RIGID CONNECTIONS
BETWEEN WOOD POSTS AND CONCRETE

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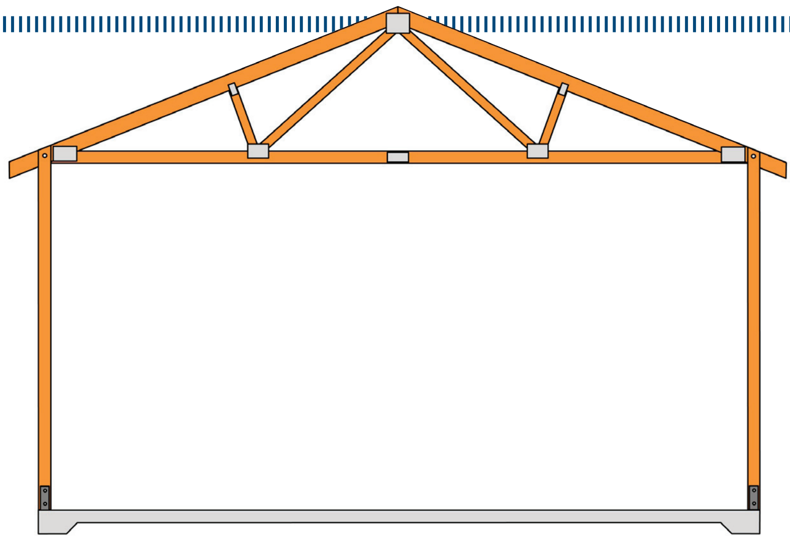
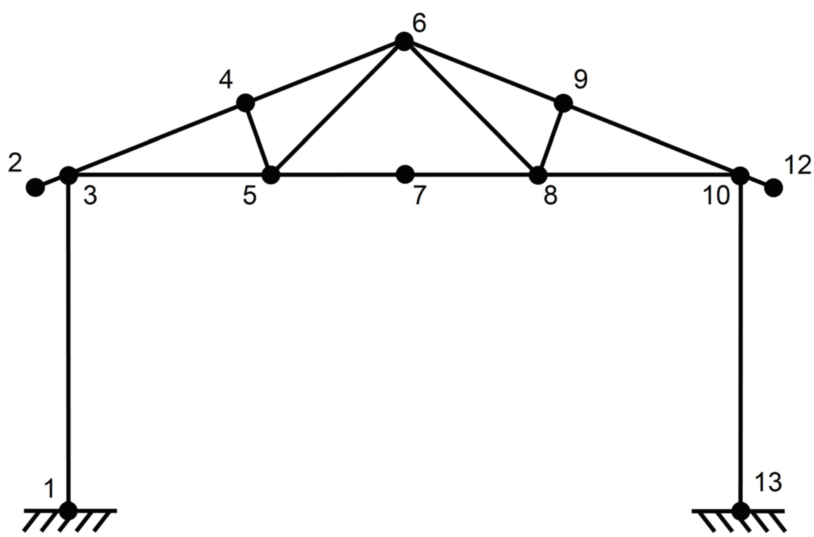


FIGURE 1. Primary frame of a post-frame building (*top*) and corresponding structural analog (*bottom*).



MODELING CONNECTIONS

The primary goal of a structural engineer is to ensure that all building components can withstand the forces to which they are subjected. The process starts with the establishment of an overall building geometry and the selection of a general framing method. With knowledge of the overall building geometry, the engineer can calculate the structural loads (e.g., wind, snow, seismic) to which the building will be subjected. Next, the engineer performs a structural analysis to determine the forces that are induced in building components by the calculated structural loads. In the final stage of the design process, the engineer checks to make sure that building components can withstand the imposed forces.

During a structural analysis, the engineer creates a model of the building's framework. A portion of the information associated with this model is frequently conveyed with a simple modeling diagram. **Figure 1** contains a diagram for the primary frame of a post-frame building. Note that lines on this modeling diagram (a structural analog) represent the centroidal axis (the center of mass) of the framing members. Nodes (solid circles on the modeling diagram) are placed at framing member ends, framing member connection points, sudden changes in framing member properties, support location and locations where concentrated loads will be applied to the model. Nodes divide the structure into elements, and each element is identified by the nodes at its ends. For example, the bottom chord in Figure 1 is composed of elements 3-5, 5-7, 7-8 and 8-10.

A mechanical connection is any connection between framing members that is made with bolts, screws, nails, truss plates, and so on. Mechanical connections can have a significant impact on the behavior of a structure and must be properly represented in the structural model.

A connection that joins framing members in such a way that they behave as if they are welded together is called a *rigid connection*. When two framing members have a rigid connection, they will translate (i.e., move vertically and horizontally) and rotate the exact same amount at their connection point.

Connections that are incapable of transferring bending forces, or bending moment, from one framing member to another are called *pin connections*. A pin connection is best thought of as a hinge. When two framing members are pin connected, they will translate the exact same amount but typically rotate a different amount at their connection point. With respect to the modeling diagram, a

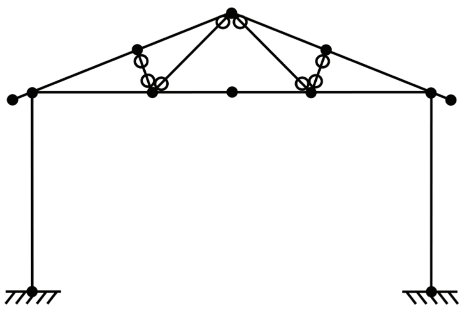


FIGURE 2. Circles on the ends of the web members indicate that the end is pin connected to the chords.

circle is placed on the end of the element if that element end represents the end of a framing member that is pin connected to other framing members that meet at that node. **Figure 2** shows a modeling diagram in which all truss web members have been pin connected to the top and bottom chords.

Rigid and pin connections represent the two extremes of connection behavior. Between these two connection types are semi-rigid connections. Although all mechanical connections behave as semi-rigid connections, engineers typically do not model them as such because of the greater complexity of the model. In other words, connections between framing members are generally modeled as either pinned or rigid.

PRIMARY FRAME MODELING AND BEHAVIOR

When components of wind forces blow against the side wall of a post-frame building, the primary frames are racked. The actual amount of sidesway that each primary frame experiences is largely dependent on (1) how the top of each post is connected to the truss (or rafter), (2) how the bottom of each post is restrained and (3) the level of diaphragm action. The level of diaphragm action is the degree to which a roof or ceiling diaphragm helps resist frame sidesway.

Figure 3 shows four deformations of the same primary frame under a wind load. In this case, the frame is assumed to be attached to a concrete base (i.e., a concrete pier, slab or wall). The differences between Figures 3a through 3d are in how the post-to-truss and post-to-concrete connections were modeled. The least frame sidesway is obtained by rigidly connecting the posts to the truss

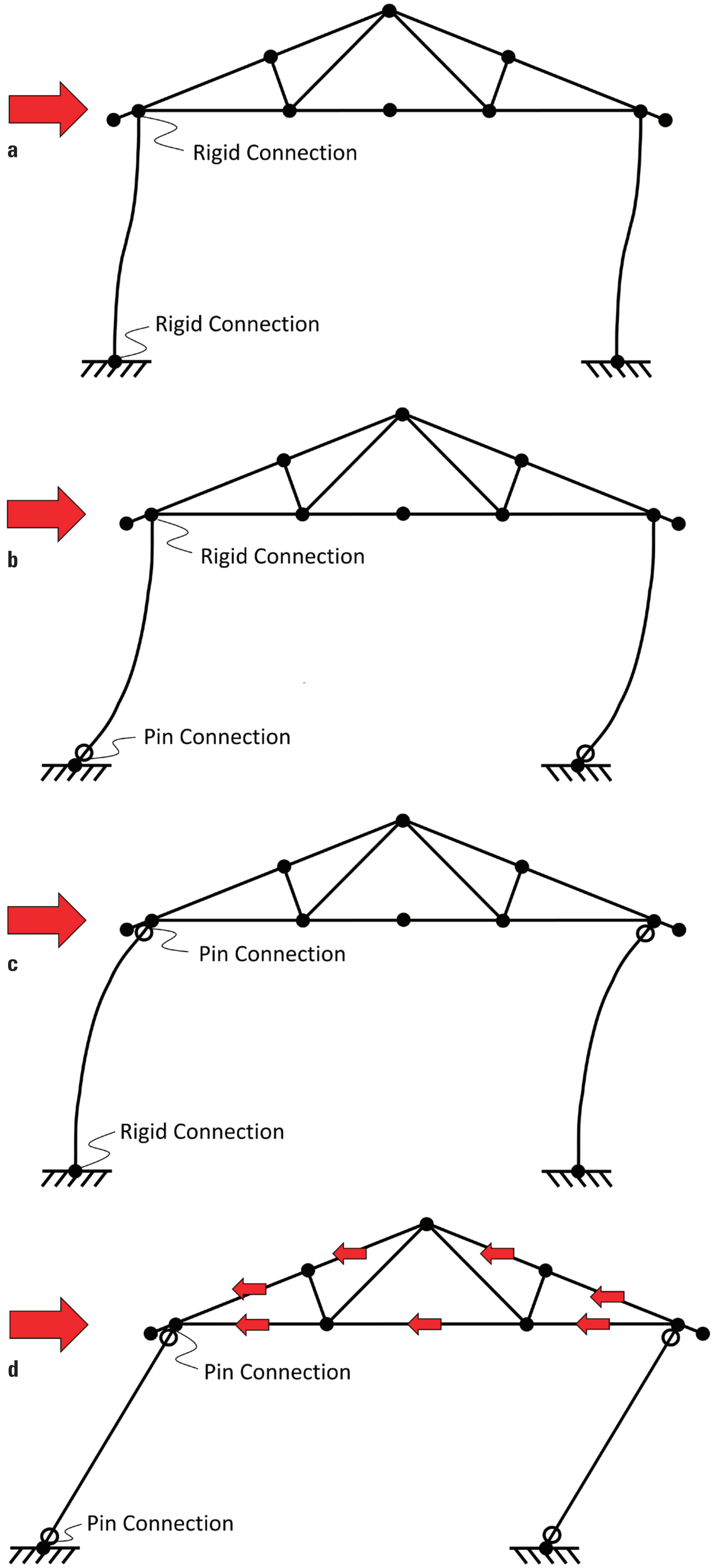


FIGURE 3. Influence of post end fixity on the racking resistance of a primary frame. A rigid-rigid combination (a) is four times stiffer than a rigid-pin connection (b) or a pin-rigid connection (c). The pin-pin combination (d) results in an unstable situation unless diaphragms resist sidesway.

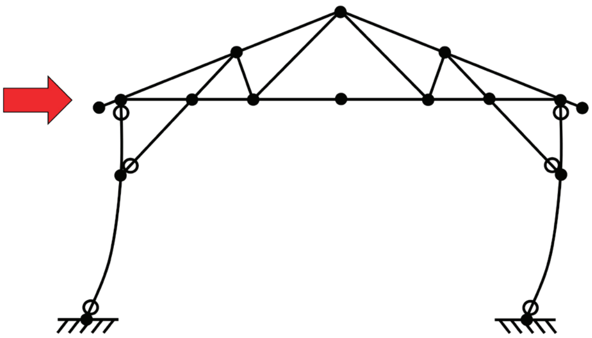


FIGURE 4. Use of knee braces to resist sidesway when posts are pin connected to truss and concrete base

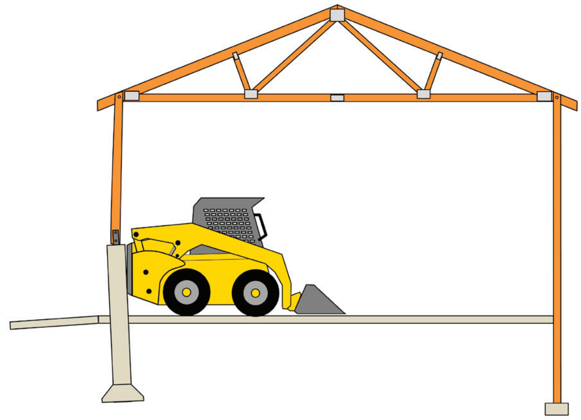


FIGURE 5. Connections must be designed to resist forces from equipment impact.

and to the concrete (Figure 3a). Pin connecting both ends of each post results in an unstable structure (Figure 3d)—a structure that must rely on support of a roof or ceiling diaphragm.

Which of the scenarios in Figure 3 is most accurate depends on how post-to-truss and post-to-concrete connections are actually made. For virtually all post-frame buildings constructed on concrete today, Figure 3d (the unstable frame) is most accurate. In other words, connections at the top and base of posts in a typical post-frame building constructed on concrete exhibit behavior resembling that of pin connections. The reason these buildings do not collapse under wind loads is that they rely on diaphragm action; that is, they rely on roof or ceiling diaphragms to transfer lateral loads to shear walls, which in turn transfer the loads into the foundation.

Prior to the mid-1980s, post-frame engineers did not rely on diaphragm action to reduce racking when placing posts on concrete. Instead they added knee braces to effectively reduce rotation between the top of the post and the truss, as shown in **Figure 4**. Knee braces have never been an adored feature of post-frame buildings because they limit full utilization of the interior, and they make it more difficult and hence more costly to clad the interior when such a finish is desired.

NEED FOR RIGID POST-TO-CONCRETE CONNECTIONS

It is clear from Figure 3d that if diaphragm action cannot be relied upon to resist frame racking, the rigidity of the post-to-truss or post-to-concrete connections must be increased, or an alternative method (e.g., knee braces, cross-bracing, exterior cabling) must be used

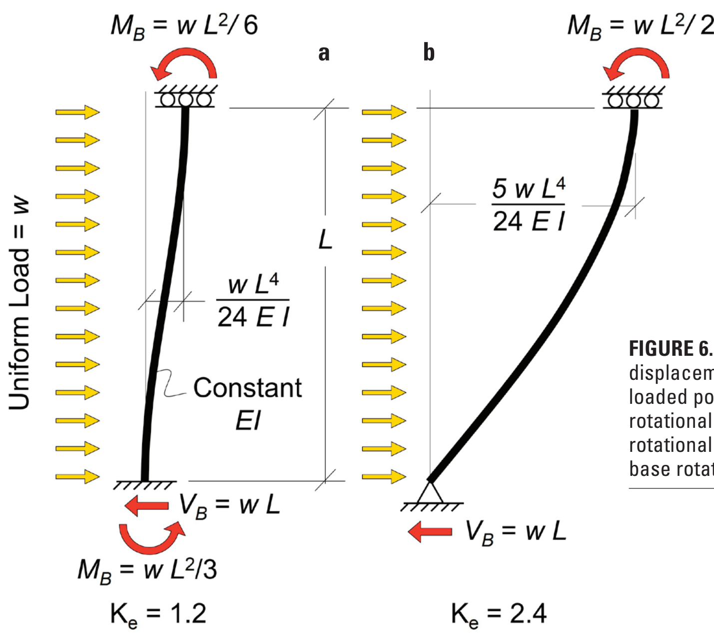


FIGURE 6. Forces and displacement for uniformly loaded posts with top rotational fixity and (a) base rotational fixity, and (b) no base rotational fixity *(right)*

to brace the frame. Of these options, increasing the rigidity of the post-to-concrete connection would appear to be the least expensive or least intrusive for many situations.

In places where a post is attached to the top of a concrete pier or wall that extends more than 2 feet above grade, it is recommended that a rigid connection be made between the post and concrete. A rigid connection at this location helps resist forces that work to overturn the wall or pier. Such forces can result from changes in below-grade soil conditions, material stored against the concrete above grade or direct impact by equipment (**Figure 5**).

When added into buildings that rely on roof or ceiling diaphragms, rigid post-to-concrete connections will attract load away from the diaphragms. The extra load that a rigidly connected post attracts increases as post flexural stiffness ($E\ I$) increases, as post height decreases and as horizontal movement at the top of the post (as dictated by diaphragm stiffness) increases. In buildings with lower eave heights and flexible diaphragms, the extra load a post attracts can be significant and may require an increase in post strength (i.e., an increase in post size or the grade of lumber used to construct the post). Because of the extra cost of stronger posts and the more rigid connections, the only reasons for using rigid concrete-to-post connections in buildings with lower eave heights and more flexible diaphragms would be a need to reduce load transferred to the diaphragm and a desire to increase the overall structural integrity of the building.

In buildings with high sidewalls and relatively rigid diaphragms, the extra load that a post attracts will generally not require an increase in post strength; and in some cases it may even enable a

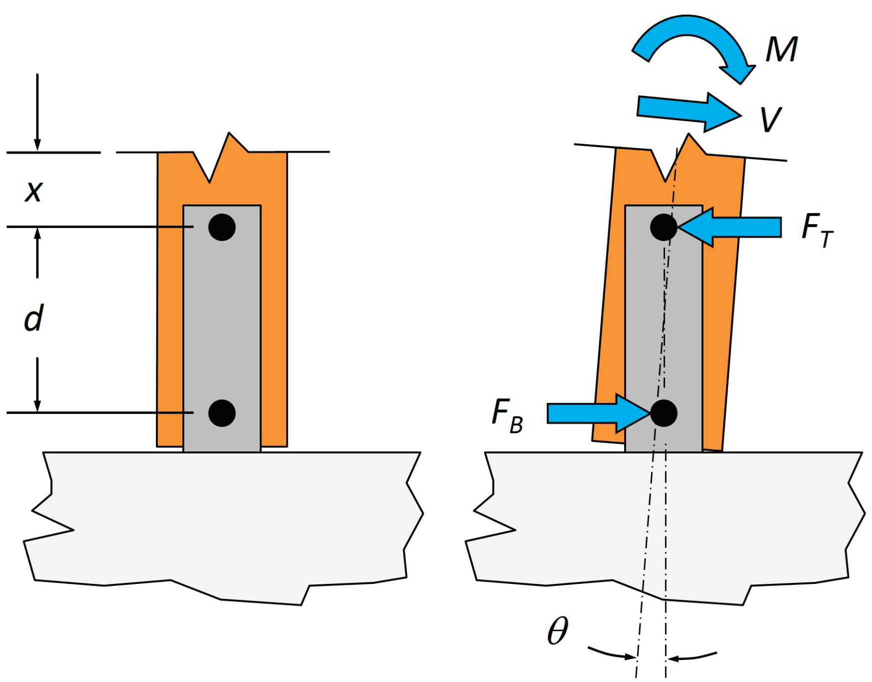


FIGURE 7. Forces applied to the wood post-to-concrete connection

reduction in post strength. The latter case is the direct result of the fact that a post modeled as a propped cantilever has a lower effective buckling length than a post pinned at both ends.

In buildings in which there is no diaphragm action but the top of posts are prevented from measurable rotation, the advantages of switching from a pin to a rigid post-to-concrete connection are significant, as a comparison between Figures 3a and 3b indicates. The free body diagrams in **Figure 6** illustrate this impact for posts subjected to a uniform load. In this case, maximum bending moment is reduced by 33 percent and horizontal displacement by 80 percent when the switch is made from a pin to a rigid post-to-concrete connection. It is also important to note that the buckling length factor, K_e, used to determine the column stability factor, C_P, is cut in half (dropping from 2.4 to 1.2) with the switch from a pin to a rigid post-to-concrete connection. When viewing the diagrams in Figure 6, it is important to keep in mind that they do not include effects of loads applied to the posts by trusses or rafters.

UNDERSTANDING CONNECTION BEHAVIOR

For a mechanical connection to have some rotational stiffness, a minimum of two fasteners (e.g., nails, bolts, screws, teeth) must be used in the connection. For the steel plate-to-wood post connection shown in **Figure 7**, the force in each of these fasteners is given as

$$F_T = (Vx + Vd + M)/d \qquad (1)$$

and

$$F_B = (Vx + M)/d \qquad (2)$$

where F_T and F_B are the forces in the top and bottom fasteners, respectively; V is the shear and M is the bending moment in the post at a distance x above the top fastener; and d is the spacing between the two fasteners.

Equations 1 and 2 are also applicable to two separate groups of fasteners with F_T and F_B the forces resisted by the top and bottom fastener groups, respectively, and d the effective distance between the two forces.

A comparison of equations 1 and 2 reveals that the force in the top fastener exceeds that in the lower fastener by an amount equal to V. It is also clear from equation 2 that the force in the bottom fastener (or fastener group) doubles every time spacing d is halved. Because the shear force in the post at locations between the two fastener groups is equal to the force in the bottom fastener group, it also doubles every time d is halved.

The ratio between the force, F, that a fastener (or fastener group) transfers and the slip, Δ, that occurs between the components at the location of the fastener is defined as the load-slip stiffness, k, of the fastener. In equation form:

$$k_T = F_T/\Delta_T \qquad (3)$$

and

$$k_B = F_B/\Delta_B \qquad (4)$$

If it is assumed that the only deformation in the connection is due to fastener load-slip, then the rotation, θ, between the steel plate and wood post is given as

$$\theta = [Vd + Vx + M]/(k_T\, d^2) + [Vx + M]/(k_B\, d^2) \qquad (5)$$

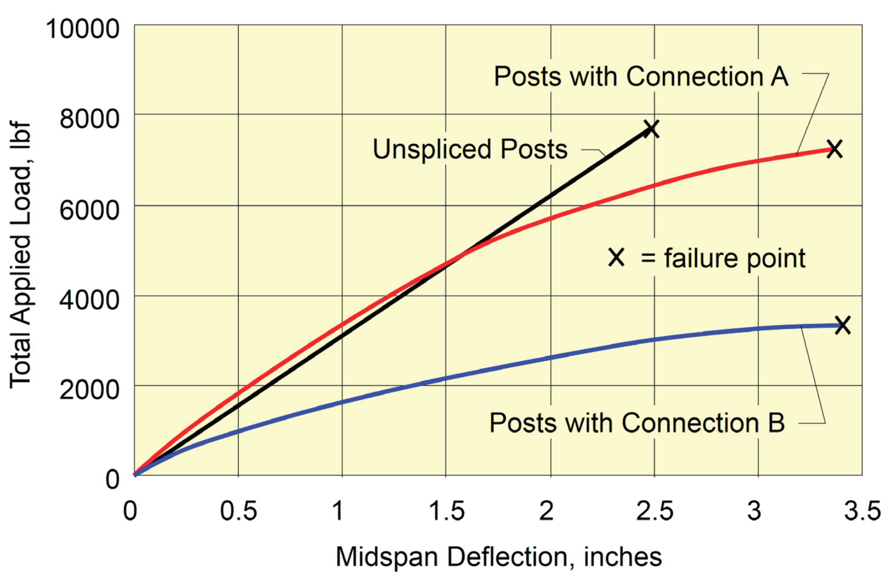


FIGURE 8. Results of bending tests showing the impact of cutting posts and splicing them back together with two different mechanical connections

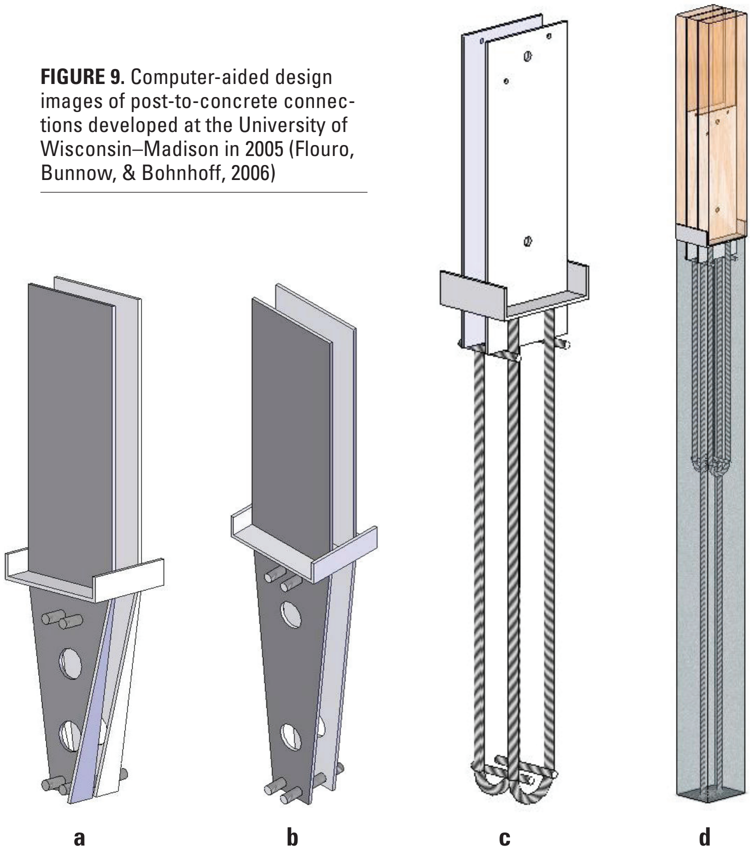


FIGURE 9. Computer-aided design images of post-to-concrete connections developed at the University of Wisconsin–Madison in 2005 (Flouro, Bunnow, & Bohnhoff, 2006)

If the load-slip behavior of each fastener is the same ($k_B = k_T = k$), then equation 5 reduces to:

$$\theta = [Vd + 2Vx + 2M]/(k\,d^2) \qquad (6)$$

The moment in the post at a location just above the top fastener (M at $x = 0$ in Figure 7) when divided by rotation θ is defined as the rotational stiffness or rigidity of the connection.

In accordance with equations 5 and 6, the rotation between the plate and the steel post in Figure 6 approximately quadruples every time spacing d is cut in half. This is very important to realize when the primary objective is to form a rigid connection.

As previously noted, equations 5 and 6 account only for rotation due to fastener load-slip. The equations do not account for bending of the wood post or steel plate in the vicinity of the connection. To this end, the actual rotational stiffness would be less than calculated using θ from equation 5 or 6.

Without knowledge of fastener load-slip behavior, one cannot use equations 5 and 6 to determine connection rigidity. In this case, practitioners typically rely on actual laboratory testing to determine whether to model a connection as a rigid or pin connection. To test the rigidity of a connection, load a framing member as a beam and measure its midspan deflection (i.e., the deflection of the framing member halfway between supports). Then cut the framing member in half, connect the two halves together with the connection in question, reload the framing member with the connection at midspan, measure the midspan deflection and compare the deflection with that of the uncut framing member (Bohnhoff, 2016).

Figure 8 shows results of bending tests conducted on unspliced posts and on posts that were cut and joined back together (i.e., spliced) with two different mechanical connections. The unspliced posts and the posts featuring connection A had a similar bending stiffness at low loads, but not at higher loads. Posts with connection B were not nearly as stiff as the unspliced posts. In this case, it may not be prudent to model connection B as a rigid connection.

The nonlinear (non-straight-line) load-displacement behavior of the spliced posts in Figure 8 is common of assemblies featuring mechanical connections and is the direct result of nonlinear fastener load-slip behavior. This in turn is due to extreme deformation (crushing) at higher loads of wood immediately surrounding fasteners, and in some cases, withdrawal of fasteners at higher loads.

It's important to realize that the bending strength of a connection is different from its bending stiffness. The plot in Figure 8 shows that both connections A and B had adverse effects on overall bending strength because the average load sustained by the spliced posts did not match that of the unspliced posts. This is not uncommon and is something to keep in mind when assessing connections.

2005 RIGID CONNECTION DEVELOPMENT

Over the past 12 years, four research projects focusing on the development of a rigid connection between wood posts and concrete have been conducted at the University of Wisconsin–Madison. Two of these projects will not be overviewed here: the development of pipe piers (Bohnhoff, Bohnhoff, & Holstein, 2011) and wood I-post-to-concrete connections (Holstein & Bohnhoff, 2015).

The first of the four UW–Madison projects was conducted in 2005 and focused on the design of a rigid connection with outer dimensions identical to those of the wood post. Some of the designs developed and investigated by the researchers are shown in **Figure 9**. The primary features of these designs are the straight steel plates that extend from the concrete up into the interfaces between post laminations. The concrete is separated from the wood post by a steel plate with upturned "lips." When a bending force is applied to the post, the lip effectively functions as the bottom fastener. This reduces tension perpendicular-to-grain stresses associated with the installation and loading of bolts and screws. The steel plate also serves as a moisture barrier between the concrete and wood post.

Design details, testing procedures, test results and recommendations relating to the 2005 UW–Madison work are contained in a report published by the researchers (Flouro, Bunnow, & Bohnhoff, 2006). The designs were publicly disclosed by Flouro during the AGCO student design competition held during the 2006 annual international meeting of the American Society of

Agricultural and Biological Engineers in Portland, Oregon. Since then, the primary features of the designs have been incorporated into products utilized in the post-frame building industry.

2016 RIGID CONNECTION DEVELOPMENT

A much more extensive study of rigid wood post-to-concrete connections was concluded during early July 2016 at UW–Madison and presented at the 2016 ASABE international meeting in Orlando, Florida (Bohnhoff, 2016). In contrast to the previous UW–Madison study, no restrictions were placed on the size of the connection. The project goal was to develop a relatively inexpensive connection for attaching a 3-ply post fabricated from nominal 2- by 6-inch lumber to concrete—a connection with (1) a bending strength no less than the wood posts being connected to the concrete, and (2) a bending stiffness that would enable it to be modeled as a rigid connection.

Several designs were fabricated and tested to failure in bending. Among these were the two designs shown in **Figures 10 and 11,** which are not recommended for use. The design in Figure 10 features 0.25-inch-thick flat plates with a coupling nut welded to each plate. Bolts threaded into these coupling nuts enable two U-shaped brackets to be tightened against the post. These brackets function much like the lips in the 2005 designs; that is, by replacing bottom fasteners the brackets reduce wood splits that occur because of the combination of high post shear forces and high tension perpendicular-to-grain forces induced by fasteners. Although this design had a bending stiffness that would enable it to be modeled as a rigid connection, it did not have a bending strength as high as the posts it was connecting because of buckling of the flat plates just above the concrete surface. One other observation: because of variations in the width of individual post laminations, the U-shaped brackets did not contact all three laminations.

The design in Figure 11 features 0.188-inch-thick plates bent into C-sections with 0.5-inch-diameter threaded rods welded to the sections.

FIGURE 10. Front, side and angle views of a 2014 UW–Madison wood post-to-concrete connection design

FIGURE 11. Front and side views of a 2016 UW–Madison wood post-to-concrete connection design

FIGURE 12. Recommended 2016 UW–Madison wood post-to-concrete connection design without wood post *(left)* and with wood post *(center)*. The tapered wood post end *(upper right)* and a view from the bottom showing space between shoe angles *(lower right)* are shown.

The threaded rods were used to tighten four U-brackets up against the post. The relatively short distance between the upper and lower brackets, combined with the width of the U-brackets, resulted in relatively high wood compressive stresses and hence deformation under the wood brackets, and this resulted in more rotation between the bracket and wood post than desired. Although this issue can be resolved by increasing the distance between the upper and lower brackets (i.e., increasing spacing *d*), the design is still not recommended because of its overall complexity and cost. In addition, designs with U brackets are applicable only in post-frame buildings that use outset girts.

The design recommended by the author is shown in **Figure 12**. This design features 0.188-inch-thick flat plates with U.S. No. 5 Grade 60 reinforcing bars extending out of the concrete and welded along the sides of the flat plates using a skip weld along one side of each rebar. These rebars significantly increase the section modulus of the assembly and thus eliminate plate buckling as a mode of failure.

Welded between the two flat plates is a tapered "shoe" that the post base is driven into. The tight fit that results reduces tension perpendicular-to-grain failures associated with stress concentrations around the mechanical fasteners that the shoe replaces. To facilitate this connection, the base of the post must also be tapered. Only dry posts should be installed into the shoe because tapering guarantees a tight fit only if the post does not shrink after installation.

Figure 13 contains dimensions for the connecting bracket shown in Figure 12. There are two sets of holes—larger ones for bolts and smaller ones for screws. When installing the bracket, you can use bolts or screws; you do not need both. Six screws were used in the assembly shown in Figure 12.

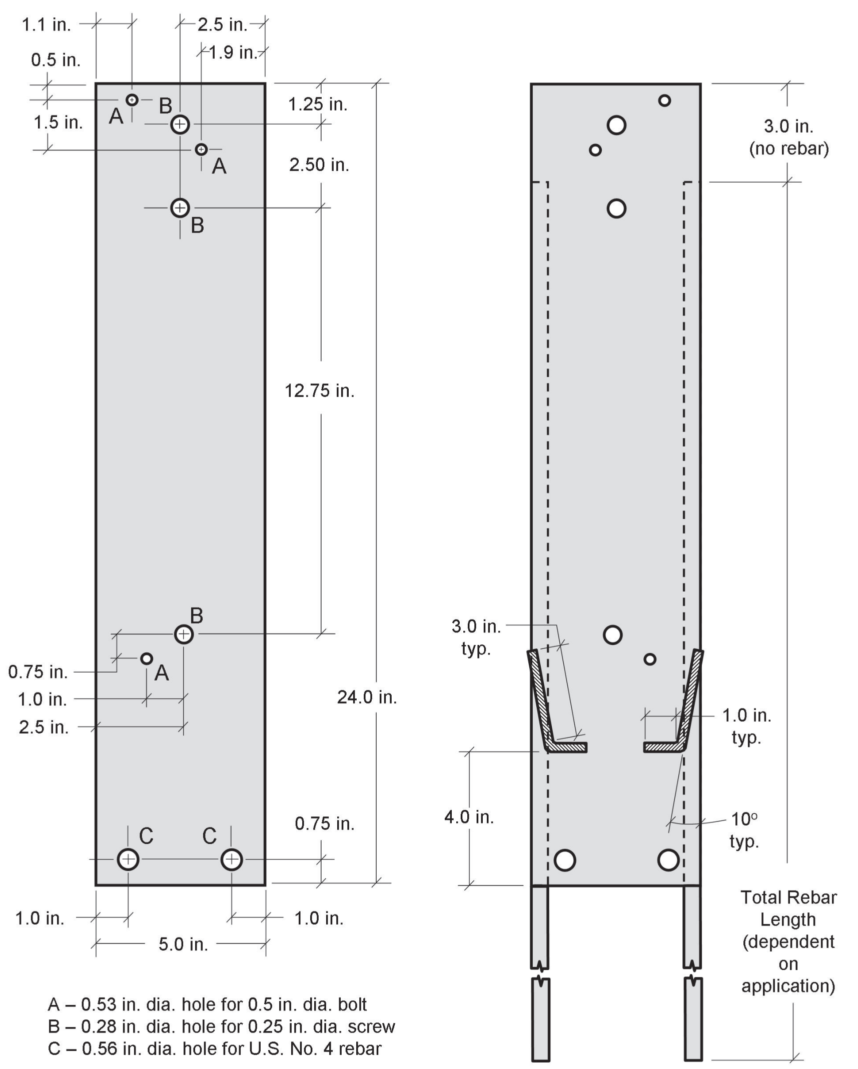


FIGURE 13. Hole locations *(left)* and assembly dimensions *(right)* are given for the wood post-to-concrete connector shown in Figure 12. Flat plates are 0.19 inches thick, and shoes (bent angles) are 0.25 inches thick. U.S. No. 5 Grade 60 reinforced bars are welded to flat plate with a skip weld (3-inch length and 6-inch pitch) on one side of each rebar.

The two holes in the bottom of each steel plate allow for the insertion of U.S. No. 4 rebars. These bars prevent the widening of any concrete crack that may extend from the edges of the embedded steel plates. The rebars are just slid into place after the connecting bracket is fixed into place on top of the concrete forms. The length of these rebars depends on the particular application. More specifically, when connecting brackets are cast into the top of a wall or slab, these two rebars would run from bracket to bracket. Short rebars would be used in a concrete pier.

As shown in Figure 13, the shoe was fabricated from two pieces of 0.25-inch-thick, 4.0- by 4.6-inch steel plate. An 80-degree bend was placed in each plate 1 inch from one end. When these two bent plates are welded into place, the space between them enables proper placement and consolidation of concrete. These bent plates also hold the spacing between the flat steel plates at 4.6 inches, and they prevent moisture in the concrete from getting wicked into the wood post.

Prior to installation of a post into a bracket, it is recommended the inside of the bracket be coated with polyurethane adhesive (e.g., Loctite PL Premium Polyurethane Construction Adhesive). This will fill in any gaps between the wood and the shoe and thus provide for a tighter joint and a more uniform distribution of pressure. The polyurethane will also prevent water from getting drawn into the connection, and hence into the wood.

ENGINEERING CALCULATIONS

Design details, testing procedures, test results and associated engineering calculations for the many connecting bracket designs tested in 2016 are in the published report (Bohnhoff, 2016). The report also includes results for screw-fastener load-slip tests, individual lumber bending tests and unspliced three-layer lumber assembly bending tests.

The 2016 research involved only the design of connections for attaching 3-ply posts fabricated from nominal 2- by 6-inch lumber. Connection designs for larger posts are best optimized by analyzing or sizing individual connection components and then validating the resulting overall design via laboratory testing. Actual testing is required because of the complex behavior of loaded connections.

For a design like that shown in Figures 12 and 13, the analysis and sizing of individual components include checks on the bending stiffness and strength of the rebar-reinforced side plates; fastener strength and interlayer slip (as determined via load-slip tests); shear forces in the base of the wood post; compressive forces in wood in contact with the shoe; strength of shoe in bending between the side plates; weld connection strength; axial stress in reinforcing bars; reinforcing bar development length; and overall rotational stiffness. Without doubt, as the face width of the post increases (e.g., when 2- by 8-inch lumber replaces 2- by 6-inch lumber), the spacing *d* between the shoe and upper fastener group must be increased in order to obtain the same relative level of rotational stiffness.

CONCLUSIONS

Rigid wood post-to-concrete connections are essential in some post-frame building designs, may reduce the required post strength in others, and may increase the overall structural integrity of the building.

Recent research on several connection designs at UW–Madison has led to the development of a simple steel bracket design for connecting concrete to a 3-ply post fabricated from nominal 2- by 6-inch dimension lumber. The connection is characterized by a rotational stiffness that enables it to be modeled as a rigid connection, and it has a bending strength on par with the wood post itself.

Like other post-frame building components developed at UW–Madison, the connectors herein described are not patented. FBN

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