Elements of Architectural Structures: Form, Behavior, and Design
ARCH 614
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lecture thirteen

Wood construction: materials & beams
Wood Beam Design

• National Design Specification
  – American Wood Council
  – ASD & LRFD (combined in 2005)
  – adjustment factors x tabulated stress = allowable stress
  – adjustment factors terms, C with subscript
  – i.e, bending:

\[ f_b \leq F_b' = F_b \times \text{(product of adjustment factors)} \]
Timber

- lightweight: strength ~ like steel
- strengths vary
  - by wood type
  - by direction
  - by “flaws”
- size varies by tree growth
- renewable resource
- manufactured wood
  - assembles pieces
  - adhesives
Wood Properties

- cell structure and density

http://www.swst.org/teach/set2/struct1.html

softwood

hardwood
Wood Properties

• moisture
  – exchanges with air easily
  – excessive drying causes warping and shrinkage
  – strength varies some

• temperature
  – steam
  – volatile products
  – combustion

http://www.swst.org/teach/set2/struct1.html
Wood Properties

- **load duration**
  - short duration
    - higher loads
  - normal duration
    - > 10 years

- **creep**
  - additional deformation with no additional load
Structural Lumber

- **dimension** – 2 x’s (nominal)
- **beams, posts, timber, planks**
- **grading**
  - select structural
  - no. 1, 2, & 3
- **tabular values**
  by species
- **glu-lam**
- **plywood**
Adjustment Factors

- **terms**
  - $C_D = \text{load duration factor}$
  - $C_M = \text{wet service factor}$
    - $1.0 \text{ dry} \leq 19\% \text{ MC sawn}$
    - $1.0 \text{ dry} \leq 16\% \text{ MC glu-lam}$
  - $C_F = \text{size factor}$
    - visually graded sawn lumber and round timber $> 12''$ depth

$C_F = \left( \frac{12}{d} \right)^{\frac{1}{9}} \leq 1.0$

Table 5.2 (pg 177)
Adjustment Factors

- \( C_{fu} = \text{flat use factor} \)
  - not decking

- \( C_i = \text{incising factor} \)
  - increase depth for pressure treatment

- \( C_t = \text{temperature factor} \)
  - lose strength at high temperatures
Adjustment Factors

• terms
  – \( C_r \) = repetitive member factor
  – \( C_H \) = shear stress factor
    • splitting
  – \( C_V \) = volume factor
    • same as \( C_F \) for glue laminated timber
  – \( C_L \) = beam stability factor
    • beams without full lateral support
  – \( C_C \) = curvature factor for laminated arches
Allowable Stresses

- **design values**
  - $F_b$: bending stress
  - $F_t$: tensile stress
    - strong
  - $F_v$: horizontal shear stress
    - weak
  - $F_{c\perp}$: compression stress (perpendicular to grain)
  - $F_c$: compression stress (parallel to grain)
    - strong
  - $E$: modulus of elasticity
  - $F_p$: bearing stress (parallel to grain)
Load Combinations

• design loads, take the bigger of
  – (dead loads)/0.9
  – (dead loads + any possible combination of live loads)/C_D

• deflection limits
  – no load factors
  – for stiffer members:
    • Δ_T max from LL + 0.5(DL)
Beam Design Criteria

• **strength design**
  - bending stresses predominate
  - shear stresses occur

• **serviceability**
  - limit deflection and cracking
  - control noise & vibration
  - no excessive settlement of foundations
  - durability
  - appearance
  - component damage
  - ponding
Beam Design Criteria

• superpositioning
  – use of beam charts
  – elastic range only!
  – “add” moment diagrams
  – “add” deflection CURVES (not maximums)

1. SIMPLE BEAM—UNIFORMLY DISTRIBUTED LOAD

\[
\begin{align*}
\text{Total Equiv. Uniform Load} & = \frac{wx}{2} \\
R & = \frac{wI}{2} \\
V_x & = \frac{w}{2} (\frac{L}{2} - x) \\
M_{\text{max. (at center)}} & = \frac{wx}{8} (L - x) \\
\Delta_{\text{max. (at center)}} & = \frac{5wx^4}{384EI} (L^2 - 2x^2 + x^4) \\
\end{align*}
\]
### Deflection Limits

- **based on service condition, severity**

<table>
<thead>
<tr>
<th>Use</th>
<th>LL only</th>
<th>DL+LL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Roof beams:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Industrial</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><strong>Floor beams:</strong></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

- lateral buckling caused by compressive forces at top coupled with insufficient rigidity
- can occur at low stress levels
- stiffen, brace or bigger $I_y$
Design Procedure

1. Know $F_{all}$ for the material or $F_U$ for LRFD

2. Draw $V$ & $M$, finding $M_{max}$

3. Calculate $S_{req'd}$ \( \left( f_b \leq F_b \right) \)

4. Determine section size

\[
S = \frac{bh^2}{6}
\]
Beam Design

4*. Include self weight for $M_{\text{max}}$
   - and repeat 3 & 4 if necessary

5. Consider lateral stability

Unbraced roof trusses were blown down in 1999 at this project in Moscow, Idaho.

Photo: Ken Carper
Beam Design

6. Evaluate shear stresses - horizontal

- \( f_v \leq F_v \)

- \( W \) and rectangles
  \[
  f_{v\text{-max}} = \frac{3V}{2A} \approx \frac{V}{A_{\text{web}}}
  \]

- general
  \[
  f_{v\text{-max}} = \frac{VQ}{Ib}
  \]
Beam Design

7. Provide adequate bearing area at supports

\[ f_p = \frac{P}{A} \leq F_p \]
Beam Design

8. Evaluate torsion

\[ (f_v \leq F_v) \]

- circular cross section
  \[ f_v = \frac{T\rho}{J} \]

- rectangular
  \[ f_v = \frac{T}{c_1ab^2} \]

<table>
<thead>
<tr>
<th>a/b</th>
<th>c_1</th>
<th>c_2</th>
</tr>
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<tbody>
<tr>
<td>1.0</td>
<td>0.208</td>
<td>0.1406</td>
</tr>
<tr>
<td>1.2</td>
<td>0.219</td>
<td>0.1661</td>
</tr>
<tr>
<td>1.5</td>
<td>0.231</td>
<td>0.1958</td>
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<tr>
<td>2.0</td>
<td>0.246</td>
<td>0.229</td>
</tr>
<tr>
<td>2.5</td>
<td>0.258</td>
<td>0.249</td>
</tr>
<tr>
<td>3.0</td>
<td>0.267</td>
<td>0.263</td>
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<tr>
<td>4.0</td>
<td>0.282</td>
<td>0.281</td>
</tr>
<tr>
<td>5.0</td>
<td>0.291</td>
<td>0.291</td>
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<tr>
<td>10.0</td>
<td>0.312</td>
<td>0.312</td>
</tr>
<tr>
<td>\infty</td>
<td>0.333</td>
<td>0.333</td>
</tr>
</tbody>
</table>
Beam Design

9. Evaluate deflections

\[ y_{\text{max}}(x) = \Delta_{\text{actual}} \leq \Delta_{\text{allowable}} \]
Joists & Rafters

- allowable load tables
- allowable length tables for common live & dead loads
- lateral bracing needed
- common spacings
LRFD

• factored loads & reduced nominal capacity

\[ M_u = \gamma_D M_D + \gamma_L M_L \leq \phi_b M_n \]

ϕ - Resistance factor

γ - Load factor for (D)ead & (L)ive load

• nominal adjusted – no \( C_D \)

\[ M_n = F'_{bn} \times S \]

\[ F'_{bn} = F_{bn} (\phi_b) (\lambda) (\text{product of adjustment factors}) \]

\[ F_{bn} = F_b \times K_F \text{ (conversion factor)} \]
Engineered Wood

- plywood
  - veneers at different orientations
  - glued together
  - split resistant
  - higher and uniform strength
  - limited shrinkage and swelling
  - used for sheathing, decking, shear walls, diaphragms
Engineered Wood

- **glued-laminated timber**
  - *glulam*
  - short pieces glued together
  - straight or curved
  - grain direction parallel
  - higher strength
  - more expensive than sawn timber
  - large members (up to 100 feet!)
  - flexible forms
Engineered Wood

- **I sections**
  - beams

- **other products**
  - pressed veneer strip panels (Parallam)

- **wood fibers**
  - Hardieboard: cement & wood
Timber Elements

• stressed-skin elements
  – modular built-up “plates”
  – typically used for floors or roofs

Figure 1. Typical Two-Sided Stressed-Skin Panel

- Plywood splice plate
- Vent holes
- Lumber header may be continuous or as shown on opposite end
- Scarf joint in lower skin is preferred method (alternate: spliced butt joint)
- Lumber stringers
- Lumber blocking (not required if pre-spliced skins are used)
- Plywood top skin
- Butt joint between plywood panels
- Glue joint
- Blanket insulation as required
- Ventilation openings
- Plywood lower skin
- Lumber headers
Timber Elements

• built-up box sections
  – built-up beams
  – usually site-fabricated
  – bigger spans
Timber Elements

• trusses
  – long spans
  – versatile
  – common in roofs
Timber Elements

• folded plates and arch panels
  – usually of plywood
Timber Elements

• arches and lamellas
  – arches commonly laminated timber
  – long spans
  – usually only for roofs
Approximate Depths

<table>
<thead>
<tr>
<th>Material</th>
<th>Approximate Depths</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planking</td>
<td>L/25–L/35</td>
</tr>
<tr>
<td>Joists</td>
<td>L/18–L/20</td>
</tr>
<tr>
<td>Stressed-skin panels</td>
<td>L/24–L/30</td>
</tr>
<tr>
<td>Laminated beams</td>
<td>L/18–L/20</td>
</tr>
<tr>
<td>Box beams</td>
<td>L/18–L/20</td>
</tr>
<tr>
<td>Trussed rafters</td>
<td>L/5–L/7</td>
</tr>
<tr>
<td>Open-web joists</td>
<td>L/18–L/20</td>
</tr>
<tr>
<td>Flat trusses</td>
<td>L/10–L/15</td>
</tr>
<tr>
<td>Shaped trusses</td>
<td>L/7–L/10</td>
</tr>
<tr>
<td>Plywood folded plates</td>
<td>L/7–L/12</td>
</tr>
<tr>
<td>Laminated arches</td>
<td>L/4–L/6</td>
</tr>
</tbody>
</table>

Key:
- Minimum span
- Possible span range
- Maximum span
- Typical span for member
- Typical member length

FIGURE 15–3 Approximate span ranges for timber systems.