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Experimental Investigation on Lateral Behavior of Light-Frame Shear Walls Augmented with Elastomeric Adhesives

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ABSTRACT

In this study, the effects of moderate to high-elongation elastomeric adhesives combined with nails between sheathing-to-framing connections on the seismic performance of light-frame shear walls (LFSWs) were experimentally investigated. Monotonic and cyclic tests were conducted on six specimens. Results reveal that adding adhesive increases strength significantly by (170~200%) and stiffness by (50~80%) and eliminates pinching and softening effects compared with the nails-only counterparts. Energy dissipation is doubled using high-elongation adhesive (i.e., 1000%), while a slight increase is observed in wall specimen using the moderate-elongation adhesive (i.e., 300%) due to the brittle wood substrates failure. As an indicator of energy dissipation through plastic deformations and ductility, the response modification factor of the high elongation adhesive shows a higher value (2.4~2.7) than the design value by the building codes (1.5). The results show the need to review the statement provisions restricting all adhesives in shear wall attachments. The low cost, ease of application, environment friendly, and efficiency of the elastomeric adhesives motivate expanding their structural applications to mitigate seismic damages.

Introduction

The seismic performance of wood buildings is intimately related to the energy dissipation of their connections. Wood has poor dissipative capacity due to its brittle behavior unless effectively strengthened [1]. The structural behavior and capacity of light-frame shear walls (LFSW) primarily depend on the sheathing-to-framing connections. Holding down and shear transfer are the two limiting criteria of importance [2]. Mechanical fasteners show a proper mechanism of dissipating energy and ductility due to their yielding and limited crushing in the wood. However, they also exhibit a significant pinching, strength degradation, and softening [3]. Building walls in high seismicity regions requires a high density of construction details to the expected level of building designers (e.g., nail size, spacing, and sheathing thickness). For example, a strengthening technique in Mid-height wood buildings using Double sheathings and sturdy end studs (i.e., 5 of 2×6 studs at each end) was proposed to resist the large horizontal loads [4]. However, high materials cost and high-level technical experience create barriers to adopting such solutions [5], [6]. Literature review of most recent research on shear walls testing and modeling with different sheathings, sizes, connectors, loading protocols directs a significant need to develop new and innovative construction materials to overcome the limitations of efficiency and cost [7]. The current study provides a shear-resistant, cost-effective, easily installed, and environmentally friendly alternative solution using moderate to high-elongation elastomeric adhesives applied to

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sheathing-to-framing connections of LFSWs. Elastomeric adhesives are synthetic polymers based. Of particular interest to this study is using the Silyl Terminated Polyether adhesive classified as thermosetting, moisture curing, and solvent-free [8]. Construction adhesives have long been used in combination with nails in the construction of LFW floor systems. American Plywood Association recommends this common practice to mitigate floor vibration, increase floor stiffness for gravity loading, and reduce the potential for squeaking [9].

Several researchers have noted that elastomeric adhesives may effectively provide increased strength and stiffness to LFSWs. Oliva [10] tested a series of wood-framed walls that used nails and construction adhesive to attach the gypsum sheathing to studs and determined that adhesive increased the wall strength by 160% and the stiffness by 230% relative to walls with nails alone. Filiatrault and Foschi [11] tested several LFSWs with plywood sheathing attached using a synthetic elastomer wood adhesive and concluded that adding the adhesive increased initial wall racking stiffness by 65% and the strength by 45–70%. Dolan and White [12] concluded that special attention is needed when designing anchorages and tie-downs of walls with sheathing connected using adhesives due to the high shear strength provided by the adhesive connections. Serrette et al. [13] tested a series of cold-formed steel framed shear walls constructed with Loctite adhesive and screws to attach sheathings to framings. In that study, wall strength exceeded the design values of walls using conventional screws. For shear wall sheathing attachment, Special Design Provisions for Wind and Seismic (SDPWS) explicitly stipulates the limited uses of adhesives for wind and seismic design in Seismic Design Categories A, B, and C, where response modification factor (R=1.5) and overstrength factor ($\Omega_o = 2.5$) [14]. This restriction was issued due to the limited ductility and brittle failure modes of rigid adhesive shear walls reported by Filiatrault and Foschi [11]. However, elastomeric adhesives are expected to perform differently due to their different mechanical properties, such as elongation and shear strength from those adhesives reported previously. These restrictions in using adhesives need to be re-examined and updated to reflect the newly developed adhesives that have proven efficient structural performance against hazardous loads [15], [16]. Therefore, this study aims to demonstrate the potential structural and economic benefits of adopting a continuous adhesive bond between the framing and sheathing to provide the primary load transfer mechanism in LFSWs.

Experimental Program

Three configurations of LFSWs (see Table 1) were designed, fabricated, and tested. Monotonic and reverse cyclic loadings were laterally applied to the specimens along the in-plane direction. Figure 1 depicts details of the test specimen and test setup. Two specimens were built for each configuration and each loading test, resulting in six specimens in total. Douglas- Fir was selected for the framing, and plywood 3/8″ was for the sheathing.

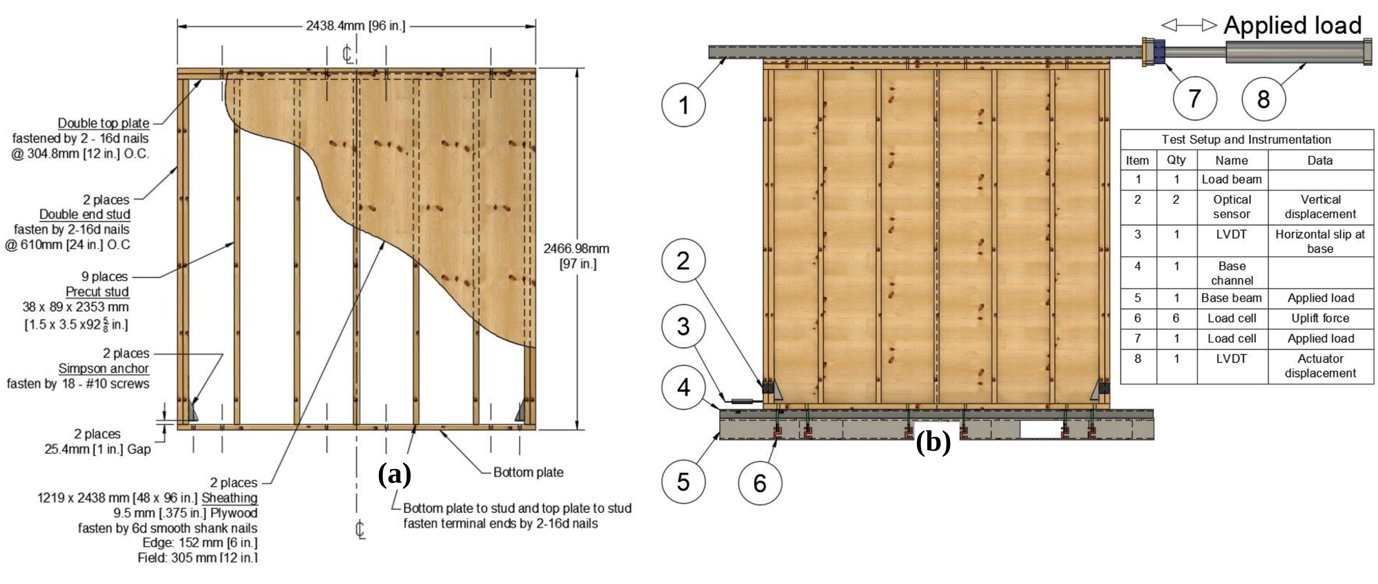

Figure 1. Schematics of experimental program: (a) test specimen; (b) test setup details

For NA and NB specimens, the adhesive thickness of approximately 1/8″ (3 mm) was applied at the contact surface to cover the entire stud width when flattened with sheathing boards. Three cartridges of 10.1 oz (300 ml) were used for a shear wall with a total cost of less than $21. The monotonic and cyclic tests were performed according to the ASTM E2126-11 [17] and the ASTM E564-06 [18]. The CUREE basic loading protocol was chosen as the cyclic loading protocol of applying displacement-controlled loading that involves cycles grouped in phases at incrementally increasing displacement levels [19].

Table 1. Shear wall configurations

Configuration index	Sheathing to framing attachment
N	Nails only: 6d shank smooth nails
NA	Nails plus Adhesive A of 300% elongation and 400 psi shear strength
NB	Nails plus Adhesive B of 1000% elongation and 300 psi shear strength

Results and Discussion

Preliminary results of the monotonic and cyclic loading tests of the six specimens are introduced herein, including force-displacement curves and characteristic parameters in strength, stiffness, energy dissipation, ductility, and design values.

Lateral Load and Displacement Relationships

Figure 2 shows hysteretic responses of the shear walls under cyclic loading, along with the force-displacement curves under the monotonic loading. The monotonic curves are close to the envelopes of the hysteresis loops, showing that monotonic tests results can be used to predict maximum loads and corresponding displacements from the cyclic testing results.

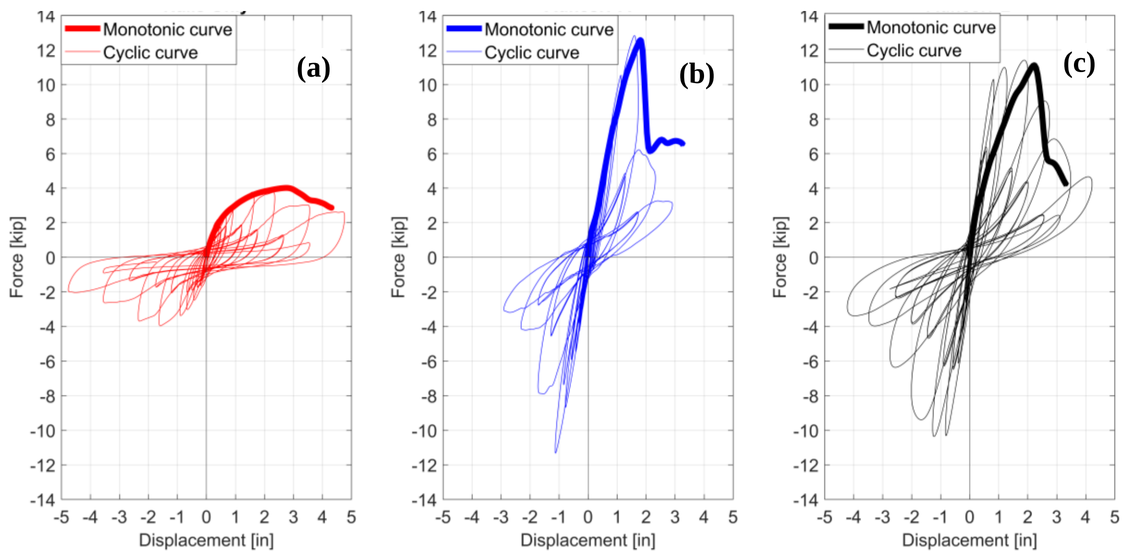

Figure 2. Lateral load and displacement relationships of monotonic and cyclic tests: (a) N; (b) NA; (C) NB

The N configuration has better ductility and load capacity at a larger displacement than adhesive walls (see Figure 2(a)). No significant damage was observed in sheathing panels nor framings. In comparison, adhesive configurations are stiffer with higher load capacity. NA configuration shows an almost linear force-deformation relationship prior to failure (see Figure 2 (b)). The higher shear strength and lower elongation of adhesive A relative to adhesive B (see Table 1) provide rigid bond strength that exceeds the wood strength. The NB configuration shows relatively more ductile behavior with a higher level of nonlinearity than NA (see Figure 2 (c)). The desired mechanical properties of adhesive B allowed a higher number of nails to fail without inciting wood failure. It is worth noting that the adhesive shear resistance mechanism eliminated the pinching in the hysteresis responses (i.e., hysteretic cycles passing closer to the horizontal axis when the direction of the load is reversed as a result of crack closure and nails slip), leading to more energy dissipation.

Characteristic Parameters

Several key parameters and design values were calculated per ASTM E2126 [17] and building codes (see Table 2).

Maximum load (P_{peak}), ultimate load (P_{ult}, last load at 0.8 P_{peak}), and the corresponding displacements were determined from the envelope curves obtained by averaging the absolute values of the corresponding positive and the negative envelope points for each cycle, whereas yield and energy dissipation from the equivalent energy elastic-plastic (EEEP) curve (*section 3.2.5* ASTM E2126). Results show that load capacities of NA and NB configurations are significantly increased by three times, and the initial stiffness by more than one and a half times when compared with the N configuration. Designing a shear wall to the same load and stiffness capacities of adhesive walls requires thicker sheathing (19/32″ rather 3/8″), larger nail size (10d rather 6d), and closer spacing (3″ rather 6″) [14]. NA configuration slightly increased energy dissipation to the limited plastic deformations, albeit higher loads achieved.

The dominant wood failure in the NA configuration reduces the contribution of nails' deformation to increase the energy dissipation. In contrast, the NB configuration doubled the energy due to the higher plastic deformations and higher loads prior to failure. The higher elongation capability of the adhesive led to expanding plastic deformations and ensuring a minimal contribution from the nails. R factor is a seismic design factor estimated based on energy dissipation through inelastic behavior [20]. The results of R_{exp} for NA configuration match well with the design values. However, the NB configuration shows a higher value than the design value by 80%, indicating that Adhesive B has an apparent impact on increasing the ductility. The R-factor in the current code provisions needs to be reviewed for the proper adhesive and wood configuration combined with mechanical fasteners.

Table 2. Monotonic and cyclic characteristic parameters of shear wall configurations

Conf. index	P_{peak} *(kips)*	P_{yield} *(kips)*	Δ_{yield} *(in)*	Δ_{ult} *(in)*	*Stiffness @ 0.4*P_{Peak} *(kips/in)*	*Energy (kips.in)*	*Ductility, D* $[\Delta_{ult}/\Delta_{yield}]$	Ω_{exp} $[P_{peak}/P_{yield}]$	R_{exp} *[sqr(2D-1). Ω]*	Ω_{design} [1]	R_{design} [2]
Monotonic Results											
N	4.0	3.5	0.65	3.9	5.0	13.3	6.0	1.2	4.0	3	6.5
NA	12.6	11.4	1.3	2.0	8.8	14.8	1.5	1.1	1.6	2.5	1.5
NB	11.1	9.4	1.1	2.5	8.5	18.1	2.3	1.2	2.4		
Cyclic Results											
N	3.9	3.4	0.4	3.2	8.5	10.1	7.9	1.2	4.4	3	6.5
NA	12.0	10.6	0.84	1.5	12.6	11.2	1.8	1.1	1.8	2.5	1.5
NB	10.7	9.9	0.63	2.3	15.7	19.9	3.7	1.1	2.7		

[1,2] *According to ACSE7-16 (Table 12.2-1) for N conf., and SDPWS (Sec. 4.3.6.3.1) for NA & NB confs.* [14], [21]

Conclusions

The current study summarizes the preliminary results of lateral monotonic and cyclic tests to quantify the behavior of nail and elastomeric adhesive connections between sheathing and framing in LFSWs. Two elastomeric adhesives were selected to build two wall configurations (i.e., NA and NB). Force-displacement curves show that the adhesives eliminate pinching and result in more energy dissipation. Load and stiffness capacities are increased significantly by (170~200%) and (50~80%) respectively, compared to the nails-only configuration (i.e., N). The NB configuration that used the high elongation adhesive (1000%) doubled the energy dissipation compared to N and NA configurations. The NA configuration showed brittle failure in wood substrates as opposed to the NB configuration that failure took place at the connection interface, leading to more ductility. Response modification factor in current building codes was found to be underestimated, especially for the adhesive with higher elongation.

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