Bracing of Beams, Trusses, and Joist Girders Using Open Web Steel Joists

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Designers typically use joists as a part of the lateral bracing for the compression flange of beams or for the lateral bracing of the top chord of trusses and joist girders. Joists serve as the connection to the primary members to deliver the brace force to a diaphragm or horizontal bracing system. The attachment of the joist seat to the primary member is an important element of the bracing system. Traditionally joist seats have been attached to primary members (beams, trusses, and joist girders) by welding. The OSHA Steel Erection Standard, Part 1926.757—Open Web Steel Joists (OSHA, 2001) states: (i) Except for steel joists that have been pre-assembled into panels, connections of individual steel joists to steel structures in bays of 40 ft (12.2 m) or more shall be fabricated to allow for field bolting during erection; (ii) These connections shall be field-bolted unless constructability does not allow.

Unless thorough coordination has taken place between the joist manufacturer, the fabricator, and the erector that joists will be pre-assembled into panels for erection, holes must be provided in the top flange of all primary members and in the joist seats. If the erector chooses not to use the holes (permitted for panelized erection), then the joists are welded to the primary member as has been standard practice. The intention of the OSHA Standard was to provide the holes for erection safety. The bolts were only to be temporary erection bolts until the joists were more permanently connected. Since the inception of the OSHA Standard, the need to permanently connect the joists to the primary members has been questioned. Some erectors would prefer to only bolt the joists to the primary member. If only the erection bolts are used, slip of the connection may occur, since slots are provided in the joist seats. If slip occurs, bracing forces are significantly magnified, as discussed below.

Regardless of whether or not bolts are used for initial connection during erection, the final connection must be specified by the designer.

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The purpose of this paper is to discuss possible alternatives to welding the joists to the primary members in order to provide bracing to the primary members.

JOIST TO PRIMARY MEMBER CONNECTIONS

Several options exist for the specifier of the bracing system, with regard to the attachment of the joists to the primary member. These include the following:

1. Require the joist seat to be welded to the primary member for the final connection.
2. Require a slip-critical connection using ASTM A325 or A490 bolts properly tensioned.
3. Rely on frictional resistance between the joist seat and the primary member.
4. Design using bolt bearing, and require that the joist seats have standard size holes.
5. Allow slip in the slotted holes, and design for the larger bracing forces.

Option 1 (welding the seats) requires no extra design work for the designer; however, it does require the erector to weld the joists in place even after erection bolting. The weld requirement must be clearly specified on the contract drawings.

Option 2 (slip-critical connection) requires additional design work by the designer, and may add cost to the project since high-strength bolts must be used. High-strength bolts are more expensive than the ASTM A307 bolts, which are normally furnished for the connection, and the bolts must be properly tightened to achieve proper slip resistance. Hardened washers are also required. In addition, the designer may specify inspection requirements for the bolts, resulting in further project cost increases. The bottom of the seat and the bearing surface on the primary member must be masked during painting (not practical), or the joist manufacturer and primary member supplier must conduct tests (Yura, 1985) to obtain the coefficient of slip resistance for the painted surface. The designer must evaluate whether sufficient resistance is provided. The designer will generally not know who is supplying the joists or primary members, and thus must specify the required slip coefficient or the brace force. Additionally, this method assumes that the joist bearing surface is in full contact with the primary framing member surface, which is typically not the case for joist seats. Joist bearing seat materials are sheared and the seat slots are punched. These processes leave an edge, preventing the bearing surfaces from being in full contact. Also the bearing seats typically "draw" after being welded and are not completely flat, nor are they necessarily fabricated to fit flat when sloped end bearings are provided for slopes of ¼ in./ft or less.

Option 3 (friction connection) requires that the designer verify the coefficient of friction between the joist seat and the primary member. This requires the fabricator and the joist supplier to conduct slip tests to determine the coefficient of friction. Because of the number of paints, and the number of different fabricators and joist manufacturers involved, tests may not be feasible, except for joist manufacturers supplying both joists and joist girders for a project. To the author's knowledge there is no standard test for determining the coefficient of friction, thus basic physics principles must be used to determine the coefficient. Also, there is no standard for what resistance factor (ϕ) or safety factor (Ω) should be used. It is interesting to note that as the bracing demand increases for the primary member, due to increasing load on the joists and primary member, the resisting force also increases, since the resistance is proportional to the reaction of the joists on the primary member. Because of this, a resistance factor of 0.90 and a safety factor of 1.67 may be appropriate, depending on the mean and standard deviation determined from tests. These values are appropriate only if the frictional resistance will not change with time. For example, if rusting, dirt or water can change the frictional resistance, then higher safety factors should be used.

Option 4 (standard holes) is very costly to the joist manufacturer and increases the project cost significantly. One of the main cost savings related to using open web steel joists is that the "exact length" of the joists does not have to be controlled during their fabrication (the reason slotted seats are used in joist fabrication). If standard-size holes are specified then these controls must be implemented. This requires the joist manufacturers to deviate from their assembly line approach, thus increasing joist cost significantly. In addition, the use of slots in the joist seats allows the erector to adjust for small construction tolerances. This adjustment is not as easily accomplished if standard-size holes are used in the seats. This solution is definitely not practical.

Option 5 (allowing joint slip) may be practical in some cases, depending on bracing force demands. Bracing forces are a function of the initial out-of-straightness of the braced member. If the braced member can move before the brace engages, the initial out-of-straightness is increased by the amount of slip possible. Joist manufacturers do not provide standard holes in joist seats, and seat slot lengths vary among joist manufacturers; however, some manufacturers may allow the designer to specify the slot length within limits. Calculations are shown in the next section demonstrating how slip can be incorporated into the bracing equations.

It should be noted that all of the solutions induce forces in the joists. Depending on their magnitude, the engineer of record should consider these forces in the design and specification of the joists.

BRACING THEORY

Equations for the calculation of bracing forces for individual members are contained in Appendix 6 of the AISC *Specification for Structural Steel Buildings* (AISC, 2005), hereafter referred to as the AISC *Specification*. Equations for required strength and stiffness are presented for both columns and beams. The column equations should be used to determine the bracing forces for trusses or joist girders, and the beam equations are applicable to joists bracing beam sections. It is the author's opinion that since the top chord of trusses are designed using column strength equations, the column bracing equations are appropriate for the trusses. In the majority of cases a roof or floor diaphragm system exists when joist construction is used. The steel deck is connected to the joists and controls the movement of one joist relative to the adjacent joists, thus the AISC *Specification* equations for relative bracing should be used. For deck systems, such as standing seam roofs, horizontal trusses or other horizontal members may have to be used to replace the deck stiffness. The relative bracing equations for columns and beams are shown below.

The furnished brace stiffness equals the stiffness of the steel deck spanning between joists. The deck stiffness can be determined by using the stiffness equations contained in the SDI *Diaphragm Design Manual* (SDI, 2004).

Columns:

The required brace strength is

$$P_{br} = 0.004P_r \qquad \text{(A-6-1)}$$

The required brace stiffness is

$$\beta_{br} = \frac{1}{\phi}\left(\frac{2P_r}{L_b}\right) \text{ (LRFD)} \qquad \text{(A-6-2LRFD)}$$

$$\beta_{br} = \Omega\left(\frac{2P_r}{L_b}\right) \text{ (ASD)} \qquad \text{(A-6-2ASD)}$$

where

ϕ = 0.75 (LRFD) Ω = 2.00 (ASD)

P_r = required compressive strength using LRFD or ASD load combinations as appropriate, kips (N)

L_b = distance between braces, in. (mm)

Beams:

The required brace strength is

$$P_{br} = 0.008 M_r C_d / h_o \qquad \text{(A-6-5)}$$

The required brace stiffness is

$$\beta_{br} = \frac{1}{\phi}\left(\frac{4M_r C_d}{L_b h_o}\right) \quad \text{(LRFD)} \quad \text{(A-6-6LRFD)}$$

$$\beta_{br} = \Omega\left(\frac{4M_r C_d}{L_b h_o}\right) \quad \text{(ASD)} \quad \text{(A-6-6ASD)}$$

where

ϕ = 0.75 (LRFD) Ω = 2.00 (ASD)

M_r = required flexural strength using LRFD or ASD load combinations as appropriate, kip-in. (N-mm)

h_o = distance between flange centroids, in. (mm)

C_d = 1.0 for bending in single curvature; 2.0 for double curvature; C_d = 2.0 only applies to the brace closest to the inflection point

L_b = laterally unbraced length, in. (mm)

Adjustments must be made to the strength equations if Option 5 (allow slip) is used. Equations A-6-1 and A-6-5 are based on an initial out-of-straightness equal to the distance between brace points divided by 500. In addition, it is assumed that the brace displaces an amount equal to the initial out-of-straightness. If slip occurs prior to brace engagement the initial out-of-straightness should be taken as the distance between brace points divided by 500, plus the initial slip amount. Letting Δ_b = L/500 + slip, the brace force equals

$$P_{br} = \left(\frac{2\Delta_b}{L}\right) P_r$$

where

L = distance between braces, in. (mm)

For example, if the bolts in the joist seat can slip 1.5 in. before going into bearing, and the joists are spaced 60 in. apart, Δ_b = 60/500 + 1.5 = 1.62 in. The brace force equals $0.054P_r$.

Similarly for beam bracing,

$$P_{br} = \left(\frac{4\Delta_b}{L}\right) M_r C_d / h_o$$

Thus, for the 1.5 in. slip, and the joists spaced at 60 in. apart, $P_{br} = 0.108 M_r C_d / h_o$.

The AISC *Specification* Commentary (AISC, 2005) provides Equation C-A-6-1, to reduce the brace force based on the provided brace stiffness, β_{act}. From the Commentary, "If the brace stiffness provided is different from the requirement, then the brace force or brace moment can be multiplied by the following factor

$$\frac{1}{2 - \dfrac{\beta_{br}}{\beta_{act}}}$$

EXAMPLE

Given

Determine the bracing requirements for a roof truss that spans 60 ft. The truss supports 40-ft-long open web steel joists which are spaced 5 ft on center. The slots in the joist seats allow for a ¾ in. slip. The roof layout is shown in Figure 1. A 22-gage-wide rib deck is used. The deck is welded to the joists using a 36/4 pattern, and one #10 side lap screw is used. The truss top chord is a WT9×43. (F_y = 50 ksi, A = 12.7 in.²) The joists support a dead load of 15 psf and a live load of 20 psf. The factored design force (LRFD), P_u, in the WT under the dead load plus live load condition is 450 kips.

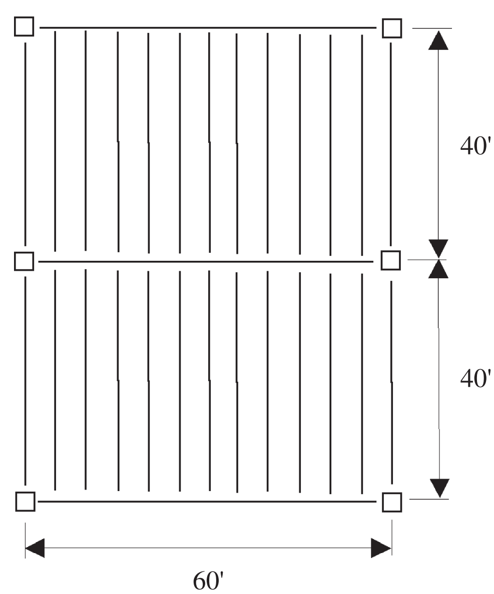

Fig. 1. Framing plan.

Solution Using LRFD (Options 1–4)

Bracing Force:

$P_{br} = 0.004P_r$

$P_{br} = 0.004(450) = 1.80$ kips

Note that this would be the maximum required brace force since the compression force in the truss chord decreases from the center of the truss to the truss ends.

Required Stiffness:

$$\beta_{br} = \frac{1}{\phi}\left(\frac{2P_u}{L_b}\right) \tag{A-6-2}$$

$$\beta_{br} = \frac{1}{0.75}\left(\frac{2(450)}{(5)(12)}\right) = 20.0 \text{ kip/in.}$$

Diaphragm Stiffness:

The provided stiffness from the steel deck equals the deck stiffness, G', times the deck length perpendicular to the truss (joist length), divided by the joist spacing. From the SDI *Diaphragm Design Manual*, for the 36/4 weld pattern and one side lap screw, $G' = 11.49$ kip/in. Thus, the provided stiffness equals (11.49)(40 ft)/(5 ft) = 91.9 kip/in. Since 91.9 kip/in. > 20.0 kip/in., the stiffness criteria is satisfied. The stiffness calculation does not include the loss of stiffness due to axial shortening of the joist. In the author's opinion this axial deformation is small and can be neglected.

Using the AISC *Specification* Commentary Equation C-A-6-1, the brace force can be reduced by the factor

$$\frac{1}{2-\frac{\beta_{br}}{\beta_{act}}} = \frac{1}{2-\frac{20.0}{91.9}} = 0.56$$

thus $P_{br} = (1.80)(0.56) = 1.00$ kip.

Since two joists frame to the truss at each panel point, the required force can be distributed equally to each joist so long as the joists are the same length on each side of the truss (stiffness distribution of bracing forces).

Option 1 (welded seat): The *Standard Specification for Open Web Steel Joists*, K-Series (SJI, 2005) requires a minimum of two ⅛ in. fillet welds 1 in. long on K-series, or two ½-in.-diameter bolts (ASTM A307), or any combination of the two on the bearing seats. The four welds have a combined design shear strength (LRFD) of 11.14 kips [(4)(0.75)(0.707)(0.125)(0.6)(70) = 11.14 kips]. Option 1 easily satisfies the bracing strength requirement.

Option 2 (slip critical): If ½-in.-diameter ASTM A325 bolts are used, the design shear strength (LRFD) is calculated as follows:

[(4)(0.85)(0.35)(1.13)(0.7)(12)(1)] = 11.3 kips

This calculation is based on unpainted surfaces, and the connection is designed to prevent slip at the required strength. Option 2 easily satisfies the bracing strength requirement, but has cost and practical limitations as mentioned.

For *Option 3* (friction connection), the joist design reaction is

[(1.2)(15) + (1.6)(20)](5)(40/2) = 5,000 lb

The required design coefficient of friction equals the brace force per joist (1,000 lbs / 2 = 500 lb), divided by the joist reaction, $\mu = 500/5{,}000 = 0.10$. Using a ϕ factor of 0.90, the required nominal coefficient of friction is 0.10/0.9 = 0.11.

Option 4 (bolt bearing): Four ½-in.-diameter (ASTM A307) bolts have a combined shear strength (LRFD) of 14.11 kips [(4)(0.75)(0.196)(24) = 14.11 kips]. Option 4 easily satisfies the bracing strength requirement, but has cost and practical limitations as mentioned.

Option 5 (allow slip), $\Delta_b = 60/500 + 0.75 = 0.87$ in. The bracing force equals

$$P_{br} = \left(\frac{2\Delta_b}{L}\right)P_r = \left[\frac{(2)(0.87)}{60}\right]450 = 13.05 \text{ kips}$$

Using the 0.56 reduction factor, $P_{br} = (13.05)(0.56) = 7.31$ kips. For Option 5, it is unlikely that the bolts are positioned in the seat slots such that all four bolts are in bearing. The author suggests that only two bolts be used to resist the brace force. Using only two bolts, the shear resistance provided by the ASTM A307 bolts is 7.06 kips. Therefore the A307 bolts are inadequate in shear. The bearing between the seat and the bolt must also be checked. The thinnest seat angle used by most joist manufacturers is approximately ⅛ in. The design bearing force can be calculated from AISC *Specification* Equation J3-6b (AISC, 2005):

$$R_n = 1.5L_c tF_u \le 3.0dtF_u \tag{J3-6b}$$

where

F_u = specified minimum tensile strength of the connected material, ksi (MPa)

L_c = clear distance, in the direction of the force, between the edge of the hole and the edge of the adjacent hole or edge of the material, in. (mm)

D = nominal bolt diameter, in. (mm)

t = thickness of connected material, in. (mm)

From Table J3.4 for a ½ in. bolt, the minimum distance from the center of the hole to the edge is ⅞ in. This distance must be increased by the value of C_2 which is found in Table J3.5. From Table J3.5, $C_2 = ¾d = ⅜$ in. Thus, $L_c = 1.25$ in. and $F_u = 65$ ksi.

$$\begin{aligned} R_n &= (1.5)(1.25)(0.125)(65) \\ &= 15.23 \text{ kips} \\ &\leq (3)(0.5)(0.125)(65) = 12.19 \text{ kips} \end{aligned}$$

$\phi = 0.75$, thus the design bearing strength per bolt equals $\phi R_n = (0.75)(12.19) = 9.14$ kips. Total bearing strength = (2)(9.14) = 18.28 kips. Bearing is adequate.

The bracing forces are transferred from the joists into the roof diaphragm. The bracing forces do not accumulate along the length of the truss since each brace force opposes the next in order to force the chord into a sinusoidal buckling mode (Nair, 1988). The diaphragm segment between joists must resist the shear between brace points. If the bracing forces for the two endwall trusses are included, and the endwall trusses have a chord force of 225 kips, the total diaphragm shear equals 3600 lb/80 ft = 45 lb/ft. The 22 gage diaphragm has a design shear strength equal to 360 lb/ft; thus the diaphragm strength is adequate.

SUMMARY

Several options have been presented for bracing trusses, beams and joist girders using open web steel joists. Procedures for the determination of bracing forces have also been presented. In general, the bracing force requirements are minimal; however, they must be considered by the Engineer of Record (EOR). The EOR must also consider the impact of the OSHA required holes on the strength of the primary members. Coordination of hole location may be required by the EOR.

The author recommends that the EOR use *Option 1* (joist seats to be welded to the primary member after placement). This option is the most positive means of attachment and requires the least coordination among contractors, fabricators, and joist suppliers.

Option 2 (slip-critical connection) should not generally be used as it adds significant costs to a project.

Option 3 (rely on friction between the joist seat and the primary member) may be the least expensive, but it requires friction tests for the paints used and does not provide a positive attachment as that for Option 1. When joists and joist girders are supplied by the joist manufacturer, the paint tests may be practical; however, if the joist manufacturer is not supplying the trusses or beams, Option 3 should not be used.

Option 4 (bolt bearing) should not generally be used as it adds significant costs to a project.

Option 5 (allow slip) may be viable in some cases; however, the author does not recommend its use since brace forces are increased significantly and extra coordination with the joist supplier is required to determine slot lengths and seat angle thickness for calculations.

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