INTRODUCTION

to

STRUCTURAL DESIGN

A Beginner's guide to Gravity Loads and Residential Wood Structural Design

by
Albert Hilton Cohen

INTRODUCTION

This guide is intended as introduction to residential gravity loads, load paths and structural wood design. Further study is recommended prior to designing structures. Proper structural design engineering requires a thorough understanding of construction materials, construction practices, engineering principles and local building codes. The following publications are suggested as important reference materials are a starting point for an education in structural engineering. There are many books published on this subject by McGraw-Hill, Inc., Wiley & Sons, Inc., Craftsman Book Company and others.

Simplified Engineering for Architects and Builders
Parker/Ambrose, author   Wiley & Sons, publisher

Design of Wood Structures
Donald Breyer, author   McGraw-Hill, publisher

National Design Specification, NDS® & design values supplement
American Forest & Paper Association, AF&PA
1111 - 19th St. N.W., Suite 800
Washington, D.C. 20036

Design manual published by your local Wood Products Association.

Manual of Steel Construction
American Institute of Steel Construction, Inc., AITC
1 East Wacker Drive, Suite 3100
Chicago, IL 60601

Your Building Code: The S.B.C.C.I., B.O.C.A., C.A.B.O., or the U.B.C.

Uniform Building Code, International Conference of Building Officials
5360 S. Workman Mill Road
Whittier, CA 90601

Product literature from your local truss manufacturers association.

Product literature and design data for structural composite lumber from your local suppliers. The national companies for these products are Trus-Joist MacMillan, Boise Cascade, Louisiana-Pacific and Georgia- Pacific.

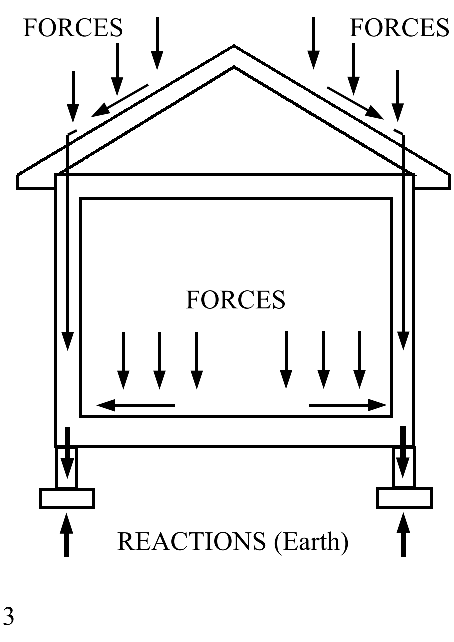
1. FORCES AND LOAD TERMINOLOGY

FORCES

Structures are subjected to many kinds of natural forces. The most basic force is gravity which is always at work and usually acts upon buildings in a simple, downward direction. Sideways or *lateral* forces can be produced by wind and earthquakes. Wind passing over a roof can also create suction which is an *uplift* force. Lateral forces vary in intensity based on the building's location on our planet, whereas gravity acts similarly on all buildings. Other forces include *impact loads*, *temporary loads* such as construction materials stockpiled while the building is being constructed, and *moving loads* caused by automobiles or construction equipment. The term *force* is used interchangeably with *load* and sometimes *weight*. This booklet deals with the vertical forces created by gravity. Lateral and moving loads require special analysis and are separate subjects.

EQUILIBRIUM

The goal of the whole design process is to achieve an *equilibrium* of the forces acting upon a structure. Without equilibrium the building will move and that is not good! Equilibrium must be accomplished for the building as a whole and for all the parts or smaller assemblies within the building as well. For all of the forces acting downward due to gravity, an equal, opposite force called a *reaction* must be pushing up. In other words, as the loads travel down *load paths* through the structure, each element such as beams and posts, must be capable of supporting or reacting to the loads above it. All of the loads acting on a structure will ultimately accumulate in the foundation and must be met with an equivalent reaction from the earth below.



TYPES OF LOADS

Vertical loads fall into two categories called ***live loads*** and ***dead loads.*** When these two are combined they are referred to as the ***total load***. Dead loads are the actual weights of all the permanent components of a structure such as wood framing, roofing, plywood sheathing, and insulation. On occasion, permanent equipment such as large air conditioners can be considered dead loads. These are loads that will be acting upon the structure throughout its life. Live loads on the other hand are transient items such as furniture, people, and snow. The anticipated weight of live loads to be used for building design are specified in the building code that is in force where the building will be constructed. Local building officials will also have site specific requirements for certain live loads such as for anticipated snow fall. The building use or *occupancy* can also affect the design load requirements.

Note: The loading examples included in this booklet may or may not represent the live load requirements of the building department having jurisdiction where your building will be constructed.
You should contact your building official to confirm the floor live load based on the type of occupancy and the roof live load based on the local history of snow fall. If the snow load is large, inquire whether a reduction is allowed for steep pitched roofs.

TERMINOLOGY OF LOADS

The structural design for gravity loads involves evaluating each member for performance under the anticipated live loads, dead loads, and a combined force of live load plus dead load often called the total load or "TL". The design process starts at the roof and continues down to the foundation. This is opposite the actual construction which starts at the bottom and works up. Loads are described in terms of pounds. An often used symbol for pounds is # or lbs. When designing large structures with large loads, engineers will often use the term kips symbolized by *k*. One kip is equal to 1000#. Kips simplify calculations by dropping the last three zeros. In residential design we deal with lower weights and use pounds for greater accuracy.

A.) PT LOAD
A ***Point Load*** is a concentrated load in pounds at a specific location. This may be the location of bearing of a beam or a post.

B.) PSF

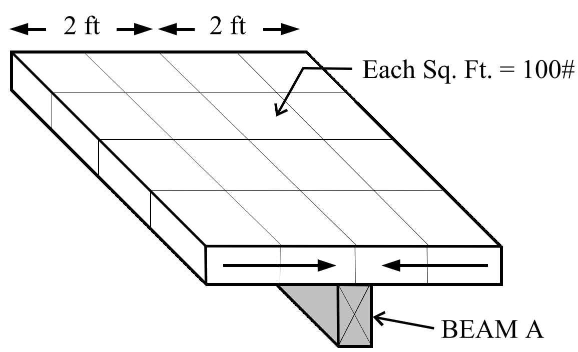
Pounds per square foot is used to describe loads on flat surfaces such as floors and roofs. Each square foot of the surface has the same load. To total the load on an area, multiply the Area times the PSF.

C.) PLF

Pounds per lineal foot is used to describe loads on walls or long members such as beams. The beam receives an equal load for each foot of length.

Example: Beam 'A' has 2 sq ft of contributing load on each side (a tributary load). The load on each sq ft is 100 PSF. Therefore 2 ft + 2 ft = a tributary width of 4 ft x 100 PSF = 400 **PLF** along the beam.

Note: Rafters and floor joists have a tributary load equal to their spacing, i.e., 12" on center, 16" on center, etc. Their PLF = PSF x spacing in feet. To convert inches to feet, divide by 12. Example: 16 inches / 12 = 1.333 ft.



D.) UNIFORM LOAD

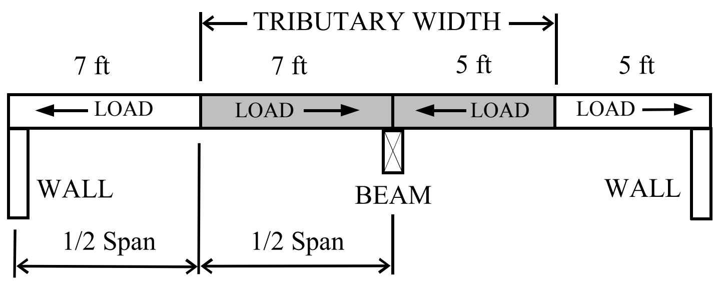
A ***uniform load*** is a continuous load along the entire length of a member and is expressed in PLF. A ***partial uniform load*** is also expressed in PLF, but does not run the entire length of the member.

Note: The ends of joists and rafters bearing on a wall or beam each produce a small point load and when spaced 24"oc or less (in a uniform manner) they can be considered to produce uniform loading.

E.) TRIBUTARY WIDTH

Tributary loading or tributary width is the accumulation of loads that are directed toward a particular structural member.

Example: Tributary width is 7 ft + 5 ft = 12 ft. If the load is 100 PSF, the load to the beam would be 12 ft x 100 PSF = 1200 PLF. The left wall has 7 ft of tributary width and would receive a load of 700 PLF. The right wall has 5 ft of tributary width and gets a load of 500 PLF.

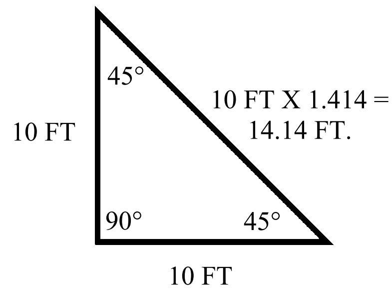


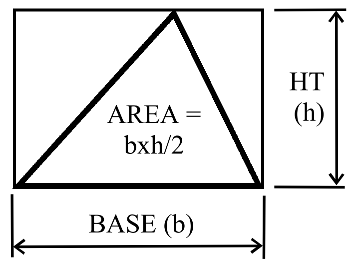
Note: No matter where the beam is located in relationship to the walls it will still have a tributary width of 12 ft which is one half the distance between the walls. The tributary width to each outside wall will be one half the distance between the outside wall and beam.

F.) UNIFORM INCREASING LOADS

Occasionally you will need to deal with triangles. Triangular areas are sometimes designed into floor plans and are also sometimes present in residential roofs. Triangular areas can contribute a *uniform increasing load* to a structural member. Most often an increasing load starts at one end of the member as a zero load and increases to the other end where it is at a maximum load. Complicated or unusual triangular shapes can be solved by trigonometry when encountered. Structural triangles are usually “right triangles” which have one angle equal to 90 degrees. Here are some short cuts for working with simple triangles...

All triangles have three angles. The sum of these angles always equal 180 degrees. If you know two of the angles you can solve for the third. *Right equilateral* triangles have two equal sides and a 90 degree angle. If you know the length of the two equal sides you can find the *hypotenuse* (the long side) by multiplying the length of a short side times 1.414. If you know the length of the longest side, divide it by 1.414 to find the short sides.

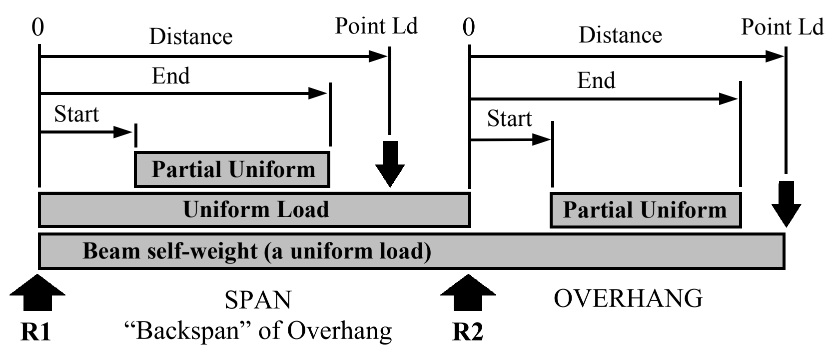




The area of a triangle with a 90° corner can be found by multiplying the two short sides and then dividing by 2. Other triangles can be solved by multiplying the base times the height and dividing by 2.

LOADING DIAGRAMS

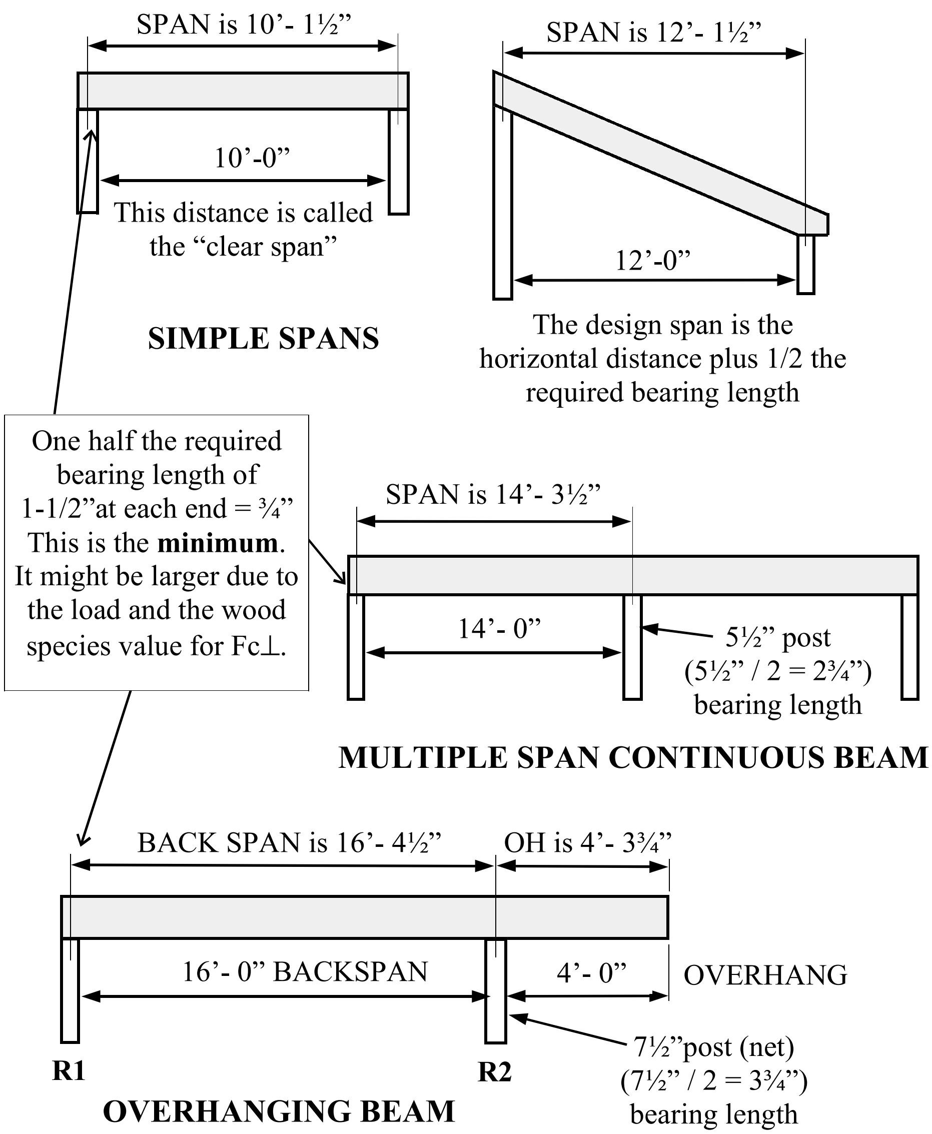
A load diagram is a working sketch of the loads present on a structural member and is recommended before tackling a complex loading problem. The diagramming convention is to select one end of the member as the left end and locate the loads and their distances toward the right. Beams that overhang a support at one end are shown at the right. The reactions at the supports may be of different magnitudes and you'll need to keep them organized as they may be used or accumulated for a beam or post load later in your design analysis. The left reaction is called R1, the right reaction is R2. The reactions are the locations of the supports such as a wall or post under the member. By identifying the distance, or start and end locations, in relationship to the reactions the loads can be accurately placed on the structural member.
Note: Overhangs are often referred to as cantilevers by the building



trade. In structural design, a cantilever is a whole different animal and should not be confused with overhanging structural members.

THE SPAN

The span of a structural member is the **horizontal** distance from face to face supports, plus **one half** the required length of bearing at each end. The minimum bearing length for wood members is 1-1/2” bearing on wood and 3” bearing on masonry. If the member is continuous over supports, the span is the distance between centers of the supports.



DEAD LOAD WEIGHT OF MATERIALS

Material	Approximate lbs/ft²
Wood shingles	2.0
Asphalt or fiber glass shingles	2 - 3
Clay tile	9 - 12
Concrete tile	8 - 12
Slate 1/4 in.	10.0
Rigid Insulation (per in.)	0.2
Batt or blown insulation (per in.) (varies!)	0.3
1/2” plywood sheathing	1.5
3/4” plywood sheathing	2.2
2” decking	4.2
concrete (light weight fill, per in.)	8.0
1/2” gypsum wall board	2.0
5/8” gypsum wallboard	2.5
1” Plaster	8.0
Double glazed skylight or wood frame window	8 - 10
Hardwood floor (3/4”)	3.8
Ceramic tile (3/4” thinset)	5.0
Carpet & pad	3.0
Stucco (7/8” on wire & felt)	10.0
4” Brick wall (per sq ft)	40.0
Wood siding	2.5

Framing members in PSF

Nominal	12” oc	16” oc	24” oc
2x4	1.4	1.1	0.7
2x6	2.2	1.7	1.1
2x8	2.9	2.2	1.5
2x10	3.7	2.8	1.9
2x12	4.4	3.3	2.2

4x framing members in PLF

4x6	5.0
4x8	6.8
4x10	8.6
4x12	10.4

DEAD LOAD ASSEMBLY EXAMPLES

ROOF	PSF
Asphalt shingles (1 layer)	2.5
Asphalt shingles (future layer)	2.5
1/2" plywood	1.5
Insulation	2.5
2x8 rafters @ 16" oc	2.2
2x6 ceiling joists @ 16" oc	1.7
5/8" gypsum wall board	2.5
TOTAL	15.4

Roof dead load is typically between 10 and 20 PSF.
As pitch increases the dead load increases.

EXTERIOR WALL	PSF
Wood Siding	2.5
1/2" Plywood sheathing	1.5
Insulation	1.2
2x6 Studs @ 16" oc	1.7
1/2" gypsum wallboard	2.0
TOTAL	8.9

Walls are typically assumed at 10 PSF, note that windows are also approximately 10 PSF.
An 8 ft high wall including double top plate and sill plate weighs about 80 PLF.
An 8 ft Interior wall weighs 45 to 55 PLF.

FLOOR	PSF
Carpet & pad	3.0
3/4" Plywood sheathing	2.2
Insulation	2.5
2x10 Joists @ 16" oc	2.8
TOTAL	10.5

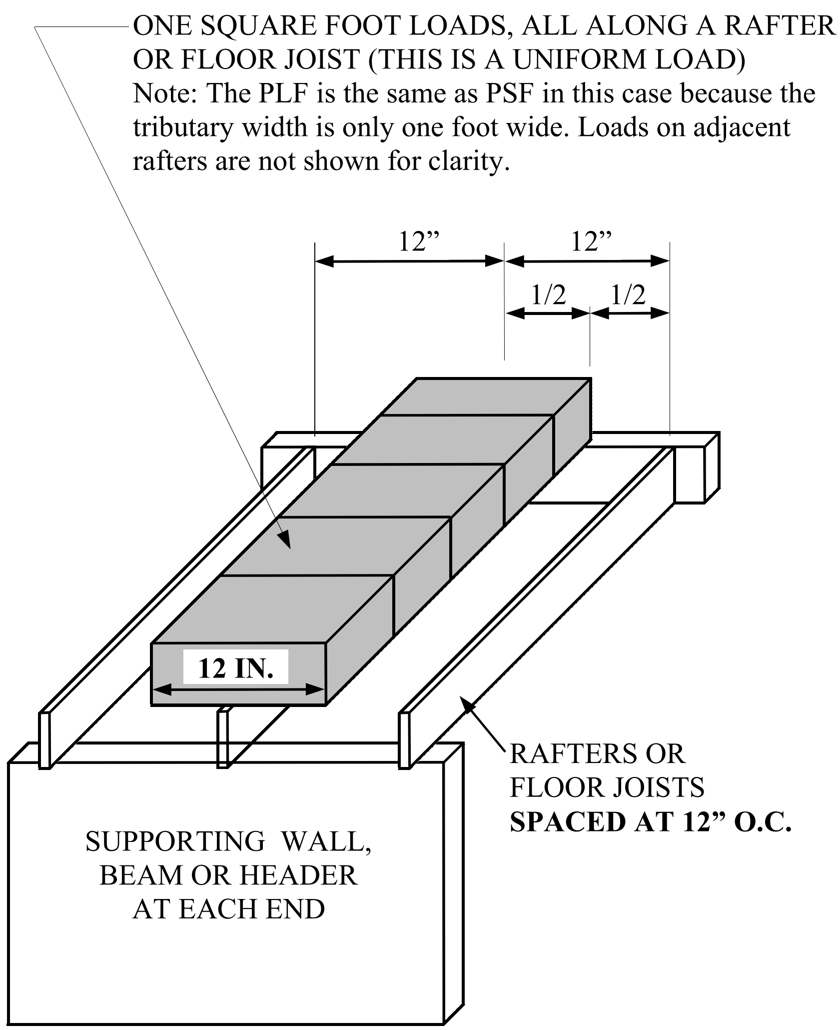
Floor dead load is typically between 10 PSF to 15 PSF.

Remember to add the ceiling material if floor is over living space, i.e., the second floor of a two story house.

2. LOAD PATH EXAMPLES

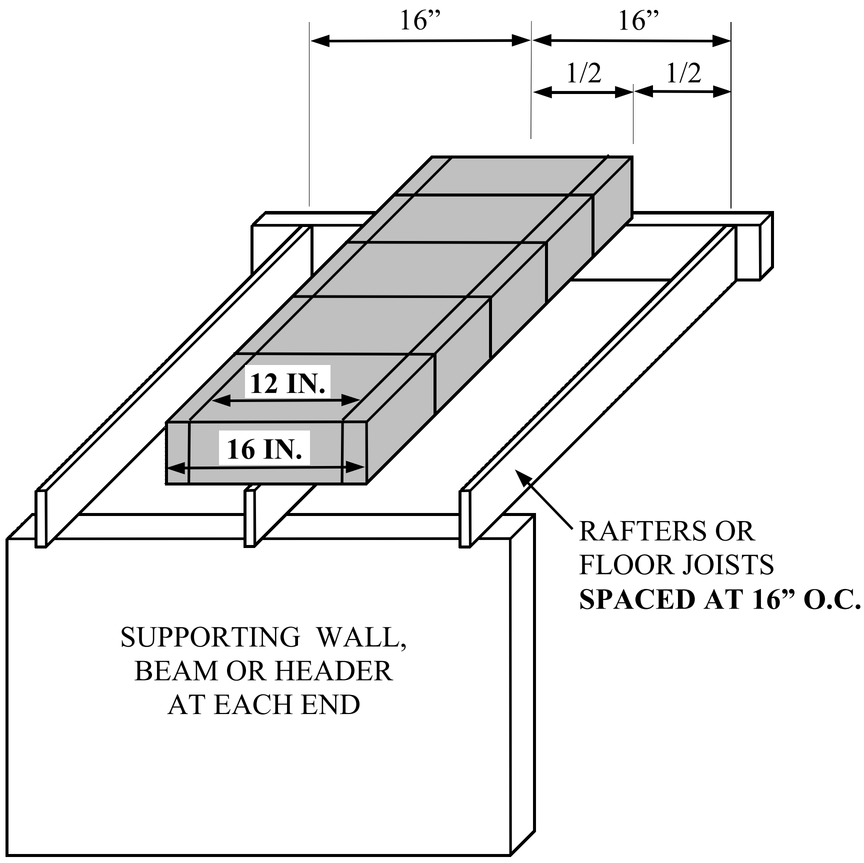
UNIFORM LOADS ON RAFTERS AND FLOOR JOISTS

Remember that rafters and floor joists are just small beams with lighter load requirements. They are usually spaced at regular intervals and are often connected to a communal diaphram of plywood or similar material. Their loading condition is usually a simple uniform load.



OTHER RAFTER AND JOIST SPACINGS

THE PLF ALL ALONG THIS RAFTER OR FLOOR JOIST IS
ONE SQUARE FOOT x **1.33** BECAUSE THE SPACING IS 16” o.c.
(16” / 12” = 1.33)
Similarly 24” o.c. would equal the load in PSF x **2.0**



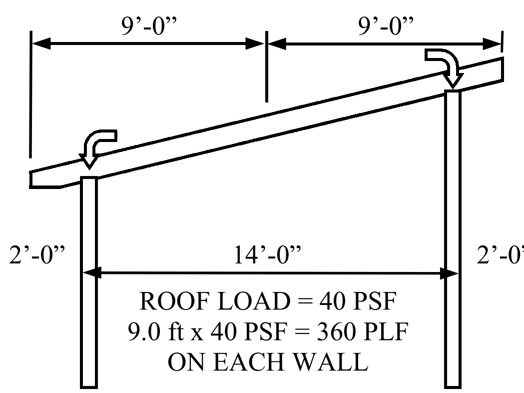
ROOF UNIFORM LOAD DISTRIBUTION

These examples use an assumed load of 40# PSF. You will be designing with two sets of loads: Live Loads and Total Loads which are dead load + live load.

The live load appropriate to your locale is specified by your building offical. The dead load is the actual weight of the construction materials to be used in the project.

Note: The dead load will increase as the roof pitch increases because the rafters and roof surface become longer. This is especially important when designing for tile and slate roofs which are heavy.

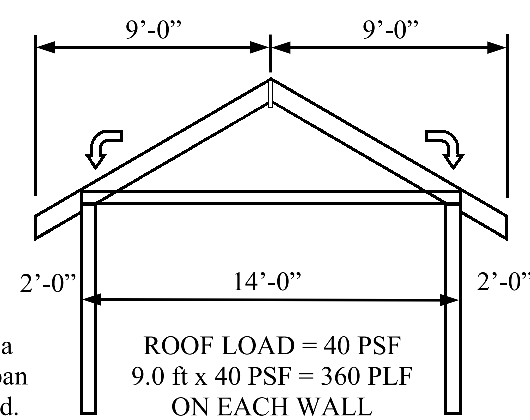
1.



Don’t forget the eaves, snow falls on them too!

2.

NON-STRUCTURAL RIDGE

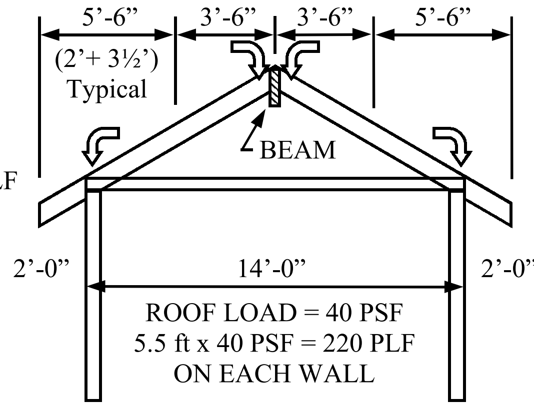


This would be typical of a trussed roof or a small span roof with a 1x ridge board.

3.

STRUCTURAL RIDGE

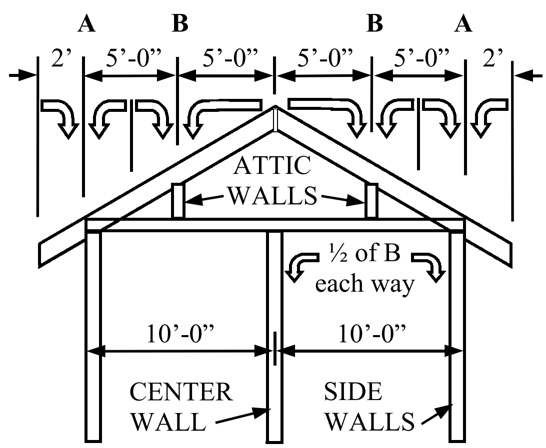
RIDGE BEAM LOAD IS
3.5 ft x 2 x 40 PSF = 280 PLF



4.

NON-STRUCTURAL RIDGE

ROOF LOAD = 40 PSF
LOAD A (OUTSIDE WALL) =
2.5’+2’ x 40 PSF = 180 PLF
LOAD B (ATTIC WALLS) =
5’+2.5’ x 40 PSF = 300 PLF
LOWER SIDE WALLS =
½ B + A = 330 PLF
CENTER WALL =
½ B + ½ B = 300 PLF
Note: Ceiling joists would be designed with a 300# point load at mid-span due to the attic walls supporting the rafters, plus a uniform live and dead load.

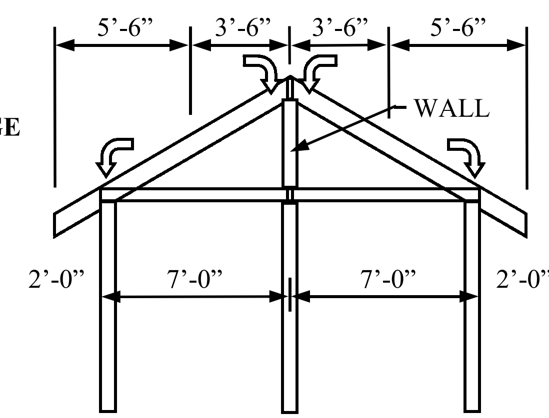


5.

WALL SUPPORTED RIDGE

ROOF LOAD = 40 PSF
5.5 ft x 40 PSF = 220 PLF
ON EACH OUTSIDE WALL

CENTER WALL LOAD IS
3.5 ft x 2 x 40 PSF = 280 PLF



FLOOR UNIFORM LOAD DISTRIBUTION

These examples use an assumed load of 50 PSF.
You will be designing with two sets of loads:
Live Loads and Total Loads (dead load + live load)

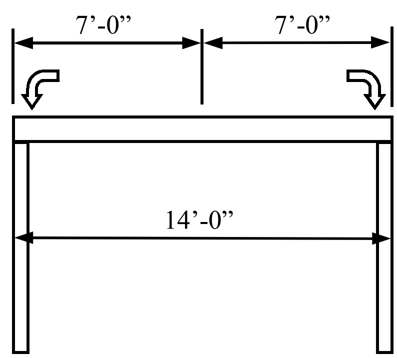
The live load appropriate to your locale is specified by your building offical. The dead load is the actual weight of the construction materials to be used in the project. Common residential loads are 40 PSF live load and 10 PSF dead load, for a total load of 50 PSF.

Note that the formulas in Example 3 provide for more accurate reactions. Beginning designers often try to be overly exact in their calculations only to find that a close approximation will often result in the same beam size selection. Accuracy is important, but the range of accuracy should to be appropriate to the task.

1.

FULL SPAN FLOOR JOISTS

FLOOR LOAD = 50 PSF
(14 ft / 2) x 50 PSF = 350 PLF
ON EACH WALL

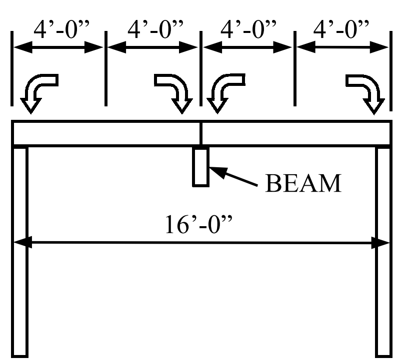


2.

FLOOR WITH CENTER SUPPORT

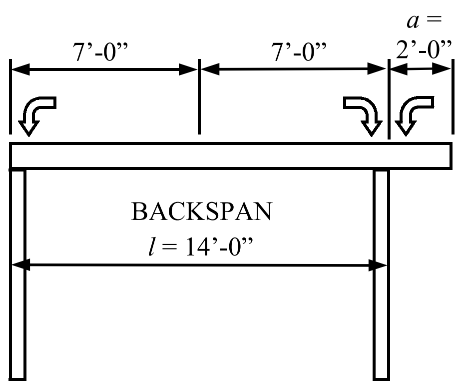
FLOOR LOAD = 50 PSF
4 ft x 50 PSF = 200 PLF
ON EACH WALL

(16 ft / 2) x 50 PSF = 400 PLF
ON CENTER BEAM



3.

OVERHANGING FLOOR JOISTS



FLOOR LOAD w = 50 PSF
(14 ft / 2) x 50 PSF = 350 PLF
APPROX. ON LEFT WALL

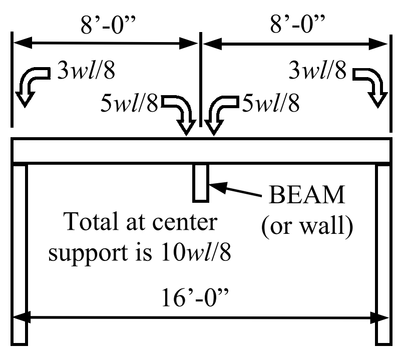
Actually 342.85 PLF $\boldsymbol{w/2l\,(l^2 - a^2)}$

7 ft + 2 ft x 50 PSF = 450 PLF APPROX. ON RIGHT WALL
Actually 457.14 PLF $\boldsymbol{w/2l\,(l+a)^2}$

4.

CONTINUOUS BEAM WITH 2 EQUAL SPANS

l = 8'-0" w = 50 PSF



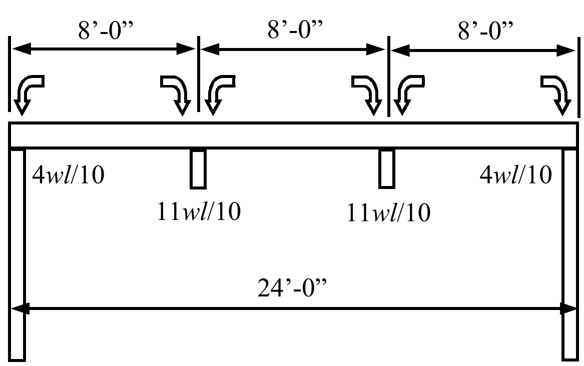
3 x 8ft x 50 PSF / 8 = 150 PLF
ON END WALLS

10 x 8 ft x 50 PSF / 8 = 500 PLF
ON CENTER SUPPORT

5.

CONTINUOUS BEAM WITH 3 EQUAL SPANS

l = 8'-0" w = 50 PSF



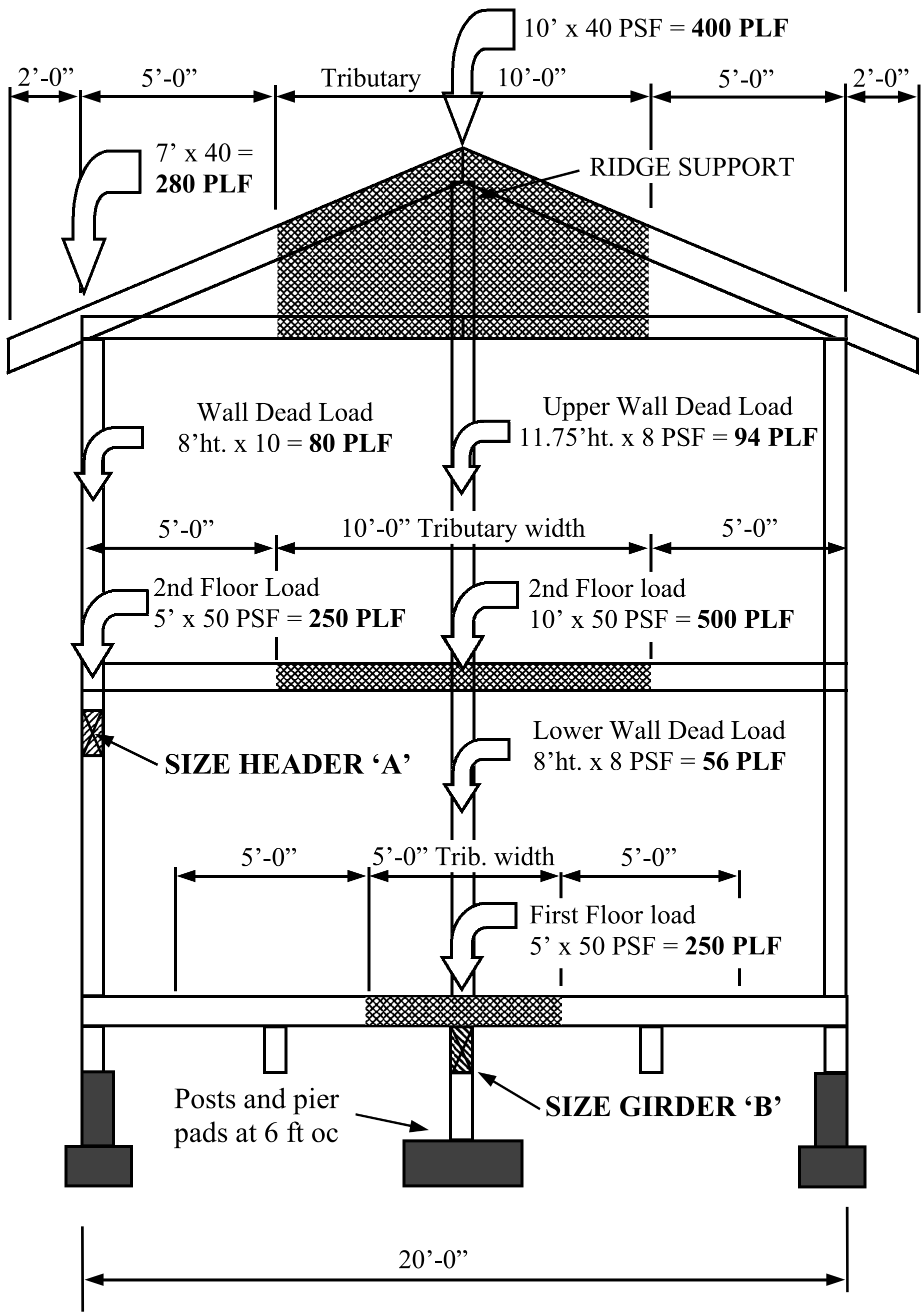
4 x 8 ft x 50 PSF / 10 =
160 PLF
ON END SUPPORTS

11 x 8 ft x 50 PSF / 10 =
440 PLF
ON INTERIOR

Check: 24' x 50# = **1200# Total** , 160# + 440# + 440# + 160# = **1200# Total, OK**

MULTI-STORY LOAD PATH EXAMPLE

Loads are the same on each side in this example because the house is symetrical.



MULTI-STORY EXAMPLE LOADS:
Given: ROOF 40 PSF, FLOOR 50 PSF

HEADER A:

Roof and eave =	280 PLF
Upper wall=	80 PLF
2nd Floor =	250 PLF
Total uniform load =	**600 PLF**

6x Header clear span is 10 ft
plus bearing area of 3” / 2 = 1.5”
Total design span is 10.125 ft

Total weight = 10.125 x 600 PLF = 6075#
Reactions are equal: 6075# / 2 = 3038# each

GIRDER B:

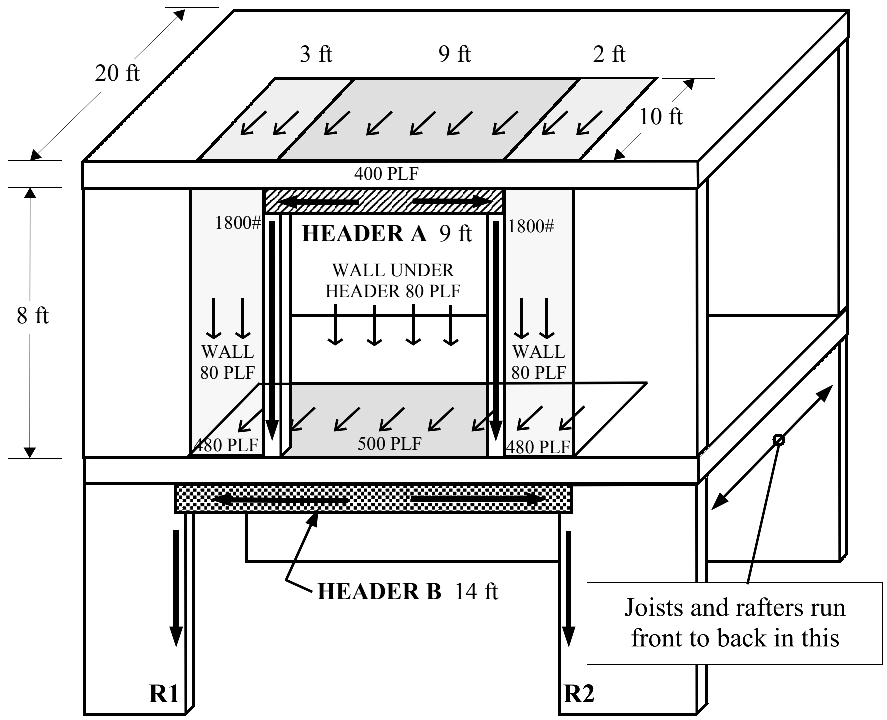
Roof =	400 PLF
Upper wall =	94 PLF
2nd Floor =	500 PLF
Lower wall =	56 PLF
First Floor =	250 PLF
Total uniform load =	**1300 PLF**

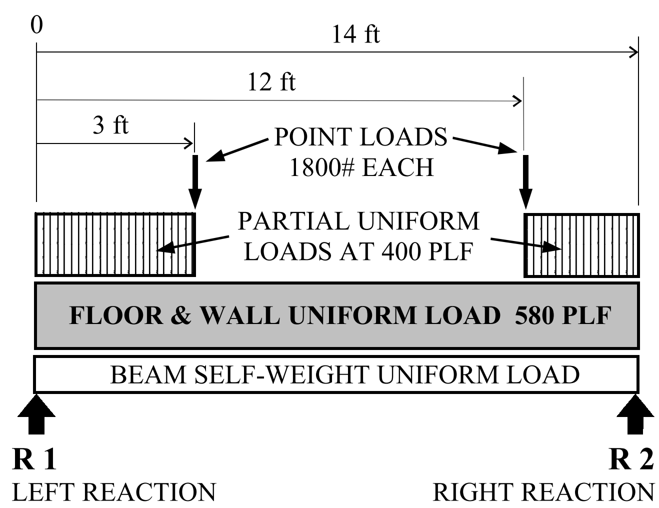
To continue...
Girder ‘B’ has a span is 6 feet.

Total weight on Girder ‘B’ = 6ft x 1300 PLF = 7800#
The reactions for the Girder would be 7800# / 2 = 3900# at each end. Therefore, posts and pier pads in the crawl space would need to be capable of supporting 3900# from half the girder at each side which is a total of
3900# + 3900# = 7800#.

COMPLEX LOADING EXAMPLE

Given PSF loads: Roof LL=30#, DL=10#; Floor LL=40#, DL=10#; Wall DL=10#





LOAD LOCATION DIAGRAM FOR HEADER B

LOADS ON HEADER A

UNIFORM LOAD
LOAD FROM ROOF   10 ft TRIB. LOAD x 40 PSF = 400 PLF
400 PLF x 9ft = 3600# TOTAL
ONE HALF TO EACH END = 1800# POINT LOADS

LOADS ON WALL

UNIFORM LOAD
ROOF LOAD TO WALLS BEYOND HEADER.
10 ft TRIB. LOAD x 40 PSF = 400 PLF

LOADS ON HEADER B

UNIFORM LOAD
LOAD FROM FLOOR
10 ft TRIB. LOAD x 50 PSF = 500 PLF

plus

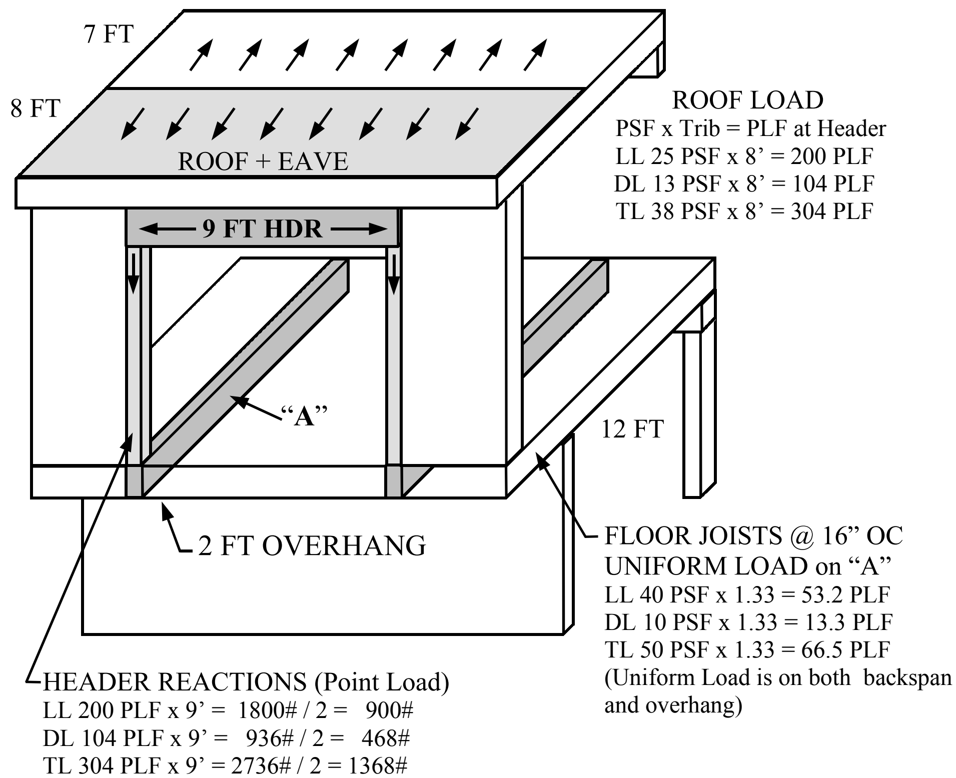
WALL DEAD LOAD (DL)
8 ft HEIGHT x 10 PSF = 80 PLF

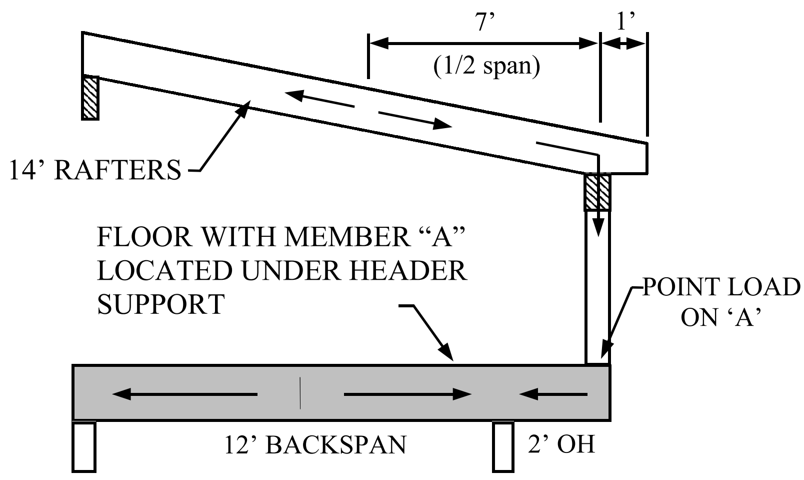
POINT LOADS
LEFT POINT LOAD AT 3 ft = 1800#
RIGHT POINT LOAD AT 12 ft = 1800#
Distance is always from the left, therefore
Right Point Load is at 3 ft + 9 ft = 12 ft

LEFT PARTIAL UNIFORM LOAD
400 PLF FROM ROOF
LOCATE FROM LEFT END:
START AT 0 ft, END AT 3 ft (3 ft long)

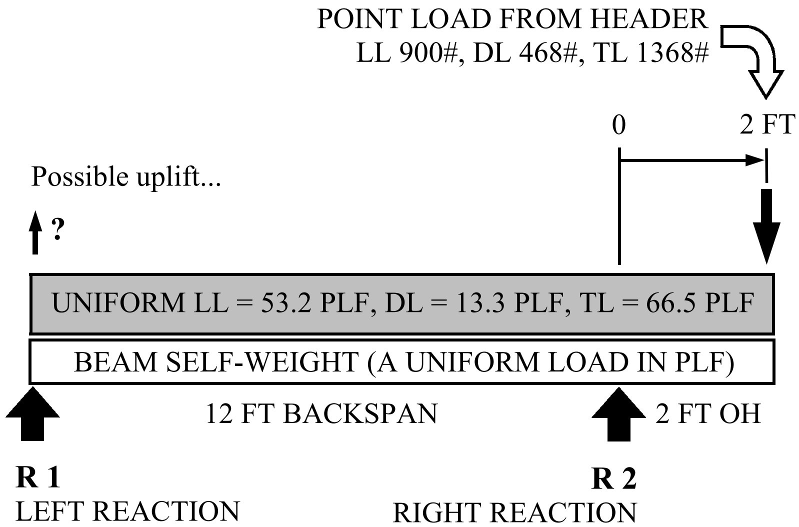
RIGHT PARTIAL UNIFORM LOAD
400 PLF FROM ROOF
LOCATE FROM LEFT END:
START AT 12 ft, END AT 14 ft (2 ft long)

OVERHANGING BEAM EXAMPLE





SECTION VIEW



LOAD LOCATION DIAGRAM FOR MEMBER "A"

NOTE: As a rule of thumb, overhangs perform best when the backspan is at least 2 to 3 times the length of the overhang.

NOTE: Overhanging members should also be designed for "unbalanced loading" to evaluate all possible conditions. Suppose this house is vacant and there is no furniture or people on the floor, but there is 3 feet of wet snow on the roof...
To unbalance the member, first check the member with all of the live loads removed from the back span, then check the member with all the live loads removed from the overhang. Always review the left reaction (R1) for possible uplift, which is a negative reaction, as it may require a special mechanical fastener to prevent the member from rising off its support. Excessive negative deflection could cause a hump in the floor.

EXAMPLE OF UNBALANCED LOADING:

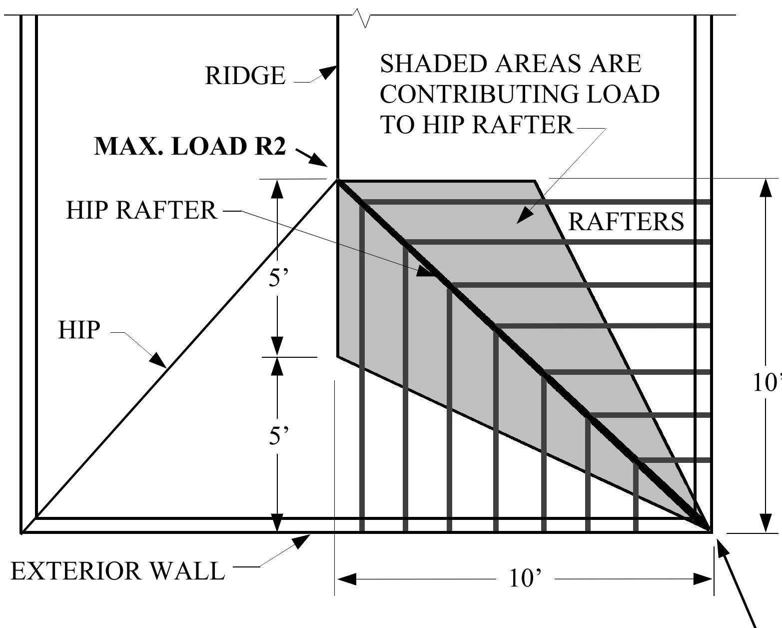
1.) Backspan DL 13.3 PLF uniform (No Live Load)
Overhang TL 66.5 PLF uniform
Overhang TL 1368# point load
CHECK FOR UPLIFT AT R1

2.) Backspan TL 67 PLF uniform
Overhang DL 13.3 PLF uniform (No Live Load)
Overhang DL 468# point load (No Live Load)

HIP RAFTER EXAMPLE

(INCREASING LOAD FROM ZERO TO A MAXIMUM)

Through common practice it has been shown that there is some buttressing effect from steep rafters pushing against each other at a hip rafter, however there isn't any provision for this in the building code and hips must be designed as a common beam as if it were horizontal.

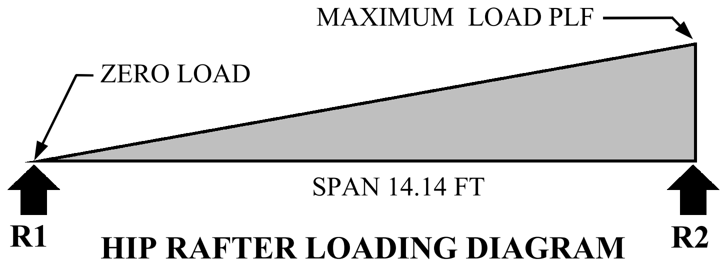


PLAN VIEW

ROOF LOAD
LL = 25 PSF (SNOW), DL = 15 PSF, TL = 40 PSF

ROOF PITCH = 9:12 (9 INCH RISE PER FOOT)
Dead Load has been increased to account for the slope of the rafters. As the slope increases the rafters are longer and the amount of roofing increases.

SPAN The length of the hip rafter (the hypotenuse of the triangle) is 1.414 x the side of the right triangle formed by the outside walls, which in this case is 10 feet. The hip (horizontal) span is 10' x 1.414 = 14.14' The true length of the member is longer because it is sloping on a 9:12 pitch.



HIP RAFTER LOADING DIAGRAM

The TOTAL WEIGHT on the Hip Rafter can be found by multiplying the sides of the square around the hip and dividing by 2 (The shaded portion of contributing load to the rafter is 1/2 the area).
10 ft x 10 ft = 100 square feet / 2 = 50 sq ft.

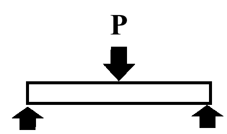
TOTAL LIVE LOAD is 50 sq ft x 25 PSF = 1250#.
TOTAL DEAD LOAD is 50 sq ft x 15 PSF = 750# plus hip's self-weight.
TOTAL WEIGHT is 1250# + 750# = 2000# (plus hip self-weight).
The weight distribution to the Reactions is 1/3 of load goes to R1 and 2/3 of the load goes to R2.

The reason for finding the total weight is that it is used in the design formulas for this loading condition. Total weight is expressed as a capitol '**W**' and should not be confused with a small '***w***' that denotes PLF.

EQUIVALENT LOAD FORMULAS (ETL)

A simple, full uniform load on a member is the easiest to condition to calculate. Many other load conditions can be translated into an ***equivalent of a uniform load*** and thus easily solved for the maximum moment, expressed as '**M**'.

EXAMPLE: A point load '**P**'at he center of a simple span has a **Total Equivalent Uniform Load** = **2P** therefore 2 x **P** = **W** and the member can be solved as if it had a simple uniform load.

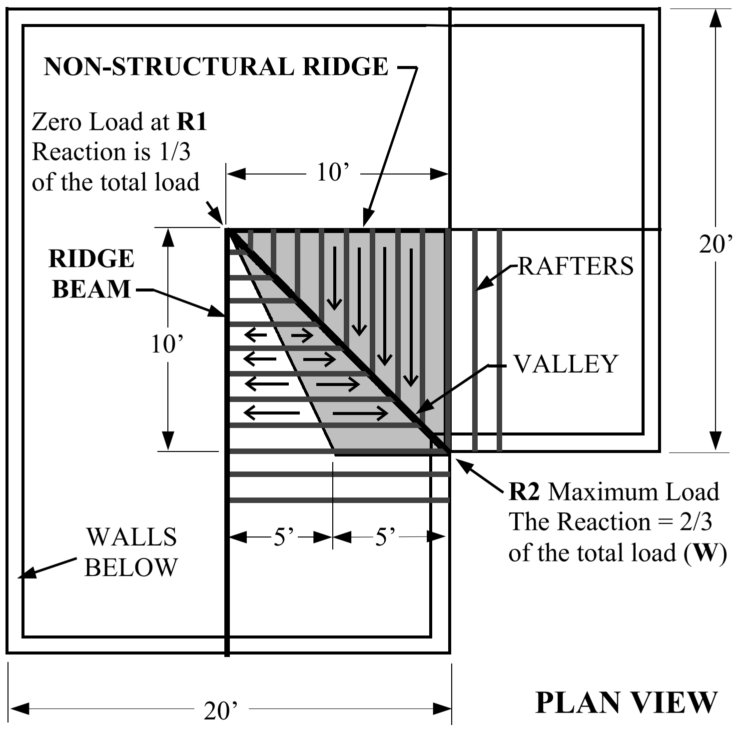


In the hip rafter example above, the Total Equivalent Uniform Load is 1.0264 x **W**
This is adding a little more than 2-1/2% to the total weight and solving it as a uniform member. Remember though, the reactions will still be 1/3 and 2/3 of the total load.

These short cut equivalents are often listed in a table of design formulas and are sometimes called the Equivalent Tabular Load or simply "ETL". Complex loading conditions don't have easy uniform load equivalents.

VALLEY RAFTER EXAMPLE
(INCREASING LOAD FROM ZERO TO A MAXIMUM)

Valley members supporting rafters are sized as beams with an increasing load from zero to a maximum. The amount of load carried by the valley depends upon the how the surrounding roof is is framed.

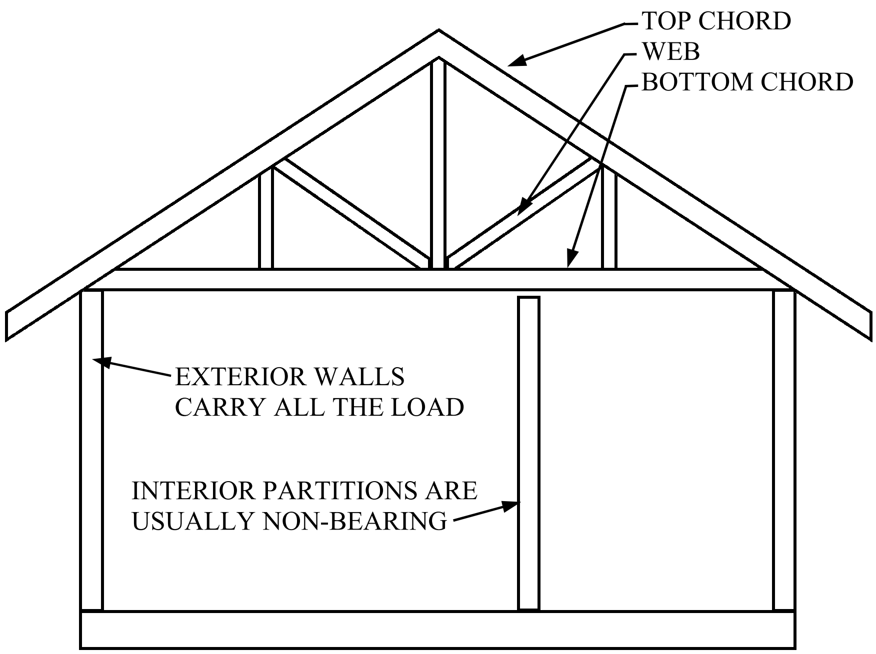


Valley Loads are totaled similarly to hip rafters, however care must be taken when determining whether the supported rafters are contributing all or only half of their load to the valley beam. The example above shows both of the possible conditions. The *ridge beam* on the left might be representative of a cathedral ceiling and the top, *non-structural ridge* might be rafters meeting at a 1x6 ridge board and typical ceiling joists below supporting a flat ceiling.

The load to the Ridge Beam shown above is an increasing load from the rafters on the valley side plus a typical uniform load from the rafters on the opposite side (1/2 the rafter span from the ridge to the outside wall). The location of the ridge beam's supporting posts would, of course, dictate whether the increasing load was uniformly increasing over the entire span or just a portion of it.

TRUSSED ROOF SYSTEMS

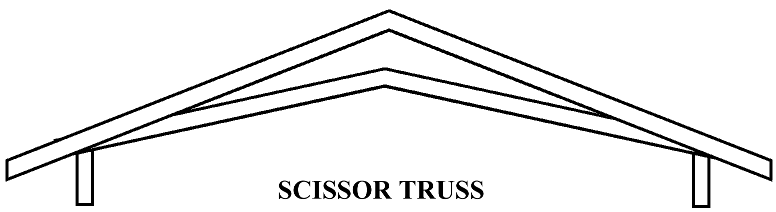
Trusses are economical, manufactured systems that are carefully engineered using small wood members connected by flat metal plates with small teeth that are pressed into the wood. A "web" structure of triangles is created which balance tension and compression in the members and can span great distances. Sometimes trusses are built on the job site using plywood and nails instead of the metal plates, but most often they are built in factories according to the design and specifications prepared by licensed engineers. The variety of truss designs are enormous, both in the 'web' design and the styles of roofs that can be created. The design of trusses is best left to professional engineers, but the designer must be aware and account for the truss loads passed to the supporting structural members below. Since the goal of trusses is to span long distances, usually from outside wall to outside wall, the loads generated are often considerable. This will mainly impact window headers as they will receive double (and sometimes more) the load generated in conventional construction with interior bearing walls.



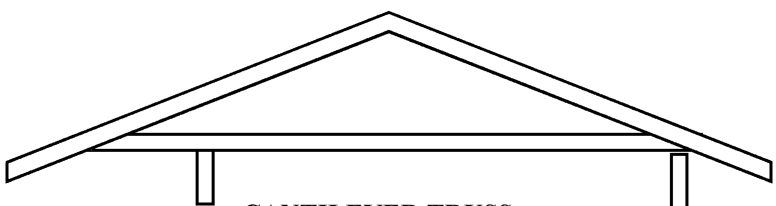
COMMON ROOF TRUSS

EXAMPLES OF TRUSS CONFIGURATIONS

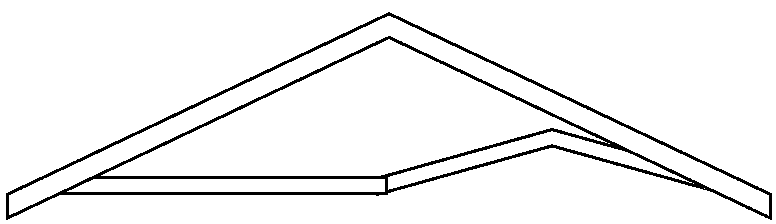
These are only a few of the hundreds of possibilities. The webbing has been omitted for clarity. A scissor truss will most often have a bottom chord pitch that is one half the pitch of the top chord unless specified otherwise. It is recommended that you obtain a general “fact” booklet about typical truss layout from your local truss manufacturer. These booklets have clear explanations and easy to understand 3-D drawings of how trusses combine to create different roof styles. By studying the drawings you will be able to see where the roof loads will accumulate and how they will be transferred to the structure below.



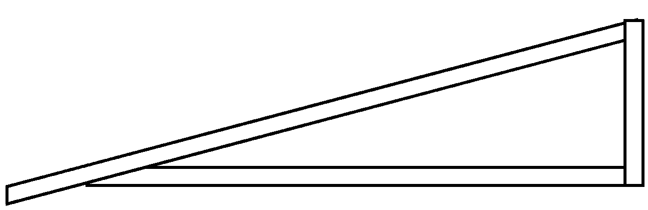
SCISSOR TRUSS



CANTILEVER TRUSS

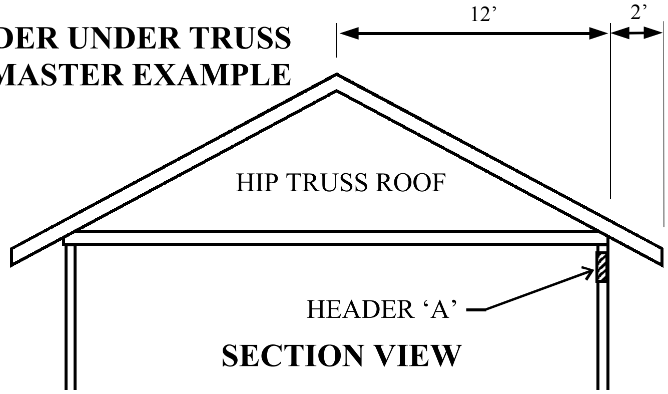


VAULTED SCISSORS

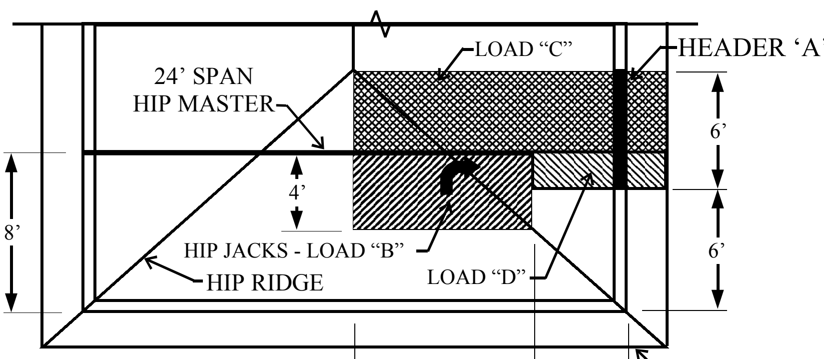


MONO PITCH

HEADER UNDER TRUSS HIP MASTER EXAMPLE

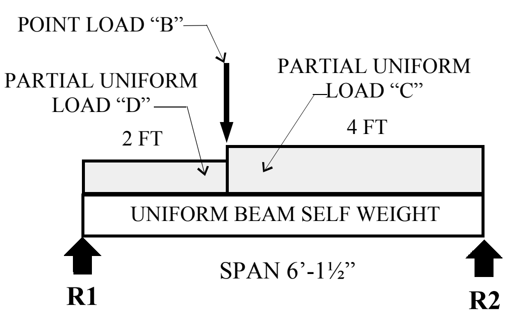


SECTION VIEW



PLAN VIEW

NOTE: These are approximate load conditions based on a truss configuration that may vary. There are several hip configurations. This example demonstrates partial uniform loads. More accuracy could be achieved by taking each truss as an individual point load.



LOAD DIAGRAM

LOADS ON HEADER 'A'

SPAN = 6'-1½" (6"-0" Rough Opening plus one half minimum 1-1/2" bearing at each end.)

ROOF LOAD DATA:
LL = 25 PSF, DL = 13 PSF
TL = 38 PSF

PARTIAL UNIFORM LOAD "C"
Tributary width = 12' + 2'eave = 14'
LL = 25 PSF x 14' = 350 PLF
TL = 38 PSF x 14' = 532 PLF

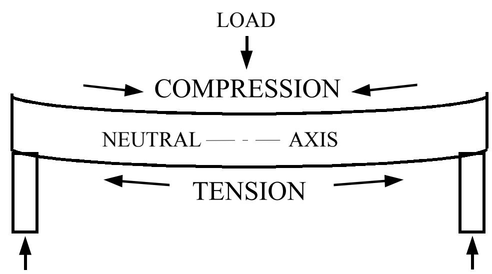
PARTIAL UNIFORM LOAD "D"
Tributary Width = 4' + 2'eave = 6'
LL = 25 PSF x 6' = 150 PLF
TL = 38 PSF x 6' = 228 PLF

POINT LOAD "B"
AREA = 8' x 4' = 32 SQ FT
LL = 25 PSF x 32 SQ FT = 800#
TL = 38 PSF x 32 SQ FT = 1216#

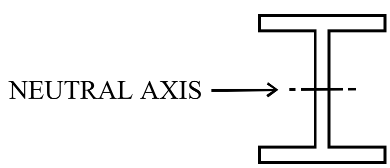
3. BASICS OF WOOD DESIGN

STRENGTH OF MATERIALS

All beams bend to some extent. How a beam bends and how it reacts to loads depends upon the natural properties of its composition. When the beam is loaded, the top of the beam becomes compressed (compression) and the bottom of the beam is stretched (tension).



Halfway between the tension and compression the forces are neutral. This is called the neutral axis. Since the upper and lower portions of a



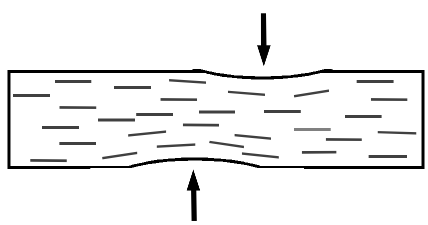
WIDE FLANGE STEEL BEAM

beam are providing almost all of the bending strength, an economy of materials can be achieved by eliminating material near the neutral axis. An example is the wide flange steel beam. It is sometimes acceptable to drill holes through a beam at or near the neutral axis without affecting its bending strength.

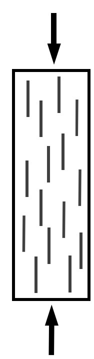
Materials such as concrete and masonry are very strong in compression, but weak in tension. This is why concrete and masonry are often reinforced with steel, which is very strong in tension. In a concrete beam the steel is added to the part of the beam which is subject to tension. This is also the reason steel is added to concrete foundations.

Wood and steel, if compared pound for pound are similar in strength. Steel is more dense, requiring a smaller amount of material to do the job, but it weighs nearly the same as wood. Steel is manufactured in different grades with different strength characteristics and is homogenous throughout.

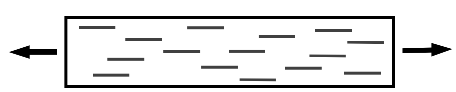
Wood consists of directional fibers, like grains of rice that lay together in the same direction. The fibers are strongest in their long direction and therefore the design of wood members requires evaluation of how the member is oriented to the loads. Wood has more attributes that refer to the direction of the wood fibers. The direction of fibers is especially important when designing fasteners and connections. Also, the design properties of wood vary with the wood species, how it is graded at the lumber mill, its moisture content, and how it will be used within the structure.



Compression Perpendicular to Grain



Compression Parallel to Grain

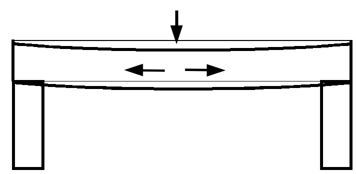


Tension Parallel to Grain

When a force is acting in the same direction as the fibers it is said to be parallel to the grain. The symbol for parallel is //. When a force is acting across the grain it is said to be perpendicular to the grain. The symbol for perpendicular is $\perp$.

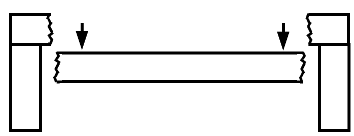
DESIGN STEPS TO SIZE A WOOD MEMBER

1. BENDING STRENGTH



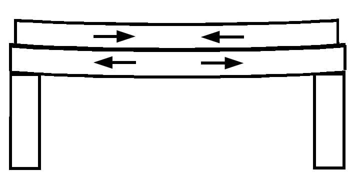
The relationship of the allowable extreme fiber bending stress **Fb** to the maximum bending moment **M**, equals the required section modulus **S**. The design equation is **S = M / Fb adj.**
Fb is a given (in psi) depending upon the species and grade.
The Fb must be adjusted for various conditions such as wet use, duration of load, size factor, repetitive use, flat use, and temperature, etc. to find the value for **Fb adj.**

2. VERTICAL SHEAR



The tendency of the member to break and fall between the supports. Expressed as **V**. Since a particular member will fail first by horizontal shear (see below), the investigation of vertical shear is not deemed necessary.

3. HORIZONTAL SHEAR



The tendency for the wood fibers to slide past each other at the center (neutral axis) of the member and fracture along its length. The maximum horizontal shearing stress for rectangular sections is one and one half times the average vertical unit shear stress.

The design formula is $\boldsymbol{v} = 1.5 \times V / A$ or $A = 3V / 2Fv$

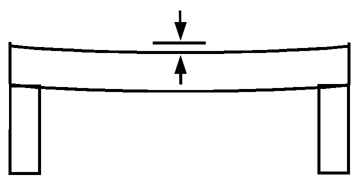
in which $\boldsymbol{v}$ = maximum unit horizontal shear stress in psi

V = total vertical shear in pounds

A = area of member in square inches (breadth x depth)

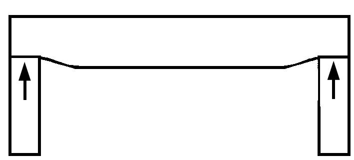
Allowable horizontal unit shear stress is a given for different species and grades, as **Fv** (in psi) and must be adjusted for different conditions of use. ***v*** must equal or be less than the **Fv adj.** in psi.

4. DEFLECTION



The tendency of the member to bend under a load. Expressed as **D** or "Δ". Excessive deflection in members can damage plaster ceilings, visually sag, or have a tendency to bounce when walked on. General limits for <u>some</u> uses are specified in the building code, expressed as **L** (length in inches) divided by a numeric limit such as 180, 240, or 360. Example: "**L / 240**" if L = 120 in. then 120 / 240 = 0.5 inch limit. Different formulas for different loading conditions are used to find an approximation of the actual deflection. These formulas use the load, the member's length, the given attribute for a species and grade called the modulus of elasticity expressed as **E**, and the member's Moment of Inertia expressed as **I**.

5. BEARING AREA



The tendency for the weight of a load or reaction at a support to crush the wood fibers if the area (in sq. inches) is not large enough.

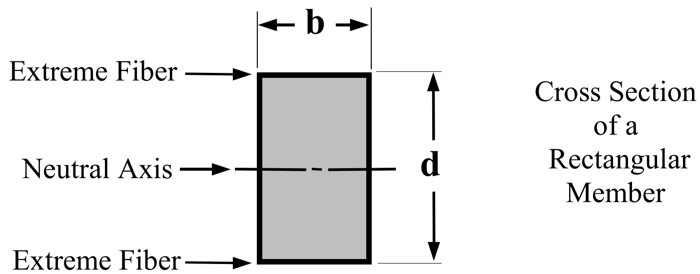
The total force **W** in pounds at a bearing location, divided by the given allowable compression perpendicular to grain, expressed as **Fc⊥** will equal the minimum required bearing area.

The formula is **W / Fc⊥adj =** Minimum bearing area in square inches.

PROPERTIES OF SAWN LUMBER

PROPERTIES OF THE CROSS SECTION

The following are mathematical expressions based on the relationship of a member's breadth (width) and depth (height) to the neutral axis, which is the line where compression and tension stress are zero.



Definitions

b = BREADTH (width) of a rectangular member in inches

d = DEPTH (height) of a rectangular member in inches

AREA is the area of the cross section.

$A = bd$ (in^2) *Used in shear calculations*

SECTION MODULUS is the moment of inertia divided by the distance from the neutral axis to the extreme fiber of the cross section.

$S = bd^2 / 6$ (in^3) *Used in bending calculations*

MOMENT OF INERTIA is the sum of the products of each of the elementary areas multiplied by the square of their distance from the neutral axis of the cross section.

$I = bd^3 / 12$ (in^4) *Used in deflection calculations*

Note: Tables are available that list the A, S, and I of common rectangular sizes.

STRUCTURAL LUMBER

Structural lumber is visually graded when sawn at the mill. The grading process takes into account which portion of the tree the member came from and any natural defects such as knots and checks. It is also classified by its size and intended final use. For special use, some members are tested by machine and re-graded into a separate category called mechanically evaluated lumber, *MEL*.
See your local Wood Products Association literature or the NDS® for a full listing of sawn lumber sizes, species groupings and design values

Note: terminology in wood design is not always consistent. Thickness or width will usually equate to the "breadth" if the member is used upright on its narrow edge and height will equate to the "depth".
Be consistent when describing a member's size. The breadth comes first, followed by the depth.

The major classifications are:

A.) **DIMENSION LUMBER 2" to 4" Thickness**
Usually seasoned or kiln-dried to a moisture content less than 19%.

Grades	*Depth*
Stud	2" to 6" stud maximum length 10 ft.
Select Structural, No. 1 & better, No. 1, 2, & 3	2" to 14" for joists, rafters, planks, and sometimes plates
Construction	2" to 4" for plates
Utility	2" to 4" for furring and non-structural uses

B.) **TIMBERS** (visually graded) **5" and larger Thickness**
Note: Size classification and types of grades vary a bit in each wood species grouping. "Green Lumber" is defined as having a moisture content greater than 19%.

1.) **Posts and Timbers** Note: depth and thickness ***are the same or within* 2"**

Grades	*Depth*
Select Structural	5" and larger
No. 1, No. 2	5" and larger

Sometimes assorted "Dense" grades are available.

2.) **Beams and Stringers** Note: depth and thickness ***are greater than 2"*** different.

Grades	*Depth*
Select Structural	larger than 7" (commonly up to 16")
No. 1, No. 2	larger than 7" (commonly up to 16")

Sometimes "Dense" grades are available.
Sometimes post and timber sizes are graded to Beam and Stringers values.

NOMINAL AND NET SIZES

When lumber is sawn to a particular size, such as 6 inches x 12 inches, it will shrink in size when it dries or when it is "surfaced" or "dressed" (smoothed through a planer). The final, or actual size of the finished member is about 1/2" smaller in width and depth. The member is still called a "6 by 12" but its actual, ***net size*** will be 5-1/2 inches x 11-1/2 inches. Dimension lumber loses 3/4 of an inch in its wide dimension. A 2 x 10's net size is 1-1/2 inches x 9-1/4 inches, except a 2 x4 which is 3-1/2".
Note: The actual or ***net*** size is used when designing structural members, but the ***nominal*** size is used for specifying members.

NEW NATIONAL DESIGN SPECIFICATION

1991 and 1997 NDS® In Grade Testing Program

Building departments across North America have adopted a new building code with fundamental changes in the way the structural wood members are designed. These changes include not only new wood design properties, but a change in the design method as well.

The USDA Forest Products Laboratory in cooperation with the North American softwood timber industry, have been conducting a comprehensive scientific research program known as the ***In Grade Testing Program***. Back in the 1920's, theoretical assumptions about the properties of domestic lumber were derived from a few limited tests. This time, over 70,000 pieces of visually graded dimension lumber were pulled directly from the shelves of U.S. and Canadian mills and tested to destruction. Evaluation included all the basic properties of structural lumber such as bending strength, stiffness and compression. Analysis of revealed a wealth of information about how and why lumber performs in different situations.

Valuable data was also obtained about specific gravity and mechanical properties relative to moisture content, size and grade.

The In Grade Testing Program only involved dimension lumber. Timbers (5x and greater) were not part of the research. Also, Glu-Lams, laminated veneer lumber and similar fabricated members have always been independently tested and were not included in the program scope.

The Test Results

- It was found that structural members with shallow depths, such as 2x4s, performed better than previous assumed. On the other hand, deeper members such as 2x10s and 2x12s did not meet expectations. Small rafters and similar members can actually span greater distances, but floor joists and headers, which are typically deeper, will span shorter distances.
- Lumber species are now regrouped into fewer categories and species designations are reorganized for marketing and manufacturing reasons.
- The design of structural columns is completely revamped to do away with separate groupings of short and long columns. The net result of calculations is similar, only the design method is changed.
- Lumber is visually graded the same as in the past and the grading designations have not changed except for the recognition of No. 1 & Better Douglas Fir-Larch and Hem-Fir.
- The new design values now reflect many slight adjustments to the stiffness (Modulus of Elasticity) values of certain species.

A New Design Method

To compensate for dimension lumber's varying performance in different depths, a new design method has been implemented. Previously, lumber of a specific grade and species was assigned a single design value regardless of the member's depth. Under the new design procedure each species and grade has been given a **Base Value** which is then modified (adjusted) by a **Size Factor**. Other routine and special use factors can also adjust this base value depending upon the specific use of the member within a structure. These include a repetitive use factor, duration of load factor, horizontal shear adjustment factors, wet use and flat use factors, along with adjustments for fire retardant and extreme temperatures.

THE WOOD ADJUSTMENT FACTORS

Wood design involves values specific to each species and grade. Modification of these values is necessary to reflect the actual use or application the wood will have within a structure.

TABLE OF ADJUSTMENT FACTORS

	Fb	Fv	Fc //	Fc ⊥	E
Load Duration	Cd	Cd	Cd	•	•
Wet Service	Cm	Cm	Cm	Cm	Cm
Temperature	Ct	Ct	Ct	Ct	Ct
Size Factor[1]	Cf	•	Cf	•	•
Volume Factor[2]	Cv	•	•	•	•
Repetitive Use[3]	Cr	•	•	•	•
Shear Stress	•	Ch	•	•	•

1. Cf, size factor applies to sawn lumber only.
2. Cv, volume factor applies to glued-laminated timber only.
3. Cr, repetitive Use factor applies to dimension lumber only, 2” to 4” thick.

There are other factors listed in the National Design Specification® (NDS) and your building code. Above are the factors commonly used for residential design with solid sawn lumber and glu-lam beams.

LOAD DURATION, Cd

Wood has a natural resiliency. When it carries a heavy load for a short period of time it will return to it’s previous shape. When it is loaded for long periods it will acquire permanent deformation. The duration of load factor allows the designer to compensate for the length of time by adjusting the design property values of the lumber. Most often this modification will apply to roofs. Duration loadings are ***not*** cumulative. In other words, you only get one of the following duration increases and it must be for the shortest applicable duration.

Some designers take this bonus by reducing the loads rather than adjusting the design values. This is incorrect because the duration factor does not apply to the E value (modulus of elasticity). Your building code specifies the load of duration factors for different conditions similar to these:

- **Permanent** load, 10 years or more (as from dead loads)
  0.90 (90% of original values)
  It is only necessary to check this condition when very high dead loads, in relationship to the live loads, are present. Otherwise the live or total load will govern.
- **Normal** duration (as for floors, decks or combined conditions)
  1.0 (no change to values)
- **Two months** duration (as for snow on roofs)
  1.15 (15% increase in values)
- **Seven days** duration (no snow, workers only on roof)
  1.25 (25% increase in values)

Other conditions such as wind, earthquake, impact, etc. are also specified in the building code and NDS®. These are beyond the scope of this booklet.

REPETITIVE USE FACTOR, Cr

A bonus in the Fb value is available when several members are connected and share the loads. Dimension lumber may have its Fb value increased by 15% (Cr = 1.15), when it is used as rafters, floor joists, decking, or similar members which are in contact or spaced not more than 24" on centers, are not less than 3 in number and are joined by sheathing, or other load distributing elements.
NOTE: All of the three above conditions must be satisfied for you to be able to apply the repetitive use increase.

WET SERVICE, Cm and **TEMPERATURE FACTOR, Ct**

When wood is subject to lots of moisture it tends to absorb the moisture and loses some strength. The same happens when it is heated to high temperatures for long periods. In moist climates, wood used for outside structures such as decks would be subject to the wet use adjustment, if deemed appropriate by the local building official. The temperature adjustment is only for locations where the temperature

exceeds normal temperatures, up to 150 degrees for long periods, as might be found in some factories. Seldom, if ever, is this encountered in residential buildings.
The Wet Service factors are Fb x 85%, Fc⊥ x 67%, and E x 90%

SIZE FACTOR, Cf

The size factor adjustment is new in the ‘91 NDS and is the result of a comprehensive testing and evaluation process conducted over the past 15 years (See the 91 NDS “In Grade Testing Program” information). Sawn dimension lumber performs differently depending upon the depth of the member. The size factor compensates for this natural property of dimension lumber, 2” to 4” thick.
Cf = 1.5 for 2x4s and slides down to Cf = 1.0 for 2 x 12s. 4x members have slightly different factors.
Larger members, 5” and wider are adjusted differently. When they are deeper than 12”, the values are modified by the formula $Cf = (12/d)^{1/9}$

VOLUME FACTOR, Cv

This adjustment is similar to the Size factor, but applies only to Glued-laminated timber. The factor is found by a complicated formula based on deviation from a typical 5-1/8”x 12”beam that is 21 feet long.

SHEAR STRESS FACTOR, Ch

The tabulated shear design values for Fv // allows for members to have splits, checks and shakes. This value can be increased in percentage increments up to 200% depending upon the condition of the actual, specific piece of wood to be installed in the structure. As a designer, it is impractical to try to specify the exact condition of the member to be installed, as outlined in the National Design Specification and local building codes. However, when a designed member fails only in shear, it **is** possible to simply specify on the plans that the member have “**No Splits**”, thus effectively doubling the Ch factor x Fc // value and have the member be acceptable.

OTHER CONDITIONS...

Wood treated with fire retardant, must be adjusted as specified by each manufacturer and your local building department.
Pressure treated wood does not normally require special adjustment.

OTHER DESIGN CONSIDERATIONS

A.) LATERAL SUPPORT or the Slenderness Factor

Lateral support is usually easy to achieve in residential structures. The guidelines for support are listed below. The calculations involved for arriving at the slenderness factor are beyond the scope of this booklet, but may be found in your building code.

When solid sawn, rectangular lumber beams, rafters, and joists are used in an upright position (bearing on their smallest edge), they must be supported to prevent them falling over or twisting. Safe ratios of depth to thickness are listed below.

These ratios are based on nominal sizes.

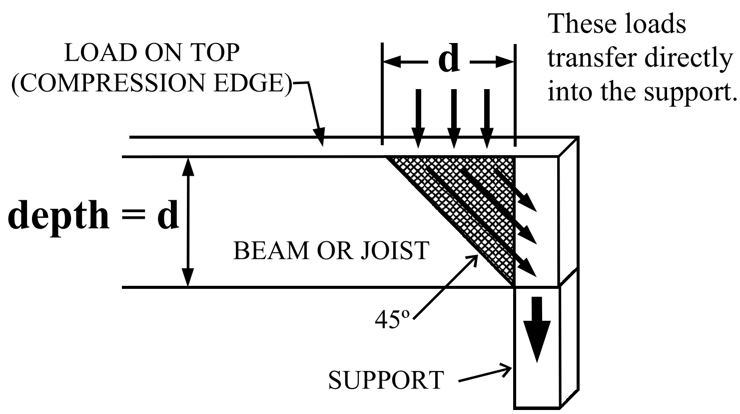
Ratio	Examples	Requirements
2 to 1	2x4, 4x8	no lateral support required.
3 to 1	2x6, 4x12 . . .	ends held in position by blocking, bridging or mechanical connection.
4 to 1	2x8, 4x16 . . .	ends held in position by blocking, bridging or mechanical connection.
5 to 1	2x10	one edge must be held in place along its entire length.
6 to 1	2x12	both edges held in line, or compression edge held in line along its entire length with sheathing or subflooring with blocking at all points of bearing, or bridging or solid blocking at 8 ft on center along its entire length.

B.) LIVE LOAD AND SNOW LOAD REDUCTIONS

Most building codes allow for a reduction of the unit (psf) live loads for floors and certain roofs when the contributing area to a structural member is greater than 150 sq. ft. The assumption being that, in a large area, not every square foot will be loaded to the full design live load. In deep snow areas it is sometimes allowable to reduce the unit snow design load if the roof has a steep pitch. The assumption being that snow will more likely slide off a roof when it has a steep pitch. The formulas for these reductions can be found in your local building code, but they may or may not be allowed by the local building official.

C.) SHEAR LOAD REDUCTION AT SUPPORTS

When designing for horizontal shear, it is allowable to neglect all of the loads next to the support for a distance equal to the depth of the member. This assumes that all the loads will transfer down directly into the support. To take this load reduction the member must be loaded on its top (compression) edge. If the member is side-loaded, such as with joists in "face nailed" joist hangers, the reduction does not apply. Normally designers don't bother with this reduction unless it is found that the chosen member only fails in shear and passes in bending and deflection. Then, sometimes the member can be shown to be acceptable if the shear load reduction is taken.



Most often the loads to be neglected when using the shear load reduction will be uniform loads. The uniform loads may actually be a series of closely spaced point loads resulting from rafters, joists or trusses and spaced anywhere from 12 inches to 24 inches apart. If the supporting member is only about 12 inches deep the nearest joist or truss may or may not be resting in the shear reduction zone ,"d". Even if you carefully plan and design the location of joists and rafters it is likely that the structure will be built slightly differently anyway. Another important consideration is that only 95% of visually graded lumber is required to meet the standard design attributes. So one of every twenty beams may not meet the design criteria for its species and grade. When in doubt, err on the side of caution and spec a larger beam.

Note: Members governed by their shear strength will most likely have a short span and a relatively high load.