ARCH 324 - Structures 2, Winter 2009

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Deflection of Structural Members

- Slope and Elastic Curve
- Deflection Limits
- Diagrams by Parts
- Symmetrical Loading
- Asymmetrical Loading
- Deflection Equations and Superposition

Pont da Suransuns, Viamala, Switzerland

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Slope

- The curved shape of a deflected beam is called the elastic curve.

- The angle of a tangent to the elastic curve is called the slope, and is measured in radians.

  \[
  \text{degrees} = \text{radians} \frac{180}{\pi}
  \]

- Slope is influenced by the stiffness of the member: material stiffness \( E \), the modulus of elasticity; and sectional stiffness \( I \), the moment of inertia, as well as the length of the beam.

$$\text{stiffness} = \frac{EI}{L}$$

Source: University of Michigan, Department of Architecture
Deflection

• Deflection is the distance that a beam bends from its original horizontal position, when subjected to loads.

• The compressive and tensile forces above and below the neutral axis, result in a shortening (above n.a.) and lengthening (below n.a.) of the longitudinal fibers of a simple beam, resulting in a curvature which deflects from the original position.

\[ \Delta = \text{deflection} \]

\[ \text{stiffness} = \frac{EI}{L} \]

Source: University of Michigan, Department of Architecture
Deflection Limits

- Various guidelines have been created, based on use classification, to determine maximum allowable deflection values.
- Typically, a floor system with a LL deflection in excess of $L/360$ will feel bouncy.
- Flat roofs with total deflections greater than $L/120$ are in danger of ponding.

<table>
<thead>
<tr>
<th>Use Classification</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</td>
<td>1/180</td>
<td>1/120</td>
</tr>
<tr>
<td>Commercial and Institutional</td>
<td></td>
<td></td>
</tr>
<tr>
<td>without plaster ceiling</td>
<td>1/240</td>
<td>1/180</td>
</tr>
<tr>
<td>with plaster ceiling</td>
<td>1/360</td>
<td>1/240</td>
</tr>
<tr>
<td>Floor Beams:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ordinary Usage*</td>
<td>1/360</td>
<td>1/240</td>
</tr>
</tbody>
</table>

*Ordinary usage is for floors intended for construction in which walking comfort and the minimizing of plaster cracking are primary considerations.


$L = \text{span}$
Relationships of Forces and Deformations

There are a series of relationships among forces and deformations along a beam, which can be useful in analysis. Using either the deflection or load as a starting point, the following characteristics can be discovered by taking successive derivatives or integrals of the beam equations.

---

\[
\text{load} = \frac{d^4y}{dx^4} = \frac{dV}{dx} \frac{1}{EI} = \frac{w}{EI} \\
\text{shear} = \frac{d^3y}{dx^3} = \frac{dM}{dx} \frac{1}{EI} = \frac{V}{EI} \\
\text{moment} = \frac{d^2y}{dx^2} = \frac{M}{EI} \\
\text{slope} = \frac{dy}{dx} \\
\text{deflection} = y
\]
Symmetrically Loaded Beams

- Maximum slope occurs at the ends of the beam.
- A point of zero slope occurs at the center line. This is the point of maximum deflection.
- Moment is positive for gravity loads.
- Shear and slope have balanced + and - areas.
- Deflection is negative for gravity loads.

Source: University of Michigan, Department of Architecture
Cantilever Beams

- One end fixed. One end free
- Fixed end has maximum moment, but zero slope and deflection.
- Free end has maximum slope and deflection, but zero moment.
- Slope is either downward (-) or upward (+) depending on which end is fixed.
- Shear sign also depends of which end is fixed.
- Moment is always negative for gravity loads.
Diagrams by Parts

marks vertex which must be present for area equations to be valid.
Asymmetrically Loaded Beams
Diagram Method

- The value of the slope at each of the endpoints is different.
- The exact location of zero slope (and maximum deflection) is unknown.
- Start out by assuming a location of zero slope (Choose a location with a known dimension from the loading diagram)
- With the arbitrary location of zero slope, the areas above and below the baseline ("A" and "B") are unequal
- Adjust the baseline up or down by D distance in order to equate areas "A" and "B". Shifting the baseline will remove an area "a" from "A" and add an area "b" to "B"
Asymmetrically Loaded Beams (continued)

• Compute distance $D$ with the equation:

$$D = \frac{|A - B|}{L}$$

• With the vertical shift of the baseline, a horizontal shift occurs in the position of zero slope.

• The new position of zero slope will be the actual location of maximum deflection.

• Compute the area under the slope diagram between the endpoint and the new position of zero slope in order to compute the magnitude of the deflection.

Source: University of Michigan, Department of Architecture
Example: Asymmetrical Loading – Diagram method
Deflection: by Superposition of Equations

- Deflection can be determined by the use of equations for specific loading conditions
- See Data Sheet D-25 for more examples
- By “superposition” equations can be added for combination load cases. Care should be taken that added equations all give deflection at the same point, e.g. the center line.
- Note that if length and load (w) is entered in feet, a conversion factor of $1728 \text{ in}^3/\text{ft}^3$ must be applied in order to compute deflection in inches.

<table>
<thead>
<tr>
<th>Beam Load and Support</th>
<th>Actual Deflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Uniform load, simple span</td>
<td>$\Delta_{\text{max}} = \frac{5wL^4}{384EI}$ (at the centerline)</td>
</tr>
<tr>
<td>(b) Concentrated load at midspan</td>
<td>$\Delta_{\text{max}} = \frac{PL^3}{48EI}$ (at the centerline)</td>
</tr>
<tr>
<td>(c) Two equal concentrated loads at third points</td>
<td>$\Delta_{\text{max}} = \frac{23PL^3}{648EI} = \frac{PL^3}{28.2EI}$ (at the centerline)</td>
</tr>
<tr>
<td>(d) Three equal concentrated loads at quarter points</td>
<td>$\Delta_{\text{max}} = \frac{PL^3}{20.1EI}$ (at the centerline)</td>
</tr>
</tbody>
</table>

Source: University of Michigan, Department of Architecture
Example: Equations Method

- To determine the total deflection of the beam for the given loading condition, begin by breaking up the loading diagram into two parts.

- Compute the total deflection by superimposing the deflections from each of the individual loading conditions. In this example, use the equation for a midspan point load and the equation for a uniform distributed load.

\[
\Delta_{\text{actual}} = \frac{PL^3}{48EI} + \frac{5\omega L^4}{384EI}
\]

Source: University of Michigan, Department of Architecture
Example: Equations Method

• For a W18x55 with an E modulus of 30000 ksi and a moment of inertia of 890 in$^4$

• Using an allowable deflection limit of $L/240$.

• Check deflection

\[
\Delta_{\text{allow}} = \frac{L}{240} = \frac{28\times 12 \text{ in./ft.}}{240} = 1.4''
\]

\[
\Delta_{\text{actual}} = \frac{PL^3}{48EI} + \frac{5wL^4}{384EI}
\]

\[
\Delta_{\text{actual}} = \frac{20 \text{ k}(28)^3 1,728}{48(30 \times 10^3)(890)} + \frac{5(1.06 \text{ k/ft.})(28)^4 1,728}{(384)(30 \times 10^3)(890)}
\]

\[
\Delta_{\text{actual}} = 0.59'' + 0.55'' = 1.41'' < 1.4'' \therefore \text{OK}
\]
Example: Asymmetrical Loading – Superposition of Equations

Standard equations provide values of shear, moment and deflection at points along a beam.

Cases can be “superpositioned” or overlaid to obtain combined values.

To find the point of combined maximum deflection, the derivative of the combined deflection equation can be solved for 0. This gives the point with slope = 0 which is a max/min on the deflection curve.

Source: Steel Construction Manual AISC 1989
Example (same as above): Asymmetrical Loading - Superposition

\[ \Delta ex = \text{Case 5} + \text{Case 6} \]

\[ \Delta = \frac{\omega a^2 (f-x)(4xf-2x^2-b^2)}{2a^4 Eis} + \frac{P_0 x (x^2-b^2-x^2)}{6 Eis} \]

\[ EIS = \frac{1}{2} \left( \frac{x}{26} - 2x^2 - 12^2 \right) \]

\[ = (6-\frac{x}{26})(144-2x^2-144) + \frac{x}{26} (x^2-16) \]

\[ = \frac{x^3}{26} - 36x^2 + 1050x - 664 \]

\[ f(x) = \frac{x^2}{2} - 72x + 1050 \]

\[ 0 = \frac{x^2}{2} - 72x + 1050 \]

\[ x = \frac{144 \pm 4\sqrt{721}}{2} \]

\[ x = 127.5 \]

\[ x = 16.466 \]