Design Aids for Unreinforced Web Openings in Steel Beams

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Several factors can impose height limitations in multistory buildings, such as zoning regulations, economic requirements, and aesthetic considerations. To minimize floor height, a common solution is to cut openings into steel beam webs in order to pass utilities through (see Figure 1; figures start on page 169). If these openings are unreinforced, they can significantly reduce the flexural and shear capacity of the beams.

In the 1960s, 1970s, and 1980s, studies on different web opening configurations were completed in the United States and Canada, including square, rectangular, circular, concentric, and eccentric openings in both non-composite and composite steel beams. In the late 1980s, Darwin and Donahey (1988), Darwin and Lucas (1990), and Darwin (1990) demonstrated that it is possible to produce a unified procedure embodying the different cases that are frequently used in steel building structures.

Some national standards, such as the British Standard (BSI, 2000) and the Canadian Standard (CSA, 2001), provide simplified rules for opening design in order to avoid weakening of the beam. However, these rules cover a wide range of possibilities, and, therefore, they are very conservative and, in general, restrict the openings to the middle third of the beam depth and to the two central quarters of the beam span. By fixing some parameters, it would be possible to get more flexible and economical results for typical situations in the floors of buildings.

This work presents the results of computational simulations in non-composite and composite steel beams with web openings, based on a unified procedure developed by Darwin (1990), and it is limited to W-shape sections. Design aids are provided that allow the identification of the beam region where unreinforced openings with specific characteristics do not reduce the member capacity. Application of these design aids avoids the use of complex and expensive analytical calculation methods. The design aids are compatible with the *Load and Resistance Factor Design Specification for Structural Steel Buildings* (AISC, 1999a) and can serve as a supplemental reference to that specification.

RANGE OF APPLICATION

The design aids were developed for non-composite and composite steel W-shape sections with the following limitations:

$$\frac{d}{b_f} > 1.20 \tag{1}$$

$$\frac{h}{t_w} \leq 3.76\sqrt{\frac{E}{F_y}} \tag{2}$$

$$\frac{b_f}{2t_f} \leq 0.38\sqrt{\frac{E}{F_y}} \tag{3}$$

where

d = overall depth of steel section

h = clear distance between flanges less the corner radius

t_w = web thickness

b_f = flange width

t_f = flange thickness

E = modulus of elasticity of steel

F_y = yield stress of the steel

The beams shall be simply supported and subject to a factored uniformly distributed load. They must have appropriate lateral bracing to avoid lateral-torsional buckling. The steel shall have maximum yield strength of 50 ksi (350 MPa).

In composite beams, the slab can be normal weight concrete or lightweight concrete with a specified compressive strength, f_c', of not more than 6.5 ksi (45 MPa). In addition,

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the slab shall have total thickness not greater than 6.3 in. (160 mm) and effective width not greater than 118 in. (3000 mm). These restrictions are applied to both solid concrete slab and concrete slab on formed steel deck. The steel-concrete interaction can be full or partial and the construction shored or unshored.

The openings considered have the following shapes: square, rectangular with aspect ratio equal to 2 (length, a_o, equal to twice the depth, h_o, as shown in Figure 1), and circular.

The span-depth ratio of the beams, L/d, shall be in the range of 10 to 30. For composite beams, this ratio refers only to the steel profile.

The corners of square and rectangular openings should have minimum radii at least twice the thickness of the web, t_w, or ⅝ in. (16 mm), whichever is greater, in order to avoid fatigue cracking due to stress concentration at these points (Darwin, 1990).

METHODOLOGY

The principal aim of this paper is to identify, by means of the procedure proposed by Darwin (1990), the region where one concentric opening with a certain shape and dimensions does not cause reduction of the beam strength. Knowing the location of this region, called the "neutral zone" and represented by the hatched area in Figure 2, it is possible to design web openings without considering the beam net section, which dispenses of analytical calculation methods.

The neutral zone depth, h_{nz}, is symmetrically positioned with respect to the centroid of the steel section and can be defined as twice the web opening half-depth plus the opening eccentricity (Figure 2). Obviously, for openings symmetrically positioned with respect to the centroid of the steel section (concentric opening), h_{nz} is the opening depth itself.

The neutral zone length, L_{nz} (Figure 2), for each case studied, is the beam length where the moment-shear interaction is not considered as critical. For this, the following expression is used (Darwin, 1990)

$$\left(\frac{M_u}{\phi M_m}\right)^3 + \left(\frac{V_u}{\phi V_m}\right)^3 \leq 1 \qquad (4)$$

where

M_u = required flexural strength at opening centerline

V_u = required shear strength at opening centerline

M_m = maximum nominal flexural strength at the location of an opening under pure bending; it occurs when $V_u = 0$ at opening centerline

V_m = maximum nominal shear strength at the location of an opening under pure shear; it occurs when $M_u = 0$ at opening centerline

ϕ = resistance factor, equal to 0.90 for steel beams and 0.85 for composite beams

The nominal flexural and shear strengths at the location of an opening, M_m and V_m, depend on (a) the shape and dimensions of the concentric opening and (b) the nominal flexural and shear strengths, M_n and V_n, respectively, of the non-composite or composite steel beam with an unperforated web. Darwin (1990) supplies the method for obtaining these values.

The required flexural and shear strengths are calculated in several intermediary sections, equally spaced along mid-span, $L/2$, with the following classical equations from the theory of structures:

$$M_u(z_o) = \frac{w_u}{2}\left(z_o L - z_o^2\right) \qquad (5)$$

$$V_u(z_o) = w_u\left(\frac{L}{2} - z_o\right) \qquad (6)$$

where

z_o = centerline position of a supposed opening (Figure 3)

w_u = uniformly distributed load on the simply supported beam

The value of w_u can vary from near zero to a maximum that can be obtained taking into account the design flexural strength, $\phi_b M_n$, and the design shear strength $\phi_v V_n$, of the unperforated section, in accordance with the *Load and Resistance Factor Design Specification for Structural Steel Buildings* (AISC, 1999a). Then, w_u is the smaller value of the following, the first related to the mid-span and the second to the support:

$$w_u \leq \frac{8\phi_b M_n}{L^2} \qquad (7)$$

$$w_u \leq \frac{2\phi_v V_n}{L} \qquad (8)$$

where

L = length of the beam

M_n = nominal flexural strength

ϕ_b = resistance factor for flexure, equal to 0.90 for steel beams and 0.85 for composite beams

V_n = nominal shear strength

ϕ_v = resistance factor for shear, equal to 0.90 for non-composite and composite steel beams

For composite beams, $\phi_b M_n$ is related to the composite section with full or partial interaction and $\phi_v V_n$ to the failure of the steel section web area, disregarding the contribution of the concrete slab.

With the shape and dimensions of the concentric opening, all the characteristics of the beam and the value of the uniformly distributed load fixed, the moment-shear interaction is verified along the beam mid-span (the same several intermediary sections are considered in which M_u and V_u were calculated) in accordance with Equation 4. The neutral zone is obtained delimiting the length in which that expression is satisfied.

It is observed that the openings cause greater reduction of shear strength than of flexural strength, and, for this reason, the neutral zone originates in the mid-span and stretches in the direction of the beam supports.

A computer program was developed to determine the neutral zone of non-composite and composite steel beams, according to the range of application presented previously. Sets of curves were developed for web openings of various shapes, dimensions, and in various locations. The envelopes of each of these groups are presented in charts that allow simplified identification of the neutral zone. The results are presented by plotting curves for different loading rates on a graph relating a variable k to the beam span-to-depth ratio.

RESULTS

The following design aids were prepared using results obtained from computational simulations in accordance with the methodology presented above. It has been determined that one or more unreinforced openings may be located in the web of W-shapes of non-composite and composite steel beams without considering net section properties when the openings are situated in the neutral zone (Figure 2).

The depth of the neutral zone, h_{nz}, was first considered equal to 33% of the overall depth of steel section, d, and then equal to 50%. These limits cover the most common situations and they do not lead to significant design restrictions. For practical reasons, Darwin (1990) limits the opening depth to 70% of the member depth.

The neutral zone must always be considered centered in relation to the depth of the steel beam. The charts in Figures 4 to 13 locate the neutral zone for beams with circular, square, and rectangular openings (Figures 1 and 2), according to Table 1. For each chart, the input data are the ratio between the beam span and the steel section depth, L/d, and the loading rate, R. The output data are the parameter k, which shall be multiplied by the beam span, L, to supply the lengths from the two ends of the beam where openings cannot be made (see Figure 2 — the neutral zone length stays between these two lengths).

The loading rate, R, is the quotient between the required strength determined from factored loads and the design strength of the beam without openings. R shall be obtained from the following condition considering Equations 7 and 8 for w_u and Equations 5 and 6 for M_u and V_u

$$R \geq \begin{cases} \dfrac{M_u}{\phi_b M_n} \\ \dfrac{V_u}{\phi_v V_n} \end{cases} \tag{9}$$

When the beam has more than one opening, the minimum spacing between edges of two adjacent openings, S (Figure 2), must be in accordance with the following criterion to avoid interaction between openings (Darwin, 1990).

For square and rectangular openings

$$S \geq \begin{cases} h_o \\ a_o \left(\dfrac{V_u}{\phi V_p - V_u} \right) \end{cases} \tag{10}$$

For circular openings

$$S \geq \begin{cases} 1.5\, D_o \\ D_o \left(\dfrac{V_u}{\phi V_p - V_u} \right) \end{cases} \tag{11}$$

where

V_p = plastic shear capacity of an unperforated beam

ϕ = resistance factor, equal to 0.90 for non-composite steel beams and 0.85 for composite steel beams

In addition to the spacing requirements above, openings in composite beams should be spaced so that $S \geq 2d$.

Table 1. Charts for Determination of the Neutral Zone Length			
Figure	Shape of the Opening	Depth of the Neutral Zone	Beam
4	Square and circular	$\leq d/3$	Steel
5	Rectangular	$\leq d/3$	Steel
6	Circular	$\leq d/2$	Steel
7	Square	$\leq d/2$	Steel
8	Rectangular	$\leq d/2$	Steel
9	Square and circular	$\leq d/3$	Composite
10	Rectangular	$\leq d/3$	Composite
11	Circular	$\leq d/2$	Composite
12	Square	$\leq d/2$	Composite
13	Rectangular	$\leq d/2$	Composite

EXAMPLES

Example 1: Steel Beam

Determine the neutral zone of a 35 ft (10.668 m) span W18×40 (W460×60) steel beam, to make unreinforced concentric rectangular openings with depth h_o equal to 6 in. (152 mm) and length a_o equal to 12 in. (304 mm). This beam has the design flexural and the design shear strengths determined in Example 5.1 (Solution a) of the *LRFD Manual of Steel Construction*, Part 5, Design of Flexural Members (AISC, 1999b):

$$\phi_b M_n = 294 \text{ kip-ft (399 kN-m)}$$
$$\phi_v V_n = 152 \text{ kips (676 kN)}$$

The beam is simply supported, with a factored distributed load of 1.6 kips/ft (23.34 kN/m). Therefore, the required flexural and shear strengths are

$$M_u = \frac{1.6 \times 35^2}{8} = 245 \text{ kip-ft (332 kN-m)}$$

and $$V_u = \frac{1.6 \times 35}{2} = 28 \text{ kips (125 kN)}$$

The loading rate R is the larger of:

$$\frac{M_u}{\phi_b M_n} = \frac{245}{294} = 0.83$$

and $$\frac{V_u}{\phi_v V_n} = \frac{28}{152} = 0.18$$

The neutral zone depth, h_{nz}, will be considered equal to the opening depth itself, h_o. Thus,

$$h_{nz} = h_o = 6 \text{ in. (178 mm)} \cong d/3$$
$$L = 420 \text{ in. (10668 mm)}$$
$$d = 17.9 \text{ in. (455 mm)}$$
$$a_o = 12 \text{ in. (304 mm)} = 2h_o$$
$$L/d = 23.5$$
$$R = 0.83$$

From Figure 5 (steel beam, $a_o = 2h_o$ and $h_{nz} = d/3$), the value of k for $L/d = 23.5$ and $R = 0.83$ is 0.045. Thus, the neutral zone for this case stretches from $0.045L = 18.9$ in. (480 mm) to 401.1 in. (10188 mm), having as reference the left support. Then, concentric rectangular openings of 12 in. × 6 in. (304 mm × 152 mm) can be made in this region, as long as the design criteria are satisfied (Figure 14).

Example 2: Composite Beam

Determine how many circular unreinforced openings with $D_o = 9.8$ in. and a downward eccentricity of 1 in. can be made in a 40 ft (12.192 m) span W24×55 (W610×82) composite steel section. The yield stress of the steel, F_y, is equal to 50 ksi. This beam had the design flexural and the design shear strengths determined in Example 5.6 of *LRFD Manual of Steel Construction*, Part 5, Design of Flexural Members (AISC, 1999b), as follows:

$$\phi_b M_n = 1{,}050 \text{ kip-ft (1425 kN-m)}$$
$$\phi_v V_n = 252 \text{ kips (1121 kN)}$$

The beam is simply supported with a total factored distributed load of 3.6 kips/ft (52.52 kN/m). The resulting required flexural and shear strengths are:

$$M_u = \frac{3.6 \times 40^2}{8} = 720 \text{ kip-ft} \quad (976 \text{ kN-m})$$

and $$V_u = \frac{3.6 \times 40}{2} = 72 \text{ kips (321 kN)}$$

The loading rate R is the larger value of:

$$\frac{M_u}{\phi_b M_n} = \frac{720}{1{,}055} = 0.68$$

and $$\frac{V_u}{\phi_v V_n} = \frac{72}{252} = 0.29$$

Thus, $R = 0.68$.

Step 1: Find the neutral zone. The depth can be calculated as

$$h_{nz} = 2\left(\frac{9.8}{2} + 1\right) = 11.80 \text{ in. (300 mm)}$$

This value is equal to half of the overall depth of the steel section (23.6 in.). The other important dimensions and parameters are:

L = 480 in. (12,192 mm)

$L/d \cong 20$

R = 0.68

From Figure 11 (composite beam, circular openings, and $h_{nz} = d/2$), the value of k for $L/d = 20$ and $R = 0.68$ is near 0.15. The neutral zone for this case, hence, stretches from $0.15L = 72$ in. (1829 mm) to 408 in. (10363 mm) from the left support. Thus, circular openings can be made in this region, as long as the design criteria are satisfied (Figure 15).

Step 2: Determine the minimum spacing between the edges of two adjacent openings. For a W24×55, $t_w = 0.395$ in. and the value of the plastic shear strength of the beam is (AISC, 1999a)

$$V_p = 0.6\, F_y\, dt_w = 0.6 \times 50 \times 23.6 \times 0.395$$
$$= 280 \text{ kips (1244 kN)}$$

For circular openings

$$S \geq \begin{cases} 1.5\, D_o = 1.5 \times 9.8 = 14.7 \text{ in.} \quad (373 \text{ mm}) \\ D_o\left(\dfrac{V_u}{\phi V_p - V_u}\right) = 9.8\left(\dfrac{72}{0.85 \times 280 - 72}\right) \\ = 4.25 \text{ in.} \ (108 \text{ mm}) \end{cases}$$

and, for a composite beam, $S \geq 2d = 2 \times 23.6 = 47.2$ in. (1200 mm).

S is the spacing between edges of two adjacent openings, therefore, the distance between centers of openings will be

$$S + D_o = 47.2 + 9.8 = 57 \text{ in. (1448 mm)}$$

The length of the neutral zone is (Figure 15)

$$L_{nz} = 480 - 2(72) = 336 \text{ in. (8534 mm)}$$

Thus, the number of spaces of 57 in. (1448 mm) possible to fit in L_{nz} is given by

$$\frac{L_{nz} - D_o}{S + D_o} = \frac{336 - 9.8}{57} = 5.72 \quad \text{use 5 spaces}$$

Therefore, the number of openings possible to fit in L_{nz} is 6 (Figure 15).

SUMMARY AND CONCLUSIONS

Design aids compatible with the *Load and Resistance Factor Design Specification for Structural Steel Buildings* (AISC, 1999a) were obtained from computational analyses based on Darwin (1990) to facilitate the design of openings in webs of non-composite and composite steel beams using W-shapes.

The set of design aids allows the identification of the "neutral zone," a region in the beam web in which openings with particular characteristics do not reduce the beam strength. This leads to more economical web penetrations.

NOMENCLATURE

D_o Diameter (or depth) of circular opening

E Modulus of elasticity of steel

F_y Specified minimum yield stress of the steel

L Length or span of beam

L_{nz} Length of neutral zone

M_u Required flexural strength

M_n Nominal flexural strength

M_m Maximum nominal flexural strength at the location of an opening under pure bending; it occurs when $V_u = 0$ at opening center line

M_p Plastic bending moment of an unperforated steel beam

R Loading rate

S Clear space between openings

V_u Required shear strength

V_n Nominal shear strength

V_m Maximum nominal shear strength at the location of an opening under pure shear; it occurs when $M_u = 0$ at the opening centerline

V_p Plastic shear strength

a_o Length of square or rectangular opening

b_f Flange width

d Overall depth of steel section

f_c' Specified compressive strength of concrete

h Clear distance between flanges less the corner radius

h_{nz} Depth of neutral zone

h_o Depth of square or rectangular opening

w_u Total factored uniformly distributed load

t_f Flange thickness

t_w Web thickness

z_o Distance from left support to opening center line

ϕ Resistance factor for moment-shear interaction or openings interaction

ϕ_b Resistance factor for flexure

ϕ_v Resistance factor for shear

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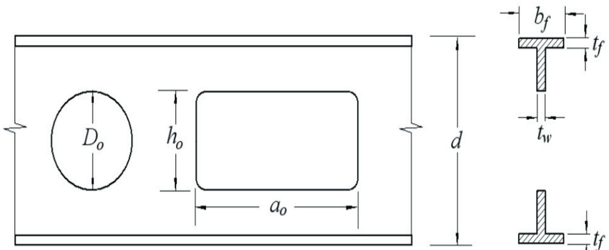
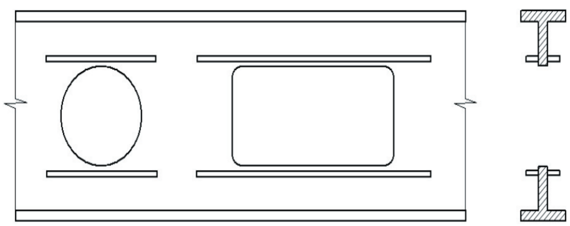


a) unreinforced opening



b) reinforced opening

Fig. 1. Openings in steel beams.

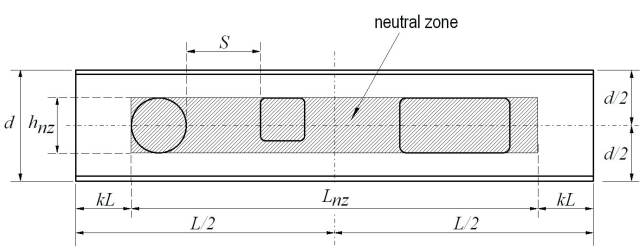


Fig. 2. Neutral zone.

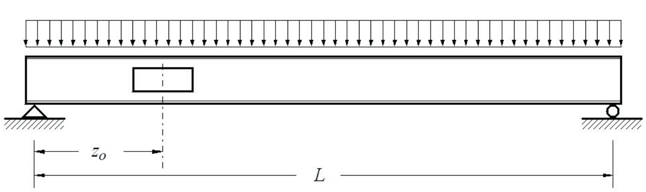


Fig. 3. Opening centerline position.

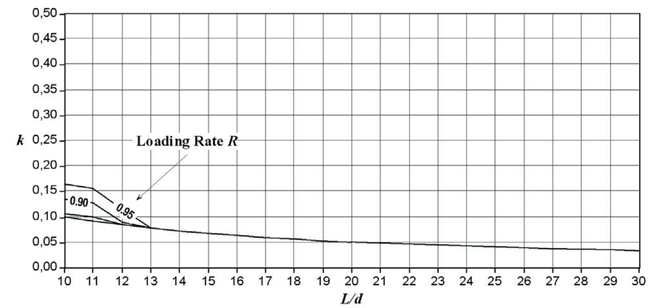


Fig. 4. Neutral zone length for square and circular openings with $h_{nz} \le d/3$ *in steel beams with W-shapes.*

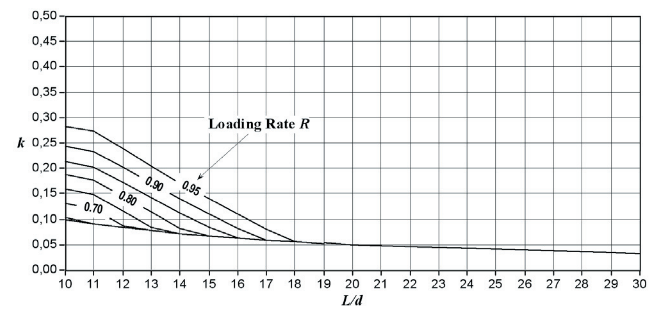


Fig. 5. Neutral zone length for rectangular openings ($a_o = 2h_o$) *with* $h_{nz} \le d/3$ *in steel beams with W-shapes.*

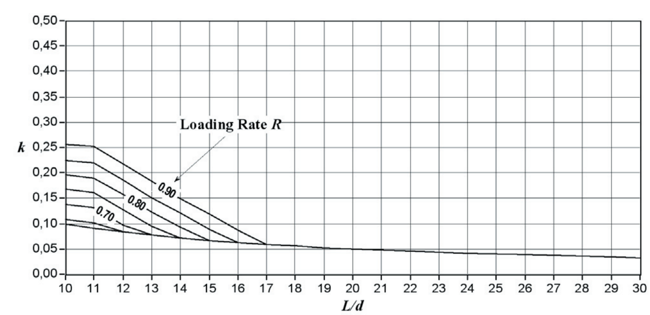


Fig. 6. Neutral zone length for circular openings with $h_{nz} \le d/2$ *in steel beams with W-shapes.*

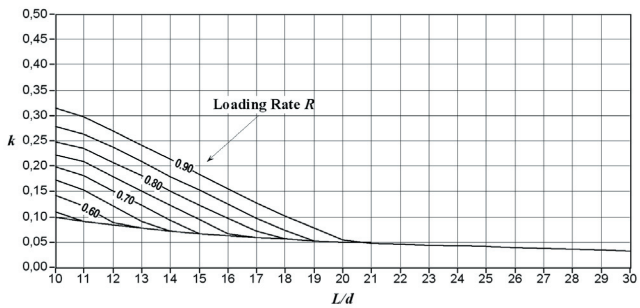


Fig. 7. Neutral zone length for square openings with $h_{nz} \leq d/2$ in steel beams with W-shapes.

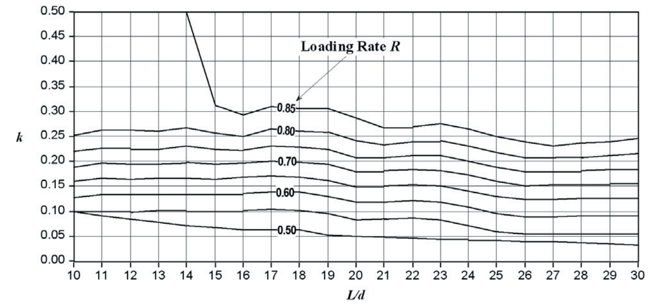


Fig. 10. Neutral zone length for rectangular openings ($a_o = 2h_o$) with $h_{nz} \leq d/3$ in composite beams with W-shapes.

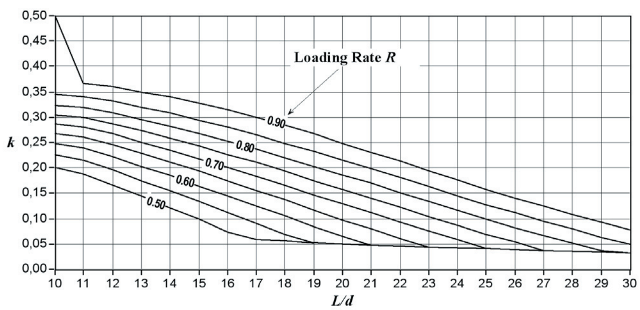


Fig. 8. Neutral zone length for rectangular openings ($a_o = 2h_o$) with $h_{nz} \leq d/2$ in steel beam with W-shapes.

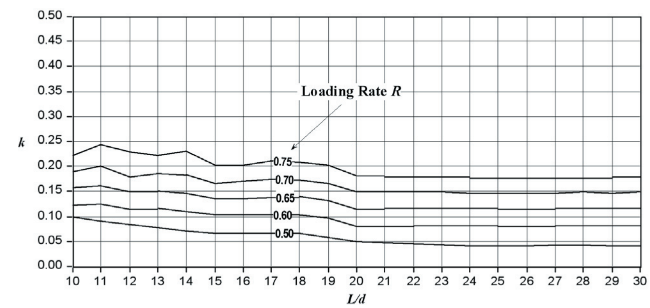


Fig. 11. Neutral zone length for circular openings with $h_{nz} \leq d/2$ in composite beams with W-shapes.

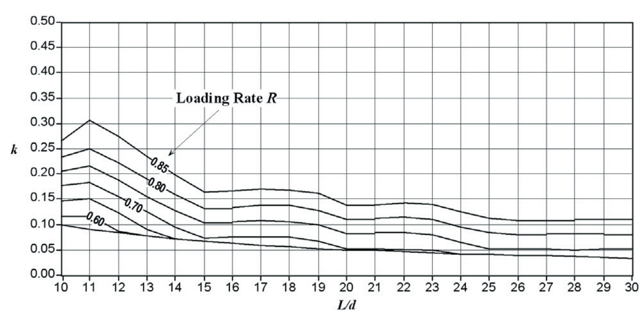


Fig. 9. Neutral zone length for square and circular openings with $h_{nz} \leq d/3$ in composite beams with W-shapes.

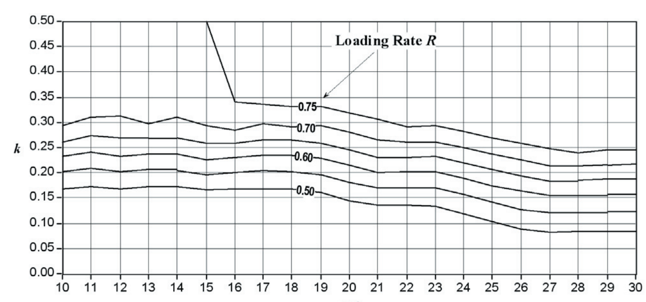


Fig. 12. Neutral zone length for square openings ($a_o = h_o$) with $h_{nz} \leq d/2$ in composite beams with W-shapes.

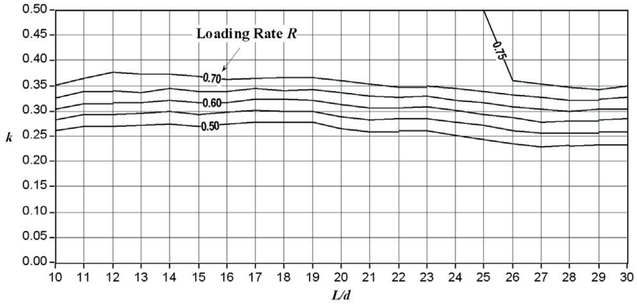


Fig. 13. Neutral zone length for rectangular openings ($a_o = 2h_o$) *with* $h_{nz} \leq d/2$ *in composite beams with W-shapes.*

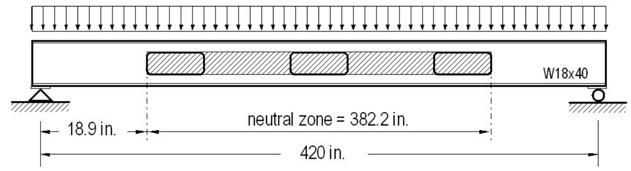


Fig. 14. Neutral zone for a steel W18×40 beam.

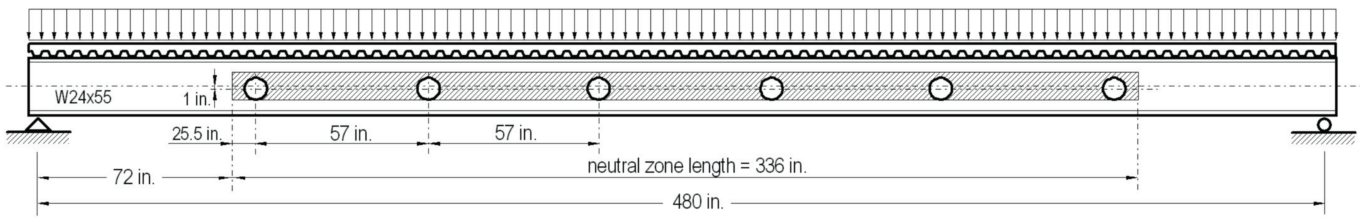


Fig. 15. Neutral zone for a composite beam with W24×55 steel section