MOMENT RESISTANT CONNECTIONS IN PREFABRICATED WOOD FRAME CONSTRUCTION

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Abstrract

The vast majority of homes and light commercial structures in the United States are constructed of wood. Typical wood frame walls consist of dimension lumber framework connected together with nails and then sheathed with structural panels. The nails used to connect the framing members provide virtually no structural benefit beyond holding the framing members together until sheathing is attached. A wood frame shear wall system is being developed that improves the utilization of the wood framework. The improved utilization of the wood framework provides dramatic increases in structural performance and should reduce up-front and life-cycle costs for wood frame construction. Toothed metal plate connectors are used to connect the wood framing members together. Research incorporating full scale walls showed that these connections provide many major structural benefits when incorporated into the shear wall system. First, the toothed metal plate connections provide moment resistance which then allows the framework to resist lateral loads. Second, the connections provide tensile strength which helps develop a continuous load path to the foundation. Third, the connections develop greater energy dissipation during plastic deformation than nailed connections. To more fully understand the behavior of the system more research needs to be conducted. The moment-curvature behavior of the connections needs to be investigated and modeled for incorporation into structural design processes. The behavior of the sheathing to framework connection needs to be investigated for the nails driven through toothed metal plate connectors. Additionally, the behavior of the system subjected to cyclic loading needs to be evaluated.

Keywords: shear walls, connections, wood, truss plates, wind, seismic, lateral load

Introduction

The vast majority of homes and light commercial structures in the United States are constructed of wood. Ninety percent of new houses built in America are of wood frame construction (Portland Cement Association, 1997). Many of these structures reside in locations exposed to lateral forces resulting from seismic activity or high winds due to hurricanes or tornadoes. These lateral forces can cause significant damage with devastating results as evidenced by the Northridge Earthquake, Hurricane Andrew, and the Great Plains Tornado Outbreak of May 3, 1999. The Northridge Earthquake caused over $20 billion of damage to woodframe construction in southern California. Hurricane Andrew's damage exceeded $30 billion to south Florida. The Great Plains Tornado Outbreak tore through parts of the southern Great Plains, devastating metropolitan areas and nearly destroying entire communities. The American Society of Civil Engineers (2001) and the Institute for Business and Home Safety have developed a ten most wanted list for research and development to reduce recurring losses from natural hazards. Three

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issues out of the top four on the list include (1^{st}) providing a continuous load path to the foundation, (3^{rd}) increasing the lateral resistance of the structural system to ground shaking, (4^{th}) improving methods of energy dissipation capacity of the system.

It is evident that the performance of wood frame shear walls directly affects the performance of wood frame structures during lateral loading events. Wood frame shear walls with increased resistance to extreme lateral loads as well as improved durability to multiple median lateral loads would save many lives and billions of dollars in repair and replacement costs. Previously proposed improvements have not been widely accepted by the building industry due to unacceptable increased costs associated with the improvements.

Typical wood frame walls consist of dimension lumber framework connected together with nails and then sheathed with structural panels (plywood & oriented strand board), insulation panels, or finishing panels (drywall). The nails used to connect the framing members provide virtually no structural benefit beyond holding the framing members together until sheathing is attached. The performance of conventional wood frame shear walls is frequently controlled by (a) the performance of the nailed connections between the sheathing and the framework and (b) the performance of hardware providing a load path to the foundation. Relying solely on the nailed connections between the sheathing and framework minimizes the potential of the underlying framework to take part in the resistance to lateral loads. Additionally, the nails connecting the framing members together provide virtually no resistance to uplift. Once the sheathing connections are damaged the load paths to the foundation become significantly compromised. Improving the connection between framing members will improve the performance and safety of wood frame construction.

Toothed metal plate connectors have been used extensively to connect light frame truss members. The metal plate connected truss industry has experienced significant growth over the last few decades. Metal plate connected trusses are custom engineered, prefabricated structural components that provide both structural and economic efficiency. Economic savings are realized through the prefabrication process where materials and labor can be efficiently controlled. In recent years the prefabricated wood frame wall industry has begun to experience growth. While prefabricated walls experience the economic benefits provided by the prefabrication process, they currently are designed following prescriptive guidelines and fabricated in a manner very similar to conventional jobsite construction. Prefabricated wood frame walls have the potential to be custom engineered and fabricated with alternative connectors that will provide superior performance relative to nailed connections. Emerson (2002) investigated the use of toothed metal plate connectors (MPC) to connect the framework of wood frame shear walls. The MPC's behaved as semi-rigid connectors that allowed the framework to resist lateral loading with and without the presence of attached oriented strand board sheathing. The improved resistance to lateral load was exhibited in improved strength, stiffness, and energy dissipation relative to wood frame walls fabricated with end-nail connected framework. The improved resistance to lateral load should improve overall durability and reduce lifecycle costs.

Current State of the Art

Conventional Shear Wall Behavior

Conventional light-frame wood construction employs horizontal diaphragms and shear walls to resist lateral forces. Horizontal diaphragms are designed as horizontal beams that transfer lateral forces to the supporting shear walls. Shear walls are designed as vertical deep cantilever beams supported by the structures foundation (Breyer, Fridley, and Cobeen, 1998; Stalnaker and Harris, 1997; Faherty and Williamson, 1997). Typical shear wall construction is depicted in figure 1. A typical shear wall is composed of dimension lumber framing overlaid with sheathing on one or both sides. Nails connect the framework together. The top plate is connected to the studs by end nailing. The studs are connected to the bottom plate by either toenailing or end nailing. The end studs are anchored to the foundation to resist uplift forces resulting from applied moments. The bottom plate is anchored to the foundation to resist base shear forces. The sheathing is attached to the dimension lumber framework with nails. The nails are spaced closely around the edges and spaced further apart in the interior of the individual sheathing panels.

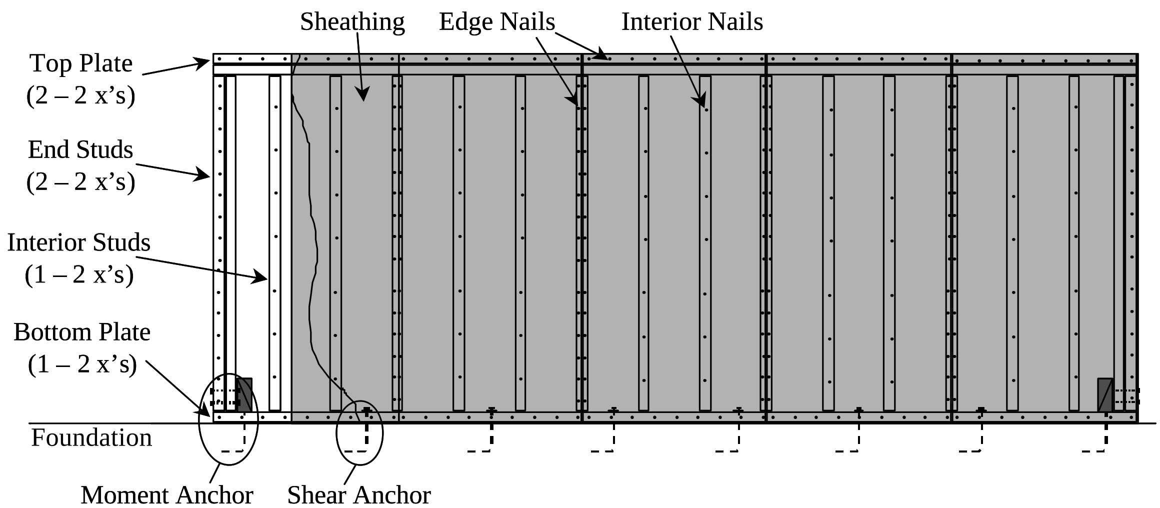

Figure 1. Typical wood frame shear wall construction

Substantial research has been performed regarding the behavior, analysis, modeling, and design of conventional wood frame shear walls. The dimension lumber chords and sheathing are designed to resist applied moment and shear, respectively. However, the behavior of the system is governed by the connections between the top and bottom plates and the studs and the connections between the sheathing and the framework. Under lateral loads the nailed connections between the plates and studs provide little rigidity. As a result, the framework distorts as a parallelogram. The sheathing remains rectangular and rotates as a rigid body. Relative displacement of the framework and sheathing due to racking forces is depicted in figure 2. The connections between the sheathing and the framework then become the controlling factor in racking behavior. The nails connecting the sheathing to the framing resist the lateral load. Typically, failure occurs when the nail heads pull through the sheathing panel or withdraw from the framework due to the large relative displacements between the sheathing and the framework at the corners of sheathing panels.

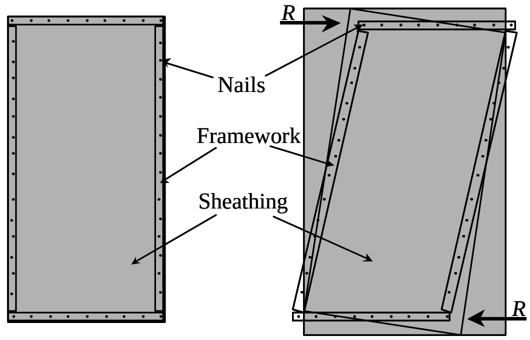

Figure 2. Conventional wood frame shear wall panel behavior due to racking forces

Tuomi and McCutcheon (1978) developed a method for calculating the racking strength of frame panels and then compared the method with experimental tests. Racking strength was calculated by accounting for panel geometry, the number and spacing of nails, and the lateral resistance of a single nail. The method also accounted for minimal frame resistance. Frame resistance was assumed to contribute less than ten percent of the overall racking strength. Calculated racking strength compared favorably to results from experimental testing.
Gupta and Kuo (1985) developed a model for shear wall behavior that was governed by nonlinear nail deformation but also accounted for bending and shear stiffness of the studs and sheathing, respectively. They found that assuming the studs were infinitely rigid in bending gave comparable results to assuming the studs held normal bending stiffness. This confirms that the nailed connections between the plates and the studs are too flexible to develop bending within the studs.

Many researchers have investigated the behavior of full-scale shear walls of various configurations or used the finite element method to model the behavior of wood frame shear walls (Easley, Toomani, and Dodds, 1982; Foschi, 1982; Itani, Tuomi, and McCutcheon, 1982; Price and Gromala, 1979). More recent studies have investigated the behavior of full-scale wood frame shear walls under a wide range of variables including: monotonic and cyclic loading (Dolan and Johnson,1997; Dolan and Heine, 1997; Salenikovich and Dolan, 2003)); with and without openings (Dolan and Johnson,1997) ; segmented and perforated design methods; with and without corner framing (Dolan and Heine, 1997); and wall aspect ratio (Salenikovich and Dolan, 2003). This research provided the following conclusions. The perforated shear wall method is valid. Perforated shear wall resistance is less than traditional shear wall resistance due to the omission of moment anchors. Moment anchors affect monotonic resistance more than cyclic resistance. Corner framing provides a hold-down effect that increases wall capacity. Narrow shear walls with high aspect ratios (4:1) are significantly less stiff than shear walls with lower aspect ratios. Cyclic load tests showed that shear walls have different failure mechanisms under cyclic loading compared to monotonic loading.

NAHB Research Center investigated the performance of perforated shear walls (McKee, Crandell, Hicks, and Marchman, 1998). Variables included in their study were narrow wall segments, reduced base restraint, and alternative framing methods. This research mainly validated Dolan's research on perforated shear walls. However, the investigation of alternative framing methods provided an interesting result. Two nearly identical perforated shear walls were tested. Both walls had a sheathing area ratio equal to 0.57 as determined from empirical equations developed by Sugiyama and Matsumoto (1993 and 1994). The control wall consisted of conventionally connected framing with moment anchors at both ends of the wall. The experimental wall with alternative framing consisted of framing connected with metal truss plate connectors at the corners and around openings. This wall also had no moment anchors to resist uplift. Even with the omission of the moment anchors, the experimental wall outperformed the control wall dramatically. The experimental wall resisted 40% more lateral load and dissipated 68% more energy than the conventionally connected perforated shear wall.

Metal Plate Connected Truss Technology

Prefabricated light frame wood trusses are commonly connected with toothed metal connector plates. The trusses are designed and fabricated according to *ANSI/TPI 1-1995, National Design Standard for Metal Plate Connected Wood Truss Construction* (Truss Plate Institute, 1995). Wood members are designed according to the *National Design Specification for Wood Construction* (American Wood Council, 2001). Guidelines for metal plate connector design regarding tooth holding, net section steel tensile capacity, net section shear capacity, and combined shear and tension capacity are presented in *ANSI/TPI 1-1995*.

In the past, metal plate connected trusses were modeled and designed assuming pinned connections. However, toothed metal plate connectors provide semi-rigid connections that will develop moment capacity. Noguchi (1980) investigated five models describing the moment resistance of metal plate connections. These models were (i) completely elastic behavior; (ii) elastic behavior of the plate with compressive yielding of the wood member; (iii) tensile yielding of the plate with elastic behavior of the wood; (iv) plastic behavior of both the plate and wood; and (v) Edlund's (1971) model for bending moment . The models were fit to experimental data and the elastic model was found to be the most conservative while the plastic model was recommended for design purposes. Kevarinmäki and Kangas (1992) and Kevarinmäki (1996) used both the elastic and plastic models to investigate the tooth withdrawal capacity of metal plate connected truss joints subjected to bending moments. O'Regan, Woeste, and Lewis (1998) developed a design method for the steel net-section of truss joints subjected to tension and moment. Their design method was based on Noguchi's model where the steel is fully plastic in tension and the wood is linearly elastic in compression. O'Regan, Woeste, and Brakeman (1998) added to the design method by developing design methodology that forces steel yielding as the failure mechanism. While these methods provide a simple design process for an ultimate state design, they do not accurately capture the moment behavior of the connections during the entire loading process.

Other researchers have investigated the fatigue and dynamic behavior of toothed metal plate connected joints. Hayashi et al. (1980) determined that fatigue failure changed from tooth shear to tooth withdrawal as the load level was increased. Emerson and Fridley (1996) found that toothed metal plate connectors perform well under cyclic dynamic loading. Kent, Gupta, and Miller (1996) also investigated the dynamic behavior of metal plate connected wood truss joints.

Engineered Wood Frame Wall Panel System Integrating Prefabricated Truss Technology

A wood frame shear wall system that improves the utilization of the wood framework is currently under development. The improved utilization of the wood framework provides dramatic increases in structural performance and should reduce up-front and life-cycle costs for wood frame construction. Toothed metal plate connectors are used to connect the wood framing members together. Ongoing research shows that these connections provide many major structural benefits when incorporated into the shear wall system. Shear walls with metal plate connected framework were found to have a 51% increase in design strength, 63% increase in maximum strength, and 60% increase in energy dissipation over conventional shear walls with end-nailed framework.

Future Research Directions

Employing the underutilized framing members to resist lateral forces provides a viable solution for increasing the performance of shear walls. Connecting the wood framework with toothed metal connector plates provides a continuous and reliable load path for both lateral and uplift forces. The toothed metal plate connections increase the lateral resistance of the wood frame shear wall system by transforming the underutilized framework into a series of moment resistant frames. The toothed metal plate connections also dissipate more energy than end-nailed connections.

Future research is required to develop the knowledge on the behavior of the components of the innovative shear wall system so that the system can be accurately designed and utilized in residential and light commercial structures. It is anticipated that the following items need to be investigated and understood in order to incorporate the wood framework into the lateral load resisting system.

Moment-Curvature Behavior of MPC

Understanding the moment-curvature behavior of the toothed metal plate connections will be critical to any design process. It is anticipated that the moment behavior of the toothed metal plate connections will be incorporated into both prescriptive and rational design procedures.

The interaction between the sheathing, framework, and the nails connecting them has been thoroughly investigated for conventional nailed frame shear walls. The sheathing rotates as a rigid body about the panel's centroid while the nail connected framework experiences different rigid body displacement in the form of a parallelogram. Plastic behavior is only developed at the nailed connections between the sheathing and framework due to the differential displacements between the sheathing and framework.

When framing members are connected with moment resistant connections, the interaction between the framing system and the sheathing is altered since the relative displacement between the framework and sheathing changes. The framework bends elastically in double curvature as the metal plate connections develop moment. Only after the connector plates begin to yield does the framework begin to experience rigid body displacement in the form of a parallelogram. The goal of the proposed research is to develop knowledge on the moment-curvature behavior of metal plate connectors used to connect wood framework. This will be extremely useful for the design of shear walls with integral moment resistant frames. The moment-curvature relationship will be able to be input into analytical models for framework and shear wall behavior.

Cyclic Loading Behavior

Previous testing of MPC connections shear walls containing framework connected with MPCs has all been conducted under monotonic static loading. In order to understand the expected behavior of the connections and shear wall system under high wind and seismic conditions, their cyclic load behavior should be investigated following the most up to date and widely accepted cyclic load testing protocol. Cyclic load testing should also be performed on a whole structure fabricated with MPC connections to evaluate whole structure performance of wood frame houses fabricated with shear walls containing MPC connected framework. The whole structure tests could also include partition walls that contain MPC connected framework.

Analysis and Design Methodology

Rational, mechanics based, analysis and design methods need to be developed that incorporate the moment-curvature behavior of MPC into the analysis and design methodology. It is anticipated that the MPCs can be modeled as semi-rigid frame connections. The design process should focus on elastic and early plastic behavior of the connections since relatively large wall displacements would have to be experienced before the connections reach their maximum load capacity.

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