FEATURE ARTICLE: Items of special interest, tutorials, and surveys

SEISMIC BEHAVIOR OF LOW-RISE WOOD-FRAMED BUILDINGS

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Abstract. This article reviews the performance of wood-frame buildings in recent earthquakes, and summarizes research performed to more fully understand their seismic behavior.

Past experience has shown that properly constructed wood-framed buildings can resist the damaging effects of seismic ground motion. Structures that are symmetrical in plan, built of lightweight materials and constructed of components that act as a unit generally perform well. The inherent damping found in wood and nailed and bolted connections also helps in the mitigation of earthquake damage.

This paper is a review of recent research that has been performed to quantify the begavior of wood buildings subjected to seismic motion. The focus will be directed towards component response since most recent research has been performed in that area. Low-rise, wood-framed buildings will be emphasized. This type of construction represents most residential and a large numbere of commercial and industrial buildings constructed in the United States.

PAST PERFORMANCE

Damage to wood buildings resulting from the 1964 Alaska earthquake (8.6 Richter) and the 1971 San Fernando earthquake (6.6. Richter) has been well documented [1-9]. Although the Alaskan earthquake was of higher magnitude, the damage to wood buildings was less severe than witnessed in San Fernando. The Alaskan homes were more symmetrical in cross section and had smaller openings than their San Fernando counterparts.

In both events, the primary cause of damage was a lack of adequate lateral support [3,5,6,10, 11]. The San Fernando event indicated that two-story and split-level homes with large garage openings at ground level are particularly susceptible to damage. Failures at sill plate connections and homes shifting off foundations were also observed. Fuller [2] noted that a deficiency of some buildings was a lack of resistance to torsional racking caused by the second story being stiffer than the first. A more thorough discussion of these two events can be found in a 1984 paper by Soltis [8].

Two recent California earthquakes causing damage to wood homes were the 1983 coalinga event (Richter 6.2) and the 1984 Halls Valley event (Richter 6.5). Danage to wood houses resulted from the same basic failure mechanisms in both earthquakes. Short wood stud walls in the substructure (cripple walls) failed due to a lack of adequate lateral resistance. Shifting of houses off of their foundations dure to lack of anchor bolts was also observed [12-14].

COMPONENT RESEARCH

Wall, floor and roof diaphragms are key features of light-frame wood buildings that provide earthquake resistance. These panel-type substructures serve to resist and transfer in-plane shear forces developed in the building.

A comprehensive bibliography prepared by Carney [15] in 1975 and later updated by Peterson [16] in 1983 lists diaphragm research from as early as 1930. This research has provided valuable information on the relative influence of various parameters that affect diaphragm response, such as nail spacing, openings and framing and sheathing material properties. Currently used diaphragm design methodologies are a result of this research [17,18].

More recent studies include the testing of several shear walls by Patton-Mallory, et al. [19] to determine the effects of wall length and openings on stiffness and strength. It was found that racking strength was linearly proportional to wall length. Results confirmed the usual design assumption that the length of wall containing openings can be neglected in calculating racking resistance.

Tests have also been performed to determine the effect of cyclic loading on racking wall behavior. Yasumura and Sugiyama [20] found a 10% to 20% decrease in the ultimate strength of plywood sheathed walls due to cyclic loading. More recently, the effects of cyclic loading on

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the strength of gypsun board-sheathed walls have been investigated [21].

Several mathematical models for the lateral load analysis of wall diaphragms have been developed and verified [22-30]. Amana and Booth [22] first presented the concept of nail joint slip modulus in 1967. Their theoretical and experimental studies showed that nail joint slip has a dominant effect on diaphragm deflection. The nonlinear nature of nail joint slip is also important, and several mathematical models have accounted for this behavior. McCutcheon recently modified a linear nail joint slip model presented in 1978 [30] to account for nonlinear behavior [29]. In 1984, Itani and Cheung [27] presented a general finite element model used for stud wall analysis. This model accounts for nonlinear nail joint modulus and does not impose restrictions on sheathing arrangement, load application or diaphragm geometry.

Fewer models have been developed for the analysis of floor, roof and ceiling diaphragms [22,24,25]. The larger sizes of these components and the common use of staggered sheathing arrangements complicate analysis.

Though none of these models have yet to be accepted as advanced design procedures by building codes, they have been important in identifying how variations in construction configurations and materials affect diaphragm stiffness and strength.

DIAPHRAGM MATERIALS

Plywood has long been used as sheathing for wood diaphragms, however, wood composite sheathing materials, such as particleboard and fiberboard, have received recognition for their lateral load resistance in wall or floor diaphragms or both [18]. Experimental tests performed by Price and Gromala [31] on wood stud walls sheathed with flakeboard indicated that the strength of these walls was slightly higher than that of plywood-sheathed walls.

Typically considered a "nonstructural" sheathing material, gypsun board can also contribute to the lateral load capacity of diaphragms. Though dependent on wall length and panel orientation, research has shown that gypsum board contributes significantly to the load capacity of interior and exterior shear walls [32,33]. The Uniform Building Code currently limits gypsum board's contribution, which cannot be added to the load capacity of other types of sheathing materials on the same wall [18].

DYNAMIC CHARACTERISTICS

Though considerable research has been performed on diaphragm behavior, it has for the most part been limited to static testing and the mathematical modeling of static behavior. Little research has been performed to determine the seismic response of wood diaphragms [34].

Quantification of the dynamic properties of diaphragms, such as natural frequencies and damping ratios, has received more attentton [35-38]. Natural frequencies of walls, floors, cellings and roofs have been measured and are found to range between approximately 4 and 30 hertz, depending on diaphragm type. Because wood diaphragms exhibit nonlinear load/displacement response when subjected to lateral loads, stiffness and natural frequency are also dependent on displacement level. Quantifying natural frequency for these components is important since earthquake signals are known to contain frequencies between approximately 0.5 and 8 hertz.

Wood buildings with nailed components have a high damping capacity. Damping capacity is the ability of a structure to dissipate energy during vibration and is usually measured by the damping ratio. The dissipation of energy generated from earthquake motion is important in reducing the seismic forces the structure must resist.

Tests on wall, floor, ceiling and roof diaphragms indicate a range of damping ratios from 0.03 to 0.34, the large values indicating higher levels of energy dissipation [24,37]. These values depend on diaphragm size and type, sheathing matertal, nail characteristics and displacement level.

Intercomponent connections are also thought to play an important role in the damping capacity of a wood building, however, little research has been performed to quantify the behavior of these connections [39].

The single nail joints used to connect sheathing to framing play a major role in the damping capacity of wood-framed buildings. Because of their nonlinear hysteretic behavior, these joints dissipate a significant mount of energy [40-43]. Even at low displacement levels, damping associated with the use of nailed joints has been found to be about six times the damping capacity of the wood material itself [43].

Single nail joints are also Influenced by the rate of loading and effects of load cycling. At small deformations, an increase in joint strength due to a high rate of loading has been found to be offset by a decreased joint capacity as a result of load cycling [42]. At large deformations and numbers of load cycles, joint resistance decreases.

BUILDING BEHAVIOR

The characteristics of a whole building differ from that of its components. To investigate the dynamic characteristics of wood-frame structures, Medearis [44] subjected 63 wood homes to low amplitude vibrations. These tests indicated a building frequency range of 4 to 18 hertz, depending on building height. More recently, Sugiyama [44] tested wooden homes constructed of plywood shear walls (similar to North American construction) and found that natural frequencies ranged from about 3 to 7 hertz.

Wood buildings subjected to earthquake motion often undergo torsional motion. Observations have shown that the greatest deficiency of wood-frame construction is its lack of resistance to torsional racking [2]. The basic cause of this motion is the eccentricity between the centers of mass and resistance at various floors of the building.

Theoretical models for the lateral-torsional analysis of low-rise timber structures have been developed [46,47]. Using nonlinear springs to model the racking walls, Naik [47] analyzed a two-story house and found first mode building frequencies between 1.79 and 4.0 hertz. Using a similar model, Moody [46] found reasonable agreement between experimental results and analytical predictions of lateral response for several wood buildings. Both models assume the ceiling diaphragms are rigid.

Attempts have been made to model a whole wood building subject to lateral loading, however, a comprehensive model that accounts for component and intercomponent behavior has yet to be developed. Chehab [48] utilized the general structural analysis program SAPV to analyze a full-size home under simulated earthquake loadings. In spite of crudely estimated input properties for the various components and intercomponents, the results indicated (qualitatively) many of the effects observed in earthquake-damaged houses.

More recently, Gupta and Kuo [49] presented a model to analyze a wood building subjected to lateral loads. Comparisons with full-scale house tests by Tuomi and McCutcheon [50] indicated reasonable agreement.

DESIGN ASPECTS

Low-rise, timber, shear-wall buildings are low mass, high stiffness structures with relatively high natural frequencies. Current code requirements are based upon seismic surveys of steel and concrete frame buildings that are generally high mass, low stiffness structures with a relatively low natural frequency. Code formulas for determining lateral response forces are based upon the approximation of response spectra developed for lumped mass, low frequency structures. These formulas may require revision for timber structures [47].

In Asian countries, old timber buildings such as pagodas, temples and pavilions have stood for thousands of years and withstood earthquakes without much damage [51]. The ductility of these structures has allowed them to undergo large deformation without failure, while dissipating large amounts of energy.

Designing structures to remain elastic during severe earthquake motion is usually uneconomical. Recent research in New Zealand has led to a ductility factor approach for determining design earthquake loads for timber structures [52]. Assuming the structure is well detailed and is able to withstand displacements greater than that attained at its design load, resistance to horizontal forces substantially less than those predicted by elastic response can be justified using this approach [41]. An advantage of this method is the utilization of reserve displacement capacity found in single nail joints. In the United States, little work has been performed on the ductility of wood structures [53].

SUMMARY

Since the 1971 San Fernando event, earthquakes have provided little new information on the seismic behavior of low-rise, wood-frame buildings, however, analytical and experimental research is continuing in an effort to more fully understand component and building response. Mathematical models have been developed and verified to predict component response, however, additional study is needed regarding intercomponent behavior and ductility requirments for seismic design. The development of a comprehensive wood building mathematical model will need to account for the dynamic characteristics of components and intercomponents. The realization of such a model will allow a more accurate prediction of the magnitude and distribution of seismic forces, and as a result more efficient wood building designs.

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