Tension Model

Based on the approximate parabolic stress distribution shown in Figure 1, the flexural strength computation, M_n, may be determined using the k_1, k_2, and k_3 values. However, a simple method that uses fundamental static equilibrium is preferable.

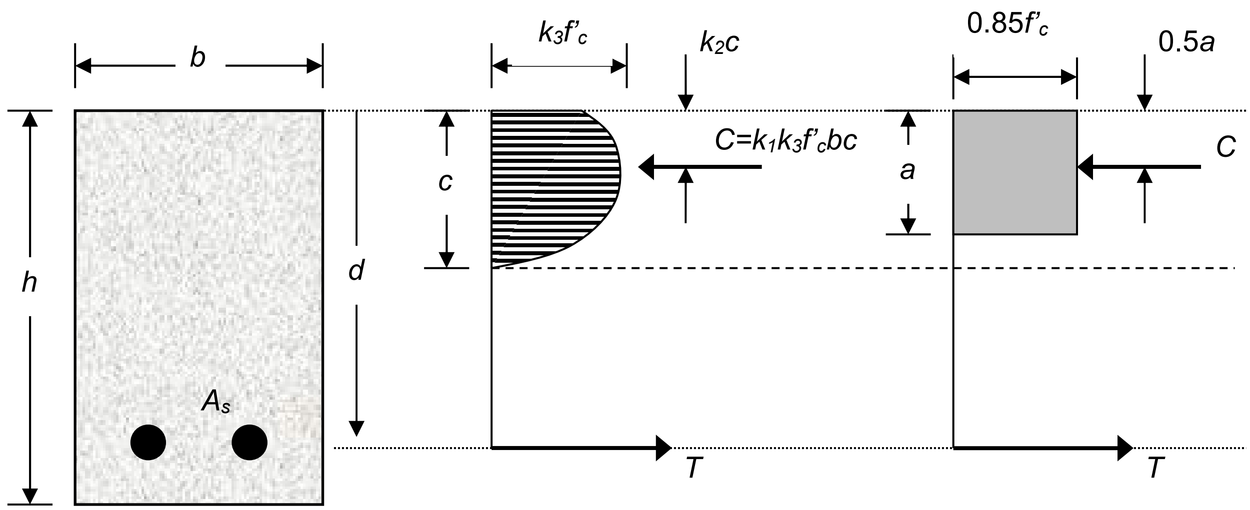

Figure 1. Definition of Whitney Rectangular Stress Distribution

In the 1930s, Whitney (1937) proposed using a rectangular compressive stress distribution in place of the parabolic distribution. As shown in Figure 1, an average stress of $0.85f'_c$ is used, with a rectangular section of depth $a = \beta_1 c$. Whitney determined that β_1 should be 0.85 for concrete with f'_c > 4,000 psi and 0.05 less for each 1,000 psi of f'_c above 4,000 psi. The value of β_1 may not be taken to be less than 0.65 (ACI 2019). The concrete below the neutral axis is ignored, and the total tension force T is due to the reinforcing steel. The Whitney stress block is used to estimate the compression force C. The forces may be determined as

$$C = 0.85 f'_c ba \tag{1}$$

$$T = A_s f_y \tag{2}$$

where f_y is the yield stress of the steel reinforcement (assuming that the steel yields before crushing the concrete). Equating $C = T$ gives:

$$a = \frac{A_s f_y}{0.85 f'_c b} \tag{3}$$

The bending strength is computed as the tensile force multiplied by the distance between the forces.

$$M_n = A_s f_y \left(d - \frac{a}{2} \right) \tag{4}$$

Combining Equations (3) and (4) gives:

$$M_n = A_s f_y \left(d - 0.59 \frac{A_s f_y}{f_c' b} \right) \tag{5}$$

The ACI Code explicitly accepts the Whitney rectangle (ACI 2019). For the loading conditions in this reinforced concrete beam competition, the ultimate force due to tensile stress would be:

$$P_{tension} = \frac{A_s f_y}{4} \left(d - 0.59 \frac{A_s f_y}{f_c' b} \right) \tag{6}$$

Shear Model

The design of shear reinforcement is based on the assumption that the shear force must not exceed the total shear capacity of the beam (ACI 2019). When shear reinforcement is used, the shear capacity of a beam cross-section can be estimated as

$$V_n = V_s + V_c \tag{7}$$

where V_n is the shear force in the beam, V_s is the shear capacity supplied by the reinforcement, and V_c is the shear strength of the concrete. The shear capacity of the reinforcement, which is assumed to be uniformly spaced across the diagonal crack, is

$$V_n = \frac{A_v f_y d}{s} + 2\sqrt{f'_c}\, bd \tag{8}$$

where A_v is the area of steel reinforcement in shear for each stirrup crossing the diagonal crack, and s is the spacing of the stirrups. For the loading conditions in this reinforced concrete beam competition, the ultimate force due to shear would be:

$$P_{shear} = 2\left(\frac{A_v f_y d}{s} + 2\sqrt{f'_c}\, bd \right) \tag{9}$$

Compression Model

The reinforcement ratio ρ (often called reinforcement percentage) may conveniently represent a beam's relative amount of tension reinforcement. Thus, using the dimensions of Figure 1, the reinforcement ratio is:

$$\rho = \frac{A_s}{bd} \tag{10}$$

Rewriting Equation (10) expresses the reinforcement ratio in terms of the *c/d* ratio.

$$\rho = 0.85\beta_1 \frac{c}{d}\frac{f_c^{'}}{f_y} \tag{11}$$

For beams controlled by tensile failure, *c/d* < 0.375 (ACI 2019).

If the *c/d* > 0.6, beam failure is controlled by compression (ACI 2019). For an overly reinforced beam, the stress in the tensile steel f_{steel} when the concrete reaches its ultimate strain is:

$$f_{steel} = 87{,}000\, psi\left(\frac{d-c}{c}\right) \tag{12}$$

If $f_{steel} < f_y$ or c/d > 0.6, then the maximum moment in compression is:

$$M_{compression} = A_s\left(\frac{d-c}{c}\right)\left(d-\frac{a}{2}\right)87{,}000\, psi \tag{13}$$

For the loading conditions in this reinforced concrete beam competition, the ultimate force due to compression would be:

$$P_{compression} = \frac{A_s}{4}\left(\frac{d-c}{c}\right)\left(d-\frac{a}{2}\right)87{,}000\, psi \tag{14}$$

Anchorage Requirements

For proper anchorage, the minimum rebar length, also known as the development length, depends on several factors, including rebar diameter, concrete strength, and whether it's a tension or compression member. According to ACI (2019), the minimum development length, $l_{d,}$ for tension is

$$l_d = \frac{f_y d_b}{24\sqrt{f_c^{'}}\left(\frac{cover}{d_b} - \frac{1}{2}\right)} \qquad (15)$$

where *cover* is the bottom cover of the reinforcing bars, and d_b is the diameter of the steel reinforcing bars. For hooked bars, a minimum length of reinforcing, L_{dh}, is required as

$$L_{dh} = \frac{1{,}200\,d_b}{\sqrt{f_c^{'}}} \qquad (16)$$

Estimation of Beam Weight and Cost

The estimated weight *W* of a reinforced rectangular concrete beam is

$$W = V_{beam}\,\gamma_{concrete} + A_s L\left(\gamma_{steel} - \gamma_{concrete}\right) \qquad (17)$$

where V_{beam} is the volume of the beam, *L* is the length of the beam, $\gamma_{concrete}$ is the unit weight of concrete (typically 145 lb./ft.^{3}), and γ_{steel} is the unit weight of steel (490 lb./ft.^{3}).

The total cost estimate for a reinforced concrete beam, C_{beam}, is

$$C_{beam} = C_{steel} + C_{concrete} \qquad (18)$$

where C_{steel} is the cost of the steel reinforcement, and $C_{concrete}$ is the cost of the concrete. Table 1 lists the unit cost for a reinforced concrete beam for this competition.

Table 1. Reinforced Concrete Material Cost

Material	Cost
Portland Type I cement	$150/ton
Coarse aggregate	$25/ton
Fine aggregate	$15/ton
Steel reinforcement	$1,000/ton
Admixtures - water reducer	$15/gal
Admixture - silica flume	$500/ton

To compute the cost of a reinforced concrete beam using the information in Table 1, use the following estimates (there is no cost associated with shear reinforcement).

The cost of the steel, C_{steel}, may be estimated as follows:

$$C_{steel} = A_s L \left(490 \frac{\text{lb.}}{\text{ft.}^3} \right) \left(\frac{\$1{,}000}{\text{ton}} \right) \left(\frac{\text{ton}}{2{,}000\ \text{lb.}} \right) \tag{19}$$

The total cost of concrete, $C_{concrete}$, is estimated from the mix design as

$$C_{concrete} = C_{cement} + C_{CA} + C_{FA} \tag{20}$$

where C_{cement} is the cost of the cement, C_{CA} is the cost of the coarse aggregate, and C_{FA} is the cost of the fine aggregate. The cost of each of these components can be computed as

$$C_{cement} = V_{beam} \left(W_{cement} \frac{\text{lb.}}{\text{ft.}^3} \right) \left(\frac{\$150}{\text{ton}} \right) \left(\frac{\text{ton}}{2{,}000\ \text{lb.}} \right) \tag{21}$$

$$C_{CA} = V_{beam} \left(W_{CA} \frac{\text{lb.}}{\text{ft.}^3} \right) \left(\frac{\$25}{\text{ton}} \right) \left(\frac{\text{ton}}{2{,}000\ \text{lb.}} \right) \tag{22}$$

$$C_{FA} = V_{beam} \left(W_{FA} \frac{\text{lb.}}{\text{ft.}^3} \right) \left(\frac{\$15}{\text{ton}} \right) \left(\frac{\text{ton}}{2{,}000\ \text{lb.}} \right) \tag{23}$$

where W_{cement} is the weight of cement, W_{CA} is the weight of coarse aggregate, and W_{FA} is the weight of fine aggregate (each weight is per ft.^3 of concrete).

Estimation of Cost-Adjusted SWR

The ultimate strength S of the reinforced concrete beam may be estimated based on the value of c/d as follows (ACI 2019):

$$\begin{aligned} &\text{If } \frac{c}{d} \le 0.375 && S = Minimun\left(P_{tension}, P_{shear}\right) \\ &0.375 < \frac{c}{d} < 0.6 && S = Minimun\left(P_{tension}, P_{shear}, P_{compression}\right) \\ &\frac{c}{d} \ge 0.6 && S = Minimun\left(P_{compression}, P_{shear}\right) \end{aligned} \tag{24}$$

The predicted strength-to-weight ratio SWR is

$$SWR = \frac{S}{W} \tag{25}$$

The predicted value of the cost-adjusted *ASWR* may be computed as follows:

$$\text{If } C_{Beam} < \$2.25 \quad ASWR = SWR$$
$$> \$2.25 \quad ASWR = SWR\left(\frac{\$2.25}{C_{Beam}}\right) \tag{26}$$

References

American Concrete Institute (2019). *Building Code Requirements for Structural Concrete and Commentary*. American Concrete Institute, Farmington Hills, MI.

Whitney, C.S. (1937) "Design of Reinforced Concrete Members Under Flexure and Combined Flexure and Direct Compression." *ACI Journal*, March-April; 33, 483-498.