Recommended Design Procedures for Beams with Web Openings

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This paper was presented at the AISC National Engineering Conference, Cleveland, Ohio, May 6–7, 1971.

IN TODAY'S construction practice, architects and engineers are specifying more and more frequently that holes be provided in the webs of both main and secondary girders and beams of buildings to accommodate the passage of utility components, and thereby minimize the story height and the cost of the building. For this reason, AISC is considering including provisions for such beams in a future addition to its *Specification for the Design, Fabrication and Erection of Structural Steel for Buildings.*[1] To aid in preparing this addition, an ASCE Subcommittee on Beams with Web Openings (Task Committee on Flexural Members) developed suggestions for the addition. This paper summarizes these suggestions.

This is not the first time that the AISC has considered holes in beam webs. In a 1956 AISC publication, *Welded Tapered Girders*,[2] some design rules were given. The experimental data available at that time was meager, however, and consequently the design rules are, in general, not precise.

SCOPE OF DESIGN RULES

In this paper, design rules are given for both allowable-stress design (elastic design) and maximum-strength design (plastic design). Plastic design has been recommended by many engineers as the more rational approach to designing steel beams with holes because the strength of such beams is often limited by the beam's capability to deform. Because only elastic design is permitted for some steels (such as the ASTM A514 steels), and because the fatigue strength of a steel beam with web hole is identified with the elastic strain range to which the beam is subjected, elastic design rules have been included.

The scope of the rules is shown in Fig. 1. Rectangular holes and circular holes are provided for quite generally. However, the rules are restricted to nonreinforced holes, and to holes whose center line coincides with the beam axis. Also, because of the sparse experimental information available about their behavior, beams with holes deeper than about ⅔ of the beam depth should not be used, although there is no specific restriction on hole size.

With regard to reinforced holes, however, AISI has sponsored a project in which design tables for beams with reinforced, rectangular holes have been prepared, and these tables[3] will soon be published. Also, some tests on nonreinforced beams with eccentric holes have been completed,[4] although the results are not yet finalized.

DESIGN METHOD

In developing the design guides, the ASCE Subcommittee decided on the following procedure as most convenient to account for the reduced section at a hole.

For allowable stress design, first the stress at the center line of the hole is computed on the basis of gross beam section, assuming the hole did not exist. Second, the computed stress is compared with a reduced allowable stress that accounts for the hole. A "hole factor" to compute the reduced allowable stress is provided.

The method is illustrated by the following equations, using the case of shear stress as an example:

$$F_{vH} = \phi\left(\frac{H}{D}, \frac{A}{H}, \frac{A_f}{A_w}\right) F_v$$

$$f_v \leq F_{vH}$$

where

F_v = AISC maximum allowable shear stress
F_{vH} = reduced allowable shear stress
ϕ = hole factor (≤ 1)
f_v = computed shear stress with no hole

and the geometric parameters in the hole factor are

H/D = depth ratio of hole height to beam height
A/H = aspect ratio of hole length to hole height
A_f/A_w = area ratio of flange area to total web area

This technique has both a disadvantage and an ad vantage. The disadvantage is that since the enginee does not compute the actual stresses in the reduced sec tion at the hole, he may miss the physical significance c

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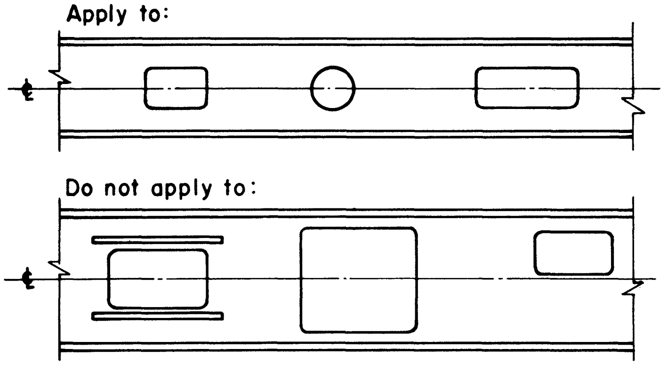

DESIGN RULES

Figure 1

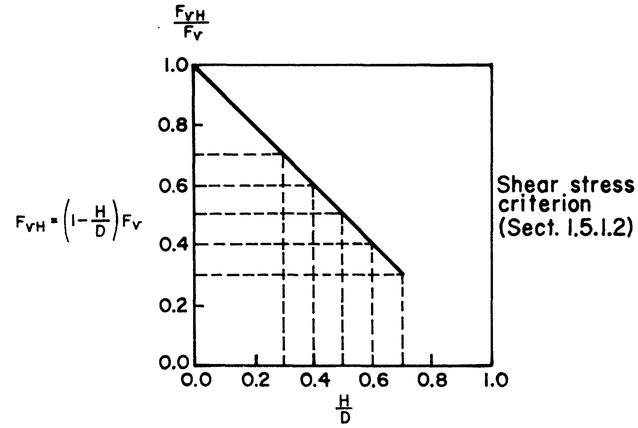

Figure 2

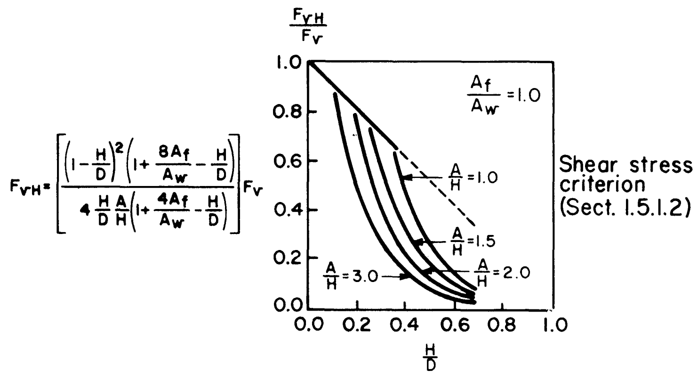

Figure 3

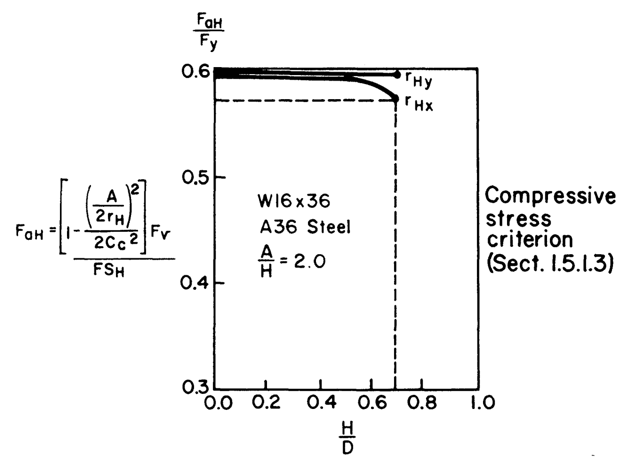

Figure 4

the effect of the hole on beam behavior. The advantage is that by examining the hole factor, the relative strength of the various geometric parameters in the hole factor are quickly evident.

The hole factors insure that the factor against yielding is no less with a hole than when no hole exists, except at points of local stress concentration. Also, the hole factors are, for the most part, direct results of the familiar Vierendeel analysis.

For plastic design, a similar technique is used:

$$M_{pH} = \psi\left(\frac{H}{D}, \frac{A}{H}, \frac{A_f}{A_w}\right) M_p$$

$$M \leq M_{pH}$$

where the moment at the center line of the hole, M, is compared with a reduced plastic moment, M_{pH}, that is obtained by using a hole factor ψ (≤ 1), and the plastic moment of the gross beam, M_p.

ALLOWABLE STRESS DESIGN

The elastic design criteria will be examined first. On the gross section of rolled and fabricated shapes with web holes, the shear stress on a transverse section at the hole shall not exceed, first of all, the linear criterion given in Fig. 2.

In Fig. 2 and similar figures that follow, the equation for the reduced allowable stress and the hole factor is shown at the left of the figure. The equation is plotted so that the ordinate shows the ratio of the reduced maximum allowable stress to the AISC allowable stress, and the abscissa shows the height ratio, H/D. Other parameters included in the hole factor appear on the graph, usually as a specific value used in developing the graph.

The linear shear stress criterion places a limit on the shear stress that is based on a straightforward reduction of web area. The dashed lines outline the usual range of hole size and corresponding stress level.

A second limitation on shear stress is indicated in Fig. 3, and is a function of the aspect ratio of the hole, A/H, as well as the area ratio, A_f/A_w. Physically, this criterion limits the Vierendeel bending caused by the shear force at the hole. For deep holes, this second criterion controls, while for shallow holes the linear criterion controls.

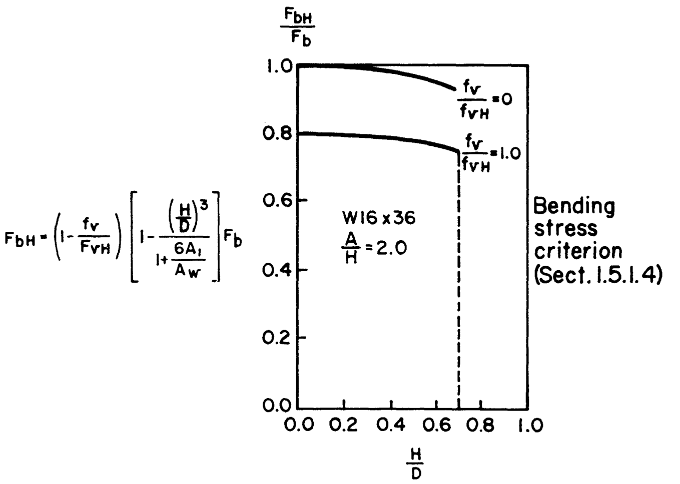

Figure 5

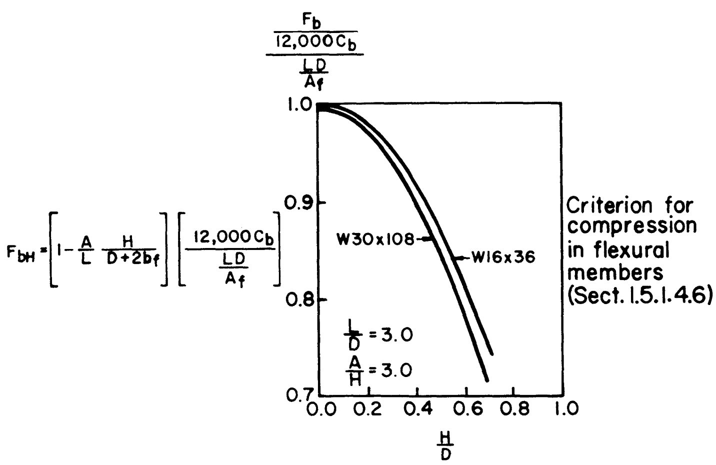

Figure 6

For compression members with web holes—members with isolated web holes rather than columns with perforated plates—it is recommended that the AISC formulas be used in two ways: (1) Choose a member that satisfies the AISC formulas without regard for the hole. (2) As shown in Fig. 4, replace Kl/R in the AISC formulas with the ratio $\frac{1}{2}(A/R_H)$, where A is the length of the hole, R_H is the minimum radius of gyration of a tee section at the hole, and $\frac{1}{2}$ is the effective length factor. Curves are shown in Fig. 4 for R_{Hx}, which is the radius of gyration about an axis parallel to the flange, and R_{Hy}, which is for an axis in the plane of the web. Generally, the reduction is quite small.

For bending stresses, several new criteria are required when there is a hole. For compact sections, the maximum allowable bending stress is generally 0.66 × yield strength. However, because the plastic moment of a beam with a hole is reduced below that of the beam itself, as shall be seen, it is recommended that the factor 0.66 be reduced by the ratio of the reduced plastic moment to the plastic moment of the beam.

For noncompact beams, the allowable stress should be reduced as shown in Fig. 5.* In regions of pure bending ($f_v = 0$), very little reduction is needed. For increasing shear force, though, the allowable bending stresses must be significantly reduced, as indicated by the lower curve, where the computed shear stress equals the reduced maximum allowable shear stress.

The AISC lateral buckling formulas must also be modified when there is a hole. Figure 6 shows the hole factor for AISC Formula (1.5–7) that is based on torsional stiffness. For the usual range of hole sizes, the reduction in allowable stress will be small. The additional AISC Formula (1.5–6), that considers the compression flange as a column supported in the plane of the web, should also be modified, but only if the hole is deeper than ⅔ of the beam depth. The specific reduction is given in the ASCE committee paper.[5]

In addition to lateral buckling, vertical buckling of the compression tee into the plane of the web can occur when web holes become too long. To examine this condition, the previous formulas for members in compression should be used, again replacing Kl/R by $\frac{1}{2}(A/R_H)$.

There are also design criteria for three possible modes of web buckling: To prevent local buckling of the stem of the compression tee sections at the hole, it is sufficient to use the present AISC width-thickness ratio for the stem of unstiffened tees, $127/\sqrt{F_y}$. To prevent web crippling due to concentrated loads placed too near a hole, Fig. 7 end-reaction and interior loads should be placed away from the edge of a hole by at least half the beam depth. Also, concentrated loads should not be placed over the hole. Lastly, for beams with multiple holes, a minimum clear web width between holes should be maintained to prevent web shear buckling. Using the relationship $s = p(1 - H/D)$, where s is the minimum clear web width and p is the center-to-center spacing (or pitch) of the holes, yielding would occur in a tee section before shear buckling occurred in the web between adjacent holes.

* *In Fig. 5, the ratio f_v/F_{vH} should be multiplied by 0.2.*

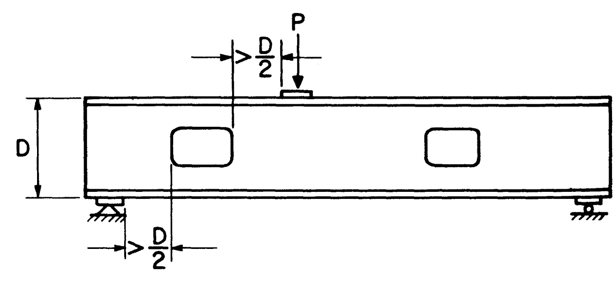

Figure 7

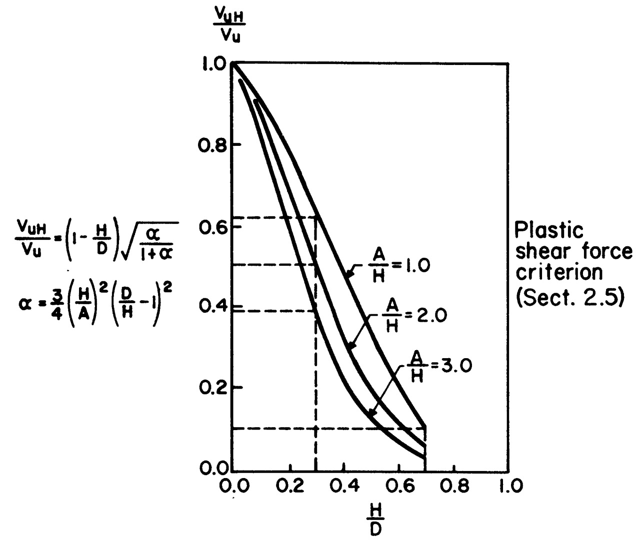

Figure 8

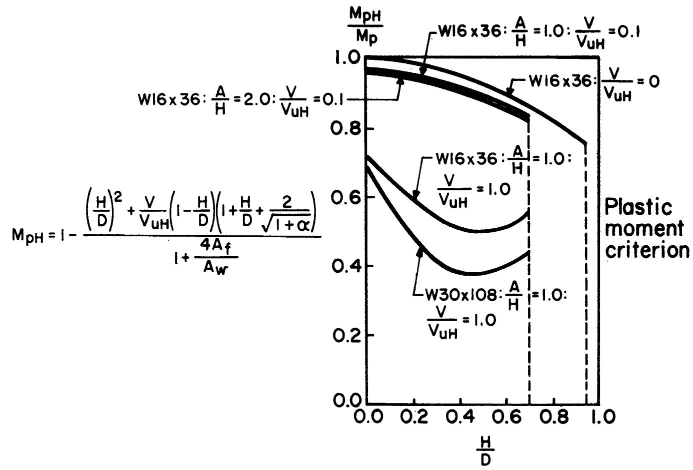

Figure 9

PLASTIC DESIGN

For plastic design, the hole factors result from lower-bound ultimate-strength analyses for beams with an elastic-perfectly plastic stress-strain behavior. The analytical bases (and the experimental verification) are presented elsewhere,[6] but basically the collapse mechanism is completed with the formation of four hinges near the corners of a hole.

The reduced plastic shear force for a beam with a web hole is shown in Fig. 8. It resembles the linear relationship for allowable shear stress except for the term with α. It depends on both the length and height of the hole, as can be determined from the multiple curves.

The reduced plastic moment at the hole is shown in Fig. 9. The hole factor depends on the shear force as well as on beam geometry. The top curve in the figure is for a W16×36 shape in pure bending. In this case, only H/D has an effect. The next two curves, which are practically coincident, show the further reduction caused by a slight amount of shear (in this case, 0.1 of the reduced plastic shear force). Since the only difference attributed to these two curves is hole size (a square hole versus a 2:1 rectangular hole), it is concluded that the shear-force ratio has a stronger effect than aspect ratio on the reduced plastic moment.

The peculiar shape of the two lower curves, which are for two different beams, both subjected to the maximum shear force ratio, is due to the fact that as the hole gets deeper, it must be placed more and more towards a region of pure bending. Thus, although the shear force ratio is maximum, the actual shear force decreases. In fact, the curve for the W16×36 beam would join the uppermost curve if extended to the largest H/D.

FATIGUE

So far, nothing has been said about cutting the hole. However, this is a most critical aspect, particularly if the beam is subjected to fatigue loadings. Therefore, the corner radius and preparation details for the hole must be specified on the plans. It is recommended that all holes be machine oxygen cut, and that manual cutting be disallowed. Figure 10 indicates why. The upper surface is the edge of a machined hole; the middle surface is the edge of a machine oxygen cut hole; and the bottom surface is the edge of a manually oxygen cut hole. The differences in roughness and notch effect are striking. With regard to corner radius, the recommended minimum radius is ⅝-in. or 2 × web thickness, whichever is greater. This is a marked change from the 1956 AISC publication,[2] which called for a minimum corner radius of 2 in.

These recommendations are based on fatigue-test results. With them, and with calculated stresses $< F_{vH}$, F_{bH}, etc, it is possible to use the AISC provisions for "stress category A" in fatigue-loading situations.

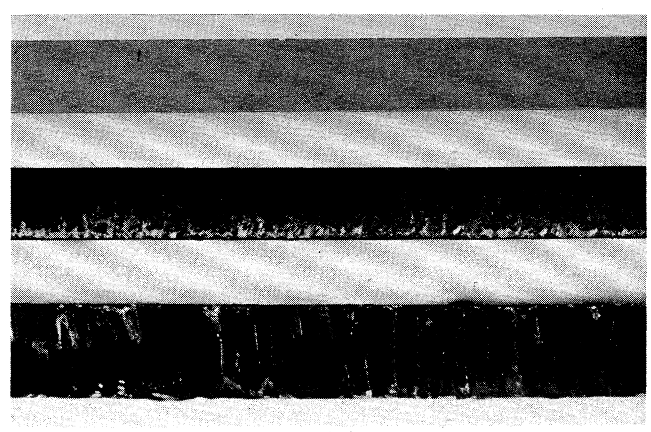

Figure 10

CIRCULAR HOLES

Thus far, the design criteria have emphasized geometric parameters that obviously belong to rectangular holes. There is adequate information,[6] however, to use these same criteria for circular holes, provided that the circular hole is replaced by a rectangular hole whose height is 0.9 × the diameter of a circular hole and whose total length is 0.45 × the diameter of the circular hole. Thus, the substitute rectangular hole would have an aspect ratio of 0.5. These criteria should be used with both elastic and plastic design.

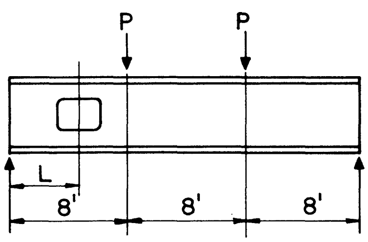

Figure 11

DESIGN EXAMPLE

To illustrate the design rules, a design example is considered. As shown in Fig. 11, it is required to place a nonreinforced 12 in. by 8 in. hole in a simple beam. There is no fatigue loading or lateral buckling problem. A36 steel is being used. The shear force is 13 kips.

Solution (plastic design):

Select beam section:

Max. factored shear force $V = 1.7\ (13) = 22.1$ kips
Max. factored moment $= 22.1\ (8) = 176.8$ kip-ft
Req'd plastic modulus $= 176.8\ (12)\ /36 = 59.0\ \text{in.}^3$

Try W14×38:

Check plastic modulus:
$Z_x = 61.5 > 59.0\ \text{in.}^3$ **o.k.**

Check shear:
$V_u = 0.55\ F_y tD = 87.5 > 22.1$ kips **o.k.**

Try W16×36:

Check plastic modulus:
$Z_x = 64.0 > 59.0\ \text{in.}^3$ **o.k.**

Check shear:
$V_u = 93.8 > 22.1$ kips **o.k.**

Both W14×38 and W16×36 shapes have adequate section modulus and shear strength for the beam without a hole. Also, both beams are compact in A36 steel.

Properties for investigating local strength at the hole:

W14×38:
$M_p = Z_x F_y = 184.5$ kip-ft
$V_u = 87.5$ kips
$A_w/A_f = 1.27$
$A/H = 12/8 = 1.5$
$H/D = 8/14.12 = 0.565$

$$\alpha = \tfrac{3}{4}\left(\frac{H}{A}\right)^2\left(\frac{D}{H} - 1\right)^2 = 0.1975$$

W16×36:
$M_p = 192.0$ kip-ft
$V_u = 93.8$ kips
$A_w/A_f = 1.58$
$A/H = 1.5$
$H/D = 8/15.85 = 0.505$
$\alpha = 0.321$

As a trial, locate the hole in the shear span:
V (factored) $= 22.1$ kips

Try W14×38:
$V_u = 87.5$ kips ; $V/V_u = 0.253$

$$\frac{V_{uH}}{V_u} = \left(1 - \frac{H}{D}\right)\sqrt{\frac{\alpha}{1+\alpha}} = 0.177 < \frac{V}{V_u} = 0.253$$

$\therefore V_{uH} < V$ **n.g.**

The non-reinforced hole cannot be placed in the shear span of the W14×38 beam.

Try W16×36:
$V_u = 93.8$ kips; $V/V_u = 0.236$

$$\frac{V_{uH}}{V_u} = 0.244 > 0.236 \quad \therefore \quad V_{uH} > V$$ **o.k.**

Use W16×36

Determine reduced plastic moment:

$$\frac{M_{pH}}{M_p} = 1 - \frac{\left(\frac{H}{D}\right)^2 + \frac{V}{V_u}\sqrt{\frac{1+\alpha}{\alpha}}\left[1 + \frac{H}{D} + \frac{2}{\sqrt{1+\alpha}}\right]}{1 + 4\left(\frac{A_f}{A_w}\right)}$$

$= 0.488$

$M_{pH} = 1.7PL = (1.7)(13)L = 0.488\ (192.0)$
$L = 4.24\ \text{ft} = 50.9$ in.

Therefore, the distance from the end reaction to the center of the hole must not exceed 50.9 in.

Check edge distance to ensure web crippling:
$L \geqslant D/2 = 7.9$ in. **o.k.**

Check deflection analysis (see full ASCE subcommittee report):
$\Delta_{℄}$ (no hole) $= 0.850$ in.
$\Delta_{℄}$ (with hole) $= 1.102$ in.

The following detail notes would be added to the drawing.

Corner radius: Machine oxygen cut.

Hole at midheight.

No reinforcement required.

If allowable stress design were used, the extended expression for the reduced allowable shear stress (see Fig. 3) would indicate that the W16×36 shape is not satisfactory with allowable stress design:

$$f_v = \frac{P}{A_w} = 2.74 \text{ ksi}$$

$$F_v = 0.4F_y = 14.4 \text{ ksi}$$

$$f_v/F_v = 0.190$$

$$\frac{F_vH}{F_v} = \frac{\left(1 - \frac{H}{D}\right)^2 \left(1 + 8\frac{A_f}{A_w} - \frac{H}{D}\right)}{4\left(\frac{H}{D}\right)\left(\frac{A}{H}\right)\left(1 + 4\frac{A_f}{A_w} - \frac{H}{D}\right)} = 0.148$$

$F_{vH} < f_v$ **n.g.**

If the elastic analysis were completed, one would find that either a W18×35 or a W16×50 shape would be satisfactory.

CONCLUSIONS

Sufficient suitable analytical and experimental analyses of steel beams with circular and rectangular web holes have been made to enable design rules for such beams to be developed. An ASCE Subcommittee developed these rules in a form that is suitable for use with the AISC Specification for the Design, Fabrication, and Erection of Structural Steel for Buildings.

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