16th World Conference on Earthquake Engineering, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 1353

Registration Code: S-B1463273306

PERFORMANCE-BASED SEISMIC ASSESSMENT OF A WOOD-FRAME HOUSE WITH STRENGTH AND STIFFNESS ENHANCEMENTS

S. Swensen[(1)], G. Deierlein[(2)], E. Miranda[(3)], B. Fell[(4)], C. Acevedo[(5)], E. Jampole[(6)]

(1) Associate, Exponent, Inc., sswensen@exponent.com
(2) John A. Blume Professor, Stanford University, ggd@stanford.edu
(3) Associate Professor, Stanford University, emiranda@stanford.edu
(4) Associate Professor, California State University, Sacramento, fellb@csus.edu
(5) Ph.D. Candidate, Stanford University, ejampole@stanford.edu
(6) Ph.D. Candidate, Stanford University, cacevedo@stanford.edu

Abstract

While light-frame residential structures generally provide a high degree of life safety, significant damage and financial losses can result from moderate and severe earthquakes. Damaging seismic deformations can be mitigated by providing 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 connections between sheathing and framing. An extensive test program has been carried out to characterize the performance of enhanced sheathing-to-framing fastener connections as well as walls, room enclosures, and structures built using these enhancements. The test program culminated in the shake table testing of a full-scale two-story wood-frame house. This paper describes the performance-based evaluation of the tested enhanced wood-frame house. The analysis was performed using multiple stripe analysis (MSA) applied to a three-dimensional nonlinear structural model. Probabilities of collapse and exceeding damaging drift thresholds were calculated for the strengthened and stiffened structure as well as for a comparable house designed to code standards with conventional wood-frame walls. The analysis indicates that instituting strength and stiffness enhancements reduces the probability of collapse by more than fifty percent, while decreasing the probability of encountering drifts that would require wall repair by approximately sixty to eighty percent. These results demonstrate the effectiveness of strength and stiffness enhancements in limiting seismic damage to light-frame residential structures while also providing enhanced life safety.

Keywords: light-frame structures; wood structures; performance-based earthquake engineering; analysis; multiple stripe analysis

1. Introduction

Light-frame structures constitute the vast majority of the residential building stock in the United States and Canada, with a significant portion of those structures being exposed to seismic hazards [1]. While conventional light-frame structures have been fairly successful in protecting human life during moderate and severe earthquakes [2], significant financial loss and the displacement of occupants can result from damage to these buildings. This seismic vulnerability was demonstrated during the 1994 Northridge Earthquake, which produced an estimated US$20 billion in losses to light-frame structures [3], representing approximately half of all losses. In a review of damage to residential structures as a result of several recent disasters, Comerio [4] found that the largest portion of financial losses was a result of widespread minor to moderate damage, not extreme damage and collapse. This costly damage occurs because conventional light-frame buildings are designed to allow large deformations during moderate and severe earthquakes; however, architectural components such as partition walls and cladding, which are integral to light-frame structures, experience significant damage at small drift levels.

Seismic building code provisions have, for many years, recognized the benefits of structural ductility to reduce the required lateral design strength of buildings. While this tradeoff of strength for ductility works well for multi-story steel and concrete buildings, the tradeoff is much less effective for low-rise residential buildings with smaller fundamental periods, where the ratio of inelastic story drift (for an inelastic structure) to elastic story drift (for an elastic structure) is very large. Additionally, for light-frame residential buildings where the total mass is small, the economic and practical incentives for reducing the required lateral design strength are less. Therefore, counter to current trends, designing for higher lateral strengths can dramatically reduce the inelastic deformation demands and damage in short period residential buildings. The resulting improvement in performance reduces economic losses and helps ensure that households can continue to occupy their residences after a large earthquake.

As part of this research, a concept for strengthening and stiffening light-frame structures was developed. This approach was achieved by unifying structural and architectural (e.g., gypsum drywall and stucco) walls as well as providing strength and stiffness enhancement to these walls through the use of improved dowel and adhesive connections. With the overall goal of drastically limiting seismic damage to light-frame structures exposed to seismic hazard, the first objective of this research was to formulate practical and cost-effective details to increase the strength and stiffness of light-frame shear walls through improved fasteners for gypsum board, stucco and other sheathing materials to wood and cold-formed steel framing. This was done through a series of component tests to quantify the strength and stiffness benefits of different connection and wall configurations. Numerical models were then calibrated to component behavior from testing. These models were utilized to validate the ability of strength- and stiffness-enhanced light-framed systems to limit seismic damage and provide acceptable life safety through a performance-based approach. While this paper is focused on the seismic performance evaluation of strength- and stiffness-enhanced light-frame systems, some results from component testing are also summarized.

2. Testing of Enhanced Light-Frame Connections, Walls, Rooms, and Full-Scale House

Fig. 1 shows an overview of the testing that took place to develop and validate the use of strength- and stiffness-enhanced light-frame structures and components. The development of enhanced light-frame systems began with the testing of screw and adhesive fastener connections between wood and cold-formed steel framing and gypsum board and stucco. These connections were later implemented in wall tests. Larger scale room assemblies were then tested to further validate the behavior of the walls built with enhanced connections and to investigate the influence of connecting elements and force transfer through floor diaphragms, ceilings, and wall returns. Validation culminated in full-scale shake table testing of a two-story wood-frame house built with shear walls sheathed only with gypsum wallboard and stucco employing enhanced fastening methods. This experiment occurred in the summer of 2014 at the Network for Earthquake Engineering Simulation (NEES) facility at the University of California, San Diego (UCSD).

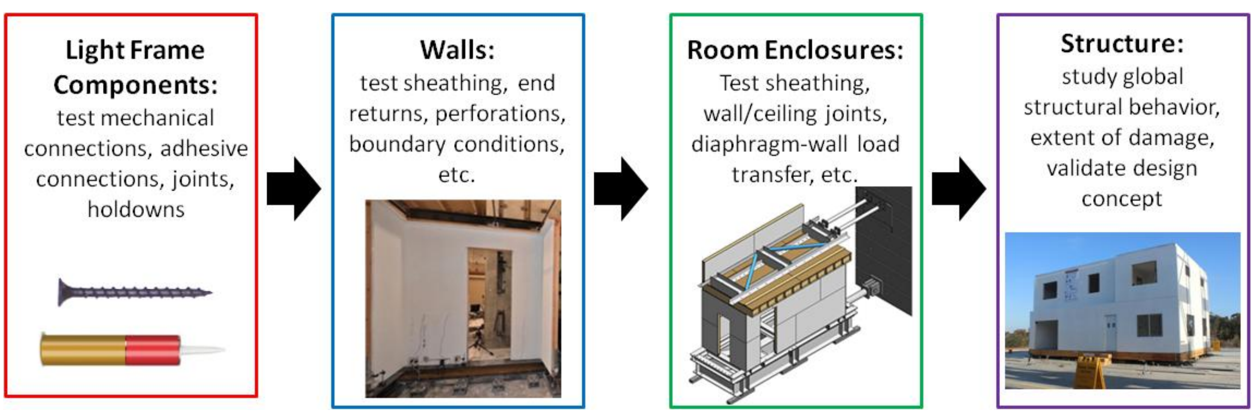


Fig. 1 - Overview of project components

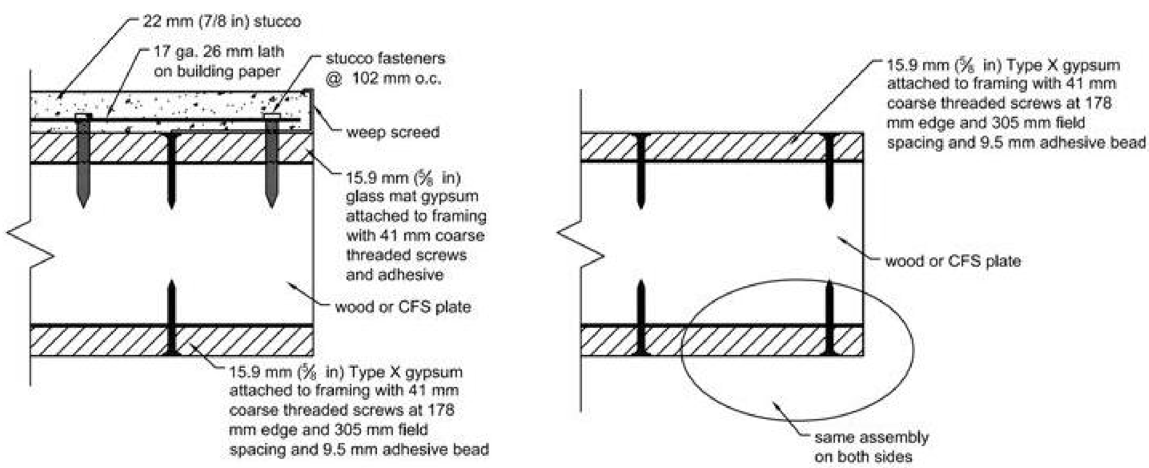
2.1 Enhanced Fastener and Wall Tests

The behavior of light-frame shear walls is controlled by the performance of individual sheathing-to-framing fasteners. Resistance to shear forces in walls built with sheathing attached with screws or nails occurs as the sheathing material bears against the fasteners. Therefore, the investigation into strength- and stiffness-enhanced light frame structures began with the testing of sheathing-to-framing connections.

Initial efforts to produce stronger and stiffer gypsum wallboard connections included testing of screw fasteners with thicker shank areas to provide increased bearing against the wallboard. While these enhanced screws provided some increased resistance when compared to conventional drywall screws, the increase in strength and stiffness was not sufficient to significantly alter wall and structural performance. Therefore, inexpensive construction adhesives were tested in conjunction with screw fasteners to augment connection strength and stiffness. Testing showed that utilizing adhesives in addition to screw connectors increased drywall-to-framing connection strength and stiffness by four to five times [5, 6]. Additionally, connection tests utilizing large screws to engage stucco sheathing led to connection strengths approximately twice that of stucco connected with conventional nail fasteners.

Due to the favorable results of wallboard connection tests utilizing adhesives, reduced-scale (1.2m x 1.2m) walls using adhesives to attach gypsum drywall framing were tested at Stanford [6] along with full-scale walls (2.4m x 2.4m and 2.4m x 4.9m) including specimens with perforations and returns at California State University, Sacramento [7]. Results showed that gypsum partition walls utilizing adhesives in addition to conventional drywall screws have strengths approximately twice as large as walls built with screws alone. The adhesive also increased wall racking stiffness by two to four times. Enhanced stucco dowel connections were found to increase wall strength by more than fifty percent when compared to conventional stucco walls.

In total, 62 fastener tests and 27 wall tests were performed utilizing both wood and cold-formed steel framing. In these tests, lateral resistance was provided by (1) gypsum board sheathing, (2) gypsum board and stucco plaster, and (3) plywood. For subsequent room tests and the shake table building design, the enhanced details for interior and exterior walls shown in Fig. 2 were used.



(a) (b)

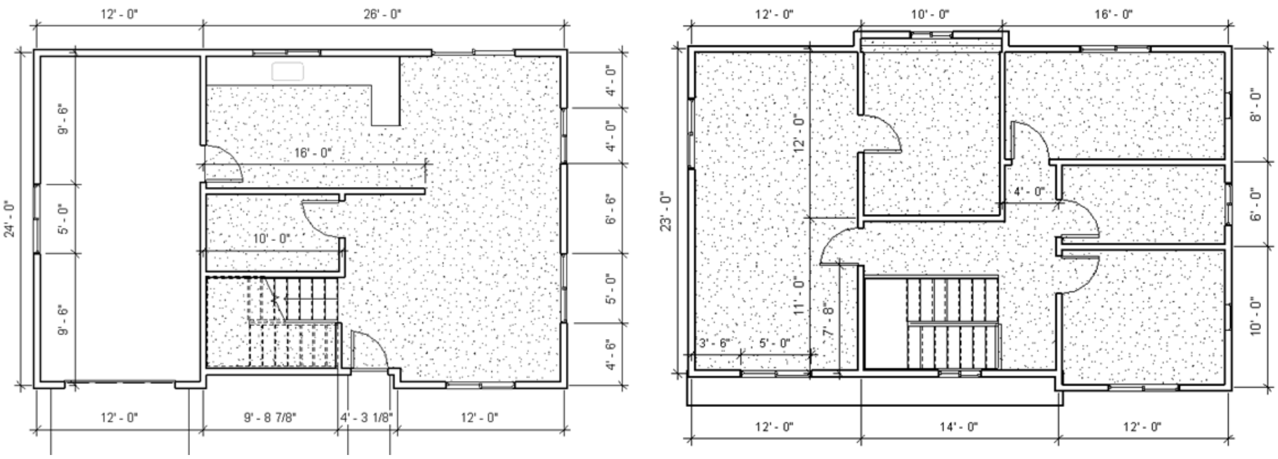
Fig. 2 - Composition of enhanced (a) stucco and (b) gypsum walls as built shown in plan [5]

2.2 Light-Frame Room Assemblies

To further study the performance of strength- and stiffness-enhanced light frame systems which include wall returns, ceilings, and floor diaphragms, four large-scale room assemblies were constructed and tested at the NEES facility at the University of California, Berkeley. In addition to further validating the influence of enhanced connections for gypsum board and stucco, the tests were intended to include boundary conditions that are more typical of those that would be found in residential construction. Three of the tested room specimens were sheathed on both the exterior and interior with gypsum drywall applied with construction adhesive in addition to drywall screws. The fourth test included enhanced gypsum drywall connections on the interior and enhanced stucco applied to the exterior (see Fig. 2). The specimens included different door and window opening configurations as well as variations in the continuity of the exterior sheathing and stucco above the ceiling level. The test setup permitted for testing of the walls up to a drift level of 10%, providing valuable information on the performance of light-frame wall assemblies at large drifts. Remarkably, the tested room specimens displayed residual lateral strengths of approximately one-third to one-half of the peak strengths at drift levels in excess of 10%. This finding demonstrates the resilience of enhanced light-frame walls when appropriate wall holdowns and anchorages are used.

2.3 Full-Scale Enhanced Wood-Frame House

The floor plans for the full-scale house tested on the shake table at the NEES@UCSD facility are shown in Fig. 3. The footprint of the house was approximately 11m x 7 m in plan with an overall total floor area on both floors of approximately 150 square meters. The floor plan was selected to approximate that of a typical four-bedroom house with an attached garage, though some rooms were somewhat smaller than typical in order to accommodate the space restrictions of the shake table. The amount and location of wall perforations including windows and doors were selected to approximate those typical in new construction.

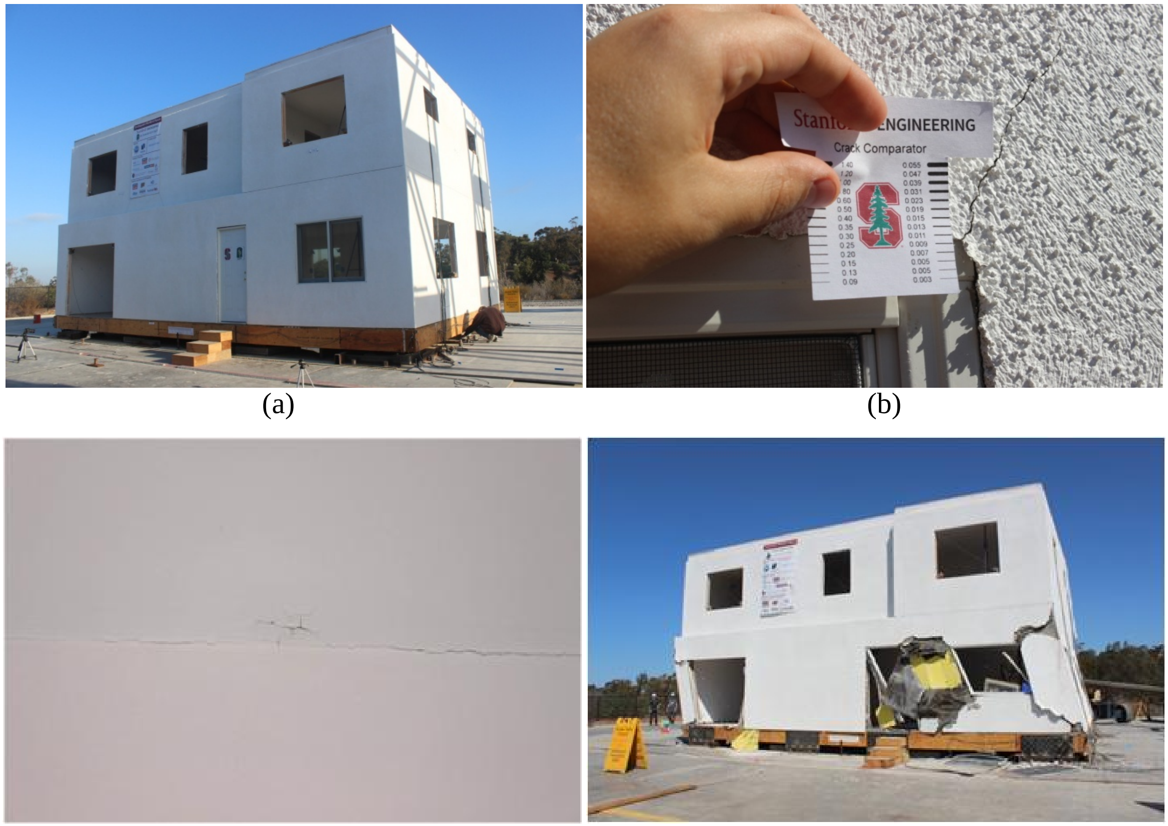


(a) (b)

Fig. 3 - Full-scale wood-frame house test specimen: (a) first floor plan; (b) second floor plan [5]

All exterior walls of the house specimen were constructed with stucco applied over glass-mat gypsum sheathing on the exterior and gypsum drywall on the interior (Fig. 2a). The glass-mat sheathing and drywall were connected to the wood framing with typical drywall screws and construction adhesive. Large screw fasteners passing through the glass-mat gypsum sheathing were used to engage the stucco when the walls were loaded laterally. Interior walls were constructed with gypsum drywall applied to both sides with drywall screws and construction adhesive (Fig. 2b). The lateral resistance of the house was provided entirely by gypsum drywall, gypsum sheathing, and stucco; no wood sheathing was used in the walls of the house. Hold-downs and shear anchorages were installed at all interior and exterior walls on both floors that were considered to provide lateral strength. This included nearly all wall segments greater than two meters in length.

Scaled ground motions were applied to the structure at increasing magnitudes through the shake table. The structure exhibited only slight indications of damage including hairline cracks in gypsum drywall and stucco cladding when subjected to ground motions scaled to up to twice the Maximum Considered Earthquake (MCE) level for a Design Category D location (short period spectral acceleration of approximately 3.0g). Extensive damage occurred when the ground motions were scaled to three-times the MCE level (short period spectral acceleration of approximately 4.5g), though collapse was mitigated. Photos of the house before testing along with representative stucco and gypsum board damage and the final house appearance after testing are shown in Fig. 4.



(a) (b) (c) (d)

Fig. 4 - Photos of (a) house before testing; (b) minor cracking to exterior stucco and (c) cracking around a drywall fastener and panel edge following an experienced ground motion corresponding to twice the MCE level; (d) damage to the house following an experienced motion of three times the MCE level

3. Performance-Based Building Analysis

In order to evaluate the damage resilience and ensure appropriate collapse safety of enhanced light-frame structures, a performance-based analysis of the tested two-story single family residence was carried out. First, a structural model was developed using data from component, wall, and room tests to simulate enhanced wall behavior. The model was then subjected to a series of ground motions selected to match hazard level spectra for a building site in Los Angeles at discrete spectral acceleration values. The results from these nonlinear time history analyses were used to evaluate the enhanced light-frame house in terms of damage and collapse resistance.

3.1 Prototype Houses

The strength- and stiffness-enhanced house tested on the shake table at NEES@UCSD (Fig. 3) was modeled using the program Open System for Earthquake Engineering Simulation [8]. Three variations of the house were modeled. These included houses of the same floor plan where lateral forces are resisted by (1) conventional structurally rated wall materials only, (2) conventional structurally rated wall materials and finishes, and (3) enhanced wood-frame stucco and gypsum drywall. The models utilizing conventional structural systems were analyzed to provide a direct comparison of building performance to the enhanced system. The simulated components for the three model variations are shown in Table 1. The first two models represent the test house had it been built using materials and construction methods conventionally used for the lateral force resisting systems of wood-frame structures as required by International Residential Code [9]. Conventional models with and without finishes were analyzed because the building code allows for design of light-frame structures without finishes, though finishes are almost always provided and have been shown to provide significant strength and stiffness in shake table testing [10, 11]. The third house included enhanced gypsum wallboard and stucco details and represents the house built and tested at NEES@UCSD as part of this research program.

Table 1 - Wall materials modeled for enhanced and typical house archetype models

House Prototype	Exterior Wall Material		Interior Wall Material (both sides)
	Exterior Side	Interior Side	
Typical (without finishes)	13mm OSB with wood screws	13mm gypsum wallboard with drywall screws	none
Typical (with finishes)	conventional stucco over 13mm OSB with wood screws	13mm gypsum wallboard with drywall screws	13mm gypsum/drywall screws
Enhanced	enhanced stucco over 16mm glass mat sheathing applied with adhesive and screws	enhanced 16mm gypsum wallboard	enhanced 16mm gypsum wallboard

3.2 Building Models

Each wall segment of the three structures was modeled with a pair of hysteretic springs with behavior that was fit to experimental test data of light-frame walls. To illustrate the accuracy of the hysteretic model fits, the unit force-displacement behavior of the enhanced interior gypsum walls and enhanced exterior stucco walls are shown in Fig. 5 and Fig. 6, respectively. The equivalent diagonal element behavior is shown along with the wall behavior from experimental testing. While the behavior shown is for walls with lengths of 4.9 m, the strength and stiffness parameters for each element model were adjusted based on wall length and the presence of openings. Based upon results of tested conventional wood framed walls [12], parameters were also fit to wall models for conventional wall assemblies.

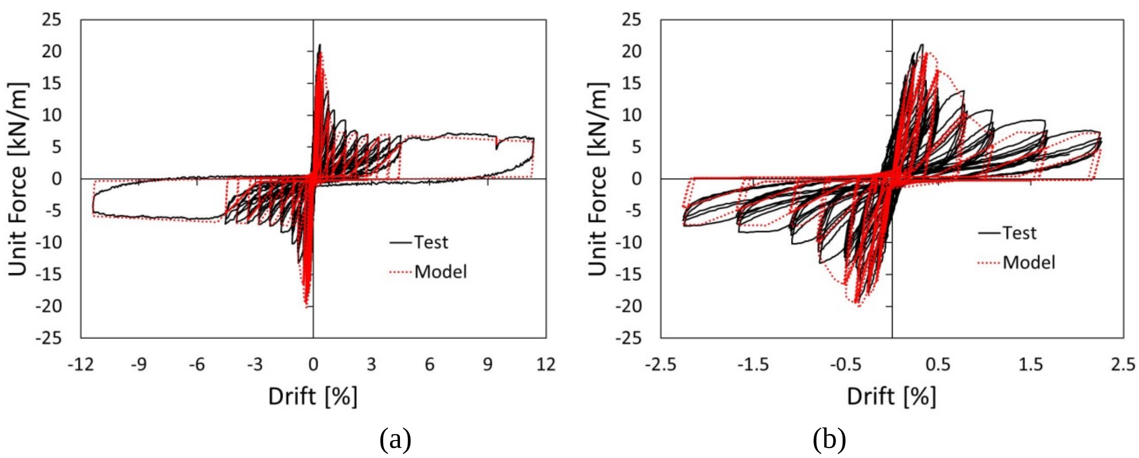


Fig. 5 – Experimental and model force-drift behavior of enhanced gypsum-gypsum wall without openings (a) at large drifts and (b) small drifts [5]

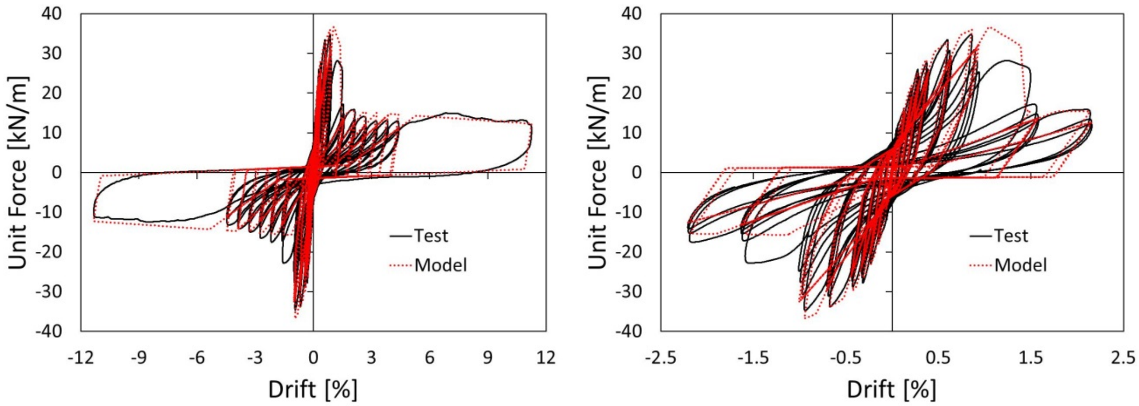


Fig. 6 – Experimental and model force-drift behavior of enhanced stucco-gypsum wall without openings (a) at large drifts and (b) small drifts [5]

3.3 Multiple Stripe Analysis

A multiple-stripe analysis (MSA) was performed on the developed conventional and enhanced house models. MSA consists of applying intensity- and site-specific ground motions to a structural model at specific spectral acceleration levels. This method differs from Incremental Dynamic Analysis (IDA) [13] where a building model is subjected to the same suite of ground motions scaled to a variety of intensities. MSA was performed because researchers have observed that site-specific elastic response spectra vary in spectral shape at different hazard intensities. The conditional spectrum reflects changes in spectral shape at different intensity levels for a building with a specific period subjected to site-specific seismic hazards [14, 15, 16]. To capture spectral shape variations at different intensities, different sets of scaled ground motions were selected at a variety of spectral acceleration levels based on hazard level using an algorithm developed by Jayaram et al. [17]. Motions scaled to the spectral ordinate and shape of the conditional spectrum were selected for probabilities of exceedance of 50%, 20%, 10%, 5%, 2%, and 1% in a 50 year period for a site in Los Angeles (zip code 90071) with ground shear wave velocity of 350 m/s. Additionally, an even larger intensity ground motion set with a 1% probability of exceedance in 200 years was considered. Twenty ground motion pairs were selected for each hazard level, applying each pair to each structural model twice, alternating the direction of the horizontal ground motions. This approach results in forty analysis runs for each model at each intensity level. Fig. 7 shows the mean MSA spectra at varying hazard levels for a structure with a period of 0.14 seconds, representative of the enhanced two-story light-frame house modeled along with the uniform hazard spectrum (UHS). As the seismic intensity at the structural period of the MSA motions is increased, the spectra show more pronounced peaks at the conditioning period.

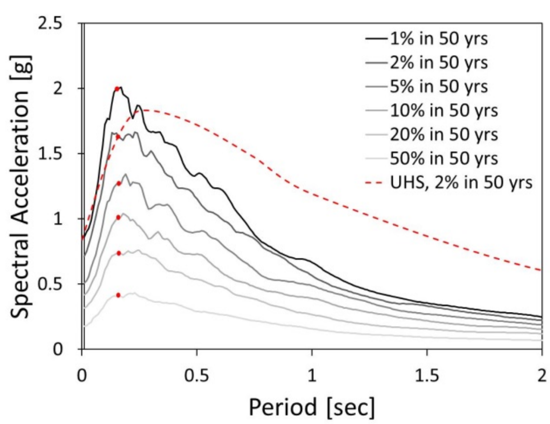


Fig. 7 – Mean response spectra of motions fitted to conditional spectra at different hazard levels for Downtown Los Angeles (zip code 90071) site class C/D [5]

The UHS shown in Fig. 7 defines the spectral acceleration at the site with a uniform 2% probability of exceedance in 50 years for buildings with natural periods varying from 0 to 2 seconds. This spectrum is shown along with the mean MSA spectra to demonstrate the difference in spectral shape between the spectra that have been conditioned at the building's period, which display a 'pinched' shape at that period, and the un-conditioned UHS. Note that the UHS and the conditional mean spectrum with a 2% probability of exceedance in 50 years have the same spectral ordinate at the building's fundamental period (0.14 seconds).

Each unique set of ground motions for each intensity were then applied to the three structural models with a total of 240 model analyses for each prototype house. The probability of collapse and the probability of exceeding drift levels associated with certain damage thresholds were determined by fitting lognormal curves to the cumulative distribution functions produced from the model results using the maximum likelihood method.

3.4 Results and Discussion

Fragility curves showing the probability of exceeding three unique drift levels as a function of spectral acceleration at the first mode period are shown in Fig. 8 and Fig. 9. Observed fragility probabilities from MSA obtained by determining the portion of applied ground motions leading to exceedance of the drift levels are shown as dots, while the dashed lines represent the lognormal fragility curves fit to those points. In Fig. 8a, the probability of exceeding a story drift of 0.2% is shown. This level of drift corresponds to initial minor damage and cracking in gypsum wallboard and stucco. The median spectral accelerations leading to this drift level are 0.49g, 0.79g, and 1.03g for the conventional house without finishes, the conventional house with finishes, and the enhanced house, respectively. These accelerations are the median spectral acceleration values (probability of exceedance of 0.5) on the fit fragility curves that would cause the target drift. At 0.3% drift (Fig. 8b), which corresponds to more widespread cracking and damage to stucco and gypsum finishes, the median spectral accelerations corresponding to this drift level are 0.76g, 1.01g, and 1.30g for the conventional house without finishes, the conventional house with finishes, and the enhanced house, respectively. These results demonstrate that the spectral accelerations required to produce damage to finish materials in the enhanced light-frame house are approximately 30 to 110% larger than the accelerations that would cause the same level of damage to the conventional house. This difference in fragilities suggests that the enhanced light-frame house can sustain significantly larger seismic intensities with less damage when compared to conventional construction.

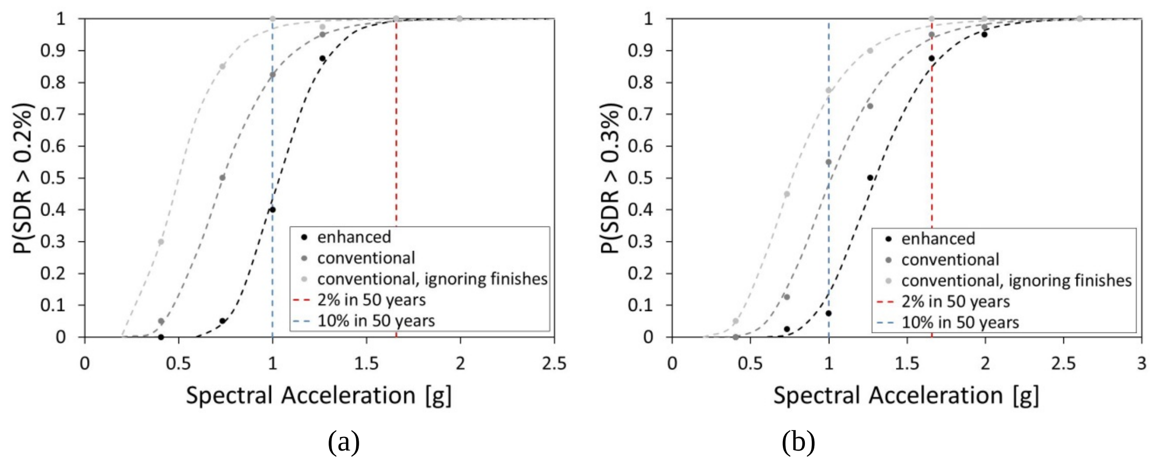


Fig. 8 – Drift fragility curves for two-story prototype house using MSA at: (a) 0.2% drift; (b) 0.3% drift [5]

At a wall drift of 1.0% (Fig. 9), significant damage is expected to light-frame walls which would likely require complete replacement of the sheathing material. The median spectral accelerations associated with this drift level are 1.69g, 1.99g, and 2.42g for the conventional house without finishes, the conventional house with finishes, and the enhanced house, respectively. This indicates that spectral accelerations causing this level of damage to the enhanced house are approximately 20 to 45% larger than the accelerations causing the same level of damage to the conventionally constructed house.

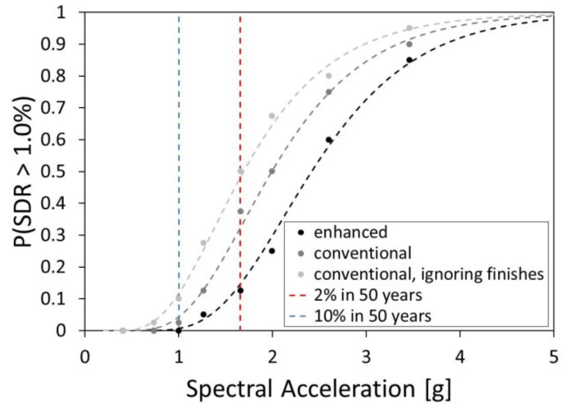


Fig. 9 - Drift fragility curves for two-story prototype house using MSA at 1.0% drift [5]

For all three drift levels studied, the lognormal standard deviations of the probabilities of exceeding each drift level are smaller for the enhanced house than for either of the conventional houses, indicating more consistent drift behavior when subjected to ground motions scaled to the same spectral ordinate. This occurs because the enhanced structure is more likely to be in the elastic range than the conventional houses at the applied ground motion intensity levels.

The collapse fragility curves for the two conventional house models and the enhanced house model are shown in Fig. 10. The largest magnitude of motions applied to the models, which corresponds to an event with a 1% probability of occurrence in 200 years, results in a collapse rate of 20 to 30% for all three of the building models. The median spectral accelerations corresponding to collapse are 4.49g, 4.45g, and 4.49g for the conventional house without finishes, the conventional house with finishes, and the enhanced house, respectively. While these median collapse intensities are similar, the lognormal standard deviation of collapse fragility is smaller for the enhanced house (0.61) than for conventional house without and with finishes (0.82 and 0.73, respectively).

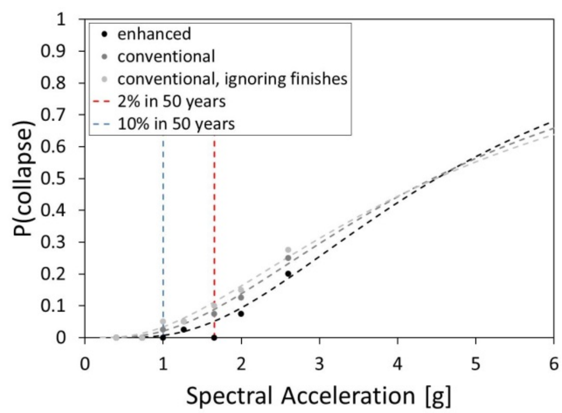


Fig. 10 – Collapse fragility curves for two-story prototype house using MSA [5]

The probability of exceeding drift limits and incurring collapse were then calculated using the seismic hazard curves for the hypothetical building site in downtown Los Angeles (Fig. 11) and the fragility functions determined from MSA. This was done by performing numerical integration on the probability of collapse or the probability of exceeding the discussed drift levels multiplied by the slope of the hazard curve at each considered spectral acceleration stripe [18].

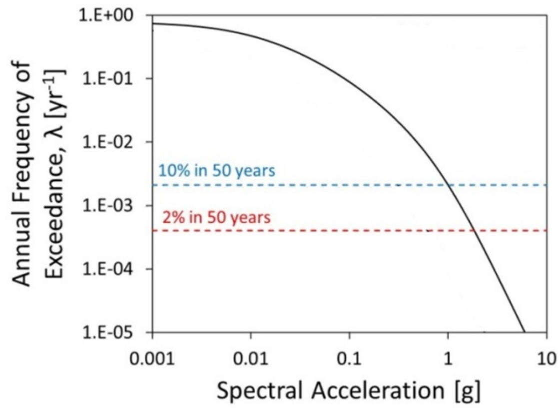


Fig. 11 - Seismic hazard curve for downtown Los Angeles (zip: 90071), V_s = 350 m/s for T_1 = 0.14 seconds

Table 2 shows the mean annual frequency of exceeding the three drift level thresholds described as well as the probabilities of exceeding these drift levels in a 50 year time period at the Los Angeles site. The probability of exceeding 0.2% drift in 50 years of building life for the conventional house with finishes is approximately three times that of the enhanced house, while the probability of exceeding 0.2% drift in a conventional house without considering finishes is approximately five times larger. This result indicates that the probability that damage requiring repair during a 50 year period is approximately 65 to 80% less likely for the enhanced house than for the conventionally constructed house. The probability of exceeding a drift level of 1.0%, which would likely require replacement of sheathing, is approximately 60 to 75% less for the enhanced house than for the conventional house. These results highlight the effectiveness of the developed strength- and stiffness enhancements in mitigating damage to light-frame residential structures.

Table 2 – Rate of exceeding drift levels for enhanced and conventional two-story house prototypes from MSA

	Enhanced House	Conventional House	
		with finishes	w/o finishes
$\lambda_{0.2\%}$ [yr^{-1}]	2.3E-03	7.2E-03	1.5E-02
$\lambda_{0.3\%}$ [yr^{-1}]	1.4E-03	3.6E-03	7.0E-03
$\lambda_{1.0\%}$ [yr^{-1}]	3.2E-04	8.2E-04	1.4E-03
$P_{0.2\%,\ 50\ yrs}$	10.8%	30.1%	52.9%
$P_{0.3\%,\ 50\ yrs}$	6.6%	16.6%	29.5%
$P_{1.0\%,\ 50\ yrs}$	1.6%	4.0%	6.6%

The mean annual frequencies of collapse as well as the probabilities of collapse in a 50 year period are shown in Table 3 for the three house models. The probabilities of collapse for the conventional house without finishes and the conventional house with finishes are approximately two to three times larger than the collapse probability for the house with strength- and stiffness-enhancements. The enhanced house demonstrates damage resilience while also maintaining a collapse probability less than that of the conventional house. This finding demonstrates that limited-ductility systems can provide acceptable collapse capacity if sufficient building strength is provided.

Table 3 – Rate of incurring collapse for enhanced and conventional two-story house prototypes from MSA

	Enhanced House	Conventional House	
		with finishes	w/o finishes
λ_C [yr^{-1}]	1.4E-04	3.2E-04	4.5E-04
$P_{C,\ 50\ yrs}$	0.7%	1.6%	2.2%

4. Conclusion

A concept for limiting damage to light-frame residential structures by increasing lateral building strength and stiffness has been developed. Results from laboratory tests to characterize the performance of strength- and stiffness-enhanced connections, walls, room enclosures, and a full building structure were presented. These experiments demonstrated that light-frame walls sheathed with gypsum board or stucco enhanced by supplementing the material connections with inexpensive construction adhesives or larger dowel fasteners can provide wall strengths and stiffnesses two to four times larger than conventionally constructed walls. The results of component structural tests were then used to calibrate structural models that simulate the performance of walls and whole building systems.

Utilizing the developed models, evaluation of a strength- and stiffness-enhanced light-frame structure was carried out through a performance-based earthquake engineering framework. An MSA procedure was used to characterize the drift and seismic collapse performance of a two-story wood-frame house designed with strength- and stiffness-enhanced walls and wood framing. Enhanced stucco-gypsum walls were used for exterior walls (Fig. 5), while enhanced gypsum-gypsum walls were used for interior walls (Fig. 6). A comparable house with the same floor plan was designed with conventional wall materials and design procedures without considering finishes (e.g., gypsum partition walls and stucco cladding) and with finishes for comparison against the enhanced house. When subjecting the three house models to MSA for a building site in Downtown Los Angeles, the probability of exceeding a drift limit of 0.2% was approximately three to five times larger for the conventional house models when compared to the enhanced house. Since this drift level corresponds to the onset of damage for gypsum and stucco walls, seismic damage initiation is significantly delayed in enhanced light-frame structures when compared to structures designed according to conventional methods. The probability of collapse for the enhanced two-story structure is less than half that of the conventional house with and without finishes over a fifty year period. This analysis suggests that for this specific archetype, the enhanced house would incur significantly less damage than a conventional light-frame structure when subjected to a wide array of seismic hazard intensities. The collapse risk of the strength- and stiffness-enhanced light-frame house is also significantly smaller than that of the comparable conventional structure.

5. Acknowledgements

This research was supported by the John A. Blume Earthquake Engineering Center at Stanford University and by a National Science Foundation (NSF) Graduate Research Fellowship for the first author. Funding and materials were provided by the late Ben Schmid, professional engineer, and through a grant by NSF under the Network for Earthquake Engineering Simulation, award #1135029.

6. References

[1] Li Y, Ellingwood B (2007): Reliability of woodframe residential construction subjected to earthquakes. *Structural Safety*, *29*(4), 294-307.

[2] Rainer J, Karacabeyli E (2000): Performance of wood-frame construction in earthquakes. In *Proceedings of the 12th World Conference on Earthquake Engineering, Auckland, New Zealand* (Vol. 30, pp. 1-8).

[3] Schierle G (2002): Northridge earthquake field investigations: Statistical analysis of wood-frame damage (CUREE Publication No. W-09). CUREE, Richmond, CA.

[4] Comerio M (1997): Housing issues after disasters. *Journal of Contingencies and Crisis Management*, *5*(3), 166-178.

[5] Swensen S (2014): *Seismically Enhanced Light-frame Residential Structures* (Doctoral dissertation, Stanford University).

[6] Swensen S, Deierlein G, Miranda E (2015): Behavior of Screw and Adhesive Connections to Gypsum Wallboard in Wood and Cold-Formed Steel-Framed Wallettes. *Journal of Structural Engineering*, E4015002.

[7] Hopkins A (2013): *Large-scale tests of seismically enhanced planar walls for residential construction* (Masters Thesis, California State University, Sacramento).

[8] Mazzoni S, McKenna F, Scott M, Fenves G (2006): *OpenSees command language manual*. Pacific Earthquake Engineering Research (PEER) Center.

[9] International Code Council (ICC). (2012). International Residential Code for One- and *Two-Family Dwellings*. Dearborn Trade Publishing.

[10] Goda K., Atkinson G (2011): Seismic performance of wood-frame houses in south-western British Columbia. *Earthquake Engineering & Structural Dynamics*, *40*(8), 903-924.

[11] Filiatrault A, Fischer D, Folz B, Uang C (2002): Seismic testing of two-story woodframe house: Influence of wall finish materials. *Journal of Structural engineering*, *128*(10), 1337-1345.

[12] CoLA-UCI Light Frame Test Committee (2001): Report of a testing program of lightframed walls with wood-sheathed shear panels. *Final Report to the City of Los Angeles Department of Building and Safety*.

[13] Vamvatsikos D, Cornell, C (2002): Incremental dynamic analysis. *Earthquake Engineering and Structural Dynamics*, *31*(3), 491-514.

[14] Baker J, Cornell, A (2005): A vector-valued ground motion intensity measure consisting of spectral acceleration and epsilon. *Earthquake Engineering and Structural Dynamics*, *34*(10), 1193-1217.

[15] Baker J, Cornell C (2006): Spectral shape, epsilon and record selection. *Earthquake Engineering and Structural Dynamics*, *35*(9), 1077-1095.

[16] Baker J (2010): Conditional mean spectrum: Tool for ground-motion selection. *Journal of Structural Engineering*, *137*(3), 322-331.

[17] Jayaram N, Lin T, Baker J (2011): A computationally efficient ground motion selection algorithm for matching a target response spectrum mean and variance. *Earthquake Spectra*, *27*(3), 797-815.

[18] Deierlein G, Krawinkler H, Cornell C (2003): A framework for performance-based earthquake engineering. In *Pacific Conference on Earthquake Engineering, Christchurch, New Zealand* (pp. 1-8).