Wood Design

**Notation:**

- $a$ = name for width dimension
- $A$ = name for area
- $A_{req\,'adj}$ = area required at allowable stress when shear is adjusted to include self weight
- $b$ = width of a rectangle
- $c_1$ = coefficient for shear stress for a rectangular bar in torsion
- $C_C$ = curvature factor for laminated arches
- $C_D$ = load duration factor
- $C_{fu}$ = flat use factor for other than decks
- $C_F$ = size factor
- $C_H$ = shear stress factor
- $C_i$ = incising factor
- $C_L$ = beam stability factor
- $C_M$ = wet service factor
- $C_p$ = column stability factor for wood design
- $C_r$ = repetitive member factor for wood design
- $C_V$ = volume factor for glue laminated timber design
- $C_t$ = temperature factor for wood design
- $C_T$ = buckling stiffness factor for wood truss design
- $d$ = name for depth
- $d_{min}$ = dimension of timber critical for buckling
- $DL$ = shorthand for dead load
- $E$ = modulus of elasticity
- $E_{min}$ = reference modulus of elasticity for stability
- $E'_{min}$ = adjusted modulus of elasticity for stability
- $f$ = stress (strength is a stress limit)
- $f_b$ = bending stress
- $f_{from\ table}$ = tabular strength (from table)
- $f_p$ = bearing stress
- $f_r$ = radial stress for a glulam timber
- $f_v$ = shear stress
- $f_{v-max}$ = maximum shear stress
- $F_b$ = tabular bending strength
- $F'_{b}$ = allowable bending stress (adjusted)
- $F_c$ = tabular compression strength parallel to the grain
- $F'_{c}$ = allowable compressive stress (adjusted)
- $F_{cE}$ = theoretical allowed buckling stress
- $F_{c\perp}$ = tabular compression strength perpendicular to the grain
- $F_p$ = tabular bearing strength parallel to the grain
- $F_R$ = allowable radial stress
- $F_t$ = tabular tensile strength
- $F_u$ = ultimate strength
- $F_v$ = tabular bending strength
- $F_{v}$ = allowable shear stress
- $h$ = height of a rectangle
- $I$ = moment of inertia with respect to neutral axis bending
- $I_{trial}$ = moment of inertia of trial section
- $I_{req\,'d}$ = moment of inertia required at limiting deflection
- $I_y$ = moment of inertia with respect to an $y$-axis
- $J$ = polar moment of inertia
- $K_{cE}$ = material factor for wood column design
- $L_e$ = effective length that can buckle for column design, as is $L_e$
- $L$ = name for length or span length
- $LL$ = shorthand for live load
- $LRFD$ = load and resistance factor design
- $M$ = internal bending moment
- $M_{max}$ = maximum internal bending moment
- $M_{max\,-adj}$ = maximum bending moment adjusted to include self weight
- $P$ = name for axial force vector
- $R$ = radius of curvature of a deformed beam
- $R_c$ = radius of curvature of a laminated arch
- $S$ = section modulus
**Wood or Timber Design**

Structural design standards for wood are established by the *National Design Specification (NDS)* published by the American Wood Council. There is a combined specification (from 2005) for Allowable Stress Design and limit state design (LRFD).

Tabulated wood strength values are used as the base allowable strength (ASD) and modified by appropriate adjustment factors:

\[
    f = C_D C_M C_F \times f_{\text{from table}}
\]

**Size and Use Categories**

<table>
<thead>
<tr>
<th>Category</th>
<th>1 to 1½ in. thick</th>
<th>2 in. and wider</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boards</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dimension lumber</td>
<td>2 to 4 in. thick</td>
<td>2 in. and wider</td>
</tr>
<tr>
<td>Timbers</td>
<td>5 in. and thicker</td>
<td>5 in. and wider</td>
</tr>
</tbody>
</table>

**Adjustment Factors**

- **C_D** load duration factor
- **C_M** wet service factor (1.0 dry ≤ 19% sawn or ≤16% glu-lam moisture content)
- **C_t** temperature factor (at high temperatures strength decreases)
- **C_L** beam stability factor (for beams without full lateral support)
- **C_F** size factor for visually graded sawn lumber and round timber > 12” depth
  \[
  C_F = (12 / d)^{1/3} \leq 1.0
  \]
- **C_V** volume factor for glued laminated timber (similar to C_F)
- **C_{fu}** flat use factor (excluding decking)
- **C_r** repetitive member factor (1.15 for three or more parallel members of Dimension lumber spaced not more than 24 in. on center, connected together by a load-distributing element such as roof, floor, or wall sheathing)
Curvature factor for glued laminated timber (1.0 straight & cambered)

\[ C_c = 1 - 2000(t / R)^2 \]

Incising factor (0.85 incised sawn lumber, 1 for sawn lumber not incised and glulam)

Shear stress factor (amount of splitting)

Column stability factor (1.0 for fully supported columns)

<table>
<thead>
<tr>
<th>Tabular Design Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>F_b: bending stress</td>
</tr>
<tr>
<td>F_t: tensile stress</td>
</tr>
<tr>
<td>F_s: horizontal shear stress</td>
</tr>
<tr>
<td>F_c⊥: compression stress (perpendicular to grain)</td>
</tr>
<tr>
<td>F_c: compression stress (parallel to grain)</td>
</tr>
<tr>
<td>E: modulus of elasticity</td>
</tr>
<tr>
<td>F_p: bearing stress (parallel to grain)</td>
</tr>
</tbody>
</table>

Wood is significantly weakest in shear and strongest along the direction of the grain (tension and compression).

Load Combinations and Deflection

The critical load combination is determined by the largest of either:

\[
\frac{\text{dead load}}{0.9} \text{ or } \frac{(\text{dead load} + \text{any combination of live load})}{C_D}
\]

The deflection limits may be increased for less stiffness with total load: LL + 0.5(DL)

Criteria for Beam Design

Allowable normal stress or normal stress from LRFD should not be exceeded:

Knowing M and F_b, the minimum section modulus fitting the limit is:

\[ S_{req,d} \geq \frac{M}{F_b} \]

Besides strength, we also need to be concerned about serviceability. This involves things like limiting deflections & cracking, controlling noise and vibrations, preventing excessive settlements of foundations and durability. When we know about a beam section and its material, we can determine beam deformations.
Determining Maximum Bending Moment

Drawing V and M diagrams will show us the maximum values for design. Computer applications are very helpful.

Determining Maximum Bending Stress

For a prismatic member (constant cross section), the maximum normal stress will occur at the maximum moment.

For a non-prismatic member, the stress varies with the cross section AND the moment.

Deflections

Elastic curve equations can be found in handbooks, textbooks, design manuals, etc...Computer programs can be used as well.

Elastic curve equations can be superpositioned ONLY if the stresses are in the elastic range. The deflected shape is roughly the same shape flipped as the bending moment diagram but is constrained by supports and geometry.

Allowable Deflection Limits

All building codes and design codes limit deflection for beam types and damage that could happen based on service condition and severity.

<table>
<thead>
<tr>
<th>Use</th>
<th>LL only</th>
<th>DL+LL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof beams:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Industrial (no ceiling)</td>
<td>L/180</td>
<td>L/120</td>
</tr>
<tr>
<td>Commercial</td>
<td></td>
<td></td>
</tr>
<tr>
<td>plaster ceiling</td>
<td>L/240</td>
<td>L/180</td>
</tr>
<tr>
<td>no plaster</td>
<td>L/360</td>
<td>L/240</td>
</tr>
<tr>
<td>Floor beams:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ordinary Usage</td>
<td>L/360</td>
<td>L/240</td>
</tr>
<tr>
<td>Roof or floor (damageable elements)</td>
<td>L/480</td>
<td></td>
</tr>
</tbody>
</table>

Lateral Buckling

With compression stresses in the top of a beam, a sudden “popping” or buckling can happen even at low stresses. In order to prevent it, we need to brace it along the top, or laterally brace it, or provide a bigger I_y.

Beam Loads & Load Tracing

In order to determine the loads on a beam (or girder, joist, column, frame, foundation...) we can start at the top of a structure and determine the tributary area that a load acts over and the beam
needs to support. Loads come from material weights, people, and the environment. This area is assumed to be from half the distance to the next beam over to halfway to the next beam.

The reactions must be supported by the next lower structural element \textit{ad infinitum}, to the ground.

\textbf{Design Procedure}

The intent is to find the most lightweight member satisfying the section modulus size.

1. Know $F_{\text{all}}$ for the material or $F_U$ for LRFD.
2. Draw $V$ & $M$, finding $M_{\text{max}}$.
3. Calculate $S_{\text{req'd}}$. This step is equivalent to determining $f_b = \frac{M_{\text{max}}}{S} \leq F'_b$.
4. For rectangular beams $S = \frac{bh^2}{6}$
   - For timber: use the section charts to find $S$ that will work \textit{and remember that the beam self weight will increase $S_{\text{req'd}}$.} $w_{\text{self wt}} = \gamma A$

   ****Determine the “updated” $V_{\text{max}}$ and $M_{\text{max}}$ including the beam self weight, and verify that the updated $S_{\text{req'd}}$ has been met.*****

5. Consider lateral stability.

6. Evaluate horizontal shear stresses using $V_{\text{max}}$ to determine if $f_v \leq F'_v$
   
   For rectangular beams $f_{v_{\text{max}}} = \frac{3V}{2A} = 1.5 \frac{V}{A} \quad \therefore A_{\text{req'd}} \leq \frac{3V}{2F'_v}$

7. Provide adequate bearing area at supports: $f_p = \frac{P}{A} \leq F'_c$ or $F'_{c_{\perp}}$

8. Evaluate shear due to torsion
   
   $f_v = \frac{T_P}{J} \quad \text{or} \quad \frac{T}{c_i ab^2} \leq F'_v$
   
   (circular section or rectangular)

9. Evaluate the deflection to determine if $\Delta_{\text{max LL}} \leq \Delta_{\text{LL-allowed}}$ and/or $\Delta_{\text{max Total}} \leq \Delta_{\text{Total-allowed}}$

   ****\textit{note: when} $\Delta_{\text{calculated}} > \Delta_{\text{limit}}$, $I_{\text{required}}$ \textit{can be found with:} $I_{\text{req'd}} \geq \frac{\Delta_{\text{allow big}}}{\Delta_{\text{limit}}} I_{\text{trial}}$

   and $S_{\text{req'd}}$ will be satisfied for similar self weight *****

FOR ANY EVALUATION:

\begin{center}
Redesign (with a new section) at any point that a stress or serviceability criteria is NOT satisfied and re-evaluate each condition until it is satisfactory.
\end{center}
Load Tables for Uniformly Loaded Joists & Rafters

Tables exist for the common loading situation for joists and rafters – that of uniformly distributed load. The tables either provide the safe distributed load based on bending and deflection limits, they give the allowable span for specific live and dead loads. If the load is not uniform, an equivalent distributed load can be calculated from the maximum moment equation.

Decking and Sheathing

Flat panels or planks that span several joists or evenly spaced support behave as continuous beams. Design tables consider a “1 unit” wide strip across the supports and determine maximum bending moment and deflections in order to provide allowable loads depending on the depth of the material.

The other structural use of decking is to construct what is called a diaphragm, which is a horizontal or vertical (if the panels are used in a shear wall) unit tying the sheathing to the joists or studs that resists forces parallel to the surface of the diaphragm. When the free edges of the panels are supported by wood blocking, the diaphragm is referred to as blocked.

Criteria for Column Design

If we know the loads, we can select a section that is adequate for strength & buckling.

If we know the length, we can find the limiting load satisfying strength & buckling.

Any slenderness ratio, \( \frac{L_e}{d} \leq 50 \):

\[
f_c = \frac{P}{A} \leq F_c'\]

\[
F_c' = F_c \left( C_{D} \right) \left( C_{M} \right) \left( C_{T} \right) \left( C_{F} \right) \left( C_{P} \right)
\]

The allowable stress equation uses factors to replicate the combination crushing-buckling curve:

where:
- \( F_c' \) = allowable compressive stress parallel to the grain
- \( F_c \) = compressive strength parallel to the grain
- \( C_D \) = load duration factor
- \( C_M \) = wet service factor (1.0 for dry)
- \( C_T \) = temperature factor
- \( C_F \) = size factor
- \( C_P = \) column stability factor off chart or equation:

\[
C_P = 1 + \left( \frac{F_{cE} / F_c'}{2c} \right) \left[ 1 + \left( \frac{F_{cE} / F_c'}{2c} \right)^2 \right] ^{-1} \frac{F_{cE} / F_c'}{c}
\]

\( c = 0.9 \) for glue-lam and 0.8 for sawed lumber

For preliminary column design:

\[
F_c' = F_c^* C_P = \left( F_c C_D \right) C_P
\]
Procedure for Analysis

1. Calculate \( L_e/d_{\text{min}} \) (KL/d for each axis and chose largest)
2. Obtain \( F'_c \)
   \[
   F_{cE} = \frac{0.822E'_{\text{min}}}{(L_e/d)^2} \quad \text{with} \quad E'_{\text{min}} = E_{\text{min}}(C_M)(C_I)(C_T)(C_I)
   \]
   where \( E_{\text{min}} \) the modulus of elasticity for stability
3. Compute \( F'_c \approx F_cC_P \) with \( C_D = 1 \), normal, \( C_D = 1.25 \) for 7 day roof, etc.
4. Calculate \( F_{cE}/F'_c \) and get \( C_P \) from table or calculation
5. Calculate \( F'_c = F_cC_P \)
6. Compute \( P_{\text{allowable}} = F'_cA \) or alternatively compute \( f_{\text{actual}} = P/A \)
7. Is the design satisfactory?
   \[
   \begin{align*}
   \text{Is } P & \leq P_{\text{allowable}}? \Rightarrow \text{yes, it is; no, it is no good} \\
   \text{or } \text{Is } f_{\text{actual}} & \leq F'_c? \Rightarrow \text{yes, it is; no, it is no good}
   \end{align*}
   \]

Procedure for Design

1. Guess a size by picking a section
2. Calculate \( L_e/d_{\text{min}} \) (KL/d for each axis and choose largest)
3. Obtain \( F'_c \)
   \[
   F_{cE} = \frac{0.822E'_{\text{min}}}{(L_e/d)^2} \quad \text{with} \quad E'_{\text{min}} = E_{\text{min}}(C_M)(C_I)(C_T)(C_I)
   \]
   where \( E_{\text{min}} \) the modulus of elasticity for stability
4. Compute \( F'_c \approx F_cC_D \) with \( C_D = 1 \), normal, \( C_D = 1.25 \) for 7 day roof...
5. Calculate \( F_{cE}/F'_c \) and get \( C_P \) from table or calculation
6. Calculate \( F'_c = F_cC_P \)
7. Compute \( P_{\text{allowable}} = F'_cA \) or alternatively compute \( f_{\text{actual}} = P/A \)
8. Is the design satisfactory?
   \[
   \begin{align*}
   \text{Is } P & \leq P_{\text{allowable}}? \Rightarrow \text{yes, it is; no, pick a bigger section and go back to step 2.} \\
   \text{or } \text{Is } f_{\text{actual}} & \leq F'_c? \Rightarrow \text{yes, it is; no, pick a bigger section and go back to step 2.}
   \end{align*}
   \]

Trusses

Timber trusses are commonly manufactured with continuous top or bottom chords, but the members are still design as compression and tension members (without the effect of bending.)
Stud Walls

Stud wall construction is often used in light frame construction together with joist and rafters. Studs are typically 2-in. nominal thickness and must be braced in the weak axis. Most wall coverings provide this function. Stud spacing is determined by the width of the panel material, and is usually 16 in. The lumber grade can be relatively low. The walls must be designed for a combination of wind load and bending, which means beam-column analysis.

Columns with Bending (Beam-Columns)

The modification factors are included in the form:

$$\left[ \frac{f_c}{F'_c} \right]^2 + \frac{f_{bx}}{F'_{bx}} \left( 1 - \frac{f_c}{F'_c} \right) \leq 1.0$$

where:

$$1 - \frac{f_c}{F'_c} = \text{magnification factor accounting for P-\Delta}$$

$$F'_{bx} = \text{allowable bending stress}$$

$$f_{bx} = \text{working stress from bending about x-x axis}$$

In order to design an adequate section for allowable stress, we have to start somewhere:

1. Make assumptions about the limiting stress from:
   - buckling
   - axial stress
   - combined stress

2. See if we can find values for $r$ or $A$ or $S$ ($=l/c_{\text{max}}$)

3. Pick a trial section based on if we think $r$ or $A$ is going to govern the section size.

4. Analyze the stresses and compare to allowable using the allowable stress method or interaction formula for eccentric columns.

5. Did the section pass the stress test?
   - If not, do you increase $r$ or $A$ or $S$?
   - If so, is the difference really big so that you could decrease $r$ or $A$ or $S$ to make it more efficient (economical)?

6. Change the section choice and go back to step 4. Repeat until the section meets the stress criteria.

Glue Laminated Timber

These members come in nominal widths of 3, 4, 6, 8, 10, 12, 14 and 16 inches. The depth can exceed 12 inches, so the size factor, $C_F$ must be used. The formula is based on a uniformly loaded beam, simply supported with an $l/d$ ratio of 21. With a single midspan load, multiply $C_F$ by 1.078. With two loads at third points, multiply $C_F$ by 0.968. (Note: The Section Properties/Standard Sizes table provides section modulus that include $C_F$).

$$C_F = \left( \frac{12}{d} \right)^{\frac{1}{6}} \leq 1.0$$
If a glulam is subject to lateral buckling, the slenderness factor is used, and the size factor is not.

Laminated Arches

The radius of curvature, $R$, is limited because of residual bending stresses between lams of thickness $t$ to 100$t$ for Southern pine and hardwoods and 250$t$ for softwoods.

The allowable bending stress for combined stresses is $F'_b = F_b (C_F C_C)$

Bending of a curved glulam causes radial stresses (like membrane pressures) in tension and compression which can be evaluated for an arc with a radius of $R$ at the neutral axis from:

$$f_r = \frac{3M}{2Rbd}$$ for constant rectangular cross section

$$f_r \leq F_R$$ where $F_R = \begin{cases} F_{C_L} \\ \frac{1}{\sqrt{3}} F_{V} \end{cases}$
Table 9.3 Column Stability Factor $C_P$

<table>
<thead>
<tr>
<th>$F_0$</th>
<th>$F_{re}$</th>
<th>$F_{re}$</th>
<th>$C_p$</th>
<th>$C_{pl}$</th>
<th>$F_{re}$</th>
<th>$F_{re}$</th>
<th>$C_p$</th>
<th>$C_{pl}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>0.822</td>
<td>0.822</td>
<td>0.822</td>
<td>0.822</td>
<td>0.822</td>
<td>0.822</td>
<td>0.822</td>
<td>0.822</td>
</tr>
</tbody>
</table>

Note: $C_p = 0.82F_0$, $c = 0.8$ for sawn, $c = 0.9$ for glulam.

Table developed and permission for use granted by Professor Ed Libbert, Dept. of Architecture, University of Washington.
**SECTION PROPERTIES / STANDARD SIZES**

To the extent that other considerations will permit, the finished sizes of structural glued laminated timber as given in Table 8 constitute normal industry practice. Industry standards do, however, permit the use of any depth or width of glued laminated timber. Dimension lumber of 1¾ in. net thickness is normally used for laminating straight members.

The modified section modulus includes size factor (C), and no further reduction of bending stress for size is needed.

<table>
<thead>
<tr>
<th>3¾&quot; WIDTH</th>
<th>8¼&quot; WIDTH</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DEPTH, d in.</strong></td>
<td><strong>AREA, A in²</strong></td>
</tr>
<tr>
<td>6.0</td>
<td>18.8</td>
</tr>
<tr>
<td>7.5</td>
<td>93.4</td>
</tr>
<tr>
<td>9.0</td>
<td>28.1</td>
</tr>
<tr>
<td>10.5</td>
<td>38.2</td>
</tr>
<tr>
<td>12.0</td>
<td>37.5</td>
</tr>
<tr>
<td>13.5</td>
<td>42.2</td>
</tr>
<tr>
<td>15.0</td>
<td>46.9</td>
</tr>
<tr>
<td>16.5</td>
<td>51.6</td>
</tr>
<tr>
<td>18.0</td>
<td>56.3</td>
</tr>
<tr>
<td>19.5</td>
<td>60.9</td>
</tr>
<tr>
<td>21.0</td>
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</tr>
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<td>256.9</td>
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<tr>
<td>64.5</td>
<td>269.2</td>
</tr>
<tr>
<td>67.5</td>
<td>281.5</td>
</tr>
</tbody>
</table>

Note: Values are approximate and subject to variation based on actual material properties and manufacturing tolerances.
<table>
<thead>
<tr>
<th>Depth (d) (in.)</th>
<th>Area (A) (in.²)</th>
<th>S_x (in.³)</th>
<th>I_x (in.⁴)</th>
<th>S_y (in.³)</th>
<th>I_y (in.⁴)</th>
<th>S_z (in.³)</th>
<th>I_z (in.⁴)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.78</td>
<td>46.41</td>
<td>37.57</td>
<td>68.40</td>
<td>8.41</td>
<td>1.02</td>
<td>7.95</td>
<td>1.08</td>
</tr>
<tr>
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</tbody>
</table>

**Section Properties of Southern Pine Structural Glued Laminated Timber (GLULAM)**

<table>
<thead>
<tr>
<th>Depth (d) (in.)</th>
<th>Area (A) (in.²)</th>
<th>S_x (in.³)</th>
<th>I_x (in.⁴)</th>
<th>S_y (in.³)</th>
<th>I_y (in.⁴)</th>
<th>S_z (in.³)</th>
<th>I_z (in.⁴)</th>
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<td>1.02</td>
<td>7.95</td>
<td>1.08</td>
</tr>
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**Note Set 19.1**

**F2016abn**
### Section Properties of Southern Pine Structural Glued Laminated Timber (GLULAM)

<table>
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<tr>
<th>Depth d (in.)</th>
<th>Area A (in.²)</th>
<th>x-axis I₁ (in.⁴)</th>
<th>S₁ (in.⁴)</th>
<th>r₁ (in.)</th>
<th>y-axis I₂ (in.⁴)</th>
<th>S₂ (in.⁴)</th>
<th>(r₂ = 2.454 in.)</th>
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</tbody>
</table>

Source: Courtesy of the American Forest & Paper Association, Washington, DC.
ASD Beam Design Flow Chart

Collect data: $L$, $\phi_0$, $\gamma$, $\Delta_{\text{limit}}$; find beam charts for load cases and $\Delta_{\text{actual}}$ equations

Collect data: $F'_b$ & $F'_v$

Find $V_{\text{max}}$ & $M_{\text{max}}$ from constructing diagrams or using beam chart formulas

Find $S_{\text{req}}$ and pick a section from a table with $S_x$ greater or equal to $S_{\text{req}}$

Calculate $\psi_{\text{self wt.}}$ using $A$ found and $\gamma$. Find $M_{\text{max-adj}}$ & $V_{\text{max-adj}}$

No

Calculate $S_{\text{req-adj}}$ using $M_{\text{max-adj}}$

Is $S_{\text{(picked)}}$ $\geq$ $S_{\text{req-adj}}$?

(OR calculate $f_b$ Is $f_b$ $\leq F'_b$?)

Yes

Calculate $A_{\text{req-adj}}$ using $V_{\text{max-adj}}$

Is $A_{\text{(picked)}}$ $\geq$ $A_{\text{req-adj}}$?

(OR calculate $f_v$ Is $f_v$ $\leq F'_v$?)

No

pick a new section with a larger area

Calculate $\Delta_{\text{max}}$ (no load factors!) using superpositioning and beam chart equations with the $I_x$ for the section

Is $\Delta_{\text{max}}$ $\leq$ $\Delta_{\text{limit}}$?

This may be both the limit for live load deflection and total load deflection.

No

pick a section with a larger $I_x$

Yes (DONE)

$\frac{I_{\text{reqd}}}{I_{\text{trial}}} \geq \frac{\Delta_{\text{no big}}}{\Delta_{\text{limit}}}$