Published in *Structure* magazine – November 2009

Coming Up with Tie-downs

Wind Uplift Restraint Design Using Continuous Rod Tie-down Assemblies

By Bryan Wert, M.S., P.E., SECB, Branch Engineer for Simpson Strong-Tie

"Continuous load path" or "complete load path" are key phrases in engineering design established in IBC sections 1604.9, 2304.9.6, and IRC section R301.1. These phrases require designers to detail connections throughout the structure to resist and transfer overturning, sliding and uplift forces from their point of origin down to the foundation. However, wind uplift restraint and load transfer may be negligible in some conditions, or unfamiliar to many engineers.

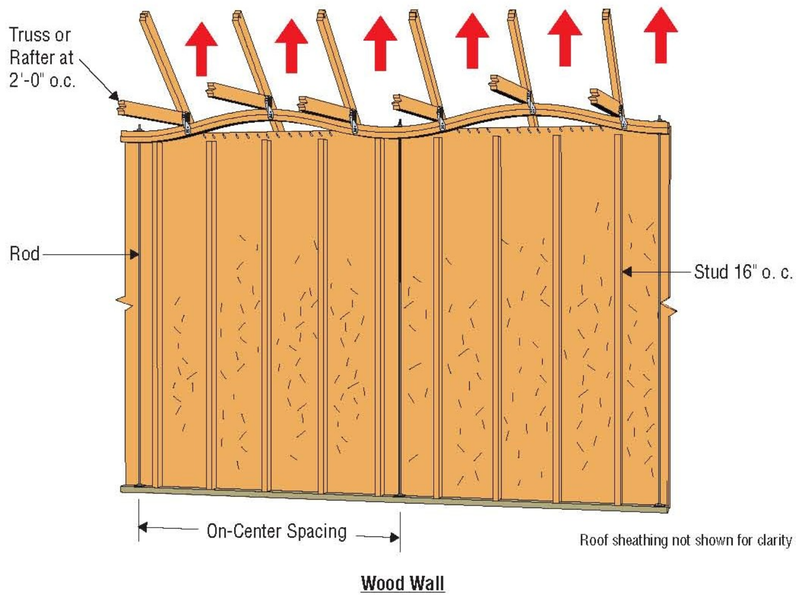
Engineers designing structures with tile roof coverings in regions with 85 or 90 mph wind speeds may have a general note or typical detail pertaining to uplift restraint on their plans. In these areas of the country, heavy dead load often allows toenail fastening of roof framing to wall framing to restrain wind uplift. That's it – end of load path.

Conversely, engineers designing structures with lighter weight roof coverings, such as asphalt shingles, in areas with relatively low 90 mph wind speeds must use hurricane ties to transfer uplift loads, ranging from 60 to almost 300 pounds per lineal foot (plf). Wall and floor dead loads reduce this force as it is transferred down the structure, but typically connections are still needed to create the required continuous load path all the way down to the foundation. This is especially true in high wind regions like the Gulf and Atlantic coasts, Hawaii, and special wind regions in the Rockies and Pacific Northwest where design wind speeds can reach up to 150 mph. Structures in these regions, depending on exposure category, may experience extremely high uplift loads exceeding 1000 plf.

A New Load Path Solution

For decades metal connectors, such as hurricane ties, twist straps, flat straps and hold-downs, have been used to resist uplift loads from the point of origin to the foundation, creating the uplift restraint load path in light-framed construction. Real-world tested and proven; these connectors, their capacities, and their installation methods are well understood by both designers and installers. Recently, rod systems have been introduced to the light-framed construction industry as a seemingly simple means of creating a continuous load path for resisting wind uplift forces.

When rod systems were first introduced, some likened all-thread rods spaced regularly every few stud bays in wood construction to vertical rebar spaced regularly every few cells in CMU construction, equating the wood double top plate to the block bond beam or concrete tie beam (*see Figure 1*). While it's fairly simple to understand how these load paths work, this is where the similarities end. The capacity of a steel reinforced bond beam or concrete tie beam clearly is much different than that of a wood top plate when acting as an uplift load collector.



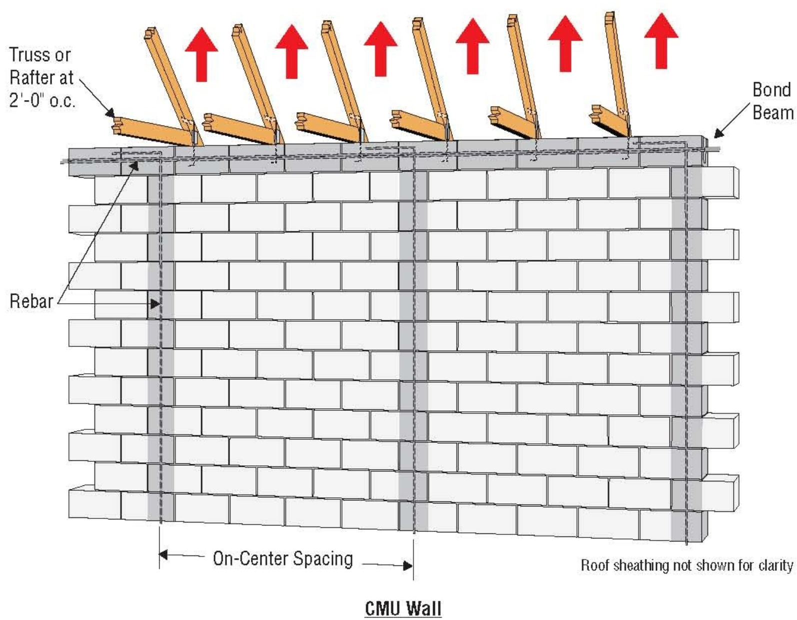


Figure 1: Load path comparison between CMU wall using steel rebar and wood wall using steel all-thread rod.

Unfortunately, some may over simplify the load path by providing rod system layouts that base the wind uplift rod restraint spacing on rod tension and bearing plate capacities alone. This inadequate design may lead to building damage, structural system performance problems, and ultimately life-safety issues. Many other factors need to be considered in the design of a wind uplift rod system, such as bending capacity of wood top plates, deflection limitations of wood top plates, top plate rotation issues, tension rod elongation limitations, wood shrinkage concerns and wood compression under dead load.

Determining Uplift Load Paths

Unlike lateral forces from wind or seismic loading which transfer into the structure at the roof and each floor diaphragm, wind uplift typically loads the structure solely at the roof diaphragm. Uplift may be calculated using *ASCE 7* or pre-calculated uplift values can be found in either Table 2.2A of the *Wood Frame Construction Manual* (WFCM) or Table 2308.10.1 of the International Building Code (IBC). Uplift reactions then may be provided in engineering plans or in roof truss calculations.

Once the uplift along each wall line of a building is determined and the appropriate hurricane ties to transfer uplift from the roof framing to the top plate are chosen, what comes next? What are the requirements to properly create a continuous load path using steel all-thread rod tie-down assemblies? What governs rod spacing? To date, there doesn't exist a guide or a design standard that provides these steps for design. Consequently, designers are currently left with using “engineering judgment” based on rational analysis to create this load path.

The Missing Link: Top Plate Considerations

Knowing rod tensile strength and wood bearing capacity are important, but they do not provide enough information to complete the rod spacing layout. Designers must verify that top plate bending capacity does not control the design of wind uplift rod systems by analyzing the flat wood plate bending (or flexural forces) in the wood top plates. Unless specifically detailed for splice conditions, only one of the wood top plate members should be considered to resist the uplift bending forces. To find the bending stress in the top plate, designers can use the simple engineering equation: $F_b = M/S$, where M = moment (possibly based on three equal span uniform loading) and S = section modulus (of the wood top plate). If the span between rods is too great, top plate bending failure will control design. Testing has shown this wood top plate flexural failure (*see Figure 2*).

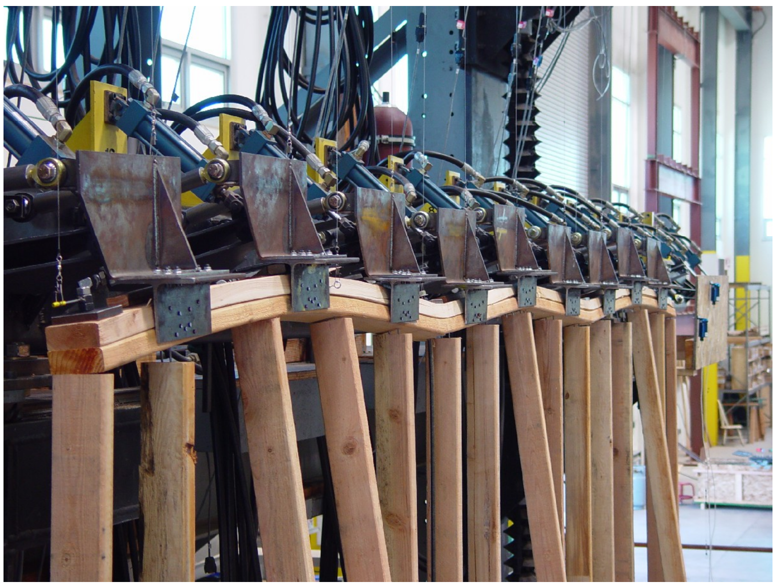
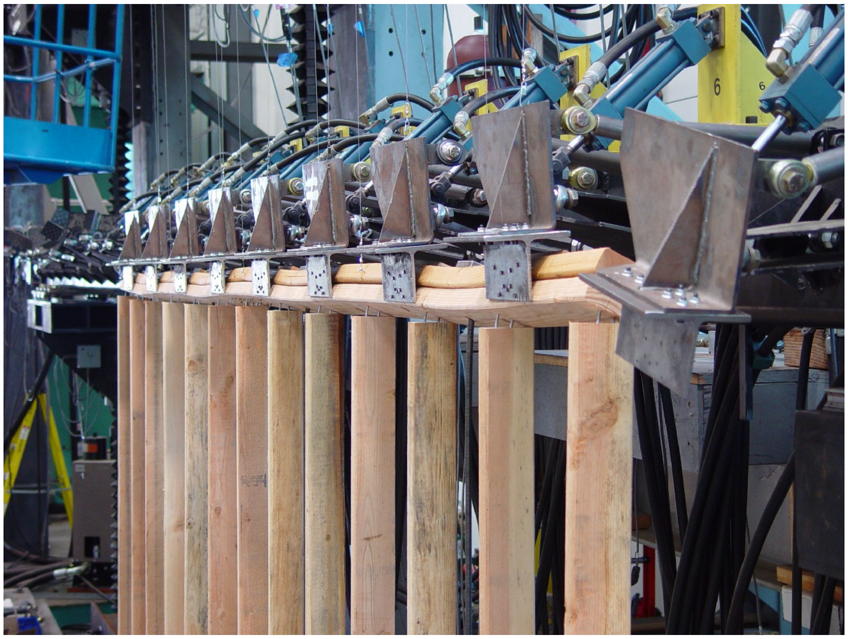


Figure 2: Obvious top plate bending in testing of rod system with 72 inch o.c. spacing at the Simpson Strong-Tie Tyrell Gilb Research Lab in Stockton, California. Ultimate load is 290 plf; using a factor of safety = 2.0, yields an allowable uplift capacity of 145 plf.

Servicibility issues also must be considered in rod spacing design. In many cases deflection, not bending strength, of the top plates may actually govern the rod spacing design. As the top plate bends, it is deflecting between supports – which in this case, are rods. Of course in extreme cases this could lead to structural system damage and possible failures, but consider the effect of top plate deflection on wall and ceiling finishes. What deflection limit should be allowed in the top plate? 1/8 inch? 1/4 inch? Should the limit be based on the span between rods, such as L/180 or L/240 as suggested by REA, an engineering group in Florida that has been working with rod systems for several years? At this point the judgment of the design professional and the requirements of the building owner govern as this is not currently defined in the code.

Another important concern is top plate rotation due to eccentric loading. The uplift load path becomes compromised if the top plate rotates. Uplift forces are generally transferred into the top plate through a hurricane tie in high-wind areas. Hurricane ties are typically installed by attaching the rafter or truss to the side of the top plate, and usually on the inside of a structure. If the next connection in the load path is in the middle of or on the opposite side of the wall, the eccentricity created by the offset load path causes the top plate to rotate, diminishing the amount of load the system is capable of transferring.

More than a decade ago, Clemson University completed a study on top plate roll showing this diminished load transfer. While their findings were published in the *Journal of Light Construction* in 1996, this phenomenon which Clemson researchers dubbed “top plate roll” still is not widely known or understood. Compared to an assembly with the rafter-to-top plate and top plate-to-stud connection on the inside of the wall, an assembly with the rafter-to-top plate connector on the inside and sheathing on the outside as the only plate to stud connection had nearly a 60% reduction in uplift capacity. The latter scenario creates an uplift load path moment arm equal to the wall width forcing the top plate to roll when loaded.



In a rod system the bearing plate transfers the load into the steel rod roughly at the center of the top plate width. This reduces the uplift load path moment arm, and thus reduces the eccentric loading. However, testing has shown that even this shorter moment arm causes the top plate to rotate before it is capable of transferring the full load into the rod system. The test in *Figure 3* shows rods at 48 inches on center and this top plate roll phenomenon in action.

Figure 3: The distance between the hurricane tie and the rod restraint creates an eccentric loading condition, causing top plate rotation and reducing the uplift load that the system is capable of transferring.

Figure 4: Sheathing and hurricane ties on opposing sides of the wall with rods at 48 inches o.c. Top plate rotation is still unrestrained.

Pulling Double Duty – What is the Effect of Sheathing?

Can sheathing installed on the opposite side of the wall from the hurricane tie help to control top plate roll by restraining the side of the top plate? Uplift testing did show that the wood top plate’s ability to transfer load increased if the wall was sheathed on one side. However, *Figure 4* shows this same rotation action even with sheathing attached to the outside of the wall and hurricane ties on the inside of the wall. Is this surprising? It shouldn't be considering why the sheathing is usually there – for shear resistance, not uplift. As a designer, if you count on that sheathing to help with uplift transfer, then the interaction effects of uplift and shear must be considered in order to know how much the shear wall capacity will be reduced.

Another design issue becomes evident in *Figure 5*, which shows that restraining the top plate on one side with structural sheathing while uplift load is transferred into the top plate with a hurricane tie on the opposite side can cause cross-grain tension failure in the top plate. The National Design Specification for Wood Construction (NDS) states in section 3.8.2 that, "Designs that induce tension stress perpendicular to grain shall be avoided whenever possible. When tension stress perpendicular to grain cannot be avoided, mechanical reinforcement sufficient to resist all such stresses shall be considered." *Figure 6* shows that top plate rotation can be compensated for with the use of top plate-to-stud connectors – so much so in fact that the test can force extreme top plate failure and achieve a true "ultimate load."

Figure 5: With rods centered in the wall and sheathing on opposite side of wall, cross-grain tension failure occurs as top plate bends upward. Mechanical reinforcement is needed.

Figure 6: Simpson Strong-Tie TSP top plate-to-stud connectors restrain the top plate rotation, allowing the maximum load to be transferred to the rod tie-down system.

This top plate rotation restraint also may be possible if the roof framing-to-top plate connections are made on the outside of the wall, on the same side as structural sheathing. This allows the sheathing to resist rotation, but it creates new design questions. Will sheathing be on every wall? If not, what detailing is required for both sheathed and un-sheathed wall conditions? If hurricane ties attach the roof framing to the top plates and sheathing is fastened over them, what installation and inspection issues arise? Do hurricane ties have similar capacities installed over sheathing? And again, by relying on sheathing for uplift resistance it's likely to reduce shear capacity which is usually the primary purpose for structural sheathing.

Wood Shrinkage Leads to a Less Effective System

At the top of a continuous rod tie-down system, uplift will not transfer into the rod unless a nut is tight against the bearing plate. As moisture escapes from wood framing the wood begins to shrink. Coupling wood shrinkage with compression due to dead load causes the bearing plate to shrink away from the nut's fixed position on the all-thread rod. The gap between the nut and the bearing plate requires additional deflection to occur prior to the system being engaged in a wind event. *Figure 7* shows a substantial gap between the nut and bearing plate in a wind uplift restraint rod system at a project in Orlando, Florida. This is the only point of restraint in wind uplift rod tie-down systems and hence the only location for the gap to occur when wood shrinks and the steel rod does not.

Even though most manufacturers recommend that contractors go back and tighten all the nuts down to the bearing plates prior to closing up the wall and ceiling assembly, it can be assumed this doesn't always happen. Furthermore, shrinkage and dead load compression may continue to occur through the first six months to one year of the life of the structure. Take-up devices will keep rod tie-down systems continuously engaged, compensating for wood shrinkage and compression. Without a take-up device, gaps are likely to occur in rod systems and will reduce the system's effectiveness and performance.

Figure 7: What was once a nut tightly secured to the bearing plate, now has a gap as wood shrinkage and dead compression occur throughout the structure.

That's Stretching it: Steel Rod Elongation

Another important consideration is steel rod elongation. The elongation or stretch of a steel rod is calculated with a simple equation, $\delta = PL/AE$, dependant on the tensile force (P), rod length (L), effective cross-sectional area (A), and modulus of elasticity (E) which is 29,000,000psi for all structural steel. From this equation it is easily surmised that the higher the tensile (uplift) force, the longer the rod, or the smaller the rod diameter, the greater the elongation. For example, in a four-story, 40-foot tall structure, a ¼-inch diameter rod with a tensile capacity of roughly 1100 lbs. would stretch more than half an inch, which is obviously not the best solution if this is your wind uplift restraint system. The more elongation that occurs in the rod, the more deflection that will occur in the structure under uplift loading. Consequently it makes sense to limit elongation, but again this limit is another issue that falls on the shoulders of the designer as there are no current code limitations.

The Bigger Picture

The uplift-force resisting system is only one of the force resisting systems in a structure. Lateral-force resisting and gravity-force resisting systems are also required. In wood construction, beams, joists, plates, and studs may initially be sized to resist gravity loads. Lateral loads, however, require reevaluation of wood members and the addition of steel fasteners, connectors, and anchors to create a properly designed continuous load path. Markedly different from the single point of origin for uplift forces, lateral forces are introduced into the structure at multiple points of origin. Diaphragms at the roof and each floor level distribute these forces; and in wood construction shear walls typically continue the load path to the foundation.

The architect's layout of door and window openings and the engineer's choice of shear wall locations, shear wall lengths, sheathing materials, end stud/post size, and overturning restraint hardware greatly affect the overturning forces in a structure. The rod sizes in wind uplift tie-down systems are generally too small to resist the higher uplift forces generated by cumulative shearwall overturning in multi-story structures, so higher capacity holdown solutions are required at the ends of shearwalls. Accordingly, uplift resisting and lateral-force resisting systems should usually be designed as two distinct systems. If not, the effects of combined loading must be considered – for example when using a steel rod to resist wind uplift and lateral force induced shear wall overturning – to properly design components of these systems.

Design with the Public in Mind

Buildings are going up every month with continuous rod tie-down assemblies used as the structural system for uplift restraint. Unfortunately not all of these systems are designed correctly. Designs often forego important constraints of wood top plate bending capacity, wood top plate deflection, wood top plate rotation, wood shrinkage, wood compression under dead load, and tensile steel rod elongation. Worse yet, some designs compound these errors by relying on rods designed solely for uplift for lateral overturning as well without proper consideration given to the effects of load interaction. It's up to the designers and professional engineers that seal continuous rod tie-down uplift restraint assemblies to ensure these design factors are taken into consideration in order to protect the life safety of the public. This task is not necessarily easy, especially without a code approved design guide or standard to follow. Engineers will have to interpret the existing information from rod system manufacturers and use their experience and judgment to create robust, economical, and most importantly, safe continuous rod tie-down uplift restraint systems.

Bryan Wert, M.S., P.E., SECB, is a branch engineer for Simpson Strong-Tie in McKinney, Texas. He can be reached at bwert@strongtie.com.