ARCH 324 - Structures 2, Winter 2009

von Buelow, Peter

<http://hdl.handle.net/2027.42/64938>
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Renforced Concrete by Ultimate Strength Design

- LRFD vs. ASD
- Failure Modes
- Flexure Equations
- Analysis of Rectangular Beams
- Design of Rectangular Beams
- Analysis of Non-rectangular Beams
- Design of Non-rectangular Beams
Allowable Stress – WSD (ASD)

\[ f_{actual} \leq (F.S.) F_{failure} \]

- Actual loads used to determine stress
- Allowable stress reduced by factor of safety

Ultimate Strength – (LRFD)

- Loads increased depending on type load
  - \( \gamma \) Factors: DL=1.4  LL=1.7  WL=1.3
  - \( U=1.4DL+1.7LL \)
- Strength reduced depending on type force
  - \( \phi \) Factors: flexure=0.9  shear=0.85  column=0.7

Examples:

WSD

\[ f_b \leq 0.45 f'_c \]

\[ f_v \leq 0.1\sqrt{f'_c} \]

Ultimate Strength

\[ M_u \leq 0.9 M_n \]

\[ V_u \leq 0.85 V_n \]

\[ P_u \leq 0.70 P_n \]
Strength Measurement

- Compressive strength
  - 12”x6” cylinder
  - 28 day moist cure
  - Ultimate (failure) strength

- Tensile strength
  - 12”x6” cylinder
  - 28 day moist cure
  - Ultimate (failure) strength
  - Split cylinder test
  - Ca. 10% to 20% of $f'c$

Photos: Source: Xb-70 (wikipedia)
Failure Modes

\[ \rho = \frac{A_s}{bd} \]

- **No Reinforcing**
  - Brittle failure

- **Reinforcing < balance**
  - Steel yields before concrete fails
  - Ductile failure

- **Reinforcing = balance**
  - Concrete fails just as steel yields

- **Reinforcing > balance**
  - Concrete fails before steel yields
  - Sudden failure

\[ \rho_{\text{min}} = \frac{200}{f_y} \]

\[ \rho_{\text{max}} = 0.75 \rho_{\text{bal}} \]

\[ \rho_{\text{bal}} = \left( \frac{0.85 \beta_1 f'_c}{f_y} \right) \left( \frac{87000}{87000 + f_y} \right) \]

\[ \rho > \rho_{\text{max}} \quad \text{SuddenDeath!!} \]

Source: Polyparadigm (wikipedia)
\( \beta_1 \)

\( \beta_1 \) is a factor to account for the non-linear shape of the compression stress block.

\[ a = \beta_1 c \]

<table>
<thead>
<tr>
<th>( f'c )</th>
<th>( \beta_1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.85</td>
</tr>
<tr>
<td>1000</td>
<td>0.85</td>
</tr>
<tr>
<td>2000</td>
<td>0.85</td>
</tr>
<tr>
<td>3000</td>
<td>0.85</td>
</tr>
<tr>
<td>4000</td>
<td>0.85</td>
</tr>
<tr>
<td>5000</td>
<td>0.8</td>
</tr>
<tr>
<td>6000</td>
<td>0.75</td>
</tr>
<tr>
<td>7000</td>
<td>0.7</td>
</tr>
<tr>
<td>8000</td>
<td>0.65</td>
</tr>
<tr>
<td>9000</td>
<td>0.65</td>
</tr>
<tr>
<td>10000</td>
<td>0.65</td>
</tr>
</tbody>
</table>

\( \beta_1 \) vs. \( f'c \) (ksi)

Image Sources: University of Michigan, Department of Architecture
Flexure Equations

actual stress block

\[
\begin{align*}
C &= T \\
0.85f_c'ab &= A_sf_y \\
\text{solving for } a, \\
\rho &= \frac{A_s}{bd}
\end{align*}
\]

ACI equivalent stress block

\[
\begin{align*}
C &= 0.85f_c'ab \\
\alpha = \beta_c \\
M_n &= T\left(d - \frac{a}{2}\right) = A_sf_y\left(d - \frac{a}{2}\right) \\
M_u &= \phi M_n \\
M_u &= \phi A_s f_y \left(d - \frac{a}{2}\right) \\
M_u &= \phi A_s f_y \left(1 - 0.59\frac{\rho f_y}{f_c'}\right)
\end{align*}
\]

Image Sources: University of Michigan, Department of Architecture
Balance Condition

From similar triangles at balance condition:

\[
\frac{c}{d} = \frac{0.003}{0.003 + (f_y/E_s)} = \frac{0.003}{0.003 + (f_y/29 \times 10^6)}
\]

\[
c = \frac{87,000}{87,000 + f_y d}
\]

Use equation for a. Substitute into \( c = a/\beta_1 \)

\[
a = \frac{\rho f_y d}{0.85 f'_c'}
\]

\[
c = \frac{a}{\beta_1} = \frac{\rho f_y d}{0.85\beta_1 f'_c'}
\]

Equate expressions for c:

\[
\frac{\rho f_y d}{0.85\beta_1 f'_c'} = \frac{87,000}{87,000 + f_y d}
\]

\[
\rho_b = \left(\frac{0.85\beta_1 f'_c'}{f_y}\right) \left(\frac{87,000}{87,000 + f_y}\right)
\]

---

Table A.8 Balanced Ratio of Reinforcement \( \rho_b \) for Rectangular Sections with Tension Reinforcement Only

<table>
<thead>
<tr>
<th>( f'_c' )</th>
<th>( f_y )</th>
<th>2,500 psi (17.2 MPa)</th>
<th>3,000 psi (20.7 MPa)</th>
<th>4,000 psi (27.6 MPa)</th>
<th>5,000 psi (34.5 MPa)</th>
<th>6,000 psi (41.4 MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \beta_1 = 0.85 )</td>
<td>( \beta_1 = 0.85 )</td>
<td>( \beta_1 = 0.85 )</td>
<td>( \beta_1 = 0.80 )</td>
<td>( \beta_1 = 0.75 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grade 40 40,000 psi (275.8 MPa)</td>
<td>0.75( \rho_b )</td>
<td>0.0309</td>
<td>0.0371</td>
<td>0.0495</td>
<td>0.0582</td>
<td>0.0655</td>
</tr>
<tr>
<td>Grade 50 50,000 psi (344.8 MPa)</td>
<td>0.75( \rho_b )</td>
<td>0.0229</td>
<td>0.0275</td>
<td>0.0367</td>
<td>0.0432</td>
<td>0.0486</td>
</tr>
<tr>
<td>Grade 60 60,000 psi (413.7 MPa)</td>
<td>0.75( \rho_b )</td>
<td>0.0115</td>
<td>0.0184</td>
<td>0.0216</td>
<td>0.0243</td>
<td>0.0243</td>
</tr>
<tr>
<td>Grade 75 75,000 psi (517.1 MPa)</td>
<td>0.75( \rho_b )</td>
<td>0.0089</td>
<td>0.0143</td>
<td>0.0168</td>
<td>0.0189</td>
<td>0.0189</td>
</tr>
</tbody>
</table>

Image Sources: University of Michigan, Department of Architecture
Rectangular Beam Analysis

Data:
- Section dimensions – b, h, d, (span)
- Steel area - As
- Material properties – f’c, fy

Required:
- Strength (of beam) Moment - Mn
- Required (by load) Moment – Mu
- Load capacity

1. Find $\rho = \frac{As}{bd}$
   (check $\rho_{min} < \rho < \rho_{max}$)
2. Find a
3. Find $M_n$
4. Calculate $Mu \leq \phi M_n$
5. Determine max. loading (or span)

Image Sources: University of Michigan, Department of Architecture
Rectangular Beam Analysis

Data:
• dimensions – b, h, d, (span)
• Steel area - As
• Material properties – f’c, fy

Required:
• Required Moment – Mu

1. Find \( \rho = \frac{A_s}{bd} \)
   (check \( \rho_{\text{min}} < \rho < \rho_{\text{max}} \))
Rectangular Beam Analysis cont.

2. Find $a$

\[ a = \frac{A_s f_y}{0.85 f_c b} = \frac{(2.37)(60000)}{0.85(4000)(12)} = 3.49 \]

3. Find $M_n$

\[ M_n = A_s f_y \left( d - \frac{a}{2} \right) \]

4. Find $M_u$

\[ M_u = 0.9(2.37)(60000)(17.5 - \frac{3.49}{2}) \]

\[ M_u = 2017000 \text{ in-lb} \]

\[ M_u = 168 \text{ ft-k} \]
Slab Analysis

Data:
- Section dimensions – h, span take b = 12"
- Steel area - As
- Material properties – f’c, fy

Required:
- Required Moment – Mu
- Maximum LL in PSF
Slab Analysis

1. Find \( a \)
2. Find force \( T \)
3. Find moment arm \( z \)
4. Find strength moment \( M_n \)

\[
d = \frac{A_s f_y}{0.85 f'_c b} = \frac{0.5267(60)}{0.85(3)(12)} = 1.033''
\]

\[
T = A_s f_y = 0.5267(60) = 31.6 \text{ k}
\]

\[
z = d - \frac{a}{2} = 9.75 - \frac{1.033}{2} = 9.23''
\]

\[
M_n = Tz = 31.6(9.23) = 291.8 \text{ k''}
\]

\[
= 24317''\]
Slab Analysis

5. Find slab DL

6. Find Mu

7. Determine max. loading

\[ W_{DL} = \gamma_c \frac{A}{144} = 150 \frac{11(12)}{144} = 137.5 \text{ PSF} \]

\[ W_{UPL} = 1.4(W_{DL}) = 1.4(137.5) = 192.5 \]

\[ W_{ULL} = 1.7(W_{UL}) \]

\[ M_u = \left( \frac{W_{UPL} + W_{ULL}}{8} \right) L^2 = \frac{4}{8} M_n \]

\[ 0.9(243.17) = \frac{[192.5 + 1.7(W_{UL})]}{8} L^2 \]

\[ W_{UL} = 204.6 \text{ PSF} \]
Rectangular Beam Design

Data:
- Load and Span
- Material properties – f’c, fy
- All section dimensions – b and h

Required:
- Steel area - As

1. Calculate the dead load and find Mu
2. \( d = h - \text{cover} - \text{stirrup} - \frac{d}{b}/2 \) (one layer)
3. Estimate moment arm jd (or z) \( \approx 0.9 \, d \) and find As
4. Use As to find a
5. Use a to find As (repeat…)
6. Choose bars for As and check \( \rho \) max & min
7. Check Mu<\( \phi \) Mn (final condition)

8. Design shear reinforcement (stirrups)
9. Check deflection, crack control, steel development length.

\[
M_u = \frac{(1.4w_{DL} + 1.7w_{LL})l^2}{8}
\]

\[
A_s = \frac{M_u}{\phi \, f_y \left(d - \frac{a}{2}\right)}
\]

\[
a = \frac{A_s f_y}{0.85 f'_c b}
\]

\[
M_n = A_s f_y \left(d - \frac{a}{2}\right)
\]
Rectangular Slab Design

Data:
- Load and Span
- Material properties – f’c, fy

Required:
- All section dimensions – h
- Steel area - As

1. Calculate the dead load and find Mu
2. Estimate moment arm jd (or z) \( \equiv 0.9 \, d \) and find As
3. Use As to find a
4. Use a to find As (repeat…)

**DATA:**
- One-way floor slab – Span = 18 Feet
- \( f_y = 60,000 \) psi
- \( f_c = 3000 \) psi
- \( \gamma_{con} = 150 \) ksf
- \( \rho = 0.5 \cdot \rho_{max} = 0.008 \)
- LL = 200 psf
- DL = Slab weight

**REQUIRED:** h and As

**ASSUME h**
\[ h = \frac{f_{20}}{f} = 10.8 \text{ in. use 11"} \]

**CALCULATE LOADS**
\[ DL = 137.5 \text{ ksf} \]
\[ LL = 200 \text{ ksf} \]
\[ W = 1.4(137) + 1.7(200) = 540 \text{ ksf} \]

**CALCULATE Mu**
\[ Mu = \frac{W \cdot f_c^2}{8} = 21.7 \text{ ksf} \]

**INITIAL AS TRIAL**
\[ As = \frac{Mu}{fy(d-\frac{a}{2})} \]
\[ = \frac{21.7 \times 12}{0.9(60)(9)} = 0.536 \]

**INITIAL a**
\[ a = \frac{As \cdot fy}{0.85 f_c b} = \frac{0.536(60)}{0.85(3)(12)} = 1.05" \]
3. Use $A_s$ to find $a$
4. Use $a$ to find $A_s$ (repeat…)
5. Choose bars for $A_s$ and check $A_s$ min & $A_s$ max
6. Check $M_u < \phi M_n$ (final condition)

7. Check deflection, crack control, steel development length.
Quiz 9

Can \( f = \frac{Mc}{I} \) be used in Ultimate Strength concrete beam calculations? (yes or no)

HINT:

WSD stress

Ultimate Strength stress

Source: University of Michigan, Department of Architecture
Rectangular Beam Design

Data:
- Load and Span
- Some section dimensions – b or d
- Material properties – $f'_c, f_y$

Required:
- Steel area - $A_s$
- Beam dimensions – b or d

1. Choose $\rho$ (e.g. 0.5 $\rho_{max}$ or 0.18$f'_c/f_y$)
2. Estimate the dead load and find $M_u$
3. Calculate $bd^2$
4. Choose b and solve for d
   - b is based on form size – try several to find best
5. Estimate h and correct weight and $M_u$
6. Find $A_s = \rho bd$
7. Choose bars for $A_s$ and determine spacing and cover. Recheck h and weight.
8. Design shear reinforcement (stirrups)
9. Check deflection, crack control, steel development length.

$$M_u = \frac{(1.4w_{DL} + 1.7w_{LL})l^2}{8}$$

$$bd^2 = \frac{M_u}{\phi \rho f_y (1 - 0.59 \rho \left(f_y/ f'_c \right))}$$

$$A_s = \rho bd$$
Rectangular Beam Design

Data:
- Load and Span
- Material properties – f'c, fy

Required:
- Steel area - As
- Beam dimensions – b and d

1. Estimate the dead load and find Mu
2. Choose $\rho$ (e.g. 0.5 $\rho$ max or 0.18f’c/fy)

Factored LL = $P_e = 1.7(L) = 1.7(20) = 34 K$

Factored DL = $W_0 = 1.4(\text{applied load + beam weight estimate}) = 1.4(2 + 6) = 3.64 Kf'$

$$M_u = P_e d + \frac{w_0 d^2}{8} = 34(10) + \frac{3.64 \times 30^2}{8} = 340 + 409.5 = 749.5 \text{ k-ft}$$

$$\rho = \frac{0.18 f_c}{f_y} = .009$$
Rectangular Beam Design cont

3. Calculate $bd^2$

\[ bd^2 = \frac{Mu}{fp f_y (1 - 0.59 \rho (f_y/f_c))} \]

\[ bd^2 = \frac{8,994}{(0.9)(0.009)(60)(1 - 0.59(0.009)(60/3))} \]

\[ bd^2 = 20.705 \text{ in}^3 \]

4. Choose $b$ and solve for $d$

$b$ is based on form size. Try several to find best

\[ \begin{align*}
\text{Possibilities} & \quad b \quad \times \quad d \\
14'' & \quad 38.5'' \\
16'' & \quad 35.97'' \\
18'' & \quad 33.9''
\end{align*} \]
Rectangular Beam Design

5. Estimate h and correct weight and Mu
6. Find \( A_s = \rho \cdot b \cdot d \)
7. Choose bars for \( A_s \) and determine spacing and cover. Recheck h and weight.
8. Design shear reinforcement (stirrups)
9. Check deflection, crack control, steel development length.

\[
\rho = 0.009 = \frac{A_s}{b \cdot d}, \quad A_s = 0.009 \cdot b \cdot d = 0.009 \cdot 18 \cdot 3a
\]

\( A_s = 5.5 \text{ in}^2 \)

**Table A-4**

Use 7 x \#8 wires

Spaced with 1" between each bar

<table>
<thead>
<tr>
<th>Bar No.</th>
<th>Area (in.²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.39</td>
</tr>
<tr>
<td>3</td>
<td>0.58</td>
</tr>
<tr>
<td>4</td>
<td>0.78</td>
</tr>
<tr>
<td>5</td>
<td>0.98</td>
</tr>
<tr>
<td>6</td>
<td>1.18</td>
</tr>
<tr>
<td>7</td>
<td>1.37</td>
</tr>
<tr>
<td>8</td>
<td>1.57</td>
</tr>
<tr>
<td>9</td>
<td>1.77</td>
</tr>
<tr>
<td>10</td>
<td>1.96</td>
</tr>
<tr>
<td>11</td>
<td>2.16</td>
</tr>
<tr>
<td>12</td>
<td>2.36</td>
</tr>
<tr>
<td>13</td>
<td>2.55</td>
</tr>
<tr>
<td>14</td>
<td>2.75</td>
</tr>
</tbody>
</table>

**Source:** Jack C McCormac, 1978 Design of Reinforced Concrete, Harper and Row, 1978
Non-Rectangular Beam Analysis

Data:
• Section dimensions – b, h, d, (span)
• Steel area - As
• Material properties – f’c, fy

Required:
• Required Moment – Mu (or load, or span)

1. Draw and label diagrams for section and stress
   1. Determine b effective (for T-beams)
   2. Locate T and C (or C₁ and C₂)
2. Set T=C and write force equations (P=FA)
   1. T = As fy
   2. C = 0.85 f’c Ac
3. Determine the Ac required for C
4. Working from the top down, add up area to make Ac
5. Find moment arms (z) for each block of area
6. Find Mn = \[Mn = \sum Cz\]
7. Find Mu = \[\phi Mn\] \(\phi = 0.90\)
8. Check As min < As < As max

Source: University of Michigan, Department of Architecture
Analysis Example

Given:  \( f'c = 3000 \text{ psi} \)
   \( f_y = 60 \text{ ksi} \)
   \( A_s = 6 \text{ in}^2 \)

Req’d:  Capacity, \( \mu \)

1. Find \( T \)
2. Find \( C \) in terms of \( A_c \)
3. Set \( T = C \) and solve for \( A_c \)

\[
T = A_s f_y = 6 \text{ in}^2 \times (60000 \text{ psi})
T = 360000 k = 360 k
\]

\[
C = 0.85 f'c A_c = 0.85 (3000 \text{ psi}) A_c \text{ in}^2
C = (2550 A_c)^k = (2.55 A_c)^k
\]

\[
T = C
360 k = 2.55 A_c k
A_c = 142 \text{ in}^2
\]
Example

4. Draw section and determine areas to make $A_c$

5. Solve $C$ for each area in compression.

\[
A_c = 142 = A_{c_1} + A_{c_2} + A_{c_3}
\]

\[
142 = 48 + 30 + A_{c_3}
\]

\[
A_{c_3} = 44 \text{ in}^2
\]

\[
C_1 = 48(2.55) = 122.4 \text{ k}
\]

\[
C_2 = 30(2.55) = 76.5 \text{ k}
\]

\[
C_3 = 44(2.55) = 113.2 \text{ k}
\]
Example

6. Determine moment arms to areas, z.

7. Calculate $M_n$ by summing the Cz moments.

8. Find $M_u = \Box M_n$

\[
\begin{align*}
Z_1 &= 22 - 1.5 = 20.5'' \\
Z_2 &= 22 - (3+2.5) = 16.5'' \\
Z_3 &= 22 - (8+2) = 12.0'' \\
M_n &= \Sigma C_z \\
M_n &= (C_1Z_1) + (C_2Z_2) + (C_3Z_3) \\
M_n &= 2509 + 1262 + 1959 \\
M_n &= 5730 \\
M_u &= 0.9(5730) = 5157 \text{ k-ft}
\end{align*}
\]
Other Useful Tables:

### Table A.1 Values of Modulus of Elasticity for Normal-Weight Concrete

<table>
<thead>
<tr>
<th>Customary Units</th>
<th>SI Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f'_c$ (psi)</td>
<td>$E'_c$ (psi)</td>
</tr>
<tr>
<td>3,000</td>
<td>3,140,000</td>
</tr>
<tr>
<td>3,500</td>
<td>3,390,000</td>
</tr>
<tr>
<td>4,000</td>
<td>3,620,000</td>
</tr>
<tr>
<td>4,500</td>
<td>3,850,000</td>
</tr>
<tr>
<td>5,000</td>
<td>4,050,000</td>
</tr>
</tbody>
</table>

### Table A.2 Designations, Areas, Perimeters, and Weights of Standard Bars

<table>
<thead>
<tr>
<th>Bar No.</th>
<th>Customary Units</th>
<th>SI Units</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Diameter (in.)</td>
<td>Cross-sectional Area (in.²)</td>
</tr>
<tr>
<td>3</td>
<td>0.375</td>
<td>0.11</td>
</tr>
<tr>
<td>4</td>
<td>0.500</td>
<td>0.20</td>
</tr>
<tr>
<td>5</td>
<td>0.625</td>
<td>0.31</td>
</tr>
<tr>
<td>6</td>
<td>0.750</td>
<td>0.44</td>
</tr>
<tr>
<td>7</td>
<td>0.875</td>
<td>0.60</td>
</tr>
<tr>
<td>8</td>
<td>1.000</td>
<td>0.79</td>
</tr>
<tr>
<td>9</td>
<td>1.128</td>
<td>1.00</td>
</tr>
<tr>
<td>10</td>
<td>1.270</td>
<td>1.27</td>
</tr>
<tr>
<td>11</td>
<td>1.410</td>
<td>1.56</td>
</tr>
<tr>
<td>12</td>
<td>1.693</td>
<td>2.25</td>
</tr>
<tr>
<td>14</td>
<td>2.257</td>
<td>4.00</td>
</tr>
</tbody>
</table>

### Table A.4 Areas of Groups of Standard Bars (in.²)

<table>
<thead>
<tr>
<th>Bar No.</th>
<th>Number of Bars</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.39 0.58 0.78 0.98 1.18 1.37 1.57 1.77 1.96 2.16 2.36 2.55 2.75</td>
</tr>
<tr>
<td>5</td>
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Structures II

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