A SunCam online continuing education course

Tiny Houses Part 2

Structural Design

by

Kelly McAtee, P.E., LEED A.P.

Course Description

This course is part two of a multi-part course series on designing tiny houses (houses 400 square feet or less in size). The majority of this multi-part course focuses on tiny houses mounted on trailers, which are often referred to as tiny houses on wheels (THOW). This second course focuses on structural design. Also presented are specific techniques to structurally handle the mobile nature of THOW. Both prescriptive and engineered methodologies are used. Five extensive examples with calculations and 35 figures and photos are included. The basis of this course came from my own research, planning, designing, and construction of a THOW I built myself.

Learning Objectives

After completing this course participants should be able to:

1. Understand the pros and cons of using wood and metal structural framing members.
2. Size floor joists and roof joists using tables from the International Residential Code.
3. Calculate the size of wood loft joists and window headers using allowable stress design methodologies.
4. Recognize when advanced framing techniques are useful or not useful in given situations.
5. Recall additional structural measures often used for highly mobile tiny houses on wheels.

Introduction

Over the past few decades a small, but growing segment of the population has moved to smaller housing options. Cable TV shows like *Tiny House Nation* and *Tiny House Hunters* have increased the popularity and general population’s awareness of “tiny living.” This course is the second part of a multi-part course series on one of these alternatives – tiny houses. Both tiny houses on foundations (THOF) and tiny houses on wheels (THOW) are topics in the course.

The first course in this series covered consulting engineering opportunities both with the house structures themselves and development of sites for tiny houses. It also discussed where tiny houses can be placed and the various construction and manufacturing standards THOW are built to, including a tiny house appendix in the 2018 International Residential Code (IRC). Finally, some information on trailers, appliances, utility connections, floor plans, and lofts was presented.

This second course goes over specific structural design considerations for floor systems, walls, headers, and roof systems. Both prescriptive and engineered methodologies are included. How to structurally handle the mobile nature of THOW is also covered.

Course three will focus on the remaining building enclosure components: ventilation, siding, doors, windows, interior finishes, insulation, and air sealing. Course four will discuss mechanical, electrical, and plumbing (MEP) systems with an emphasis on going off-grid or mobile with a tiny house. Look for courses three and four to be released in late 2019 or early 2020.

The basis of these courses came from my own research, planning, designing, and construction of a THOW I have built myself.

A Brief Review

There is no universally accepted definition of a tiny house. For the purpose of this course we will define a tiny house as a dwelling unit 400 square feet or less.

All material and product costs or estimated costs in this course are given in 2018 dollars. Some costs vary greatly from region to region. Also, mention of a specific product is not necessarily a recommendation of that product. While I have specified and personally used many of the products listed, others I have not. The purpose of listing products I have not used is to illustrate that products exist for a specific application. Please perform your own due diligence.

The Engineer's Role

House Structure and Systems

The building code governs THOF construction. Since meeting most requirements of building codes can be achieved through prescriptive means, THOF in many jurisdictions can be approved, permitted, and constructed without the assistance of any design professionals. Similar to larger, traditional home construction, the use of engineers for a THOF is most likely a voluntary one on the part of the client or builder. Some structural components of a tiny house may be oversized if the building code span tables are used (due to the much shorter spans present in tiny houses) so the services of a structural engineer may be desired. Also, due to the mobile aspect of THOW, structural engineering services are often needed.

Drawings

The level of drawing detail required for a THOW is generally greater than for most other residential projects. See the section on “Drawings” in *Tiny Houses Part 1 – Planning and Design Considerations, Legality, and the Engineer’s Role* for more information.

THOW Trailer Characteristics

Early THOW were constructed on modified flatbed, utility, and occasionally gooseneck trailers. Sidewalls, decks, and ramps would be removed and holes drilled through the metal frame to facilitate tiny house floor and/or wall connection to the trailer using bolts, washers, and nuts. Since trailer electrical wiring for lights and signals is often run inside of structural steel members, the chance of damaging wiring while drilling holes was not insignificant.

As demand rose, local and regional trailer manufacturers as well as some tiny house builders began fabricating and selling trailers designed specifically for tiny houses.

Tiny house specific trailer with galvanized sheet metal bottom pan

Common characteristics of these specialty trailers include:

- Larger structural members around the perimeter of the trailer for exterior load bearing walls to sit on and smaller structural members in the interior of the trailer where no walls or non-load bearing walls are present. Most flatbed trailers have larger structural members in the interior trailer area to support uniform loading, such as a car being driven up on them; however, this is an unnecessary weight penalty for a THOW.
- Slightly lower trailer deck heights to maximize available headroom.
- The interior structural members are smaller in both cross-section and height to allow for floor framing (some trailers have enough room for 2x6 floor joists) and insulation below the deck instead of above the deck. This also increases available headroom and reduces thermal bridging due to smaller areas of trailer structural steel extending through the entire floor assembly.
- Differing axle positioning compared to cargo trailers to provide better balance for the typical house loading distribution.
- Trailer widths at or just narrower than the maximum allowed without an oversized load permit. The slightly narrower widths are intended to leave room for wall sheathing, siding, and trim and still remain narrower than 8 feet 6 inches.
- Pre-drilled holes in the trailer structure for both floor system connection and wall system connection.
- Galvanized, sheet metal pan installed on the bottom side of the trailer deck to protect insulation and floor framing from road water splash in mobile applications and from vegetation, insects, and the elements in stationary applications. Depending on the manufacturer this may be a standard feature or an upgrade.
- Scissor jacks welded to each trailer corner to assist with quicker leveling. Depending on the manufacturer this may be a standard feature or an upgrade.
- Welded fenders flashing to eliminate the need for custom flashing above the fenders and wheel wells. Depending on the manufacturer this may be a standard feature or an upgrade.

You can see large structural members on the perimeter, pre-drilled holes for connecting walls to the trailer frame, small interior structural members, and room for floor framing below trailer deck. The steel angles welded to the steel tube(s) forming the perimeter frame are great for placing the exterior walls on, but there is one negative tradeoff – plumbing drains must go through the floor adjacent to the exterior walls, not in the walls as they normally would.

Deciding Between Wood or Metal Structural Members

Wood framing dominates the residential framing market in the United States (except in hurricane prone areas) while metal framing is the norm for the commercial framing market. There are pros and cons of using either material. THOW are more often than not framed with wood. However, there are still those who choose to use light gauge steel framing. Usually this decision is based on the substantial weight savings that can be achieved using metal framing members.

A 350S162-18 galvanized steel stud with pre-punched holes for plumbing and electrical installation. The stud is 3.5 inches wide by 1.625 inches thick and the web and flange thickness are 25 gauge (18 mil). This stud is only suitable for non-load bearing walls. A thicker gauge is required for bearing walls.

Benefits of Wood Framing

- Wood is much less expensive than steel (equivalent galvanized steel members cost 2 to 4 times that of wood)
- Lumber of all size is very commonly available
- Almost every carpenter is experienced in framing with wood and has the necessary tools
- Less additional framing components are needed (stiffeners, blocking, plates, clips, etc.)
- Heat transfers through wood less easily than through steel (less thermal bridging with wood framing)
- All the common residential electrical components can be used, which makes the electrical system slightly less expensive than when using steel framing
- Wood structural members like joists can be left exposed, they don't require a separate finish material to cover them
- Wood is a renewable resource

Benefits of Light Gauge Steel Framing

- Steel members are 2 to 4 times lighter than wood. A wood 2x4 weighs about 1.3 pounds/foot depending on species and moisture content. A load bearing steel 350S162-33 weighs about 0.55 pounds/foot and a non-load bearing steel 350S162-18 weighs about 0.35 pounds/foot.
- Unless damaged, steel framing members don't have bows, wanes, splits, or other common wood imperfections
- Steel doesn't change volume with changes in moisture (wood does)

- Steel doesn't catch on fire (but it can deform and fail under extreme temperatures)
- Steel studs come with pre-punched holes for electrical and plumbing installation
- Steel is insect resistant
- Steel is a recyclable resource

Certainly all the shortfalls of either framing material can be overcome. For example, using exterior sheets of rigid insulation over metal framing can nearly eliminate thermal bridging in a tiny house. However, this comes with the penalties of higher material costs and losing valuable living space for a given house width. In the end, the decision of wood or metal needs to be made on a case-by-case method. In general, my personal recommendation for tiny houses is to use wood framing. The exceptions to this recommendation would be THOW moved very frequently or THOF built in hurricane country.

Grade Stamps

Grade stamps are placed on wood products to convey critical information to people who use them. Most panel or sheet goods will bear a stamp from the Engineered Wood Association which is called the APA for short (this acronym is a holdover from when it was called the American Plywood Association). Sawn lumber in the Unites States is graded by several different sets of rules and as a result some regions of the country will have different looking grade stamps. Most sawn lumber is visually graded, but some is mechanically graded. Mechanically graded grade stamps usually have a term like "Machine Graded" at the top of the stamp and include additional numbers not seen on visually graded lumber. One of the most common grading standards is the standard developed by the Western Wood Products Association (WWPA). Refer to Figures 1 and 2 for typical APA and WWPA grade stamps.

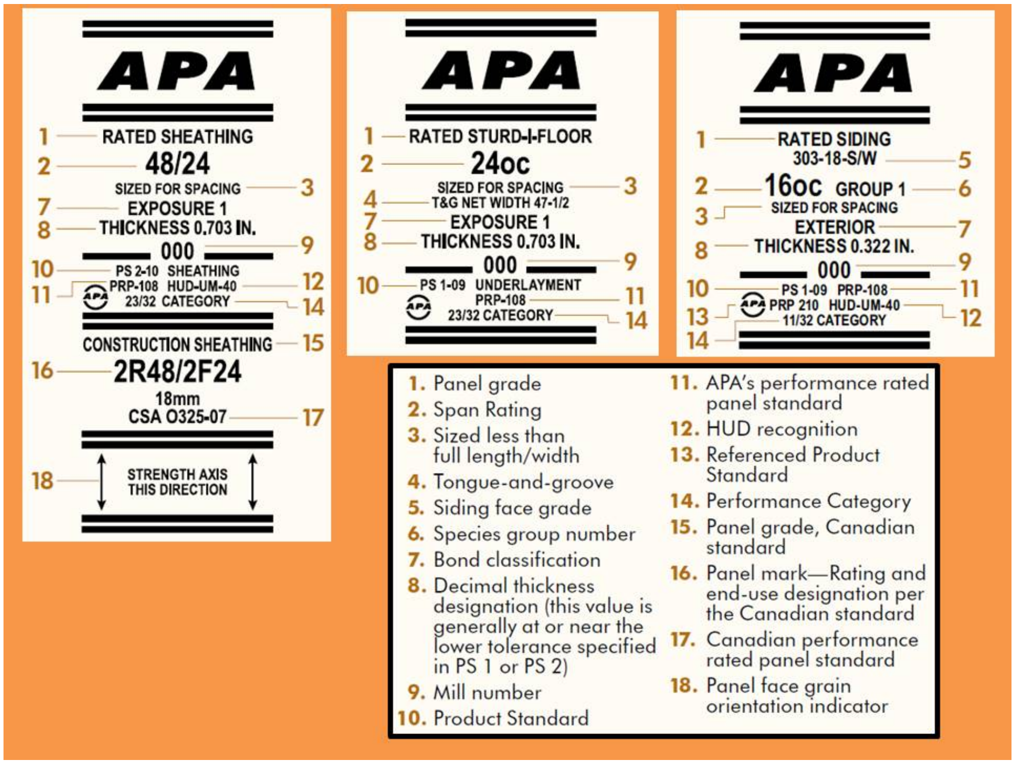


Figure 1: Typical Plywood Grade Stamps (from APA Engineered Wood Construction Guide)

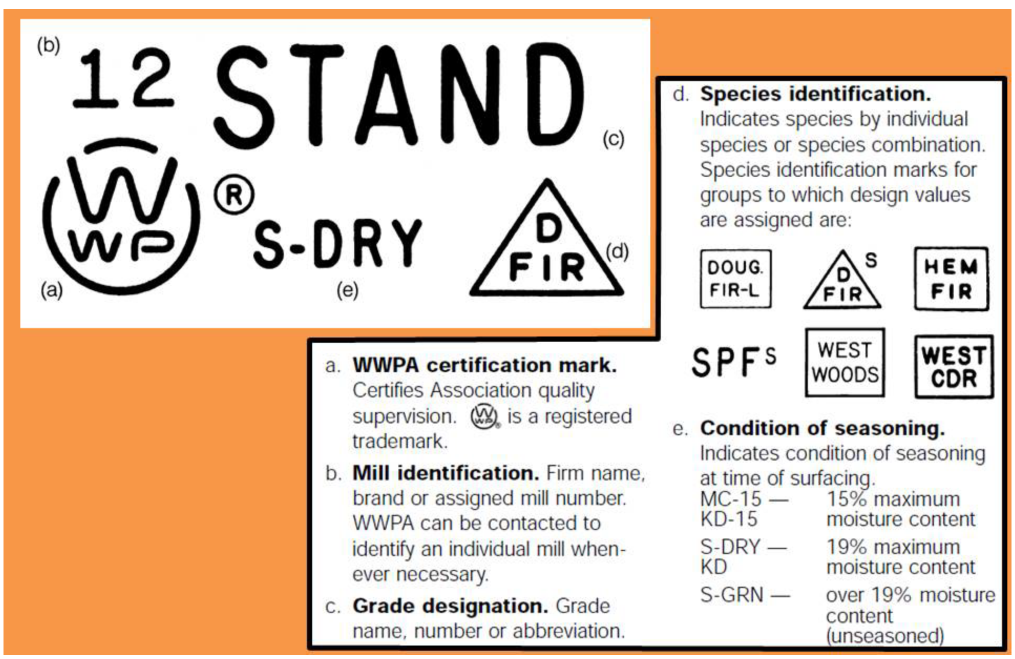
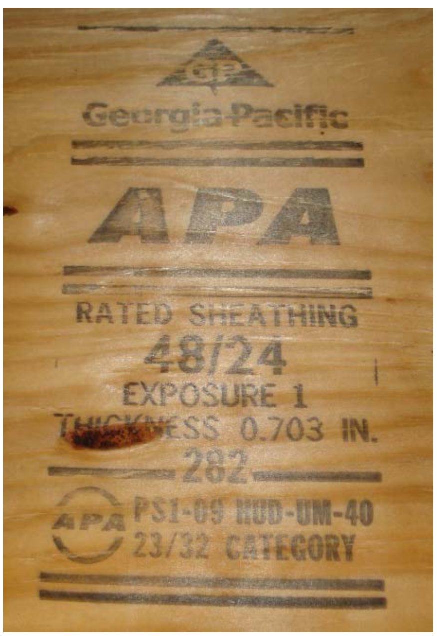


Figure 2: Typical Visually Graded Sawn Lumber Grade Stamps (from WWPA Grade Stamp Fact Sheet)

The two most commonly referenced pieces of information on panel grade stamps are the span rating and bond classification. Let's begin with the span rating. If there are two numbers in the span rating separated by a forward slash the first number gives the maximum allowable on-center support spacing for roofing applications. The second number gives the maximum allowable on-center support spacing for floor applications. There are two APA bond classifications: Exterior and Exposure 1. Exterior panels are able to withstand long-term exposure to weather and repeated cycles of wetting and drying. Exposure 1 panels are not intended for either of these conditions, but rather for limited exposure and wetting during construction. Exposure 1 panels can be used for exterior purposes if they are covered by another suitable building layer such as roofing material, wall siding, etc. Exposure 1 panels may be left exposed in locations like soffits, awnings, and roof overhangs. C-D Exposure 1 plywood sheathing, which is often referred to as CDX, should only be used in the same applications as Exposure 1. It is not equivalent to Exterior rated panels.



Left: 23/32 inch thick, Exposure 1 plywood sheathing

Right: 2x4 graded using the Canadian Softwood Inspection (CSI) standards, not the WWPA Standards. Regardless, the format is similar enough to tell it is No. 2 Spruce-Pine-Fir (SPF) that was kiln-dried (KD) and heat treated (HT) for export purposes. The 1/4 EE means the 2x4 has a 1/4 inch eased edge (round edge).

Left: 1/2 inch thick, Exposure 1 oriented strand board (OSB) sheathing

Right: 2x6 graded using the Timber Products (TP) standards. This is a No. 2 Prime Southern Yellow Pine (SYP) that was kiln-dried (KD) and heat treated (HT). The term "No. 2 Prime" means structurally it was graded the same as a No. 2, but the physical appearance is better than a "normal" No. 2.

As you can see from comparing the typical grade stamps to actual photos, not all markings are present or consistent on every panel or piece of lumber; however, normally grade stamps look similar enough that you can glean the needed information off them.

Structural Design

Main Floor Joists

To properly size floor joists we first need to determine floor live loading. Minimum live load design values are found in IRC Table R301.5. The 2018 IRC can be viewed online for free on the International Code Council (ICC) website at https://codes.iccsafe.org/content/IRC2018. The two values used in most tiny houses are "sleeping rooms" and "rooms other than sleeping rooms." The values from the table are 30 pounds per square foot (psf) and 40 psf, respectively.

Main floor (non-loft) floor joists can be sized using IRC Table R502.3.1(2) for solid sawn wood joists and IRC Table R505.3.2 for cold-formed steel joists. Table R502.3.1(2) is for live loads of 40 psf which is appropriate for non-sleeping rooms. Even if a mixture of sleeping and non-sleeping rooms is on the main floor assume 40 psf live loading for the entire floor for the sake of simplicity.

Engineered wood I-joists are another common option for floor joists. I-joists are manufactured with top and bottom flanges to efficiently carry bending moments and a web which provides much of the shear capacity. Laminated veneer lumber (LVL) or solid sawn lumber is usually used for the flange material. Webs are made of plywood or oriented strand board (OSB). Engineered wood I-joists are lighter and straighter than solid sawn lumber, but generally cost slightly more and often require additional framing members like blocking and stiffeners. The IRC does not include tables for sizing engineered I-joists. Sizing is accomplished using tables supplied by each joist manufacturer. It would be unusual to use engineered wood I-joists for a THOW's floor joists since the thinnest commonly manufactured depth is 8.5 to 9.5 inches, depending on the manufacturer. Except for the coldest climates or THOW without lofts, it is unlikely the reduction in head room would be worth the small increase in insulation that can be achieved by using such deep floor joists.

Concrete slabs-on-grade should be strongly considered for THOFs in almost all climate zones. IRC R506 provides requirements for fill, base course, and vapor retarders. IRC Chapter 4 covers footings.

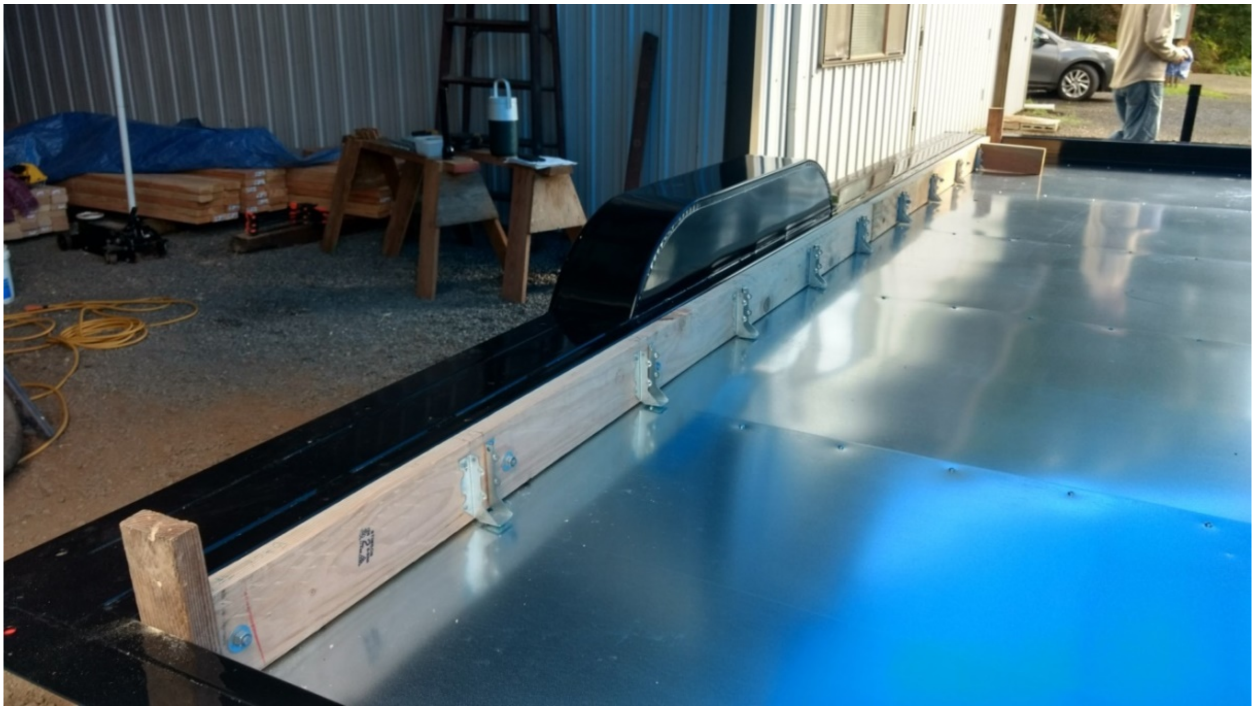
EXAMPLE:

The floor joist span needed for a THOW is 7 feet 8 inches. The local lumber yard carries mostly spruce-pine-fir #2 dimensional lumber so specify that species and grade. Assume the dead load of the floor joists, sheathing, and flooring is less than 10 psf. The tiny house specific trailer being used for the project was designed to use 2x6 floor joists that sit below the trailer deck. What is the maximum joist spacing for the 2x6s?

SOLUTION:

In IRC Table R502.3.1(2) follow the column for 2x6 joists in the 10 psf section of the table downward until you see the spruce-pine-fir #2 row in the 12 inch joist spacing section. Record the maximum floor joist span of 10'-3". The 10'-3" spanning capacity is greater than the necessary span of 7'-8" so follow the same procedure, but this time look in the 16 inch joist spacing section. Record the maximum floor joist span of 9'-4" when using 16 inch on-center spacing, which also is greater than the required span of 7'-8". Proceed to the 19.2 inch joist spacing section and find a span of 8'-9". Proceed to the 24 inch joist spacing section and find a span of 8'-1" which is still larger than the 7'-8" span needed. Use 24 inch on-center floor joist spacing. The table does not go beyond 24 inch joist spacing since 3/4 inch thick floor sheathing, which is used for most residential floors, is not rated for greater than 24 inch joist spacing.

Many of the tiny house specific trailers are manufactured with bolt holes to connect a floor joist ledger to. The floor joists are then hung from the ledger using joist hangers.



A floor joist ledger bolted to the trailer frame with joist hangers attached. The bottom of the joist hangers are slightly higher than the trailer's sheet metal bottom pan to allow for the installation of expanded polystyrene insulation to reduce thermal bridging. The exterior walls will sit on the wide perimeter steel trailer frame, not directly on the floor framing.

Two of the larger wood construction hanger companies are Simpson Strong-Tie (carried by Home Depot) and USP (carried by Lowe's). Both companies' websites have downloadable product brochures to help you select appropriately sized joist hangers. To use these brochures to select a proper joist hanger you first need to determine the vertical reaction at the ends of the joist.

EXAMPLE:

Using the information from the previous example, calculate the vertical reaction at the ends of the 2x6 joists and select an appropriate joist hanger from Simpson Strong-Tie. The ledger is also a 2x6 (5.5 inches actual depth). Assume the walls of the house sit on the trailer frame and do not bear on the floor joists.

SOLUTION:

First calculate the tributary area of each floor joist. Since 24 inch on-center spacing was selected the tributary area is 24 inches wide by 92 inches long (from the 7'-8" joist span) which is 15.33 ft^2. The total floor loading is the sum of the live loading and dead loading, in this case a total of 50 psf. For a simply supported joist, which is a joist supported only at each extreme end with no intermediate supports, the vertical reactions at each end are equal in magnitude and can be calculated as shown.

$$Vertical\ Reaction = \frac{(15.33\ ft^2)\left(50\ \frac{lbs}{ft^2}\right)}{2} = 383\ lbs$$

Figure 3 shows an excerpt from a product catalog downloaded from the Simpson Strong-Tie website.

Simpson Strong-Tie® Wood Construction Connectors

SIMPSON Strong-Tie

Face-Mount Hangers – Solid Sawn Lumber (DF/SP)

The Joist Hanger Selector software enables you the most optimum product for your project.
The software takes into consideration all the characteristics seen in this catalog. Visit **strongtie.com/jhs**.

These products are available with additional corrosion protection. For more information, see p. 15.

SS For stainless-steel fasteners, see p. 21.

SD Many of these products are approved for installation with Strong-Drive® SD Connector screws. See pp. 335–337 for more information.

Solid Sawn Joist Hangers

Joist Size	Model No.	Ga.	Dimensions (in.) W	Dimensions (in.) H	Dimensions (in.) B	Min./Max.	Fasteners (in.) Header	Fasteners (in.) Joist	DF/SP Allowable Loads Uplift (160)	DF/SP Allowable Loads Floor (100)	DF/SP Allowable Loads Snow (115)	DF/SP Allowable Loads Roof (125)	Installed Cost Index (ICI)	Code Ref.
Sawn Lumber Sizes														
2X4	LU24	20	1 9/16	3 1/8	1 1/2	—	(4) 0.162 x 3 1/2	(2) 0.148 x 1 1/2	240	555	630	655	Lowest	IBC, FL, LA
	LUS24	18	1 9/16	3 1/8	1 3/4	—	(4) 0.148 x 3	(2) 0.148 x 3	435	670	765	820	3%	
	U24	16	1 9/16	3 1/8	1 1/2	—	(4) 0.162 x 3 1/2	(2) 0.148 x 1 1/2	240	575	650	705	67%	
	HU26	14	1 9/16	3 1/16	2 1/4	—	(4) 0.162 x 3 1/2	(2) 0.148 x 1 1/2	305	595	670	720	295%	
DBL 2X4	LUS24-2	18	3 1/8	3 1/8	2	—	(4) 0.162 x 3 1/2	(2) 0.162 x 3 1/2	410	800	905	980	Lowest	
	U24-2	16	3 1/8	3	2	—	(4) 0.162 x 3 1/2	(2) 0.148 x 3	240	575	650	705	33%	
	HU24-2 / HUC24-2	14	3 1/8	3 1/16	2 1/2	—	(4) 0.162 x 3 1/2	(2) 0.148 x 3	380	595	670	720	240%	
2x6	LUS26	18	1 9/16	4 3/4	1 3/4	—	(4) 0.148 x 3	(4) 0.148 x 3	1,165	865	990	1,060	Lowest	
	LU26	20	1 9/16	4 3/4	1 1/2	—	(6) 0.162 x 3 1/2	(4) 0.148 x 1 1/2	540	835	950	1,030	6%	
	U26	16	1 9/16	4 3/4	2	—	(6) 0.162 x 3 1/2	(4) 0.148 x 1 1/2	535	865	980	1,055	43%	
	LUC26Z	18	1 9/16	4 3/4	1 3/4	—	(6) 0.162 x 3 1/2	(4) 0.148 x 1 1/2	730	710	810	875	160%	
	HU26	14	1 9/16	3 1/16	2 1/4	—	(4) 0.162 x 3 1/2	(2) 0.148 x 1 1/2	305	595	670	720	179%	
	HUS26	16	1 5/8	5 3/8	3	—	(14) 0.162 x 3 1/2	(6) 0.162 x 3 1/2	1,320	2,735	3,095	3,235	276%	

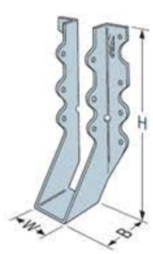


Figure 3: Face-Mount Hangers for Solid Sawn Lumber Product Info (from Simpson Strong-Tie 2019-2020 Wood Construction Connectors Catalog)

Looking at the "DF/SP Allowable Loads Floor" column in Figure 3 for all six 2x6 joist hangers we see that all hanger models provide greater than our necessary 383 pounds of downward force resistance. We are not concerned with uplift capacity because this floor is not subject to uplift forces. Second, look at the "Dimension H" column for the height dimension of all six hangers. We see that all are less than 5.5 inches in height so all six hangers would fit on the 2x6 joist ledger and not conflict with any other building components. As a result, any of the six hangers would work. Let's make our final decision based on labor to install and cost. Looking at the "Installed Cost Index" column the two least labor intensive hangers are the LUS26 and LU26. The LU26 is about $0.70 while the LUS26 is about $0.90. Let's go with the less expensive option since both hangers take about the same time to install. For the hangers to support the allowable loads listed in the table, the size and number of nails specified in the table must be used. Follow the same steps using the USP product catalog and place both joist hanger models on the framing plans so the builder can choose from either brand. Also include the number and size of nails required for each joist hanger.

If a sheet metal pan is installed on the bottom side of the trailer it is generally not advisable to install plumbing running horizontally above the metal pan, as it would be inaccessible for maintenance. As a result, no cutting, drilling, or notching of floor joists would be required and the requirements of IRC R502.8 would be not applicable. If a bathtub will be installed, some designers include additional framing or joists in the vicinity of the tub.

Main Floor Sheathing

IRC Table R503.2.1.1(1) can be used to determine the thickness of main floor sheathing. Easier yet, just read the second number of the span rating stamped on the plywood or OSB, which gives the maximum floor joist spacing in inches. 15/32" and 1/2" thick sheathing are rated for 16 inch on-center floor joist spacing. 23/32" and 3/4" thick are rated for 24 inch on-center floor joist spacing. Tongue and groove sheathing is commonly specified for floor sheathing since it eliminates the need for sheathing edge blocking or sheathing clips. Blocking reduces the amount of floor insulation that can be installed and clips are not appropriate for floors since they don't provide load transfer along the entire length of the joint and they would cause issues when installing the final floor covering. 23/32" thick sheathing is the thinnest commonly available sheathing with tongue and groove edges, so thinner sheathing is often not specified for floors even if the joist spacing is 16 inches on-center. The stamped span ratings are for when the long dimension of the sheathing is installed perpendicular to the joists. This long direction, or strength axis, can be determined in plywood even after cutting by looking at the grain direction of the exterior plys. For example, 5-ply plywood has three plys oriented along the strength axis direction and two plys along the weak axis direction. When using this method make sure the plys are of equal thickness since occasionally the exterior plys are much thinner. OSB normally has a stamp showing the strength axis direction.

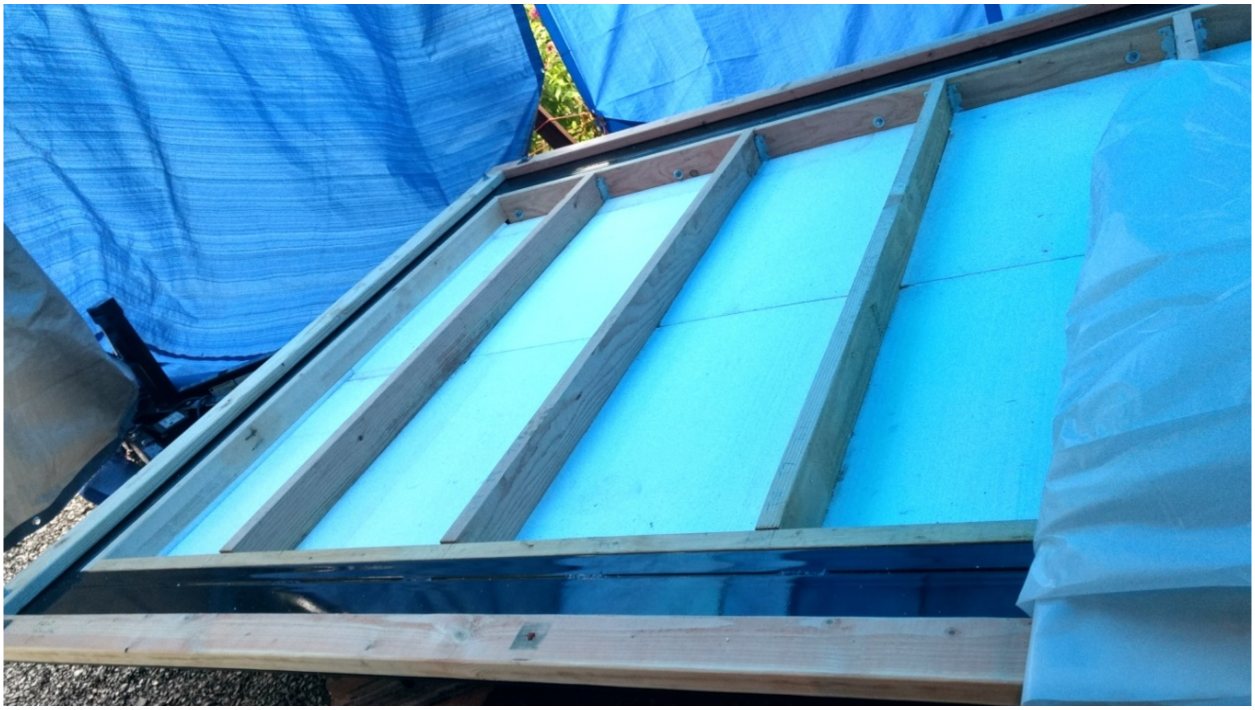
OSB with a stamp showing the strength axis direction

IRC Table R602.3(1) gives the number, type, size, spacing, and location of fasteners for wood-frame construction. Item 37 of the table shows either 6d deformed or 8d common nails may be used for 3/4” thick floor sheathing.

Main Floor Joist Ledgers

Tiny house trailers designed to allow floor framing below the trailer deck instead of above the deck usually use floor joist ledgers to support the floor joists. Pre-drilled holes in the trailer frame for 1/2 or 5/8 inch diameter bolts spaced approximately every 2 feet is fairly typical.

Structurally, the worst case scenario would be where the ledgers do not sit on any trailer framing members and are entirely supported by these bolts. If the bolts are roughly centered between the top and bottom of the ledger, the bearing of the wood ledger on the bolts is the weakest link (as opposed to bending or shear). Using 1/2 inch diameter bolts at 2 foot centers is sufficient for 50 psf loading across the entire floor for almost any common species and grade of wood. If you’re concerned, upsizing to 5/8” diameter bolts will increase the bearing capacity by 25 percent compared to 1/2 inch diameter bolts.



Installed floor ledgers, floor joists, and first layer of expanded polystyrene insulation in a THOW. Some of the ledger bolts are visible at the top of the photo.

Loft Floor Joists

Material options for loft joists are the same as for main floor joists. The prescriptive sizing method is the same unless the loft space is a "sleeping room" in which case the live loading only needs to be 30 psf, not 40 psf. In these cases use IRC Table R502.3.1(1) to size solid sawn wood joists as opposed to IRC Table R502.3.1(2).

IRC Tables R502.3.1(1) and R502.3.1(2) have multiple limitations. The maximum joist spacing shown in the tables is 24 inches and two inch nominal width joists are the only joist sizes shown. Often in tiny houses, especially THOW, shallower and wider joists are desired to maximize head room. On-center joist spacing in excess of 24 inches can allow a standard 6'-8" tall door to open between loft joists instead of below them, thus increasing loft ceiling height by four inches if located above a bathroom or kitchen. This is because IRC Appendix Q allows for ceiling heights of 6'-4" in these types of areas. If, for any reason, the IRC tables can't be used to size the joists you can perform engineering calculation instead.

EXAMPLE:

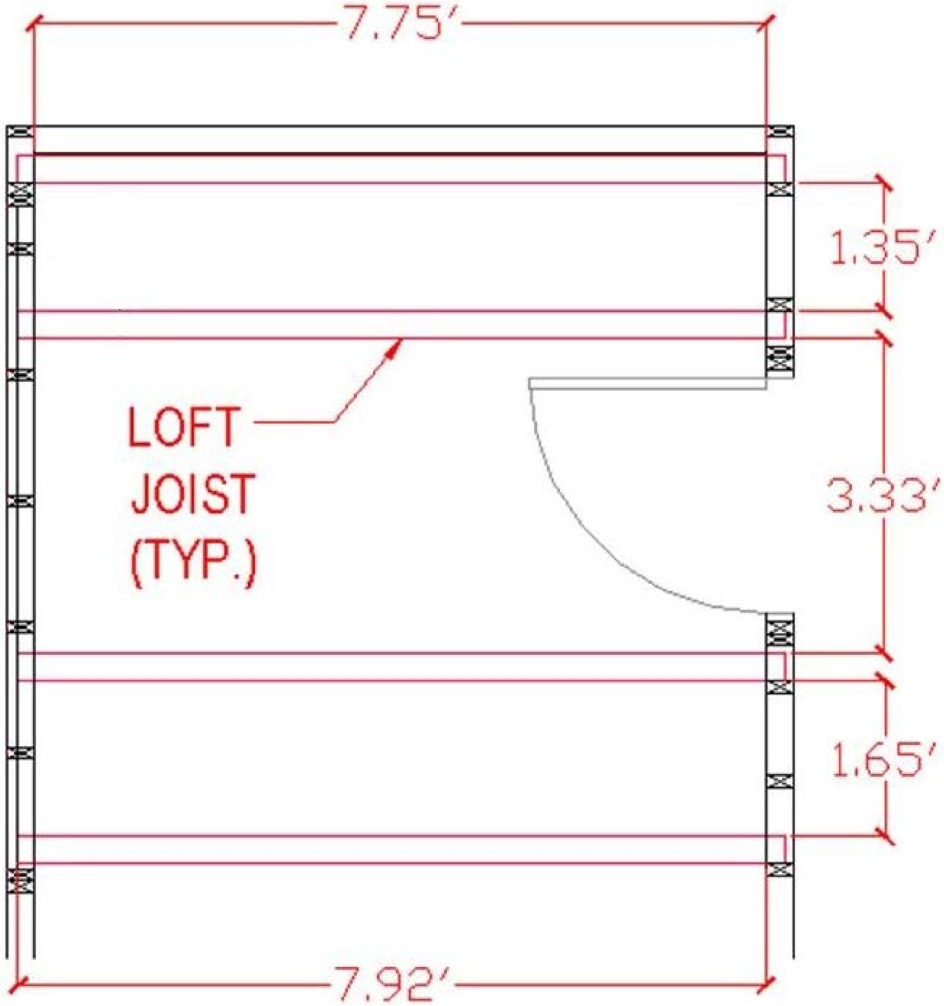


Figure 4: Layout for Loft Floor Joist Example

The loft floor joist span needed for a THOW is 7 feet 11 inches (7.92'). The loft will serve as sleeping quarters. The local lumber yard carries mostly Douglas fir No. 2 dimensional lumber so specify that species and grade. Refer to Figure 4 for the layout and proposed loft joist spacing. This layout was chosen to allow the entry door to open between the joists as opposed to under the joists. To save additional loft headroom 4 inch wide joists are desired. Based on experience you suspect a 4x4 joist will not be sufficient. You think likely a 4x6 joist will be required. As such, you calculated the dead load of the 4x6 loft floor joists and decking boards to be 6 psf. Are 4x4 or 4x6 joists needed? Check bending, shear, and deflection. For the purpose of this example, assume bearing is not an issue.

SOLUTION:

IRC Table R502.3.1(1) cannot be used to size the joists due to the on-center joist spacing and joist width desired. The IRC does not specify load combinations, but IRC R301.1.1 requires the use of the IBC "where engineered design is used." Use the load combinations in IBC 1605.3.1 since an allowable stress design (ASD) method will be used. Chapter 16 of the 2018 IBC can be viewed for free online at https://codes.iccsafe.org/content/IBC2018/chapter-16-structural-design. The controlling load combination for this scenario is IBC Equation 16-9:

$$D + H + F + L \quad (Equation\ 1)$$

Where: D = Dead load
H = Load due to lateral earth pressures, ground water pressure, or pressure of bulk materials
F = Load due to fluids with well-defined pressures and maximum heights
L = Floor live load

Both H and F are not applicable in this situation. So the design loading is 36 psf, which is the given 6 psf dead load plus the 30 psf live load (since the loft is a "sleeping room"). Next determine the widest tributary area of the four loft joists as this will result in the largest loading any of the joists will need to carry. The widths of tributary areas can be delineated by drawing a line parallel to the joist length half the distance between the adjacent joists on each side of a given joist. From Figure 5, the widest tributary area is 2.78 feet wide.

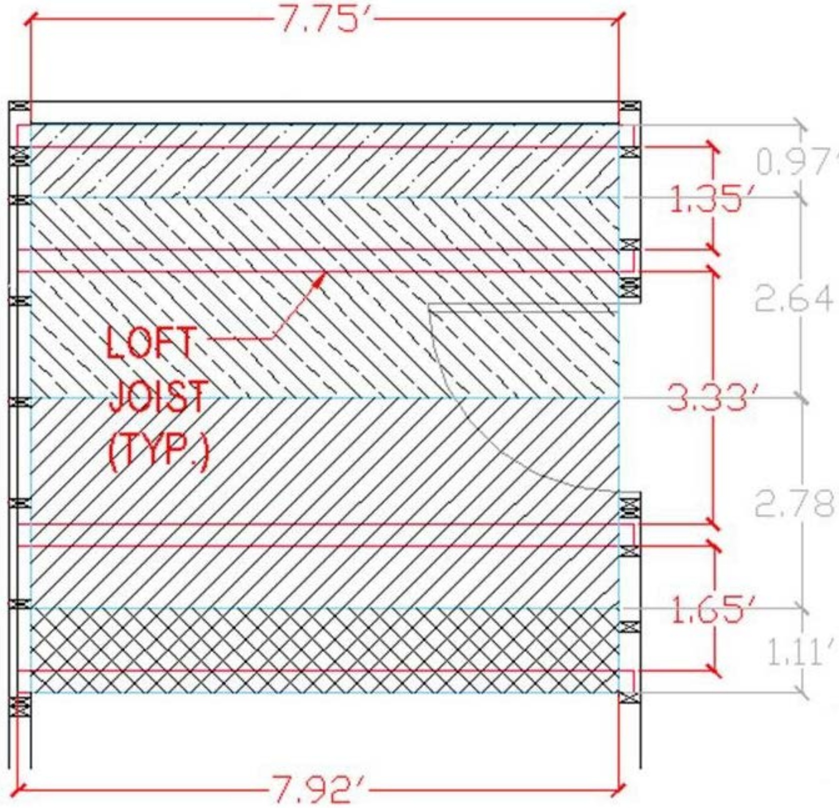


Figure 5: Tributary Areas for Loft Floor Joist Example

The joist's distributed load, *w* is 36 psf times 2.78 feet which equals 100 lbs/ft. See Figure 6 for the associated free body diagram.

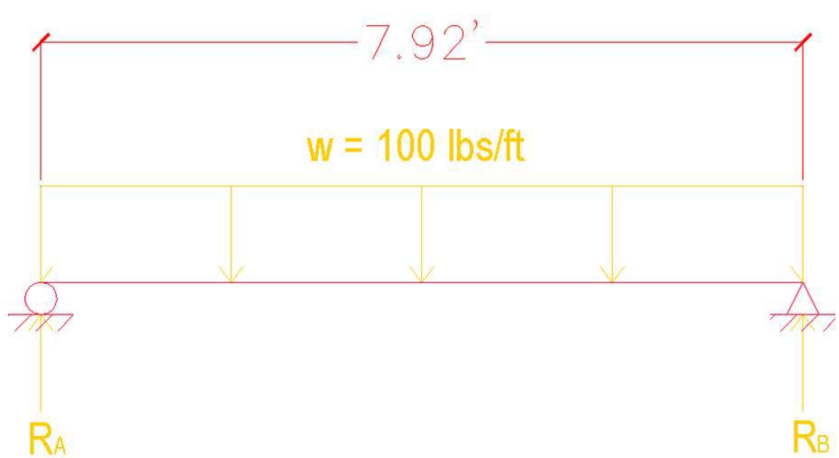


Figure 6: Free Body Diagram for Loft Floor Joist Example

At this point use undergraduate statics to calculate Reaction A (R_A), Reaction B (R_B), the maximum shear, and the maximum moment resulting from the loading. The maximum shear and moment can be determined using shear and moment diagrams or the appropriate equations for a simply supported beam under uniform distributed load. These equations are:

$$R_A = R_B = V_{max} = \frac{wL}{2} \quad (Equation\ 2)$$

Where: V_{max} = Maximum shear
w = Uniform distributed load
L = Length of span

$$M_{max} = \frac{wL^2}{8} \quad (Equation\ 3)$$

Where: M_{max} = Maximum moment
w = Uniform distributed load
L = Length of span

Using Equations 2 and 3 for our example yields:

$$R_A = R_B = V_{max} = \frac{wL}{2} = \frac{(100\frac{lbs}{ft})(7.92\ ft)}{2} = 396\ lbs$$

$$M_{max} = \frac{wL^2}{8} = \frac{(100\frac{lbs}{ft})(7.92\ ft)^2}{8} = 784\ ft - lbs$$

The next step is to check both a 4x6 and 4x4 for bending, since bending is most likely the controlling design criterion. Bending stress, f_b, must be less than or equal to the allowable bending stress, F'_b for the joist to be sufficiently sized for bending. For a square or rectangular beam (or joist) the bending stress about the strong axis is:

$$f_b = \frac{M}{\left(\frac{bd^2}{6}\right)} \quad (Equation\ 4)$$

Where: f_b = Bending stress (actual)
M = Maximum moment in beam
b = Beam width
d = Beam depth

Recalling a 4x6 is actually 3.5 inches wide by 5.5 inches deep and using Equation 4 results in:

$$f_b = \frac{M}{\left(\frac{bd^2}{6}\right)} = \frac{784\ ft - lbs}{\left(\frac{\left(\frac{3.5}{12} ft\right)\left(\frac{5.5}{12}\ ft\right)^2}{6}\right)\left(\frac{144\ in^2}{1\ ft^2}\right)} = 533\ psi$$

The majority of the dead weight is due to the decking boards so assume the 6 psf dead load also applies to a 4x4. For a 4x4, Equation 4 results in:

$$f_b = \frac{M}{\left(\frac{bd^2}{6}\right)} = \frac{784\ ft - lbs}{\left(\frac{\left(\frac{3.5}{12} ft\right)\left(\frac{3.5}{12}\ ft\right)^2}{6}\right)\left(\frac{144\ in^2}{1\ ft^2}\right)} = 1{,}317\ psi$$

Since our loft joists are not subject to sustained wet conditions (moisture content above 19%), are not subject to high temperatures (over 150 degrees Fahrenheit), are continuously supported along their compression face by the decking boards, and are not incised for pressure treatment the allowable bending stress equation simplifies to:

$$F'_b = F_b(C_D)(C_F)(C_r) \quad (Equation\ 5)$$

Where: F'_b = Allowable bending stress
F_b = Tabulated bending stress (table lookup)
C_D = Load duration factor
C_F = Size factor
C_r = Repetitive member factor

The four needed values can be looked up in the National Design Specification (NDS) for Wood Construction or the NDS Supplement; both can be viewed on the American Wood Council's website at: https://awc.org/codes-standards/publications/nds-2018. The following two tables are excerpts from these publications. From the three Douglas fir species shown in the NDS supplement we'll choose to use the Douglas fir – South design values since they are the most conservative.

Species and commercial grade	Size classification	Design values in pounds per square inch (psi)						
		Bending F_b	Tension ‖ to grain F_t	Shear ‖ to grain F_v	Compression ⊥ to grain $F_{c\perp}$	Compression ‖ to grain F_c	Modulus of Elasticity E	Modulus of Elasticity E_{min}
DOUGLAS FIR-SOUTH								
Select Structural	2" & wider	1,350	900	180	520	1,600	1,400,000	510,000
No. 1	2" & wider	925	600	180	520	1,450	1,300,000	470,000
No. 2	2" & wider	850	525	180	520	1,350	1,200,000	440,000
No. 3	2" & wider	500	300	180	520	775	1,100,000	400,000
Stud	2" & wider	675	425	180	520	850	1,100,000	400,000
Construction	2"-4" wide	975	600	180	520	1,650	1,200,000	440,000
Standard	2"-4" wide	550	350	180	520	1,400	1,100,000	400,000
Utility	2"-4" wide	250	150	180	520	900	1,000,000	370,000

‖ means parallel
⊥ means perpendicular

Table 1: Excerpt from Table 4A of the NDS Supplement

Load Duration	C_D	Typical Design Loads
Permanent	0.9	Dead Load
Ten years	1.0	Occupancy Live Load
Two months	1.15	Snow Load
Seven days	1.25	Construction Load
Ten minutes	1.6	Wind/Earthquake Load
Impact	2.0	Impact Load

Table 2: Load Duration Factors from the NDS for Wood Construction

From Table 1, find an F_b value of 850 psi for grade No. 2 Douglas fir. From Table 2, select a C_D value of 1.0. The size factor table in the NDS Supplement shows a C_F of 1.3 for a 4x6 and a C_F of 1.5 for a 4x4. Among other criteria for the repetitive member factor is a requirement for joists to be spaced not more than 24 inches on-center. While some of our loft joists are less than 24 inches on-center, not all are, so use a C_r value of 1.0.

Using Equation 5 to solve for F'_b of a 4x6 results in:

$$F'_b = F_b(C_D)(C_F)(C_r) = (850\,psi)(1.0)(1.3)(1.0) = 1{,}105\,psi$$

Since an F'_b (allowable bending stress) of 1,105 psi is greater than the calculated f_b (actual maximum bending stress) of 533 psi a 4x6 is sufficient for bending.

Using Equation 5 to solve for F'_b of a 4x4 results in:

$$F'_b = F_b(C_D)(C_F)(C_r) = (850\,psi)(1.0)(1.5)(1.0) = 1{,}275\,psi$$

Since an F'_b (allowable bending stress) of 1,275 psi is less than the calculated f_b (actual maximum bending stress) of 1,317 psi a 4x4 is not sufficient for bending.

The next step is to check the 4x6 for shear. Shear stress, f_v, must be less than or equal to the allowable shear stress, F'_v for the joist to be sufficiently sized for shear. For a square or rectangular beam (or joist) the shear stress can be calculated by:

$$f_v = \frac{1.5V}{bd} \quad (Equation\ 6)$$

Where: f_v = Shear stress (actual)
V = Maximum shear in beam
b = Beam width
d = Beam depth

Equation 6 results in:

$$f_v = \frac{1.5V}{bd} = \frac{(1.5)(396\,lbs)}{(3.5\,in)(5.5\,in)} = 31\,psi$$

Since our loft joists are not subject to sustained wet conditions, not subject to high temperatures, and not incised for pressure treatment the allowable shear stress equation simplifies to:

$$F'_v = F_v(C_D) \quad (Equation\ 7)$$

Where: F'_v = Allowable shear stress

F_v = Tabulated shear stress (table lookup)
C_D = Load duration factor

From Table 1 find an F_v value of 180 psi for grade No. 2 Douglas fir. As already found for bending, use a C_D value of 1.0.

Using Equation 7 to solve for F'_v results in:

$$F'_v = F_v(C_D) = (180\,psi)(1.0) = 180\,psi$$

Since an F'_v (allowable shear stress) of 180 psi is greater than the calculated f_v (actual maximum shear stress) of 31 psi a 4x6 is sufficient for shear.

Next check deflection under total load (dead plus live load). The allowable modulus of elasticity, *E'* must first be calculated. In this example *E* and *E'* are the same since the loft joists are not subject to sustained wet conditions, not subject to high temperatures, and not incised for pressure treatment. From Table 1 find an *E* value of 1,200,000 psi for grade No. 2 Douglas fir. Maximum deflection for a simply supported square or rectangular beam (or joist) under uniform distributed load can be calculated by:

$$\Delta = \frac{5wL^4}{384E'\frac{bd^3}{12}} \qquad (Equation\ 8)$$

Where:
Δ = Maximum deflection (actual)
w = Uniform distributed load
L = Length of span
E' = Allowable modulus of elasticity
b = Beam width
d = Beam depth

Using Equation 8 to check total load maximum deflection gives:

$$\Delta = \frac{5wL^4}{384E'\frac{bd^3}{12}} = \frac{5\left(100\,\frac{lbs}{ft}\right)(7.92\,ft)^4(1728\,\frac{in^3}{ft^3})}{384(1{,}200{,}000\,\frac{lbs}{in^2})\left(\frac{(3.5\,in)(5.5\,in)^3}{12}\right)} = 0.15\,in$$

Allowable deflection equations are found in IRC Table R301.7. Allowable deflection for floors is L/360, where L is the length of span.

$$Allowable\ \Delta = \frac{L}{360} = \frac{(7.92\ ft)\left(12\frac{in}{ft}\right)}{360} = \ 0.26\ in$$

Since Δ (actual maximum deflection) of 0.15 inches is less than the allowable Δ of 0.26 inches a 4x6 is sufficient for deflection.

Loft Floor Sheathing

Since loft joists are frequently at greater than 24 inch on-center spacing and the loft joist are often left exposed, it can be unsightly to use plywood or OSB loft floor sheathing. As a result, tongue and groove decking boards or dimensional lumber is often chosen for loft sheathing. IRC Table R503.1 can be used to determine the minimum thickness needed.

Wall Framing and Sheathing

Prescriptive methods for wood framed, cold-formed steel, masonry, concrete, and structural insulated panel wall construction are in IRC Chapter 6. There are dozens of tables for various situations that can be used similarly to the tables previously used to size floor joists. If you choose this method, see Section R602 for wood wall framing and Section R603 for cold-formed steel framing.

Alternatively, for THOW, you can use the following structural exterior wall assembly. It will meet or exceed most structural provisions of the IRC in most geographic areas.

Structural Exterior Wall Assembly

- 2x4 studs, No. 2 grade (or better), at 16 inches on-center
- 2x4 bottom plate (sometimes called sole plate)
- Double 2x4 top plates
- Use IRC Table R602.3(1) for number, type, size, spacing, and location of fasteners for wood framing connections
- 3/8" or 7/16" thick Exterior or Exposure 1 plywood for exterior sheathing on all exterior walls. Per the IRC, the sheathing long direction can be either parallel or perpendicular to the studs.
- Fully block all sheathing edges

- Use 8d common nails every 6 inches along the edges and every 12 inches in the field to attach exterior sheathing to studs, plates, and blocking
- Connect the 2x4 bottom plate to the trailer using 1/2" or 5/8" diameter Grade 8 galvanized steel bolts, washers, and nuts at 6 feet on-center maximum and no more than 12 inches away from the end of all bottom plate sections. The washer on the top side of the bottom plate should be as large as possible to increase the bearing area. At minimum, use galvanized steel plate washers 2 inches square and 3/16" thick as top washers. In higher risk earthquake areas (seismic design categories D_0, D_1, D_2, and E) and higher risk wind areas, use galvanized steel plate washers 3 inches square and 0.229 inch thick as top washers or use holdowns. Maps showing seismic design categories are in IRC Figure R301.2(2). Maps showing design wind speeds are in IRC Figure R301.2(5)A.

Straightened, leveled, and plumbed THOW framed walls

Left: 3" x 3" x 9/64" bearing plate with slotted hole for 5/8" diameter bolt (USP LBPS58-TZ). This specific bearing plate does not meet the IRC thickness requirement for seismic design categories D0, D1, D2, and E).

Right: 2" x 2" x 3/16" bearing plate with circular hole for 1/2" diameter bolt (Simpson Strong-Tie BP 1/2)

This structural wall assembly basically makes all exterior walls, whether load bearing or non-load bearing, into shear walls. While the 16 inch on-center stud spacing reduces the whole wall R-value compared to 24 inch on-center stud spacing there are few other advantages for using 24 inch spacing. For 24 inch stud spacing 3/8" thick sheathing can't be used, so the combined weight of 2x4s and sheathing is about the same for both stud spacing distances. If gypsum board is planned for the interior, definitely use 16 inch stud spacing since 24 inch stud spacing needs 5/8" thick gypsum board compared to 1/2" thick for 16 inch stud spacing. The IRC allows 1/2" thick gypsum, but it is often wavy if installed on 24 inch spaced studs. With 5/8" thick gypsum board, the 24 inch stud spaced wall is heavier than the 16 inch spaced wall. THOW plans typically show all stud locations. After performing the drafting work you'll likely find there are very few studs actually 24 inches apart. This is due to the location of windows, doors, and wheel wells – just another reason to go with 16 inch stud spacing.

In typical home construction water supply piping and drain-waste-vent (DWV) system piping is installed after framing is complete. All non-flexible piping (pretty much everything other than PEX for water supply pipes) is installed by notching studs. The IRC prohibits notches in exterior and bearing wall studs from exceeding 25 percent of the stud width. For space saving reasons almost all THOW are built with 2x4 stud walls. To meet the code this means no more than 7/8 inch may be notched. This would be sufficient for most water supply piping, but certainly not for DWV pipes which are 1.5 inches and larger in diameter. The IRC allows drilled holes in the studs to be 40 percent or less of the stud width (1.4 inches for a 2x4) or if the stud is doubled up 60 percent of the stud width (2.1 inches for a 2x4). Since structurally it is best to remove material from the center rather than edge of a stud, avoid notches altogether in a THOW and used drilled holes instead. This means drilling holes and installing CPVC or copper water supply pipes before attaching wall sheathing.

CPVC water supply piping placed in walls prior to wall sheathing installation. The piping extending past the front of the trailer will be cut and connected to pipes yet to be installed in the front wall. The holes in the front wall studs have been drilled and are ready for pipe installation.

PEX piping is flexible enough to install after framing is completed and as a result it is now the go to material for THOW water supply piping. If at all possible, place any DWV system piping that crosses studs into non-load bearing walls only. Larger diameter DWV pipes may not meet code even by doubling up studs. Place restrictions on notches and details on large drilled holes on the drawing details.

Advanced Framing

Advanced framing, also known as optimum value engineering, is a platform framing method developed to use less material, less labor, and increase building energy efficiency compared to traditional platform framing used in most residential construction. Using less wood allows for more insulation in a given floor, wall, or roof assembly. Advanced framing uses some or all of the following techniques:

- 24 inch on-center stud spacing combined with fully sheathed exterior walls
- Corner and wall intersections using fewer studs
- Single member headers or box headers
- Elimination of headers in non-load bearing walls
- Reduction in number or elimination of jack studs and cripples in certain circumstances
- Single top plate (Achieved by aligning/stacking floor joists, studs, and roof framing members. See Figure 7.)
- Increased use of metal hardware in place of extra lumber

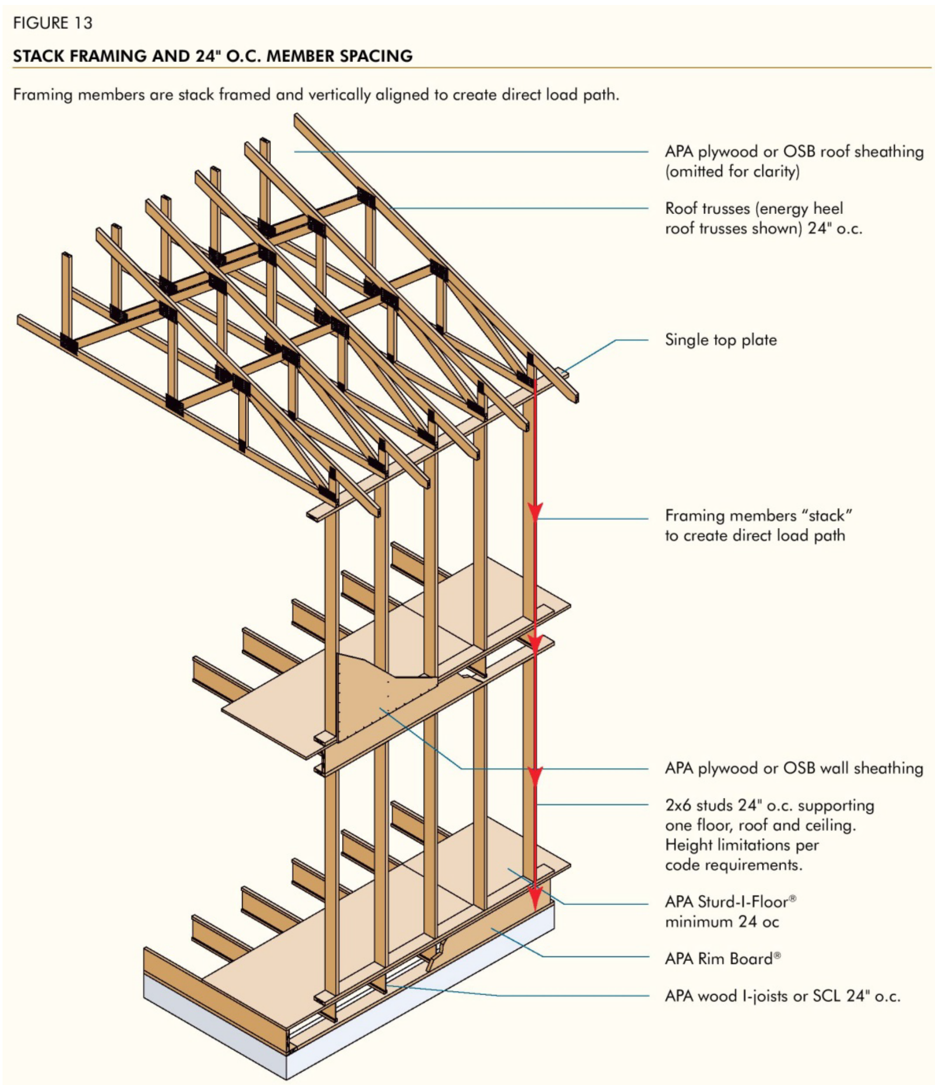


Figure 7: Stacked Framing at 24 inch on-center (from APA Advanced Framing Construction Guide)

The IRC provides prescriptive options for most or all of these techniques. The APA's *Advanced Framing Construction Guide* can be downloaded for free for more information. It includes many diagrams, sketches, and photos of the listed techniques.

Most, if not all, advanced framing techniques can be easily used for THOFs; however, that is not the case for THOW. As previously explained in the Wall Framing and Sheathing section, using 24 inch stud spacing is not very practical and in some cases will increase the overall THOW weight. It is however, easy and practical to use single member headers, eliminate headers in non-load bearing walls, and reduce the number or eliminate jack studs in THOW. Utilizing these three techniques provides weight savings compared to traditional framing techniques.

Some examples of advanced framing including a single 2x12 header instead of two 2x8s, single jack stud for each end of the 2x12 header, and no header for the non-load bearing wall window. This single 2x12 header does not meet the prescriptive requirements of IRC R602.7.1 because it does not have a 2x4 attached to the bottom of the header. Instead the header was designed using allowable stress design methods and a 2x2 was added later to serve as a nailer for the interior wall covering material.

Roof Framing

Most THOW use either rafters or roof joists for their primary roof framing. Figure 8A shows a THOW that would use rafters in conjunction with a ridge beam. Figure 8B shows a THOW that would utilize roof joists.

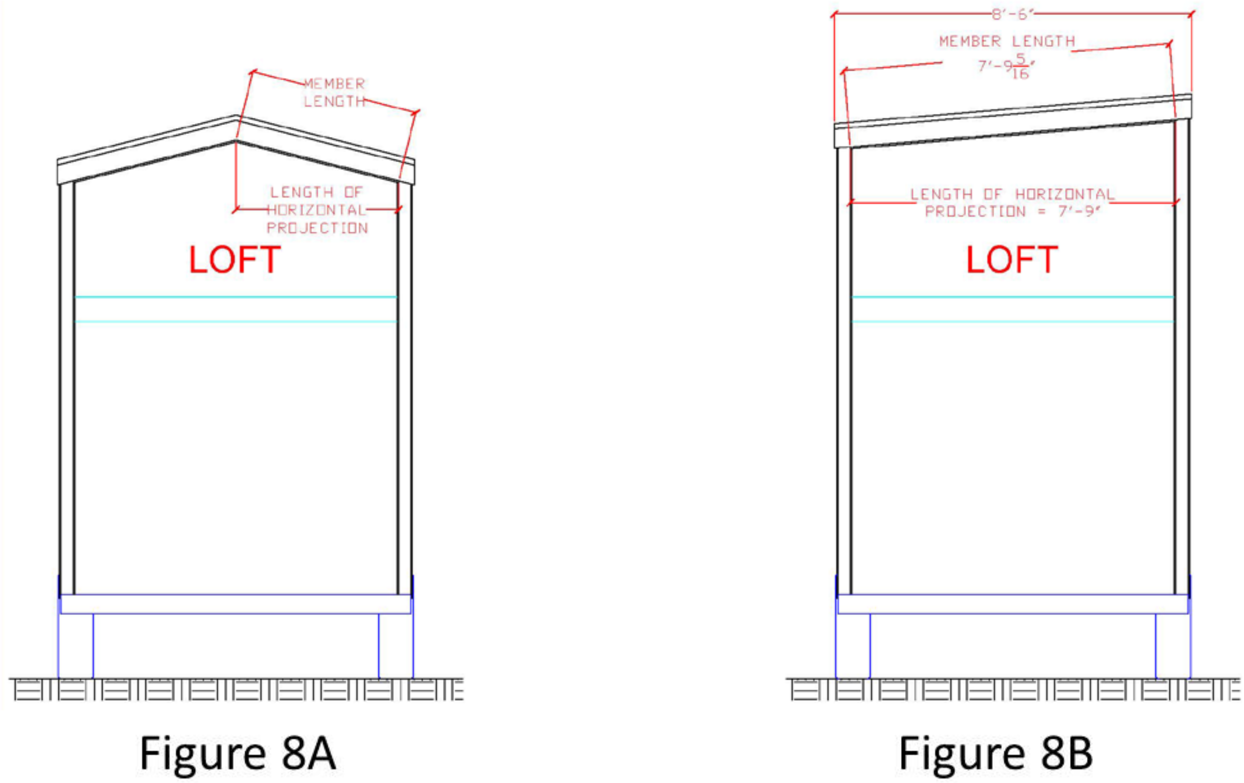


Figure 8: Common THOW with Gable Roof Cross-Section and Common THOW with Shed Roof Cross-Section

The choice of a gable roof or shed roof will likely be made more for aesthetic or headroom reasons since structurally either will work. Prior to sizing roof members using tables in IRC Chapter 8 you must look up some design requirements in IRC Chapter 3. The process will be illustrated through an example.

EXAMPLE:

For the THOW shown in Figure 8B determine the minimum spruce-pine-fir No. 2 roof joist size for 24 inch on-center spacing. Every year the THOW will be moved to the outskirts of Portland, Oregon in late spring and just west of the Phoenix, Arizona suburbs in late autumn. The site elevation in Oregon is 700 feet and the site elevation in Arizona is 1,500 feet. Assume the dead load of the roof joists, sheathing, insulation, standing seam metal roof, and interior ceiling gypsum board (which is attached to the underside of the roof joists) is less than 10 psf. The roof pitch is 1 inch per foot. Photovoltaics will not be mounted on the roof.

SOLUTION:

From Figure 8B we see the roof joist length of horizontal projection is 7 feet 9 inches. IRC Table R301.7 shows the allowable deflections for both "Ceilings with flexible finishes (including gypsum board)" and "All other structural members" are L/240, where L is the span length.

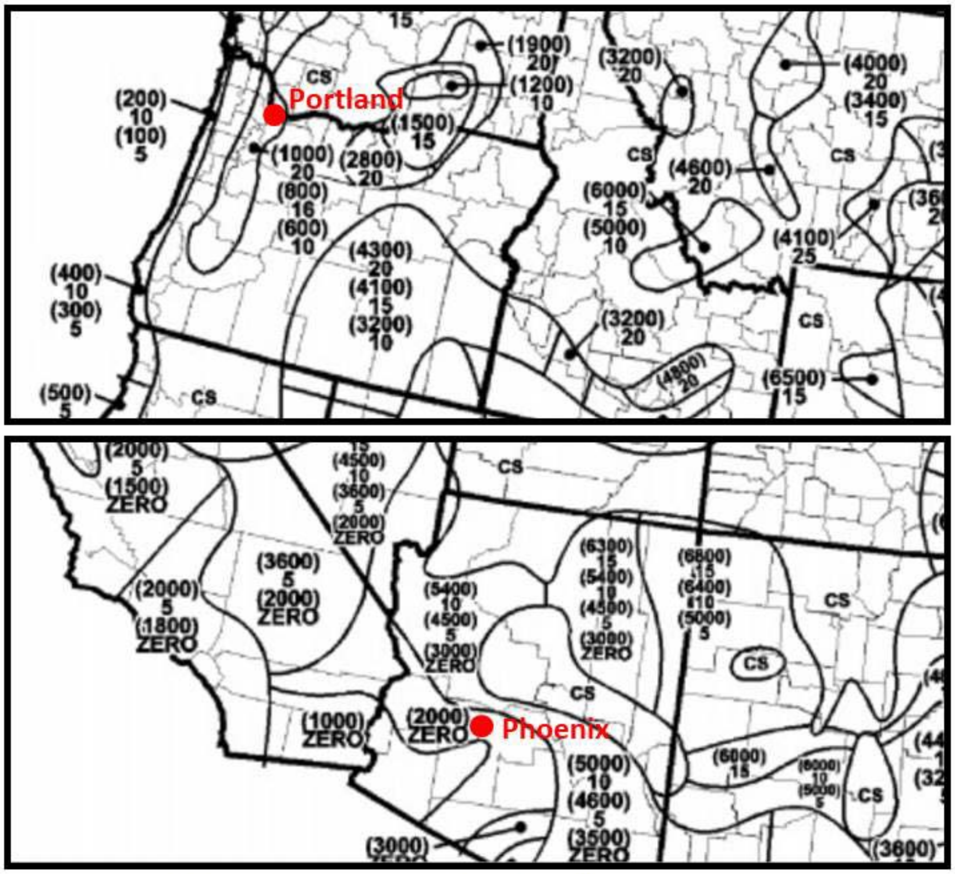
When using IRC tables for roof design, the roof load used is the roof live load or snow load, whichever is greater.

To determine the roof live load use IRC Table 301.6 (see Table 3). The roof joist tributary area is 17 square feet. The tributary area is calculated by multiplying the 24 inch on-center joist spacing by the width of the roof, which is 8 feet, 6 inches. Since the roof slope is less than 4 inches per foot the roof live load required for design is 20 psf.

Roof Slope	Tributary Loaded Area in Square Feet for Any Structural Member		
	0 to 200	201 to 600	Over 600
Flat or rise less than 4 inches per foot (3:1)	20	16	12
Rise 4 inches per foot (1:3) to less than 12 inches per foot (1:1)	16	14	12
Rise 12 inches per foot (1:1) and greater	12	12	12

Table 3: Reproduction of IRC Table R301.6 Minimum Roof Live Loads in Pounds-Force per Square Foot of Horizontal Projection (from 2018 IRC)

To determine the ground snow load for each location use IRC Figure R301.2(6). See Figure 9 for portions of IRC Figure R301.2(6).



For SI: 1 foot = 304.8 mm, 1 pound per square foot = 0.0479 kPa, 1 mile = 1.61 km.

a. In CS areas, site-specific Case Studies are required to establish ground snow loads. Extreme local variations in ground snow loads in these areas preclude mapping at this scale.

b. Numbers in parentheses represent the upper elevation limits in feet for the ground snow load values presented below. Site-specific case studies are required to establish ground snow loads at elevations not covered.

Figure 9: Portions of IRC Figure R301.2(6) Ground Snow Loads, P_g, for the U.S. (lb/ft^2) (from 2018 IRC)

We see the ground snow loads are 16 psf and 0 psf for the Portland and Phoenix sites respectively. The largest of the three loadings controls the design, which in this case is the 20 psf roof live load.

There are eight IRC tables for sizing rafters (IRC Tables R802.4.1(1) to R802.4.1(8)). The rafter tables can also be used to size roof joists. Do not use IRC Tables R802.5.1(1) to R802.5.1(2) for ceiling joists because roof joists and ceiling joists are different types of members. IRC Table R802.4.1(2) is the correct table for our example since it is for a roof live load of 20 psf, ceiling attached to the joists/rafters, and a deflection of L/240. From this table (see Table 4 for a reproduced excerpt) we see the maximum span for spruce-pine-fir #2 at 24 inch on-center spacing is 7'-6" for 2x4s and 11'-9" for 2x6s. Since our required span is 7 feet 9 inches we choose 2x6s. If the ground snow load had controlled in this example it would not have been necessary to convert into a roof snow load since the IRC tables are based on ground snow loads not roof snow loads.

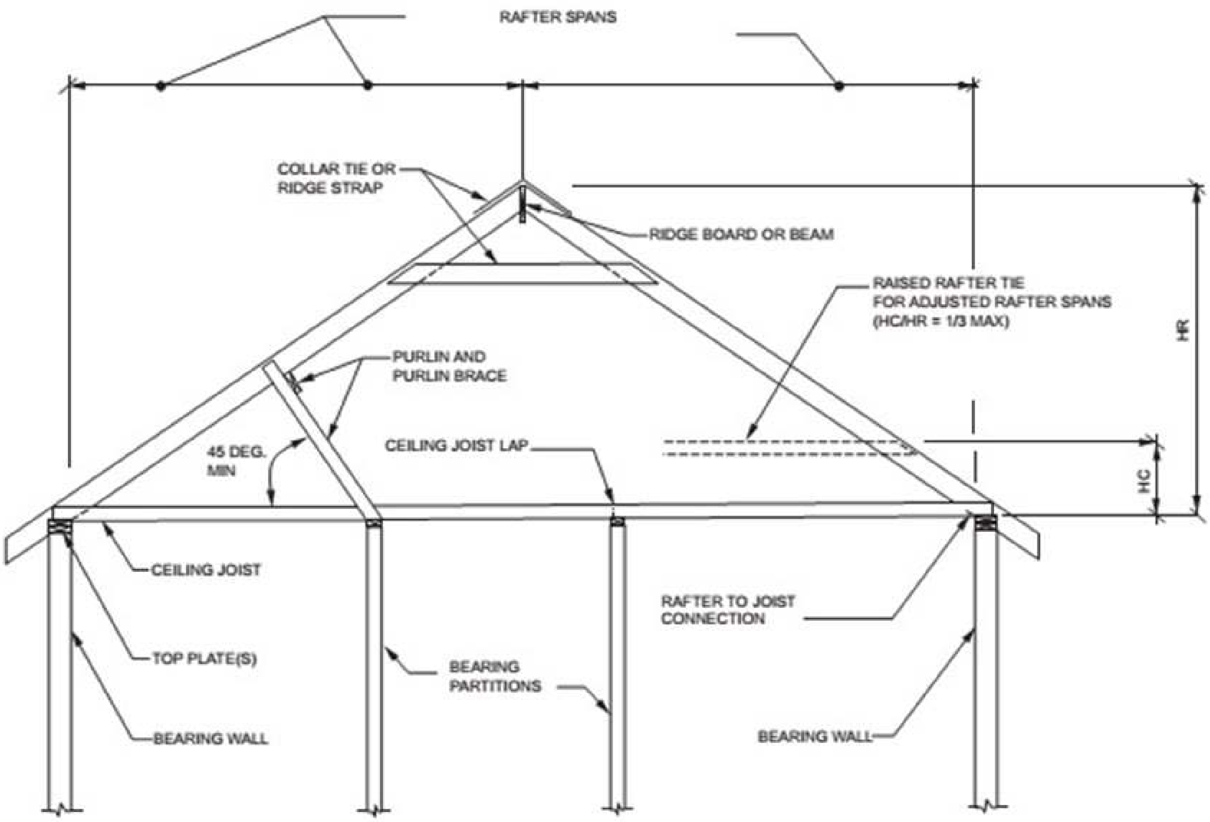
RAFTER SPACING (inches)	SPECIES AND GRADE	DEAD LOAD = 10 psf				
		2 x 4	2 x 6	2 x 8	2 x 10	2 x 12
		Maximum Rafter Spans [a]				
		(feet-inches)	(feet-inches)	(feet-inches)	(feet-inches)	(feet-inches)
24	Spruce-pine-fir SS	7-8	12-0	15-10	20-2	24-7
	Spruce-pine-fir #1	7-6	11-9	14-10	18-2	21-0
	Spruce-pine-fir #2	7-6	11-9	14-10	18-2	21-0
	Spruce-pine-fir #3	6-1	8-10	11-3	13-8	15-11

Table 4: Reproduction of excerpt from IRC Table R802.4.1(2) Rafter Spans for Common Lumber Species (Roof Live Load = 20 psf, ceiling attached to rafters, L/Δ =240) (from 2018 IRC)

Gable roofs with rafters at a pitch 3:12 and steeper may use ridge boards, which are non-structural members that the rafters simply abut to. Typically, a ridge board for 2x4 rafters would be a 2x6, for 2x6 rafters a 2x8, etc. When using a ridge board, the IRC also requires the use of ceiling joists or rafter ties (see Figure 10).

It is likely practical to use either ceiling joists or rafter ties for a THOF or a THOW without lofts. It is not very practical for a THOW with lofts since these members would both run directly through the loft space. Using a ridge beam is a better option in these situations. Gable roofs with rafters at a pitch of less than 3:12 need a ridge beam, which is a structural member. Ridge beams are supported at each end by the gable end walls or posts. Size ridge beams in a manner similar to the example provided previously for loft floor joists or later example for headers. The load magnitudes, load locations, member length, and controlling load combination are the only major differences.

Lateral support of rafters and roof joists is only required for very deep members. If you use 2x10 or larger rafters or roof joists check IRC R802.8 for details.



For SI: 1 inch = 25.4 mm, 1 foot = 305 mm, 1 degree = 0.018 rad.

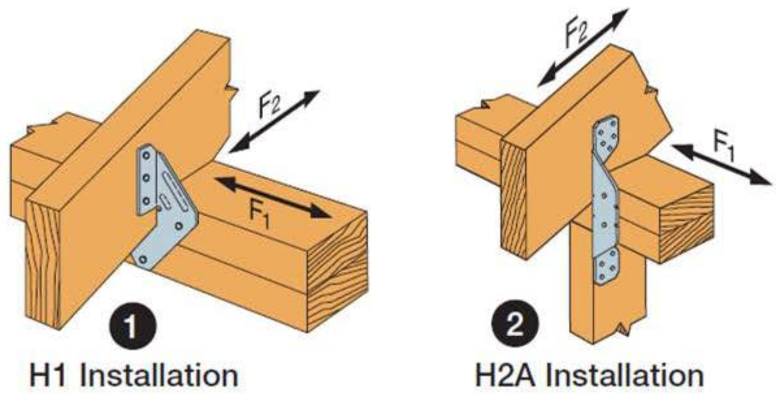
H_C = Height of ceiling joists or rafter ties measured vertically above the top of rafter support walls.

H_R = Height of roof ridge measured vertically above the top of the rafter support walls.

FIGURE R802.4.5
BRACED RAFTER CONSTRUCTION

Figure 10: IRC Figure R802.4.5 Braced Rafter Construction (from 2018 IRC)

IRC Table R802.11 provides calculated uplift forces for roof framing members. In general, if the rafter or roof joist uplift force does not exceed 200 pounds, only nails are required for the roof-to-wall connection. I think this is a connection where it is wise to far exceed the code, especially for a THOW. Hurricane ties are available for less than $1 per tie. Including nails, the cost of using hurricane ties on a 20' long THOW's roof is about $20 in materials. For the wood species used in our example, the Simpson Strong-Tie H1 Hurricane Tie is rated for 425 pounds of uplift when all fastener holes are used with the nails size indicated in the product catalog (see Figure 11). This is more than sufficient for our example.



Seismic and Hurricane Ties (cont.)

These products are available with additional corrosion protection. For more information, see p. 15.

SS For stainless-steel fasteners, see p. 21.

SD Many of these products are approved for installation with Strong-Drive® SD Connector screws. See pp. 335–337 for more information.

Model No.	Ga.	Fasteners (in.) To Rafters/Truss	Fasteners (in.) To Plates	Fasteners (in.) To Studs	DF/SP Allowable Loads Uplift (160)	DF/SP Lateral (160) F_1	DF/SP Lateral (160) F_2	Uplift with 0.131" x 1½" Nails (160)	SPF/HF Allowable Loads Uplift (160)	SPF/HF Lateral (160) F_1	SPF/HF Lateral (160) F_2	Uplift with 0.131" x 1½" Nails (160)	Code Ref.
H1	18	(6) 0.131 x 1½	(4) 0.131 x 2½	—	480	510	190	455	425	440	165	370	IBC, FL, LA
H1.81Z	18	(6) 0.131 x 1½	(4) 0.131 x 2½	—	350	335	195	330	300	290	150	260	—
H2A	18	(5) 0.131 x 1½	(2) 0.131 x 1½	(5) 0.131 x 1½	525	130	55	—	495	130	55	—	IBC, FL, LA

Figure 11: Seismic and Hurricane Tie Product Info (from Simpson Strong-Tie 2019-2020 Wood Construction Connectors Catalog)

Trusses and engineered wood I-joists are other common options for THOF roof framing. The IRC does not include tables for sizing trusses or engineered I-joists. Sizing is accomplished using tables supplied by manufacturers. Sometimes trusses are custom designed by the truss manufacturer's engineer. It would be somewhat unusual to use engineered wood I-joists for a THOW's roof framing since the thinnest commonly manufactured depth is 8.5 to 9.5 inches, depending on the manufacturer. Except for the coldest climates or THOW without lofts, it is unlikely the reduction in head room would be worth the small increase in insulation that can be achieved by using such deep floor joists. This is even truer for trusses so they would likely never be used in a THOW.

Cold-formed steel roof rafters and roof joists can be sized using IRC Tables R804.3.2.1(1) and R804.3.2.1(2). There are numerous figures in IRC Section R804 showing connection details that will likely need to be used if steel framing is used.

Roof Sheathing

In all but the most stringent seismic design categories, IRC Section R803 allows both structural panel sheathing and lumber sheathing as roof sheathing. The most typical construction method for tiny houses is to use 3/8” or 7/16” thick plywood or OSB with an Exterior or Exposure 1 classification. Both of these thicknesses are allowed on roofs with on-center framing 24 inches or closer together. For spans greater than 24 inches, consult IRC Table R503.2.1.1(1). While 3/8” thickness may be allowable based on spans, many roof manufacturers require 1/2” thick sheathing for warranty purposes. Again the strength axis of the sheathing is installed perpendicular to the joists. Whether edge support is required or not is determined by looking at IRC Table R503.2.1.1(1). Either solid lumber blocking, sheathing clips (the IRC calls them panel edge clips and some people call them plywood clips), or tongue and groove (T&G) sheathing may be used for edge support. T&G is only used for the widest of spans so sheathing clips are the lightest option. Sheathing clips (see Figure 12) also allow for more consistent insulation thickness in THOW vented roof assemblies.

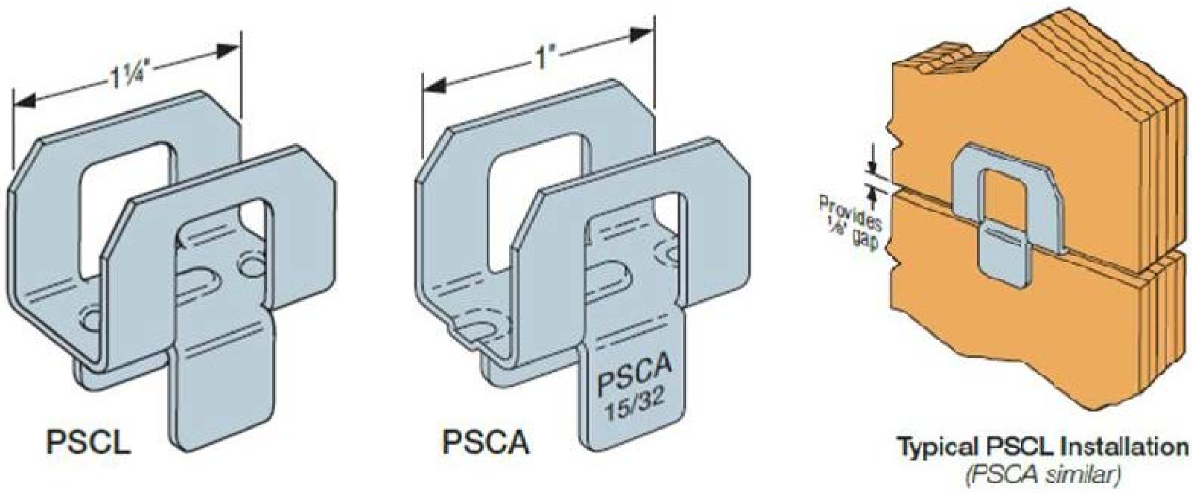


Figure 12: Panel Sheathing Clips (from Simpson Strong-Tie 2019-2020 Wood Construction Connectors Catalog)

Lumber sheathing is usually only used if exposed roof framing members are wanted or if wood shingles or shakes are used and a historical look is desired. Exposed roof framing members mean insulation must be installed above the roof sheathing and this almost always results in using an unvented roof assembly. Vented and unvented roof assemblies will be addressed in the next course in this series, *Tiny Houses Part 3 – Building Enclosure Design*.

Exposed roof framing members with tongue and groove lumber roof sheathing

Window and Door Headers

The IRC provides a prescriptive method for sizing window and door headers made from the most common wood framing species (Douglas fir-larch, hem-fir, Southern pine, and spruce-pine-fir). Simply use IRC Table R602.7(1) when using one of these four species for headers in exterior load bearing walls. Using IRC Table R602.7(1) will often overdesign headers in THOW because the minimum building width shown in the table is 12 feet and most THOW are 8 feet 6 inches or less in width. An example will illustrate this typical overdesigning.

EXAMPLE:

This example uses the same THOW as the roof framing example. From that previous example we determined the ground snow loads were 16 psf in Portland and 0 psf near Phoenix. The roof live load was 20 psf. Assume the total dead load for the header is equivalent to 7 psf over the roof tributary area. The wall studs are spaced at 16 inches on-center. Figure 13 shows the exact cripple stud spacing above the window header. Size the Douglas fir-larch No. 2 window header using both IRC Table R602.7(1) and National Design Specification (NDS) for Wood Construction methods. Check bending and shear. For the purpose of this example, assume deflection and bearing are not issues.

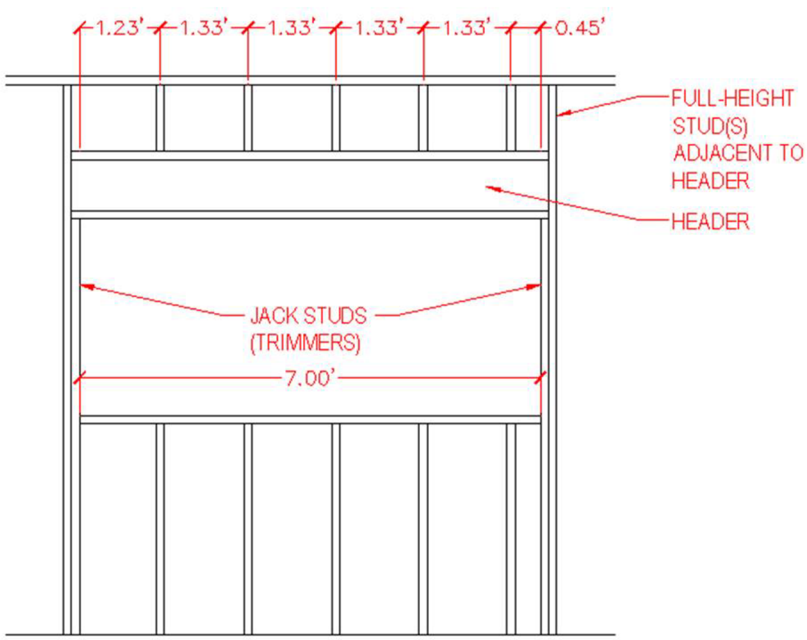


Figure 13: Layout for Header Example

SOLUTION:

Sizing the header using IRC Table R602.7(1) requires knowing the ground snow load, building width, and necessary header span. Per footnote E of Table R602.7(1) we are to use the 30 psf snow load column for cases when the "ground snow load is less than 30 psf and the roof live load is equal to or less than 20 psf." This is our situation, so for this example we use the 30 psf snow load column. From Figure 8B we see the building width is less than 12 feet and Figure 13 shows a header span of 7 feet. Using Table 5, which is an excerpt from IRC Table R602.7(1), we see that one 2x12 with 2 jack studs can span 7 feet 1 inches or two 2x8s with 1 jack stud can span 7 feet 7 inches. Either option will work, but for this example let's choose the single 2x12.

When framing anchors are used they eliminate the need for jack studs. This reduces weight and increases the amount of insulated wall area. Look for concealed face-mount joist hangers from Simpson Strong-Tie or USP to use as framing anchors. The chosen hanger needs to be rated to support a vertical downward load greater than the largest header end support reactions (the larger of R_A or R_B). We will calculate R_A and R_B for this example a little later.

Girders and Headers Supporting	Size	Ground Snow Load (psf)					
		30					
		Building Width (feet)					
		12		24		36	
		Span	NJ	Span	NJ	Span	NJ
Roof and Ceiling	1-2x6	4-0	1	3-1	2	2-7	2
	1-2x8	5-1	2	3-11	2	3-3	2
	1-2x10	6-0	2	4-8	2	3-11	2
	1-2x12	7-1	2	5-5	2	4-7	3
	2-2x4	4-0	1	3-1	1	2-7	1
	2-2x6	6-0	1	4-7	1	3-10	1
	2-2x8	7-7	1	5-9	1	4-10	2
	2-2x10	9-0	1	6-10	2	5-9	2
	2-2x12	10-7	2	8-1	2	6-10	2

Table 5: Reproduction of excerpt from IRC Table R602.7(1). NJ = Number of jack studs required to support each end. (from 2018 IRC)

Next we'll size a single header using allowable stress design methods from the NDS and compare that header to the header sized by the IRC prescriptive method just used. First, we need to calculate the load each cripple stud exerts on the window header. Use the load combinations in IBC 1605.3.1 since an allowable stress design (ASD) method will be used. The controlling load combination for this scenario is IBC Equation 16-10:

$$D + H + F + (L_r \text{ or } S \text{ or } R) \quad (Equation\ 9)$$

Where:
- D = Dead load
- H = Load due to lateral earth pressures, ground water pressure, or pressure of bulk materials
- F = Load due to fluids with well-defined pressures and maximum heights
- L_r = Roof live load of 20 psf or less
- S = Snow load
- R = Rain load

H, *F*, and *R* are not applicable in this situation. As a result, the design loading is 27 psf, which is the given 7 psf dead load plus the 20 psf roof live load. Next, multiply the design loading by the tributary area of each stud. The tributary area width is the on-center stud spacing (16 inches). The tributary area length is the roof width (8.5 feet).

$$Vertical\ Load\ (each\ stud) = \left(27\ \frac{lbs}{ft^2}\right)\left(\frac{16}{12}\ ft\right)(8.5\ ft) = 306\ lbs$$

See Figure 14 for the window header's free body diagram.

Figure 14: Free Body Diagram for Header Example

Using undergraduate statics, R_A and R_B are calculated as 680 and 850 lbs, respectively. Using shear and moment diagrams, the maximum shear and moment are 850 lbs and 1,424 ft-lbs, respectively. See Figure 15 for the completed shear and moment diagrams.

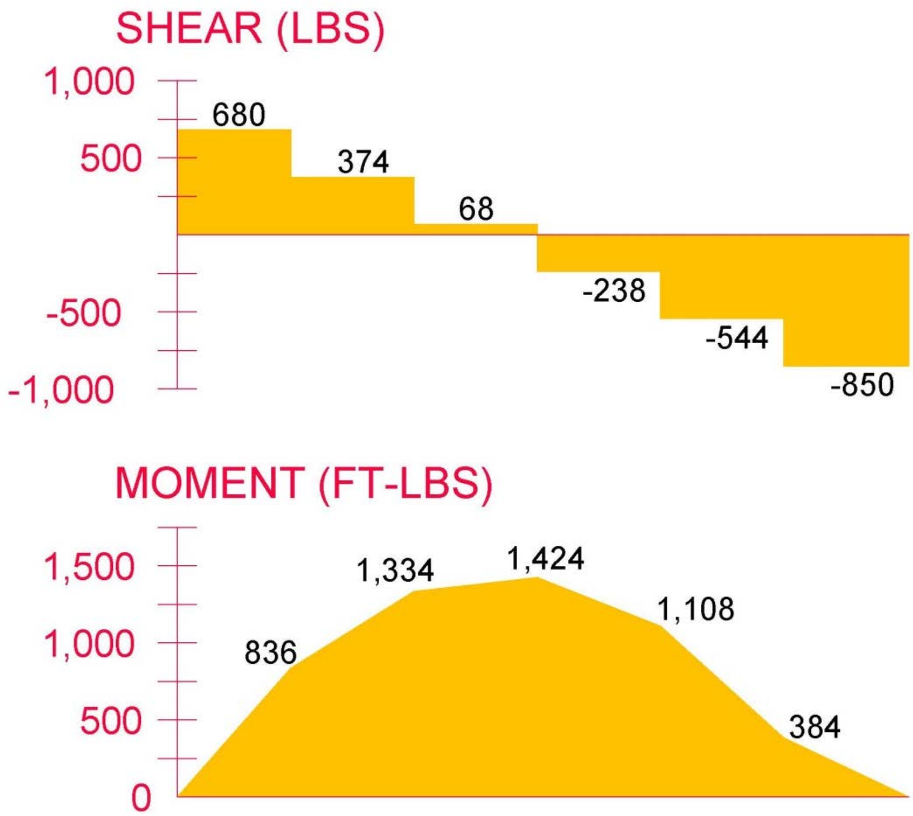


Figure 15: Shear and Moment Diagrams for Header Example

Since the prescriptive method required a 2x12, we will calculate if the next smaller standard dimensional lumber size works. So we'll check a 2x10 for bending, since bending is most likely the controlling design criterion. Recall a 2x10 is actually 1.5 inches wide by 9.25 inches deep. Using Equation 4 results in:

$$f_b = \frac{M}{\left(\frac{bd^2}{6}\right)} = \frac{1{,}424\ ft - lbs}{\left(\frac{\left(\frac{1.5}{12} ft\right)\left(\frac{9.25}{12}\ ft\right)^2}{6}\right)\left(\frac{144\ in^2}{1\ ft^2}\right)} = 799\ psi$$

Since the header is not subject to sustained wet conditions, is not subject to high temperatures, is continuously supported along its compression face by 2x4 framing, and is not incised for pressure treatment the allowable bending stress equation again simplifies to Equation 5.

From Table 1, find an F_b value of 850 psi for grade No. 2 Douglas fir. Table 1 is actually for Douglas fir south which has a slightly lower F_b value than Douglas fir-larch we're using in this example, so we are being conservative. From Table 2, select a C_D value of 1.15 for snow loads. Some engineers might use a C_D value of 1.25 for construction loads (since roof live loads are construction loads). Using the 1.15 value is more conservative. The size factor table in the NDS Supplement shows a C_F of 1.1 for a 2x10. The repetitive member factor, C_r has a value of 1.0 for a single header.

Using Equation 5 to solve for F'_b results in:

$$F'_b = F_b(C_D)(C_F)(C_r) = (850\,psi)(1.15)(1.1)(1.0) = 1{,}075\,psi$$

Since an F'_b (allowable bending stress) of 1,075 psi is greater than the calculated f_b (actual maximum bending stress) of 799 psi a 2x10 is sufficient for bending. When the same calculations are repeated for a 2x8, F'_b is less than f_b so a 2x8 can't be used.

The next step is to check the 2x10 for shear. Using Equation 6 results in:

$$f_v = \frac{1.5V}{bd} = \frac{(1.5)(850\,lbs)}{(1.5\,in)(9.25\,in)} = 92\,psi$$

Since the header is not subject to sustained wet conditions, not subject to high temperatures, and not incised for pressure treatment the allowable shear stress equation again simplifies to Equation 7.

From Table 1, find an F_v value of 180 psi. As already found for bending, use a C_D value of 1.15. Using Equation 7 to solve for F'_v results in:

$$F'_v = F_v(C_D) = (180\,psi)(1.15) = 207\,psi$$

Since an F'_v (allowable shear stress) of 207 psi is greater than the calculated f_v (actual maximum shear stress) of 92 psi a 2x10 is sufficient for shear. From using engineering analysis we see that we can reduce the header size to a 2x10 instead of using the 2x12 the prescriptive method required.

After sizing a header using either method presented, use IRC Table R602.7.5 to determine the number of full-height studs (most people refer to them as king studs) at each end of the header. Using Table R602.7.5 usually overprescribes the number of full-height studs for a THOW. A column design using NDS methods would need to be completed to reduce the full-height stud quantity.

Additional Structural Components for THOW

Due to their mobile nature, many THOW builders include additional structural components that are not universally required by the IRC. The most commonly used products and techniques include:

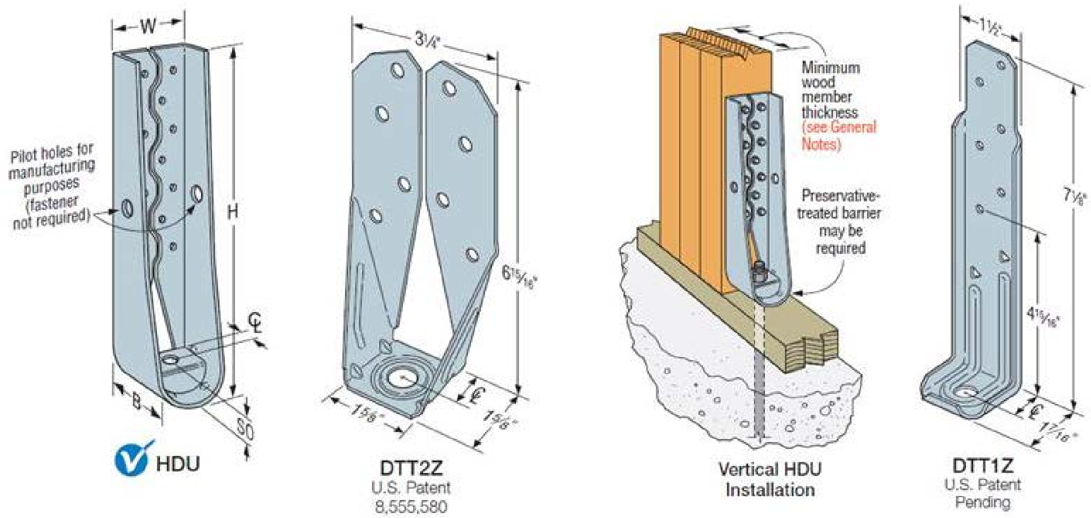
- Coiled metal strapping: To add shear strength to walls and better connect the end and side walls to each other, some builders wrap steel straps around all or portions of a THOW's perimeter. Example products include Simpson Strong-Tie CS-14, CS-16, CS-20, or CS-22. Given the number of nails required to fully utilize the allowable tensile capacity of the steel cross-section (see Figure 16) it is unlikely a THOW will have enough studs or space to attach enough fasteners to fully utilize the capacity of CS-14 or CS-16. Specifying CS-20 or CS-22 is a more efficient use of materials and these smaller gauge products are easier to bend than the larger gauges.

Model No.	Total L	Ga.	DF/SP Fasteners (in.)	DF/SP End Length	SPF/HF Fasteners (in.)	SPF/HF End Length	Allowable Tension Loads (160)	Code Ref.
CMST12	40'	12	(74) 0.162 x 2½	33"	(84) 0.162 x 2½	38"	9,215	IBC, FL, LA
			(86) 0.148 x 2½	39"	(98) 0.148 x 2½	44"	9,215	
CMST14	52½'	14	(56) 0.162 x 2½	26"	(66) 0.162 x 2½	30"	6,475	
			(66) 0.148 x 2½	30"	(76) 0.148 x 2½	34"	6,475	
CMSTC16	54'	16	(50) 0.148 x 3¼	20"	(58) 0.148 x 3¼	25"	4,690	
CS14	100'	14	(26) 0.148 x 2½	15"	(30) 0.148 x 2½	16"	2,490	
			(30) 0.131 x 2½	16"	(36) 0.131 x 2½	19"	2,490	
CS16	150'	16	(20) 0.148 x 2½	11"	(22) 0.148 x 2½	13"	1,705	
			(22) 0.131 x 2½	13"	(26) 0.131 x 2½	14"	1,705	
CS20	250'	20	(12) 0.148 x 2½	6"	(14) 0.148 x 2½	9"	1,030	
			(14) 0.131 x 2½	9"	(16) 0.131 x 2½	9"	1,030	

Figure 16: Coiled Strap Product Info (from Simpson Strong-Tie 2019-2020 Wood Construction Connectors Catalog)

Coiled metal strapping (Simpson Strong-Tie CS-22) running diagonally between studs

- Holdowns: Holdowns are an anchorage solution used in some high earthquake hazard areas (see Figure 17). Holdowns provide a direct connection between a foundation (or trailer) and studs (or columns) and helps bridge a weaker connection between the bottom plate and studs. Example products include Simpson Strong-Tie DTT2Z or HDU-4.



Model No.	Ga.	Dimensions (in.)					Fasteners (in.)		Minimum Wood Member Size (in.)	Allowable Tension Loads (160)			Code Ref.
		W	H	B	CL	SO	Anchor Bolt Dia. (in.)	Wood Fasteners		DF/SP	SPF/HF	Deflection at Allowable Load (in.)	
DTT1Z	14	1½	7⅛	1 7/16	¾	3/16	⅜	(6) SD #9 x 1½	1½ x 5½	840	840	0.17	IBC, FL, LA
								(6) 0.148 x 1½		910	640	0.167	
								(8) 0.148 x 1½		910	850	0.167	
DTT2Z	14	3¼	6 15/16	1⅝	13/16	3/16	½	(8) ¼ x 1½ SDS	1½ x 3½	1,825	1,800	0.105	
								(8) ¼ x 1½ SDS	3 x 3½	2,145	1,835	0.128	
DTT2Z-SDS2.5								(8) ¼ x 2½ SDS	3 x 3½	2,145	2,105	0.128	
HDU2-SDS2.5	14	3	8 11/16	3¼	1 5/16	1⅜	⅝	(6) ¼ x 2½ SDS	3 x 3½	3,075	2,215	0.088	
HDU4-SDS2.5	14	3	10 15/16	3¼	1 5/16	1⅜	⅝	(10) ¼ x 2½ SDS	3 x 3½	4,565	3,285	0.114	
HDU5-SDS2.5	14	3	13 3/16	3¼	1 5/16	1⅜	⅝	(14) ¼ x 2½ SDS	3 x 3½	5,645	4,340	0.115	

Figure 17: Holdown Product Info (from Simpson Strong-Tie 2019-2020 Wood Construction Connectors Catalog)

- Threaded rods: To provide a continuous metal connection from trailer to wall top plate, some builders install 3/8" to 5/8" diameter zinc coated threaded rods in wood framed THOW. Often they install four to eight rods (one or two per wall), place washers and nuts on each end of the rods, and tighten. The nuts below the trailer frame are always accessible, but the nuts above the top plates are not accessible once the roof and interior wall finishes are installed. Be sure to specify kiln-dry lumber. Wetter lumber will shrink enough during the first year that the nuts will likely require retightening to maintain the effectiveness of the method.

- Interior sheathing: To add even more shear strength to walls and/or roofs some builders sheath not only the exterior, but also the interior of the building frame. This approach will add significant weight (around 20 pounds per foot of trailer length).

This THOW has interior wall sheathing. In this case OSB was added to the inside of the stud walls and painted as the finished wall surface. The OSB also could have been covered with a separate finish material.

- Screws: Screws have greater withdrawal resistance than comparably sized nails – which is even more important when a structure is subject to movement and vibrations. A common usage is to add a 3.5 inch long deck screw to each wall plate/stud connection (in addition to the nails required by the IRC). Don't replace all the nails with screws in this connection because screws are both more brittle and provide less shear resistance than comparably sized nails.
- Framing angles: Toenailing and end nailing are two of the weaker types of nailed connections. The use of framing angles can strengthen these connections; especially in certain problem areas (see Figure 18 for examples of various framing angles).

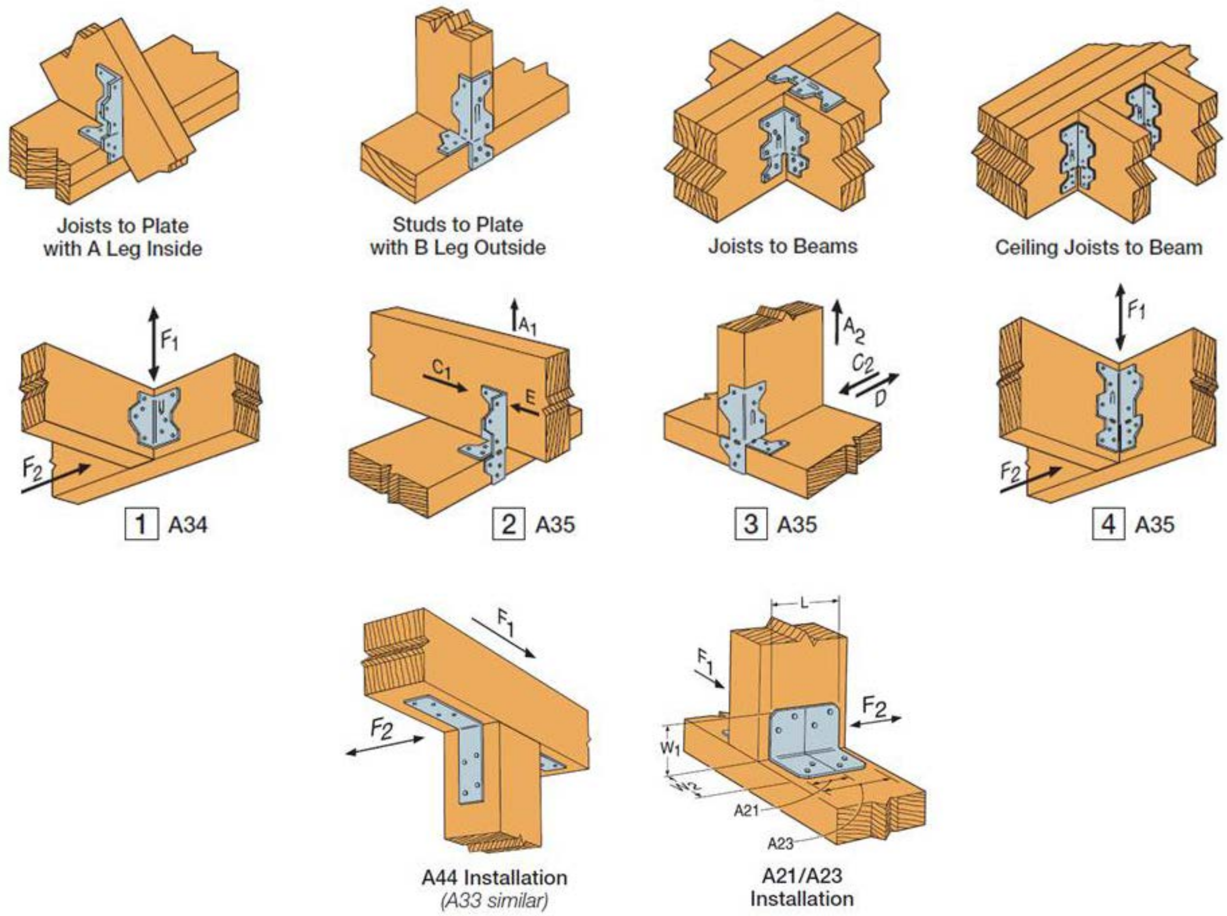


Figure 18: Framing Angle Product Info (from Simpson Strong-Tie 2019-2020 Wood Construction Connectors Catalog)

Whether or not you choose to design a THOW with any, some, or all of these features should be highly contingent on the design wind speed and earthquake risk for the building location as well as the frequency of THOW movement. Loads experienced during transportation are in many ways similar to wind loadings on a stationary house.

Keep in mind that in most situations, building to the minimum requirements of the IRC, will result in a THOW that will blow over, trailer and all, before the walls or roof fail due to wind loading. While many factors come into play, a typical THOW becomes susceptible to overturning sideways by winds somewhere around 90 miles per hour (mph). Consequently there is little reason to design a wall to withstand 150 mph or greater winds. Now, certainly there are combined and additive forces a THOW can experience while in movement that a THOF normally would not. For instance, wind load perpendicular to a side wall and lateral forces on the front end wall due to the direction of travel. Or both wind and direction of travel loads on the front end wall. However, it would be unwise and unlikely for someone other than James Bond to continue driving 70 mph in an 80 mph windstorm and experience these simultaneous loadings. Anecdotal observations seem to confirm this as well. When I see accidents involving single- or double-wide manufactured homes along roadways they all seem to have overturned first. Any damage that occurred was the result of hitting the ground.

Unless extreme loadings or frequent travelling are expected I usually only use three of the six products/techniques mentioned: screws, coiled metal strapping, and framing angles in select locations.

Conclusion

This course was intended to provide detailed prescriptive and engineered solutions for structural systems of tiny houses. Special emphasis was placed on the mobile considerations of THOW.

Remember there will be two more courses in this series. Course three will focus on the remaining building enclosure components: ventilation, siding, doors, windows, interior finishes, insulation, and air sealing. Course four will discuss mechanical, electrical, and plumbing (MEP) systems with an emphasis on going off-grid or mobile with a tiny house. Look for courses three and four to be released in late 2019 or early 2020.

References

1. American Wood Council, 2007. *Beam Design Formulas with Shear and Moment Diagrams.*
2. American Wood Council, 2017. *National Design Specification (NDS) for Wood Construction, 2018 Edition.*
3. American Wood Council, 2018. *National Design Specification (NDS) Supplement: Design Values for Wood Construction, 2018 Edition.*
4. American Wood Council, 2015. *Span Tables for Joists and Rafters.*
5. Breyer, D.E., Fridley, K.J., Cobeen, K.E., 1999. *Design of Wood Structures ASD, Fourth Edition*. McGraw-Hill, New York, New York.
6. Engineered Wood Association, 2014. *APA Advanced Framing Construction Guide.*
7. Engineered Wood Association, 2016. *APA Engineered Wood Construction Guide.*

8. International Code Council. 2018 International Building Code. Retrieved from https://codes.iccsafe.org/content/IBC2018
9. International Code Council. 2018 International Residential Code. Retrieved from https://codes.iccsafe.org/content/IRC2018
10. Simpson Strong-Tie Company, Inc., 2019. *Wood Construction Connectors 2019-2020.*
11. Western Wood Products Association. *Guide to Understanding WWPA Grade Stamps and Quality Control Identification.*

