Transfer Forces in Steel Structures

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ABSTRACT

Transfer forces are loads that are transmitted across joints in a structure. For connections to be designed properly, the transfer forces must be communicated to the connection designer. This paper discusses the calculation of transfer forces and how the connection configuration affects the calculations. Two examples are provided to illustrate the calculation process.

Keywords: transfer forces, connections

Transfer forces are loads that are transmitted across joints in a structure. For connections to be designed properly, the transfer forces must be communicated to the connection designer. In simple structures, the force paths can be easily identified, but for more complicated structures such as the one shown in Figure 1, the force paths are not obvious. The process is further complicated by the fact that multiple load cases must be considered.

This paper discusses the calculation of transfer forces and how the connection configuration affects the calculations. Two examples are provided to illustrate the calculation process.

BRACING CONNECTIONS

A standard vertical bracing connection is shown in Figure 2. When this type of connection is used, the transfer forces should be calculated assuming the horizontal component of the brace load is transferred through the gusset-to-beam interface and the vertical component is transferred through the gusset-to-column interface. Technically, this assumption may not be true, because the connection designer may choose to transfer the forces in a different way, but the additional loads will be accounted for in the connection design process and the end result will be as assumed. There are many different methods to determine the force distribution in bracing connections, but to illustrate this point, only the KISS method and the Uniform Force Method will be used.

The lower bound theorem of limit analysis states that a load calculated based on an assumed force distribution that satisfies equilibrium conditions with forces nowhere exceeding the capacity will be less than or equal to the true limit load. The designer can choose any force path that is convenient, if the following three conditions are satisfied:

1. Equilibrium must be satisfied.
2. All components in the force path must be designed for the assumed force distribution.
3. All components in the joint must have adequate ductility to allow the stresses to redistribute so the assumed force distribution can be achieved.

Although condition 1 must always be satisfied, the contract drawings usually show the maximum load in the members. In most cases, the maximum loads for each member at a particular node will occur at different load cases, and a free body diagram of the node using these maximum loads will not be in equilibrium.

The external loads acting on a vertical bracing joint are shown in Figure 3.

The KISS method, described by Thornton (1984), has been used extensively in the past to distribute the brace forces through the connection. The assumed force distribution is

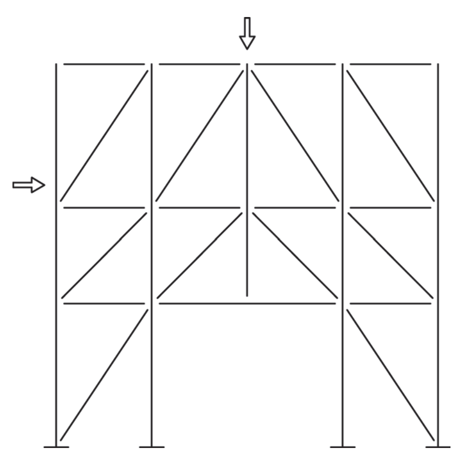

Fig. 1. Elevation of a braced frame.

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shown in Figure 4. Because the horizontal load at the gusset-to-beam interface, H_b, is equal and opposite to the horizontal component of the brace load, P_h, the beam-to-column connection is not affected by the brace load. Therefore, the beam connection can be designed as if the brace were not present.

The force distribution for the general condition of the Uniform Force Method (AISC, 2005) is shown in Figure 5. In addition to the beam reaction and transfer force, the beam-to-column connection must be designed for additional forces generated by the assumed force distribution. To maintain equilibrium, the horizontal force at the gusset-to-column interface, H_c, must be transferred into the beam. Similarly, the vertical force at the gusset-to-beam interface, V_b, should be added (algebraically) to the beam reaction.

Although the beam-to-column connection can be affected by the gusset interface loads, the transfer forces are calculated independently, and the beam-to-column connections are designed considering the transfer force and any additional load from the assumed distribution of the brace loads. This can be seen in the free-body diagram of the column in Figure 5, where the horizontal force carried by the beam-to-column connection, H, must equal the algebraic sum of F_t and H_c.

Conversely, this assumption is not correct if the gusset plate is attached at only one interface as shown in Figure 6. For the connection in Figure 6(a), the horizontal component of the brace goes into the column through the gusset-to-column interface. Then it passes through the beam-to-column connection. If no other forces are acting on the joint, the transfer force is equal and opposite to the horizontal component of the brace. In Figure 6(b), a similar situation exists, and the vertical component of the brace must be transferred into the column. In this case, the beam end connection should be designed to carry the algebraic sum of the beam end reaction and the vertical component of the brace.

Standard horizontal bracing connections are shown in Figure 7. When these connections are used, the components of the brace force transfer directly into the beams. The components at each gusset-to-beam interface are parallel to the longitudinal axis of the beam.

BEAM CONNECTIONS FOR LARGE TRANSFER FORCES

It is common to use ⁵⁄₁₆-in.-thick clip angles for standard double angle connections; however, the axial capacity of these connections is low. For axial loads exceeding the capacity of

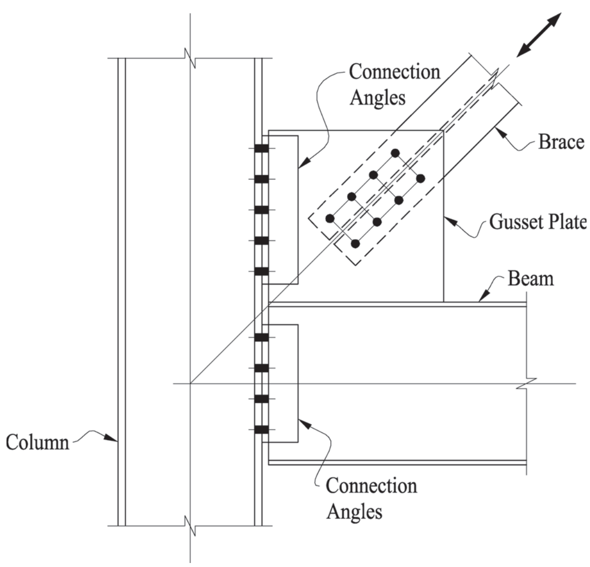


Fig. 2. Standard vertical brace connection.

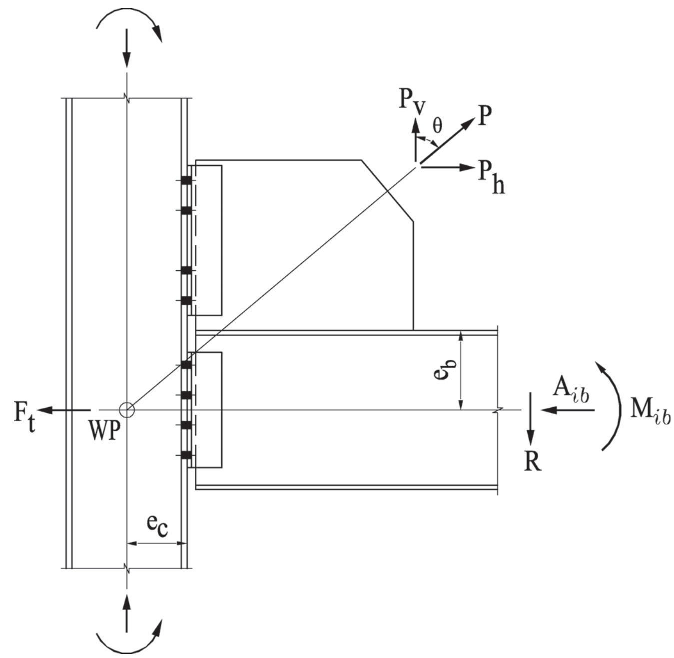


Fig. 3. External loads acting on a vertical bracing joint.

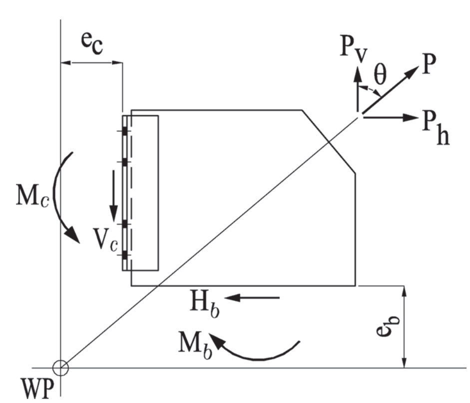


Fig. 4. Gusset plate interface forces for the KISS method.

standard connections, the most common connections are the double-angle connection and the shear end plate connection shown in Figures 8(a) and 8(b), respectively.

Transfer forces occasionally exceed the axial capacity of the common connection configurations. In these cases, alternative connections must be used. If the connection is required to carry axial load only, it can be designed as a strut connection with a gusset plate as shown in Figure 9. If the beam shear is significant, the connections in Figure 10 can be used. These connections have a significant rotational stiffness and will behave as moment connections in the real structure. The fin plate connection in Figure 10(a) has traditionally been used by fabricators to increase the axial load capacity of beam-to-column connections. Williams (1986) showed that the plates cause the connection to perform as a fully fixed moment connection. Figure 10(b) shows a flush end plate connection that can be used to carry very large compression loads and moderately large

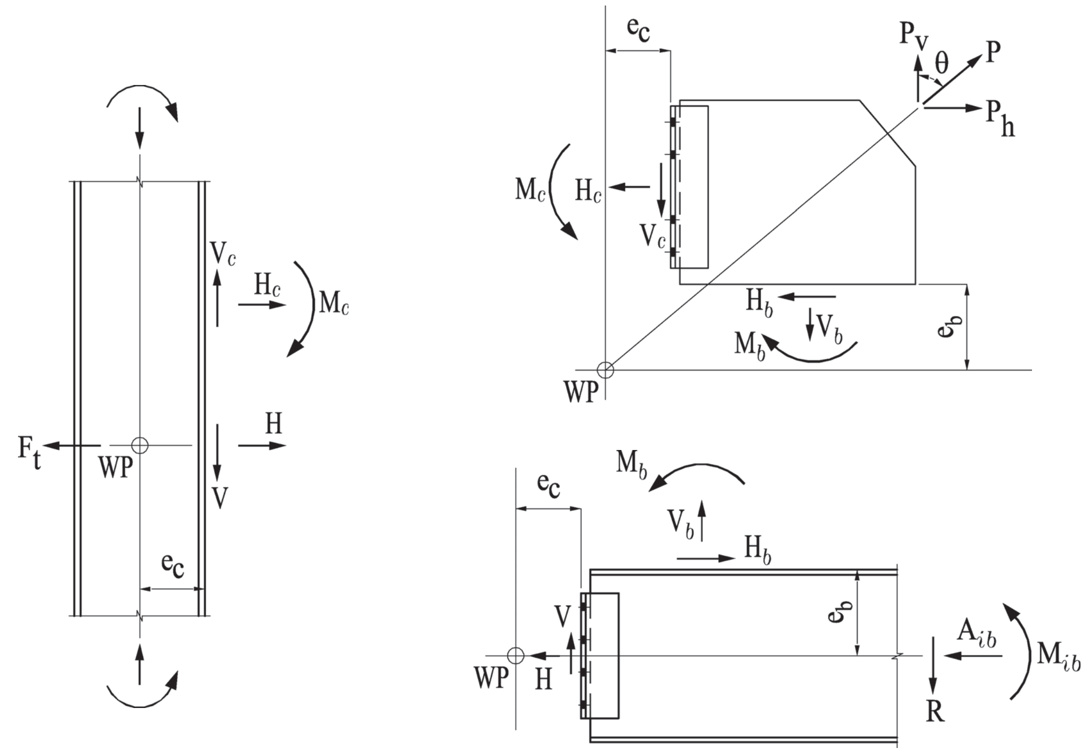
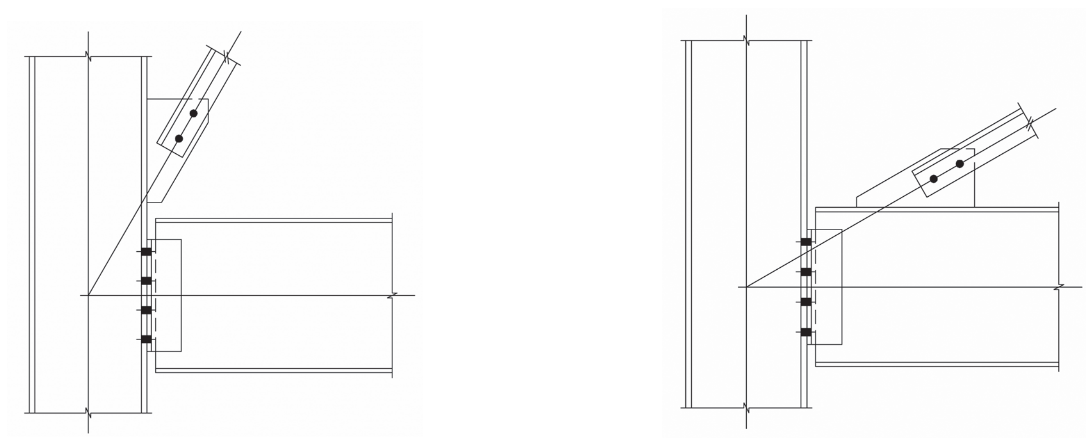


Fig. 5. Gusset plate interface forces for the Uniform Force Method.



(a)

(b)

Fig. 6. Nonstandard vertical brace connections. (a) Gusset plate welded directly to column. (b) Gusset plate welded directly to beam.

tension loads. Figure 10(c) shows an extended end plate that can be designed for large tension and compression loads. If designed correctly, this connection can develop the full strength of the member. Figure 10(d) shows a flange plate connection that can carry very large loads, such as truss chord pass-through loads.

VERTICAL TRANSFER FORCES

Generally, transfer forces are thought of as acting in the horizontal plane of a structure, but there are cases where vertical transfer forces should be indicated on the drawings. The connections shown in Figure 11 have vertical loads entering the gusset plate from a beam or truss chord. Figure 11(a) shows a truss panel point with a vertical transfer force across the chord due to the purlin load. In most cases, if the transfer force is not shown, the gusset-to-chord interface will be designed for the horizontal force only. Figure 11(b) shows an inverted V-brace with a vertical transfer force due to the gravity floor load. Figure 11(c) shows an inverted V-brace with a vertical transfer force due to column above. Figure 11(d) shows the mid-point of an X-brace, where vertical forces may be transferred from one gusset plate to the other.

DIAPHRAGM FORCES

Forces in the horizontal plane of a structure can be transferred to the vertical bracing system with a horizontal bracing system or a diaphragm. If a diaphragm is used, the forces can be transferred to the struts using deck welds, screws or composite studs. Forces can also be transferred from a concrete floor diaphragm into the column by bearing directly on the column. The forces will then be transferred from the column into the strut. The transfer mechanism for these forces dictates the amount of load in the beam-to-column connections.

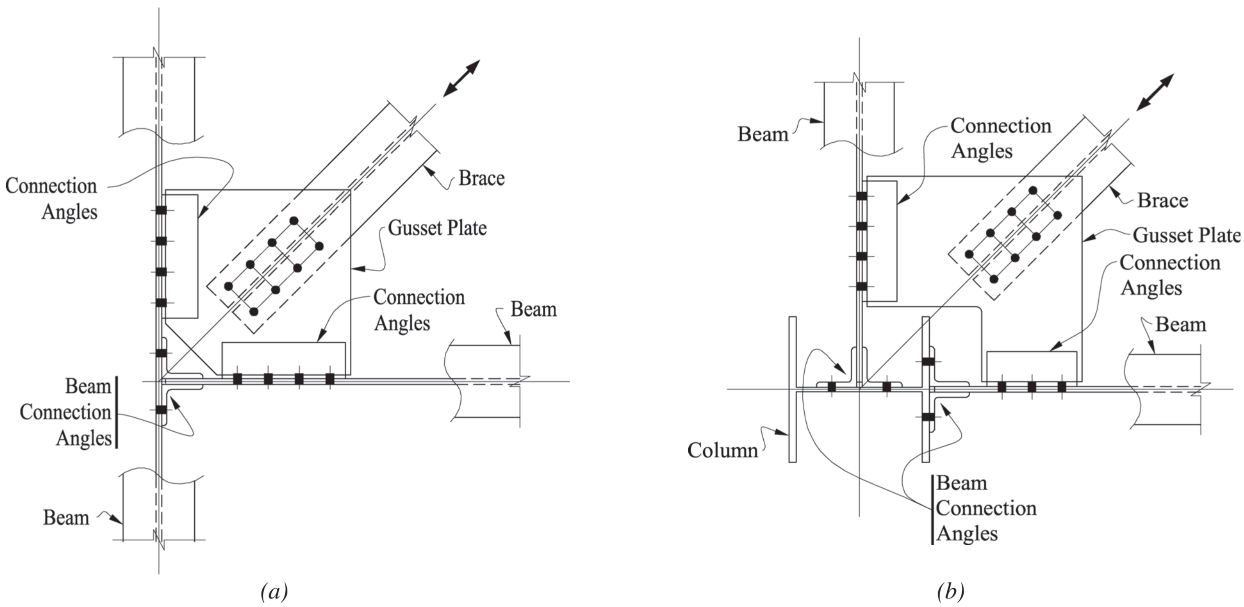


Fig. 7. Standard horizontal brace connections. (a) Beam-to-beam interface. (b) Beam-to-column interface.

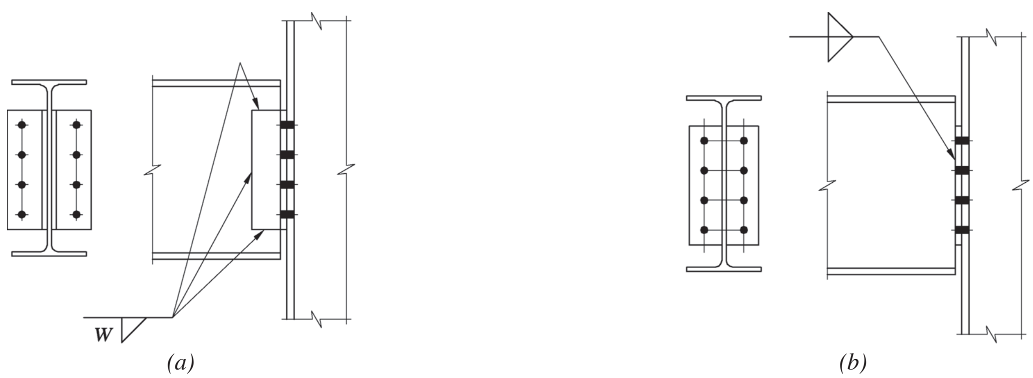


Fig. 8. Common beam connections for axial loads. (a) Double clip angle connection. (b) Shear end plate connection.

EXAMPLE 1

Example 1 shows the calculation of transfer forces in a simple structure as it would be done by hand. The structure has a horizontal bracing system at level 2 and a diaphragm at level 3, which are shown in Figures 12(b) and 12(a), respectively. Three different vertical bracing arrangements are considered. The elevations along lines A and B are identical and are shown in Figure 13 for each of the three bracing arrangements considered.

An 80-kip lateral load is applied at level 2 simultaneously with a 100-kip lateral load applied at level 3. The forces will be calculated by hand and will not include the effects of member stiffness. Standard connections will be assumed.

Figure 14 shows the forces entering the beams from the diaphragm and horizontal braces. The component from each horizontal brace is 10 kips. This load enters the beam through the standard gusset plate connection. The horizontal component of the top vertical brace is 50 kips.

Figure 15 shows the transfer forces and axial loads in the beams, which were calculated using simple statics. The transfer force across column line 2 at level 2 for each bracing arrangement are:

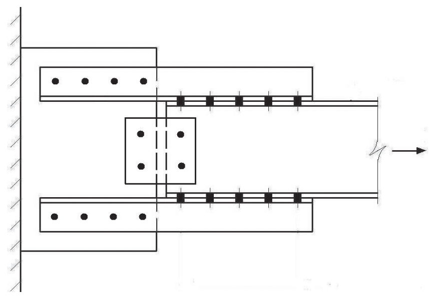


Fig. 9. Strut connection.

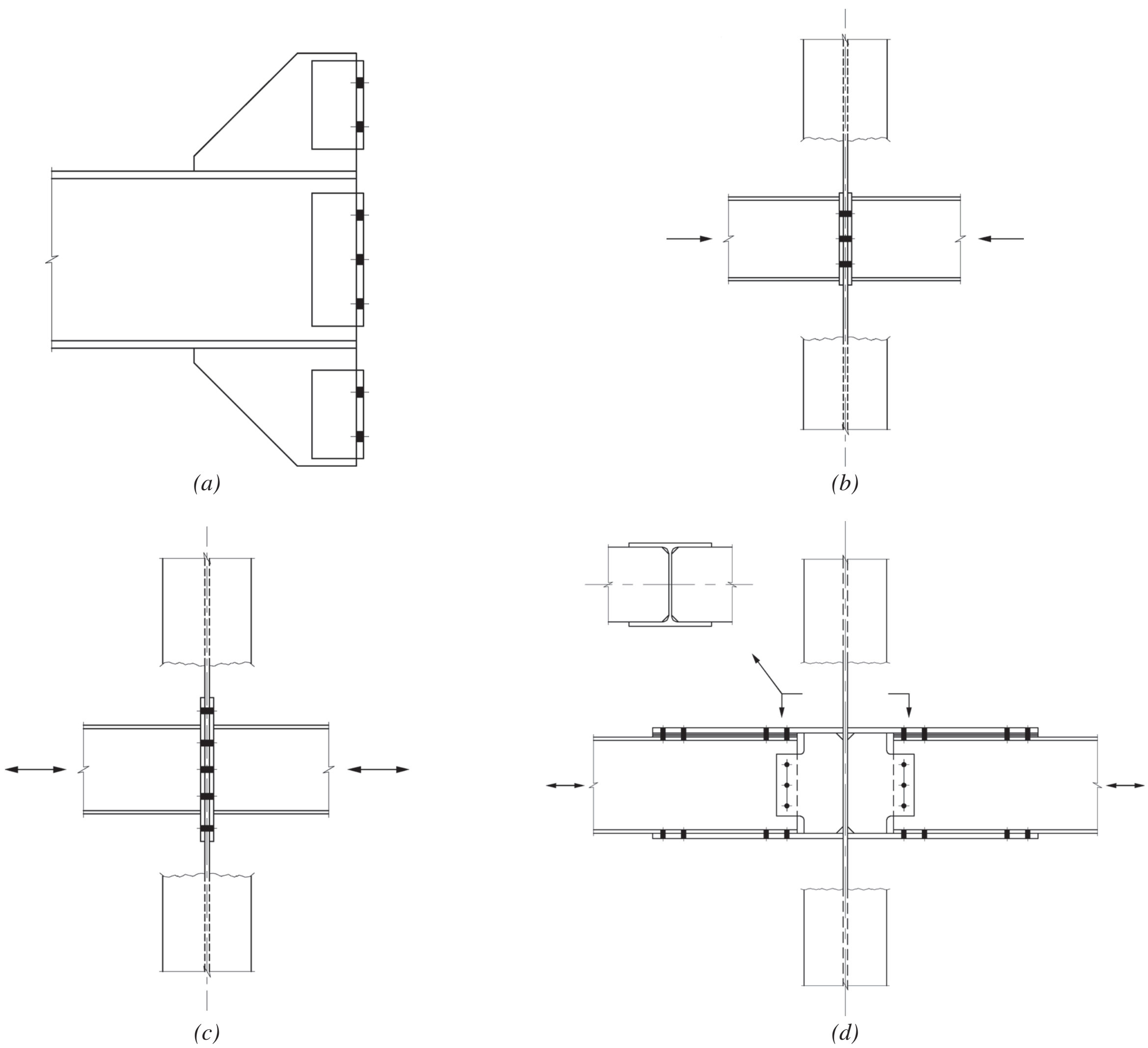


Fig. 10. Connections for very large axial loads. (a) Fin plate connection. (b) Flush end plate. (c) Extended end plate. (d) Flange plate connection.

Bracing arrangement 1
F_t = 10 kips + 10 kips = 20 kips (compression)

Bracing arrangement 2
F_t = 50 kips + 10 kips + 10 kips = 70 kips (compression)

Bracing arrangement 3
F_t = 10 kips + 10 kips + 50 kips = 70 kips (compression)

This example clearly shows that the axial load in the beam is not a good indicator of the transfer force. For bracing arrangement 3, the transfer force at level 2 and column line 2 is 70 kips, but the axial load in the beams is only 10 kips. If the axial load in the beam was used to design the beam-to-column connection, the connection would be underdesigned.

The opposite problem occurs at the same location for bracing arrangement 1. The axial load in the beam is 80 kips on one side of the column and 10 kips on the other side, but the transfer force is 20 kips. In this case, using the largest axial load instead of the transfer force would be conservative, but this could cause the connection to be much more expensive than is required.

The transfer force will be zero at column lines 1 and 3 for all three vertical bracing configurations, but the beam-to-column connections must be adequate to brace the columns against buckling. Except for structures with very high column loads, most standard connections have enough strength and stiffness to act as a brace point.

EXAMPLE 2

Example 2 shows the transfer force calculation for a joint in a large industrial structure as it would be done using the output from a finite element model. For simplicity, only one load case is considered. The node has two vertical braces and three horizontal braces, and standard connections are assumed. The structural elements and loads are shown in Figure 16.

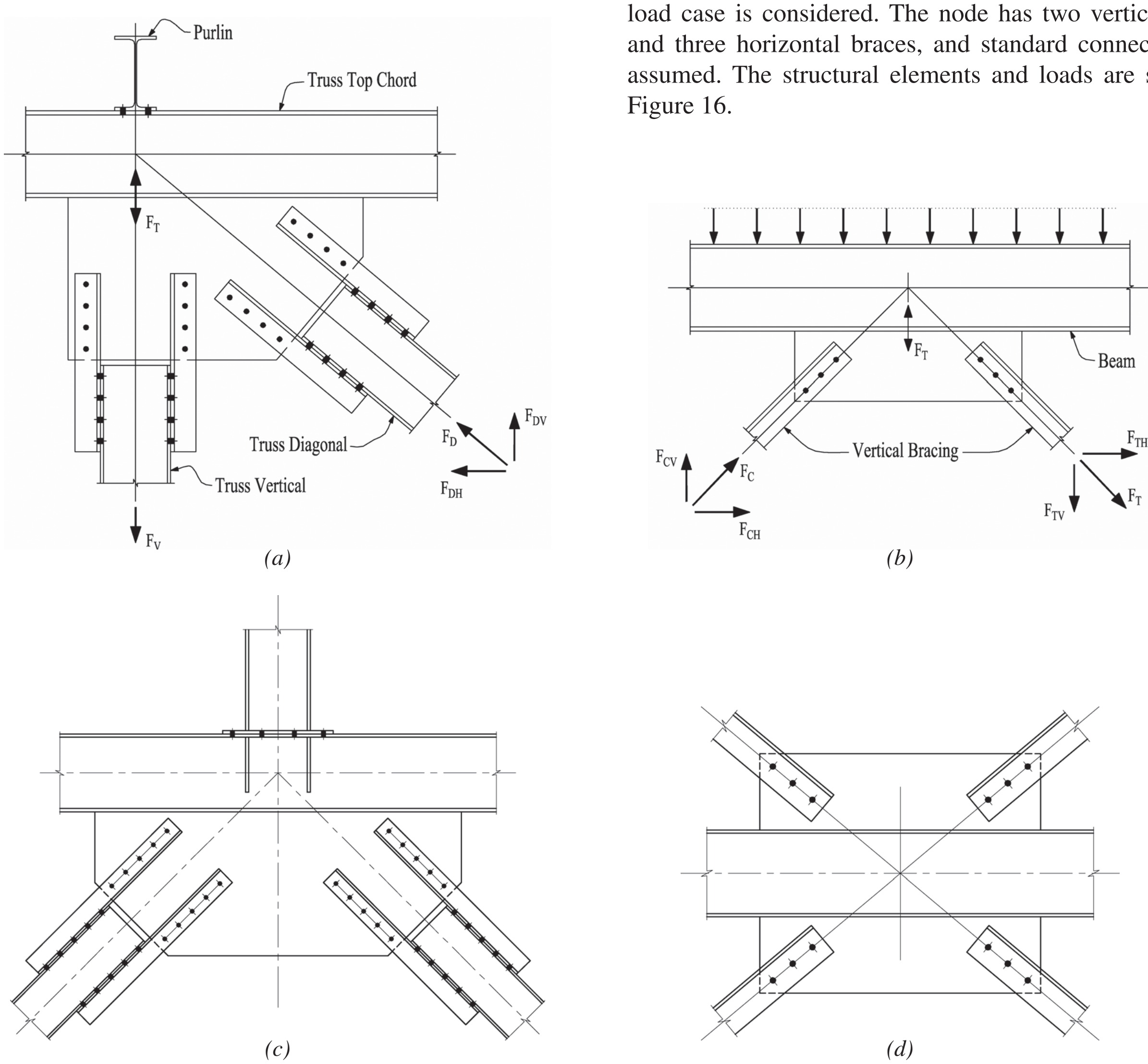


Fig. 11. Joints with vertical transfer forces. (a) Truss panel point with purlin. (b) Inverted V-brace with gravity floor load. (c) Inverted V-brace with column above. (d) Mid-point of an X-brace.

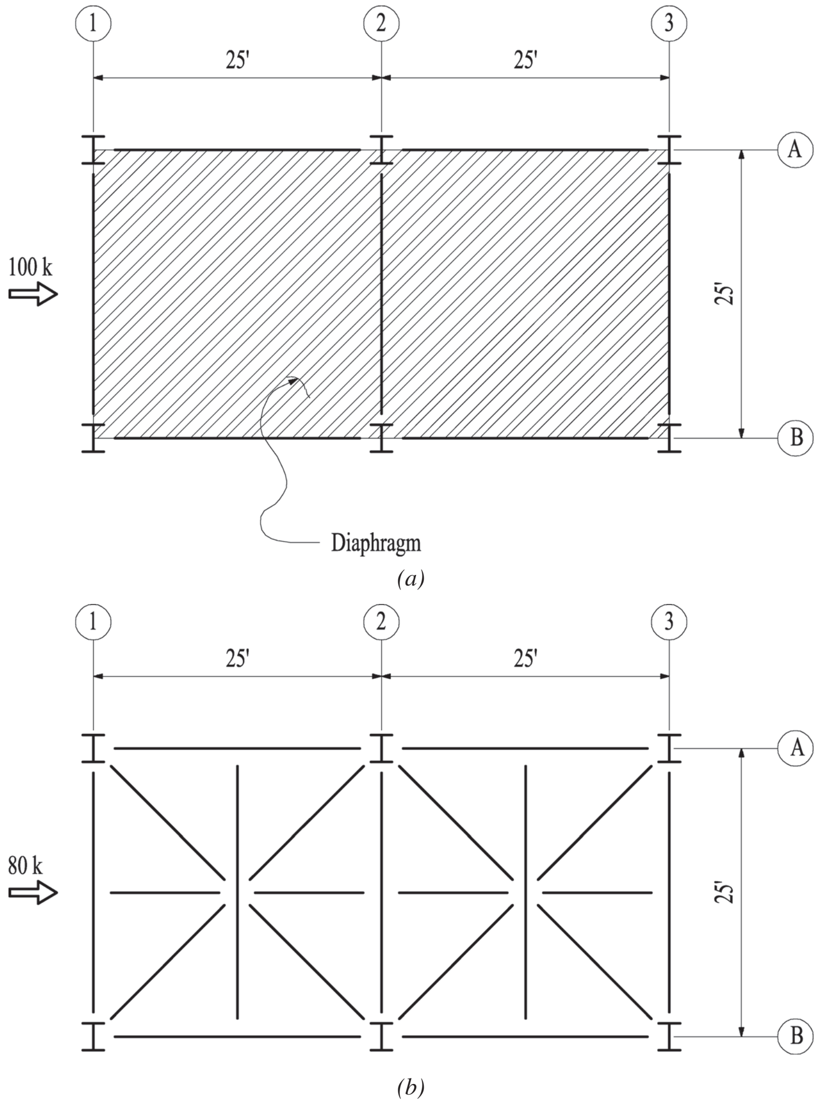


Fig. 12. Plan views of example structure. (a) Level 3. (b) Level 2.

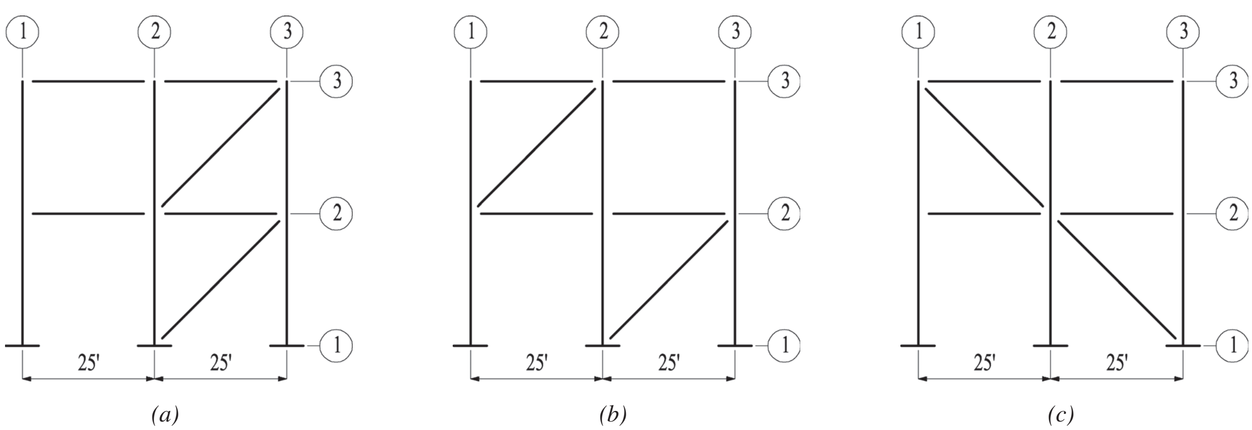


Fig. 13. Elevation along lines A and B. (a) Bracing arrangement 1. (b) Bracing arrangement 2. (c) Bracing arrangement 3.

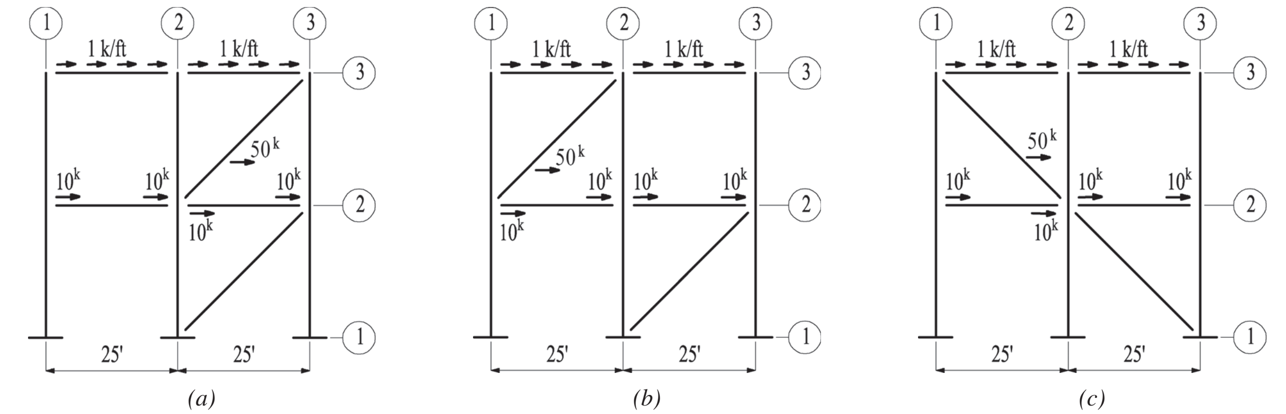


Fig. 14. Forces entering beams from diaphragm and horizontal bracing. (a) Bracing arrangement 1. (b) Bracing arrangement 2. (c) Bracing arrangement 3.

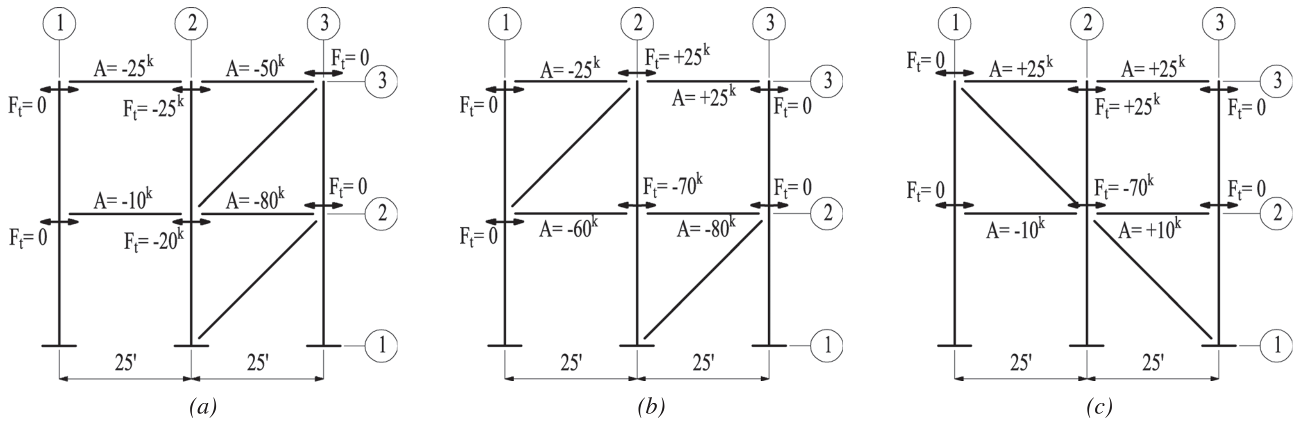


Fig. 15. Transfer forces and axial loads in beams. (a) Bracing arrangement 1. (b) Bracing arrangement 2. (c) Bracing arrangement 3.

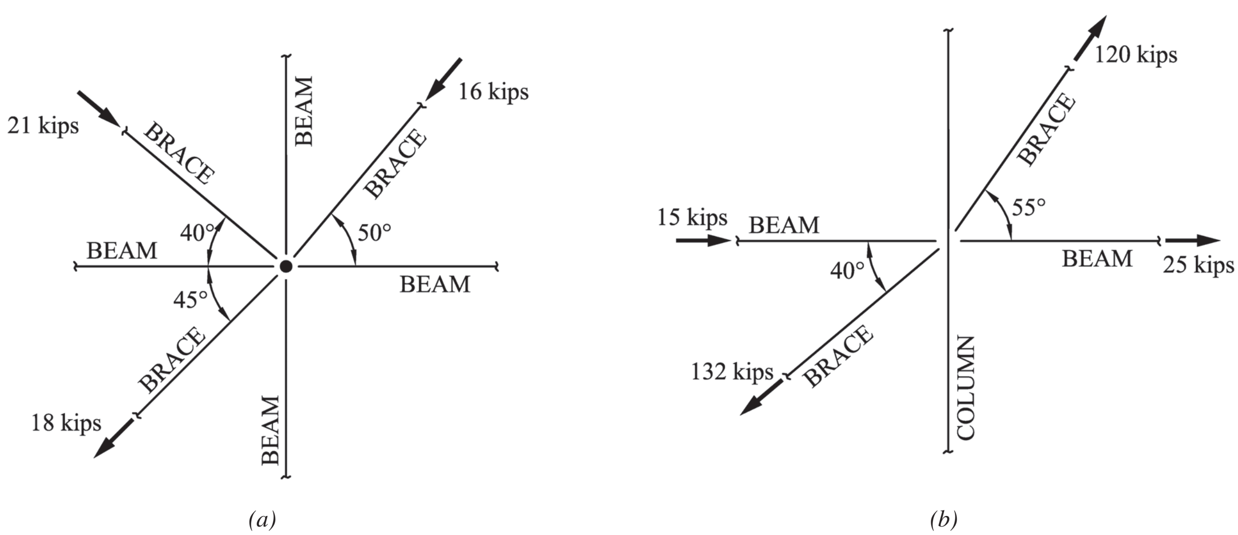


Fig. 16. Partial structure for Example 2. (a) Plan. (b) Elevation.

The net horizontal load on the right-hand side of the column is

$$F_R = 25 \text{ kips} + (120 \text{ kips})\cos(55°) - (16 \text{ kips})\cos(50°)$$
$$= 83.5 \text{ kips}$$

The net horizontal load on the left-hand side of the column is

$$F_L = -15 \text{ kips} + (132 \text{ kips})\cos(40°) + (18 \text{ kips})\cos(45°)$$
$$- (21 \text{ kips})\cos(40°)$$
$$= 82.7 \text{ kips}$$

Note that F_R and F_L will be equal and opposite if the column is pinned at the node; however, if the column is modeled as a continuous member, some of the load will transfer into the column causing flexural stresses. For design purposes, the transfer force can be the largest of F_R and F_L; therefore, the transfer force is 83.5 kips.

CONCLUSIONS

For connections to be designed properly, transfer forces must be communicated to the connection designer. General guidance was provided on nonstandard beam-to-column connections that can accommodate large transfer forces, and the importance of providing vertical transfer forces in special situations was discussed. Two examples were provided—one showing the basic calculation procedure and one showing the procedure for calculating transfer forces from computer output. These examples were very simple, but for most real structures, the determination of transfer forces can be a time-consuming, but essential step in the design of safe and economical structures.

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