# Seismic Testing of a Full-Scale Woodframe Building

*Andre Filiatrault, Professor; Ioannis P. Christovasilis, Graduate Student Researcher; Assawin Wanitkorkul, Research Engineer Specialist*
*University at Buffalo, State University of New York*
*Buffalo, New York*

## Abstract

An impediment to the development of performance-based seismic design for woodframe buildings is the lack of understanding of the factors that affect the seismic behavior of woodframe structural systems. Few numerical seismic analysis models capable of considering all the factors influencing the seismic behavior for three-dimensional woodframe structures currently exist. Furthermore, only limited experimental data have been generated at the system level and never on a structure with realistic dimensions. This paper discusses the results of a shake table testing program on a full-scale woodframe structure conducted within the NSF-funded NEESWood Project.

The test structure considered was a full-scale two-story townhouse, having approximately 1800 $ft^2$ of living space with an attached two-car garage. It was assumed to be located on a level lot with a slab-on-grade and spread foundations and to have been built as a "production house" in either the 1980's or 1990's, located in either Northern or Southern California. The design was based on engineered construction. The size and weight of the test structure required the simultaneous use of the two three-dimensional shake tables at the Structural Engineering and Earthquake Simulation Laboratory (SEESL) at the University at Buffalo.

The testing program focused on the various construction elements that have significant influence on the seismic response of woodframe buildings. Five different testing phases were conducted to investigate the influence of the following elements on the seismic behavior: Phase1 - Engineered wood structural (shear) walls alone; Phase 2 - Wood structural walls incorporating viscous fluid dampers; Phase 3 - Installation of gypsum wallboards to engineered wood structural walls; Phase 4 - Installation of gypsum wallboards to interior partition walls and ceilings; and Phase 5 - Installation of stucco as exterior wall finish.

## Introduction

An impediment to the development of performance-based seismic design for woodframe buildings is the lack of complete understanding of the factors that affect the seismic behavior of woodframe structural systems. Few numerical seismic analysis models capable of considering all the factors influencing the seismic behavior of three-dimensional woodframe structures currently exist. Furthermore, only limited experimental seismic response data have been generated at the building system level and never on a woodframe structure with realistic dimensions. This paper discusses the results of a benchmark shake table testing program on a full-scale woodframe structure conducted within the NSF/NEES-funded NEESWood Project. The emphasis of this paper is on the effect of interior (gypsum wallboard) and exterior (stucco) finishes applied to the surfaces of structural wood shear walls and to interior partition walls and ceilings on the seismic response of the test building.

## Description of Test Building

The test structure is one of the four index buildings designed within the recently completed CUREE-Caltech Woodframe Project (Reitherman et al., 2003). It represents one unit of a two-story townhouse containing three units, having approximately 1800 $ft^2$ of living space with an attached two-car garage, as shown in Fig. 1. This building is assumed to have been built as a "production house" in either the 1980's or 1990's, located in either Northern or Southern California. The design is based on engineered construction according to the seismic provisions of the 1988 edition of the Uniform Building Code (ICBO, 1988). The height of the townhouse from the first floor slab to the roof eaves is 17'-2" and its total weight is 72 kips (36 tons). The exterior walls of the townhouse test building were covered on the outside with 7/8" thick stucco over 7/16" thick OSB sheathed shear walls and ½" thick gypsum wallboard on the inside. Details regarding the two-story townhouse building are given by Reitherman et al. (2003). The floor plans of the test building are shown in Fig. 2.

## Experimental Set-up

The twin re-locatable, 50-ton, tri-axial shake tables of the Structural Engineering and Earthquake Simulation

Laboratory (SEESL) at the University at Buffalo (UB) were utilized for the NEESWood benchmark experiment. The two tables acting in unison were required to accommodate the weight of the full-scale building. As shown in Figure 3a, the 23 ft x 23 ft extension steel frames available on both of the UB-SEESL shake tables were connected together by a steel link structure to support the entire woodframe structure across the two shake tables with minimal vertical deflection. Figure 3b shows a photograph taken during the construction of the foundation of the test building on the two shake tables and link structure. Threaded A-307 steel rods bolted to the existing extension frames were used as anchor bolts for the sill plates. A 2-1/4 in. thick layer of grout was installed on top of the steel base beneath the pressure treated sill plates to represent a foundation. The friction of the sill plate against the grout was similar to that of a true concrete foundation.

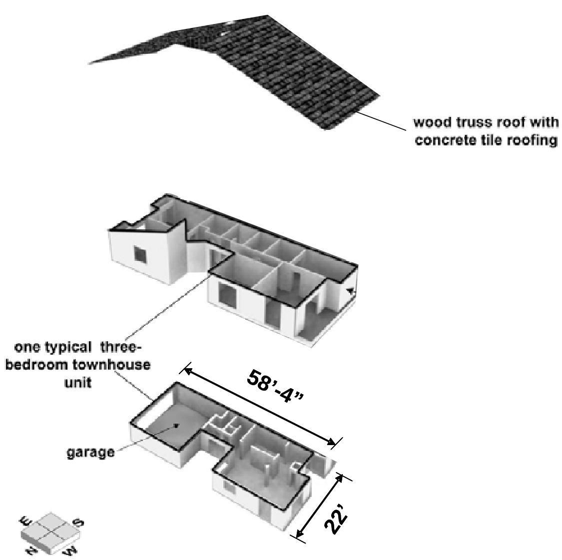



**Figure 1- Full-Scale Woodframe Test Building**.

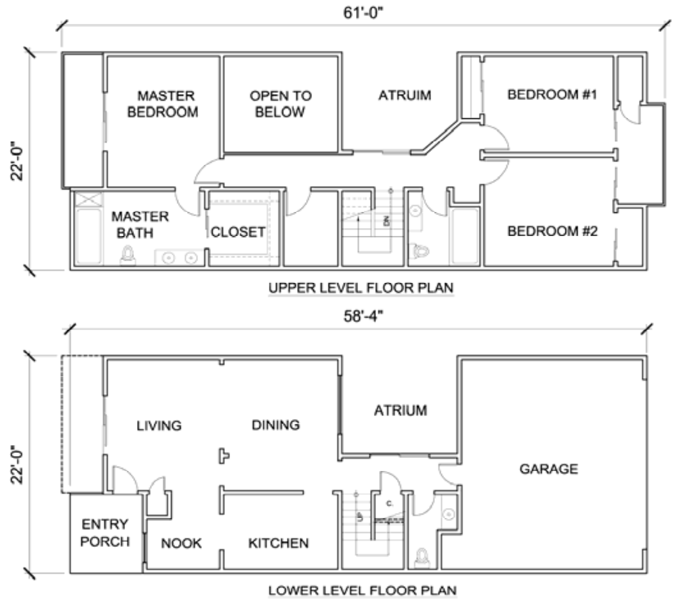
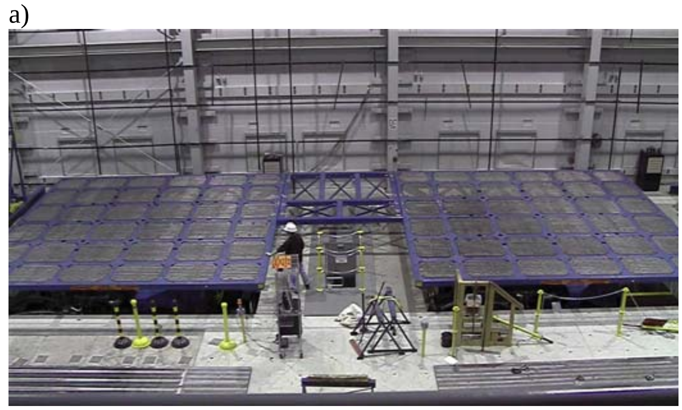



**Figure 2 - Floor Plans of Test Building.**

a)



b)

**Figure 3 - a) Extension Frame of Shake Tables Connected by Steel Link Structure, b) Foundation of Test Building Under Construction.**

## Testing Protocol

Multiple seismic tests were conducted for various configurations of the test building. Table 1 presents a summary of the five seismic test phases included in the test program and the corresponding configurations of the test building. Low amplitude white noise tests were also conducted between the seismic tests of each phase to determine the variations of the dynamic characteristics (natural periods, mode shapes and damping) of the test building as it experienced increasing levels of damage. The test structure was repaired after each test phase in an attempt to return the lateral load-resisting system to its original characteristics before the start of each subsequent test phase. Note that all test phases were performed for a constant mass of the test building by incorporating ballast weights at the floor level for the test phases in which some of the wall finish materials were omitted.

**Table 1 - Test Phases and Building Configurations.**

| Test Phase | Test Building Configuration |
|---|---|
| 1 | Wood structural elements only |
| 2 | Test Phase 1 structure with passive fluid dampers incorporated into selected wood shear walls |
| 3 | Test Phase 1 structure with ½" thick gypsum wallboard installed with #6-1-1/4" long screws @ 16" O.C. on structural (load bearing) walls |
| 4 | Test Phase 3 structure with ½" thick gypsum wallboard installed with #6-1-1/4" mm long screws on all walls (16" O.C.) and ceilings (12" O.C.) |
| 5 | Test Phase 4 structure with 7/8" thick stucco installed with 16 gage steel wire mesh and 1-1/2" long leg staples @ 6" O.C. on all exterior walls |

In this paper, only Phases 1, 3, 4 and 5 are discussed. These four test phases were designed to evaluate the effect of interior and exterior wall finishes on the seismic response of the test building. In Phase 1, the test building incorporated only the wood structural members without any wall finishes. In Phase 3, ½" thick gypsum wallboard was applied to the interior surfaces of the structural perimeter walls and to both sides of the two interior structural shear walls located at the fist level of the test building in the North-South direction. In Phase 4, gypsum wallboard was also applied to all interior partition walls and ceilings. Finally, in Phase 5, 3-coat, 7/8" thick, stucco was applied to the exterior wall surfaces of the building.

## Input Ground Motions

Two different types of tri-axial historical ground motions were used for the seismic tests: ordinary ground motions and near-field ground motions. The ordinary ground motions represented a Design Basis Earthquake (DBE) having a probability of exceedance of 10% in 50 years (10%/50 years), or equivalently, a return period of 475 years. The 1994 Northridge Earthquake ground motions recorded at Canoga Park, with an amplitude scaling factor of 1.20, were selected as the DBE. The near-field ground motions represented a Maximum Credible Earthquake (MCE) having a probability of exceedance of 2% in 50 years (2%/ 50 years), or a return period of 2475 years. The unscaled 1994 Northridge Earthquake ground motions recorded at Rinaldi were selected as the MCE.

In addition to the DBE and MCE hazard levels, the Canoga Park ground motions were scaled to simulate hazard levels of 99.9%/50 years, 50%/50 years and 20%/50 years. The resulting Peak Ground Accelerations (PGA) used in the tests are summarized in Table 2. Up to five seismic test levels were considered on the test building during each phase of seismic testing. Note that during Test Phases 1, 3 and 4, only Seismic Test Levels 1 and 2 were conducted in order to limit the damage to a repairable level.

**Table 2 – Ground Motions for Seismic Tests.**

| Seismic Test Level | Ground Motions | Hazard Level %/50 years | Scaled PGA (g) | | |
|---|---|---|---|---|---|
| | | | East-West | North-South | Vertical |
| 1 | 1994 Northridge Canoga Park | 99.99 | 0.04 | 0.05 | 0.06 |
| 2 | 1994 Northridge Canoga Park | 50 | 0.19 | 0.22 | 0.26 |
| 3 | 1994 Northridge Canoga Park | 20 | 0.31 | 0.36 | 0.42 |
| 4 | 1994 Northridge Canoga Park | 10 (DBE) | 0.43 | 0.50 | 0.59 |
| 5 | 1994 Northridge Rinaldi | 2 (MCE) | 0.47 | 0.84 | 0.85 |

## Selected Test Results

<u>Initial Dynamic Characteristics</u>

Table 3 lists the initial fundamental periods in each principal direction of the test building before the beginning of Test Phases 1, 3, 4 and 5, respectively. Not surprisingly, the fundamental periods of the test building are significantly longer in its transverse (North-South) direction than in its longitudinal (East-West) direction. The introduction of gypsum wallboard finishes on the structural (load bearing) walls in Test Phase 3 causes a reduction in the fundamental period of 9% and 5% along the transverse and longitudinal direction of the test building, respectively. From a single-degree-of-freedom system point of view, these fundamental period reductions correspond to increases in lateral stiffness of 21% and 9% along the transverse and longitudinal direction of the test building, respectively. These results indicate that introducing gypsum wallboard finishes on the interior surfaces of the structural walls increased the lateral stiffness of the test building. On the other hand, the introduction of similar gypsum wallboard finishes to all the interior partition walls and ceilings in Test Phase 4 has no effect on the fundamental periods and, thereby, the lateral stiffness of the test building (at least at low level shaking). This lack of positive effect can be attributed to the lack of structural connections between the interior partition walls and the floor and roof diaphragms of the test building. These partition wall connections were left to the discretion of the builder and were not designed as structural connections, thereby allowing differential movements between the top and bottom of the partition walls and adjacent diaphragms. The introduction of stucco on the exterior walls of the test building in Phase 5 causes a supplemental reduction in the fundamental period of 3% and 9% along the transverse and longitudinal direction of the test building compared to the Phase 4 configuration. In term of equivalent lateral stiffness, the Phase 5 exhibits an increase in lateral stiffness of 29% and 32% along the transverse and longitudinal direction, respectively compared to the original Phase 1 building.

**Table 3 – Initial Fundamental Periods.**

| Test Phase | Test Building Configuration | Initial Fundamental Period (sec) | |
|---|---|---|---|
| | | East-West | North-South |
| 1 | Wood structural elements only | 0.23 | 0.33 |
| 3 | Gypsum wallboard on structural walls only | 0.22 | 0.30 |
| 4 | Gypsum wallboard on all interior walls and ceilings | 0.22 | 0.30 |
| 5 | Gypsum wallboard on all interior walls and stucco on all exterior walls | 0.20 | 0.29 |

Figure 4 shows the fundamental mode shapes measured in each principal direction of the building for each test phase. For both directions, the deformations are concentrated mainly in the first level of the test building, indicating the potential for a weak first story collapse mechanism. The fundamental model shapes in the longitudinal direction are also affected by torsional response and by the significant in-plane shear deformations of the floor diaphragm between the two main units of the townhouse, particularly for the Phases 1 and 3. For Phases 4 and 5, the shear deformations of the diaphragm are greatly reduced because of the in-plane stiffness provided by the gypsum ceilings.

<u>Global Hysteretic Responses</u>

Figure 5 shows the global hysteretic (base shear force vs relative horizontal displacement at the center of the roof eaves level) responses of the test building during Test Phases 1, 3, 4 and 5, respectively and under Seismic Test Level 2 (see Table 2). The base shear was computed by summing the inertia forces at each level of the test building based on horizontal acceleration recordings. As expected, the lateral displacements in the transverse (North-South) direction are significantly larger than those in the longitudinal (East-West) direction.

In Test Phase 1, the wood-only building experienced a peak roof displacement of 2.5” (1.3% building drift) in its transverse direction under the Seismic Test Level 2 representing amplitude of 44% of that expected for the Level 4 Design Basis Earthquake. The introduction of gypsum wallboard finishes on the structural walls in Test Phase 3 resulted in a significant reduction in transverse roof displacements (approximately 44% reduction compared to the wood-only building of Phase 1). The overall hysteretic response of the building in Test Phase 3 is also stiffer than that of Test Phase 1, indicating the important effects that the gypsum wallboard had in stiffening the structural walls. The introduction of gypsum wallboard on the interior partition walls and ceilings in Test Phase 4 resulted in a further reduction of 29% in roof displacements in the transverse direction (1.4” in Phase 3 vs 1.0” in Phase 4). Finally, the introduction of stucco on the exterior walls reduced even further the roof displacements (0.71”). Similar results can be observed in the longitudinal direction.

These results indicate the effect that interior and exterior wall finishes have on the seismic response of the test building. Figure 6 shows the effective stiffness in each direction and for each building configuration. The effective stiffness values were obtained by computing the slope linking the positive and negative peak base shear forces and peak roof displacement coordinates from the graphs shown in Fig. 5. The effective stiffness values increase significantly in both directions with the application of interior wall finishes. The increase of stiffness after the application of the exterior stucco finish in Test Phase 5 is more significant in the longitudinal (East-West) direction than in the transverse (North-South) direction. This can be attributed to the more pronounced shear deformations of the low aspect ratio walls in the longitudinal direction. In the transverse direction, significant foundation uplift and rocking occurred, which reduced the shear stiffness contribution of the wall elements.

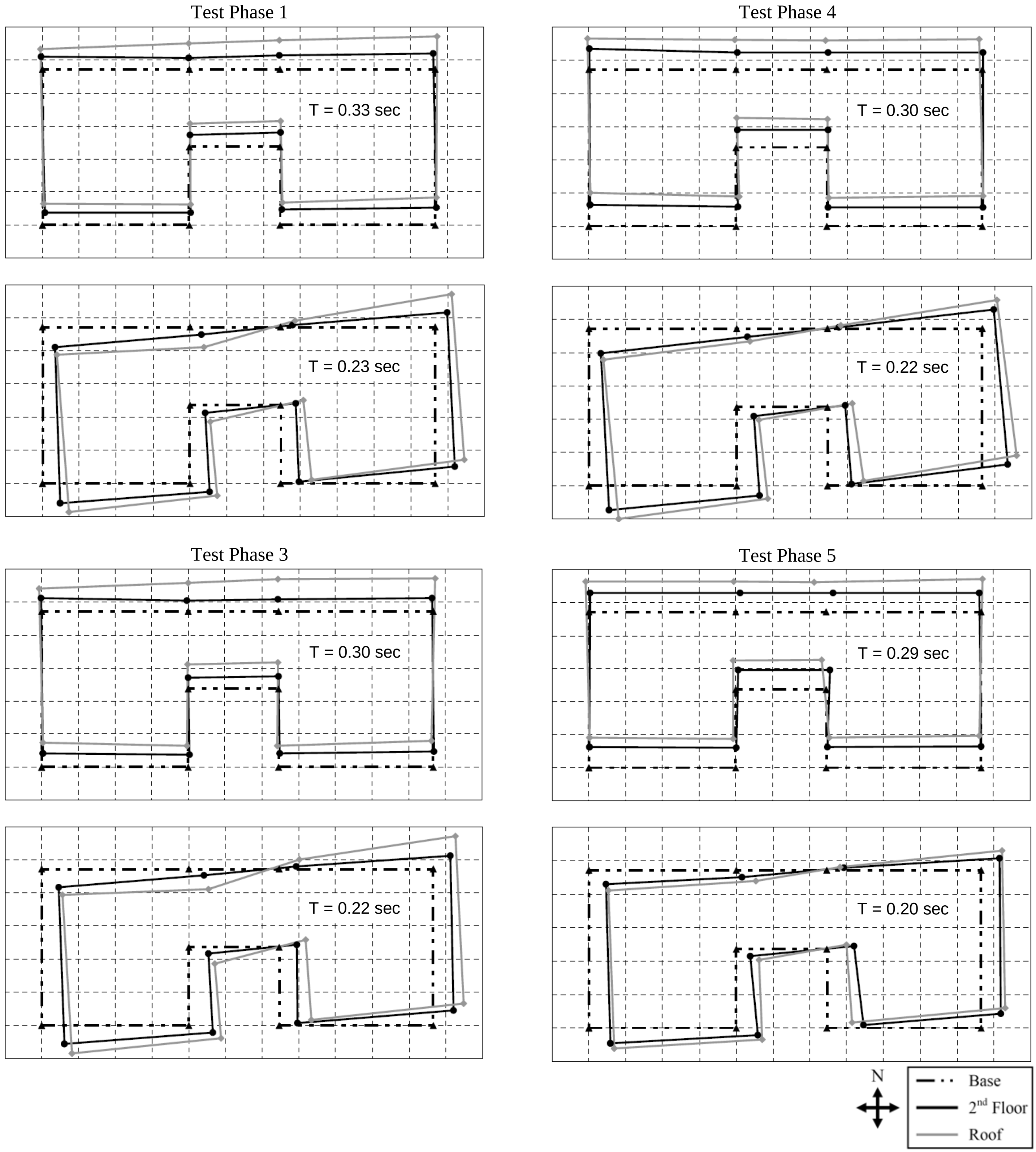



**Figure 4 – Initial Mode Shapes of Test Structure.**

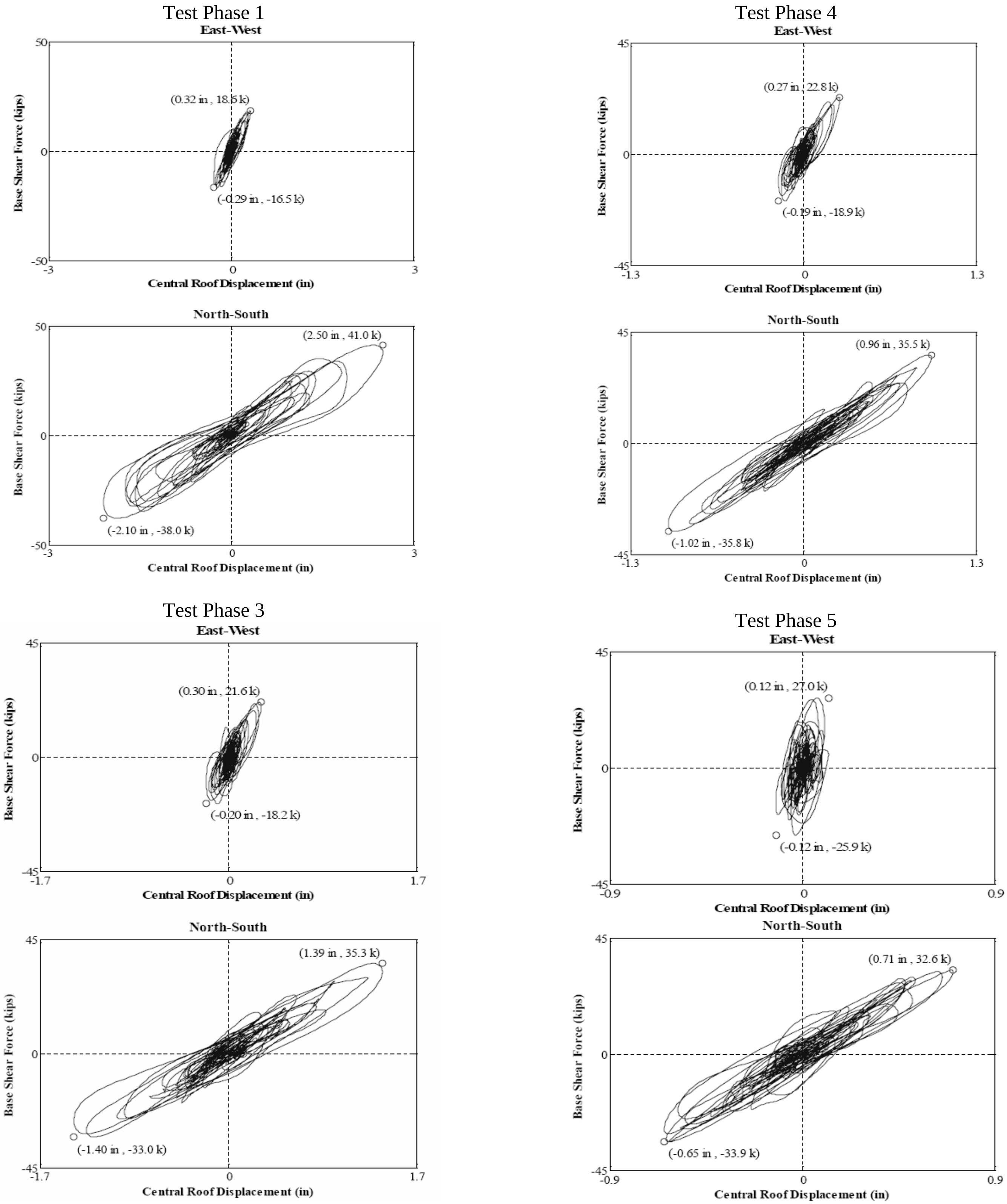



**Figure 5 – Global Hysteretic Responses, Test Level 2.**

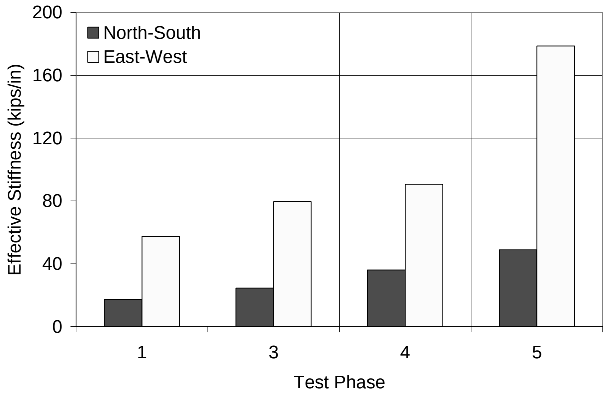



**Figure 6 – Effective Stiffness of Test Building, Test Level 2.**

Figures 7 and 8 show the global hysteretic responses obtained with the complete (Phase 5) building under Test Levels 4 (DBE) and 5 (MCE), respectively. In the transverse direction, the maximum roof displacement reached 1.61" (0.8% drift) under the DBE level and 3.98 (1.9% drift) under the MCE level. Note that the wood-only building of Phase 1 exhibited, under Test Level 2, a peak roof displacement larger than the Phase 5 building under the DBE Test Level 4.

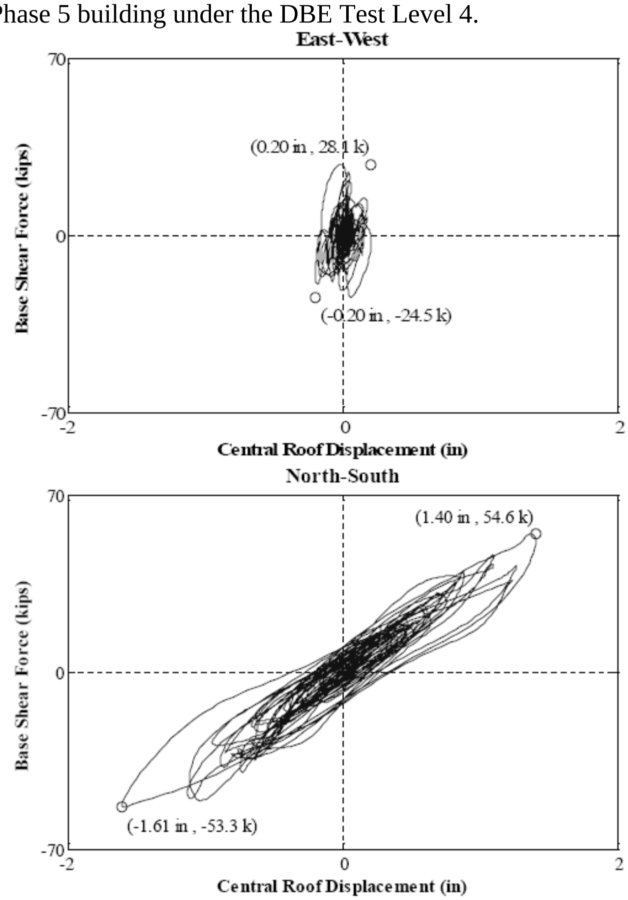



**Figure 7 – Global Hysteretic Responses, Test Phase 5, Test Level 4 (DBE).**

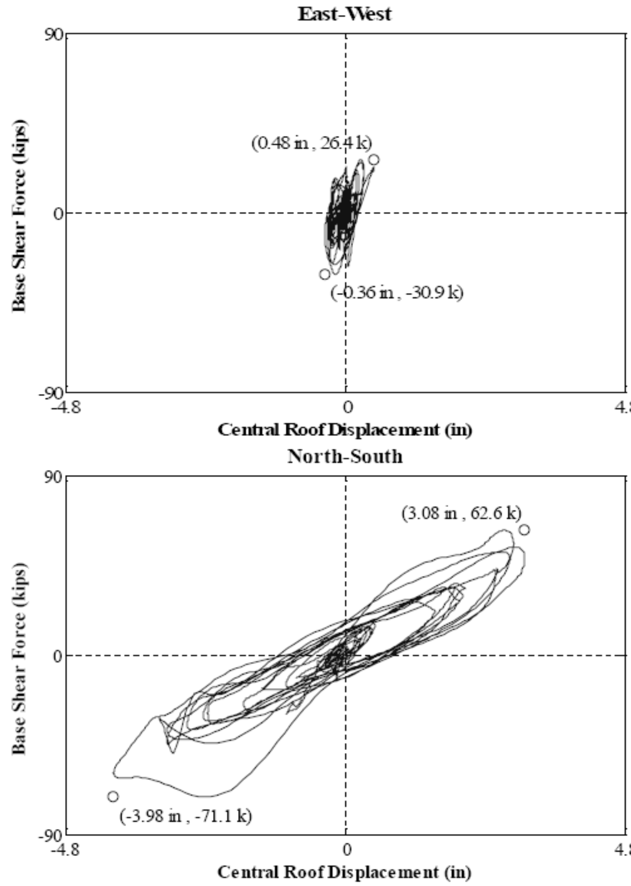



**Figure 8 – Global Hysteretic Responses, Test Phase 5, Test Level 5 (MCE).**

<u>Response of Garage Wall Line</u>

The seismic response of the test building in its transverse (North-South) direction was significantly influenced by the response of the garage wall line at the first level. The narrow wall piers (aspect ratio of 2.5:1) on each side of the garage opening compounded by the significant torsional response of the building under high intensity shaking, caused this garage wall line to experience the largest inter-story drifts.

Figure 9 shows the inter-story drift time-histories measured along the garage wall line during Test Phases 1, 3, 4, and 5, respectively and under Seismic Test Level 2 (see Table 2). The garage wall line of the wood-only building of Phase 1 experiences a peak relative displacement of 1.66 in. (1.5% inter-story drift) which corresponds to 65% of the total building drift developed in the transverse direction during this test (see Fig. 5). This result indicates that most of the transverse lateral displacements of the test building occurred at the first level, which suggests a possible soft-story collapse mechanism under higher amplitude base excitations.

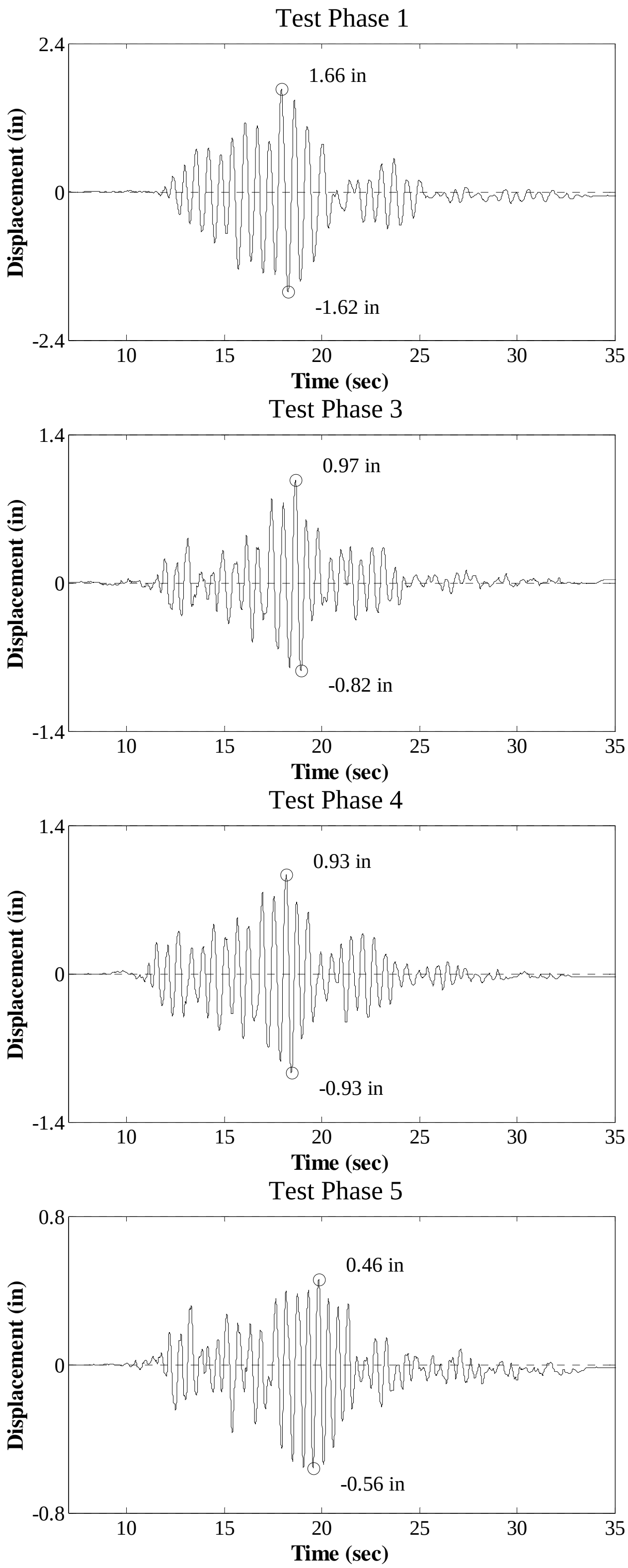



**Figure 9 – Response of Garage Wall Line, Test Level 2.**

Again, the introduction of gypsum wallboard finishes on the structural walls in Test Phase 3 caused a significant reduction in the peak drift experienced by the garage wall line (42% reduction compared to the wood-only building of Phase 1). The response of the Test Phase 4 building, however, is almost identical to that of Phase 3. This can be explained by the fact that very little interior partition wall lines were incorporated in the first level of the test building (see Fig. 2). The incorporation of exterior stucco finish caused also a significant reduction in the peak drift experience by the garage wall line (66% reduction compared to the wood-only building of Phase 1 and 42% reduction compared to the Phase 3 building.

Figure 10 shows the inter-story drift time-histories measured along the garage wall line of the complete Test Phase 5 building under Seismic Test Levels 4 (DBE) and 5 (MCE), respectively.

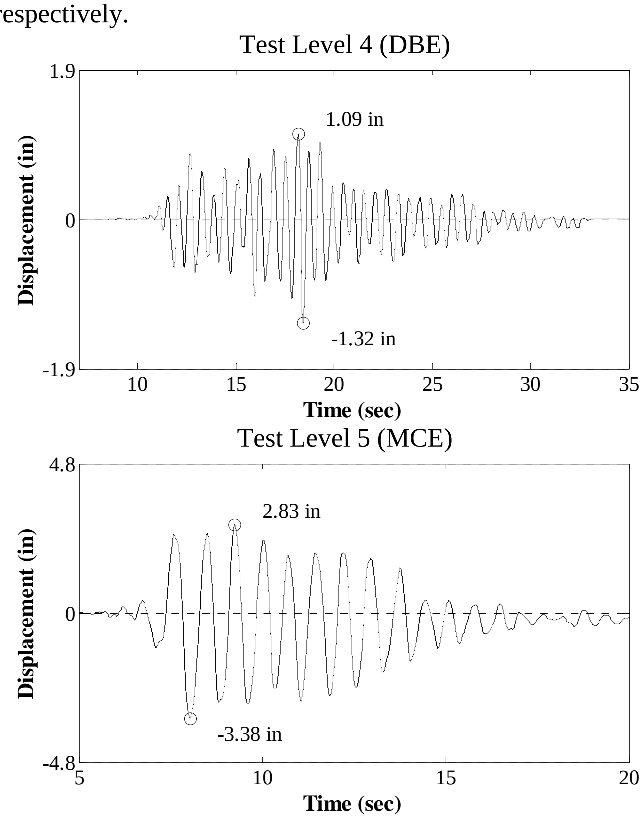



**Figure 10 – Response of Garage Wall Line, Test Phase 5.**

The Test Phase 5 building experience a peak relative displacements at the garage wall line of 1.32 in. (1.2% inter-story drift) and 3.38” (3.1% inter-story drift) under the DBE and MCE levels, respectively. Note again that the wood-only

Phase 1 building experienced higher drifts at the garage wall line under Test Level 2 (44% DBE) than the complete Test Phase 5 building under Test Level 4 (100% DBE). This result illustrates again the significant contribution of the wall finishes in improving the seismic response of the test building.

### Observed Damage

After the completion of each seismic test, a detailed damage survey was conducted on the test building in order to document the evolution of damage with test phases and test levels. In this section, the damage observed on the various structural and non-structural components of the test building is briefly described.

Damage to Gypsum Wallboard

Hairline cracking occurred in the gypsum wallboard applied to the interior surfaces of the structural walls of the Phase 3 test building after the Test Level 2 shaking, as shown in Fig. 11. This cracking occurred mainly at corners of the openings of the interior shear walls (see Fig. 2). This cracking propagated with increasing level of shaking.

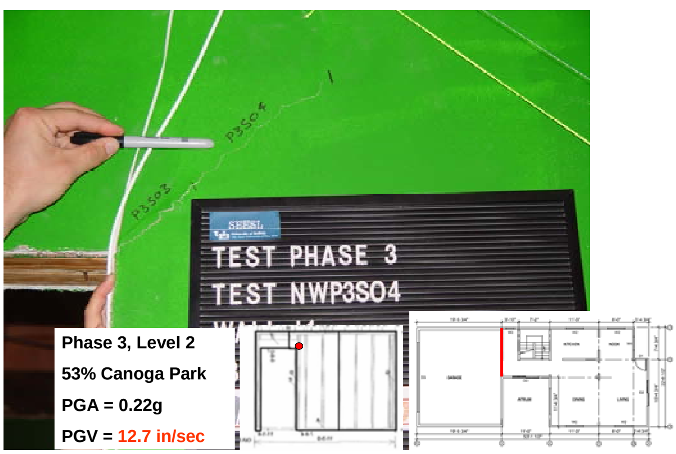



**Figure 11 – Hairline Cracking in Gypsum Wallboard, Test Phase 3, Test Level 2.**

Ceiling damage was also observed in the Test Phase 4 building. Cracking of the partition-to-ceiling connections in the transverse direction of the test building started occurring under the Test Level 2 shaking, as shown in Fig. 12. Ceiling damage increased in the Test Phase 5 building until a large portion of the ceiling gypsum failed under the Test Level 5 shaking, as shown in Fig. 13. This failure occurred in the second level ceiling connecting the two main rectangular units of the test building and can be attributed to the in-plane shear deformation of the ceiling diaphragm at that location (see Fig.4).

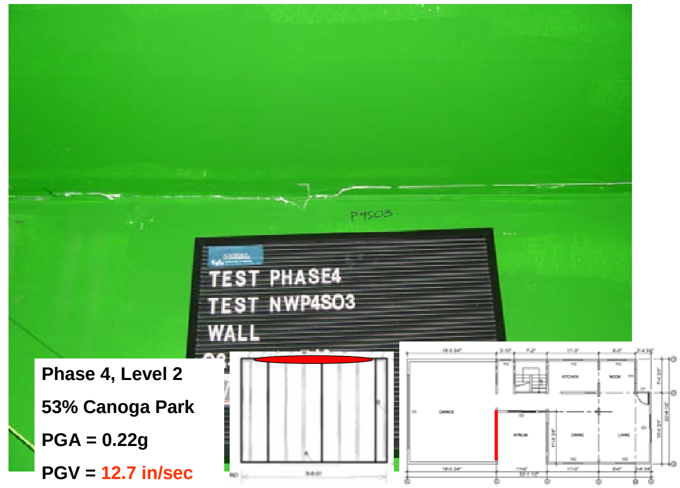



**Figure 12 – Cracking of Partition-to-Ceiling Connection, Test Phase 4, Test Level 2.**


**Figure 13 – Ceiling Failure, Test Phase 5, Test Level 5.**

## Damage to Stucco

Hairline cracking of stucco in the Phase 5 test building started after the Test Level 2 shaking. This cracking occurred mainly at corners of windows and door openings and propagated with increasing level of shaking. After Test Level 5 (MCE), significant spalling and cracking of stucco occurred around the garage door opening, as shown in Figs. 14 and 15.

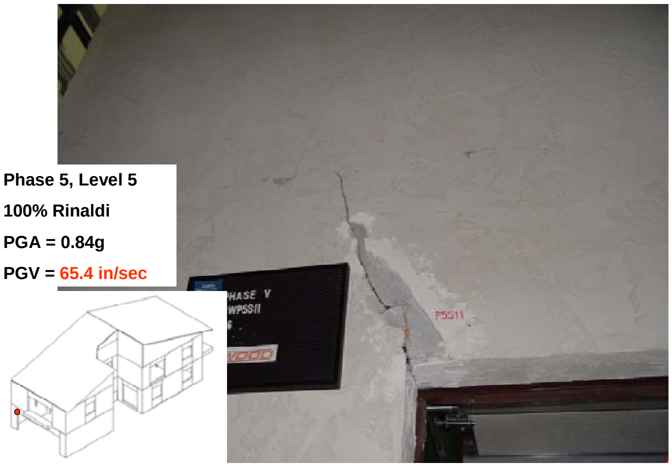



**Figure 14 – Stucco Cracking, Test Phase 5, Test Level 5.**

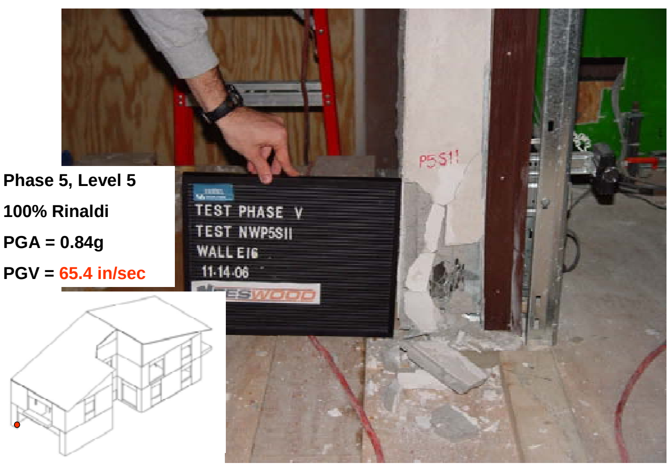



**Figure 15 – Stucco Spalling, Test Phase 5, Test Level 5.**

<u>Damage to Sill Plates</u>

The most significant damage observed in the Test Phase 5 building after Test Level 5 was the splitting of the 2x4 and 2x6 sill plates around the entire perimeter of the building. In particular, the sill plate of the narrow wall piers of the garage separated by more than ½”, as shown in Fig. 16. This damage would be very costly to repair in a real building.

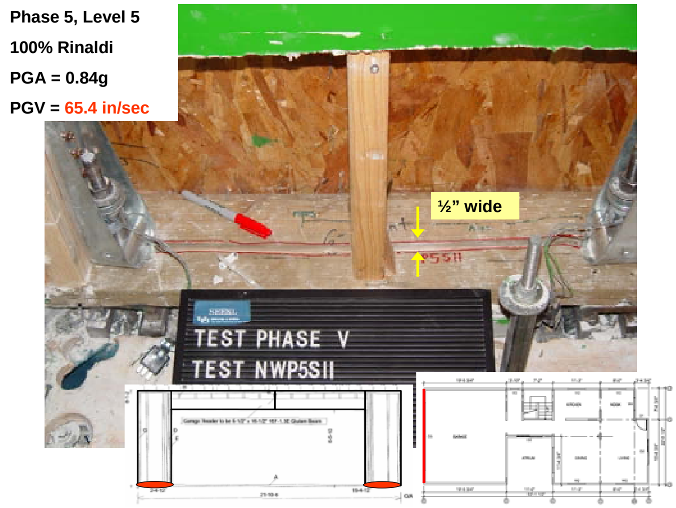



**Figure 16 –Sill Plate Failure, Test Phase 5, Test Level 5.**

## Conclusion

The benchmark shake table testing of a full-scale two-story woodframe townhouse building within the NEESWood project has provided an opportunity to study various parameters that influence the seismic response of woodframe structural systems. This paper has concentrated on the effect of interior and exterior wall finishes. Based on the experimental results obtained, it can be concluded that the installation of gypsum wallboard to the interior surfaces of structural walls improved substantially the seismic response of the test building. The application of exterior stucco improved further the seismic response of the test building, particularly in its longitudinal direction, where the shear response of the wall piers dominated. Further information on this benchmark project and on the overall research program of the NEESWood project can be obtained at the following web site: [http://www.engr.colostate.edu/NEESWood/](http://www.engr.colostate.edu/NEESWood/)

## References

ICBO, 1988, *Uniform Building Code,* 1988 edition, International Conference of Building Officials, Whittier, California.

Reitherman, R., Cobeen, K. and Serban, K. “Design Documentation of Woodframe Project Index Buildings,” Report No. W-29, *Consortium of Universities for Research in Earthquake Engineering*, Richmond, CA, 2003, 258 p.

## Acknowledgements

This material is based upon work supported by the National Science Foundation under Grant No. CMS-0529903 (NEES

Research) and CMS-0402490 (NEES Operations). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

The authors gratefully acknowledge the Principal Investigators of the NEESWood Project who supported the NEESWood benchmark testing: John van De Lindt, Michael Symans, David Rosowsky and Rachel Davidson.

The following organizations are also acknowledged for providing financial and in-kind support to the NEESWood benchmark testing described in this paper: APA - The Engineered Wood Association, B&L Wholesale Supply Inc., Buffalo Plastering Inc., Erie Community College, Gambale USA, Georgia Pacific, Hartland Builders, MiTek Industries Inc., National Gypsum Company, NGC Testing Services, National Overhead Door Inc., Niagara Truss & Pallet LLC, Northeast Window and Door, Ridg-U-Rick Inc, Simpson Strong-Tie Inc., Stanley Bostitch, and Taylor Devices Inc.