear transfer details, is designed. However, the "nonstructural" sheathing on the inside and outside of the structure significantly contributes to the performance during an earthquake. While largely ignored, this extra contribution is thought to be inherent in the code *R* factors used for design.

Wood Structure LFRS Design Methods: Engineered

Diaphragm Terminology



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Note that a diaphragm boundary exists because of connectivity to a line of shear resistance containing vertical elements of the lateral force resisting system. Blocking is not shown at panel edges (somewhat self explanatory) so be sure to note that.

Wood Structure LFRS Design Methods: Engineered

Diaphragm Design Tables

- Tables are for DFL or SYP – need to adjust values if framing with wood species with lower specific gravities.
- Partial reprint of engineered wood structural panel diaphragm info in 2003 IBC Table 2306.3.1.
- Major divisions: Structural 1 vs. Rated Sheathing and Blocked vs. Unblocked panel edges.

RECOMMENDED SHEAR (POUNDS PER FOOT) FOR HORIZONTAL APA PANEL DIAPHRAGMS WITH FRAMING OF DOUGLAS-FIR, LARCH OR SOUTHERN PINE[a] FOR WIND OR SEISMIC LOADING

Panel Grade	Common Nail Size	Minimum Nail Penetration in Framing (inches)	Minimum Nominal Panel Thickness (inch)	Minimum Nominal Width of Framing Member (inches)	Blocked Diaphragms: Nail Spacing (in.) at diaphragm boundaries (all cases), at continuous panel edges parallel to load (Cases 3 & 4), and at all panel edges (Cases 5 & 6)[b] 6 / Nail Spacing (in.) at other panel edges (Cases 1, 2, 3 & 4) 6	4 / 6	2-1/2[c] / 4	2[c] / 3	Unblocked Diaphragms: Nails Spaced 6" max. at Supported Edges[b] Case 1 (No unblocked edges or continuous joints parallel to load)	All other configurations (Cases 2, 3, 4, 5 & 6)
APA STRUCTURAL I grades	6d[e]	1-1/4	5/16	2	185	250	375	420	165	125
				3	210	280	420	475	185	140
	8d	1-1/2	3/8	2	270	360	530	600	240	180
				3	300	400	600	675	265	200
	10d[d]	1-5/8	15/32	2	320	425	640	730	285	215
				3	360	480	720	820	320	240
APA RATED SHEATHING, APA RATED STURD-I-FLOOR	6d[e]	1-1/4	5/16	2	170	225	335	380	150	110
				3	190	250	380	430	170	125
			3/8	2	185	250	375	420	165	125
				3	210	280	420	475	185	140
			3/8	2	240	320	400	545	215	160
				3	270	360	540	610	240	180
	[illegible]	[illegible]	[illegible]	2	255	340	505	575	230	170

(a) For framing of other species: (1) Find specific gravity for species of lumber in AFPA National Design Specification. (2) Find shear value from table above for nail s[illegible] for Structural I panels (regardless of a[illegible]ual grade). (3) Multiply value by [illegible] for species with specific gravity of [illegible] or greater, or 0.65 for all other sp[illegible]cies..

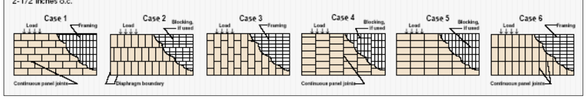
(b) Space nails maximum 12 in. o.c. along intermediate framing members (6 in. o.c. when supports are spaced 48 in. o.c.).

(c) Framing at adjoining panel edges shall be 3-in. nominal or wider, and nails shall be staggered where nails are spaced 2 inches o.c. or 2-1/2 inches o.c.

(d) Framing at adjoining panel edges shall be 3-in. nominal or wider, and nails shall be staggered where 10d nails having penetration into framing of more than 1-5/8 [illegible] are spaced 3 inches o.c.

(e) 8d is recomme[illegible]d minimum for roofs due to negat[illegible] pressures of high winds.

Notes: Design for diaphragm stresses depends on direction of continuous panel joints with reference to load, not on direction of long dimension of sheet. Continuous framing may be in either direction for blocked diaphragms.



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The numbers are small, but that's the nature of a table like this.

Via an example, show the selection of a proper sheathing-framing-blocking-nailing solution given a particular shear demand from the diaphragm. Be sure to have two examples, one for blocked and another for unblocked. Emphasize that for most residential it is preferred to keep to an unblocked solution even if that means adding lines of shear resistance to the structure to reduce demands on the diaphragm. Emphasize the reductions (footnotes) for non DFL or SYP lumber, and be sure to note that when using metal plate connected wood trusses the species of top chord lumber needs to be confirmed.

Wood Structure LFRS Design Methods: Engineered

Shear Wall Design Tables

- Partial reprint of engineered wood structural panel diaphragm info in 2003 IBC Table 2306.4.1.
- Tables are for DFL or SYP – need to adjust values if framing with wood species with lower specific gravities.
- Major divisions: Structural 1 vs. Rated Sheathing and Panels Applied Directly to Framing vs. Panels Applied Over Gypsum Wallboard.
- NO UNBLOCKED edges allowed.

RECOMMENDED SHEAR (POUNDS PER FOOT) FOR APA PANEL SHEAR WALLS WITH FRAMING OF DOUGLAS-FIR, LARCH, OR SOUTHERN PINE[a] FOR WIND OR SEISMIC LOADING[b]

Panel Grade	Minimum Nominal Panel Thickness (in.)	Minimum Nail Penetration in Framing (in.)	Panels Applied Direct to Framing: Nail Size (common or galvanized box)	Nail Spacing at Panel Edges (in.): 6	4	3	2[e]	Panels Applied Over 1/2" or 5/8" Gypsum Sheathing: Nail Size (common or galvanized box)	Nail Spacing at Panel Edges (in.): 6	4	3	2[e]
APA STRUCTURAL I grades	5/16	1-1/4	6d	200	300	390	510	8d	200	300	390	510
	3/8	1-1/2	8d	230[d]	360[d]	460[d]	610[d]	10d[f]	280	430	550	730
	7/16			255[d]	395[d]	505[d]	670[d]					
	15/32			280	430	550	730					
	15/32	1-5/8	10d[f]	340	510	665	870	—	—	—	—	—
APA RATED SHEATHING; APA RATED SIDING[g] and other APA grades except species Group 5	5/16 or 1/4[c]	1-1/4	6d	180	270	350	450	8d	180	270	350	450
	3/8			200	300	390	510		200	300	390	510
	3/8	1-1/2	8d	220[d]	320[d]	410[d]	530[d]	10d[f]	260	380	490	640
	7/16			240[d]	350[d]	450[d]	585[d]					
	15/32			260	380	490	640					
	15/32	1-5/8	10d[f]	310	460	600	770	—	—	—	—	—
	19/32			340	510	665	870	—	—	—	—	—
APA RATED SIDING 303[g] and other APA grades except species Group 5			Nail Size (galvanized casing)					Nail Size (galvanized casing)				
	5/16[c]	1-1/4	6d	140	210	275	360	8d	140	210	275	360
	3/8	1-1/2	8d	160	240	310	410	10d[f]	160	240	310	410

(a) For framing of other species: (1) Find specific gravity for species of lumber in the AFPA National Design Specification. (2)(a) For common or galvanized box nails, find shear value from table above for nail size for STRUCTURAL I panels (regardless of actual grade). (b) For galvanized casing nails, take shear value directly from table above. (3) Multiply this value by 0.82 for species with specific gravity of 0.42 or greater, or 0.65 for all other species.

(b) All panel edges backed with 2-inch nominal or wider framing. Install panels either horizontally or vertically. Space nails maximum 6 inches o.c. along intermediate framing members for 3/8-inch and 7/16-inch panels installed on studs spaced 24 inches o.c. For other conditions and panel thicknesses, space nails maximum 12 inches o.c. on intermediate supports.

(c) 3/8-inch or APA RATED SIDING 16 oc is minimum recommended when applied direct to framing as exterior siding.

(d) Shears may be increased to values shown for 15/32-inch sheathing with same nailing provided (1) studs are spaced a maximum of 16 inches o.c., or (2) if panels are applied with long dimension across studs.

(e) Framing at adjoining panel edges shall be 3-inch nominal or wider, and nails shall be staggered where nails are spaced 2 inches o.c.

(f) Framing at adjoining panel edges shall be 3-inch nominal or wider, and nails shall be staggered where 10d nails having penetration into framing of more than 1-5/8 inches are spaced 3 inches o.c.

(g) Values apply to all-veneer plywood APA RATED SIDING panels only. Other APA RATED SIDING panels may also qualify on a proprietary basis. APA RATED SIDING 16 oc plywood may be 11/32 inch, 3/8 inch or thicker. Thickness at point of nailing on panel edges governs shear values.

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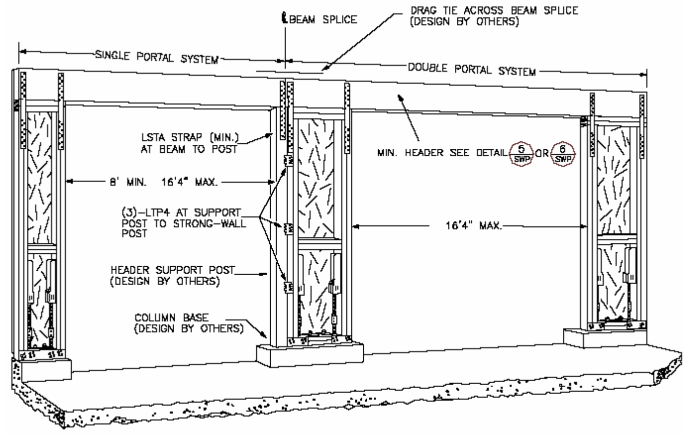
Again, small numbers, but it can't be helped. As for diaphragms, walk the class through a couple of specific solutions for specific shear demands. Again, emphasize the reductions (footnotes) for non DFL/SYP framing members. Point out that it is not uncommon to have pressure treated sill plate material of a softer species of lumber than the framing members, in which case the reductions are needed even if using DFL or SYP studs.

Wood Structure LFRS Design Methods: Engineered

Proprietary Moment Frames



SINGLE & DOUBLE PORTAL ASSEMBLY

- **Traditional vertical diaphragm shear walls less effective at high aspect ratios.**
- **Prefabricated proprietary code-approved solutions available.**

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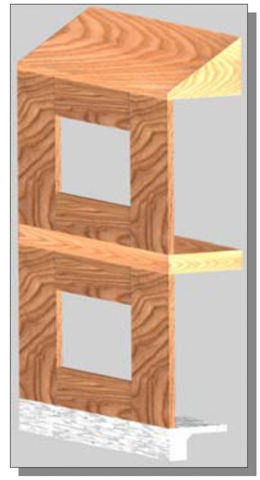
Timber Structures 13 - 23

The code places limits on maximum aspect rations for nailed wood structural panel diaphragms, with 3.5:1 being the maximum, along with reductions in the tabulated capacities when the AR exceeds 2:1. Some areas of typical light framed structures, such as garage returns, are problematic in using wood as a solution to the LFRS. Companies such as Simpson Strong-Tie have developed tested, code-approved solutions for these areas using advanced materials and construction techniques. One such system, shown above, employs a partially restrained moment connection between the wall and the header to enhance the performance of high AR panels.

Wood Structure LFRS Design Methods: Engineered

Complete Load Path

- Earthquakes move the foundations of a structure.
- If the structure doesn't keep up with the movements of the foundations, failure will occur.
- Keeping a structure on its foundations requires a complete load path from the foundation to all mass in a structure.
- Load path issues in wood structures can be complex.
- For practical engineering, the load path is somewhat simplified for a "good enough for design" philosophy.



FEMA

Instructional Material Complementing FEMA 451, *Design Examples*

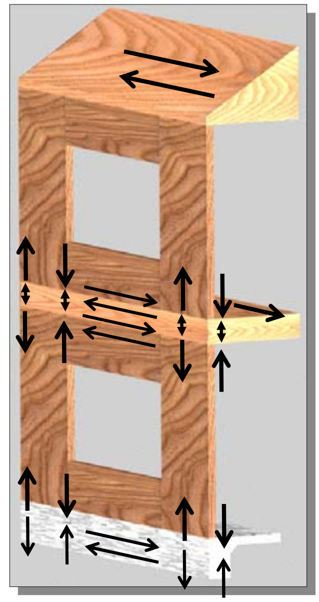
Timber Structures 13 - 24

Self explanatory.

Wood Structure LFRS Design Methods: Engineered

Complete Load Path

- Diaphragm to shear wall
- Shear wall overturning
- Diaphragm to shear wall
- Overturning tension/compression through floor
- Shear transfer through floor
- Overturning tension/compression to foundation
- Shear transfer to foundation



FEMA

Instructional Material Complementing FEMA 451, *Design Examples*

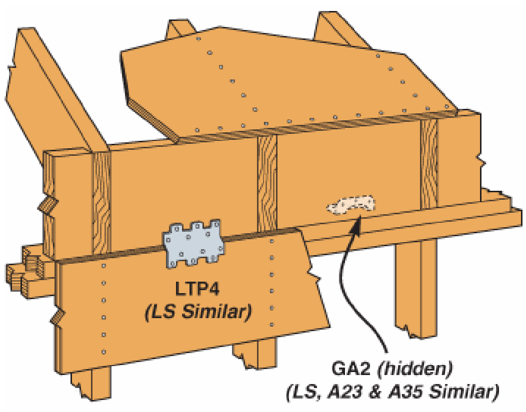
Timber Structures 13 - 25

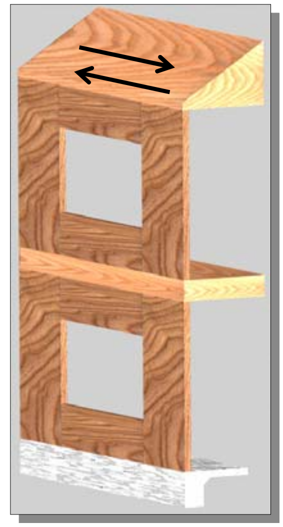
Self explanatory.

Wood Structure LFRS Design Methods: Engineered

Complete Load Path

- Diaphragm to shear wall





Toe nails: 2003 IBC 2305.1.4 150 plf limit in SDCs D-F.

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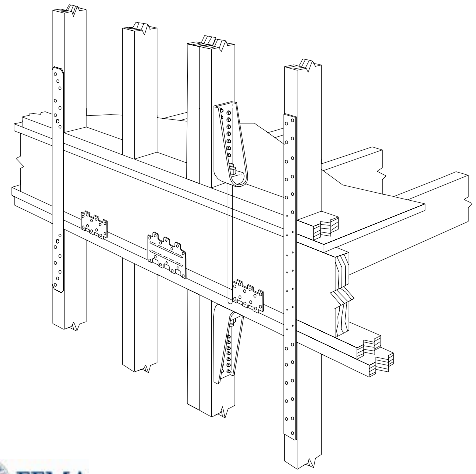
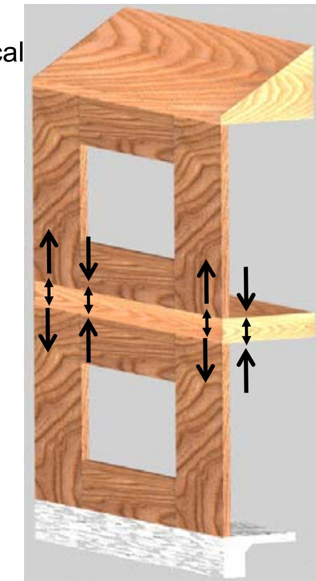
Point out roof diaphragm sheathing, framing members, and especially the blocking between the framing members which serves to transfer shear from the roof diaphragm to the wall double top plates. The wall double top plates serve as the primary collector element for moving lateral forces collected from the diaphragms to the shear walls wherever they may be. Note that toe nails can be used to connect the blocks to the double top plates, but when the collected shear exceeds 150 plf in SDC D-F, they are not allowed because of brittle behavior and metal connectors must be used (IBC 2305.1.4). Additionally, the blocks that transfer shear through the framing members also act like mini-shear walls. As such, they may develop their own overturning problems if they become too tall, such as with taller framing or at the interior of a trussed roof system where the designer is trying to use a shear wall below the trusses. In these cases, the shear blocks will need to be fastened to adjacent vertical framing elements to resist the overturning. Adjacent blocks create opposing vertical forces, but the beginning of the first block in the line, and the end of the last block will need some sort of positive overturning resistance, such as straps or tie-down devices. Note that the LTP4 shown above is bent over the sheathing per manufacturer's recommendations.

Wood Structure LFRS Design Methods: Engineered

Complete Load Path

- Shear wall overturning / transfer of vertical forces through floor





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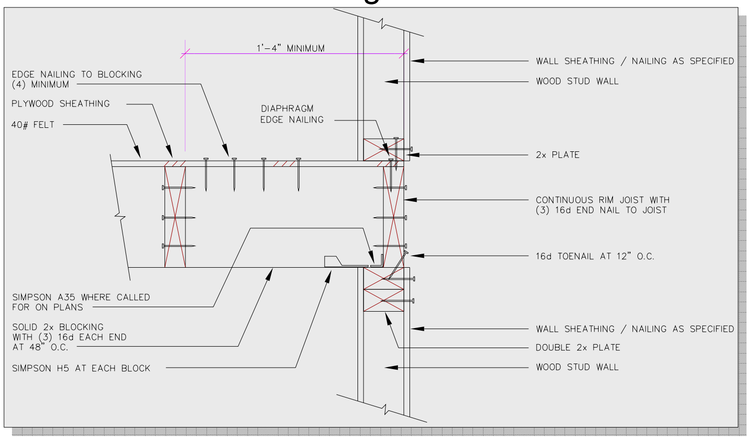
Timber Structures 13 - 27

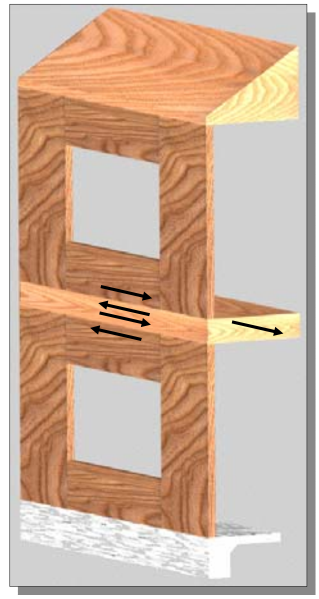
Consider the need to support the shear wall chords for overturning compression via full bearing blocking between the floor sheathing and the double top plates below, particularly on highly loaded shear walls. A point could also be made here about perforated shear wall design, both for the approach in which shear transfer around the openings explicitly engineered, and the approach where this is not addressed (and the perforated shear wall reduction tables are used).

Wood Structure LFRS Design Methods: Engineered

Complete Load Path

- Diaphragm to shear wall / shear transfer through floor





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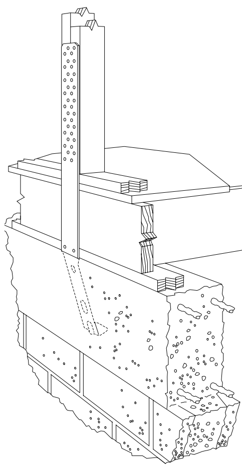
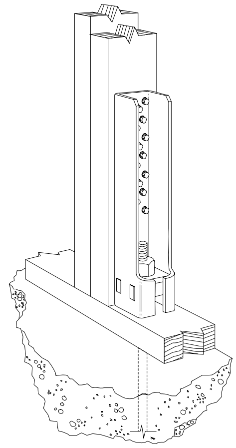
Load paths for shear through a platform can be complex. Shear must be transferred from the wall structural sheathing above, through its edge nailing to the single 2x sill plate, through nailing of the sill plate through the floor sheathing and into the rim joist below, out of the rim joist, and into the dbl top plate of the wall below, where it enters the wall structural sheathing through the edge nailing of the sheathing to the double top plate. Additionally, diaphragm shear must be removed form the diaphragm through the diaphragm edge nailing and into the rim joist, where it adds to the wall shear from above and then follows the same load path. Note that in this case we are showing the joists as continuous parallel to the wall. To provide for out of plane support for the wall, blocking between joists is called out, with a nailed connection to the diaphragm, and a metal connector to handle transfer of wall suction forces into the blocking and thus into the diaphragm.

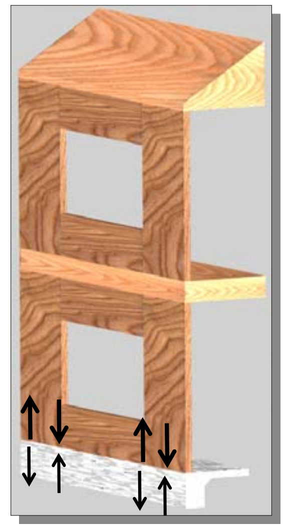
Wood Structure LFRS Design Methods: Engineered

Complete Load Path

- Overturning tension/compression to foundation





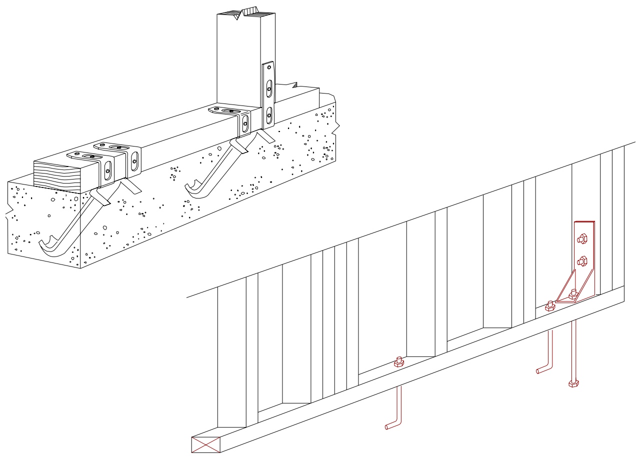


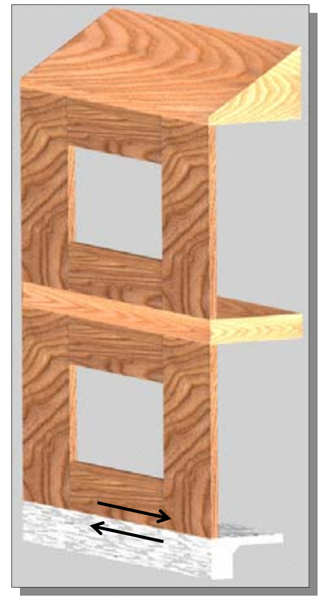
Two fundamental types of uplift restraint at the foundation: embedded straps and holdowns that connect to either a cast-in-place or post-installed anchor. Note that in addition to out-of plane post buckling on the compression side of a shear wall, due to gravity plus overturning loads, the interface between the chord bottom and the top of the sill plate must satisfy perpendicular-to-grain stress limitations (no load duration increase allowed!).

Wood Structure LFRS Design Methods: Engineered

Complete Load Path

- Shear transfer to foundation





Instructional Material Complementing FEMA 451, *Design Examples*

Timber Structures 13 - 30

The usual connection for transferring shear from the sill plate to the foundations is either ½" to 5/8" anchor bolts cast in place or post installed, or with cast in place prefabricated metal connectors.

Wood Structure LFRS Design Methods: Prescriptive

- Also referred to as "*Conventional Construction*" or "*Deemed to Comply*"

- Traditionally, many simple wood structures have been designed without "engineering."
- Over time, rules of how to build have been developed, most recently in the 2003 International Residential Code (IRC).
- For the lateral system, the "dedicated" vertical element is referred to as a ***braced wall panel***, which is part of a ***braced wall line.***
- Based on SDC and number of stories, rules dictate the permissible spacing between braced wall lines, and the spacing of braced wall panels within braced wall lines.

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Self explanatory.

Wood Structure LFRS Design Methods: Prescriptive

- While rules exist for the "dedicated" elements, testing and subsequent analysis has show these structures do not "calc out" based on just the strength of braced wall panels.
- In reality, the strength, stiffness, and energy dissipation afforded by the "nonstructural" elements (interior and exterior sheathing) equal or exceed the braced wall panels in their contribution to achieving "life safety" performance in these structures.
- Load path not explicitly detailed.

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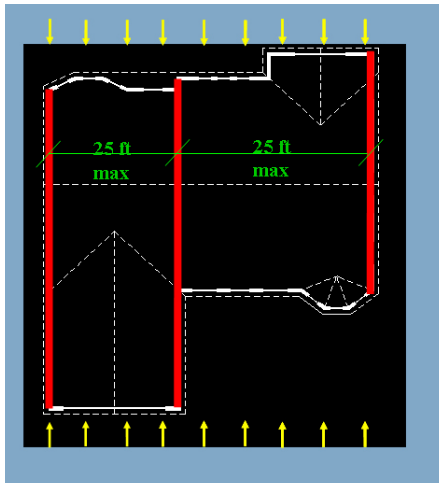
Self explanatory.

Wood Structure LFRS Design Methods: Prescriptive

(Seismic Design Category D1 or D2 and/or Wind Speeds < 110 mph)



- **Example 2003 IRC Spacing Requirements for *Braced Wall Lines***

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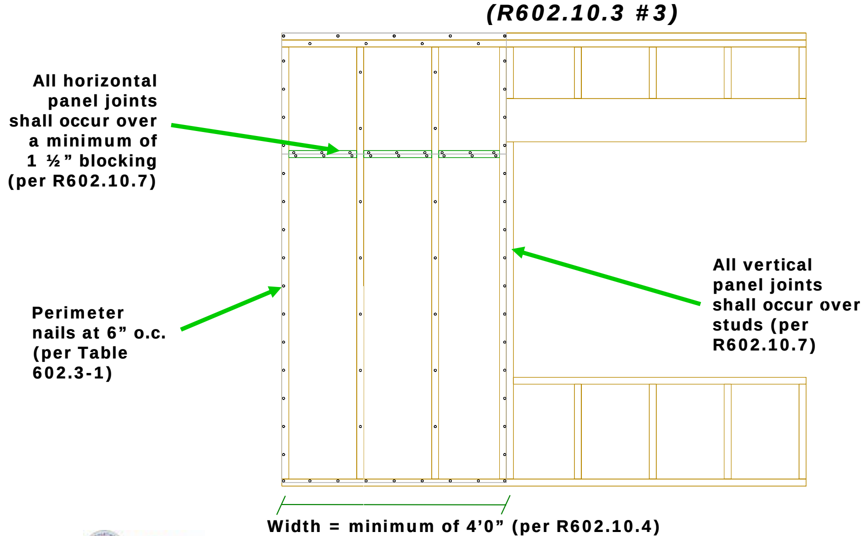
Timber Structures 13 - 33

Note how the spacing requirements would hold for the other direction too.

Wood Structure LFRS Design Methods: Prescriptive

- **Example of *Braced Wall Panel* construction (2003 IRC references)**



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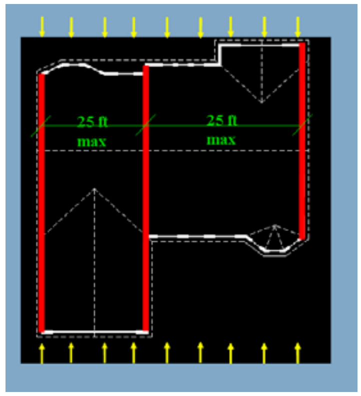
Timber Structures 13 - 34

Note that his is one of 10+ methods of constructing braced wall panels. Others include 8' gyp or stucco walls, narrower walls with holdowns, and quasi-moment frames that rely on fully sheathing the structure above and below all openings. The "technical" jury is still out on this latter method even though it has made it into the IRC.

Wood Structure LFRS Design Methods: Prescriptive



- Prescriptive provisions in the 2003 IRC are more liberal than in the 2003 NEHRP *Provisions.*
- The NEHRP Provisions and Commentary can be downloaded from http://www.bssconline.org/. Also available from FEMA and at the BSSC website is FEMA 232, an up to date version of the *Homebuilders' Guide to Earthquake-Resistant Design and Construction*.

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Self explanatory.

Expected Response Under Lateral Load: Wind

- **Unlike seismic *design* loads, wind *design* loads are representative of the real expected magnitude.**
- **When built properly, structural damage should be low.**
- **Missile or wind born projectile damage can increase damage (this could potentially breach openings and create internal pressures not part of the design).**

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Failure due do lack of load path. Nice installation of "hurricane ties“ – the metal connectors connecting the rafters to the wall dbl top plate. However, note the lack of nail holes in the top of the rafter, which indicates that the sheathing nailing was deficient.

Source of photo: Simpson Strong-Tie hurricane Katrina reconnaissance.

Expected Response Under Lateral Load: Seismic

5.3 Daly City, CA March 22, 1957

7.0 Imperial Valley, CA Oct 15, 1957

- **Engineered wood structures are thought of as having good flexibility/ductility, but can also be quite brittle.**
- **Wood structures can be engineered with either "ductile" nailed wood structural panel shear walls or "brittle" gypsum board and/or stucco shear walls as their primary LFRS.**
- **2003 IBC *R* factors: Wood – 6.5; All Others – 2.0.**

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Timber Structures 13 - 37

Source of photo: Karl V. Steinbrugge Collection, Earthquake Engineering Research Center from http://nisee.berkeley.edu/visual_resources/steinbrugge_collection.html

Picture with cripple wall damage is from the 7.0 Imperial Valley, California earthquake Oct 15, 1979.

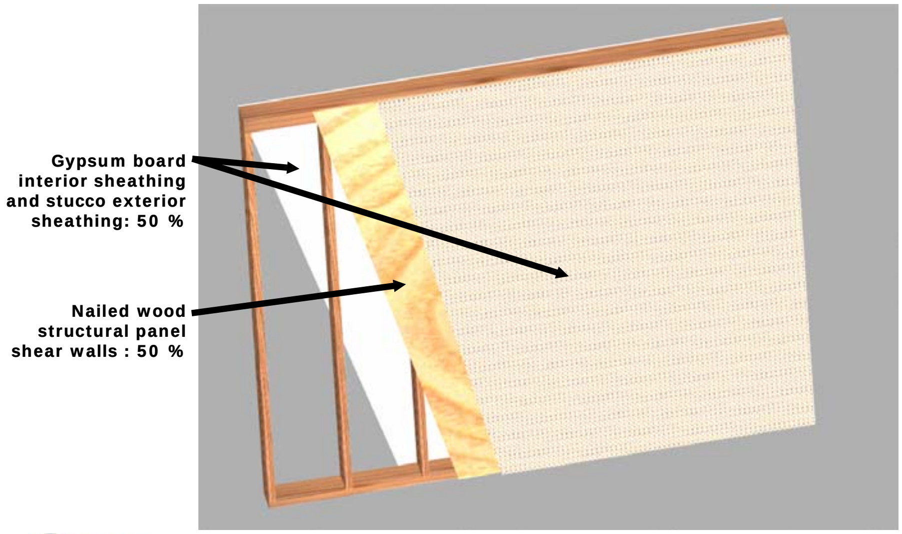
Picture with cracked first floor stucco is from the magnitude 5.3 Daly City, California Mar 22, 1957.

Discuss the difference in displacement capacity for gyp/stucco: ~1% interstory drift at peak capacity, whereas for nailed wood structural panel it is ~ 2 – 4 %.

Picture on left shows "expected" response of light frame structure. Picture on right shows collapse of weak cripple wall, a common occurrence in earthquakes.

Sources of Strength for Seismic Lateral Resistance

- **<u>Rough</u> estimates for *engineered single family home***



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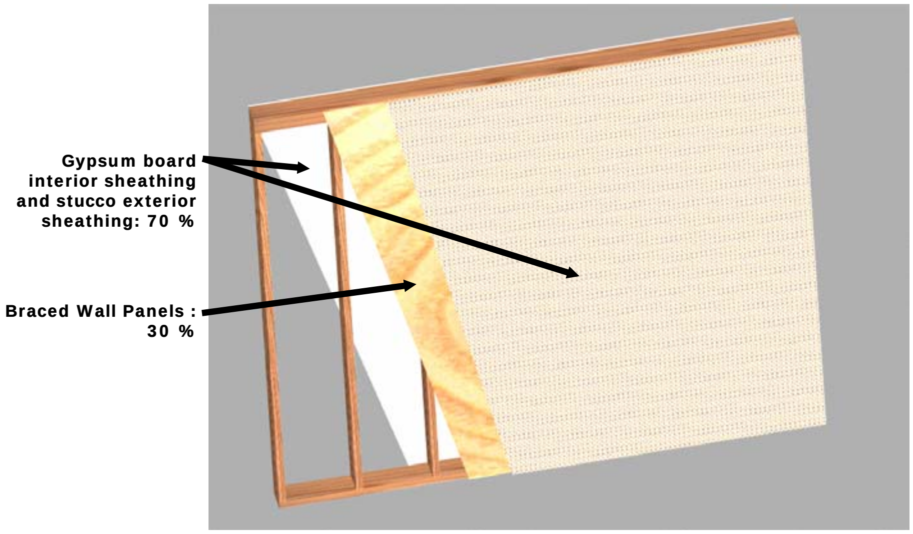
The purpose of the next few slides is to convey that typical ENGINEERED single family homes have a large part of their strength tied up in elements that the designer doesn't consider and that is why the *R* factor is so high (6.5)

Prescriptive homes rely even more on the nonstructural elements.

Note that non-stucco exterior sheathing, such as lap siding, would increase the reliance on the primary LFRS.

Sources of Strength for Seismic Lateral Resistance

- **<u>Rough</u> estimates for *prescriptive single family home***



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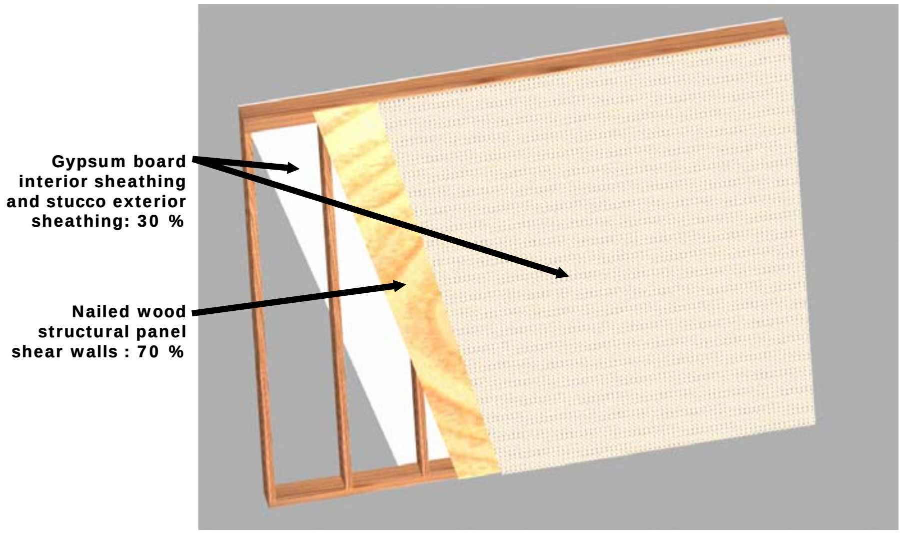
Timber Structures 13 - 39

Note that non-stucco exterior sheathing, such as lap siding, would increase the reliance on the primary LFRS.

Discuss the relative strength distribution.

Sources of Strength for Seismic Lateral Resistance

- **<u>Rough</u> estimates for *engineered light commercial* structures**



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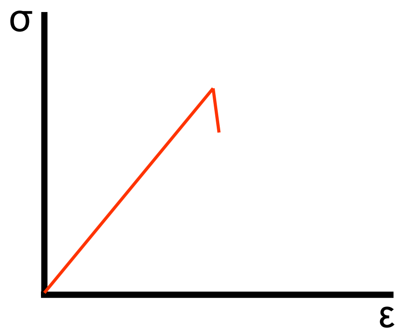
Commercial wood structures, such as dentists buildings and such, are often just a four sided shell with interior walls that are not structurally attached to the roof diaphragm and with ceilings that lack diaphragm capacity. In these kinds of structures, there is much more reliance on the exterior dedicated vertical elements of the LFRS. One could argue that with less redundancy in these structures, the *R* factor may warrant lowering. However, they are also the most likely to be well designed and constructed with more attention usually paid to the lateral load path.

Sources of Ductility and Energy Dissipation in Wood Structures

Stress in the wood

- **Tension parallel to the grain: not ductile, low energy dissipation**

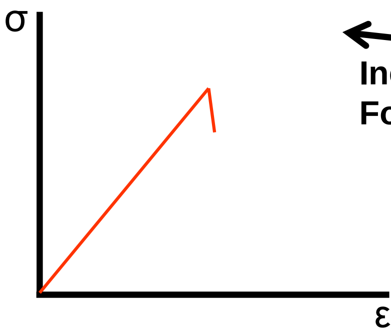


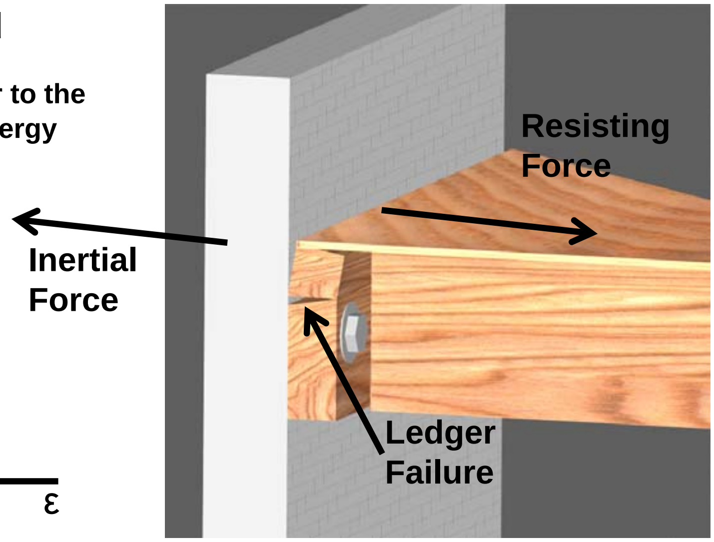
Self explanatory.

Sources of Ductility and Energy Dissipation in Wood Structures

Stress in the wood

- **Tension perpendicular to the grain: not ductile, low energy dissipation**





- **Need to have positive wall ties to perpendicular framing**

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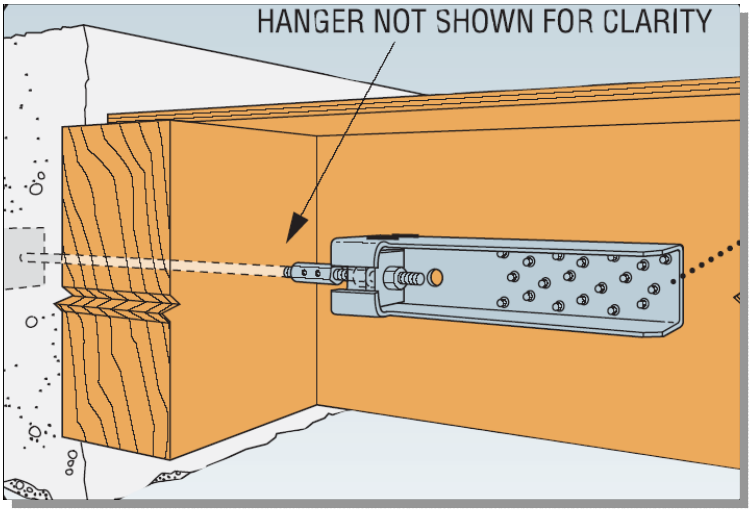
Comment on how inertial force of wall will pull away from roof. Also note that if there are no ties between the framing members perpendicular to the wall and the wall, the sheathing attachment to the ledger will fail the ledger in cross grain bending/tension, causing collapse of the roof and wall.

Sources of Ductility and Energy Dissipation in Wood Structures

Positive Wall Tie



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Timber Structures 13 - 43

Self explanatory.

Sources of Ductility and Energy Dissipation in Wood Structures

Stress in the wood

- **Compression perpendicular to the grain: ductile, but not recoverable during and event – one way crushing similar to tension only braced frame behavior – ductile, but low energy dissipation**
- **Design allowable stress should produce ~0.04" permanent crushing**

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For single excursions, wood perpendicular to grain nonlinear behavior can be a good one-time energy dissipater. However, for cyclic loading, such as seismic, it becomes a poor energy dissipater because the wood won't recover from the crushing, leading to slack behavior in the system connected to it.

Sources of Ductility and Energy Dissipation in Wood Structures

Stress in the fastener

- **Nailed joint between sheathing and framing is source of majority of ductility and energy dissipation for nailed wood structural panel shear walls.**
- **The energy dissipation is a combination of yielding in the shank of the nail, and crushing in the wood fibers surrounding the nail.**
- **Since wood crushing is nonrecoverable, this leads to a partial "pinching" effect in the hysteretic behavior of the joint.**
- **The pinching isn't 100% because of the strength of the nail shank undergoing reversed ductile bending yielding in the wood.**
- **As the joint cycles, joint resistance climbs above the pinching threshold when the nail "bottoms out" against the end of the previously crushed slot forming in the wood post.**

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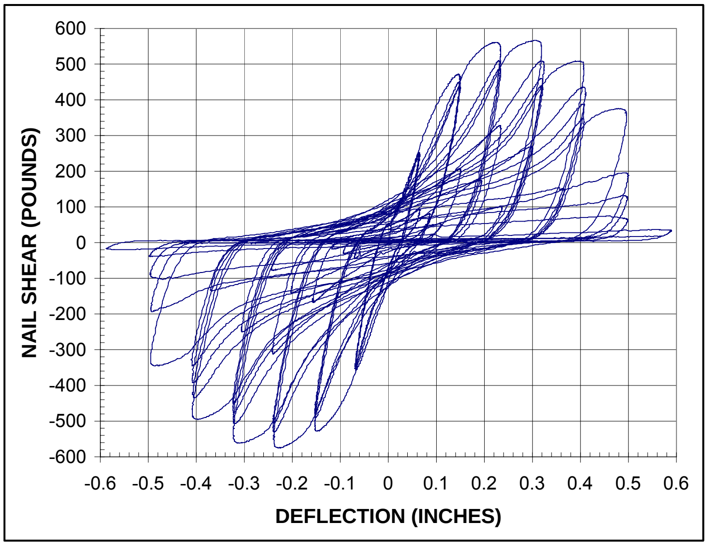
Self explanatory.

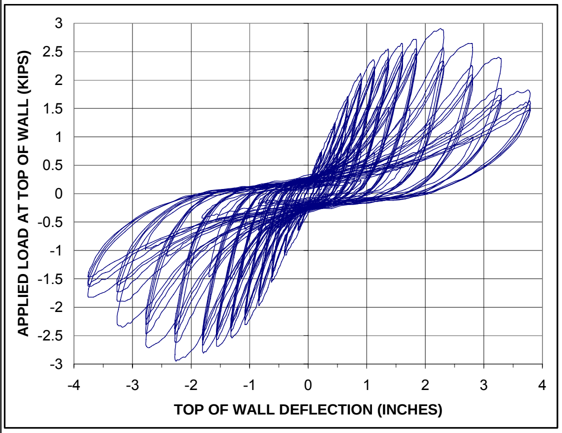
Sources of Ductility and Energy Dissipation in Wood Structures



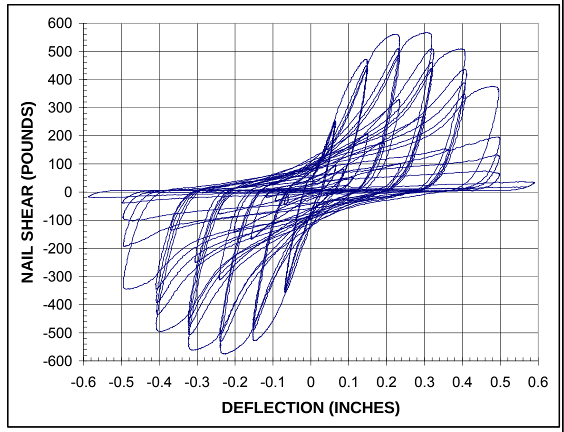
Individual nail test

Comment on how permanent crushing of wood around shank of nail leads to pinched nature of nail hysteresis.

Sources of Ductility and Energy Dissipation in Wood Structures



Full-scale shear wall test



Individual nail test

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Note similarities between single nail hysteresis and global shear wall hysteresis. Comment on how shear wall behavior, globally, is a product of local fastener hysteresis.

Vertical Elements of the LFRS: Prescriptive

NEHRP Section 12.4

- **Numerous geometry limitations**
- **Two types of braced wall panel construction: gypsum wall board and wood structural panel**

IRC 2003 Methods

- **Numerous geometry limitations**
- **Numerous types of braced wall panel construction: NEHRP methods + ~10 more**

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Self explanatory.

Vertical Elements of the LFRS: Engineered

NEHRP Methods

- **Nailed/stapled wood structural panel**
- **Cold-formed steel with flat strap tension-only bracing**
- **Cold-formed steel with wood structural panel screwed to framing**

IBC 2003 Methods

- **Nailed wood structural panel shear walls**
- **Sheet steel shear walls**
- **Ordinary steel braced frames**
- **All others: gypsum and stucco**
- **Proprietary shear walls**

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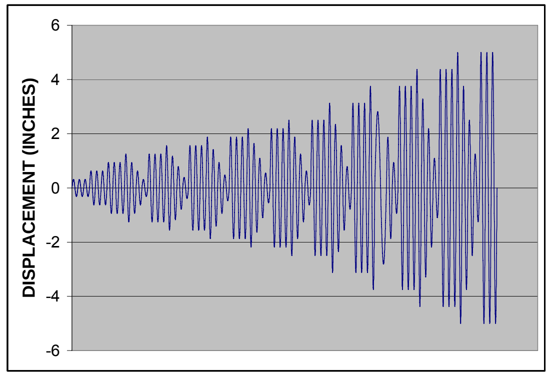
Self explanatory.

Wall Performance Based on Testing

- First cyclic protocol to be adopted in the US for cyclic testing of wood shear walls.
- 62 *post yield* cycles.
- Found to demand too much energy dissipation compared with actual seismic demand.
- Can result in significant underestimation of peak capacity and displacement at peak capacity.



Cyclic Test Protocols
TCCMAR (SPD)

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Timber Structures 13 - 50

TCCMAR = Joint Technical Coordinating Committee on Masonry Construction. SPD = Sequential Phased Displacement.

Wall Performance Based on Testing

- Developed by researchers at Stanford University as part of the CUREE/Caltech Woodframe Project

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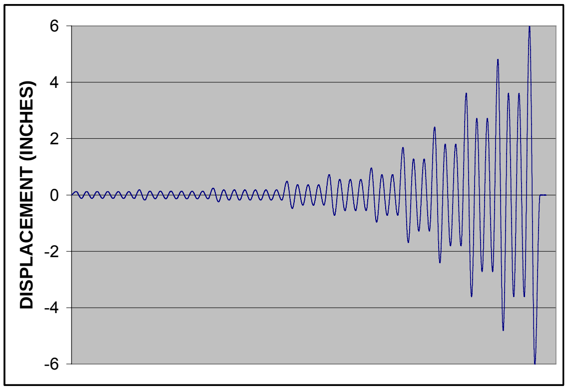
- Based on nonlinear time history analysis of wood structures considering small "non-design" vents preceding the "design event."
- Currently the "state-of-the-art" in cyclic test protocols.
- More realistically considers actual energy and displacement demands from earthquakes.



Cyclic Test Protocols -- CUREE

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Timber Structures 13 - 51

CUREE = Consortium of Universities for Research in Earthquake Engineering.

Code Basis of Design Values

Nailed Wood Structural Panel Shear Walls

- Values currently in the code were developed by the APA – The Engineered Wood Association (used to be the American Plywood Association) in the 1950s.
- These values are based on a principles of mechanics approach.
- Some monotonic testing was run to validate procedure.
- Testing was conducted on 8'x8' walls (1:1 aspect ratio), with very rigid overturning restraint.
- Test was more of a sheathing test, not shear wall system test.
- Extrapolation of use down to 4:1 aspect ratio panels proved problematic on 1994 Northridge earthquake.
- Code now contains provisions to reduce the design strength of walls with aspect ratios (AR's) > 2:1 by multiplying the base strength by a factor of 2 / AR.

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Self explanatory.

Code Basis of Design Values

Proprietary Wood Structural Panel Shear Walls:

- Proprietary shear wall systems for light frame construction have been developed to provide higher useable strength when the AR exceeds 2:1.
- Values are determined according to Acceptance Criteria 130 (AC130) developed by the International Code Council Evaluation Services (ICC ES).
- AC130 requires full-scale cyclic testing of the wall seeking approval based on either SPD or CUREE protocols.
- Design rating based on either strength (ultimate / safety factor) or displacement (deflection which satisfies code deflection limits based on C_d, the deflection amplification factor associated with the rated R factor, and the appropriate maximum allowed inelastic drift ratio).

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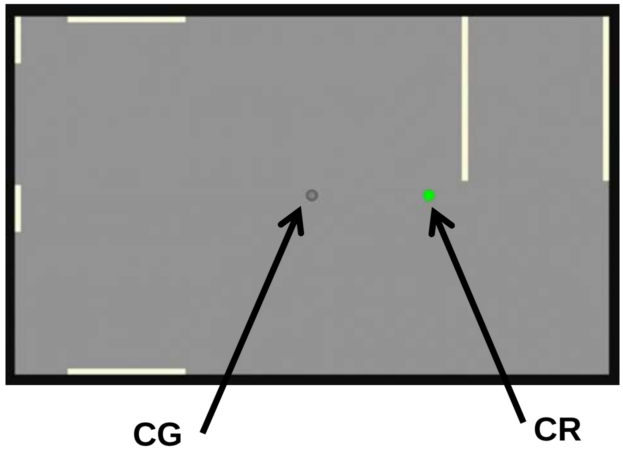
Self explanatory.

Typical Woodframe Analysis Methods

- **Flexible diaphragm analysis**
- **Rigid diaphragm analysis**



- **Worry about it??**

Most residential light frame design is performed using the flexible diaphragm method. Some jurisdictions require rigid diaphragm analysis as well. These will be discussed in more detail on the following slides.

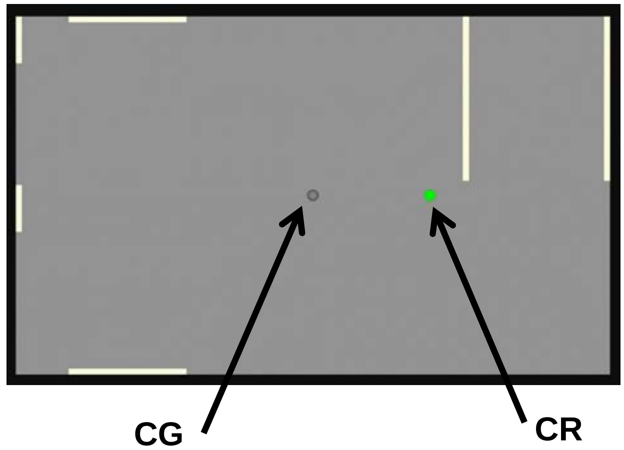
CG = center of gravity

CR = center of rigidity

Typical Woodframe Analysis Methods

Flexible Diaphragm Analysis

- Lateral loads distributed as if diaphragm is a simple span beam between lines of lateral resistance.
- Diaphragm loads are distributed to lines of shear resistance based on tributary area between lines of shear resistance.



- **Worry about it??**
- **No**

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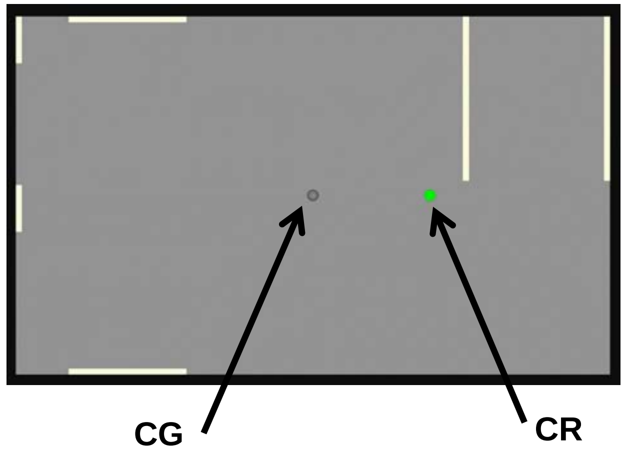
Self explanatory.

Typical Woodframe Analysis Methods

Rigid Diaphragm Analysis

- **Lateral loads distributed as if diaphragm is rigid, rotating around the CR.**
- **Force in shear walls is a combination of translational and rotational shear.**



- **Worry about it??**
- **Yes**

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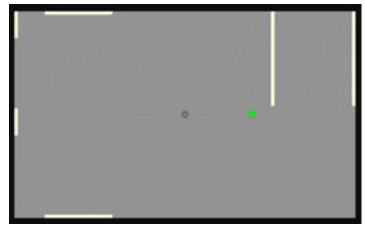
Note that with respect to length effects, wood structural panel shear walls have a stiffness that is LINEARLY proportional to their length. This differs from concrete and masonry shear walls. The reason for this is that the walls are assemblies of individual wood structural panels that rotate individually on a shear wall as it is loaded.

Typical Woodframe Analysis Methods

Comments on Analysis Methods



- Neither the rigid nor flexible diaphragm methods really represent the distribution of lateral resistance in a typical structure.
- Both methods (typically) ignore the stiffness distribution of interior and exterior wall finishes.

- Wood structural diaphragms are neither "flexible" or "rigid" – they are somewhere in between. "Glued and screwed" floor sheathing makes floors more rigid than flexible. The nailing of interior wall sill plates across sheathing joints has the same effect. Exterior walls can act as "flanges", further stiffening the diaphragm.
- However, encouraging rigid diaphragm analysis is also encouraging the design of structures with torsional response – may not be a good thing!

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Comment on how designers must have techniques that are "good enough" for design. While neither the flexible nor rigid methods are perfect, the flexible method, used more often by far than the rigid method, has a good track record in properly designed structures.

Rigid Diaphragms: When are they Rigid?

- **2003 *NEHRP Recommended Provisions* in Sec. 12.1.2.1 refers to the ASD/LRFD Supplement, *Special Design Provisions for Wind and Seismic*, American Forest and Paper Association, 2001:**

  "A diaphragm is rigid for the purposes of distribution of story shear and torsional moment when the computed maximum in-plane deflection of the diaphragm itself under lateral load is less than or equal to two times the average deflection of adjoining vertical elements of the lateral force-resisting system of the associated story under equivalent tributary lateral load." (Section 2.2, Terminology)

- **Same definition in 2003 IBC Sec. 1602.**

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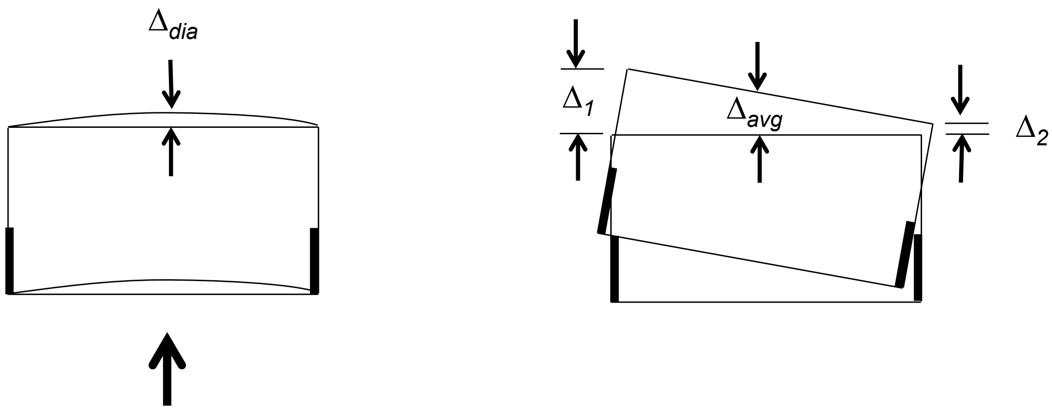
Self explanatory.

Rigid Diaphragms: When Are They Rigid?

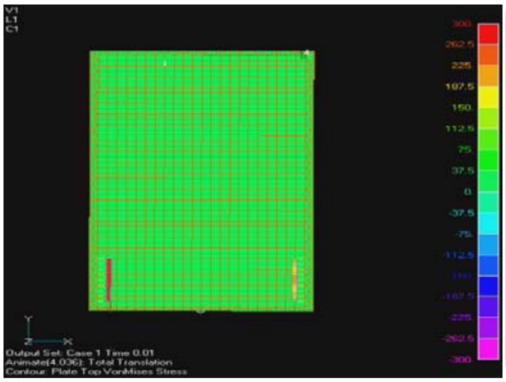


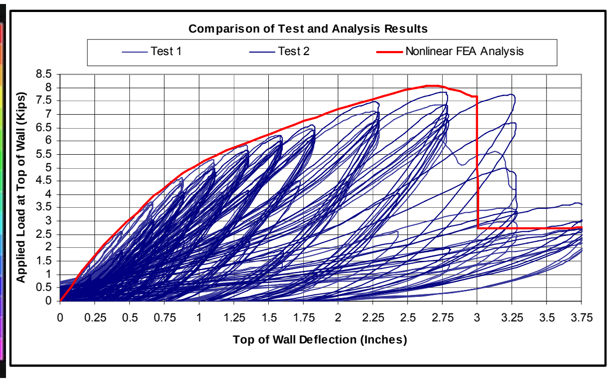
If Δ_{dia} [2(Δ_{avg}) then diaphragm is classified as rigid

Note that this is definition has been around for some time, but good information on the validity of this definition is lacking.

Advanced Analysis

- **FEA : nail-level modeling is possible, with good correlation to full-scale testing.**
- **Requires a "true direction" nonlinear spring for the nails, as opposed to paired orthogonal springs.**





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Animation of nonlinear static analysis where true direction, or self aligning, nonlinear springs were used for analysis. Spring properties follow backbone curve from cyclic nail tests. Graph shows good results, including failure, obtainable with careful modeling (first quadrant only of cyclic test is shown). Typical nail modeling uses paired orthogonal springs. However, relative movement between sheathing and framing at some vector other than one of the two primary axis will always cause the paired spring model to over-predict strength and displacement capacity. Analytical work is from Simpson Strong-Tie as part of effort to understand post tension and bending demands at holdown locations.

Advanced Analysis

- **NLTHA: rules based phenomenological elements fitted to full scale test data to predict structural response.**
- **Good correlation to simple tests – more work needed for complex, full structures.**

Max Rel Disp		
Story	Predicted	Tested
1	1.14	1.57
2	2.65	2.3
3	1.76	1.92

Three story shake table testing at Simpson Strong-Tie's state-of-the-art Tyrell T. Gilb Research Laboratory. Video shows testing as part of program to better understand the effects of not restraining overturning at each floor (skipping floors). In this video, overturning is restrained at each floor and performance is good. Tests show that skipping the first floor, while properly designed for strength, can cause first story interstory drift to be amplified by a factor of 2 because of the reduced stiffness of the overturning restraint. Ground motion used is the Rinaldi record from the 1994 Northridge earthquake.

Summary

- Timber structures have a good track record of performance in major earthquakes
- Their low mass and good damping characteristics help achieve this.
- The orthotropic nature of wood, combined with the discontinuous methods of framing wood structures, requires careful attention to properly detailing the load path.
- There is still much room for improvement in our understanding of force distribution within wood structures, and the development of design tools to better model this.

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Self explanatory.