CHAPTER 2

Literature Review of Wood-frame Structure Tests

This dissertation focuses on the investigative process of extracting dynamic characteristics of wood-frame structures from measured seismic response. Although there has been some research measuring modal parameters in an experimental setting, most tests have been conducted on a structural component level (Fischer, et al. 2001). Many of the tests on full-scale wood-frame housing since the 1950s have been summarized in W*ood-frame Project Testing and Analysis Literature Review* (Filiatrault 2001). Instead of replicating the entire literature review, accomplishments pertaining to the modal parameters and dynamic characteristics of full-scale wood-frame housing are highlighted in this chapter. An overall summary at the end of the chapter will present notable findings and identify areas of further research.

2.1 Significant Case Studies

Yokel, His and Somes (1973) tested a full-scale two-story house representative of housing in the United States. The experiment tested whether existing drift limitations for medium-rise and high-rise structures can be applied to low-rise housing, and measured dynamic response characteristics of conventional housing. The wood-frame structure was 47 ft (14.3 m) long by 26 ft (7.9 m) wide.

Results from four static tests designed to measure stiffness of the structure under simulated wind loads in the transverse direction showed that the walls behaved elastically. Results also showed that the roof diaphragm behaved like a flexible diaphragm, whereas the second floor diaphragm behaved more like a rigid body.

A dynamic test measured the natural frequency to be around 9 Hz, and the percentage of critical damping to be between 4-9%, with an average of 6%. Due to resolution limits in the recording equipment, the test was inconclusive.

Sugiyama et al. (1988) subjected a full-scale house to lateral loads. The researchers examined the influence of wall sheathing above and below door and window openings on the racking resistance of the wall, as well as the effect of shear frames placed perpendicular to the direction of lateral loading. The test structure was a full-size, Japanese style two-story house measuring 7.28m (24 ft) wide by 10.01 m (33 ft) long, and was subjected to loading at various stages during construction. Each shear wall frame was loaded individually on the second floor during test Stages 1 through 5; during Stage 6, the entire structure was loaded at once.

The researchers found that the total stiffness of the first floor walls were almost equal during Stages 1 and 2, and lateral stiffness was similar between Stages 3 and 4. However, the total stiffness in Stage 3 was about 50% greater than that of Stages 1 and 2 due to the sheathing of shear walls. Total stiffness in Stage 5 was about 10-15% greater than that of Stage 4 with the installation of exterior wall siding. Local failure of the house occurred during test Stage 6. The researchers concluded that differences in floor diaphragm openings had little effect on wall stiffness, whereas the addition of calcium silicate sidings to walls parallel to loading increased lateral stiffness in that direction. They also concluded that sidings installed perpendicular to loading had little effect on lateral stiffness, but conceded that more testing was needed.

Yasamura et al. (1988) examined the safety of a wood-frame three-story house when subjected to lateral loads. The researchers tested three different sheathing configurations and compared the shear resistance of each story to theoretical calculations. In Specimen A, the load was applied monotonically at three loading points, while increasing cyclic loads were applied at each of the three shear walls in Specimens B and C. Furthermore, interior shear walls in Specimens B and C received one and a half times the load compared to exterior shear walls.

The researchers found that the shear resistance of the north longitudinal wall was one and a half times the shear resistance of the south longitudinal wall. The discrepancy, possibly caused by more openings in the south wall, had little effect on the torsional deformation. Forced vibration tests on Specimens B and C revealed that damage caused by horizontal loads decreased the natural frequency from 5.8 Hz to 3.1 Hz. On the other hand, the addition of sheathing to transverse walls increased the torsional natural frequency from 4.8 Hz to 8.8 Hz.

Carydis and Vougioukas (1989) subjected a two-story timber frame construction house to 40 repetitions of the 1986 Kalamata Earthquake, measuring 6.2 on the Richter scale. The structure was 3.6 m (11.8 ft) both in width and length. The measured natural periods of the structure slowly increased throughout the shocks – starting from 0.18 seconds in the longitudinal and transverse directions and 0.16 seconds in the vertical direction after the 1st repetition, to 0.22 seconds in the longitudinal and transverse directions and 0.17 seconds in the vertical direction after the last repetition. The damping varied across repetitions – with the damping at 17% after the 15th repetition.

Phillip, Itani and McLean (1993) studied the effect of a horizontal diaphragm on the distribution of load into shear wall elements, as well as the stiffness of the wooden shear walls with different sheathing materials. The full-scale, single story wood-frame structure was 16 ft (4.9 m) wide and 32 ft (9.8 m) long. The structure was subjected to loading at four stages during construction. In Stage I, sheathing was added on one side of the shear walls, whereas in Stage II sheathing was added on both sides. Test results showed that shear wall stiffness was additive with more sheathing. The roof diaphragm was not present in Stage III to transfer applied loads to unloaded walls, but was installed for Stage IV. During Stage IV, the longitudinal walls carried up to 23% of the load distribution, but decreased at higher loads. Results demonstrated that the roof diaphragm behaved more like rigid diaphragm as opposed to a flexible diaphragm.

Kohara and Miyazawa (1998) tested six two-story wood-frame houses using a shake table generating a sine-wave sweeping frequency motion, as well as a Japan Meteorological Agency (JMA) 1995 Kobe Earthquake record, and the 1940 El Centro Earthquake record with a scale factor of 1.5. The tests aimed to assess damage from ground motions and to examine the dynamic behavior of the structures. Results for two of the structures – Type B and Type F – were discussed in the paper. Both structures were 11.83 m (33.8 ft) long by 7.28 m (23.9 ft) wide. Both were tested during five different phases with varying amounts of diagonal braces, plywood sheathing, and gypsum wallboards. Gypsum wallboards were installed for the interior wall surfaces for both structures. The exterior wall surfaces for structures Type B and F were mortar stucco and siding boards, respectively.

Initial natural frequencies for structures Type B and F were 6.49 Hz and 6.05 Hz, respectively. The natural frequencies decreased as a result of sheathing and wallboard removal as well as cumulative damage effects. Damage occurred to exterior wall surfaces and the gypsum wallboard when the natural frequency was 4-5 Hz. Furthermore, damage occurred to the structural frame when the natural frequency was 3 Hz. Diagonal braces resisted 7-17% and 29-54% of total base shear for structures Type B and F, respectively. In structure Type B, mortar stucco resisted between 21% and 47% of the base shear. The researchers concluded that the walls in Type B covered with mortar stucco had higher stiffness than those in Type F, which were sheathed with siding.

Using a shake table, Tanaka, Ohasi and Sakamoto (1998) tested a full-scale, two-story wood-frame house against the 1995 Kobe Earthquake record by the Japan Meteorological

Agency (JMA) at the Kobe station, and the 1940 El Centro Earthquake record with an amplitude scale factor of 1.5. The goal of the experiment was to test the safety of wood-frame houses, and to determine the effect of nonstructural sheathing materials on the dynamic response of the structure. The structure measured 7.28 m (23.9 ft) wide by 7.28 m (23.9 ft) long, and was designed using a seismic shear coefficient of 0.28. The interior wall surfaces were covered with gypsum wallboard, while the exterior was sheathed with siding. The structure was tested during three phases of construction. Various amounts of sheathing were removed after each phase. Analysis of frame damage revealed that the nonstructural finish materials resisted a significant portion of the lateral forces in the structure. Drift results also showed that these materials added considerable stiffness to the structure.

Seo, Choi and Lee (1999) used a shake table to test two single-story one-quarter-scale wood-frame house models. The researchers measured the natural frequency and damping in the test models while determining the maximum peak ground acceleration these models can withstand without collapsing. The models were 1.8 m (5.9 ft) long by 0.9 m (3.0 ft) wide by 0.7 m (2.4 ft) high. The first model was tested with the 1985 Nahanni Earthquake recorded at a rock site, while the second model was tested with the 1979 Imperial Valley Earthquake recorded at a soft soil site. Random white noise tests showed that the natural frequencies of Model 1 were 3.32 Hz and 3.52 Hz in the longitudinal and transverse directions, respectively; natural frequencies of Model 2 were 3.32 Hz and 4.29 Hz in the longitudinal and transverse directions, respectively. The natural frequencies of an actual prototype would then be expected to be one-half of the frequencies in the models. The modal damping ratio of both models was 7% in both directions.

Yamaguchi and Minowa (1998) tested timber shear walls with a shake table, and compared dynamic hysteresis loops of these shear walls with static hysteresis loops previously developed. They also performed a collapse analysis using conservation of energy. The shear walls tested were 3.64 m (12 ft) long by 2.94 (9.6 ft) high with a 1.82 m (6 ft) wide opening at the center. Three specimens, with seismic shear coefficients 0.3, 0.4, and 0.5, were excited with the Japan Meteorological Agency (JMA) Kobe North-South ground motion record. The dynamic hysteresis of the specimen with a 0.3 seismic shear coefficient matched well with the static hysteresis. However, the tilting angle of the static hysteresis increased rapidly after a tilting angle of about 1/120 rad. Maximum strength of the shear wall during the dynamic test was 114% of the maximum strength during the static test. The researchers concluded that shear walls, when subjected to dynamic loads, have more strength but less ductility compared to when they are subjected to static loads.

Polensek and Schimel (1991) found that damping in wood subsystems increases with increasing amplitude of vibration. After reaching a certain threshold, damping and stiffness decrease due to reduced interface friction caused by prior damage. They also observed that the behavior was independent of lumber grade, and more dependent on nailed joints.

Seo, Choi and Lee (1999) observed viscous damping ratios between 13% and 27% while performing static and cyclic lateral load tests on wooden frames with tenon beam-column joints. Stiffness was also reduced with increased amplitude of displacement.

Hirashima (1988) performed static loading tests on a two-story building, and found that it oscillated mainly in its fundamental mode of vibration in each direction. The corresponding frequency was mostly constant, at 4 Hz and 4.5 Hz in the transverse and longitudinal directions, respectively. Damping ratios were 2.4% and 1.4% in the transverse and longitudinal directions, respectively, from a free vibration test with initial peak-to-peak displacements of about 0.5 mm.

Fischer et al. (2001) conducted a shake table test on a two-story single family wood-frame house. The 16×20 structure was tested in ten different phases. Each of the ten phases differed in their structural configurations, ranging from sheathed shear walls, symmetrical and unsymmetrical openings, and the presence of non-structural wall finish materials. Results showed that the building exhibited a fundamental frequency that ranged from 3.96 Hz to 6.49 Hz dependent on the presence of non-structural wall finish materials. There were also significant variations in the equivalent viscous damping. The measured mean damping was 7.6% of critical.

Camelo, Beck and Hall (2002) performed a series of forced vibration tests on multi-storied wood-frame housing. These studies identified transverse and longitudinal fundamental frequencies of 5.5 Hz and 5.7 Hz which were lower than the ones identified from ambient survey (6.5 Hz and 7.8 Hz). Damping ratios range from 4% to 6% of critical. Camelo also performed a data analysis of the shake table test done by Fischer et al. (Camelo 2003). The most apparent finding was the discrepancy of damping estimates. Camelo's analysis showed 15%-20% of critical damping compared to Fischer's average damping value of 7.6%.

2.2 Informative Findings

Results from full-scale testing of wood-frame housing support many findings that are documented at the subsystem level. For one, nonstructural wall-finish elements add substantial lateral stiffness to the overall structure. Experimental results show that the nonlinear behavior of the structure depends more on the connection joints and nailing as opposed to the grade of lumber used. Observations made solely from full-scale testing include the effects of symmetric and asymmetric openings on torsional modes and the role the diaphragm plays in distributing loads on walls.

Table 2-1 provides a summary of the observed dynamic characteristics of the test structures from the preceding reports. A trend apparent from the results is the increase in stiffness when additional sheathing to the shear wall is applied. When there is a decrease in stiffness, either the amplitude of the loading has increased or the test specimen has been damaged. The trend for damping ratios seems less conclusive. Although some investigators have observed its dependence on amplitude, reported ratios have ranged from as low as 2% to as high as 27%. The discrepancies can be a result of several factors such as resolution of recording equipment, the method used to calculate ratios, amplitude of loading, and the presence of nailing and connection joints. Substantial differences in damping ratios can cause some uncertainties when selecting an appropriate value for numerical models. This dissertation will attempt to remove any confusion and uncover apparent trends in modal damping estimates.

Table 2-1: Summary of observed dynamic characteristics of full-scale wood-frame tests

Author	Test Specimen	Frequency (Hz)	Damping (%)	Notes
(Yokel, Hsi and Somes 1973)	2 story house 47x 26	9	6 (4-9)	Roof (flexible), 2nd floor (rigid)
(Sugiyama, et al. 1988)	2 story house 33 x 24	N/A	N/A	Diaphragm opening little effect on wall stiffness; wall siding parallel to loading increased later stiffness
(Yasamura, et al. 1988)	3 story	5.8 → 3.1 (damaged) 4.8→8.8 (sheathing)	N/A	Stiffness changes
(Carydis and Vougioukas 1989)	2 story 11.8 x 11.8	5.8 → 4.5 6.25 →5.88	17	High damping ratios
(Phillips, Itani and McLean 1993)	32 x 16	N/A	N/A	Roof(rigid), distribute to unloaded walls
(Kohara and Miyazawa 1998)	2 story house 33.8 x 23.9	6.5, 6.05 → 4-5	N/A	Damages lower stiffness
(Tanaka, Ohasi and Sakamoto 1998)	2 story	N/A	N/A	Nonstructural elements provide significant lateral force resistance
(Seo, Choi and Lee 1999)	1 story (1/4 scale)	3.32, 3.52 3.32, 4.29	7 7	Low frequencies
(Polensek and Schimel 1991)	Wood Subsystems	Decrease with amplitude	Increase with amplitude	Independent of lumber grade; dependent on nail joint
(Seo, Choi and Lee 1999)	Wooden frames (tenon joints)	Decrease with amplitude	13-27	High damping ratios
(Hirashima 1988)	Free vibration test (.5 mm peak to peak)	4 to 4.5	1.4 – 2.4	Low damping ratios
(Fischer, et al. 2001)	2 story (16x20)	3.96 to 6.49	7.6 (5-11)	Nonstructural wall finishes played significant role
(Camelo 2003)	Multi-story houses	5.5 and 5.7 (shaking) 6.5 and 7.8 (ambient)	4-6 (shaking) 15-20 (analysis)	Discrepancies between analysis and experimental results