ABSTRACT

Damaging seismic deformations to wood and cold-formed steel farmed structures can be mitigated by supplying supplementary strength and stiffness to the lateral force resisting system. This can be accomplished in a cost-effective manner by enhancing existing partition walls and cladding through the use of improved mechanical and adhesive fasteners. While experiments have been performed to assess the behavior of enhanced gypsum and stucco fasteners, framed walls, and building substructures, effective numerical modeling techniques are necessary to understand the performance of walls and structures with varying geometries subjected to different types of loading. This paper describes the development of finite element models for the analysis of strength- and stiffness-enhanced light framed walls and structures. These models include discrete elements representing each sheathing-to-framing fastener and panel connection. Models of a conventional gypsum wall, an adhesive enhanced gypsum wall, and an enhanced stucco wall are developed. The analytical behavior of these models loaded cyclically is compared to experimental data. The models are shown to effectively capture the force-deformation behavior, rate of energy dissipation, and stiffness degradation of each of the walls.
Finite Element Analysis of Light-Frame Unibody Residential Structures

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ABSTRACT

Damaging seismic deformations to wood and cold-formed steel farmed structures can be mitigated by supplying supplementary strength and stiffness to the lateral force resisting system. This can be accomplished in a cost-effective manner by enhancing existing partition walls and cladding through the use of improved mechanical and adhesive fasteners. While experiments have been performed to assess the behavior of enhanced gypsum and stucco fasteners, framed walls, and building substructures, effective numerical modeling techniques are necessary to understand the performance of walls and structures with varying geometries subjected to different types of loading. This paper describes the development of finite element models for the analysis of strength- and stiffness-enhanced light framed walls and structures. These models include discrete elements representing each sheathing-to-framing fastener and panel connection. Models of a conventional gypsum wall, an adhesive enhanced gypsum wall, and an enhanced stucco wall are developed. The analytical behavior of these models loaded cyclically is compared to experimental data. The models are shown to effectively capture the force-deformation behavior, rate of energy dissipation, and stiffness degradation of each of the walls.

Introduction

A large proportion of residences and businesses in North America consist of wood or cold-formed steel framed structures. In most cases, these structures have been proven to provide a high degree of life safety during moderate and large earthquakes [1]. However, these structures are vulnerable to costly damage at small levels of deformation. More than half of the $40 billion in building damages caused by the 1994 Northridge Earthquake occurred to wood framed buildings [2]. Seismic damage to light framed structures is capable of not only causing large monetary losses, but also displacing thousands of people and producing considerable downtime to businesses. One study estimates that a repeat of the 1906 San Francisco Earthquake could displace up to 250,000 households, largely due to damage of light framed structures [3].

The lateral force resisting system of wood and cold-formed steel structures is usually provided by shear walls covered with rated wood or steel sheathing. Walls of this type are assigned large response modification factors of up to 6.5 [4]. Though these large factors indicate ductile structural performance, architectural components such as partition walls and cladding are very drift sensitive and will be heavily damaged before the strength of the lateral system is reached. The contribution of partition walls, cladding, and other finishes is often neglected in

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design, though experimentation has shown that these components can contribute greatly to the lateral strength and stiffness of light framed structures [5]. As part of a new design methodology, the authors propose integrating architectural components such as gypsum partition walls and stucco cladding into the lateral resisting system. The strength and stiffness of these components can be further enhanced by using improved mechanical and adhesive connections between sheathing and framing. This design approach can be compared to the transition from body-on-frame to unibody construction that occurred in the automobile industry in the 1970’s. Instead of neglecting walls not sheathed with rated sheathing panels, the lateral resistance of all walls and finishes is utilized to reduce earthquake deformations. This method only increases building costs marginally since the partitions and finishes used to provide enhanced strength and stiffness already exist in the layouts of most light framed structures.

Experimental Testing Program

To understand how enhancing gypsum partition walls and stucco cladding can be utilized to increase seismic strength and stiffness, a significant experimental testing program has been underway. This program began with the testing of mechanical and adhesive gypsum fasteners in both wood and cold-formed steel framing. Enhanced mechanical stucco connections were also investigated along with gypsum panel joint connections. Small 1.22 m x 1.22 m framed gypsum-walls built with the different fasteners were tested at Stanford University while larger 2.44 m x 2.44 m and 4.88 m x 2.44 m gypsum and stucco walls were tested at California State University, Sacramento [6]. These larger wall tests explored the effects of using different mechanical and adhesive fasteners, framing materials, perforation patterns, and anchorage configurations on wall racking behavior. Both walls with and without end returns were investigated. Following these experiments, four 2.13 m x 4.88 m one-story three-dimensional room specimens were tested at the Network for Engineering Simulation (NEES) laboratory at the University of California, Berkeley. Three rooms were tested with adhesive and screw fastened gypsum on both interior and exterior walls while the fourth specimen was covered in enhanced stucco on glass-mat gypsum on the exterior and adhesive and screw attached gypsum on the interior. All specimens included finished ceilings and plywood-sheathed floors on a second floor. These room tests examined the effect of different second floor diaphragm details, wall perforation patterns, and holdown configurations on the lateral resistance and damage progression of three-dimensional light framed structures. While these experiments have been performed statically, dynamic experiments are also planned. In the summer of 2014, a full-scale shake table test of an enhanced two-story unibody house will be carried out at the NEES laboratory at the University of California, San Diego. A low-cost base isolation system for wood and cold-formed structures will also be tested as part of that experiment.

Finite Element Modeling of Wood and Cold-Formed Steel Structures

Over the past few decades, several researchers have developed detailed models and analysis tools for light frame construction. Tuomi and McCutcheon [7] formulated a model in which elements with a linear force-displacement represented each sheathing-to-framing fastener within a shear wall. While this model was effective in calculating ultimate racking strength, wall stiffnesses were not accurate due to the highly nonlinear fastener behavior of actual mechanical fasteners. Itani and Cheung [8] developed a model in which sheathing-to-framing fasteners were
represented by four-node nonlinear elements along each framing member while framing and sheathing members were modeled with beam and plane stress elements, respectively. This model allowed for variations in sheathing arrangement and panel shape and included a more accurate representation of monotonic dowel-type fastener behavior. An analysis tool called CASHEW (Cyclic Analysis of SHEar Walls) was developed by Folz and Filiatruilt [9] as part of the CUREE Woodframe Project. This tool condenses the degrees of freedom in a light framed shear wall by assuming no holdown uplift, rigid framing members, and uniform sheathing shear deformations. Each sheathing-to-framing connector is modeled as a pair of uncoupled orthogonal un-oriented springs. The spacing of these fasteners is adjusted to match the monotonic energy dissipation of a comparable wall with single oriented springe representing each fastener. A new ten-parameter model for dowel type fasteners was also presented. This tool was found to produce static and dynamic results that compare well with test data. Judd and Fonseca [10] demonstrated that more accurate model results can be attained when the orthogonal spring pairs representing each sheathing-to-framing fastener are rotated such that one of the springs is oriented in the direction of initial deformation during wall racking. More recently, Van de Lindt et al. [11] developed analysis software called SAPWood where each wall is represented by hysteretic nonlinear springs. The parameters for each wall model are calibrated to wall models where each fastener is represented explicitly. The tool also considers wall uplift, diaphragm rotation, and foundation rocking. Model results were shown to compare well with those from an experimental shake table test.

While several researchers have developed both detailed and simplified wall models for light framed structures, data to model enhanced unibody connections in gypsum and stucco has been needed. With new test data on enhanced mechanical and adhesive connections on partition and stucco walls, the verification of high fidelity finite element models built with novel fasteners is now possible. In order to understand the behavior of light framed systems that vary from those tested, it is important to develop and validate numerical models that can adequately predict the performance of light framed unibody residential structures. As part of this effort, high fidelity finite element models have been formulated. These models explicitly model each sheathing-to-framing fastener, adhesive connection, framing joint, and anchorage with elements that mimic the behavior observed during component testing. This paper explains the formulation of these models and compares the results to those from substructure testing.

### Analysis Method

The finite element software ABAQUS was used to analyze three-dimensional wood and cold-formed steel framed walls and room specimens covered in gypsum sheathing and stucco cladding. The framing and sheathing members were composed of beam-column (ABAQUS type B31) and plane stress shell (ABAQUS type S4R) elements, respectively. Framing members were hinged at their intersections using connector elements (ABAQUS type CONN3D2). Both framing and sheathing members were assigned elastic properties. Mechanical and adhesive fasteners between framing and sheathing were represented by bi-direction uniaxial hysteretic spring pairs what were modeled using user-defined elements (ABAQUS type UEL). These user-defined elements require the development of scripts that ABAQUS queries at every load step for each fastener to determine current stiffness and force properties. The fastener pairs were oriented such that one of the orthogonal springs in each pair aligned with the direction of initial motion.
under wall racking. Different hysteretic models were used for mechanical and adhesive connections and calibrated to fastener test data. Taped and mudded connections between gypsum sheathing panels were also modeled explicitly with element behavior based on data from experimentation. A schematic showing the deformation and orientation of fastener pairs within a wall model during racking is shown in Fig. 1.

A series of experiments were performed to determine the monotonic and cyclic behavior of mechanical and adhesive connections to gypsum wallboard and stucco cladding. Tested fasteners included conventional drywall screws, enhanced mechanical fasteners, inexpensive construction adhesives and various stucco dowel fasteners in both wood and cold-formed framing. Fig. 2 shows the experimental test setup used for the fastener tests.
Mechanical connections in gypsum display highly pinched hysteretic behavior. This occurs because under new loading, the dowel fastener crushes the gypsum, leaving virtually no resistance under reverse loading until the maximum displacement in that direction has been exceeded. This highly nonlinear pinched hysteretic behavior is also seen in mechanical stucco fasteners as well as nail and screw connections in wood or metal sheets. Adhesive connections in gypsum, however, are highly elastic with little degradation until peak strength is reached. During testing, failure of adhesive connections occurred with the removal of the paper gypsum backing in some cases and through the thickness of the wallboard in others. Somewhat higher strengths were reached for adhesive connections to wood framing compared to cold-formed steel framing as wood is porous and formed a better bond with the adhesives tested. For mechanical connections, several models were investigated. The ten-parameter CUREE model developed by Folz and Filiatrult [9] was used in this analysis, though other pinching models were also found to produce good matches with fastener test data [12, 13]. Adhesive fastener connections were modeled using a peak-oriented model developed by Ibarra et al. [14]. Force-displacement responses from testing and fitted models are shown in Fig. 3 for a 41 mm (1-5/8 in) coarse threaded screw and an inexpensive construction adhesive, respectively.

Figure 3. Experimental and model force-displacement relationships for (a) 41 mm drywall screw and (b) construction adhesive fasteners in wood framing

These figures show connections of 16 mm (5/8 in) Type X gypsum drywall to wood framing, though models for the other tested fastener assemblies were also fitted. The forces shown for the adhesive are for a 178 mm (7 in) length along the 2 x 4 stud that was tested and represent the forces per 6770 mm² (10.5 in) of contact area. A scheme which reduces the sum of the squares error in both the hysteretic force and dissipated energy domains was utilized to select hysteretic parameters for each model. The figures show good agreement between the force envelopes of the models and tested fastener connections. Similar models were also fitted to test data for enhanced 6.4 mm (1/4 in) diameter screw fasteners in stucco cladding. The connections between adjacent gypsum sheathing panels were modeled using user-defined elements with behavior based on edge shear tests performed at Stanford University.
Results

Models of gypsum walls built with conventional 41 mm coarse threaded drywall screws only and conventional screws with adhesive were built in ABAQUS. Each wall was sheathed on both sides with mechanical fasteners spaced at 178 mm (7 in) at panel edges and 305 mm (12 in) in the field. Adhesive fasteners were modeled on all framing edges as well as mid-height wall blocking for the enhanced wall. Additionally, a wall with adhesive-applied gypsum on one side and stucco on a gypsum substrate on the other side was modeled. Mechanical fasteners were placed in the stucco at 102 mm (4 in) along the wall edge and 178 mm in the field. All walls were 2.44 m long (8 ft.) and 2.44 m tall and matched walls tested at the California State University, Sacramento [6]. The results shown are for wood framed walls only, though models were also formulated for the cold-formed steel walls tested. The results from these experiments are used here for model validation. Fig. 4 shows the cyclic skeleton curves for the conventional and adhesive enhanced gypsum sheathed walls from testing compared to those obtained from the finite element analysis.

![Cyclic skeleton curves showing experimental and finite element model responses of 2.44 x 2.44 m conventional and enhanced gypsum walls](image)

For both the conventional and enhanced gypsum walls, the finite element models were able to accurately capture the force envelopes. For the wall built with adhesive, the model suffers a loss of strength at slightly larger displacements than the experimental wall. The peak racking force observed in the enhanced gypsum wall was more than twice that of the conventional wall. The secant stiffness at a story drift ratio of 0.1 of the adhesive-enhanced wall was more than two and half times larger than that of the conventional gypsum wall. Figure 5 compares the cyclic energy dissipated and cyclic stiffness degradation per cycle in experimental and analytical gypsum walls.
For the conventional gypsum wall, the rate of energy dissipation for the finite element model closely matches that obtained from testing. For the adhesive wall, the initial rate of energy dissipation is underestimated in the model, though cumulative energy dissipation at larger displacement cycles is comparable. The model secant stiffness at each loading cycle compares well to test data for the conventional wall, but is less accurate for the enhanced wall. In the adhesive wall model, very little stiffness degradation occurs until the peak strength of the wall is approached. The experimental adhesive wall shows stiffness deterioration even at small displacement load cycles. After peak wall strength is reached, the finite element model continues to overestimate the secant stiffness until larger deformations are reached. This discrepancy in absorbed energy and secant stiffness for the enhanced gypsum wall occurs because the adhesive fasteners assume an almost elastic fastener behavior before fracture. The test results suggest that more deterioration of the adhesive fasteners exists before fracture than what was assumed in the finite element model. Fig. 6 compares the cyclic skeleton curves for the tested wall with interior adhesive-attached gypsum and exterior enhanced stucco with the behavior of the corresponding finite element model.

Figure 5. (a) Energy dissipation and (b) secant stiffness degradation of experimental and finite element models of 2.44 x 2.44 m conventional and enhanced gypsum walls

Figure 6. Cyclic skeleton curves showing experimental and finite element model responses of 2.44 x 2.44 m enhanced stucco and gypsum walls
The force envelope of the analytical model compares well to that obtained from testing, though the peak racking forces seen in the model are about ten percent higher than those observed during experimentation between racking displacements of about 5 and 15 mm. A comparable conventionally built wall with interior gypsum and exterior stucco was not tested, though experiments from others suggest the strengths and stiffnesses achieved in the enhanced stucco wall are significantly higher than those of conventional stucco walls [15,16]. Fig. 7 shows the cumulative energy dissipation and the secant stiffness per cycle for both the tested and finite element enhanced stucco wall.

![Energy dissipation and secant stiffness degradation of experimental and finite element models of 2.44 x 2.44 m walls with adhesive applied gypsum on one side and enhanced stucco on the exterior](image)

Figure 7. (a) Energy dissipation and (b) secant stiffness degradation of experimental and finite element models of 2.44 x 2.44 m walls with adhesive applied gypsum on one side and enhanced stucco on the exterior.

The finite element model was able to fairly accurately capture the rate of energy dissipation in the enhanced stucco wall, especially at small displacement steps. At larger displacement cycles, the model overestimates the rate of energy dissipation. This occurs because the test wall showed a slightly more pinched hysteretic behavior than the model. The secant stiffnesses per cycle also compare well, though the model again shows little stiffness degradation at small amplitude loading cycles because the adhesive fastener models used are nearly elastic until the adhesive bond breaks.

To illustrate the effect of using significantly strengthened and stiffened wall finishes in light frame construction, both the conventional and enhanced gypsum wall models were subjected to dynamic seismic loading. A line load mass of 17.5 kN/m (1200 lbs/ft) was applied to the top of each 2.44 m square wall representing the tributary load to a wall from a second floor or roof. Rayleigh damping was applied using a damping ratio of 0.01 at the first and second natural periods, assuming that most damping in framed structures is hysteretic. The walls were restrained from out-of-plane motion. Both walls were subjected to the full Northridge Canoga Park station record. Fig. 8 shows the in-plane response of both walls.
The results of the dynamic finite element models indicate that enhanced unibody gypsum walls may undergo much less deformation than conventional walls subjected to the same level of earthquake loading. For this configuration, the adhesive enhanced wall reached a peak drift of 0.34% while the conventional wall reached a drift of 1.7%. Since visible damage to partition walls occurs at drifts of about 0.25%, controlling wall drifts using strengthened and stiffened walls can greatly reduce seismic damage and repair costs to light framed structures.

**Conclusions**

The development of detailed finite element models of enhanced light framed walls sheathed with gypsum and stucco has been introduced. These models use oriented bi-directional hysteretic spring pairs with behavior fit to fastener experimental data to represent mechanical and adhesive sheathing-to-framing fasteners and panel edge connections. This modeling technique can be applied to walls and substructures of all geometries and does not make kinematic assumptions that restrict framing and sheathing deformation modes. The models are shown to capture the cyclic skeleton force backbone behavior of comparable walls from testing. Energy dissipation and cyclic stiffness degradation of the finite element walls also compared well to experimental results, though the tested walls built with adhesives showed somewhat more degradation than the finite element model walls during small displacement amplitude cycles due to only modest degradation of the adhesive models before connection failure. Analytical dynamic loading demonstrates that enhanced unibody walls can substantially reduce seismic drift demands when compared to conventional gypsum partition walls.

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