PROPERTIES OF STRUCTURAL LUMBER

Grading
- Load carrying capacity effected by:
  - Size and number of knots, splits & other defects
  - Direction of grain
  - Specific gravity of wood
- Grading done under standards established by agencies certified by American Lumber Standards Committee
- **Visually graded lumber**: divided into categories based on nominal size so same grade of lumber in a species may have different allowable stresses depending on which category its in
- **Beams & stringers**: 5” and wider with depth more than 2” greater than the width
- **Post & timbers**: 5” x 5” and larger with depth not more than 2” greater than width

Design Values
- Different values required based on direction of loading b/c wood is not an isotropic material
  - Tables give values for extreme fiber stress in:
    - Bending: $F_b$
    - Tension parallel to grain: $F_t$
    - Horizontal shear: $F_v$
    - Compression perpendicular to grain: $F_c$
    - Compression parallel to grain: $F_p$
- Additional variables for selecting the extreme fiber in bending stress
  - If member is being used alone or with other members (rows of joists)
  - In order to qualify for repetitive member use, there must be at least three members spaced not more than 24" on center and method to distribute the load among them such as bridging or sheathing
Repetitive Member Factor, \( C_r \)
- Bending design values \( F_b \), for dimension lumber 2” – 4” thick shall be multiplied by the repetitive member factor, \( C_r = 1.5 \) when such members are used as joists, truss chords, rafter studs, planks, decking or similar that are in contact or space not more than 24”oc & not less than 3 in quantity and are joined by floor, roof, or other load distributing elements

Wet Service Factor, \( C_m \)
- When dimension lumber is used where moisture content will exceed 19% for an extended period, design values shall be multiplied by appropriate wet service factors from:

\[
\begin{array}{cccccc}
F_b & F_t & F_v & F_c & E \\
.85 & 1.0 & .97 & .67 & .8 \\
\end{array}
\]

Size Factor, \( C_f \)
- Tabulated bending, tension and compression parallel to grain design values for dimensional lumber 2” – 4” thick shall be multiplied by the following size factors:

<table>
<thead>
<tr>
<th>Grades</th>
<th>Width/Depth</th>
<th>Size Factor, ( C_f )</th>
</tr>
</thead>
<tbody>
<tr>
<td>select</td>
<td>2” x 3”</td>
<td>( 2^{1/2} )</td>
</tr>
<tr>
<td>structural</td>
<td>3”</td>
<td>1.3</td>
</tr>
<tr>
<td>no. 1 &amp; no. 2</td>
<td>4”</td>
<td>1.3</td>
</tr>
<tr>
<td>no. 3</td>
<td>5”</td>
<td>1.2</td>
</tr>
<tr>
<td>14” &amp; wider</td>
<td>6”</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Flat Use Factor, \( C_{fu} \)
- Bending design values adjusted by size factors are based on edgewise use (load applied to narrow face)
- When lumber is used flatwise (load applied to broad face) the bending design value \( F_b \) shall be multiplied by factors:

<table>
<thead>
<tr>
<th>Width (depth)</th>
<th>2” &amp; 3”</th>
<th>4”</th>
</tr>
</thead>
<tbody>
<tr>
<td>2” &amp; 3”</td>
<td>1.0</td>
<td>-</td>
</tr>
<tr>
<td>4”</td>
<td>1.1</td>
<td>1.0</td>
</tr>
<tr>
<td>5”</td>
<td>1.1</td>
<td>1.05</td>
</tr>
<tr>
<td>6”</td>
<td>1.15</td>
<td>1.05</td>
</tr>
<tr>
<td>8”</td>
<td>1.15</td>
<td>1.05</td>
</tr>
<tr>
<td>10” &amp; wider</td>
<td>1.2</td>
<td>1.1</td>
</tr>
</tbody>
</table>

- Amount of stress members can withstand is dependent on length of time load acts on member
  - Design values given are based on what is considered a normal duration of loading (10 years)
  - **However:** shorter loading duration *allowable unit stresses* may be increased as follows
    - 15% for two months duration (snow)
    - 25% for seven days duration (roof loading)
    - 60% for wind or earthquake loading
    - 100% for impact

Moisture Content
- **Moisture content:** weight of water in wood as a fraction of the weight of oven-dry wood
  - Affects shrinkage, weight, strength and withdrawal resistance of nails
- Ideally moisture content of wood when installed should be same as prevailing humidity to which it will be exposed however, this is seldom possible
  - **Dry lumber:** moisture content cannot exceed 19%
  - **Kiln dry:** max moisture content is 15%
Design values in tables assume maximum moisture content will not exceed 19%.

Wood shrinks perpendicular to the grain in the direction of the annual growth rings (tangentially) and about half as much across the rings (radially) or parallel.

**WOOD BEAMS**

**Designing Wood Beams:**

- **First:** *loads and stresses* on beam are determined
  - Support reactions
  - Vertical shear
  - Bending moments
  - Basic flexural formula used to find required *section modulus* needed to resist bending moment
    - A beam size is then selected that has the required section modulus
- **Second:** *horizontal shear stresses* are calculated and compared with allowable horizontal shear for species and grade
  - Important b/c wood has tendency to fail parallel to grain
- **Finally:** *Deflection* is checked to see if it is within acceptable limits
  - Even though may be strong enough to resist bending moment, the deflection may be outside of tolerable limits

**Designing for Bending**

- To design for bending, the *basic flexural formula* is used:

\[ S = Fb/M \]

- The basic *allowable extreme fiber stress in bending*, \(F'_b\), is found in Table 9.2a and *section modulus* is found in Table 9.1
  - This value must be modified for many factors including those shown in Table 9.2b
  - For sawn lumber under *major axis bending* the following formula is used

\[ F'_b = FbCDCMCtCLCF \]

- Definitions of \(C_m, C_f, \) and \(C_r\) are given in Table 9.2b
- Values for \(C_d\) are used to include the duration of load. In any combination of loads the largest value for \(C_d\) is used which corresponds to the shortest load duration which are:

  Permanent duration, dead load = .90
  Normal, 10 year duration, floor live load = 1.00
  2-month duration, snow load = 1.15
  7-day duration, roof live load
  10-minute duration
  wind or earthquake = 1.60
  Impact duration = 2.00

- Other values are for special cases
  - \(C_t\) = high temperature
  - \(C_l\) = laterally unbraced beams
  - \(C_i\) = incised members
- For laterally braced beams under normal usage, these values along with \(C_m\) may all be taken as 1.0
• **Example 9.1:** a simply supported wood beam spans 12′ and carries a combined dead and roof live load of 350plf. If the beam is Douglas fir-larch, no.2 what size beam should be used?
  - **First:** find **maximum bending moment**
    \[ M = \frac{wL^2}{8} \]
    \[ M = \frac{(350)(12)^2}{8} \]
    \[ M = 6300\text{ft}-\text{lbf} \]
  - **Second:** using Table 9.2a find the “bending” column & for Douglas fir-larch no.2, the tabulated value for \( F_b \) is 900psi
    - **All appropriate adjustments must be made to this value**
      - Load is due to dead and roof live load so the value of \( C_0 \) is 1.25
      - Since beam size is unknown a value of \( C_f \) must be assumed. A reasonable assumption is 1.1
    - **Allowable bending stress** is then found by multiplying the tabulated values by the appropriate factors using:
      \[ F'_b = C_0 C_f F_b \]
      \[ F'_b = (1.25)(1.1)(900) \]
      \[ F'_b = 1237\text{psi} \]
  - **Third:** the required **section modulus** is then found from the **basic flexural formula**:
    \[ S = \frac{M}{F'_b} \]
    \[ S = \frac{(6300)(12)}{1237} \]
    \[ S = 61.11\text{in}^3 \]
    - **Remember:** to multiply the moment by a factor of 12 to convert foot-pounds to inch-pounds
  - **Fourth:** looking in Table 9.1 the smallest beam that will provide this section modulus is a 4x12 with an \( S \) of 73.828in\(^3\)
    - **Notice:** a 6x10 would also provide the required value but this has more area and therefore costs more than the 4x12
    - The assumed value for \( C_f \) of 1.1 is correct. This value is given in Table 9.2b for a no.2 grade 12” wide and 4” thick.
    - The 4x12 is the most appropriate section to support the load

• **Example 9.2:** What is the maximum moment-carrying capacity in foot pounds of a 2x10 select structural Douglas fir-larch beam with applied dead and floor live load?
  - **First:** rearrange the equation for **section modulus** \( (S = \frac{M}{F'_b}) \) and divide by 12 to convert inch-pounds to foot-pounds
    \[ M = \frac{S F'_b}{12} \]
    - The **allowable tabulated unit stress** \( F_b \) from Table 9.2a is 1500psi and the **section modulus** from Table 9.1 of a 2x10 is 21,391in\(^3\)
    - The **load duration factor** \( C_0 \) for combined dead and floor live load is 1.0
    - **Size factor** \( C_f \) from Table 9.2b is 1.1
      \[ F'_b = C_0 C_f F_b \]
      \[ F'_b = (1)(1.1)(1500) \]
      \[ F'_b = 1650\text{psi} \]
      \[ M = \frac{S F'_b}{12} \]
      \[ M = \frac{(21.391)(1650)}{12} \]
      \[ M = 2941 \text{ ft-lbf} \]
- Sometimes either the width or depth of a beam is established by some limiting factor such as the ceiling clearance and the other dimension must be found.
  - Recalling section modulus for a rectangular beam is
    \[ S = \frac{bd^2}{6} \]

- Example 9.3: A wood beam spanning 10’ must be designed to support a concentrated load of 2900lbf in the center of the span but there is only enough room for a nominal 8” deep beam. If the beam can be dense select structural Douglas fir-larch with an allowable unit stress of 1900psi what beam width is necessary?
  - The moment of a beam with a concentrated load is \( M = \frac{PL}{4} \)
    \[
    \begin{align*}
    M &= \frac{PL}{4} \\
    M &= \frac{(2900)(10(12))}{4} \\
    M &= 87000\text{in-lbf}
    \end{align*}
    \]
  - The required section modulus is
    \[
    S = \frac{M}{F'_{b}} \\
    S = \frac{87000}{1900} \\
    S = 45.79\text{in}^3
    \]
  - There were no limitation on the depth of the beam a 4x10 would work with a section modulus of 49.911
    - However: a maximum depth of 7 1/2” (actual) of a nominal 8” beam then the required width from section modulus of rectangular beam is
      \[ S = \frac{bd^2}{6} \]
      \[
      \begin{align*}
      b &= \frac{6S}{d^2} \\
      b &= \frac{(6)(45.79)}{(7.5)^2} \\
      b &= 4.88\text{in}
      \end{align*}
      \]
    - A nominal 6” wide beam will work with an actual width of 5 1/2”

- Example 9.4: A Douglas fir-larch no1 beam supports a roof with a dead load of 100plf and a snow load of 150plf. If the beam must span 8’ what is the most economical size to use?
  - For snow load a load reduction factor of 1.15 is multiplied by the tabulated allowable stress
    - However: when there are loads of different durations on members, each load combination should be checked
    - For dead load a duration of .9 is used
    - Moment for a uniformly loaded beam due to the dead loads is
      \[
      \begin{align*}
      M &= \frac{wl^2}{8} \\
      M &= \frac{(100)(8)^2(12)/8} \\
      M &= 9600\text{in-lbf}
      \end{align*}
      \]
    - Moment due to dead load and snow load is
      \[
      \begin{align*}
      M &= \frac{(250)(8)^2(12)/8} \\
      M &= 24000\text{in-lbf}
      \end{align*}
      \]
    - Remember: factor of 12 used to convert foot-pounds to inch-pounds
    - Since beam size is unknown, the size factor will be assumed to be 1.1
    - The tabulated bending stress from Table 9.2a for Douglas fir-larch no1 is 1000psi
    - The required section modulus for dead load only is
Design For Horizontal Shear

- B/c it is easy for wood to shear along the grain, **actual horizontal shear** must always be checked against the **allowable unit shear stress** $F_v$
  - Especially important for short spans with large loads
  - Frequently a beam sufficient in size to resist bending stresses must be made larger to resist horizontal shear stresses
- B/c horizontal shear failure will always occur before vertical shear failure, it is not necessary to check for vertical shear except for beams notched at their supports
- The **maximum unit horizontal shear stress** for rectangular beams is
  
  $$F_v = \frac{3V}{2bd}$$

  - The **basic allowable stress in shear** $F_v$ is found in Table 9.2a and sizes are found in Table 9.1
    - This value must be modified for five factors including those shown in Table 9.2b
    - **Allowable shear stress** is
      
      $$F'_v = F_v C_D C_M C_I C_H$$

      $F_v$ = design value for horizontal shear
      $C_D$ = duration factor
      $C_M$ = wet service factor
      $C_I$ = high temperature factor
      $C_i$ = incised member factor
      $C_H$ = ???

      - Values of $C_D$, $C_M$ and $C_i$ are found in a manner similar to that for finding the values applied to bending stress
      - Values of $C_H$ are omitted from table 9.2b & are only used if need to verify the extent of cracking in the wood member
      - When calculating vertical shear $V$, the loads within a distance from the supports equal to the depth of the member may be neglected

**Example 9.5:** Check the beam in Ex 9.1 for horizontal shear
- The load is 350plf for 12’ or 4200lbf total
- The vertical shear at each reaction is 2100lbf
- Subtract the load within a distance equal to the depth of the beam 11 1/4”

  $$V = 2100 - (11.25/12)(350)$$

  $$V = 1722\text{lbf}$$

  - The value of $bd$ is the area found in Table 9.1 to be 39.375in$^2$
  - The **actual horizontal shear** is found by
\[ f_v = \frac{3V}{2bd} \]
\[ f_v = \frac{(3)(1772)}{(2)(39.375)} \]
\[ f_v = 67.50 \text{ psi} \]

- From Table 9.2a the **allowable tabulated horizontal shear** \( F_v \) is 180 psi for Doug fir-larch no2
  - This must be multiplied times the **duration of load factor** of 1.25
  - The **allowable shear stress** \( F'_v \) is 225 psi and is larger than the actual stress, so the beam is adequate to resist horizontal shear
  - If the actual value were greater than the allowable, a larger beam would be needed

**Design For Deflection**
- Formulas for deflection are the same for other materials
- Criteria is given in IBC and requires that two different conditions of loading be checked
  - The first **limits deflection due to live load** only to L/360 of the span
  - The second **limits deflection due to live load and dead load for unseasoned wood** to L/240 of the span
- IBC does allow a reduction by half the dead load for the condition of the live load and dead load if seasoned wood is used
  - Seasoned wood: moisture content of less than 16% at time of installation and used under dry conditions
- Since wood will deflect under long term use beyond its initial deflection, it is common practice to use the full value of dead load and live load when checking deflection against the L/240 criterion
  - This provides for the extra stiffness necessary to limit deflection under long term loading
- The **basic modulus of elasticity** \( E \) is found in Table 9.2a
  - Must be modified for four factors including those shown in Table 9.2b
  - The following formula is use for **allowable modulus of elasticity**

\[
E' = ECMC_tC_tC_T
\]

- \( E \) = modulus of elasticity
- \( CM \) = wet service factor
- \( Ct \) = high temperature factor
- \( Ci \) = incision factor
- \( CT \) = ???

  - The values for \( CM \), \( Ct \) and \( Ci \) are found in a manner similar to values applied to bending stress
  - Values of \( CT \) only apply to small truss members in compression
  - All of these values are 1.0 under normal conditions

- **Example 9.6:** Using the same beam found in Ex9.1 check to see that its deflection is within allowable limits. Assume that of the total load of 350plf, dead load is 150lbf and live load is 200plf
  - The **deflection for a uniformly loaded beam** is

\[
\Delta = \frac{5wl^4}{384EI}
\]

- The **modulus of elasticity** of Douglas fir-larch no2 is 1,600,000 psi as found in Table 9.2a and the moment of inertia of a 4x12 is 415.283 as found in Table 9.2
  - It is important to keep units consistent so answer is in inches
  - **Remember:** equation for the deflection of a uniformly loaded beam \( \Delta = \frac{5wl^4}{384EI} \), \( w \) is the load per unit length and \( l \) is the length
    - If \( l \) is in inches, the load must be in pounds per inch, not feet so calculating the total dead and live load, 360plf is 350/12 or 29.167lbf/in
  - The beam length of 12’ must be converted to inches and then raised to the fourth power

\[
\Delta = \frac{(5)(29.167)[(12)(12)]^4}{(384)(1600000)(415.283)}
\]
\[ \Delta = .25" \]
Another way to arrive at the same answer is to remember that $\Delta = \frac{5Wl^4}{384EI}$ can also take the form of

$$\Delta = \frac{5Wl^4}{384EI}$$

W is the total uniformly distributed load on the beam and length still needs to be converted to inches and raised to the third power so the calculation is

$$\Delta = \frac{(5)((350)(12))((12)(12))^3}{(384)(1600000)(415.283)}$$

$$\Delta = .25\"$$ for dead and live load

- For deflection of live load only

$$\Delta = \frac{5Wl^4}{384EI}$$


$$\Delta = .14\"$$

- Now determine the allowable deflection limits for live load only

$$\frac{L}{360} = \frac{(12)(12)}{360}$$

$$= .40\"$$

- This is more than the actual deflection under live load only of .14\" so this is acceptable

- Determine allowable deflection limits for total load

$$\frac{L}{240} = \frac{(12)(12)}{240}$$

$$= .60\"$$

- This is also more than the actual deflection under total load of .25\" so the 4x12 beam is acceptable for deflection requirements

**MISCELLANEOUS PROVISIONS**

**Notched Beams**

- Should be avoided but if done, IBC states that notches in sawn lumber bending members cannot exceed 1/6th the depth and cannot be located in the middle third of the span
- When at supports, depth cannot exceed 1/4th of beam depth

- If beams are notched, the *vertical shear* cannot exceed the value determined by the formula

$$V = \frac{2bd'}{3}(d'/d)$$
Example 9.7: If the beam in Ex 9.1 is notched 2” is it still an acceptable size?
- The beam is a 4x12 so its actual width is 3.5” and depth 11.25”
- Subtracting 2” gives a d’ value of 9.25”
- From Ex 9.5 the allowable horizontal shear for Douglas fir-larch no2 is 225psi
- Solving for Vertical shear is

\[
V = \frac{(2bd'F'v/3)(d'/d)}{\frac{2(3.5)(9.25)(225)/3(9.25/11.25)}{}}
V = 3993\text{lbf}
\]

- From Ex 9.5 the vertical shear at each reaction is 2100lbf so this beam could be notched 2” without exceeding the allowable vertical shear limitation

Size Factor
- As depth of a beam increases there is a slight decrease in bending strength
  - IBC requires allowable unit stress in bending $F_b$ be decreased by a size factor as determined by

\[
C_f = (12/d)^{1/9}
\]

- Only applies to rectangular sawn bending members that are visually graded timber or visually graded southern pine dimension lumber exceeding a depth of 12”
- Design values for bending, tension and compression parallel to the grain for visually graded dimension lumber excluding southern pine 2” – 4” thick must be multiplied by size factors given at the beginning of Tables 4A, 4B and 4E of NDS-01 of the Nat’ Design Specification of Wood Construction
  - The size factor does not affect the allowable strength to any great amount
    - Example: $C_f$ for a 14” deep beam is only .987 and for a 16” deep beam is .972

Lateral Support
- When wood beam is loaded in bending there is a tendency for it to buckle laterally
  - IBC provides decrease in allowable bending strength be made if certain conditions are not met
  - Mostly not required if proper lateral support is provided
    - Providing continuous support at compression edge such as with sheathing or subflooring and providing restraint against rotation at the ends of the members and at intervals with bridging

Bearing
- Load on a wood beam compresses the fibers where the weight is concentrated at the supports
  - To determine required bearing area the total reaction load is divided by the allowable compression perpendicular to grain, $F_{c\perp}$ found in Table 9.2a
  - For joists, IBC states that there must be at least 1 1/2” bearing on wood or metal and at least 3” bearing on masonry
  - Beams or girders supported on masonry must have at least 3” of bearing surface

Example 9.8: What is the required bearing area on a masonry wall for the beam selected in Ex 9.1?
- The total reaction of the beam is

\[
R = \frac{WL}{2}
R = \frac{(350)(12)}{2}
R = 2100\text{lbf}
\]

- The required bearing is

\[
A = \frac{R}{F_{c\perp}}
A = \frac{2100}{625}
A = 3.36\text{in}^2
\]

- Since the beam is 3 1/2” wide, the required length of bearing is 3.36/3.5 or .96in
  - However: since this is less than the code requirement of 3”, 3” must be used
WOOD COLUMNS

- Even though column may have enough cross sectional area to resist the unit compressive forces, it may fail to buckle
  - For wood columns, the ratio of length to width is just as important as for concrete and steel columns
  - However: wood columns the slenderness ratio is defined as the laterally unsupported length in inches divided by the least dimension of the column
    - Different than the length divided by radius of gyration but same in principle
- Load carrying capacity depends on the way the ends of the column are fixed
  - Effective length: total unsupported length multiplied by an effective buckling length factor \( K_e \)
  - Factors for various end conditions:

\[
\begin{array}{cccc}
K_e & \text{K_e value} \\
0.85 & 1.0 & 1.5 & 2.0 \\
\end{array}
\]

- B/c of wood construction details, columns are usually fixed in translation but free to rotate so the \( K \) value is taken as 1 and the effective length is taken as the actual unsupported length
  - \( l \) indicates the effective length of a column in inches

JOISTS

- Size: usually nominally 2” wide x 6, 8, 10 & 12”
- Spacing: 12”, 16” or 24” oc
- When they are designed as beams, the design value of \( F_b \) from Table 9.2a should be multiplied by the repetitive use factor \( C_r \) from Table 9.2b
  - Design value is slightly larger for multiple member use than for single member

GLUE-LAMINATED CONSTRUCTION

- Consist of a number of individual pieces of lumber glued together and finished under factory conditions for use as beams, columns, purlins, etc
- Used when larger members are required for heavy loads or long spans and where unusual structural shapes are required and appearance is a consideration
  - Can be formed into arches, tapered and pitched
- Standard sizes of width and depth
  - 1 1/2” actual depth pieces used so overall height a multiple of
  - 3/4” when tight curve must be formed

- B/c pieces can be selected free of defects, seasoned to proper moisture content and manufacturing conducted under controlled conditions the allowable stresses are higher than for solid sawn lumber
- Designated by size and commonly used symbol that specifies its stress rating
- Appearance grades: do not affect structural properties
  - Industrial: appearance is not issue
  - Architectural: appearance is factor but best grade not required
  - Premium: highest grade appearance
PLANKING

- Also called decking and is solid or laminated lumber lain on face spanning between beams
- Nominal thickness of 2, 3, 4 and 5” with actual sizes varying with manufacturer
- T&G to distribute load
- Span depends on thickness
- Often used with heavy timber construction