

An Engineer's Responsibility in the Design and Detailing of a Structure's Lateral Force Resisting System (a Case Study)

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Abstract

This paper will discuss the responsibilities of the structural engineer in designing and detailing conventionally framed multi-story structures. Specifically, this paper will identify the importance of a clear layout of intended shear walls, detailing for the transfer of design wall loads, and for the transfer of design diaphragm loads. The necessity for these design and detailing requirements, including the issues that result when the structural engineer fails to do its job properly, will be illustrated through a case study of a multi-family residential complex located in southwest Colorado.

Structural deficiencies resulting directly from improper design and/or detailing of the lateral force resisting system, and the potential for, and consequences of, unintended construction deficiencies will also be addressed.

Introduction

The United States has seen the proliferation of multi-story, multi-family structures throughout the country, many of which were designed and constructed with conventional "stick" framing. Material for these buildings typically consists of wood or light gauge metal studs and joists and plywood/OSB decking and sheathing. For these buildings to perform correctly, it is imperative that the structural engineer properly design and detail a functional gravity load resisting system, a functional lateral load resisting system, and proper connections and load transfer throughout the structural system to assure a well-performing and safe structure. It is the opinion of the authors that the structural engineer of record (EOR) is responsible for the design of the entire gravity and lateral load resisting structural system in order to assure its ability to resist required design loads. The structural EOR's design responsibility includes the specification and detailing of the design requirements in a clear, unambiguous manner on the structural design documents. It is standard structural engineering practice for the following information regarding the lateral force resisting system to be included in the structural design documents:

- ❑ Clear identification of shear wall locations;
- ❑ Details for structural diaphragms;
- ❑ Details for shear wall assemblies;

- ❑ Details for anchorage and connections for shear transfer.

Failure to properly convey this information can, at best, result in an increased need for clarification by the EOR on the construction project in order to achieve the intended structural capacity. At worst, this oversight can result in construction of a structurally deficient building. Basic requirements to create a competent structural Lateral Force Resisting System (LFRS) will be described in the following section.

Lateral Force Resisting System

The lateral force resisting system (LFRS) of a conventionally framed structure typically consists of the following components:

Diaphragms

A structural diaphragm is a horizontal or inclined structural element that distributes lateral loads to the vertical portion of the lateral load resisting system. In conventionally framed construction, horizontal structural diaphragm systems are typically provided by the framing and decking systems of the roof and the elevated floors of the structure. Diaphragms can be designed to transfer lateral forces to exterior shear walls, interior shear walls, or a combination of exterior and interior shear walls. Major components of a competent structural diaphragm system include:

- ❑ **Specification of decking** including thickness and span ratio;
- ❑ **A defined and detailed fastener pattern** for the connection of the roof and/or elevated floor decking to the framing below;
- ❑ **Continuous load paths** for tension and compression forces at the perimeter of and at significant penetrations within the diaphragm. Due to the irregular footprint of some buildings, detailing on the structural plans may be required in the design and drawings to provide a continuous load path and to convey the structural intent to the construction team;
- ❑ **A diaphragm connection** to transfer loads to the vertical shear wall system.

Shear Walls

Shear walls support the diaphragm and transfer lateral forces into the foundation. For small buildings, the exterior walls are often designed as shear walls to transfer all of the lateral forces to the foundation. The strength and stiffness provided by interior partition walls is generally not included by the structural engineer in designing this type of lateral force resisting system. For larger buildings, it is a common design practice to include and identify interior walls chosen to transfer lateral forces to the foundation. The inclusion of interior shear walls in the lateral force resisting system reduces the shear load which the exterior shear walls must resist. Major components of conventionally framed shear walls include:

- ❑ **Specification of sheathing** including thickness and span ratio;
- ❑ **A defined and detailed fastener and blocking pattern** for the connection of the exterior sheathing to the wall framing;
- ❑ **Continuous load paths** for tension and compression forces at the ends of the shear walls, typically achieved by providing hold-downs and/or strapping;

- ❑ **Specification and identification of hold-down/strapping type and location** within the vertical shear wall system.

Proper anchorage and connections of the LFRS are vital to its ability to adequately transfer forces through the diaphragm, into the shear walls, and ultimately into the foundation system. Failure to provide adequate direction for foundation anchorage and connections to tie the components of the LFRS together is considered a design defect and would result in non-continuous lateral load paths. A lateral force resisting system with a non-continuous lateral load path would be structurally deficient in transferring loads into the foundation system without relying upon unintended and typically not quantified structural capacity within the constructed building assembly.

As discussed in the following section, the design of a competent LFRS is not a "cookbook" exercise; proper detailing for each specific LFRS is essential to convey the design intent to the construction team.

Design and Detailing Considerations

Good design and detailing practices will go a long way toward achieving a quality installation of a structural LFRS. **The design of a competent LFRS is not simply an exercise in choosing components from a table.** Great care must go into the selection of the LFRS components, development of loads on the LFRS, and detailing of the interaction of the LFRS components. Some examples of specific LFRS design considerations include, but are not limited to:

Diaphragm Specification and Detailing

Depending on the width that the diaphragm is intended to span, the lateral shear loads within the diaphragm may be quite high; however, diaphragm assemblies do have maximum capacities. Table 2306.3.1 in the 2006 International Building Code (IBC) provides allowable shear loads for various diaphragm assemblies. The 2006 IBC was the governing code at the time of evaluation of the structures presented in the case study. Depending on the chosen diaphragm assembly, additional detailing or direction may be required. For example, according to Table 2306.3.1, a blocked diaphragm consisting of 3/8" thick Structural 1 plywood panels with 8d nails spaced at 6" o.c. can resist up to 300 plf of shear (neglecting any potential allowable increase for wind/seismic forces), **only** if the diaphragm is attached to 3x framing/blocking at adjoining panel edges. Failure to include a specification or detail in the construction documents for the diaphragm to be blocked and framed with 3x members reduces the allowable load resistance of the diaphragm, potentially to an allowable load less than calculated during the load development process.

Diaphragm design considerations may include the need for drag-struts and/or specific chord tie detailing. Drag struts are typically required when a diaphragm is of an irregular shape, which is common on more architecturally creative buildings with reentrant corners, balconies, atriums, etc. Drag struts are essential to provide a path for lateral forces to transfer into and out of a shear wall or to transfer across openings or breaks in shear walls.

Additionally, since the diaphragm acts essentially in the same manner as a deep beam, lateral forces typically create compressive forces on the windward side of the diaphragm and tensile

forces on the leeward side. Chord ties are included at the diaphragm boundary to provide resistance for these forces. In conventional wood framing, the double top-plate of a wall can act as the chord tie unless dimensional irregularities exist at the building's footprint where blocking and strapping across the irregularity is necessary to provide the continuous force path required.

Transfer of Forces from the Diaphragm into the Shear Walls

Once the lateral forces affecting the structure have been collected by the diaphragm, they must then be transferred into the designated shear walls below. The structural engineer must provide proper detailing on the construction documents to ensure that the shear loads can be transferred from the roof/floor deck, through the deck fasteners, into the framing/blocking, and then through the framing fasteners and into the shear wall framing below. Since lateral forces affect structures in more than one direction, the EOR must provide detailing and/or direction for attachment for this load transfer at a minimum of two conditions: where roof/floor framing is oriented perpendicular to the wall framing, and where roof/floor framing is oriented parallel to the wall framing.

Shear Wall Specification and Detailing

Shear walls act in a similar manner to their diaphragm counterpart; therefore, their specification and detailing requirements are very much the same, including specification of sheathing type, sheathing thickness, blocking, fastener types and patterns, etc. In an ideal situation, the shear walls would consist of completely unobstructed framing with no openings. Unfortunately, architects usually discourage this, and thus the structural engineer is required to address the issue of transferring lateral loads around window and door openings.

The structural engineer can analyze the shear walls in one of two ways. The first is through the segmented or panel method which essentially treats full height wall sections as individual panels and neglects any contribution of shear resistance through sections of the wall with door/window openings as shown in **Figure 1**.

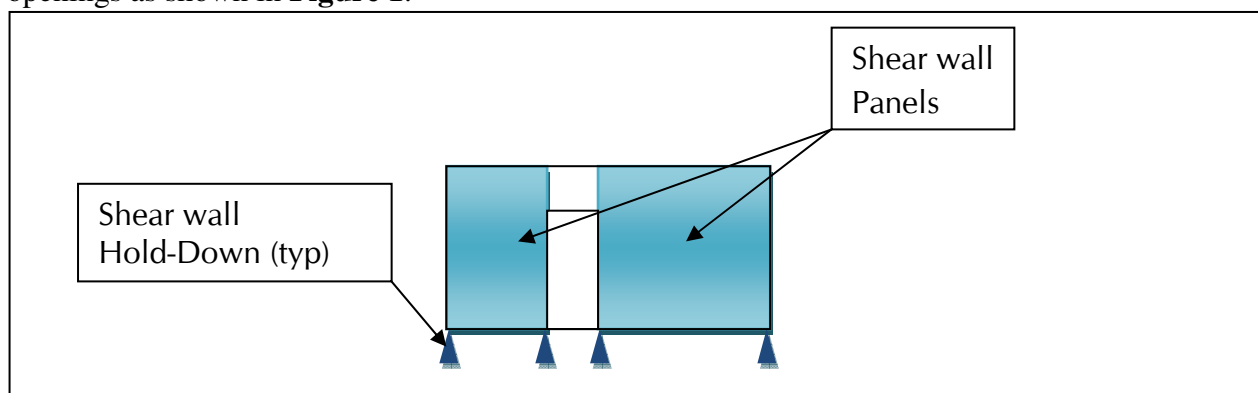


Figure 1: Shear wall Panels (Segmented/Panel Method)

The second method of shear wall analysis is through the perforated method. This approach essentially treats the entire wall section as an entire shear resisting unit as shown in **Figure 2**. Unlike the panel method, requirements for blocking and/or strapping must be included around openings in order to transfer the shear loads around the perforation.

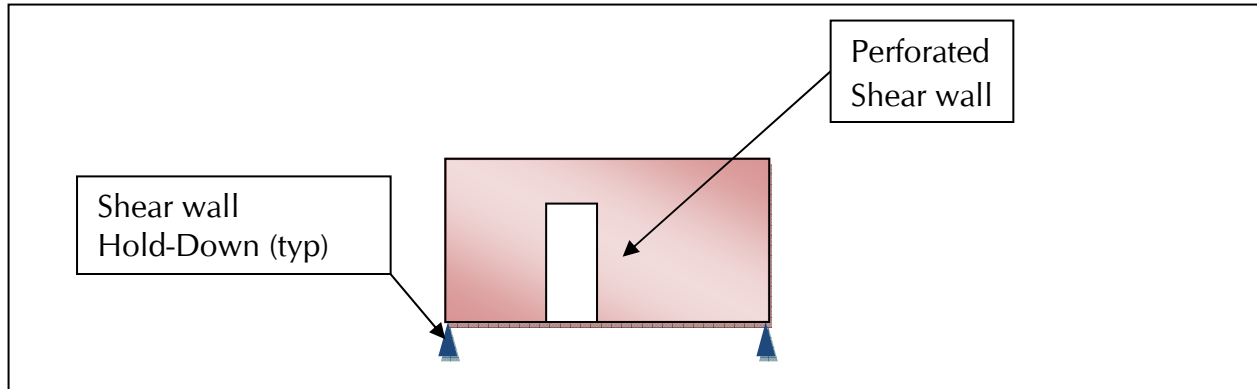


Figure 2: Shear wall (Perforated Method)

While it is acceptable to analyze shear walls within the LFRS by either the segmented or perforated method, design and detailing differences exist between the two. As seen in the figures above, four hold-downs are required at the segmented wall in Figure 1 while only two hold-downs are required for the perforated wall in Figure 2. This is only one of the differences which the structural engineer of record must take into account and clearly convey on the structural design drawings.

While there are a number of other design requirements that the structural engineer of record must take into account during the design of the shear walls, this paper is only intended to illustrate some of the options that are presented to the EOR during the design process and to convey the overall premise that design and construction of a structure's LFRS is not a "cookbook" exercise, thus the need for clear, concise design direction. The case study presented below will further explore some of these options and the consequences of providing inadequate design direction.

Case Study – "The Complex"

Over the past few years, the authors have taken part in the evaluation of a multi-story, mixed-use complex located in southwestern Colorado. The evaluation was performed as part of a forensic investigation regarding alleged construction defects at the buildings which will be referred to as "The Complex". The subject buildings consisted of four separate residential structures framed primarily with light-gage steel studs, cold-formed steel joists, OSB and plywood exterior sheathing, and plywood roof deck. The Complex was designed and permitted under requirements of the 1997 Uniform Building Code (UBC). The structures were generally long and slender with many openings, balconies, re-entrant corners, offset walls, etc.

Interior Shear Walls

Due to the long, slender footprint of the multi-story buildings, the need to engage interior shear walls in the short direction should have been evident to a prudent structural engineer; however, a review of the structural drawings revealed that the structural engineer of record failed to identify which, if any, of the interior walls were intended to perform as shear walls. Further, due to the complexity of the footprint of the buildings and the many offset walls and balconies in the long dimension, the need for shear wall identification and assembly requirements should have also been evident to the structural engineer. No specific detailing was provided regarding how to construct these walls and transfer/collect lateral loads at these dimensional offsets.

Observations of destructive testing performed during a forensic investigation at The Complex indicate that the interior demising walls consisted of 8" metal studs with one layer of 5/8" gypsum board fastened directly to one side of the stud and two layers of 5/8" gypsum board fastened to a resilient channel on the opposite side of the stud. This constructed assembly was in general compliance with wall details located within of the architectural design documents. Observations also indicated that the stud size, spacing, and material strength as installed at the interior demising walls were in general conformance with the "shearwall/bearing wall schedule" included within the structural design documents.

Although the as-constructed wall assemblies appeared to conform to the limited design details and notes within the architectural and structural drawings, the structural engineer of record failed to provide the design direction required to construct a functional LFRS. Deficiencies noted within the structural design documents related to interior shear walls include:

- ❑ **A lack of direction regarding fastener spacing requirements:** Fasteners at the interior wall assemblies appeared to comply with the assembly requirements set forth within the architectural drawings (generally related to fire and sound ratings); however, no direction regarding fastener type and/or spacing was provided by the structural engineer. As detailed in the design documents, the interior demising walls failed to provide lateral load resistance without relying upon unintended structural capacity.
- ❑ **Identification of shear wall locations:** Although a "shearwall/bearing wall schedule" was included within the structural design drawings, the information provided within the table was ambiguous and confusing. Furthermore, intended interior shear wall locations were not identified on the structural framing plans.
- ❑ **Details regarding diaphragm to shear wall load transfer:** Where details were provided, they typically included the identification of major structural components (joists and wall framing); however, **no information which would be required to construct a functional LFRS was provided** including, but not limited to, the attachment of sheathing to floor or roof framing, attachment of floor framing to the wall framing below, blocking type and attachment, etc.

Exterior Shear Walls

In the absence of interior shear walls, the exterior shear wall system is required to resist the lateral loads on the building. For the exterior walls to function in this capacity, a horizontal diaphragm provided by some combination of the roof and elevated floor levels is required to transfer lateral loads from the interior of the building to the end walls.

Observations of destructive testing performed at The Complex indicate that the exterior walls consisted of 8" metal studs with one layer of 5/8" gypsum board fastened directly to the interior side of the stud and 1/2" plywood/OSB fastened to the exterior side of the stud. The stud size, spacing, and material strength as installed at the exterior walls were in general conformance with the "shearwall/bearing wall" schedule as shown within the structural design documents. The fastener pattern at the exterior sheathing ranged from approximately 5" to 7" at vertical joints and approximately 10" to 12" in the field. No blocking or fasteners were observed at the horizontal sheathing joints between stud locations.

The east and west facing exterior walls at all four buildings typically included window and door openings in addition to east/west set-backs. Since these exterior walls included perforations and dimensional irregularities, the structural engineer of record should have identified the need for specific detailing for the transfer of lateral forces around openings if the walls were intended to perform as shear walls, including:

- ❑ Blocking at studs;
- ❑ Strapping around openings;
- ❑ Hold-down locations;
- ❑ Hold-down specifications;
- ❑ Blocking of floor/roof joists to collect and transfer lateral loads around wall set-backs.

Since none of the aforementioned detailing requirements were included in the structural drawings, it is not surprising that destructive testing performed at these locations revealed a lack of blocking, strapping, and hold-downs.

The only indication of shear wall requirements found within the drawings were included in two separate notes located within the structural design drawings. Note A located within the light-gage metal framing section of the General Structural Notes stated:

*Exterior sheathing shall be 1/2" gypsum sheathing fastened to resist 500 plf minimum shear. Gypsum sheathing shall be applied **perpendicular** to framing with strap blocking behind the horizontal joint and with solid backing between the first two end studs. Space screws at 4" on center edges and 7" on center field. [Emphasis added]*

The "shearwall/bearing wall schedule" located within the structural design drawings included Note B which stated:

*Exterior shear wall sheathing shall be 1/2" OSB or 1/2" gypsum sheathing. Install sheathing **vertically**. Provide 18 ga. strap at all sheathing joints perpendicular to framing. Fasten perimeter at 4" o.c. and 12" o.c. at **intermediate framing**. [Emphasis added]*

A review of these two notes identifies multiple conflicts in the direction given to the construction team which illustrates poor structural design practices, including:

- ❑ **Option to install either OSB or gypsum sheathing as part of an exterior shear wall assembly:** Tables 22-VIII-A and 22-VIII-B in the 1997 UBC (the applicable code at the time of design/construction) provide nominal shear values for wind forces for shear walls faced with OSB and Gypsum Wallboard, respectively. Additionally, Note 1 in both tables gives the requirement of applying an applicable strength reduction factor or appropriate safety factor to the nominal shear values shown in order to determine design shear strengths (LRFD) or the allowable shear values

(ASD). **Table 1** and **Table 2** show design shear strengths and allowable shear values for shear walls framed with cold-formed steel studs and faced with gypsum wallboard and 7/16" OSB on one side, respectively.

Table 1: Design Shear Strength and Allowable Shear Value for Shear Walls Framed with Cold-Formed Steel Studs and Faced With Gypsum Wallboard.

Assembly	Orientation	Fastener Spacing (Edges/Field)	(LRFD) Design Shear Strength with 0.45 Reduction Factor Applied per Section 2219.3	(ASD) Allowable Shear Value with 3.0 Safety Factor Applied per Section 2219.3
1/2" Gypsum board on both sides	Gypsum board applied perpendicular to framing with strap blocking behind the horizontal joint and with solid blocking between the first two end studs.	7"/7"	263 lbs/ft	195 lbs/ft
		4"/4"	382 lbs/ft	283 lbs/ft

Table 2: Design Shear Strength and Allowable Shear Value for Shear Walls Framed with Cold-Formed Steel Studs and Faced With 7/16" OSB, One Side.

Assembly	Fastener Spacing (Edges/Field)	(LRFD) Design Shear Strength with 0.45 Reduction Factor Applied per Section 2219.3	(ASD) Allowable Shear Value with 3.0 Safety Factor Applied per Section 2219.3
7/16" OSB on one side	4"/12"	634 lbs/ft	470 lbs/ft

As displayed in Table 1, the 500 lbs/ft shear strength required in Note A cannot be achieved with 1/2" gypsum board. Furthermore, Note A does not require cladding the exterior shear walls with OSB.

Note B gives the option of cladding the exterior shear walls with OSB or gypsum board. Comparison of the values within Tables 1 and 2 above indicates significantly different design shear strengths and allowable shear values when gypsum board is used versus OSB. Giving the option to the construction team to choose between materials with vast differences in strengths illustrates that the structural engineer lacked understanding of shear wall systems.

Neither of these conflicting exterior shear wall assembly requirements would result in a system capable of resisting the design shear loads expected at The Complex without the inclusion of functional interior shear walls and are, therefore, not capable of functioning as the sole vertical component of the main wind force resisting system.

- **Sheathing attachment patterns between Note A and Note B:** Sheathing attachment instructions vary between 4" (edge) / 12" (intermediate framing) in Note A and 4" (edge) / 7" (field) in Note B. As displayed in Table 2, the 4"/12" fastener

pattern design shear strength and allowable shear value is provided in the 1997 UBC. It is likely that the 4"/7" fastener pattern would provide a higher design shear strength/allowable shear value; however, the 1997 UBC does not address the 4"/7" fastener pattern.

- ❑ **Orientation of sheathing:** The structural design drawings also had a conflict in sheathing orientation direction. The orientation of the sheathing varied between Note A and Note B. Note A indicates that sheathing was to be oriented perpendicular (long dimension horizontal) to the wall framing, whereas Note B indicates that sheathing was to be oriented vertically (long dimension vertical). As evidenced in Tables 1 and 2, this orientation is an important component of design.

These three examples are just some of the instances of conflicting or incomplete information provided by the structural EOR within the design documents for The Complex.

Structural Diaphragm

Observations of destructive testing performed at The Complex indicate that the attachment of the OSB floor/roof decking appeared to consist of self-tapping screws and Ramset® fasteners; however, no minimum required fastening pattern was indicated on the structural drawings for the attachment of the floor/roof decking to the structural floor/roof joists. Furthermore, during review of the structural design documents it was revealed that **none of the aforementioned major diaphragm components were detailed/scheduled** and it is therefore the opinion of the authors that a competent structural diaphragm was not conveyed on the design drawings.

Unintended Construction Deficiencies

In addition to design and detailing failures, the design documents indicate that it was the structural engineer's intent to rely upon the construction team to provide the framing, supports, and connections to resist lateral loads. A note located within the General Notes stated that "the structural plans show principal framing members only; contractor shall provide for all framing and supports necessary to resist lateral and vertical loads, as well as connections of these members." **The design of the vertical and lateral load resisting systems is the responsibility of the structural EOR, not the construction team.**

Observations performed during forensic testing at The Complex indicate that the as-built construction was in general conformance with the requirements provided within the structural design documents. Since the design documents included incomplete and conflicting information, the resulting LFRS was also incomplete and therefore deficient in its ability to collect and transfer lateral loads without relying on the unintended structural capacity of the as-constructed system. Examples of unintended construction deficiencies present at The Complex as a direct result of design and detailing failures on the part of the EOR include:

- ❑ Floor-to-floor framing assemblies with inadequate capacity for lateral load transfer at the interior and exterior;
- ❑ Shear walls without blocking or strapping around openings;
- ❑ Cantilevered diaphragms with inadequate capacity;
- ❑ Missing diaphragm drag struts.

It is the opinion of the authors that the structural engineer of record at The Complex failed in his duty to provide a structurally competent design and inappropriately relied upon the construction team to install the main lateral force resisting systems for the subject structures. Because of these failures on the part of the EOR severe design deficiencies were present within The Complex's lateral force resisting system including, but not limited to:

- ❑ The lack of an interior shear wall system;
- ❑ Conflicting and inappropriate shear wall sheathing designations, orientation, and fastener patterns;
- ❑ Lack of a competent structural diaphragm.

At the time of the evaluation, no significant visible distress was observed at The Complex as a direct result of these design and unintended construction deficiencies. However, at the time of the evaluation a review of meteorological and seismic data at the subject site revealed that The Complex had not yet been subjected to a design loading event, much less an ultimate loading event.

Conclusions

The design, detailing, and resulting construction deficiencies outlined within the case study are just some of the deficiencies that may arise from improper design and/or detailing of the lateral force resisting system; however, the type and magnitude of the highlighted deficiencies illustrate how important it is that the structural EOR provide a clear, concise, and complete set of design documents to the construction team.

The ramifications of an inadequately detailed and constructed LFRS can be costly and life-threatening. Under normal conditions, an inadequate LFRS can result in distress to interior and exterior finishes, requiring repair work and reducing the value of the property. Under more severe conditions, such as a wind or seismic event that a building with a properly constructed LFRS would withstand with little or no damage, an inadequate LFRS could result in full or partial collapse of the structure and loss of life. The design of the vertical and lateral load resisting systems is the responsibility of the structural EOR. Furthermore, a structural EOR attempting to rely on a contractor to provide the LFRS for a building is reckless and in direct conflict with his/her responsibility to protect life safety and the welfare of the public.

References

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