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DEVELOPMENT OF A UNIBODY SYSTEM TO IMPROVE THE SEISMIC PERFORMANCE OF LIGHTWEIGHT RESIDENTIAL WOOD STRUCTURES

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

(1) PhD Candidate, Dept. of Civil and Environmental Engineering, Stanford University, cacevedo@stanford.edu, ejampole@stanford.edu
(2) Professor, Dept. of Civil Engineering, Stanford University, ggd@stanford.edu
(3) Associate Professor, Dept. of Civil Engineering, Stanford University, emiranda@stanford.edu
(4) Associate Professor, Dept. of Civil Engineering, California State University, Sacramento fellb@stanford.edu
(5) Associate, Building & Structures Exponent, s.d.swensen@gmail.com
(6) Project Engineer, Buehler & Buehler Structural Engineers, sac_amy_hopkins@yahoo.com

Abstract

A new design and construction approach is proposed to significantly improve the seismic performance of lightweight residential woodframe structures. We refer to this new approach as "unibody" construction, where the architectural nonstructural walls and finishes, such as gypsum wallboard in the interior walls and stucco in the exterior walls, are better connected to the framing elements and work together with structural walls to significantly increase the lateral stiffness and strength of the structure. Improvement of the connection of wall finishes to framing elements is done through the use of off-the-shelf construction adhesives, stronger fasteners and hold-downs. As a result, the lateral strength and particularly the lateral stiffness of the structure are significantly increased, resulting in significantly smaller lateral deformation demands and better seismic performance. The increments in strength and stiffness together with the corresponding reductions in lateral displacement demands are such that the structure remains elastic or practically elastic even under severe earthquake ground motions. The novel approach is aimed at achieving a nearly damage-free performance at the design level earthquake and limited amount of damage at the maximum considered earthquake, allowing their residents to remain in their residential units with limited disruptions even after severe earthquake ground motions.

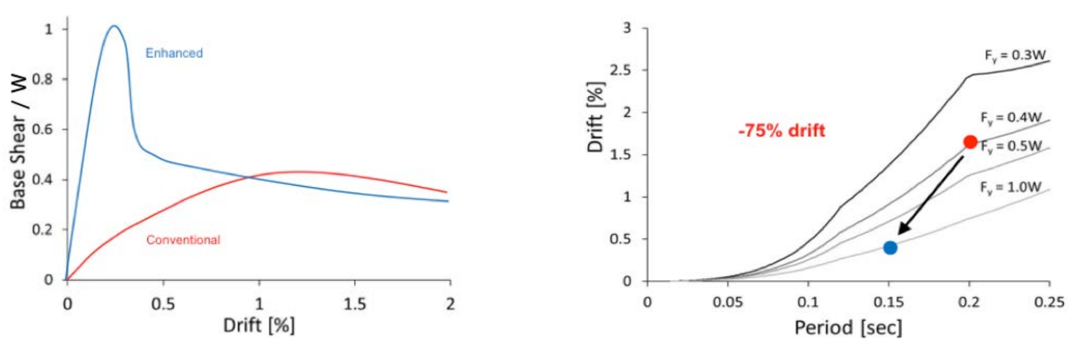
Over a period of four years, a series of carefully planned experimental tests of increasing level of size and complexity were conducted to develop the unibody approach. The first phase of experiments set out to investigate ways to improve connections between architectural finishes to wood framing elements. These experiments involved several different connector tests and half-scale wall tests, conducted at Stanford University. In the second phase, full-scale walls with different configurations were tested under quasi-static loading at the California State University Sacramento (CSUS). The third phase, investigated the system behavior of unibody structures through the testing of full-scale rooms incorporating floor systems under quasi-static loading at NEES@Berkeley. Using the data and knowledge gained from the first three phases, a full-scale, two-story 3-bedroom wood-frame house was built using the unibody method of construction and tested at the NEES@UCSD outdoor shake table. This final phase, investigated the behavior of a unibody house, subjected to simulated earthquake ground motions at increasing levels of intensity ranging from a service level earthquake to intensity levels 2 and 3 times larger than the maximum considered earthquake intensity. The house remained damage free under a ground motion with an intensity corresponding approximately to that of the maximum considered earthquake and with minimal level of damage even at twice that intensity, demonstrating that the unibody construction approach, with very small increments in cost and small modifications to current practice provides a much better alternative to current methods of design and construction which are only aimed at avoiding collapse.

Keywords: unibody; wall; quasi-static; shake table; house

1. Introduction

Recent earthquakes have shown that light-frame wood structures, in general, can resist strong earthquakes without collapsing. However, the current design methodology allows these structures to undergo damaging deformations by reducing the lateral resisting capacity and lateral stiffness through the use of response modifications factors (R-values) in the order of 6 or 6.5. As a result, architectural nonstructural elements, whose damage is initiated at very small levels of lateral deformation, often get damaged during moderate earthquakes, which can be costly and very disruptive to the home/building owner. The extent and impact of this damage was well illustrated by the 1994 Northridge earthquake, where half of more of the $40 billion dollars in property damage caused by the earthquake was due to damage to wood-frame residential structures [1]. Moreover, approximately 48,000 housing units, almost all of them in wood-frame buildings, were rendered uninhabitable by the earthquake [2]. This large impact and disruption to society demonstrates that there is need to search for methods of design and construction that provide a better seismic performance beyond just avoiding collapse but do so in an economically feasible manner; especially, since the majority of residential structures in countries such as Japan, United States, Canada, New Zealand and other seismic regions are light-frame wood structures. With this in mind, we have developed a new low-cost design and construction approach, which significantly improves the seismic performance of lightweight residential wood-frame structures. This new approach, which is also applicable to lightweight residential structures with light-gage cold-formed steel framing, is referred to as "unibody methodology," and is based on integrating architectural nonstructural walls and finishes (e.g., gypsum wallboard, stucco) and structural walls to work together to resist the lateral demands of an earthquake. Several previous studies have found that finishes contribute to the racking resistance of shear walls [3, 4, 5]. This research builds on that previous research, but develops ways to engage these nonstructural walls and finishes even more and fully integrates them as part of the lateral resisting system.

To incorporate these nonstructural elements as part of the lateral resisting system, off-the-shelf construction materials, such as inexpensive construction adhesives, stronger fasteners, and readily available hold-downs are used to achieve the unibody behavior. Consequently, the lateral strength and particularly the lateral stiffness of the structure are significantly increased in comparison to the conventional system (see Fig.2a), reducing the lateral deformation demands, allowing the structure to remain essentially elastic and damage free under large earthquake shaking demands. Increasing the stiffness and yield strength significantly reduces the drift. The latter can be observed from Fig.2b, where we consider the spectral displacement demands for a design level earthquake in a structure with a period of 0.2 s and yield strength of 0.4 W (where, W is the seismic mass weight). By increasing the structural stiffness by a factor of 1.8 and its strength by a factor of 2.5, the resulting drift demands are reduced by 75% (note, the drift is calculated by normalizing the spectral displacement demand by an assumed story height of approximately 2.44 m) [6]. In terms of collapse safety, although the strength of the unibody system quickly decreases from its peak, it provides significant residual strength comparable to that of a conventional ductile system. With those details in mind, it is important to note that the main goal of this approach is to obtain nearly damage-free performance at the design level earthquake (DLE) and limited amount of damage at the maximum considered earthquake (MCE).



(a) (b)

Fig. 1 – Unibody vs. Conventional: (a) Normalized base shear versus drift response and (b) drift [6]

A series of experiments and supporting analyses have been conducted to develop the unibody approach and to demonstrate its proof of concept. This paper will cover the sequence of experiments completed—illustrated from left to right in Fig.1—which included the testing of: 1) screw and adhesive fasteners to improve the stiffness and strength of sheathing-to-framing connection, 2) half-scale walls to further understand the screw with adhesive connection enhanced performance, 3) large-scale walls to understand effects of different configurations of the unibody concept, 4) large-scale room tests to understand the unibody behavior at the system level, introducing floor systems and its connections to walls and 5) a large-scale shake table test of a two-story house to understand the dynamic behavior of the unibody approach.

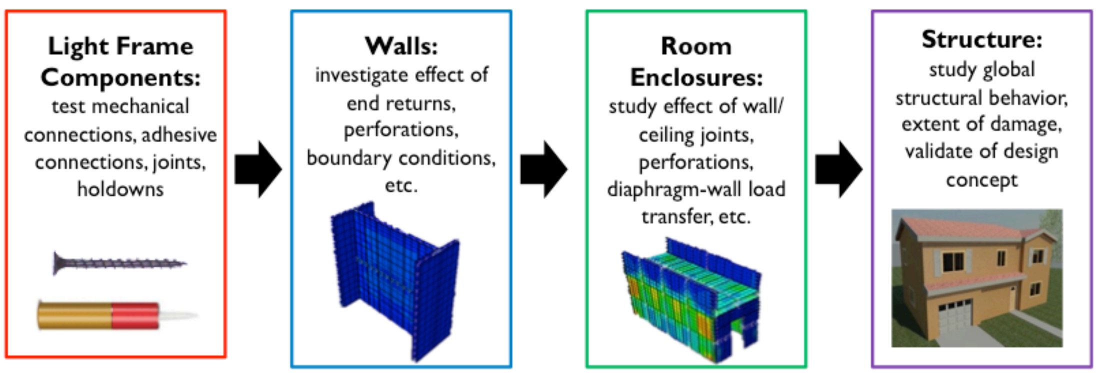


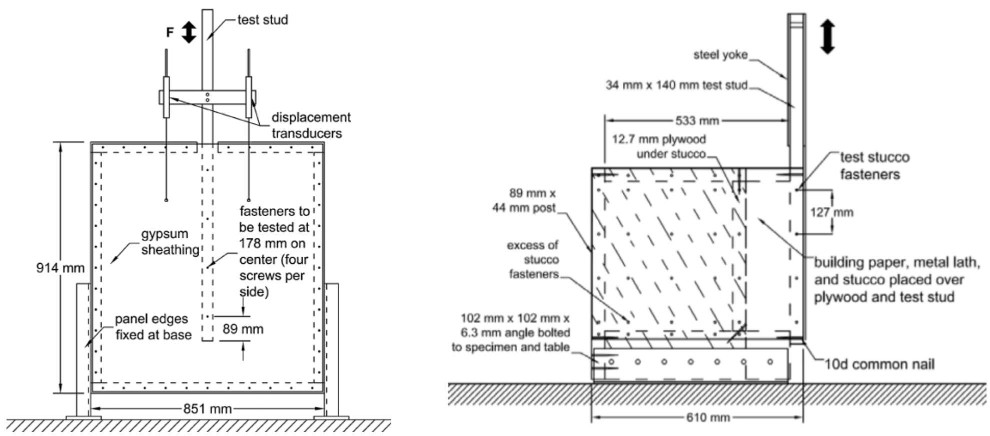
Fig. 2 – Experimental Sequence [6]

2. Development of the Unibody Approach

2.1 Connector Tests

A series of small connector tests were conducted at Stanford to quantify the behavior of different gypsum wallboards with various screws, adhesives, and a combination of the two on wood studs (Douglas Fir) as well light-gauge cold-formed steel studs. Fig.3a shows the setup that was used to test these different connectors. The setup was made of a stud in the middle with a steel loading yoke on top attached to a loading piston. A wall-like frame was made around the center stud to attach the sheathing. The end studs were attached to a reaction table. These tests revealed the following: 1) 15.9 mm Type X gypsum wallboard is on average *1.1 times stronger* and about *3.5 times stiffer* than the 12.7 mm gypsum wallboard with enhanced connector, 2) adhesive connectors are approximately *four times stronger* and *five times stiffer* than screw connectors, and 4) combination of adhesive and screws significantly increases strength and stiffness of the connection [7]. Table 1 shows a table summary of these tests for the wood framing connections only under cyclic loading. The peak strength (F_{max}) and secant stiffness (K_{secant} – *calculated at* ± *0.16 kN*) values per fastener are presented to provide the reader with a sense of the results. For more details on these tests, the reader is encouraged to read [7].

In addition to investigating ways to improve the connection between gypsum and the wall's studs, connection tests for stucco were also conducted at Stanford. The setup for the stucco connector tests can be seen in Fig.3b. This time, the loading stud is at the edge, with a cantilever. Although an architectural finish, previous studies have found that stucco provides additional stiffness and strength to the lateral resisting system [8]. Thus, these tests investigated ways to improve the engagement of the stucco to the wood framing. Prior studies have found that using stronger connectors to attach the stucco to the wood framing increases the racking strength [9]. Table 2 shows the peak strength (F_{max}) and secant stiffness (K_{secant} – *calculated at 0.1% drift of small wall*) from the stucco connector tests. Three types of connectors were explored: 1) self-furring nails (typically used for stucco construction, 2) 16d ring-shank nail, and 3) #14 wood lag screw with a self-drilling tip [10]. The results showed that the strength of #14 wood lag screws during the cyclic tests was about *25% stronger* than the conventional fastener but the stiffness was not affected as much. In general, the tests showed that improving the connections between the architectural finishes and structural framing significantly increases the stiffness and strength.



(a) (b)

Fig. 3 –Test Setup: (a) Gypsum Connector Tests [7] and (b) Stucco Connector Tests [10]

Table 1 – Gypsum connector tests results summary per fastener under cyclic loading [7]

Sheathing/Finish Type	Fastener Type	F_{max} [kN]	K_{secant} [kN/mm]
12.7 mm (on 2x4 wood stud)	31 mm Coarse	0.5	1.2
	Enhanced	0.7	0.52
15.8 mm Type X (on 2x4 wood stud)	41 mm Coarse	0.6	1.8
	Enhanced	0.8	1.8
	Adhesive 2	3.0	7.2
	Adhesive 2 + Enhanced	3.6	7.4

2.2 Small Wall Tests

A series of small wall tests (1.22 m x 1.22 m) were also conducted at Stanford to further understand the behavior of these connections, but now being used in laterally loaded walls. Fig.4 shows a schematic drawing of the small walls tested. Drywall coarse screws were used spaced at 178 mm o.c. at edges and 305 mm in the field. Table 3 presents a summary of these small walls tested. The peak strength (F_{max}) and secant stiffness (K_{secant} – *calculated at 0.1% drift of small wall*) of the small walls are presented for the wood specimens only. The results also showed screws with adhesive connections significantly enhanced the strength and stiffness, two and three times, respectively, with respect to the wall with regular screw connection. Furthermore, it provided information on how these enhancements affect a more complex specimen versus a simple connector test. When comparing the two results, the connector tests yielded larger increases than the small wall tests since deformations of fasteners on wall specimens is not uniform across all fasteners [7]. The progression of damage was also tracked, where cracking along the perimeter of the screws occurred at about 0.2% drift and popping of screws occurred at 0.5% drift.

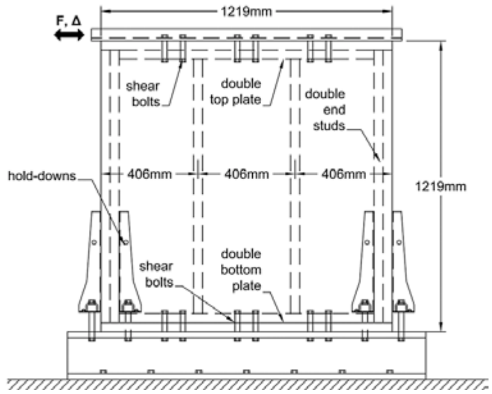


Fig. 4 –Test Setup for Small Walls [7]

Table 3 – Small wall tests summary for wood framing under cyclic loading [7]

Fastener Type	F_{max} [kN/m]	$K_{Secant\ 0.1\%}$ [kN/mm/m]
Enhanced	12.0	4.4
Adhesive 2 + Enhanced	21.0	10.3

3. Full-Scale Unibody Tests

3.1 Full-Scale Unibody Wall Tests

To investigate how these improvements translate to a full-scale wall, a series of 20 full-scale walls were tested quasi-statically at CSUS [11]. The tests involved walls with 15.8 mm gypsum Type X (gypsum), some with different aspect ratios (2.44 m x 2.44 m and 2.44 m x 4.88 m), with and without door openings, with and without end returns. Walls with different sheathings (e.g., plywood and 15.8 mm fiberglass mat-board (DensGlass®) and finishes (i.e., stucco) were also tested. The test setup can be seen in Fig.4.

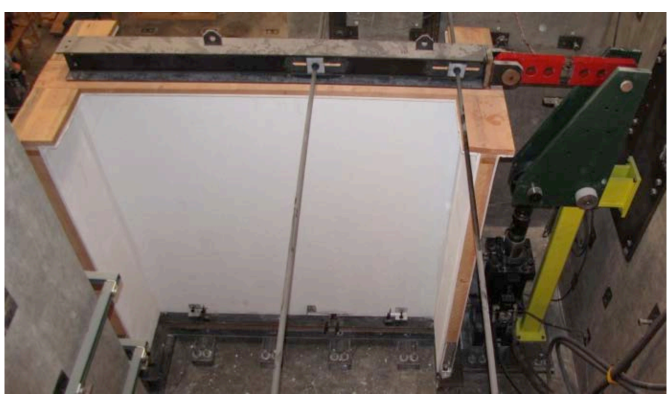


Fig. 4 – Test setup for full-Scale walls [11]

Table 4 shows a summary of the unit value results for the interior and exterior walls compared to conventional construction values (normalized by dividing by the length of the wall—2.44 m). The values were also adapted from [12]. All the walls were built with Douglas Fir Larch 2x4 studs spaced at 406 mm on center (o.c.). The conventional interior wall was sheathed with gypsum on both sides and attached with coarse threaded screws at 178 mm o.c. at edges and 305 mm o.c. in the field and hold-downs. Meanwhile, the unibody wall was built with blocking at the mid-height of the wall, and a slightly stronger hold-down, and the gypsum wallboard was connected with adhesive and coarse screws spaced same as conventional wall. *As can be seen, the unibody wall was 2.6 times stiffer and two times stronger than the conventional interior wall. The drift at the peak strength for the unibody wall occurred at the threshold of damage, while the conventional wall reached that peak strength well beyond that threshold.* The unibody exterior wall featured 22.2 mm thick stucco with DensGlass® substrate on one side and conventional gypsum wallboard on the other side. The sheathing was installed using the unibody procedures and the stucco lath was installed using strong 6.4 mm Dia. lag screws at 102 mm on edges and 178 mm in field. *These results show that the unibody approach provide substantial additional stiffness and strength and have better performance than the conventional method in terms of stiffness and strength.*

Table 4 –Unit Values Summary for Interior and Exterior Walls with Same Aspect Ratio [11, 12]

Wall Type	**Wall Specimen Description (2.44 m x 2.44 m)**	$K_{ASTM\ @\ 0.33Fmax}$ **[kN/mm/m]**	F_{max} **[kN/m]**	$Drift_{@Fmax}$ **[%]**
Interior	GYP - GYP (Conventional)	2.0	8.7	0.6
	GYP - GYP (Unibody)	5.2	18.1	0.3
Exterior	STU/DG – GYP (Unibody)[a]	5.9	29.6	1.0

[a] This wall had L-shape returns on both ends, making it a C-shape wall
Unibody: screws with adhesive for sheathing, stronger screws for stucco, and strong hold-downs
GYP = 15.8 mm Type X Gypsum; DG = 15.8 mm DensGlass® (fiberglass mat-board);
PLY = 11.9 mm Structural I Plywood; STU = 22.2 mm Stucco

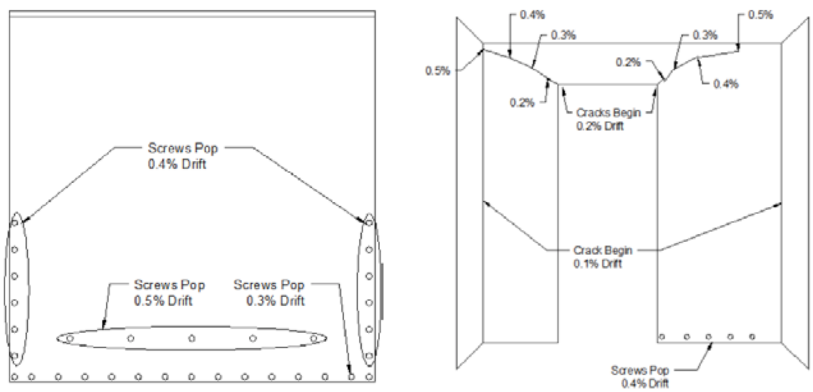
Table 5 –Unit Values Summary for Interior Walls with Different Aspect Ratios and Door Openings [11, 12]

Wall Type	**Wall Specimen Description***	$K_{ASTM\ @\ 0.33Fmax}$ **[kN/mm/m]**	F_{max} **[kN/m]**	$Drift_{@Fmax}$ **[%]**
Without Door Openings	GYP – GYP, 2.44 m x 2.44 m	7.9	20.8	0.2
	GYP – GYP, 2.44 m x 4.88 m	8.2	23.7	0.3

*All specimens were unibody walls and had T-shaped returns on both ends, forming an I-shaped wall
Unibody: screws with adhesive for sheathing and strong hold-downs
GYP = 15.8 mm Type X Gypsum

The aspect ratio (total height/total length) and wall opening effects on the unibody walls were also investigated by [11]. Table 5 shows a summary of the unit value results for these walls (also normalized by dividing by the length of the wall). All the walls were built using the unibody approach as explained earlier. The walls featured T-shaped end returns, which added approximately *50% stiffness* and *10% strength* to the wall. The results showed that the aspect ratio of the wall had no significant impact on the stiffness of the walls without openings. Nevertheless, it also showed that the strength increases as the length of the wall increases (~15% in this case).

In terms of damage, the conventional gypsum wall screws popped much earlier than the unibody wall (0.15% drift versus 0.3% drift), where the unibody wall only saw small hairline cracks. The unibody walls with exterior sheathing/finish also saw screws pop at 0.3% drift. Since these walls had returns, they also saw cracks at corners at 0.2% drift. The other unibody walls tested (those with returns and door openings) saw similar damage. The walls with door openings saw damage at the corners of the openings around 0.2%. The screws popped between 0.2% and 0.4% drift. Fig.5 shows an example of two schematics of the damage progression for two unibody walls, GYP – GYP and the GYP – GYP, 2.44 m x 2.44 m wall with door opening and T-shaped returns. Damage progression for the exterior conventional wall was not reported by [12]. *The results were promising and showed that the unibody methodology has great performance in terms of resisting damage.*



(a) (b)

Fig. 5 –Damage Progression Unibody Walls: (a) GYP – GYP, (b) GYP – GYP (wall returns, door opening) [11]

3.2 Full-Scale Unibody Room Tests

In an effort to further understand the behavior of these walls and their interaction with the floor system, four full-scale unibody rooms were tested at the University of California, Berkeley (NEES@Berkeley) quasi-statically [12]. These experiments aimed to investigate the transfer of forces from the diaphragm to the walls, the orientation of the wall sheathing, the effects of openings, and behavior at large drifts. The wall lengths of the rooms were 4.88 m in the direction parallel to the loading, and 2.13 m in the perpendicular direction, and the height was 2.44 m. The wall studs were also Douglas Fir Larch 2x4s spaced at 406 mm o.c. with fire blocking mid-height. Three of the room specimens were sheathed with GYP (as defined in the previous section) on both sides and the fourth one with GYP on one side and DG and 22 mm stucco on the other. All sheathing was connected with adhesive and 41.3 mm coarse threaded screws with a spacing of 178 mm o.c. at edges and 305 mm o.c. in the field. The stucco had a stronger self-furring lath, which was attached with 6.4 mm Dia. lag screws at 102 mm o.c. at edges and 178 mm o.c. in the field. Each room had its own diaphragm, constructed using TJI 360 joists and 44.5 mm thick Laminated strand board (LSL), with a depth of 302 mm. Two layers of 18.3 mm Sturd-I-Floor plywood were used to sheath the diaphragm. Blocking was installed in the middle of the diaphragm using TJI360 joists. All adhesive applications were done using construction adhesive. LTP4 shear plates spaced 267 mm o.c. were used to transfer the forces from the diaphragm to the walls. Furthermore, to demonstrate ease of constructability, a local contractor built all room specimens.

Fig.6 shows room specimen 1 (R1) on the testing setup. Each room had a different configuration. As can be seen from the figure, the sheathing for R1 was oriented vertically on the exterior and horizontally in the interior. In addition it had parapet walls above the diaphragm. Meanwhile, R2 had no parapet walls; instead, the diaphragm extended about 305 mm beyond the top of the wall on the exterior. The sheathing was placed horizontally on both sides. R4 was similar to R1, except it had DG (vertically oritented) and stucco on the exterior as opposed to GYP. For a more detailed description of the rooms, the reader is encouraged to read [12].

The results from the room were fairly consistent from that of the unibody walls. As expected, the returns in the form of perpendicular walls provided additional strength and stiffness (see Table 6). The strength and stiffness for R1 and R2 were fairly similar despite having different configurations and sheathing orientation. In addition, the ultimate strength was reached at lower drift values than what was observed in the conventional system. Meanwhile, the stucco room performed much better, with the ultimate strength occurring at a lower drift than previous tests. The connectors between the diaphragm and the walls were more than sufficient to develop the strength of the walls. One important thing to note from these experiments is the residual strength at large drifts. As can be seen in Table 6, these unibody rooms had significant residual strength, raging from 23 – 35%, after undergoing 11% drift. In terms of collapse safety, this is rather promising. The damage progression was similar to that observed in the unibody walls. For more details, refer to [12].

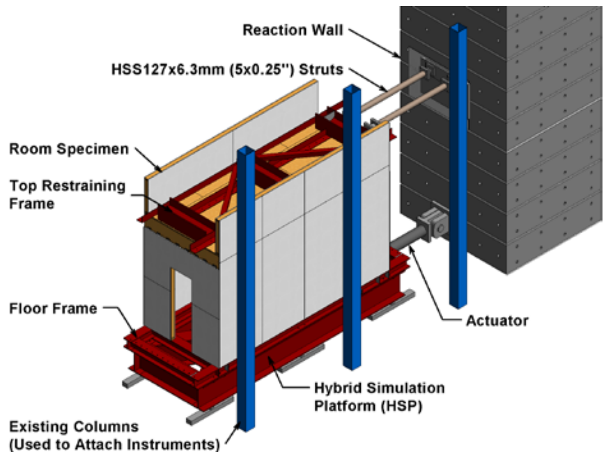


Fig. 6 – Unibody room test setup [13]

Table 6 – Unit Values Summary for Unibody Rooms [12]

Room	Longitudinal Wall Description (2.44 m x 4.88 m)	$K_{ASTM\ @\ 0.33Fmax}$ [kN/mm/m]	F_{max} [kN/m]	$Drift_{@Fmax}$ [%]	$F_{residual@11\%}$ [kN/m]	% of F_{max} [%]
R1	Wall 1 & 2: GYP Ext. (Vertical) – GYP Int. (Horizontal) Parapet Walls	6.0	19.7	0.3	5.8	29
R2	Wall 1 & 2: GYP Ext. (Horizontal) – GYP Int. (Horizontal)	6.0	18.3	0.2	4.2	23
R4	Wall 1 & 2: STU + DG (Vertical) Ext. – GYP Int. (Horizontal)	8.4	34.7	0.9	12.0	35

Unibody: screws with adhesive for sheathing, stronger screws for stucco, and strong hold-downs
GYP = 15.8 mm Type X Gypsum; DG = 15.8 mm DensGlass® (fiberglass mat-board); STU = 22.2 mm Stucco

3.3 Exterior Unibody Wall vs. Conventional Wall

The results from the stucco unibody room were compared in Table 7 to the conventional values from previous tests [13]. In order to compare these stiffness values, the stiffness was computed using the ASTM E 564 method at approximately one-third of the peak strength (*0.33 x Fu*). The conventional walls were sheathed with 12.7 mm oriented strand board (OSB) and 12.7 mm gypsum board in one case and 22.2 mm stucco in the other. The OSB was attached with two rows of 8d nails at 102 mm o.c. at edges and one row at 305 mm o.c., meanwhile, the gypsum was attached using screws at 305 mm o.c. at edges and in the field. *As can be seen from the table, the ASTM stiffness from the unibody is eight to nine times higher than that of this wall, while the peak strength is* *about between 1.5 to 1.8 times higher. The peak strength for the unibody is reached at 1% drift, while for the conventional it is reached at three times that drift level.*

Table 7 – Comparison of Exterior Conventional Walls vs. Unibody Walls

Wall Type	**Wall Specimen Description (2.44 m x 2.44 m)**	**$K_{ASTM\ @\ 0.33Fmax}$ [kN/mm/m]**	**F_{max} [kN/m]**	**$Drift_{@Fmax}$ [%]**
Exterior	12.7 mm OSB + 12.7 mm Gypsum (Conventional) [13]	1.0	19.1	2.9
	12.7 mm OSB + STU* (Conventional) [13]	0.9	22.8	2.5
	STU/DG + GYP (Unibody) [12]	8.4	34.7	0.9

*Loaded dynamically
Unibody: screws with adhesive for sheathing, wood lag screws for stucco, and strong hold-downs
GYP = 15.8 mm Type X Gypsum; DG = 15.8 mm DensGlass® (fiberglass mat-board); STU = 22.2 mm Stucco, OSB = Oriented Strand Board

4. Proof of Concept: Shake Table Test of Two-Story Unibody House

A full-scale two-story unibody 3-bedroom house was built and tested at the University of California, San Diego ((NEES@UCSD) on the outdoor uni-directional shake table. The structure was 11.3 m long x 7.0 m wide with a height of 5.6 m (story height was 2.44 m) [15]. The objective of the test was to show proof of concept of the unibody methodology under dynamic loading. The design was based on the stiffness and strength per wall obtained from the full-scale unibody wall and room tests. For the exterior wall, this was about *8.4 kN/mm/m* in stiffness and *34 kN/m* in wall strength and for the interior wall this was about *5 kN/mm/m* in stiffness and *20 kN/m* in strength. The hold-downs were designed based on the strength of the walls. ETABS was used to model the elastic response of the unibody house and calculate the hold-down forces. In addition, OpenSees was used to model the nonlinear behavior. Fig. 7 shows the elevation of the house for south and east face. The numerical model calculated a period of *0.14 s* and the hazard level was for a Maximum Considered Earthquake with a deterministic short period spectral ordinate of approximately *1.5 g* and class *D* soil. The ground motion used for the tests was from the 1989 Loma Prieta Earthquake in California, from Capitola 000 station. This record was chosen due to its close match to the Spectrum Design Level Earthquake (DLE) with its recorded un-scaled intensity. Fig.8 shows the response spectra of the input and achieved ground motion compared to the DLE. The unibody house was subjected to this ground motion scaled at different intensities.

The built structure had a natural period of *0.09 s* in the direction of shaking and weighed *266 kN*. A total of 148 instruments were used to monitor the displacements and accelerations of the house.

Fig. 7 – Unibody house on shake table

Table 7 shows a summary of the ground motion properties, natural periods before each intensity (as the structure gets damaged, the period elongates), spectral target and achieved values, and the first story drift and normalized base shear obtained during the tests. The periods were calculated using white noise before each ground motion along the direction of shaking. As can be seen from the table, due to the behavior of the table at high frequencies, the target values were sometimes higher than the achieved values. Nevertheless, the structure performed extremely well after being subjected to a series of increasing intensities. In particular, the house remained entirely damage free during intensity level GM3 which approximately corresponds to the maximum considered earthquake intensity if it was located near downtown Los Angeles and sustained only mininal damage even at twice that intensity level during GM5.

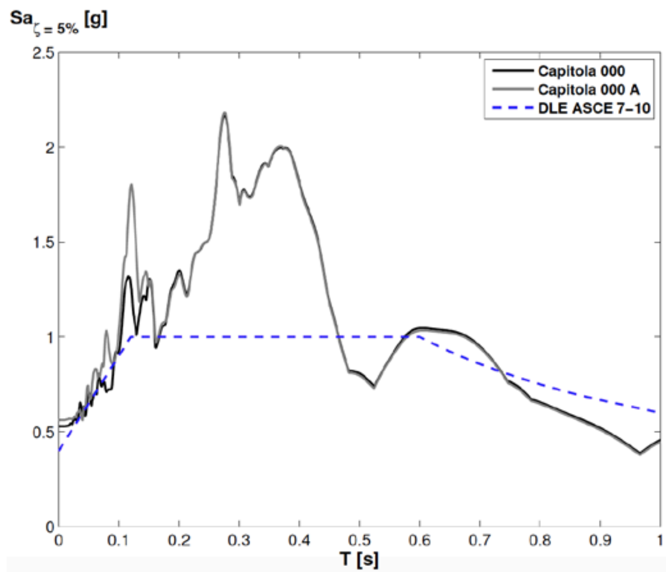


Fig. 8 – DLE vs. Capitola 000 input and achieved ground motion [15]

Table 9. Summary of Capitola 000 Properties & Unibody House Results [15]

GM	Scale Factor	*PGA* [g]	T_1 [s]	$Sa_{T1\ target,}$ 5% damping [g]	$Sa_{T1\ achieved,}$ 5% Damping [g]	Peak $Drift_{1st\ story}$ [%]	$V_{Max\ 1st\ Story}/W$
1	0.4	0.2	0.09	0.3	0.4	< 0.1	0.36
2	1.0	0.6	0.09	0.8	0.9	< 0.1	0.86
3	1.5	0.8	0.09	1.2	1.1	0.1	1.17
4	2.3	1.2	0.10	2.1	1.6	0.2	1.75
5	3.0	1.5	0.10	2.8	2.1	0.3	2.10
6	1.5	0.8	0.12	1.9	1.6	0.2	1.30
7	4.5	2.3	0.13	4.6	4.5	23.9	2.74

The damage progression is consistent with what was observed in the wall and room tests. The second story drifts were very low, with a maximum drift of *0.13 %* during the last ground motion. The results and observations from the tests show that the unibody methodology great performance in terms of damage resistance and collapse safety. As can be seen, during the last ground motion, the structure drifted close to *25%* drift and still had enough residual strength that allow it to avoid collapse. Such behavior was also observed in the room tests during the large drifts. Overall, the dynamic behavior of the unibody structure was indicative that the unibody methodology can help reduce the damage seen in moderate to large earthquakes.

5. Conclusions

This paper presented the evolution of the unibody design concept through various experiments and its importance for improving damage performance. The research began with connector tests, extending into large scale quasi-static wall and room tests, and culminated in shaking table tests that showed the proof of concept and validated the analyses and design approach under dynamic loading. The research demonstrates how a combination of screws, construction adhesives, and wall tie-downs can successfully integrate the wallboards to the framing providing significant increase in stiffness and strength. In addition, stronger lag screws are shown to better integrate the stucco and lath to the structural frame. Compared to conventional construction, the unibody system is significantly stiffer and stronger. The statics tests and dynamic tests were consistent with the propagation of damage, demonstrating that the unibody methodoloy has high stiffness and strength when subjected to groundmotions. To conclude, a new construction methodology using off-the-shelf components was presented. The results show that integrating nonstructural and structural components in light-frame construction significantly improves the seismic performance of wood strutures.

6. Future Work

Ongoing research is underway to validate and apply analytical models of unibody structures to capture their response under dynamic loading. These studies include evaluation of foundation uplift and its effects on the seismic performance as well as design and detailing of seismic holddowns. Finally, a detailed loss analysis is underway to demonstrate the cost-benefit of unibody structures compared to conventional structures.

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