PROGRESSIVE ROOF COLLAPSE DUE TO CLR SHIFTING

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Overview

Progressive roof collapse is a roof collapse in which the failure of a single structural component triggers a chain reaction of failures that result in a large portion of a roof collapsing onto the contents below. The shifting of continuous lateral restraint is well known as a leading cause of progressive roof collapse. Within post-frame buildings, CLR is commonly used to laterally brace top and bottom truss chords, compression web members, interior and exterior posts and post-to-truss connections. Failures due to CLR shifting are reduced by properly attaching and anchoring CLR, ensuring that the CLR itself does not buckle and using framing elements that do not require CLR.

Preventing Buckling with CLR

CLR is a continuous line of bracing used to provide lateral support to a series of structural elements. By preventing lateral movement, CLR reduces the effective length of a member it braces, thereby increasing the amount of load it would take to buckle the member. Use of a single row of CLR to brace a series of compressive web members is shown in **Figure 1**.

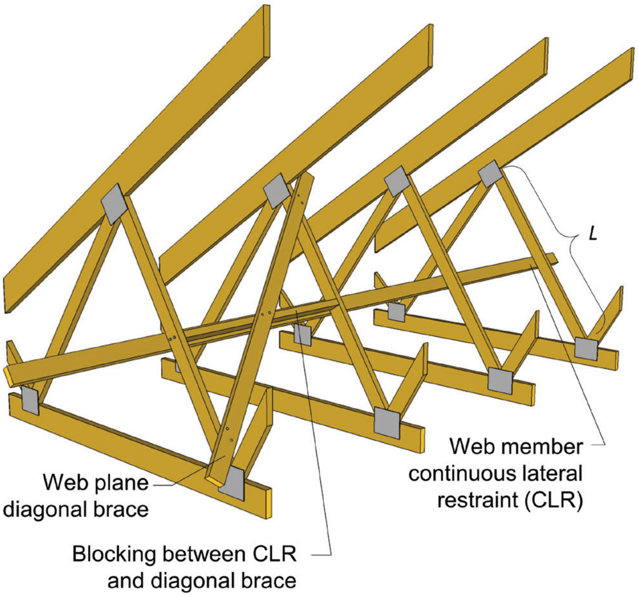

Figure 1. Web member CLR with a diagonal brace for prevention of shifting

For a pinned-end component, the relationship between the component's length and the load required to buckle the component is given by Euler's equation as

$P_c = n^2 \bullet E \bullet I \bullet \pi^2 / L^2 = 9.87 \bullet E \bullet I / L_e^2$

or for pinned-end rectangular components as

$P_c = 0.822 \bullet E \bullet A \bullet d^2 / L_e^2 = 0.822 \bullet E \bullet A / (L_e / d)^2$

where

P_c is critical buckling load for a pinned-end component,
n is the number of uniform-length, buckled segments within the component,
E is modulus of elasticity,
L is component length,
L_e is component effective length or L/n,
I is moment of inertia about the buckling axis,
A is cross-sectional area,
d is depth of the component in the direction of buckling, and
L_e/d is slenderness ratio.

Euler's equation sets an upper limit on the axial compressive load that can be applied to a long member that is not subjected to any other loads. In accordance with the equation, the amount of compressive load it takes to buckle a component

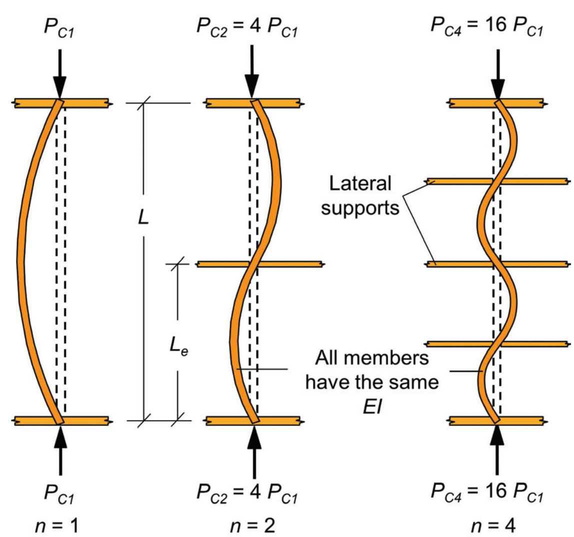

Figure 2. Cut the effective length in half, and the load required to cause buckling quadruples.

increases by a factor of four every time the component's effective length (i.e., *L/n*) is halved. This is graphically illustrated in **Figure 2**.

It is important to note that Euler's equation holds only as long as buckling is the controlling mode of failure. At some point, reducing the unsupported length of a component will no longer increase the amount of load the component can support because the component will fail in compression (i.e., a crushing failure occurs) before it buckles.

Figure 3 shows a typical relationship between the slenderness ratio (L_e/d) of a component subjected to compression (also known as a column) and the component's mode of failure. In this plot, a short column is one that fails via crushing of wood fibers across the component's entire cross-section. A long column is one that fails because of buckling and hence behaves in accordance with Euler's equation. Between long and short columns are intermediate ones whose exact failure mode is less certain.

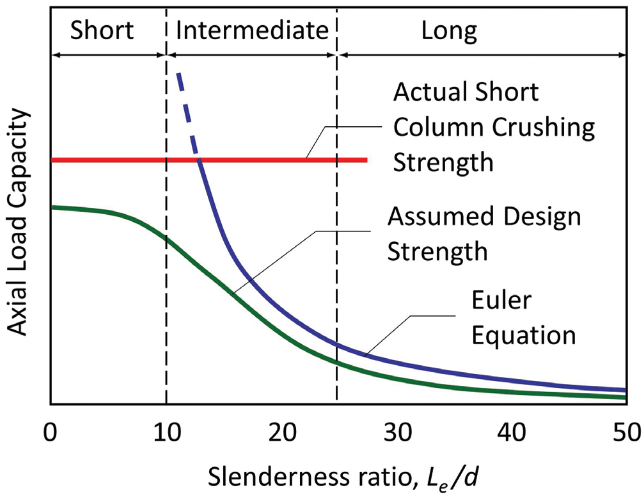

Figure 3. Typical categorization of columns based on mode of failure

Uses of CLR in Post-Frame Buildings

Although ANSI/ASABE S618 *Post-Frame Building System Nomenclature* (American Society of Agricultural and Biological Engineers, 2016) defines two types of CLR—web member CLR (Figure 1) and bottom chord CLR (**Figure 4**)—they are not the only or the most common uses of CLR in post-frame building. The most common CLRs in post-frame buildings are roof purlins and wall girts. Purlins are CLRs that prevent rafters and truss top chords from buckling (Figure 4), and girts perform the same function for many exterior posts.

Other uses of CLR in post-frame buildings include the lateral braces used to decrease the effective buckling length of interior posts and the lateral braces used to prevent rotation of post-to-truss connections. These two types of lateral braces are herein referred to as interior post CLRs and post-to-truss connection CLRs, respectively, and are shown in **Figure 5**.

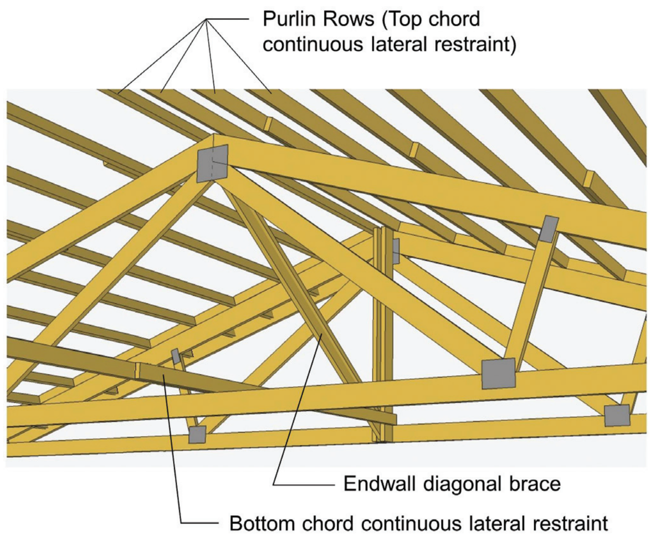

Figure 4. Bottom and top chord continuous lateral restraint

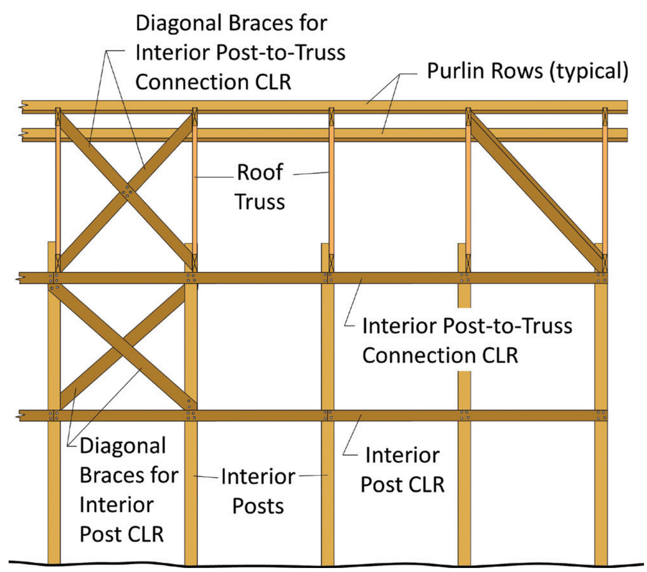

Figure 5. Interior post-to-truss connection CLR and interior post CLR with associated diagonal bracing

CLR Shifting and Shifting Prevention

CLRs are effective only if they do not allow movement of the component they are bracing. As soon as there is CLR movement parallel to the CLR (i.e., CLR shifting), the effective length of the components braced by the CLR will increase, thus reducing their critical buckling strength.

CLR shifting generally occurs because (1) the CLR is not properly anchored, (2) the CLR itself is allowed to buckle and/or (3) a CLR connection fails. Of these three, the most common cause is failure to properly anchor the CLR.

Proper CLR anchorage is generally accomplished by diagonal bracing of the CLR to a roof, wall or ceiling assembly in such a way as to make use of the in-plane stiffness of the roof, wall or ceiling assembly. In short, use a series of diagonal braces to connect the CLR to a roof, wall or ceiling assembly that is parallel to the CLR (Structural Building Components Association & Truss Plate Institute, 2015). Both the web member CLR in Figure 1 and the post-to-truss connection CLR in Figure 5 are kept from shifting with diagonal members that rely on the in-plane stiffness of the roof for anchorage.

It is important to note that connecting a CLR to a wall running perpendicular to the CLR seldom constitutes proper anchorage because the attachment doesn't benefit from the in-plane stiffness of the wall. In fact, wind pressure acting on an end wall can actually induce web member CLR shifting when the CLR is anchored only to one or both end walls.

Progressive Roof Collapse

CLR shifting is responsible for the progressive collapse of many roofs. An example of how this occurs is shown in **Figure 6**, which shows five compression web members braced with two rows of continuous lateral restraints.

As the magnitude of CLR shifting increases (Figure 6a), a compression web member or chord in one of the trusses will fail (Figure 6b), which significantly increases the load the two adjacent trusses must support (as indicated by the size of the arrows above the trusses in Figure 6b). As the failed truss is pulled downward by gravitational forces, it pulls on the CLRs. As shown in Figure 6c, this action will help straighten the web members on one side of the failed truss (right side in Figure 6c) and cause further curvature in the web members on the other side of the failed truss (left side in Figure 6c). Because of the combination of this action and the additional load the truss must sustain, the truss just to the left of the failed truss will also fail. This action repeats itself until all similarly compromised trusses to the left of the first collapsed truss have failed (Figure 6d).

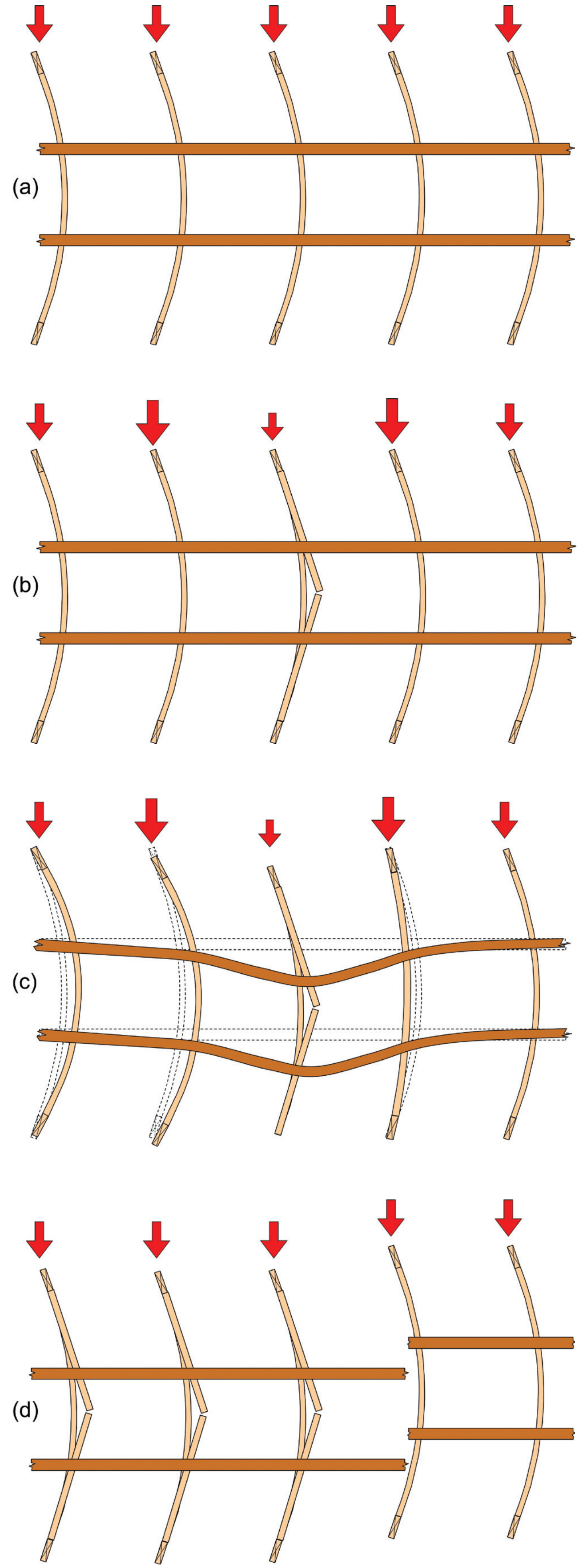

Figure 6. Cut-away view showing (a) the shifting of two rows of CLR connecting five compression webs, (b) the subsequent failure of a truss, (c) CLRs being pulled on by the falling truss and (d) the resulting progressive collapse.

Given the collapse scenario diagrammed in Figure 6, the first truss to fail would be the one adjacent to that portion of the roof still standing. In addition, the direction of CLR shifting is always toward that portion of the roof still standing. **Figure 7**, a photograph of such a collapse, verifies the direction of CLR shifting.

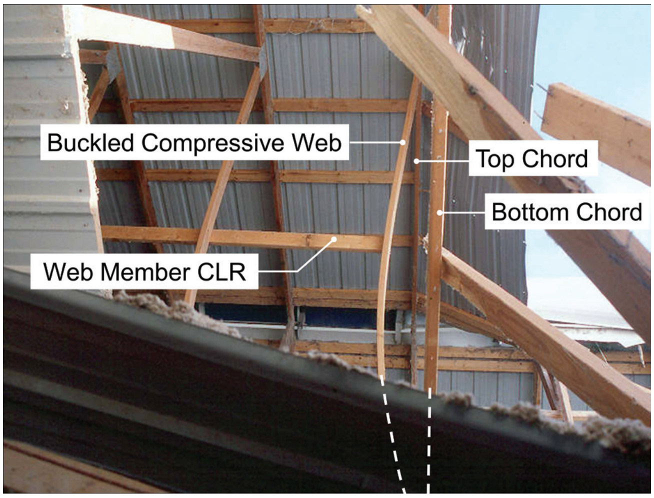

Figure 7. Web member CLR shifting is typically in the opposite direction of a progressive roof collapse. The amount of CLR shifting is fully understood when one notes that the compressive web and the top and bottom chords should lie in the same plane.

The most common failure in post-frame buildings under construction is the progressive collapse that occurs when rows of purlins are allowed to simultaneously shift because of a lack of diagonal bracing (**Figure 8**). In this situation, the simultaneous shifting is almost always caused by wind forces acting on the trusses. In rare instances, the shifting has been caused by construction equipment accidently bumping up against or otherwise striking the roof framing.

The diagonal braces shown in Figure 8 are generally temporary—their function being replaced by nailed- or screwed-down roof sheathing. Where this is the case, it is important that the diagonal braces *not* be removed until a portion of the nailed- or screwed-down sheathing has been installed. This is especially true for larger buildings because the probability of failure without truss chord or rafter CLR bracing increases exponentially with an increase in the distance the trusses must clearspan, or span without immediate support (Bohnhoff, 2003). Practitioners who transition from residential to post-frame building construction are often not aware of this and thus ignore the need for diagonal bracing in the plane of the roof during construction. This results in job sites like those shown in **Figure 9**.

Figure 10 contains images of a progressive roof collapse that occurred when the CLR on a series of post-to-truss connections

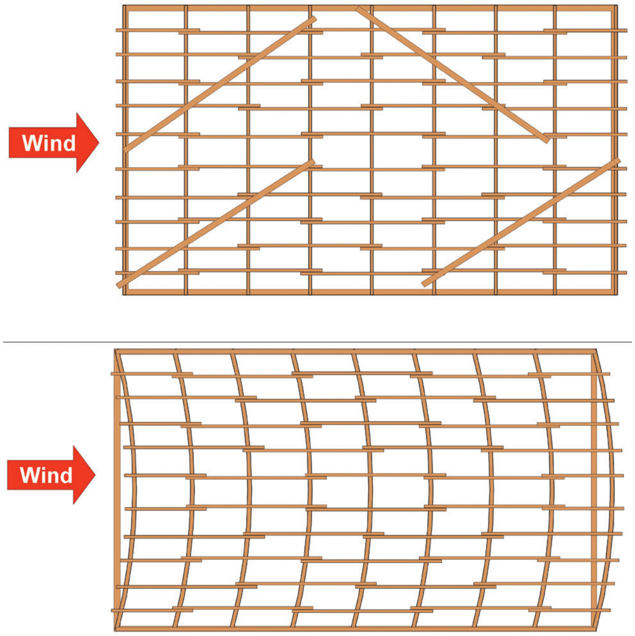

Figure 8. Plan view of roof framing illustrating how a lack of diagonal bracings can result in simultaneous lateral shifting of CLR and truss top chords

Figure 9. Progressive roof collapses during construction are due to the lack of temporary diagonal bracing on top chord CLR. The bottom image is of a conventional stick-frame building with 2-foot on-center trusses.

was allowed to shift. This particular collapse occurred in two stages, with the second collapse injuring workers who were trying to remove animals after the first collapse. To prevent further bays from collapsing, a chain and come-along were used to pull remaining post-to-truss connections back to their original positions.

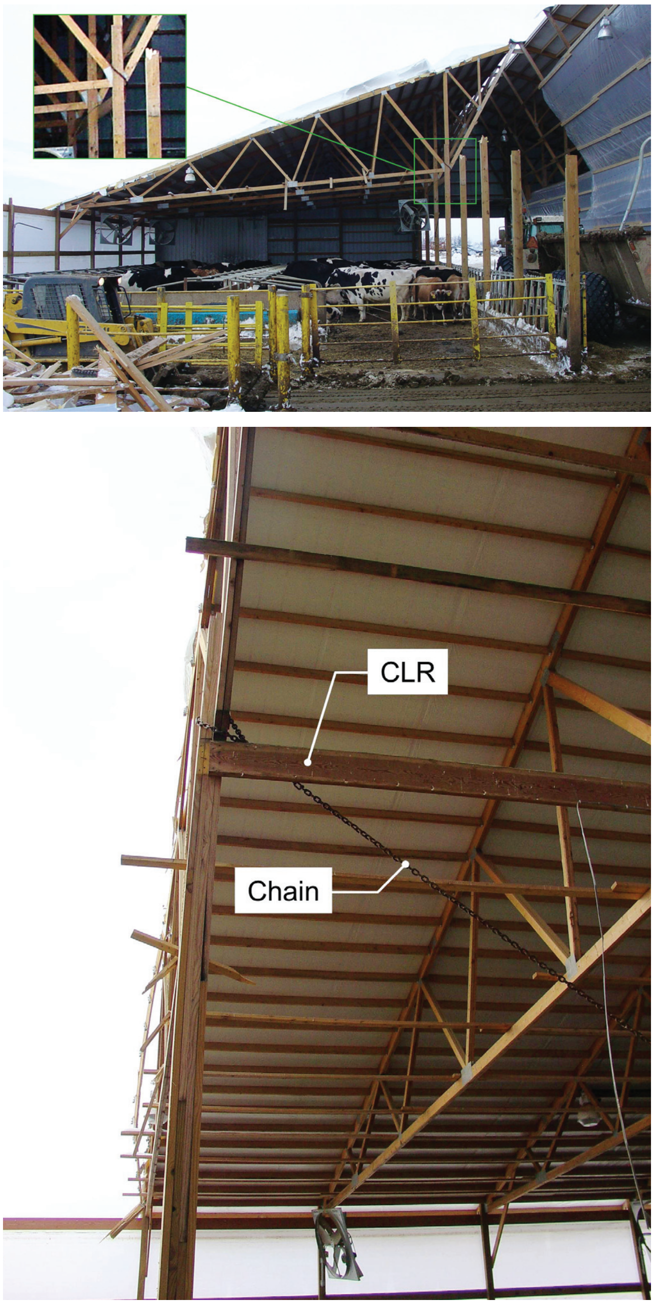

Figure 10. This progressive roof collapse was due to shifting of post-to-truss connection CLR. The chain in the lower image, which is also visible in the inset image, was used to pull the remaining post-to-truss connections back to their original positions.

Reducing Progressive Roof Collapse

Many progressive roof collapses can be prevented by properly anchoring CLR, which, as previously noted, generally involves using diagonal braces to attach the CLR to a roof, wall or ceiling running parallel to the CLR.

It is also fundamentally important to check that every connection has been made between the CLR and the members the CLRs are bracing. Omitting a single connection between a CLR and a compression web member will generally double the effective length of that web member, thus potentially reducing its axial load capacity by a factor of four (Figure 2). Note that even if the CLR-to-web member connection is missing, the fact that the CLR still passes through the truss means that the CLR will be pulled downward as the truss collapses. This can result in the same type of progressive collapse illustrated in Figure 6.

By far the best way to prevent progressive roof collapse associated with web member CLR is to entirely forgo the use of web member CLR, opting instead to increase the resistance to buckling (about the weak bending axis of the web members) with the addition of T-, L-, U-, I- or scab reinforcement as shown in **Figure 11**.

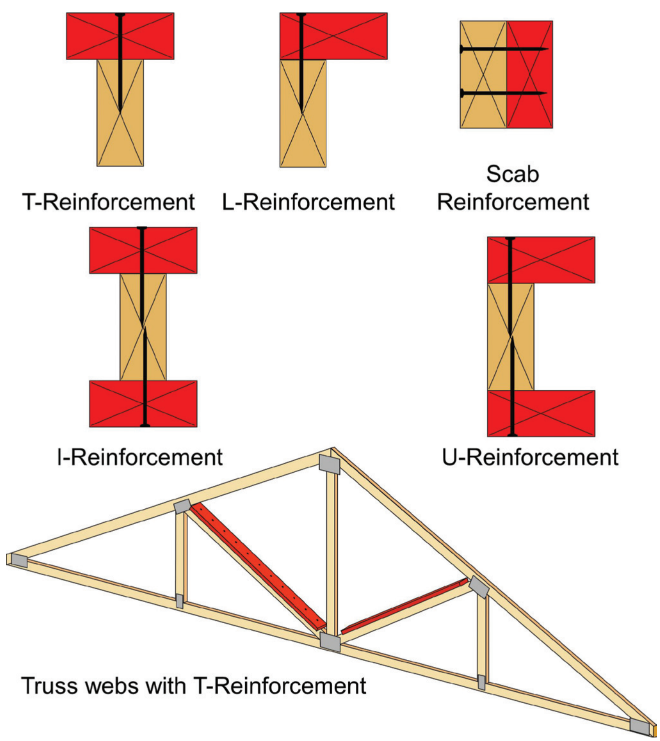

Figure 11. T-, L-, U-, I- or scab reinforcement of compressive web member—an alternative to continuous lateral restraint

Replacing CLR with T-, L-, U-, I- or scab reinforcement in post-frame buildings has several advantages. First, as noted, the chance of a progressive roof collapse is much lower because the buckling of one member does not immediately or directly affect buckling in another component. Second, it requires less lumber (significantly less where two or more rows of CLR per member are required and/or truss spacing exceeds 4 feet). Third, it can be installed on the ground. Fourth, it is simpler and less likely to be compromised by an omission during construction. The latter includes the failure to complete all CLR-to-compression-member connections as well as the failure to properly anchor the CLR.

Table 1 contains requirements for sizing and fastening T-, L-, U-, I- and scab reinforcement. The requirements in this table are fairly conservative. For more reasonable guidelines, see the article by Anderson, Woeste and Bender that appeared in the June 2002 issue of *Frame Building News*.

Table 1. Web Reinforcement for Single-Ply Trusses [a, b, c, d, e]

Specified CLR	Size of Truss Web	Type and Size of Web Reinforcement	
		T, L or Scab	I or U
1 Row	2x4	2x4	
	2x6	2x6	
	2x8	2x8	
2 Rows	2x4		2-2x4
	2x6		2-2x6
	2x8		2-2x8

[a] From Building Component Safety Information-B3 Table B3-2 (Structural Building Components Association & Truss Plate Institute, 2015)

[b] Applies only to web members 14 feet or less in length

[c] Web reinforcement must be the same species and grade or better than the web member.

[d] Web reinforcement length must be at least 90 percent of the web member or extend to within 6 inches of the end of the web member, whichever is greater.

[e] T-, L-, U- and I-reinforcement must be fastened to web with 16d (0.131- by 3.5-in.) nails spaced 6 inches on center. Attach scab reinforcement to web with two rows of minimum 10d (0.120- by 3.0-in.) nails.

As illustrated in Figure 3, the amount of axial compressive load that can be applied to a member is increased by reducing the slenderness ratio L_e/d. By adding T-, L-, U-, I- or scab reinforcement along a web member, the designer is effectively turning a long column into an intermediate or short column by increasing d (as opposed to decreasing L_e with the addition of CLR). This same approach is commonly used to eliminate the need for CLR on interior posts. That is, interior post dimensions are made large enough (see **Figure 12**) so that the need for continuous lateral restraint is eliminated.

The impact of a progressive roof collapse in a very long

Figure 12. The lengthy interior posts being installed in this photo were five-ply glulam assemblies that did not require CLR to withstand design loads.

building (e.g., a building several hundred feet in length) can be reduced by turning the building into one that behaves (from a structural perspective) as a series of shorter, independent structures. This often happens automatically when a designer adds one or more interior shear walls along the length of a long building to make more effective use of diaphragm action.

Where diaphragm action is ignored in the design of a very long building, the impact of a progressive roof collapse can be reduced by (1) doubling up trusses at one or more locations and (2) making sure that there is a joint in all CLR rows at the location where the trusses are doubled. Doubling up trusses helps ensure that when an adjacent truss collapses, the load transferred to the doubled-up trusses does not fail the trusses. Placing joints in all CLR rows at the location of the doubled trusses will reduce the load that is applied to the trusses when an adjacent truss fails, because it is generally easier to pull a wood connection apart than it is to fracture a wood member. Inasmuch as purlins function as CLR for truss top chords, it is important that they not be continuous over the top of double trusses used to limit the extent of a progressive roof collapse.

Finally, perhaps the best way to reduce the likelihood of a progressive roof collapse is to have a qualified, professionally registered or licensed engineer both design the building and inspect it during and after construction.

Figure 13 contains photos of a non-engineered building with roof sections that collapsed when several interior posts buckled. The interior posts were substantially undersized, given that they were supported by only a single row of CLR. The lower image in Figure 13 shows the significant curvature of one of the interior posts that did not fail. The point of contraflexure in this post is at the single CLR attachment point. In this particular case, the CLR was kept from shifting with a pair of diagonal braces.

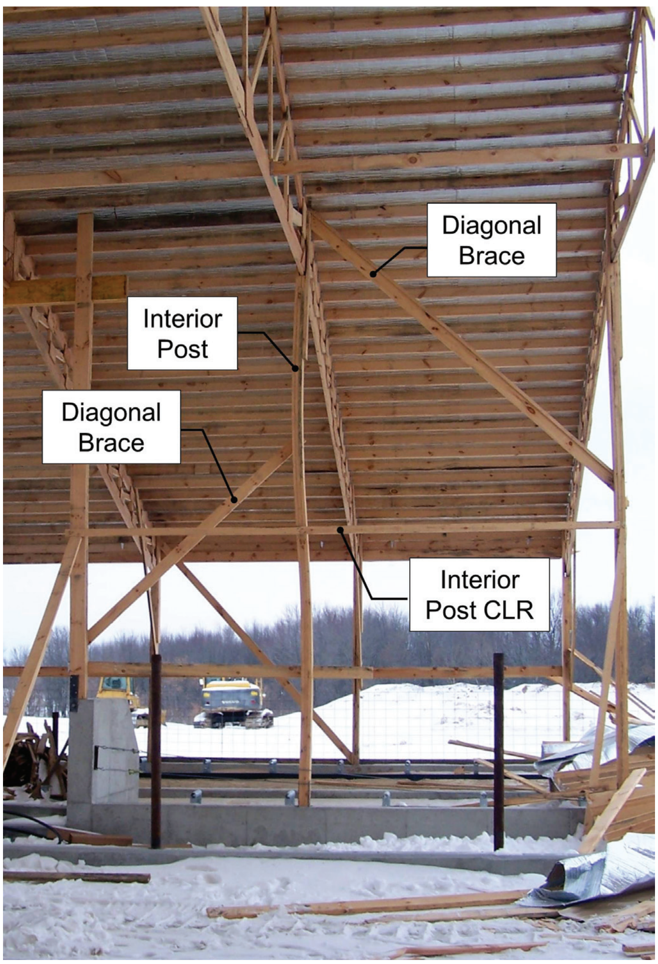

Figure 13. A building with roof sections that would probably not have collapsed if the interior posts had been increased in size and/or supported with additional rows of CLRs

Summary

Progressive roof collapse is frequently due to the shifting of the CLR used to increase the axial compressive load capacity of components. In most cases, this shifting is due to improper anchorage of the CLR.

In addition to ensuring that CLR is properly anchored, one can reduce the probability of progressive roof collapse by switching to designs that do not rely on CLR. This latter approach is strongly recommended for compression web members and is frequently used for interior posts.

In very long buildings, the extent of a progressive roof collapse can be reduced by doubling up trusses at one or more locations and making sure that there is a joint in all CLR rows at the location where the trusses are doubled.

In all cases, it is recommended that the design and construction inspection of larger or longer buildings be conducted by qualified professionals.

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