Under Foot

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Horizontal floor diaphragm load effects on composite beam design.

ONE OF THE MOST NEGLECTED ELEMENTS in the design of buildings is the horizontal floor diaphragm and its interaction with the lateral load resisting systems. Most multi-story structures depend on the floor slab and roof systems to act as horizontal diaphragms to collect and distribute the lateral loads to the vertical framing members, which provide the overall structural stability.

In steel structures, floor diaphragms are most commonly constructed using composite steel deck with concrete fill, although other systems, such as pre-cast planks, formed reinforced concrete, or concrete on non-composite steel deck, may also be used. While there are numerous references that discuss the design of the diaphragm itself, there is little guidance available on the transfer of diaphragm forces into the lateral load resisting system. In addition, the specific issues related to beam design for members collecting lateral loads in composite floor systems has gone largely undocumented. The intent of this article is to help "fill in the gaps" on these issues through a discussion of the effect of diaphragm forces on the supporting steel beam behavior, as well as through practical detailing guidelines.

General Diaphragm Behavior

Before delving into the specific issues associated with the transfer of diaphragm forces to the supporting framing, it is necessary to understand general diaphragm behavior and how assumptions made affect the detailing required in establishing a robust load path. Figure 1 depicts a floor plan for a typical steel building. Braced frames are provided adjacent to stairwells near each end of the building to resist the lateral loads, and the diaphragm strength is assumed to be adequate to transfer the shear around the openings. In a simple analysis, the floor diaphragm is idealized as a continuous cantilevered beam and the braced frames are treated as beam supports. Due to the symmetry of this example and assuming the braced frames have the same geometry and stiffness, the diaphragm force at each braced frame will be equal to 50% of the total applied lateral load.

Depending on the magnitude of lateral load to be transferred to the braced frames, the designer can detail the force transfer to occur uniformly along the entire frame line between grids *A* and *D* on the grid lines where the braces occur, or they may elect to concentrate the load transfer to a segment of this length, such as the beam in the braced frame between grids *B* and *C*.

In the first scenario, the load distribution is proportional to the overall available transfer length, and beams *A-B* and *C-D* each collect 35% of the total force while beam *B-C* collects 30% of the total force. Beams *A-B*, *B-C* and *C-D* are all crucial members for getting load to the lateral load resisting system, and the connections of these beams to the columns at grids *B* and *C* must be designed for a horizontal force equal to the axial load being transferred through the column joint to the braced frame plus a vertical shear force resulting from the eccentricity of the diaphragm relative to the beam centerline. These member forces will occur simultaneously with the vertical beam shear reactions due to the gravity loads. Design and detailing of these joints for the combined forces is often overlooked.

In the second scenario, beam *B-C* collects 100% of the force. The distribution of axial, shear, and flexural member forces due to the applied lateral load for this beam will depend on the specific braced frame configuration. Once defined, these forces can be transferred into the braces with standard braced frame connections. Figure 2 illustrates the shear flow associated with this scenario.

Tension and compression chord forces are developed at the perimeter of the floor diaphragm due to the lateral loads. Typically, the floor slab concrete can resist the compression chord forces. Tension chord forces can be resisted by the spandrel steel beams, continuous steel closure plates, or by reinforcing steel within the concrete slab. In order to use the spandrel steel beams as the tension chord, the diaphragm chord forces must be transferred into the steel beams, and the steel beam connections at the columns must have sufficient strength to transfer the beam forces through the column joints. Again, this is a condition that often is overlooked, where the beam connections must be designed for the combined effects of vertical shear loads and horizontal axial loads.

Once the basic distribution of horizontal forces is understood, the effect of these forces on the design of the composite beams can be examined.

Figure 1. Typical building floor plan

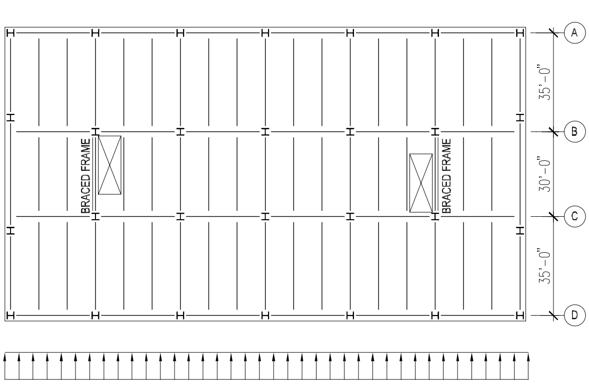
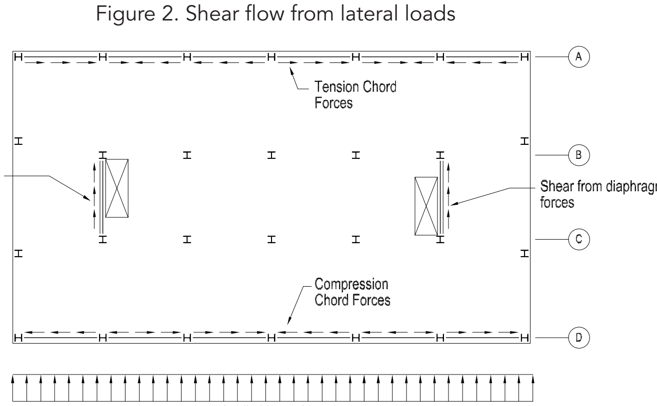


Figure 2. Shear flow from lateral loads



Additional Shear Connection?

The mechanical connection of the floor system to the supporting steel beams in a composite beam system is achieved using headed steel studs or hot-rolled channel shear connectors. Often, the beams are designed as composite members for the gravity loads applied to the floor system. Traditionally, if the beam also serves as a collector element, additional shear studs are added to account for transfer of the superimposed horizontal load into the beam. However, this practice is not always necessary for two primary reasons.

First, the quantity of shear studs selected for a composite beam is usually determined based on a gravity load combination, such as 1.2*D*+1.6*L* (LRFD) or 1.0*D*+1.0*L* (ASD). When lateral loads are applied in conjunction with the gravity loads, the load combinations of ASCE 7 reduce the live load levels. Under these reduced live loads, the shear studs provided to develop the composite action required for the gravity loads will be under-used and thus have additional capacity available for the transfer of the diaphragm forces.

Second, the interaction of the shear flow from the different loading conditions is additive for some studs but opposite for others. The distribution of horizontal shear from beam flexure is assumed to flow in two directions from the point of maximum moment to the point of zero moment. For a typical simple-span composite beam with uniform gravity loads, this shear flow is as indicated in Figure 3. While the beam shear is greatest at the ends of the beams, it is common practice to assume that the shear studs will deform and redistribute the shear uniformly to all studs.

Conversely, lateral loads induce shear in only one direction. When these beams are used to collect the diaphragm forces, the shears due to the lateral loads are superimposed on the horizontal shears due to the gravity loads, as indicated in Figure 4. On one side of the beam, the lateral loads increase the horizontal shears over the gravity-induced values, while on the other side of the beam, the lateral loads oppose the gravity-induced horizontal shears.

Assuming the shear studs have sufficient ductility to distribute the horizontal shears evenly along the beam, a composite beam can transfer a horizontal shear due to lateral loads between the floor diaphragm and steel beam that is equal to the summation of the strengths of all the shear studs on the beam regardless of demand on the shear studs from the gravity loads.

"Non-Composite" Composite Beams

Designers encounter many conditions where steel beams are designed as non-composite members under gravity loads. Shear studs placed on these beams for transfer of lateral forces still will be subjected to horizontal shears due to flexure from gravity loads. This is unavoidable. Therefore, in order to ensure the anchors are not overloaded under the gravity loads, it is recommended that all beams that transfer diaphragm forces to the lateral load resisting systems have enough anchors to achieve a minimum 25% partial composite action. When less anchors than this are provided, large deformations of the studs may occur under the gravity load case, inhibiting the ability of the beam to function as intended under lateral loading.

To Phi or not to Phi?

The nominal strength of the individual shear studs, Q_n, can be determined from the equations in the AISC *Specification*. The current shear connector strength equations generally are used as nominal strength equations in composite beam design where the anchors are part of a composite system; the φ and Ω come in later in the calculation of the beam flexural strength. However, when the shear stud strength is checked as a connection between the diaphragm and beam, a resistance (or safety) factor should be applied to the shear stud nominal strength. Based on preliminary results of ongoing research at the University of Illinois at Urbana-Champaign, φ = 0.65 (LRFD) or Ω = 2.30 (ASD) are recommended. These values are in line with similar recommendations by PCI and ACI.

Secondary Shears and Moments

Once the designer deals with the transfer of force from the floor diaphragm into the supporting steel beam, the effect of the diaphragm forces on the design of the beam and its connections to the remainder of the lateral load resisting system must be considered. Of particular concern is the effect of the vertical offset (eccentricity) between the plane of the diaphragm and the centerline of the supporting beam as indicated in Figure 5. Intuitively, one would anticipate additional moments imposed on the beam as a result of the eccentricity. However, this is not the case.

As an example, consider a simple-span beam with uniform horizontal shears from the lateral loads and resulting reactions as shown in Figure 5. For this scenario, assume the member is connected to the lateral load resisting system at the left end of the beam only.

The free body diagram in Figure 6 shows the internal member forces that result from this applied uniform load. The axial load in the beam will increase linearly toward the end of the beam designed to transfer the collected force to the lateral load resisting system, but the internal moment due to this applied lateral load, even considering the *d*/2 eccentricity, will be zero. The member should be designed as a beam-column, considering the combined effects of the axial forces due to the lateral loads and the flexural forces due only to the gravity loads. The shear is a constant value and must be considered in the connection design at both ends of the member.

Force Interaction

The rigorous design of composite beams for combined axial force and flexure is complex. As a reasonable simplification for design purposes, it is acceptable to use the non-composite axial strength and the composite flexural strength in combination using the interaction equations in the AISC *Specification*, Chapter H. Note that for compressive loading, this type of composite beam-column is generally considered unbraced for buckling between braced points about the major axis, and fully braced by the composite diaphragm for buckling about the minor axis.

As with all structural systems, there is an element of engineering judgment involved in the proper design and detailing of horizontal diaphragms and composite beam interaction. Careful consideration should be made to provide a continuous load path. The designer must account for the required axial forces and shears to be transferred at the end connections of all beams. Though there are many aspects to consider for the design of composite beams subject to horizontal diaphragm forces as reviewed in this article, their implementation is straightforward, thus allowing the composite beams to be used as an economical and efficient component of the lateral force resisting system. MSC

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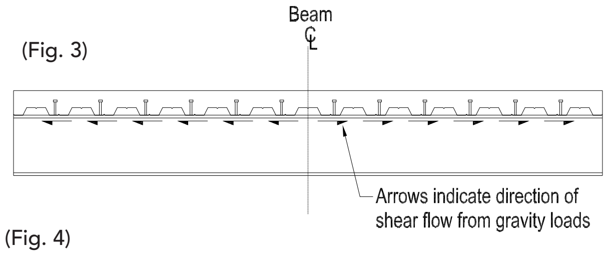
(Fig. 3)



(Fig. 4)

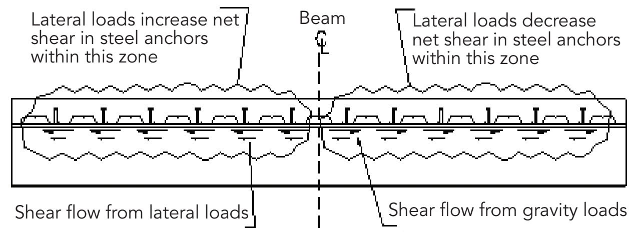
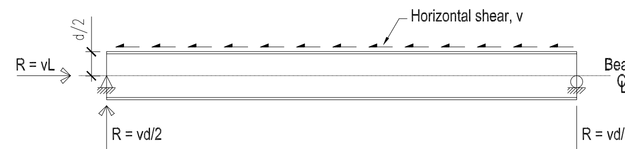
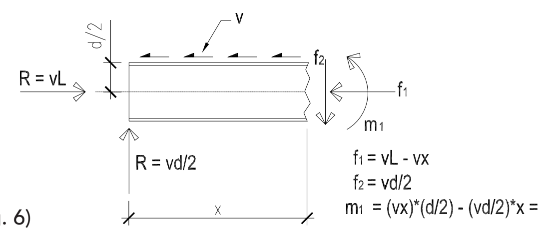


Fig. 3. Shear flow due to gravity loads only
Fig. 4. Shear flow due to gravity and lateral loads in combination



(Fig. 5)



(Fig. 6)

Fig. 5. Analytical model of simple span beam
Fig. 6. Free body diagram of beam segment