FRP-Reinforced Oriented Strand Board Panels in Wood-Framed Shear Wall Construction

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Abstract

The resistance of wood-framed structures to extreme loads from earthquakes and hurricanes depends in large part on the strength and energy absorption characteristics of the shear walls. This paper reviews state-of-the-art in the testing and analysis/design of shear walls, as well as the use of innovative materials in wood-framed shear walls to enhance their resistance to extreme events. Recent research detailing the development and structural testing of an Advanced Oriented Strand Board (AOSB) panel that utilizes selectively located fiber-reinforced polymer composites (FRPs) to increase the lateral load resistance of wood-framed shear walls is discussed. Further, the use of AOSB in narrow-panel shear walls – an increasingly common pre-fabricated construction element in earthquake-prone regions of the United States – is briefly overviewed. Future research directions are also addressed, with special attention given to the opportunities for advanced materials, as well as the need for the development and implementation of more advanced analysis methods.

Keywords: wood shear walls, FRP composites, seismic loads, wind loads, wood connections

Introduction

The resistance of conventionally constructed wood-framed structures to extreme events such as earthquakes and hurricanes depends in large part on the strength and energy absorption characteristics of the shear walls. These shear walls are often sheathed with oriented strand board (OSB) panels, and their performance is primarily a function of the nailed sheathing-to-framing connections at the panel edges and tension tie effectiveness. This paper reviews the current state-of-the-art in the testing and analysis/design of shear walls, as well as the use of innovative materials in wood-framed shear walls to enhance their resistance to extreme events. The development and structural testing of an Advanced OSB (AOSB) panel that is selectively reinforced with fiber-reinforced polymer composites (FRPs) to increase the lateral resistance of conventional wood-framed shear walls is presented. Included is a summary of the results of lateral load tests of single-nail connections as well as the results of full-scale shear wall tests. The preliminary results of ongoing research into the performance of narrow-panel shear walls are also presented. Finally, specific areas in which further research is needed to enhance our understanding of the performance of wood-framed structures to extreme loads are discussed.

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Current State-of-the-Art

In recent years, a large amount of research has focused on the performance of wood-framed construction to extreme loads, and in particular the strength and ductility of shear walls has been examined. Most studies have focused on the performance of traditional structures built with conventional materials. This section reviews recent research into shear wall performance; trends in analysis and design for lateral loads; and overviews current and ongoing research involving emerging engineered materials such as AOSB to improve the lateral load resistance of shear walls.

Shear Wall Performance

Current experimental research into the structural performance of shear walls invariably incorporates cyclic loading to determine design strengths. Dinehart and Shenton (1998) compared the static and cyclic behavior of both plywood and OSB shear walls, using the draft sequential phased displacement test procedure developed by the Structural Engineers Association of Southern California (SEASOC) (*Standard* 1996). They found that failure modes differed significantly between the static and dynamic tests: the static tests caused nail pullout and base plate splitting, while the primary failure modes in the dynamic tests were nail fatigue and nail pullout. The tests of Rose (1998) on two-panel shear walls employing the SEAOSC loading also showed that nail fatigue is the most common failure mode. However, Dinehart and Shenton (1998) and He et al. (1998) note that the observed nail fatigue failures are likely a result of the large number of high amplitude cycles imposed by the cyclic testing protocol, and that actual failures in earthquake events usually occur due to nail withdrawal or nails tearing through the edge of the sheathing.

Salenikovich (2000) performed 56 monotonic and cyclic tests of wood-frame shear walls to study the effects of wall construction and aspect ratio on performance. Salenikovich concluded that for engineered walls with tension ties, the sheathing-to-framing connector performance governs capacity, and that the performance of shear wall tie-downs has a dramatic effect on the performance of narrow walls. More recently, Jones and Fonseca (2002) experimentally examined the effect of over-driven nails on OSB-sheathed shear wall performance, and concluded that over-driven nails can significantly reduce strength and ultimate displacement.

It must also be noted that in addition to shear wall testing, full-scale cyclic and dynamic tests of entire wood-framed structures have also been recently conducted in an attempt to better understand load distribution and system performance (Paevere et al. 2003). A major conclusion of Paevere et al. (2003) is that commonly used techniques for lateral load distribution in light-frame structures do not adequately account for the actual redistribution of load.

Trends in Analysis and Design for Lateral Loads

The nail fatigue failures observed in cyclic shear wall tests, which are inconsistent with damage observed from field observations, have helped propel the development of cyclic loading protocols that produce levels of damage more consistent with that of an actual seismic event. Most notable is the CUREE protocol (Krawinkler et al. 2000), which was developed using time-history analyses of structures subjected to actual earthquake records from the Los Angeles area produced by a 475-year return period event. The protocol consists of 43 total cycles of varying amplitude, which differs significantly from the 72 cycles of loading used by the SEAOSC protocol (*Standard* 1996). Further, a CUREE loading protocol is developed using the ultimate displacement of a component, which is easily determined from a monotonic test; a SEAOSC loading protocol relies on a yield displacement, which is more difficult to define.

In addition to analytical research into the development of loading protocols, recent efforts have focused on the use of performance-based seismic design methodologies for wood-framed structures. Performance-based design incorporates different ground motion intensities and associated performance limits to keep damage to acceptable levels under both moderate and extreme events, and explicitly incorporates the ductility of the structure. This contrasts with force-based design, which focuses on providing sufficient strength to ensure that a structure can withstand an extreme event without collapse, and a sufficient level of ductility is implicit in the reduction of design forces from their elastic values. Filiatrault and Folz (2002) note that while the performance-based design of concrete structures has been studied extensively, the performance-based design of wood structures is largely unexplored. They then develop a framework for the performance-based design of wood structures, but note that further work is required before performance-based design can be used reliably for entire wood-framed buildings. Rosowsky (2002) describes a framework for the performance-based design of wood shear walls that incorporates reliability-based design concepts.

Emerging Engineered Materials and Components

Another area of active research is the development of engineered materials and components. Many researchers have observed that shear wall capacity is limited by the capacity of the sheathing-to-framing connections. Fonseca et al. (2000) addressed this issue by reinforcing the edges of plywood sheathing with a plain weave fiberglass tape, and testing small sheathing-to-framing connection specimens for connector strength. These tests showed significant improvements in strength, stiffness, and ductility by eliminating nail edge tear failures and delaying nail head pull-through. In a parallel study, Judd and Fonseca (2000) used fiberglass panels in place of damaged plywood to rehabilitate wood shear walls, finding that nail edge tear and pull-through could be eliminated and the strength of full-scale diaphragms increased by 35%. However, they observed a large amount of fastener fatigue failures in the fiberglass-sheathed panels.

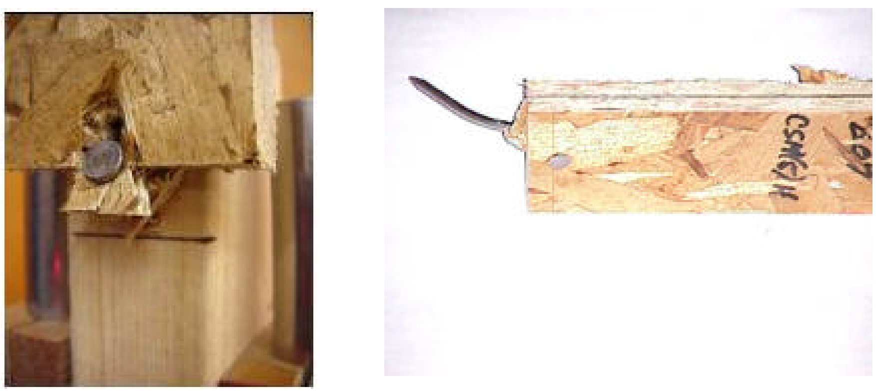
Cassidy (2002) and Davids et al. (2003) present the development of an advanced oriented-strand board (AOSB) panel that consists of plain OSB and a core of FRP composite reinforcement produced under a combination of heat and pressure in a hydraulic press. The final thickness of the reinforcement is approximately 1.3mm, and the total panel thickness is approximately 14mm. The development of AOSB was also driven by the fact that the weakest component in a shear wall is often the panel-to-framing connections, and the FRP reinforcing strengthens the panel edge-tear and nail head pull-through resistance. In addition, shear walls constructed with AOSB panels may be more resistant than conventionally constructed shear walls to construction errors such as missing or over-driven fasteners.

The screening of reinforcing material type and thickness and evaluation of manufacturing parameters were accomplished by testing the lateral strength of single nailed connections according to ASTM D1761 (ASTM 1998a). Both monotonic and cyclic tests were performed. All specimens were constructed with the code-minimum distance of 9.5mm from the nail to the panel edge. The control specimens were fabricated with conventional 11mm thick OSB, and pneumatically driven 8d nails were used for all tests. The results of the tests are summarized in Table 1, which shows an average increase in monotonic connection strength of 42% and significant increases in connection ductility and energy absorbed when AOSB is used. The failure mode was successfully shifted from edge tear to nail withdrawal accompanied by the formation of two plastic hinges within the nail, which accounts for the increased strength and ductility (see Figure 1).

Table 1. Summary of Results for AOSB and OSB Single-Nail Connection Tests*

		Max. Load (N)	**Displ. @ Max. Load (mm)**	**Residual Strength (N)**	**Energy Absorbed (N-m)**
Monotonic	OSB	1360 (14%)	5.6 (42%)	—	—
	AOSB	1930 (17%)	10.7 (48%)	—	—
Cyclic	OSB	1170 (22%)	4.8 (35%)	0	66.0 (24%)
	AOSB	1390 (20%)	8.4 (34%)	890 (39%)	133 (15%)

*Number in parentheses is the coefficient of variation



Typical OSB Specimen Typical AOSB Specimen

Figure 1: Connection Failure Modes for Monotonic Loading

In addition to connection tests, 24 tests of 2-panel (2.44m x 2.44m) shear walls (12 constructed with OSB and 12 constructed with AOSB) were conducted in accordance with ASTM E564 (ASTM 1998b). Twelve of the specimens were tested under monotonic loading, and twelve were tested using the CUREE cyclic loading protocol (Krawinkler et al. 2000). Six nominally identical shear walls used 11mm OSB with 102mm perimeter nailing, six used AOSB with 102mm perimeter, six used 11mm OSB with 154mm nailing, and six used 11mm AOSB with 154mm perimeter nailing. Within each group of six nominally identical walls, three were tested monotonically to failure, and three were tested cyclically. All walls were unblocked, and the nail spacing used for the interior studs was 305mm.

Figure 2 shows the shear wall test apparatus. Load was distributed to the top plate via a bolted load distribution beam. The base of the wall was supported by, and bolted to, a steel tube section. Heavy tension ties (Simpson HD10A) were used at both bottom wall corners, and the end studs were double 2x4s. All framing was Southern Yellow Pine. The same 8d pneumatically driven nails used for the connection tests were employed in the wall construction. All walls were constructed at least two weeks prior to being tested to permit relaxation of the wood around the nails, which better simulates as-built conditions. Instrumentation consisted of DCDTs and string potentiometers that measured horizontal displacements at the top and bottom of the wall and uplift at the wall base. Table 2 summarizes the results of the monotonic tests. The primary failure modes for the OSB-sheathed control walls were edge-tear and nail head pull-through of the perimeter fasteners. However, for the AOSB specimens, these fastener failure modes were nearly eliminated, and the primary failure mode was nail withdrawal from the framing. This is consistent with the observed failure modes for the individual connector tests described previously. While the strength gain for the AOSB wall is less than that for the AOSB connection tests, the ductility and energy absorption gains are significant. On average, the AOSB walls absorbed 27% more energy than the OSB walls with a 152mm perimeter nail spacing, and 43% more energy with a102mm perimeter nail spacing.

Figure 2: Shear Wall Test Apparatus

Table 2: Summary of Results for Monotonic Wall Tests*

Nail Spacing	**Wall Type**	**Peak Load (kN)**	**Displ. @ Peak Load (mm)**	**Failure Modes for Failed Perimeter Nails**		
				% Edge Tear	**% Pull Through**	**% Pull Out**
152mm	OSB	26.3 (9%)	78.5 (10%)	43	54	3
	AOSB	26.1 (10%)	99.8 (8%)	11	0	89
102mm	OSB	32.6 (12%)	83.8 (10%)	41	53	6
	AOSB	40.4 (9%)	96.5 (12%)	20	0	80

***Number in parentheses is the coefficient of variation

The cyclic shear wall tests were performed in the same test apparatus as the monotonic tests. Figure 3 shows cyclic test results for typical OSB and AOSB specimens. It is interesting to note that the AOSB specimens exhibit less pinching of the hysteretic curves and larger peak loads for both nail spacings. This indicates that the FRP is serving to prevent localized crushing and damage of the OSB under repeated loading. Prior research has identified this as the predominant damage mechanism under load cycling (Chui and Ni 1997).

Table 3 summarizes the results of the cyclic shear wall tests. On average, the AOSB specimens absorbed 52% more energy than the control specimens with a 152mm nail spacing, and 73% more energy than the control specimens with a 102mm nail spacing. As with the static tests, the AOSB specimens exhibited very few nail edge tear or nail head pull through failures. However, a large number of nail fatigue failures were observed for the AOSB specimens, with the remainder of the nails failing largely through nail pull out.

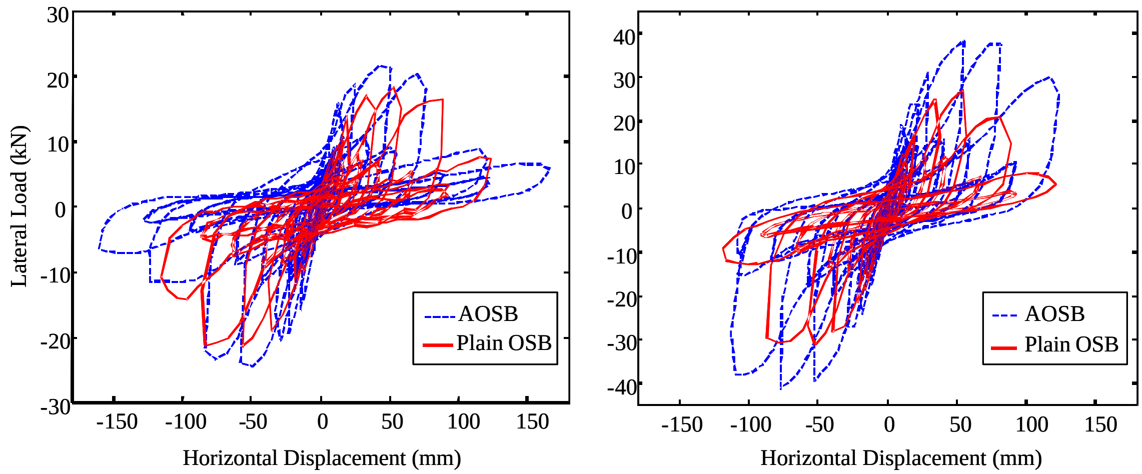


Figure 3: Typical Cyclic Shear Wall Test Results

Table 3: Summary of Results for Cyclic Wall Tests*

Nail Spacing	**Wall Type**	**Peak Load (kN)**	**Energy Absorbed (kN-m)**	**Failure Modes for Failed Perimeter Nails**			
				% Edge Tear	**% Pull Through**	**% Pull Out**	**% Fatigue**
152mm	OSB	23.1 (8%)	10.1 (6%)	46	54	0	0
	AOSB	25.3 (8%)	15.3 (1%)	4	0	77	19
102mm	OSB	32.3 (6%)	13.2 (8%)	37	62	0	1
	AOSB	39.6 (5%)	22.9 (2%)	6	0	48	46

*Number in parentheses is the coefficient of variation

Based on the results achieved thus far with the AOSB panels, they appear to have significant potential for increasing the energy dissipation capacity and lateral load resistance of wood-framed structures subjected to extreme wind and seismic events. The primary failure mode for the nails has been shifted from edge-tear or nail head pull-through to a more ductile withdrawal of the nails from the stud under static loading. However, the nail withdrawal failures do not allow the full fastener edge tear and pull-through resistance of AOSB to be utilized in conventional shear walls. Recognizing this, current research at the University of Maine is focusing on the development and testing of innovative narrow-panel shear walls that incorporate several unique design features. In particular, stronger framing, a special integral tension tie, and the use of screws instead of nails allow the full fastener edge tear and pull-through resistance of the AOSB to be developed.

Preliminary fastener and wall tests conducted thus far indicate that the narrow-panel walls utilizing AOSB have more strength than similar walls currently on the market that utilize conventional OSB or plywood sheathing. Three nominally identical, 0.61m wide x 2.44m high walls have been tested cyclically thus far using the CUREE loading protocol and a test apparatus similar to that shown in Figure 2. During cycling, the three walls sustained an average maximum load of approximately 43 kN. To put this value in perspective, it is higher than the average maximum cyclic load observed for the 2.44m x 2.44m walls using AOSB and conventional framing, tension ties, and perimeter nailing (see Table 3). The narrow-panel walls are also substantially stiffer than conventionally constructed shear walls due to the use of screws and special tension ties.

Future Research Directions

The review of current state-of-the-art suggests many fruitful areas for future research. This section briefly summarizes the opportunities, potential benefits, and challenges in three such areas.

Continued Development of Engineered Materials

The successful development of materials such as AOSB indicates that there are potential benefits to incorporating advanced engineered materials in conventional stick-built construction. The most significant of these may include superior disaster-resistance, greater tolerance to construction errors, and increased durability. Future research should continue to focus on the development of engineered materials to achieve these objectives. One important area that has not received attention in prior studies is the improvement of inter-component connections – for example connections between shear walls and diaphragms – through the use of engineered materials. Since a component cannot be fully utilized unless it is adequately connected to the entire structure as part of a continuous load path, this is equally as important as improving the performance of an individual component.

However, there are several challenges to the incorporation of advanced engineered materials in conventional home construction that must be addressed. First, the structural response of a component, such as a shear wall, is a function not only of its weakest link (often the perimeter fasteners), but also of tension ties, framing member strength, etc. Strengthening only one portion of a component with an engineered material can simply shift the failure mode of that component to another element without substantially benefiting overall structural performance. Second, the wide and effective use of new materials necessitates their inclusion in building code provisions, with associated design strengths that allow them to be fully utilized. Third, the wood products industry must be able and willing to produce these materials, which requires the development of large-scale production methods, extensive market studies and demonstrated economic viability.

Incorporation of New Engineered Materials into Pre-fabricated Construction Elements

Pre-fabricated construction elements, such as structural insulated panels, narrow-panel shear walls, roof trusses, etc. are continuing to gain market share. The incorporation of advanced engineered building materials into these products may represent a good point of market entry for a number of reasons. First, pre-fabricated elements can incorporate more complex and costly construction details and elements and remain economical due to the efficiency of their automated factory assembly. Second, in contrast to conventional stick-built construction, their installation often requires the use of specific methods and materials that can readily accommodate advanced engineered materials. Third, the higher quality control inherent in pre-fabricated elements may result in the more efficient use of advanced engineered materials.

Improve Our Understanding of the Structural Response of Wood-framed Structures

One critical area of future research is the development of a better understanding of structural response and load sharing in light wood-framed construction. It has long been recognized that load transfer between components – for example, from horizontal diaphragms to shear walls – is poorly understood. In addition, recent studies have highlighted the inability of commonly used analysis tools to predict load sharing between components (Paevere et al. 2003) as well as the potential beneficial effects of non-structural elements such as stucco and sheetrock. The successful development of advanced engineered materials and components requires both that the demands on these elements be accurately predicted, and that inter-component forces developed at connections be adequately characterized. Future research should focus on the large-scale testing of assemblies and entire structures, and the development of new analysis methods.

The challenges inherent in large-scale experimental work are tremendous: it is always difficult to control and realistically apply loads, enforce boundary conditions, and accurately measure critical response values. Further, designing a suite of tests that incorporates the range of design details and structural configurations possible with wood-framed construction will be extremely difficult. The development of new analysis methods must incorporate research into both detailed nonlinear finite-element techniques, as well as simplified modeling strategies with fewer degrees-of-freedom that are suitable for use in design. Finally, it is imperative that basic research involving large-scale testing and analysis be explicitly coupled so that the models are adequately validated, and that sophisticated modeling can be used in the design of the testing program.

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