Figure 1

Multi-Story Light-Frame Construction

Understanding Continuous Tiedown Systems

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Infill and high-density development is a fast growing segment of the construction industry. As a result, light frame construction of multi-story buildings has significantly increased in recent years and this trend is expected to continue in the future. Engineers naturally tend to simply extend the design approaches used for one and two story structures to the three to five story light-frame structures being built today (*Figure 1*).

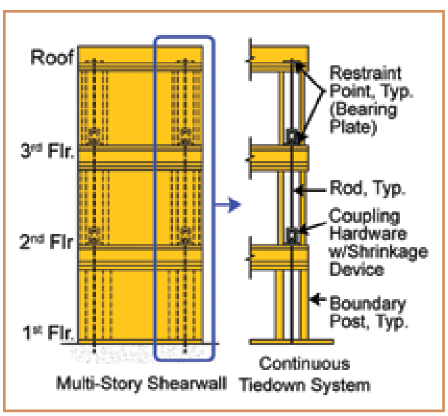


Figure 2

To resist the high overturning forces generated by the lateral loads of these mid-rise light-frame structures, continuous tiedown systems have emerged on the market over the past decade. However, there can be significant differences in load paths and performance, due to the variety of systems, which require the engineer to carefully consider all aspects of the chosen system prior to specification.

Background

Continuous tiedown systems (*Figure 2*) typically consist of a continuous rod, from the foundation to the top of structure, employing either a bearing plate device or a bolted holdown as the restraint (*Figure 3*) at selected locations. The two basic types of systems shown on *Figure 3* can be configured such that the restraints are either provided at every story (a tied-off system), or are provided at a single story such that multiple stories are tied together (a skipped-story system).

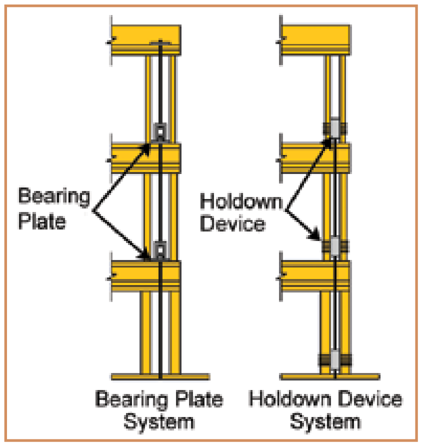


Figure 3: Basic types of continuous tiedown systems

The popularity of these systems results from hardware and labor cost savings. For example, a continuous bearing plate tiedown system only requires a single vertical oversized hole drilled through the framing to connect the hardware. With bolted holdowns, there are more holes and the post bolt holes cannot exceed the bolt diameter plus 1/16 inch. Over-drilling of post bolt holes can lead to increased drift in the shearwall.

In addition to the installation benefits, continuous tiedown systems provide higher capacities to resist the demands of mid-rise structures. Most continuous tiedown systems can accommodate loads up to 50,000 lbs. Continuous tiedown systems can also address shrinkage concerns with the use of shrinkage compensating devices.

Design Issues

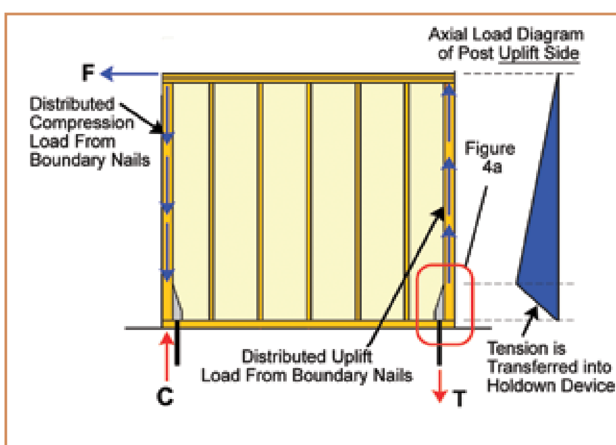
The primary issues that a building engineer should consider in the design of multi-story tiedown systems are: (1) load path, (2) shrinkage, (3) drift, and (4) the effect of skipping stories on system behavior and performance.

Load Path

In continuous tiedown systems, uplift forces are continuously and cumulatively collected in a central member, usually a steel rod or cable, that is anchored to the foundation. In a traditional floor-to-floor holdown system, however, the uplift forces are transferred into and out of the holdown devices and posts.

The load paths of continuous tiedown systems are different from traditional floor-to-floor holdown or strap systems. *Figures 4* and *5* illustrate the basic difference on the transfer of overturning forces. Notice that for the rod and bearing plate systems (*Figure 5*), the posts on the uplift side of the wall are engaged in compression whereas for bolted holdown systems (*Figure 4*), the post on the uplift side is engaged in tension.

Another distinct concept with continuous tiedown systems is that of *cumulative* and *incremental* loading. *Figure 6* compares the uplift load paths at the floor level. With the continu-



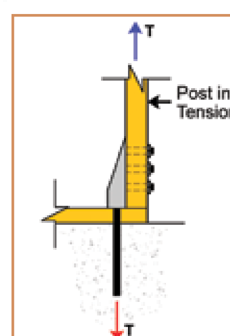


Figure 4a: Typical load path of holdown device

Figure 4: Shearwall with traditional holdown devices

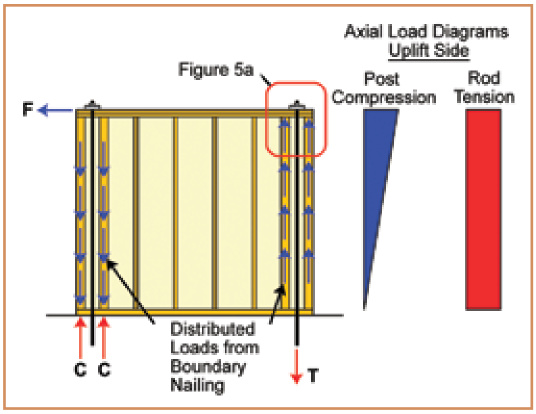


Figure 5: Shearwall with bearing plate tiedown system

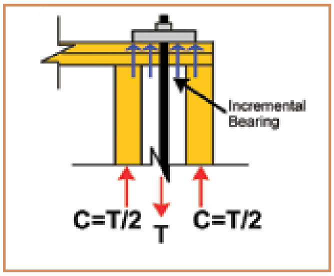


Figure 5a: Typical load path of bearing plate tiedown system

ous bearing plate tiedown system, the rod at the lower shearwall is designed for the cumulative tension load, but the bearing plate is designed to resist only the *incremental* (story) uplift from the shearwall below. From statics,

$T_{below} = T_{above}$ + Incremental Bearing
Incremental Bearing = Interstory Uplift of Level Below

Similarly, the holdown device in a continuous tiedown system with bolted holdowns (*Figure 3, Holdown Device System*) only receives the incremental uplift load (provided the rod is continuous through the holdown).

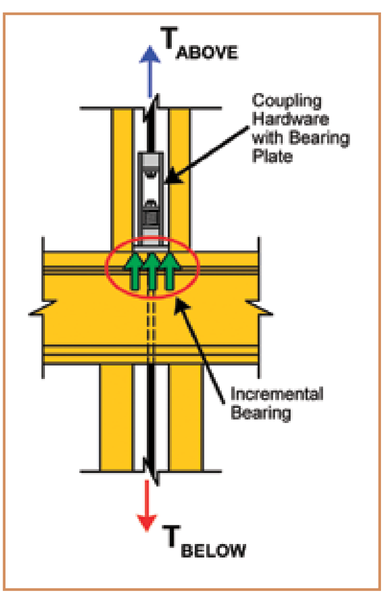


Figure 6: Load path at floor level

The cumulative uplift is collected in the central rod, just as in bearing plate systems, however the incremental uplift force is transferred through bolts instead of bearing plates.

Figures 7a and 7b show the axial load diagrams of the posts on the uplift side of a shearwall for a continuous tiedown system with bearing plate restraints at each level, versus a traditional floor-to-floor holdown system. For floor-to-floor holdown systems, the axial load for the post is a tension load, but for the continuous tiedown system with bearing plates, the axial load is in compression.

Shrinkage

Wood buildings typically shrink, and the effect on the overturning restraint system becomes more pronounced as the number of floors increases. Because steel doesn't shrink, gaps can develop between the nuts and bearing plates (*Figure 8*). When the shearwall overturns, these gaps must be closed through vertical movement before the tiedown system can engage. This results in additional drift and can adversely affect the performance of the shearwall system.

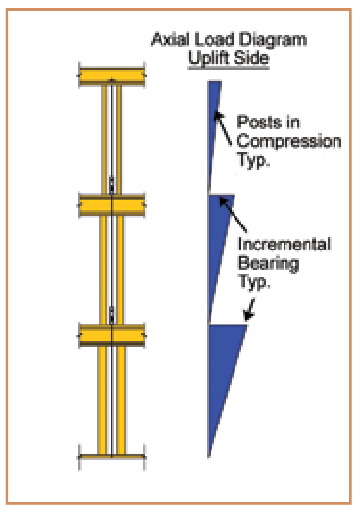


Figure 7a: Multi-Story Load Path for Continuous Tiedown System

For this reason, continuous tiedown systems may utilize shrinkage compensating devices (*Figure 9*) which are designed to expand and fill the gaps. There are various ways in which these devices work. One such device utilizes a dual steel hollow cylinder that expands through a means of a spring but will not compress back down, thus ensuring a snug fit between the restraint and the nut.

The amount of movement that a shrinkage compensating device must accommodate depends on the system. In systems that use threaded couplers to splice the rod over the height of the structure, the rod length becomes fixed, and thus upper stories accumulate shrinkage around the rod equal to *all* of the shrinkage in the platforms below. For systems that splice the rod inside of 'cages', the rod length is not fixed, and thus shrinkage compensating devices need only accommodate the shrinkage for the story under consideration. Regardless of the system, a shrinkage compensating device must have adequate capacity at its full rated extension.

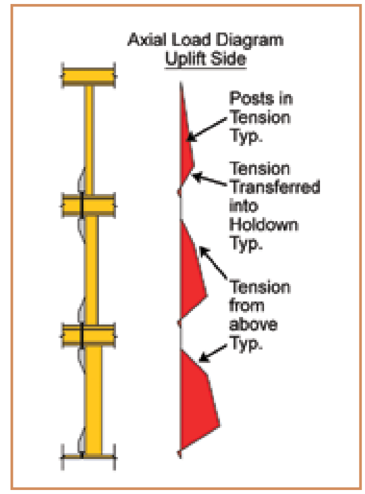


Figure 7b: Multi-Story Load Path for Floor-to-Floor Holdown System

The engineer of record should evaluate whether shrinkage-compensating devices are required. Some engineers do not require these devices in structures with engineered wood floor systems since those structures experience less shrinkage than structures with sawn lumber floor systems. Shrinkage in the wall studs and posts is usually much less than that of floor systems, and because of this it is not usually considered.

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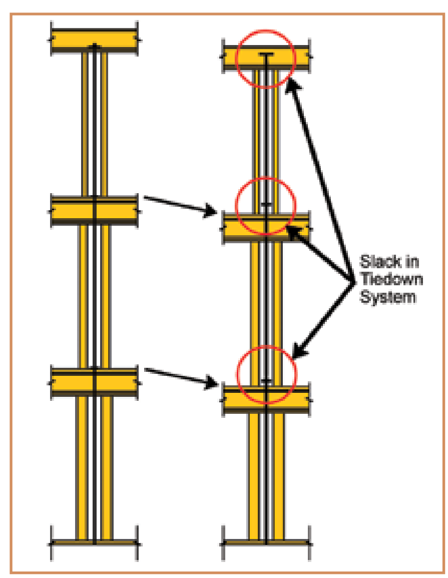

Figure 8: Shrinkage in Multi-Story Wood Buildings

Drift

Drift is a major factor in the performance of continuous tiedown systems and should be checked in the design process. *Figure 10* shows the equation for drift of wood structural panel shearwalls based on the NDS. Note that Δ_A is horizontal drift of the shearwall due to rigid body rotation of the shearwall as a whole. The d_a term needs to include the uplift effects of the tiedown (rod elongation, bearing deformation, fastener slip, etc. as applies). Standard practice only includes these uplift side effects in the evaluation of Δ_A, but compression side deformations (i.e., through-floor compression deformation) also contribute to Δ_A, regardless of the type of tiedown system. Evaluation of this effect is beyond the scope of this article.

Figure 9: Shrinkage Compensating Device

Skipping Stories

A skipped-story system occurs when the rod used in a tiedown system is installed such that two or more stories have overturning resistance provided by a common point of restraint. In other words, the structure lacks a positive uplift restraint at each story (*Figure 11*), and multiple stories are held down by one restraint. With a tied-off system (*Figure 12*), each story is tied off with a restraint.

At first glance, the two systems seem very similar, but the lack of a restraint at each story results in very different behavior for a skipped-story system as seen by the uplift load path (*Figures 13 and 14*). In the tied-off system (*Figure 14*), the incremental uplift of each story is locally addressed by its own restraint at the top of the wall. With a skipped-story system (*Figure 13*) incremental uplift of each story must travel up the building until it finds the point of restraint.

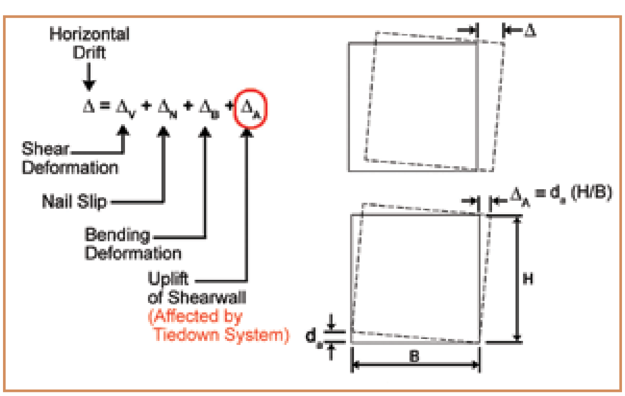

Figure 10: Hoirzontal Drift of Wood Shearwalls

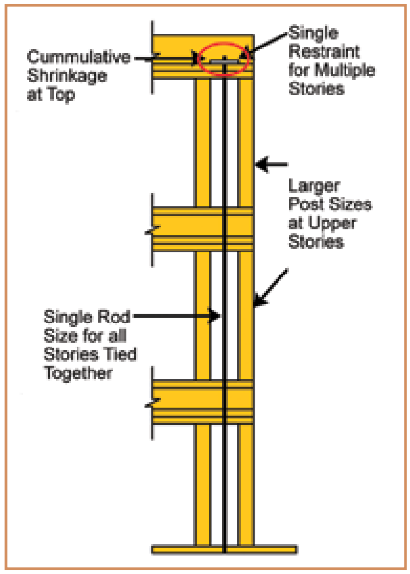

Figure 11: Skipped-Story System

In a skipped-story system, the lower shearwalls rely on the upper shearwalls for stability as they transfer their overturning forces up the building. As a result of this multistory load path, elements at and below the point of restraint need to resist cumulative loads for the entire system up to that point. For the skipped three-story system shown on *Figure 13*, if the overturning tension force in the rod at the base of the structure is 34,000 lbs, then the posts and the restraint at the top of the structure must also be able to transfer that total force.

In lieu of a restraint at the top of wall, some systems utilize a bridge block at mid-height level (*Figure 15* and *15a*). If a bridge block is used, it is important to follow the load path through every single component. *Figure 15* summarizes the load path through these elements.

Redundancy should also be considered. If a single element of the restraint system fails in a skipped-story system, then the entire uplift resistance for the walls below is compromised. With a tied-off system, the lower story walls do not rely on the upper story elements for uplift resistance.

Shrinkage is also affected with a skipped-story system since the gaps created by shrinkage accumulate at restraint points. Shrinkage compensating devices are used to address this shrinkage but must have the capacity to expand to a length equal to the accumulated shrinkage and also have the capacity to resist the cumulative uplift force while fully expanded. With a tied-off system, shrinkage can be compensated for each story.

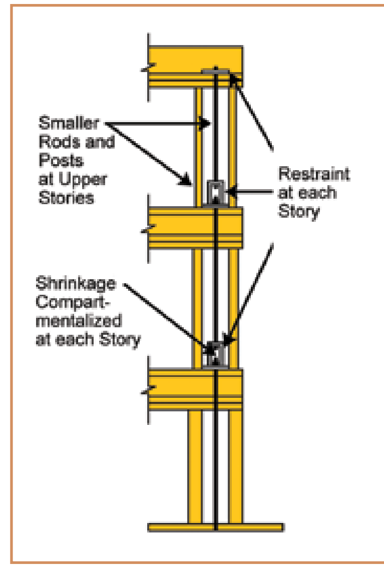

Figure 12: Tied-Off System

Construction stability is yet another consideration in skipped-story systems. By skipping stories, temporary instability is created because shearwalls lack an overturning restraint system until multiple stories are constructed. If a high

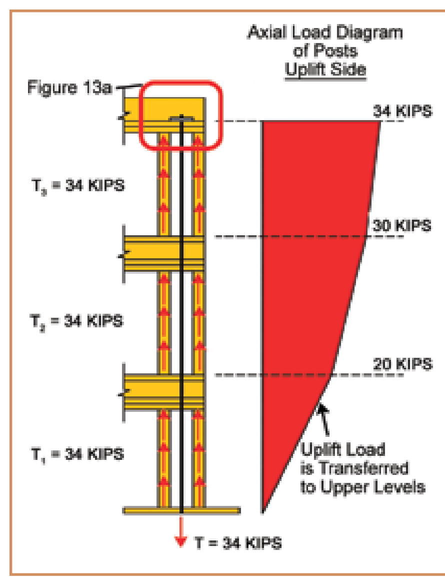

Figure 13: Skipped-Story System Uplift Load Path

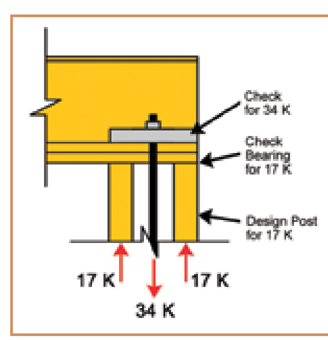

Figure 13a: Tiedown Load Transfer (Skipped-Story System)

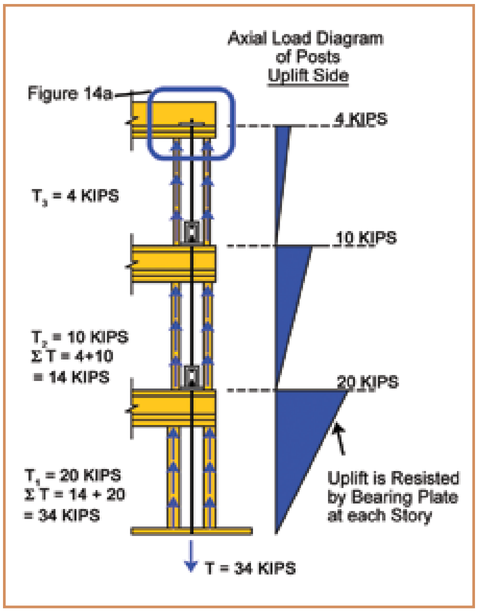

Figure 14: Tied-Off System Uplift Load Path

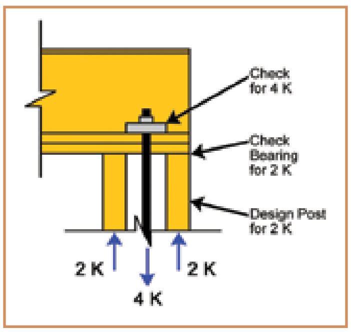

Figure 14a: Tiedown Load Transfer (Tied-Off System)

wind or a seismic event occurs during construction, the structure could be susceptible to damage or collapse. With a tied-off system, however, the restraints at each level provide overturning resistance during construction. Therefore, in a skipped-story system, the engineer and contractor need to consider additional stability bracing during construction.

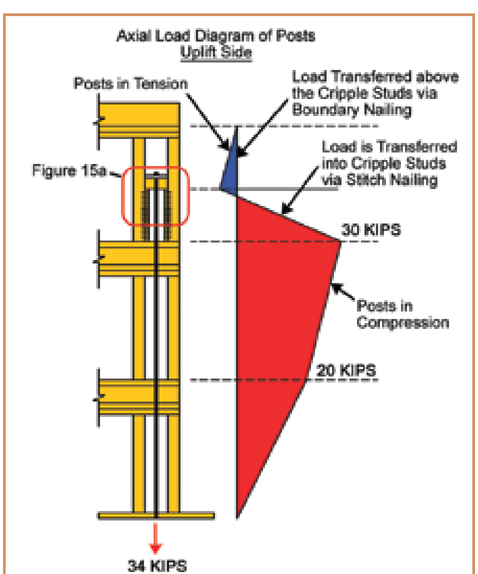

Figure 15: Skipped-Story System with Bridge Block

Drift can also be affected significantly by skipping stories. Since the loads in a skipped-story system must travel up the building, the lower floors experience larger interstory drift compared to those in a tied-off system. *Figures 16* and *16A* show an overturning analysis for a skipped-story system considering lateral loads only. As shown in *Figure 16A*, the bottom two floors rely on a downward force from the shearwall above for restraint.

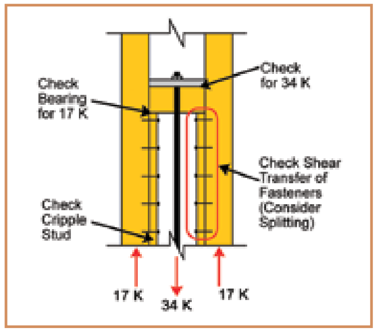

Figure 15a: Tiedown Load Transfer at Bridge Block

Since the compression forces on the uplift side of the wall are cumulatively larger in a skipped-story system, there is additional compression and deformation on framing elements. The *accumulation* of this deformation on the *uplift side of the wall* in a skipped-story system contributes significantly to the increased interstory drift, especially at the lowest story of a set of skipped-stories. Tied-off systems also have uplift deformations from compression of wood elements and rod stretch, however they are not based on *accumulated* deformations and therefore they experience less drift as illustrated in *Figures 17* and *18*.

Thus, although a skipped-story tiedown system may be designed properly for allowable stresses, the design may be insufficient for satisfying Code required drift limits, which could negatively impact the overall performance of the system. Whether a system is tied-off or skipped, the engineer should always check interstory drift.

Full-Scale Testing of Tied-Off vs. Skipped-Story Systems

To better understand and verify the performance difference between systems, full-scale multi-story quasi-static/cyclic and dynamic (shake table) testing of both skipped-stories and tied-off systems was recently performed at the *Tyrell T. Gilb Research Laboratory* in Stockton, California. Three-story tall shearwall test assemblies were constructed with the A.T.S. overturning restraint system manufactured by Simpson Strong-Tie Co. The wall height and width were 8 feet with 12-inch platform floor framing assemblies. To limit the variables, the same wall system was tested for both skipped-

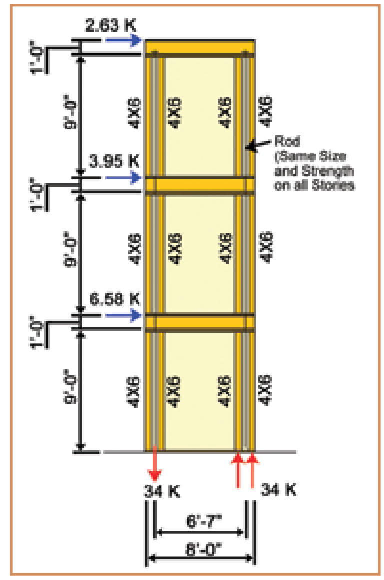

Figure 16: Skipped-Story System Example (External Statics)

story and tied-off conditions with the exception of the rod size, which was based solely on requirements for stress, not drift. Therefore, the skipped-story systems had the same rod size for that set of stories tied together, but the tied-off system had different rod sizes based on the calculated uplift demand at each floor.

The ground motion used in these tests was the Rinaldi ground motion record from the 1994 Northridge Earthquake, which had a peak ground acceleration of 0.84 g's and measured 6.7 on the Richter scale. Four types of three-story shearwall systems were tested (*Figure 19*):

1. 1st Story Only Skipped (No uplift restraint provided at top of 1st story).
2. 2nd Story Only Skipped (No uplift restraint provided at top of 2nd story).
3. 1st and 2nd Stories Skipped (No uplift restraint provided at top of 1st and 2nd stories)
4. All Stories Tied-Off (uplift restraint provided at top of each story)

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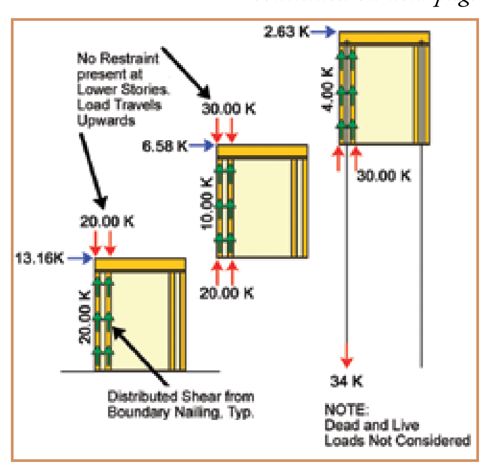

Figure 16a: Free Body Diagram of Skipped-Story System Uplift Side Shown Only (For Clarity)

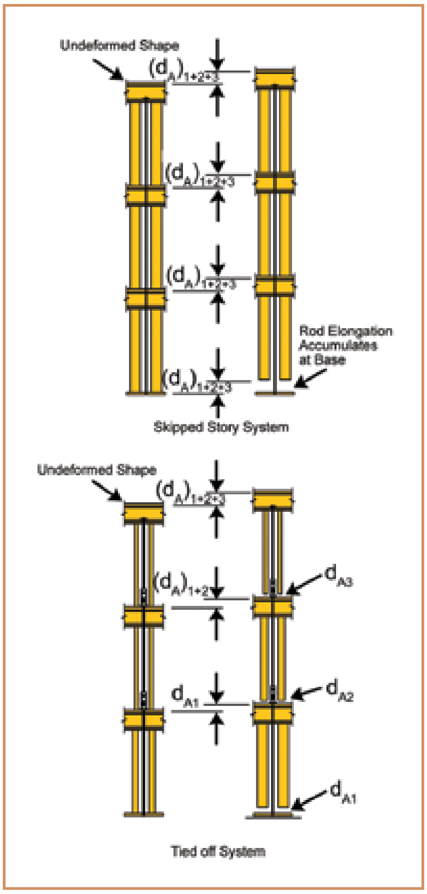

Figure 17: Initial Uplift Due to Rod Elongation Only

Each configuration was tested twice and the average response of the largest cycle of interstory drift is shown on *Figures 20-22*. The results of these tests show that skipping stories has the potential to significantly increase interstory drift, especially at the lowest story of any set of skipped-stories that are tied together by one restraint.

Figure 20 shows a dramatic increase in interstory drift at the first story when the first story restraint is skipped. *Figures 21* and *Figure 22* show less significant differences for interstory drift at the upper stories. This is expected since there is less accumulation of rod elongation and compression of wood elements at the upper levels. However, at the first story, the rod elongation and compression of wood elements of all stories accumulated enough to result in large uplifts and significant drift.

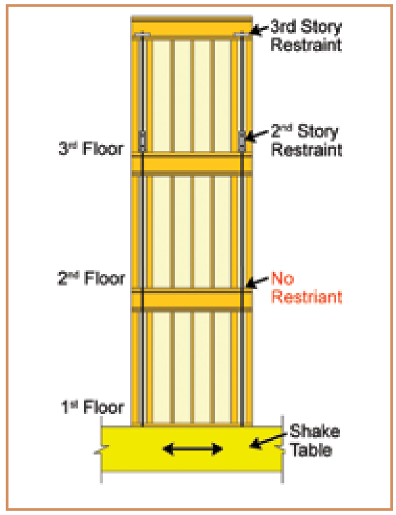

Figure 19a: 1st Story Only Skipped

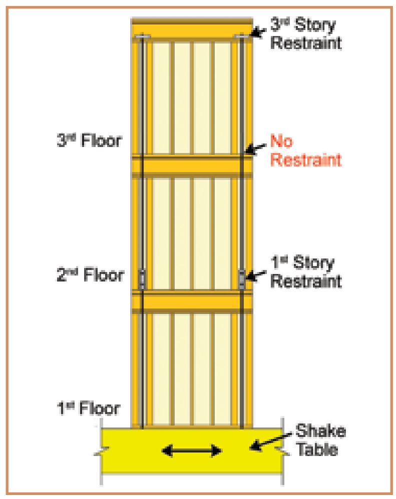

Figure 19b: 2nd Story Only Skipped

Figure 20 shows that it is especially critical to tie-off the first story. The 1st and 2nd Story Skipped system and the 1st Story Only Skipped system both had similar interstory drifts and neither system satisfied Code drift limitations at the lowest level whereas the All Stories Tied-Off system did comply with drift limits.

A common way stories are skipped is to have the first story tied-off, but then to have one or more of the upper stories skipped. For instance, consider a second story that is skipped relying instead on the third story above for uplift resistance. In such configuration, it becomes important to consider the interstory drift of the lowest story within that set of skipped-stories, or in this case, the second story. *Figure 21* shows the interstory drift of the second story test assemblies. As expected, the largest interstory drift occurred with the Second Story Only Skipped system. Since the second story was the lowest story, test results confirm that the lowest story in a set of skipped-stories tied together experiences the largest interstory drift when compared to a system with all of its stories tied-off.

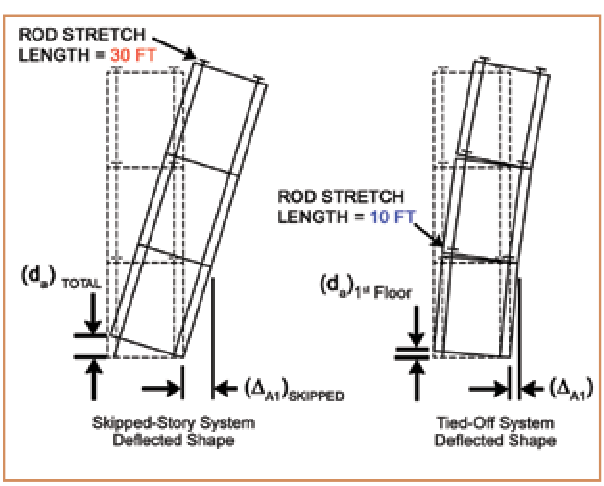

Figure 18: First Story Drift Due to Rod Elongation Only

Figures 23-24 illustrate the uplift of the posts at the first story for the different systems at the left and right ends of the wall. These graphs confirm that the uplift is indeed much higher for the skipped-story systems compared to the tied-off system, and is therefore contributing significantly to the horizontal interstory drifts seen in *Figure 20*.

The most important aspect of skipped-story systems that can be understood from the full-scale testing was overall system performance. The results point to a potentially serious problem, primarily for seismic loading, when skipped-story systems are designed for stress only, and not for deformation compatibility. When the overturning restraint skips the lower stories, the lateral stiffnesses of these stories are reduced. Combined with the fact that the first story of multi-story structures

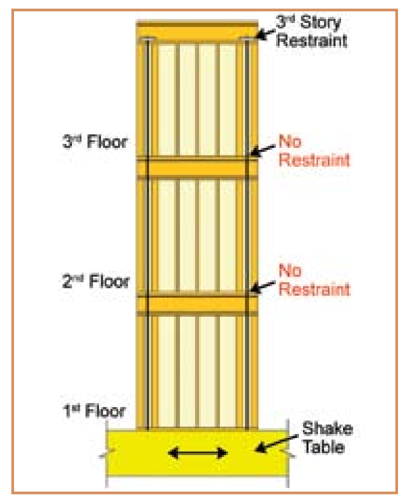

Figure 19c: 1st and 2nd Story Skipped

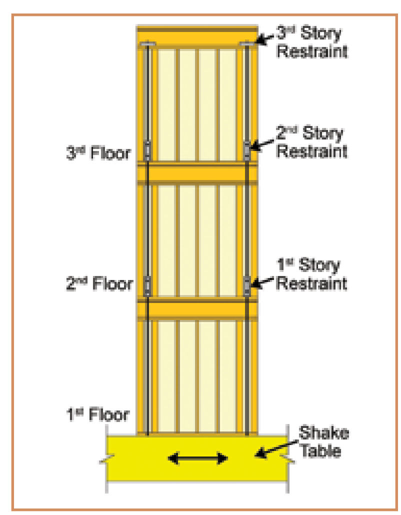

Figure 19d: All Stories Tied-Off

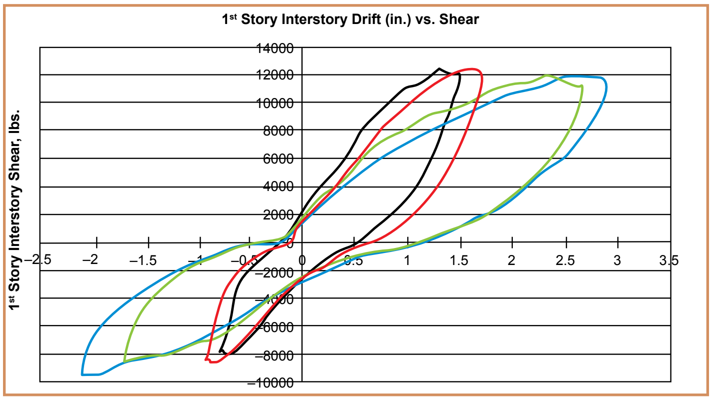

Figure 20

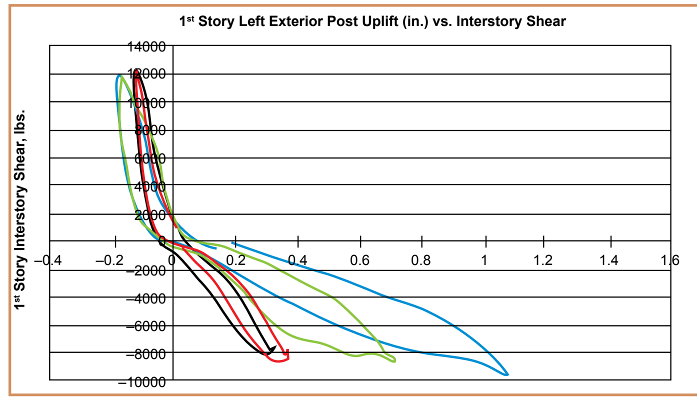

Figure 23

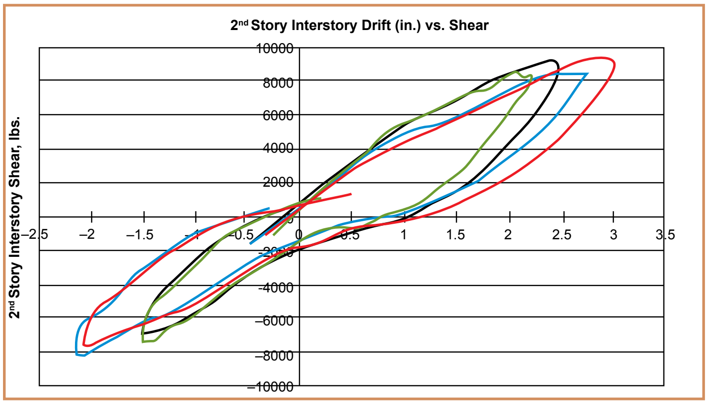

Figure 21

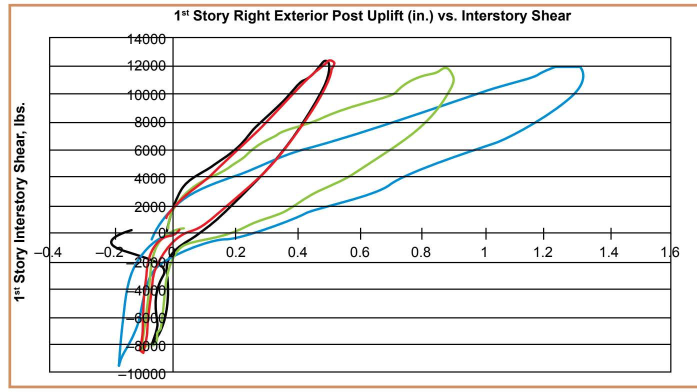

Figure 24

Legend Figures 20-24

- Average All Stories Tied-Off
- Average 1st Story Only Skipped
- Average 1st & 2nd Story Skipped
- Average 2nd Story Only Skipped

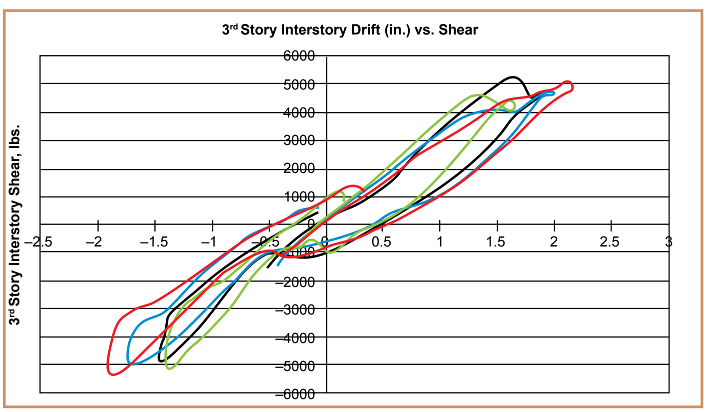

Figure 22

usually has more openings, less shear panels, and taller plate heights, a soft-story type of effect may occur. This can become more pronounced during high seismic demand when nonlinear response becomes concentrated in the lower skipped stories and ground shaking leads to degradation of strength and stiffness in the shearwalls at that story. However, it should be noted that this can be alleviated in a skipped-story system if the boundary members, both rods and posts, are sized to ensure that the cumulative uplift does not adversely affect the stiffness of the lowest shearwall in the set of stories tied together.

Conclusion

In summary, the use of continuous tiedown systems is increasing with the growth of multi-story light-frame structures. As a result, engineers need to analyze and design these structures with the understanding that these systems can significantly affect the behavior of the lateral load resisting system as a whole. In addition, engineers should understand how these systems affect construction sequencing and how they are affected by shrinkage and load path. Having a firm understanding of load path is the foundation for understanding how a slight modification in detailing, design, or deletion of an element, can radically change (and sometimes compromise) the integrity of the structure as a whole. By understanding the key issues with continuous tiedown systems, engineers can feel more confident that a proper design is provided and a safer structure is built. ▪

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