PDHonline Course S245 (2 PDH)

Steel Beam Reinforcement

Instructor: Jonathon C. Creviston, P.E.

2020

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5272 Meadow Estates Drive
Fairfax, VA 22030-6658
Phone: 703-988-0088
www.PDHonline.com

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1. Introduction

A common problem in industrial facilities is reinforcement of existing beams either due to corrosion damage, increased loading or cutting of the beam in critical areas. Reinforcement may be for bending moment (flanges) or shear (web). The following course presents analysis techniques, suggested details and general guidelines of reinforcement of steel beams for bending. Although specific to steel, the same engineering principles are applicable to other materials.

All examples assume that those taking this course are familiar with static analysis of beams. Any reference to the term "manual" refers to the *AISC Manual of Steel Construction Thirteenth Edition*.

2. Notations

A = Area, in^2.
A_i = Initial beam cross sectional area, in^2.
A_f = Built-up beam cross sectional area, in^2.
A_c = Corroded beam cross sectional area, in^2.

I = Moment of inertia, in^4.
I_i = Initial beam moment of inertia, in^4.
I_f = Built-up beam moment of inertia, in^4.
I_c = Corroded beam moment of inertia, in^4.

S_i = Initial beam section modulus, in^3.
S_f = Built-up beam section modulus, in^3.
S_c = Corroded beam section modulus, in^3.

y = Distance to the centroid of a built-up section component, in.
Y = Distance to the neutral axis of a built-up section, in.
y' = Distance from the centroid of a component to the neutral axis of the built-up section.

V = Shear, k.
M = Moment, ft-k.
q = Shear Flow, k/in.

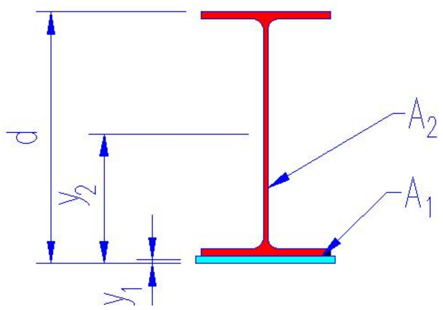
F_y = Yield strength, ksi.

r = Radius of gyration, in.

d = Depth of built-up section, in.

3. Built-up Sections and Shear Flow

The following section is a review of the procedures for analyzing built-up sections and calculating shear flow. Both are necessary for the design of beam reinforcement.



$Y = \Sigma(yA) / \Sigma A$
$I_{total} = I_1 + I_2 + A_1(Y-y_1)^2 + A_2(Y-y_2)^2$
$S_{compression} = I / Y$
$S_{tension} = I / (d-Y)$
$r_x = (I_{total} / \Sigma A)^{1/2}$
The same procedures are followed for the weak axis.

Figure 1. Built-up Section

Shear flow, q, is the horizontal shear at the interface of the different components of a built-up section induced by bending moment. In Figure 1 this would be at the interface of the plate and wide flange. Shear flow is used to determine connection requirements between the components of a built-up section. The general form of the equation is:

$$q = (VAy') / I_{total}$$

For the example given above the equation would be:

$$q = (VA_1(Y - y_1)) / I_{total}$$

4. General Procedures

It is often unnecessary and uneconomical to reinforce a beam along its entire length. The first step is to determine the shear and moment diagrams in order to locate the regions requiring reinforcement. The following example uses a W12x26 twenty feet long with a load of 2.0 klf. The beam is continuously braced and grade A992.

A check of the Table 3-6 (ASD) in the manual gives a maximum allowable shear (V_n/Ω_n) of 56k, well above the shear on this particular beam. See Figure 2 below. The same table gives an allowable bending moment (M_p/Ω_b) of 92 ft-k. The capacity can also be obtained by working backwards from the section modulus. Referring to Figure 3 below the bending moment is 100 ft-k.

The beam, therefore, requires reinforcement for bending moment. The length of reinforcement can be determined by drawing a horizontal line at the moment capacity then vertical lines down at the points of intersection. Referring to Figure 2, the beam requires reinforcement roughly between 85” and 155” from the left end. Reinforcement should extend a minimum of 12” on either side of this area to allow the abrupt change in cross section to occur outside the region of greater demand.

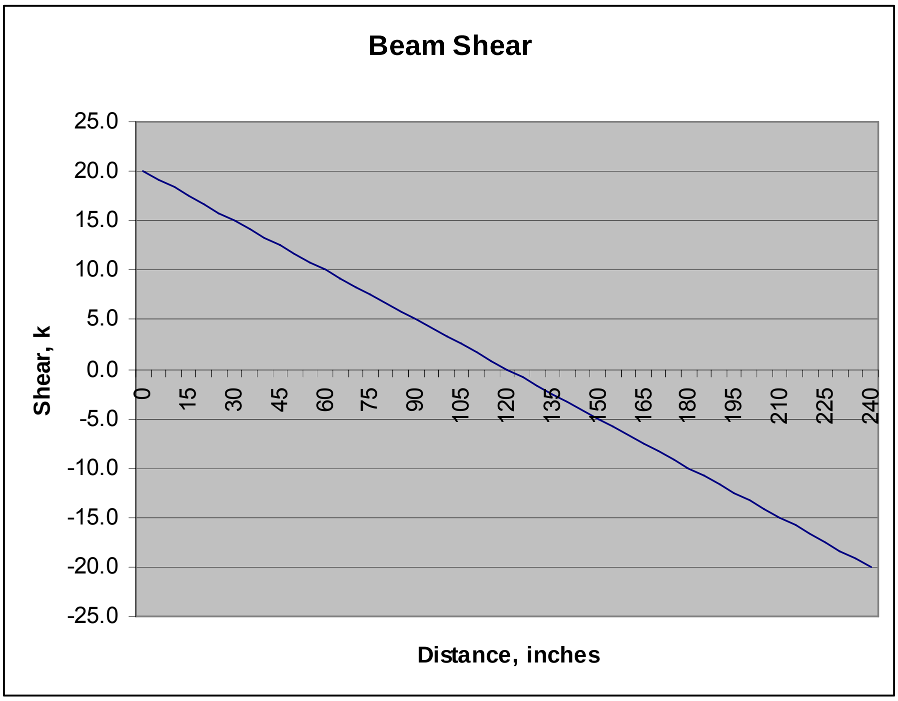


Figure 2.

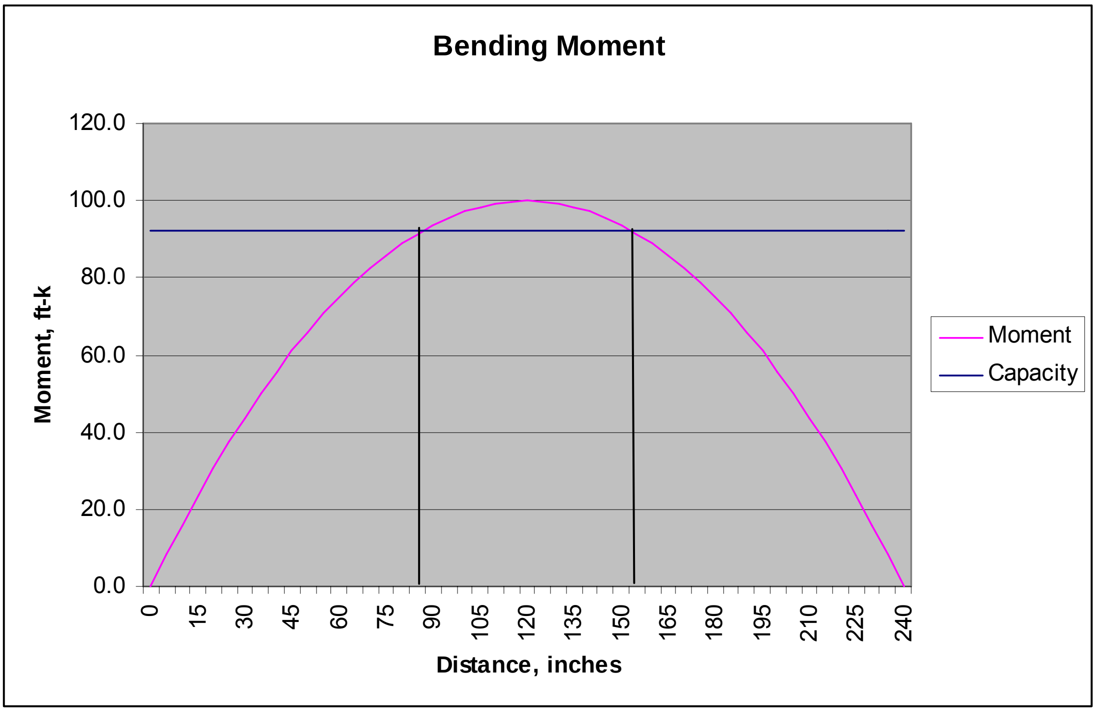


Figure 3.

The second step is to determine the required section modulus, working backward from the bending moment. At this point, it is acceptable to assume the reinforcement to be the same grade as the beam, giving a required section modulus of 36.4 in^3.

Next, a method of reinforcement is selected based upon field conditions, experience and the amount of reinforcement required. Field conditions will generally govern the selection due to the presence of conduit, piping, finishes, stiffeners, etc.

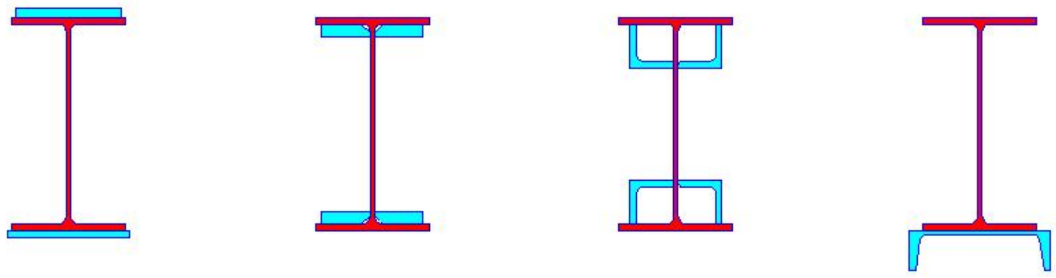


Figure 4. Examples of Beam Reinforcement

A plate will be added to the bottom flange of this beam to obtain the necessary strength. This is often a trial and error procedure; an A36 3/8”x7” plate will the first selection. The width is selected wider than the beam flange to allow a downward fillet weld when possible.

Element	y	A	yA	I
Plate	0.19	2.63	0.49	0.03
W12x26	6.49	7.65	49.61	204.00
	Σ	10.28	50.10	204.03
	Y	4.88		
	I_{total}	281.5		
	$S_{compression}$	41.9		
	$S_{tension}$	57.7		

The compression flange governs and exceeds the required section modulus of 36.4 in^3.

The final check before designing the connections involves the difference in yield strength between the plate and the W12. When the section modulus greatly exceeds what is required it is generally acceptable to ignore this difference. In this example, the plate is in the tension zone and is 150% greater than required. To check, convert the bending moment into a force couple in the flanges:

$$\text{Tension} = \text{Compression} = M/d;\ d = 12.22'' + 0.375'' = 12.60''$$
$$= (100\ \text{ft-k})(12\ \text{in/ft}) / 12.60'' = 95.3\text{k}$$

Then convert the area of the reinforcement into an equivalent area of A992 material and add it to the area of the W12 flange (2.47 in^2) to obtain the total equivalent area of the tensile flange:

$$A' = (A_{plate})(F_{y,plate} / F_{y,W12}) = (2.63\ in^2)(36 / 50) = 1.89\ in^2$$
$$A_{tension} = 1.89\ in^2 + 2.47\ in^2 = 4.36\ in^2$$

The tensile stress can then be checked and compared to the allowable stress, $0.60F_y$ (30 ksi for A992 steel):

$$f_t = T / A_{tension} = 95.3\ k / 4.36\ in^2 = 21.9\ ksi;\ OK$$

The last step is designing the connection between the reinforcement and the beam using the shear flow equation. As previously discussed,

$$q = (VA_1(Y - y_1)) / I_{total}$$
$$= (20\text{ k})(2.63\text{ in}^2)(4.88\text{ in} – 0.19\text{ in}) / 281.5\text{ in}^4 = 0.9\text{ k/in}$$

Since the connections will be through each side of the bottom flange this value can be divided by two; q = 0.45 k/in.

The choice of a bolted or welded connection will depend on field conditions. Welding is generally preferred since it requires less labor than field drilling holes and surface preparation. To determine the spacing of bolts simply divide the capacity of a slip-critical bolt by the shear flow. Using 3/4" A325-SC bolts (7.38 k shear capacity) results in:

Bolt spacing = 7.38 k / 0.45 k/in = 16.4"

Note that slip-critical bolts are to be used. Similarly, weld requirements are determined by calculating the shear flow per foot and designing the weld accordingly:

q = 0.45 k/in = 5.4 k/ft

Field welds should be 5/16" or less whenever possible, allowing the welder to place the beads in a single pass. Fillet welds of 1/4" are preferred. Using E70XX electrodes,

Shear strength of 1/4" fillet = (21 ksi)(0.707)(0.25 in) = 4.6 k/in
Required weld length/foot = (5.4 k/ft) / (4.6 k/in) = 1.2" of weld per foot

Finally, the connection strength should be doubled at each end to account for higher shear concentrations in these areas. The final details are as shown in Figures 5 and 6 below.

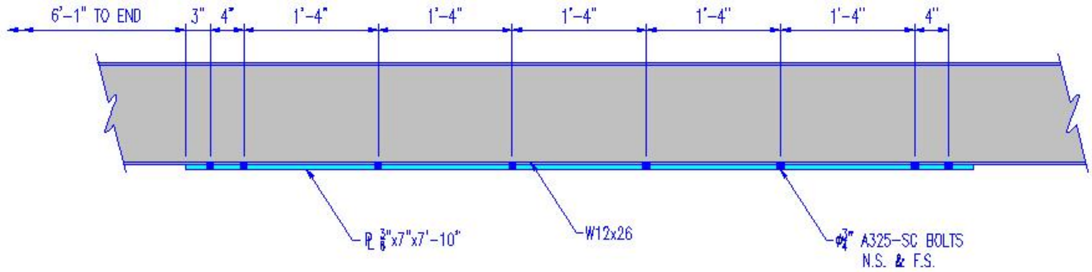


Figure 5. Bolted Reinforcement Detail

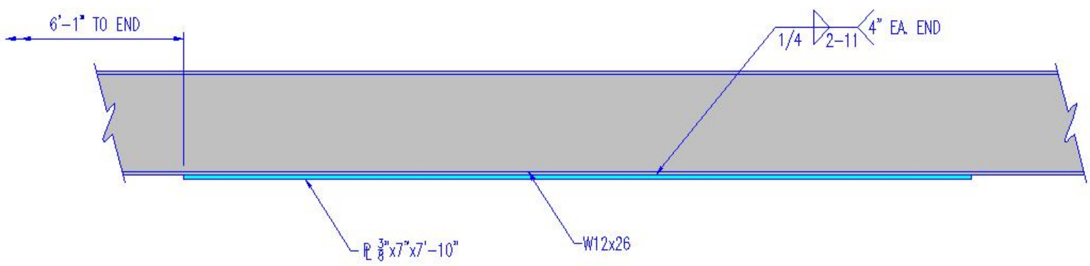


Figure 6. Welded Reinforcement Detail

5. Reinforcement for Notched Flanges

Reinforcement for damaged or notched must bridge across the damaged area to transfer the tension or compression forces. Notches in the tension flange can be reinforced by simply adding an area of material greater than or equal to the flange area; adjusted for yield strength as previously discussed.

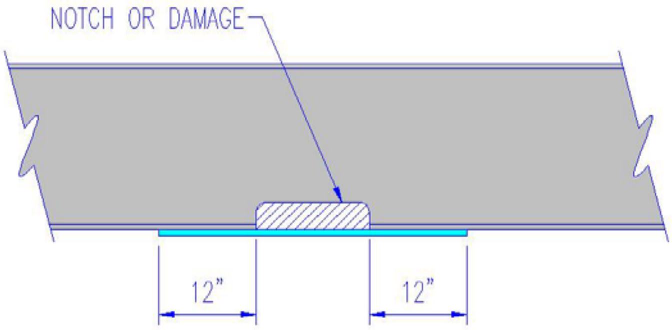


Figure 7.Notched Tension Flange Reinforcement

Reinforcement for the compression flange is designed as a column with the effective length equal to the distance between connections. Plate may be utilized for short gaps but the low buckling strength generally prohibits their use for longer notches.

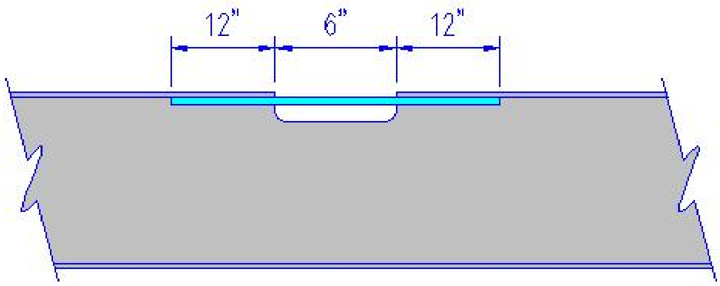


Figure 8.Notched Compression Flange Reinforcement

As an example we will look at a W12x26 beam with a 6" notch in the compression flange. The bending moment is 92 ft-k. The beam is grade A992 and reinforcement will be grade A36. As a starting point, select reinforcement with an area 1.5 times greater than the flange area multiplied by the ratio of beam to plate yield strengths:

$$A_{initial} = 1.5A_{flange}(F_{y,beam} / F_{y,reinforcement})$$
$$= (1.5)(2.47\text{ in}^2)(50 / 36) = 5.15\text{ in}^2$$

For reinforcement will try two 2-3/4" x 1" x 2'-6" bars, as shown in Figure 9.

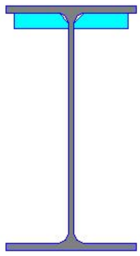


Figure 9.Reinforcement for Notched Compression Flange

Calculate the allowable compression stress:
Area of one bar = (2.75 in)(1 in) = 2.75 in^2
$I_x = (1\text{ in})^3(2.75\text{ in}) / 12 = 0.229\text{ in}^4$
$r_x = (I/A)^{1/2} = (0.229 / 2.75)^{1/2} = 0.29$ in
Use K = 1.0
Use L = notch width + 1 = 7 in.
KL/r = (1.0)(7 in) / (0.29 in) = 24.1

Using Table 4-22 the critical stress (F_{cr}/Ω_c) for A36 material is 20.9 ksi. The total allowable compressive load for the two plates is:

$$F_c = (2)(2.75\ in^2)(20.9\ ksi) = 115\ k$$

The compression force is determined by converting the bending moment into a force couple:

$$T = C = (92\ ft\text{-}k)(12\ in/ft) / (12.22\ in) = 90.3k$$

The selected reinforcing plates have adequate capacity. Had it not, a larger plate could be used or a grade with a higher yield stress used. Connection of the reinforcement to the beam follows the same procedures as previously discussed. Note, however, that the unbraced length of the reinforcement will be equal to the maximum spacing between connectors.

6. Corrosion

Steel exposed to harsh environments, such as water or chemicals, will corrode over time. Corrosion results in a loss of cross sectional area that reduces the load carrying capacity of the beam. For a beam with near uniform corrosion the loss in moment of inertia and section modulus will be nearly proportional to the loss in cross sectional area:

$$I_c = (A_c/A_i)I_i \qquad S_c = (A_c/A_i)S_i$$

For beams with non-uniform corrosion the section must be analyzed to determine the properties. Corrosion of the bottom flange only, for instance, will cause the centroid to move upward and reduce the tension flange. Modeling the beam with rectangular elements will simplify calculations and yield conservative results. Where a flange or web is partially corroded using the least dimension, or an average value, will likewise simplify calculations. The reduced cross section shown in Figure 1, for example, can be modeled as three rectangular plate elements and the composite properties determined:

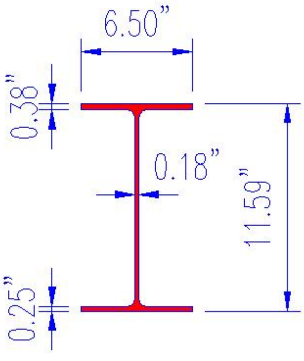


Figure 10. Cross Section of Corroded Beam

Element	y	A	yA	I
Bottom Flange	0.13	1.63	0.20	0.03
Web	5.73	1.97	11.30	30.10
Top Flange	11.40	2.47	28.16	0.03
	Σ	6.07	39.67	30.16
	Y	6.54		
	I_{total}	157		
	$S_{compression}$	31		
	$S_{tension}$	24		

Referring to the *AISC Manual of Steel Construction*, I = 204 in^4 and S = 33.4 in^3 for a W12x26. The tension flange has been significantly reduced and may require reinforcement.

Prior to reinforcement the steel must be cleaned of all loose materials, generally with the use of a grinder or needle gun. Beams that are corroded to the point that little or no material exists should be replaced or reinforced following the same procedures as notched or cut beams.

7. Other Considerations

The majority of beams or girders requiring reinforcement will be existing construction with material properties that may vary from modern materials. For instance, structural steel dated between the mid-1960s and late-1980s will generally have yield strength of 36 ksi while later structural steel will generally be 50 ksi. Structural steel earlier than the 1960s may be 33 ksi or lower with carbon contents that may influence welding. As a further complication, AISC increased the allowable stresses during World War II to conserve steel. AISC provides several valuable resources on this topic:

Design Guide 15: AISC Rehabilitation and Retrofit Guide; free to members for members.

Specification for Structural Steel Buildings 1923-2005; free to download for members.

Specification for Structural Steel Buildings 2005; free to download for the public.

The student is required to read Appendix 5, Evaluation of Existing Structures, of the *Specification for Structural Steel Buildings 2005* to provide a foundation of knowledge prior to implementing any portion of this course.

Economy should also be considered in every project. Bolted reinforcement is labor intensive, which far outpaces material costs. Use of A490 bolts may reduce the numbers required and result in a net savings. Likewise, maximizing use of single-pass welds (5/16" or less), elimination of special weld requirements and elimination of awkward weld positions will reduce labor cost. Finally, where reinforcement is required in multiple areas the use of repetition, and possibly higher grade materials, may result in a savings.

Finally, increased loading conditions will likely result in increased reactions at the beam supports. Connection capacity at these supports should always be checked to ensure adequacy.

8. Summary

Beams and girders may require reinforcement due to a variety of reasons; increased loading, corrosion and cutting have been presented as examples. Understanding the conditions and materials is essential to proper design; the general procedures presented here are applicable to most building materials. The use of these procedures, with engineering judgment and proper reference materials, will enable the structural engineer to design a safe and economical solution.