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A RATIONAL APPROACH TO THE INVESTIGATION, EVALUATION, AND SEISMIC RETROFIT OF MODERN RESIDENTIAL WOOD-FRAMED STRUCTURES

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SUMMARY

Modern wood-framed structures can often have significant construction defects and design deficiencies. Common construction defects in the lateral force resisting systems of wood-framed structures include poor installation of sheathing; failure to properly install holddowns; failure to install shear transfer details at perpendicular walls; failure to install attic and through-floor shear transfer details; failure to install collector elements; and over-notching of top plates and sheathing to install plumbing and HVAC. Design flaws and errors in wood-frame structures include specifying too many shear wall and holddown types, use of short shear walls that exceed the maximum allowed aspect ratio, not addressing construction tolerances, underestimating building weight, improperly distributing and accumulating lateral loads, not accounting for architectural constraints, and failure to provide adequate detailing. This paper discusses a rational approach to the investigation, evaluation, and retrofit of the lateral force resisting systems of modern wood-framed residential structures based on the authors' combined decades of experience in this field. Selection of an adequate sample basis, reduction and evaluation of field data, and simple, cost-effective approaches to the repair and retrofit of these structures are discussed. This paper is also intended to educate designers on the most common construction errors that may occur during implementation of their designs, so that new designs will be less susceptible to these errors.

INTRODUCTION

On the west coast of the United States, most wood-framed homes built around the turn of the 20th century were relatively small, with relatively simple architectural features, small windows, small rooms, and numerous walls. Modern wood-framed structures, however, push wood design to its limit – particularly the design of lateral force resisting systems. Today's modern structures include large single-family residences as well as multi-story, multi-unit condominium and apartment buildings, with complicated architectural features, large windows, large rooms, and fewer walls. Consequently, proper design and

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construction of the lateral force resisting systems of wood-framed structures are more important than before. However, modern wood-framed structures can often have significant construction defects and design deficiencies. Common construction defects include poor installation of sheathing; failure to properly install holddowns; failure to install shear transfer details at perpendicular walls; failure to install attic and through-floor shear transfer details; failure to install collector elements; and over-notching of top plates and sheathing to install plumbing and HVAC. Design flaws and errors include specifying too many shear wall and holddown types, use of short shear walls that exceed the maximum allowed aspect ratio, not addressing construction tolerances, underestimating building weight, improperly distributing and accumulating lateral loads, not accounting for architectural constraints, and failure to provide adequate detailing.

This paper discusses a rational approach to the investigation, evaluation, and retrofit of the lateral force resisting systems of modern wood-framed residential structures based on the authors' combined decades of experience in this field. Selection of an adequate sample basis, selection of inspection openings at critical load path details, reduction and evaluation of field data, and simple, cost-effective approaches to the repair and retrofit of these structures are discussed. This paper is also intended to educate designers on the most common construction errors that may occur during implementation of their designs, so that new designs will be less susceptible to these errors. For this paper, the term "plywood" includes any wood structural panel sheathing.

INVESTIGATION SAMPLING BASIS

During an investigation, it is important to investigate a sufficient number of locations that will provide an adequate basis for analyzing the in-field capacity of the lateral force resisting system. While it is theoretically *possible* to open up and expose every element of a lateral force-resisting system to determine whether or not it was built correctly, it is simply not *practical* since this would require that most if not all architectural finishes be removed and that the entire lateral force resisting system be disassembled (including elements that were installed adequately) before being able to conclude what defects were present. Fixing the defects would then be as simple – and as expensive – as reconstructing the entire lateral force resisting system correctly.

A more rational approach that is more in keeping with the engineering principle of finding the most economical solution to a problem is to randomly investigate a limited number of locations and then rationally analyze the data that results from that investigation. In our experience, detailed investigation of five to ten percent of the units (in the case of an apartment building, condominium complex, or housing development) typically will identify nearly all of the types of deficiencies that may be present and provide a rational basis from which to draw conclusions about what kinds of deficiencies are present and just how significant each deficiency is.

COMMON CONSTRUCTION ERRORS

The most common construction errors include poor installation of sheathing; failure to properly install holddowns; failure to install shear transfer details at perpendicular walls; failure to install through-floor shear transfer details at floor lines and in attics; failure to install collector elements; and overnotching of top plates and sheathing to install plumbing and HVAC.

Poor Installation of Sheathing

One of the most ubiquitous problems we see in existing construction is poor installation of sheathing. Sheathing is arguably the most important aspect of modern wood-frame construction, since it precludes the walls from racking significantly during wind- or earthquake-loading.

Missing sheathing
In a significant number of projects, we have found that contractors often omit plywood at some of the walls where plywood is required. We have never come up with a satisfactory reason for how or why specified plywood gets omitted; but it occurs (or fails to occur) in many projects that we have investigated. Omission of sheathing might be a function of difficulty or sequencing of construction trades; certainly plywood installation is labor intensive and somewhat expensive, but plywood shear walls are typically relatively easy to identify on the plans. We often see walls where the designer specified plywood on both sides that lack plywood on one of the two sides. We also often find plywood to be missing above the ceiling level in attic spaces or in ceiling soffits (Figure 1). Our best assessment is that the plywood is sometimes simply missed or overlooked when multiple construction trades are working simultaneously and are under a tight construction schedule. In any case, it is important to probe walls and inspect attics to ensure that the specified plywood is present.

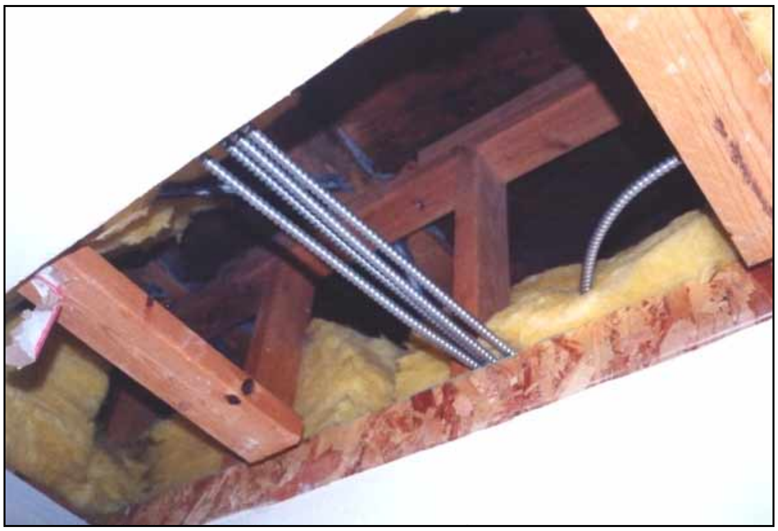

Figure 1: The plywood sheathing on this wall stopped at the underside of the ceiling and was not installed above the ceiling, resulting in a discontinuous load path.

A subset of the missing sheathing deficiency is the failure to install gypsum wall sheathing in architectural soffits, in attics, in crawlspaces, and behind architectural elements (e.g. bathtubs and showers). If walls are missing sufficient lengths of sheathing or are not continuously sheathed, the capacity of the overall structure can be significantly reduced. This defect often occurs because the gypsum sheathing is installed *after* the wood framing for these architectural elements is installed. The wood-framer is often required to install gypsum board in confined or difficult-to-access spaces. However, since it is generally possible for the gypsum board installer to install the sheathing in these areas even after the framing is installed, it is often not clear which trade was responsible for the failure to install the required sheathing. Consequently, it is important that the general contractor properly oversee and coordinate the work of the subcontractors.

Failure to follow nailing schedule
The wood-frame construction industry is not a rocket-science. We have found highly skilled and knowledgeable contractors; however, their laborers usually have focused skills and no engineering knowledge. For example, nail gun or stapler operators are often the least experienced members of a construction crew. In many of our projects, we have found that there is no statistical difference between the actual in-field nailing of walls with specified closely spaced fasteners (e.g. 2-inches on center) and fasteners that are specified at a maximum design spacing (e.g. 6-inches on center). This fact indicates that

the requirement for different nail spacing on different shear walls is not properly communicated by the contractor to his or her labor force; instead, one typical nail spacing is used – usually the maximum spacing – and the laborer nails the sheathing at that spacing no matter what the specified spacing. Even if the contractor is conscientious, there are almost always some conditions that preclude the achievement of the specified nailing. These small "conditions" can be as simple as failure to nail the plywood in some areas due to the presence of pipes or electrical conduits (and not adding supplemental nails on each side of the obstruction), installation of a few nails too close to the edge of the sheathing, or installation of a few nails that split or do not hit the wood framing behind the sheathing.

Failure to stagger nails is also a common problem, even among the best contractors. Even with notes and diagrams showing that nails should be staggered or "weaved," the laborer's natural instinct is to install the nails in a nice, straight line. Failure to stagger the nails has the potential to cause splitting (Figure 2).

Figure 2: Nails were installed too close together at this stud, causing the stud to split.

Another common problem is that the top edge nailing of the sheathing frequently ends up in the lower plate of the double top plate. While this deviation does not affect the strength of the plywood nailing, it does present through-floor shear transfer problems. Through-floor blocking is usually toe-nailed or clipped to the upper plate of the double top plate. If the sheathing is nailed to the lower plate (instead of the upper plate), then the through-floor shear transfer capacity may be governed by the internailing of the double top plates, which commonly only consists of a single 16d nail at 16 inches on-center (or sometimes less).

Substitution of box nails

Many of the projects we have investigated had smaller nails installed than were originally specified. These box nails are more readily available and are driven more easily than the larger common nails. The switch from 8d common nails to 8d box nails results in an approximately 20% loss of lateral strength due to the smaller shank diameter of the box nails. Unless the designer was particularly conservative when specifying shear wall nailing schedules, this switch alone can cause walls to be overstressed when analyzed for the required lateral forces.

Overdriven nails

Overdriven nails can significantly weaken a shear wall. Overdriving typically occurs when the nail gun operator uses a gun without a stop and increases the driving pressure to prevent underdriven nails, which, in order to install the finishes, require that the contractor go back with a hammer and hand-drive the nails that were not driven flush with the plywood. Due to the increased pressure, each nail is shot into the wood at a higher than necessary velocity, causing the nail head to be driven past the surface of the plywood. The nail head often crushes the first lamination of plywood and drives a wedge of compressed and broken wood fibers into the second and third laminations of plywood. Nails overdriven into OSB sheathing affect the capacity in a similar way. In some projects, we have seen nails so deeply overdriven that the heads of the nails are no longer visible.

According to our interpretation of research by the American Plywood Association (1990), if there are a substantial number of overdriven nails, the capacity of the wall is reduced significantly. While shallow overdrive depths (<1/16” for 3/8” plywood), do not cause a loss of capacity, a significant number of moderate overdrive depths (1/8” to 1/16”) will reduce the capacity of each overdriven nail by 50%. Nails that are overdriven more than 1/8” (in 3/8” plywood) have lost nearly all capacity.

Failure to install blocking in gypsum board shear walls

Designers often specify blocked gypsum board shear walls. The addition of blocking can add 25% to the allowable strength of the wall; however, installation of these blocks is problematic because it involves two trades – the wood framer and the gypsum board installer. Ideally, the framer installs the blocks and the gypsum board contractor installs and nails the gypsum board. Unless the gypsum board contractor communicates the exact locations where the blocks should be added, the framer doesn’t know where the blocks are required. (E.g. if the ceiling height is 8’-0”, the gypsum board theoretically would not need any blocks, as long as the 4’x 8’ sheets are installed vertically. However, since most gypsum board installers like to install sheets of gypsum board horizontally, blocking is then required at the horizontal joint between sheets. Thus, the framer is asked to do more work so that the gypsum board contractor has an easier job – definitely a hard “sell” to the framer). Furthermore, the gypsum board installer may not arrive on the site until after the framer has left, and many walls that are specified to be blocked end up being unblocked. To avoid this problem, the general contractor needs to properly clarify and coordinate the work of his or her subcontractors.

Failure to Properly Install Holddowns

The most common problems we typically encounter with holddowns include excessive inset, improper installation, and problems specifically associated with holddown straps.

Inset installation

Generally, the designer calculates the tension in a particular holddown assuming that the holddown is at the very end of the wall, and the structural plans typically reflect this assumption. Unfortunately, most holddowns that we find are inset (Figure 3), either to allow installation of bolts to connect the holddown to the studs or due to possible uncertainty in the concrete subcontractor where exactly to locate the holddown rods. This inset increases the holddown forces and can cause other problems associated with the inset, as described below.

Figure 3: This holddown is inset by more than 12-inches.

Improper installation

If the post or studs to which the holddown is connected is not at the very end of the wall, failure to edge-nail the sheathing to the holddown posts is a common mistake and can result in a load path discontinuity (i.e. the sheathing is not well-connected to the holddown post and can then uplift much sooner than the design engineer anticipated). Figure 4 shows this deficiency.

Figure 4: This holddown was inset; the holddown studs were not internailed; and the plywood was not nailed to the holddown studs.

Other holddown installation problems include countersinking of holddown bolts (to allow installation at the very end of a wall), which reduces the tension capacity of the holddown posts; use of multiple studs in lieu of a single solid post, which often causes only one stud to receive edge nailing; bending and angling of holddown rods, which can increase eccentricities in the holddown connection as well as decrease the rigidity of the lateral force resisting system; as well as simple failure to install the holddowns. Sometimes, it is clear from the installation that the contractor never really understood the purpose of the holddowns in the first place (Figure 5).

Figure 5: The holddown on the first floor is not connected to anything but a plate washer on the underside of the double top plate of the crawlspace (yellow arrow), resulting in a discontinuous load path.

Holddown straps

Holddown straps pose unique problems, since they require that the installer understand the purpose for which the strap is being used. Often we see the wrong size nails used (i.e. whatever size nail is readily available is used, rather than the nails specified by the strap manufacturer). Other common errors are failure to install the straps plumb or level, resulting in some nails missing the wood studs altogether, often called “air nails” or “shiners”; failure to install wood studs behind the straps, also resulting in air-nails or shiners; and failure to install the strap symmetrically so that the strap has an equal number of nails to each element that they are connecting. In a recent project in the San Francisco Bay Area, failure to connect the lower halves of a number of holddown straps to the supporting wood framing resulted in large wood-framed chimneys toppling over during a moderate windstorm (Figure 6).

Figure 6: This chimney collapsed during a wind storm due to the contractor's failure to nail the bottom halves of the holddown straps.

Failure to Install Shear Transfer Details at Perpendicular Walls

When a shear walls is intersected by a perpendicular wall, we commonly find a load path discontinuity due to inadequate shear transfer details at the intersection. Sheathing on the wall is often interrupted by the perpendicular wall, necessitating significant internailing of the studs or addition of sheet metal clips to provide shear transfer through the intersection. Failure to provide this connection creates an incomplete lateral load path.

Failure to Completely Install Attic and Through-Floor Shear Transfer Details

In our experience, attic and through-floor shear transfer details are some of the most poorly constructed details in wood-frame construction.

Failure to install attic shear transfer details

Attics, which are typically unfinished, should be the easiest place to install shear transfer details; however, we commonly find construction defects in attics. Failure to install trusses directly over designated parallel shear walls on the floor below is a common mistake that results in a discontinuous load path. Similarly, failure to install truss-blocking or other shear transfer details where shear walls on the floor below are perpendicular to the attic trusses also results in a discontinuous load path.

In our experience, V-type attic bracing, intended to transfer roof shear into shear walls perpendicular to roof trusses, is frequently improperly installed. Most installation problems with this type of bracing are associated with the connections at the underside of the roof sheathing and at the top of the shear wall.

Failure to install sheet metal clips or toenailing

Sheet metal clips or toenailing are often omitted in the construction of through-floor shear transfer details (Figure 7). If the clips (or toenailing) are present, they may be installed at a spacing that exceeds the design requirements, may lack the required nailing, or may have smaller-than-required nails. It is not clear why sheet metal clips are so often mis-installed; however, it may be explained by a simple lack of understanding of the purpose and importance of the details.

Figure 7: The required clips from the rim joist (yellow arrow) to the double top plate (red arrow) were not installed.

Missing or inadequate sole plate nailing

Sole nailing is another poorly constructed aspect of through-floor shear transfer details. The most common problem is installation of sole plate nailing at one nail per stud space (1 nail every 16-inches is code minimum), when closer spacing is required by the structural drawings (such as 6-inches on center or 2-inches on center). Another problem is that nails that are installed in the center of the sole plate often miss the rim joist or solid blocking below, decreasing the shear capacity of the shear transfer detail. Figure 8 shows a sole plate without the required nailing.

Figure 8: This sole plate only had one nail (yellow arrow) in 48-inches.

Failure to nail adjacent plywood sheets to a common member

Where plywood sheathing is installed, a common problem is the failure to nail adjacent sheets to a common member. We often find that exterior wall sheathing is typically installed similar to interior sheathing at floor levels. For example, while plywood installed on exterior walls is often nailed to the top plate at the top of the first floor walls and the bottom of the second floor plywood is often nailed to the second floor sole plate (Figure 9), resulting in a discontinuous load path unless sheet metal clips are installed to connect the second floor sole plate to the rim joist and the rim joist to the double top plate. Similarly, if a lower sheet of plywood is nailed to the bottom plate of the double top plate and the upper sheet of plywood is nailed to the upper plate, a load path discontinuity results unless the double top plates are internailed with sufficient capacity to transfer the design shear.

Figure 9: The second floor plywood was nailed to the second floor sole plate and the first floor plywood was nailed to the first floor double top plate, resulting in a discontinuous load path. Furthermore, the first floor plywood nails were installed *between* the plates of the double top plate, resulting in a connection with little or no capacity.

Failure to Install Collector Elements

Often, structural plans become so congested with information that specified collector elements or "drag struts" are difficult to discern. Combined with the framing contractors' typical lack of understanding of the purpose of the collectors and the potential difficulty in constructing collectors that may be perpendicular to the floor or roof framing, collector elements are often omitted from the construction.

Overnotching of Top Plates and Sheathing to Install Plumbing and HVAC

Plumbing and HVAC systems are typically installed after the wood framing, and these contractors often cut numerous holes in top plates, sole plates, and sheathing during their installation efforts (Figure 10). Typically, the damage that these contractors do to the wood framing is not identified or repaired during construction, potentially resulting in a significantly damaged lateral force resisting system.

Figure 10: This plywood shear wall is severely compromised by the HVAC and plumbing installation.

COMMON DESIGN FLAWS AND ERRORS

The most common design flaws and errors that we find when we evaluate the designs of modern wood-frame construction include specification of too many shear wall and holddown types, use of short shear walls that exceed the maximum allowed aspect ratio, failure to account for construction tolerances, underestimation of building weight, failure to use a triangular load distribution, failure to accumulate overturning in shear wall design, failure to account for architectural features such as floor toppings or sound transmission reduction techniques, and failure to provide adequate detailing.

Specification of Too Many Shear Wall and Holddown Types

Shear wall types can range from gypsum board, stucco, and plywood, can be one- or two-sided, and can have a variety of specified fastener spacings. Many designers apparently believe that a good design provides exactly the correct capacity at each wall. Consequently, many designers include and use up to 15 different shear wall types in the design of wood-framed structures, using these shear wall types to get almost exactly the "correct" capacity (Figure 11). As discussed above, we have found that there often is no statistical difference between the actual in-field nailing of walls with specified closely spaced fasteners (e.g. 2-inches on center) and fasteners that are specified at a maximum design spacing (e.g. 6-inches on center). To expect a contractor to keep track of 15 different shear wall types within a complex project is unrealistic. Keeping it simple is the approach that should be incorporated into the design. In our opinion, it is better to choose one type of material (e.g. plywood) and only a few spacings (e.g. 4-inches on center and 2-inches on center) and possibly "overdesign" a few walls, rather than design each wall with just enough capacity to work – if the wall is constructed perfectly.

SHEARWALL SCHEDULE

1. (2) LAYERS 5/8" BLOCKED DRYWALL WITH 6D COOLER NAILS @ 9" O.C. @ EDGES AND FIELD AT BASE LAYER WITH 8D COOLER NAILS @ 7" O.C. @ EDGES AND FIELD AT FACE LAYER
2. 1/2" DRYWALL WITH 5D COOLER NAILS @ 7" O.C. @ EDGES AND FIELD
3. 5/8" DRYWALL WITH 6D COOLER NAILS @ 7" O.C. @ EDGES AND FIELD
4. 1/2" DRYWALL WITH 5D COOLER NAILS @ 4" O.C. @ EDGES AND FIELD
5. 5/8" DRYWALL WITH 6D COOLER NAILS @ 4" O.C. @ EDGES AND FIELD
6. 1/2" BLOCKED DRYWALL WITH 5D COOLER NAILS @ 4" O.C. @ EDGES AND FIELD
7. 5/8" BLOCKED DRYWALL WITH 6D COOLER NAILS @ 4" O.C. @ EDGES AND FIELD
8. 7/8" STUCCO OVER PAPER BACKED LATH 2/16 GAUGE STAPLES @ 6" O.C. AT TOP AND BOTTOM PLATES, EDGES OF SHEAR WALL, AND FIELD. ICBO REPORTS NOS. 1823 & 1318
9. 7/8" STUCCO OVER PAPER BACKED LATH 2/16 GAUGE STAPLES @ 3" O.C. AT TOP AND BOTTOM PLATES, EDGES OF SHEAR WALL, AND 6" O.C. AT FIELD. ICBO REPORTS NOS. 1823 & 1318
10. 3/8" STRUCTURAL II PLYWOOD WITH 8D NAILS @ 6" O.C. @ EDGES AND 12" O.C. @ FIELD
11. 3/8" STRUCTURAL II PLYWOOD WITH 8D NAILS @ 4" O.C. @ EDGES AND 12" O.C. @ FIELD
12. 3/8" STRUCTURAL II PLYWOOD WITH 8D NAILS @ 3" O.C. @ EDGES AND 12" O.C. @ FIELD
13. 3/8" STRUCTURAL II PLYWOOD WITH 8D NAILS @ 2" O.C. @ EDGES AND 12" O.C. @ FIELD
14. 1/2" STRUCTURAL II PLYWOOD WITH 10D NAILS @ 2" O.C. @ EDGES AND 12" O.C. @ FIELD
15. 1/2" STRUCTURAL I PLYWOOD WITH 10D NAILS @ 2" O.C. @ EDGES AND 12" O.C. @ FIELD

Figure 11: This designer specified 15 types of shear walls.

Similarly, choosing a different holddown – one to match as nearly as possible the calculated uplift forces – for each particular wall can prove troublesome during construction. Each different type of holddown can involve different hardware, installation procedures, and tools. It becomes difficult for the subcontractors (concrete and framing) to keep track of the different hardware, where it is to be placed, and what specific procedures need to be followed for each installation if a large number of types and sizes of holddowns are specified.

Use of Short Shear Walls that Exceed the Maximum Allowed Aspect Ratio

Often, a lack of coordination between the architect and engineer results in the use of shear walls that are too short to be useful. The model building codes require walls to maintain a certain height to width ratio (typically 2:1 in high seismicity regions and 3.5:1 in lesser seismicity regions). Failure to coordinate the final structural drawings and calculations with the final architectural drawings can result in shear walls that are too narrow and exceed the maximum allowed aspect ratio.

Failure to Account for Construction Tolerances

Based on our review of numerous designs, designers often fail to account for construction tolerances in their design. Failure to understand that traditional bolted holddowns are difficult to install at the very end of a shear wall can result in undersized and inset holddowns. Because the holddown posts are not at the extreme edge of the wall and are usually installed as a supplement to the 16-inch on center wall framing, the posts often receive no nailing whatsoever, since the operator of the nail gun cannot see the extra holddown post and often skips this element entirely. It is important that the sheathing installer mark the locations of the holddown posts on exposed surface of the plywood so that the nail gun operator knows to nail the plywood to the posts. If the designer does not provide a detail to show how sheathing should be nailed to an inset holddown post, the framer is more likely to construct this connection improperly. What we typically see is edge nailing to a 2x trimmer stud at the end of the wall, and nominal nailing or no nailing at the holddown post.

Similarly, the design of extremely short shear walls can place an undue burden on the concrete subcontractor, who is unable to place the holddown rods without some variation in location. A 24-inch wide shear wall may seem like a good idea to a designer, but the physical reality is that there may be insufficient room for the required anchor bolts, the end studs, the holddown rods, and the studs for any intersecting walls. Holddown rods must necessarily be located several inches inboard of the end of the wall, *plus* any construction tolerances associated with the placement of the holddown rods. Designers should appreciate and incorporate construction tolerances into the design of shear walls, especially short shear walls.

As described above, plumbing as well as heating, ventilation, and cooling (HVAC) contractors can also wreak havoc with shear wall framing. Plumbing and HVAC systems are typically installed after the wood framing, and these contractors often cut numerous holes in top plates, sole plates, and sheathing during their installation efforts. Failure to recognize that a wall that also serves as a plumbing or HVAC chase can be significantly damaged by these utilities can result in reliance on an ineffective shear wall.

Underestimation of Building Weight

Quite often, designers underestimate the actual weight of a structure, resulting in a reduced earthquake design base shear. This underestimation can result from failure to account for architectural finishes such as a nonstructural floor topping (such as gypcrete or lightweight concrete, installed to reduce sound transmission between units), failure to accurately estimate the lengths and weights of nonstructural partitions, or failure to accurately estimate the weight of the floor, wall, and roof assemblies. Finishes such as nonstructural floor toppings or the presence of a tile roof can dramatically increase the lateral loads on a structure, and failure to account for these finishes can cause the lateral system for the building to be significantly under-designed.

Failure to Use a Triangular Load Distribution

It is unknown to the authors why designers fail to use a simple triangular load distribution, but sometimes they do. Historically, uniform load distribution was removed from the Uniform Building Code in 1961 (1976 for two-story buildings) and is currently only acceptable when seismic loads are increased 20%. We believe the mistake may come from a desire to compare the wind loads and the seismic loads in a simple manner (such as comparing only base shear) and then designing for the lateral load type that has the largest base shear; however, failure to account for the triangular load distribution that is associated with seismic design can lead to under-design of the upper floors of a structure.

Failure to Accumulate Overturning

Sometimes, designers fail to accumulate overturning on multi-story walls or fail to track forces down to the foundation for walls that are discontinuous, resulting in under-designed or missing holddowns. In the authors' opinion, drawing free-body diagrams of the shear walls could preclude such design errors. By drawing a free-body diagram and rationally resolving the forces on each wall segment, the designer can more clearly see where the forces are going and adequately design the lateral force resisting system to resist these forces.

Failure to Account for Architectural Features

Floor toppings or sound-transmission-reduction techniques cause significant problems with a lateral force resisting system. Floor toppings, such as gypcrete or lightweight concrete, are generally added to reduce sound transmission between units; however, the floor toppings can significantly increase the weight of the structure (and hence the seismic demands) as described above. In addition, the floor toppings often require the use of a double sole plate, with the lower sole plate used as formwork for the topping. After the topping cures, the upper sole plate is added and the wall sheathing nailed to the upper sole plate. Even if the upper sole plate is well nailed, the connection between the lower sole plate and the floor plywood is often deficient due to the fact that the lower sole plate was only tacked into place as the formwork. This is often as much of a construction error as a design deficiency.

Horizontal diaphragms between units are often cut to reduce sound transmission between units. If the designer has failed to account for this technique and has supported lateral loads from one unit with the shear walls in a horizontally adjacent unit, the lateral load path becomes discontinuous.

Failure to Provide Adequate Detailing

We find that many designs lack detailing adequate to properly convey the designer's intent. Areas found to lack adequate detailing include through-floor transfer details, roof connection details, holddown installation requirements (as discussed above), and shear nailing around openings. It is important to show sufficient details in the plans so that the contractor can construct the design without having to extrapolate the design or "improvise."

EVALUATION AND ANALYSIS OF CONSTRUCTION AND DESIGN DEFICIENCIES

Once the most common deficiencies have been identified (by investigating the deficiencies described above), the in-field capacity of the elements of the lateral force resisting system can be calculated and any significant deficiencies can be addressed. Determination of the effective capacity of the nailing of the various elements is one of the most important steps in the analysis. A method pioneered by the authors and one that has generally achieved acceptance in the wood-frame engineering community – at least in the San Francisco Bay Area – is the determination of an effective in-field capacity by disregarding the worst 10% of the nailing data samples and using the 90^{th} percentile spacing to compute an effective capacity. This approach discounts the 10% worst data points (assuming that these data points are anomalies that would not significantly affect the strength of the structure as a whole) but avoids the pitfalls of using an average or mean spacing that has the potential to overestimate the capacity of shear walls and through-floor connections.

Effective in-field capacities are then compared to code-specified demand forces. Only shear walls or components that do not have adequate effective in-field capacity require repair. This approach is rational and can significantly reduce the scope and cost of the repairs.

REPAIR AND RETROFIT OF THE LATERAL FORCE RESISTING SYSTEM

A rational design can substantially reduce costs and disruption associated with a repair or retrofit. Some examples of rational designs follow.

Often, construction errors can be so rampant in a development that nearly all of the shear walls have significant deficiencies. Rather than open up and correct all deficiencies at all of the walls, it can sometimes be better to abandon most of the walls and strengthen a few select walls. For example, rather than renail a large number of gypsum shear walls and strengthen through-floor shear transfer mechanisms at all of these walls (to correct inadequate nailing, lack of solid blocking, and deficient through-floor shear transfer mechanisms), it may be better to select a few reasonably long walls in each direction, remove the gypsum board, add plywood and holddowns and through-floor shear transfer, and re-engineer the entire lateral force resisting system to rely entirely on these few walls.

Simple cost-effective solutions can also be implemented. If through-floor clips are missing at one level and sole plate nailing is deficient directly above, the simple solution is to open the ceiling, install the through-floor clips and using long nails or screws to engage the sole plate above. In this example, costly repairs to wall finishes can be avoided.

One other consideration that must be kept in mind when assessing these types of structures is that failure to comply with the drawings does not necessarily constitute defective construction. As discussed above, there will be elements of the construction that do not match exactly what is shown on the drawings. It is the job of the investigating engineer to determine whether or not these variances are significant, whether the construction deviations constitute a failure to meet the governing building code, and whether the conditions require a repair. The engineer performing the assessment must use a rational approach that involves accepted engineering principles as well as his or her own engineering judgment to determine whether or not deviations from the plans result in actual deficiencies.

SUMMARY AND CONCLUSIONS

Modern wood-framed structures can often have significant construction defects, and design flaws and errors. Design engineers are encouraged to reduce the complexity of their designs and make their designs more constructible, include in their designs some margin of conservatism to account for less-than-perfect construction, and perform in-field construction observation to help the contractors build the design correctly, clarify the design. General contractors need to understand the importance of all the components of the lateral load resisting systems and convey this information to his or her subcontractors and the individuals who are actually installing the components. The contactors must identify conflicts between trades and resolve them before construction is concluded. Engineers evaluating existing structures, and designing repairs and upgrades to such structures are encouraged to look for the typical errors described above and make rational and practical repair recommendations to the owner.

REFERENCES

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2. International Conference of Building Officials, *Uniform Building Code, 1961 Edition*, Los Angeles, California, 1961.
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