CHAPTER 2

2. Literature Review

2.1 Introduction

This chapter serves as a summary of relevant research that has been conducted to date. Most of the research presented is related to timber shear walls. No published research results on the racking performance of structurally insulated panels was identified. In the past, the majority of research focused on monotonic performance of timber shear walls. More recently, research has been focused on the performance of timber shear walls under cyclic and dynamic loading.

2.2 Background

Shear walls are the vertical component of the lateral load resisting system of a timber structure. Shear walls transfer lateral loads from a horizontal diaphragm above to a diaphragm or wall below, or to the foundation. Shear walls resist loads being induced in the walls from the horizontal diaphragms in the system like a small shear element (Breyer 1993). Shear walls also act as load bearing walls in some cases to carry vertical loads to the foundation.

Before structural use panel shear walls were accepted for use, timber structures used let-in corner bracing or diagonal lumber sheathing and bracing to resist lateral loads. The Federal Housing Administration (FHA) issued guidelines for the use of panel sheathed shear walls in 1949. The FHA recommended that 8 ft by 8 ft panels be able to resist a minimum racking strength of 5200 lb. The American Plywood Association (APA) performed tests on the performance of timber shear walls, and in 1955 the Uniform Building Code (UBC) accepted these values. In the late 1960’s and early 1970’s, the department of Housing and Urban Development (HUD) performed racking strength tests on numerous shear walls using a standard developed for testing wall panels, ASTM E72.

2. 3 Shear Wall Testing

This section summarizes the research focusing on monotonic, cyclic, and dynamic racking performance of timber shear walls. Different types of racking tests are discussed. Variables such as different sheathing materials, different connecting elements, and wall geometry are also discussed.

2.3.1 Racking Performance

American Society of Testing and Materials (ASTM) published the first standard on testing wall panels for monotonic racking resistance, ASTM E72. Tests have been performed on many different configurations of walls using the ASTM E72 standard. ASTM E564 is another racking strength standard developed due to controversy over steel tie-down rods present in the ASTM E72 tests. Both testing specifications involve the same type of monotonic loading. However, the testing frames used to rack the walls differ. Many researchers such as Soltis et al (1981) identified potential problems with the ASTM E72 test. Griffiths (1984) said the ASTM E72 standard was unacceptable because the tie-down rod led to unrealistic failures. Suzuki et al (1978) performed tests to quantify the differences in the monotonic tests with and without the tie-down rods. They concluded that capacities of the shear walls were greater for the tests with tie-down rods (ASTM E72). They also found that the shear loads were linearly proportional to the length of the wall for either test. ASTM E564 allows researchers to investigate other variables such as tie-down anchorage, lateral slippage at the sole plate, and the effect of vertical load (Skaggs and Rose 1996).

Tuomi and Gromala (1977) studied the effects of variations in the ASTM E72 standard testing procedure by performing the tests on specimens and comparing the corresponding racking strengths. They determined that the rate of loading used in the test does not effect the ultimate strengths of walls. They also tested walls which had let-in corner braces but not horizontal board sheathing and found that they were below the FHA recommendations for minimum performance.

Lyons and Barnes (1979) studied the racking resistance of particleboard used as sheathing material. They performed tests varying the type of particleboard, weathering conditions, adhesive type, framing member size, and orientation and compared the results with those for plywood sheathed shear walls. It was determined that framing size did not effect the wall performance and that performance of shear walls with adhesive was not affected by adhesive type. Minimum performance standards were met with all the particleboard shear walls.

Several researchers have investigated the performance of Oriented Strand Board (OSB) or Waferboard sheathed shear walls and compared their performance with plywood sheathed shear walls. Price and Gramola (1980) conducted ASTM E72 tests on 8 ft by 8 ft as well as 2 ft by 2 ft wall panels on 10 different groups of flakeboard (waferboard) comprised of different species of wood to determine racking strengths and effects of moisture content. Hardwood and Pine composite flakeboards were found to be slightly stiffer than southern pine plywood sheathing. Plywood walls on the average, however, had higher capacities than the flakeboard. Effects of moisture content were examined by allowing the sheathing to soak in water for 24 hours. The racking resistance and lateral nail strength decreased with moisture content. Racking strengths obtained from testing were compared to theoretical racking strengths based on a linear prediction model and were found to be only slightly lower than the theoretical results.

TECO (1980) performed 138 racking tests on 5/16 in. thick through 5/8 in. thick waferboard sheathed walls, roofs, and floors to evaluate the performance of the product based on HUD’s minimum property standards. The effect of moisture content on the waferboard was also investigated. Minimum performance criteria set forth by HUD were met for all walls tested. TECO (1981) also performed ASTM E72 tests to investigate the performance of 7/16 in. thick Waferfeld waferboard sheathing. Dolan (1989) compared plywood to waferboard shear walls and found little or no difference in their performance monotonically or cyclically.

The performance of gypsum wall board has also been investigated by several researchers. Freeman (1976) performed static and cyclic tests on building partitions with doors and windows included. Freeman performed tests on 34 partitions with gypsum wall board sheathing. Results from these tests are included in the discussion of cyclic tests. Wolfe (1983) tested 30 light-framed walls ranging in size from 8 ft by 8 ft to 8 ft by 13 ft to investigate the effects of wind bracing, wall length, and panel orientation. Twenty-two of the 30 walls were framed with gypsum wall board. Wolfe concluded that gypsum wall board contributes to the racking strength regardless of wind bracing or panel orientation. Wolfe also found that the racking resistance of a shear wall with gypsum wall board is equal to the sum of the racking resistance of individual panel elements.

Patton-Mallory et al (1984) conducted small scale tests on 22 in. shear walls and concluded that shear walls sheathed on both sides behavior can be defined by the sum of the behavior of the two facing panels. The effect of aspect ratio on racking resistance and stiffness was also investigated. Strength and stiffness behavior increased linearly with wall length for aspect ratios up to 3. Interior wall construction (gypsum wall board) was found to provide significant racking resistance when compared to typical exterior wall (plywood) construction. Patton-Mallory et al (1985) performed full-size ASTM E564 tests to determine wall racking strengths. They concluded that the wall length, for aspect ratios of 1 to 3, is proportional to the ultimate racking load. Racking strength of plywood is linearly proportional to wall length for aspect ratios up to 4. Racking stiffness, however, is not directly proportional to length of wall for gypsum walls. They determined that the ultimate racking strength of walls sheathed with gypsum is the sum of the resistance of the sheathing materials tested separately in singly sheathed walls.

Some monotonic shear wall testing has been conducted in order to verify models proposed by researchers. Easley et al (1982) tested 8 ft by 12 ft wall panels as well as performed finite element analysis to verify formulas they proposed for shear wall fastener forces, shear wall stiffness, and the load-strain behavior of a wall based on corrugated metal sheet sheathing. Easley et al concluded that the equations developed accurately depicted the load-deflection behavior of the walls well into the nonlinear region of loading as long as separation of the framing member joints between studs and header or sill plates did not occur. Dolan and Foschi (1991) performed seven 8 ft by 8 ft static shear wall tests in order to verify Dolan's finite element program SHWALL, an improvement of the finite element program SADT developed by Foschi (1977). They concluded that SHWALL predicted the capacity and load-deflection of the walls well. White (1995) used test results from Dolan (1989) on 8 ft by 8 ft walls both statically and cyclically to verify the accuracy of his finite element program WALSEIZ.

Griffiths (1984) performed monotonic racking tests on 8 ft by 8 ft panels to investigate the effects of different cladding and the effects of vertical loads on the panels. Tissell (1990) has summarized ASTM E72 tests conducted by the American Plywood Association to investigate unblocked, stapled, metal-framed, and double-side sheathed shear walls. He also investigated the effects of panels over gypsum sheathing and stud spacing and width.

Line and Douglas (1996) describe the perforated shear wall method of design for shear walls with openings. The perforated shear wall method uses equations derived by Sugiyama to design shear walls with opening without the need for intermediate over-turning restraint. Sugiyama and Matsumoto (1993) derived a simplified method for computing panel shear forces and shear deformation angles of plywood-sheathed shear walls with openings assuming that hinges form at points where studs and lintels separate. Sugiyama and Matsumoto (1994b) present empirical equations for the shear load fraction as a function of sheathing area ratio for different shear deformation angles. Sugiyama and Matsumoto (1994a) used 1/3 scale shear wall tests of walls with openings performed by Yasumura and Sugiyama (1984) to verify these empirical equations.

Johnson (1997) also studied the effects of openings on 8 ft by 40 ft shear walls loaded both monotonically and cyclically in order to validate Sugiyama's perforated shear wall method of design. He concluded that Sugiyama's equations were overly conservative for shear walls with large openings. Heine (1997) studied the effects of openings and tie-down anchorage both monotonically and cyclically.

2.3.2 Cyclic Performance

Understanding cyclic performance of shear walls is important because shear walls must resist high wind pressure changes and loads from seismic events. Medaris and Young (1964) conducted 8 cyclic tests to determine the energy dissipation and structural damping characteristics of plywood shear walls. The tests consisted of increasing peak cycle loads by 4 kips per cycle, with each cycle consisting of 4 loading increments. They found that the equivalent viscous damping ratios of plywood shear walls sheathed on both sides were approximately 0.2. Lateral instability of the system was found to not be a problem. Under low cyclic loads, no harmful effects to the walls were noted.

Freeman (1976) conducted cyclic tests on 8 ft by 8 ft wall sections of building partitions to determine the damping and stiffness properties of non-load-bearing partitions in high-rise buildings. Tests were run between 0.7 Hz and 2 Hz with an increasing peak displacement of each cycle consisting of 4 increments of displacement. Freeman presents a method for determining the effect the partitions would have on the stiffness and damping properties of the high-rise structure they were contained within.

Thurston and Hutchison (1984) performed cyclic tests on full-size walls and small wall specimens. They tested the performance of both plywood and particleboard sheathed walls, and their ductility as a function of the hysteresis loop. They concluded that the small test units could predict the performance of wood-sheathed shear walls.

Faulk and Itani (1987) tested 4 walls, 3 floors, and 3 ceilings cyclically and in free vibration. It was concluded that natural frequencies decreased and damping ratios increased with increasing diaphragm displacement. It was also concluded that the reduction of stiffness for a diaphragm with openings is proportional to the size of the opening in the wall. Thurston (1993) also investigated the effects of openings as well as gypsum wall board by performing 10 racking tests using a pseudo-static reversed cyclic racking test. Thurston compared the test results with theoretical predictions, and also noticed that rocking of the entire panel dominated deflections. The theoretical predictions were found to be good for walls with large openings. Johnson (1997) and Heine (1007) also studied the cyclic performance of shear walls with openings as discussed previously.

Several researchers have discussed the performance of adhesives under cyclic loading. Hayashi (1988) studied plywood glued to the frame of shear walls. Hayashi found that the failure did not occur in the shear wall panel, but occurred in the sill for walls with adhesive. Pellicane (1991) tested the lateral performance of nail-glue joints and concluded that the connection was stiffer and stronger than connections with just nails. Pellicane also concluded that it is conservative to superimpose the strengths of the nails and the glue for modeling purposes. Sadakata (1994) described the hysteresis loop of nail-glue walls as having a sharp slope for early loops and exhibiting a steep descent after maximum strength. Adhesives lower the ductility of a wall. Dolan and White (1992) reported that walls with adhesives in addition to nails exhibit lower ductilities.

Kamiya et al (1996) performed pseudo-dynamic tests on 6 ft by 8 ft shear walls with gypsum wall board and different thicknesses of plywood. The pseudo-dynamic tests involved a time-history response analysis while the test was being performed to predict earthquake ground motion. The relationship between mass the wall supports and maximum deflection at ultimate racking strength was investigated through these tests. The response of the shear walls was found to be sensitive to equivalent damping ratios.

Leiva-Arevena (1996) tested 8 ft by 8 ft shear walls using the BRANZ P21 testing procedure. This procedure subjects walls to a series of reversed cyclic loads of increasing amplitude. The procedure permits standard building end restraints and predicts the behavior of a wall in service more closely that the ASTM E564 configuration does. Leiva-Arevena found the shear walls tested to be ductile and exhibited good energy dissipation characteristics. Equivalent viscous damping ratios were found to range between 0.2-0.4.

Karacabeyli and Ceccotti (1996) performed ramp and cyclic displacement tests on shear walls to study the contribution of gypsum wall board as well as the difference between using nails and drywall screws to attach gypsum wall board to the framing. They concluded that walls with nails attaching the sheathing had greater ductility and greater capacity than walls with drywall screws. The also found that walls with OSB and gypsum wall board sheathing on both sides exhibited lower ductility than walls sheathed with OSB only.

Attempts have been made to develop a standard testing procedure for cyclic shear wall tests. Porter (1987) developed a testing procedure for the Joint Technical Coordinating Committee on Masonry Research (TCCMAR) called Sequential Phased Displacement. This procedure is a reversed cyclic quasi-static test involving cycles of increasing magnitude to the peak displacement followed by degradation cycles followed by stabilization cycles. This process is then repeated at a higher peak displacement until failure. Most of the test takes place at displacements over the inelastic deflection range of the wall. The Structural Engineers Association of Southern California (SEAOSC) modified the Sequential Phased Displacement testing procedure to develop a standard test for fully-reversed cyclic loading and submitted the procedure to ASTM for review. The modifications made were to specify a testing frequency of 0.2 to 1.0 Hz and the stabilization cycles were removed. Testing frequencies are lower than would typically be expected in an earthquake to limit the inertial effects during the test and to allow equipment not capable of very high frequencies to be used. The stabilization cycles were removed because nail fatigue was not experienced in the Northridge, California earthquake (Skaggs and Rose 1996), and the walls do not respond as slack systems.

2.3.3 Dynamic Performance

Foliente (1996) discusses the advantages and disadvantages of using cyclic and dynamic testing procedures. Quasi-static tests are economical and practical and give a consistent means of comparing test data from different studies. Quasi-static tests, however, do not accurately depict how a shear wall will perform under true dynamic loading. Pseudo-dynamic tests, though versatile, are not practical and require controversial decisions on the input of motion. Shake-table, dynamic, testing is the test which most closely models reality. Inertial forces are properly distributed and the correct failure modes of the wall are experienced. These dynamic tests, however, are expensive and require vast knowledge of the system being tested before being performed.

Stewart (1987) performed tests on 11 full-scale plywood sheathed shear walls. Four quasi-static reversed loading, 4 sinusoidal shake-table motion, and 3 earthquake shake-table motion tests were performed to validate a theoretical time-history shear wall model. The model was developed using the computer program EQUAKE to solve the equation of motion of a nonlinear single degree-of-freedom oscillator system. A design methodology for earthquake resistant plywood-sheathed shear walls was presented assuming the sheathing nails are the ductile component of the system. The tests performed verified the models developed. Stewart also noticed that dynamic loading enhanced the stiffness and strength properties of the plywood sheathed shear walls over quasi-static loading.

Dolan (1989) performed dynamic tests on 8 ft by 8 ft shear walls in order to verify his finite element program DYNWALL. Static cyclic, sine wave, free vibration, and dynamic earthquake simulation tests were conducted. Earthquake simulation tests were performed on an earthquake shake-table using the 1952 Kern County, California earthquake as well as a higher intensity earthquake based on the 1971 San Fernando earthquake and are discussed by Dolan and Madsen (1991). They found no significant deviations in the behavior of plywood and waferboard sheathed shear walls. They also concluded that corner or anchorage requirements would have to be met in order for the shear walls deform in a racking fashion. Damage in the walls throughout the dynamic tests lead to degrading stiffness, longer natural periods, change in damping characteristics, and possible strength loss.

Foschi and Filiatrault (1990) performed shake table tests on 8 ft by 8 ft shear walls using hold down connectors to study the performance of shear walls with adhesive. It was concluded that adhesive walls failed more suddenly with a brittle failure mode being controlled by the connection of the wall to the base plate. The walls behaved almost linearly until failure. It was suggested that careful attention be paid to the connection of the bottom plate to the framing members. Dolan and White (1992) reported that walls with nails and adhesive exhibit a higher racking resistance and lower ductility than walls with only nails. Walls with adhesives also experience higher shear loads under seismic loading shifting the probable failure mechanism from the sheathing nails to the anchorage of the walls.

2.4 Summary

An overview of research on shear walls pertinent to this thesis has been presented. It is necessary to study the effects of static and cyclic racking loads on structurally insulated panels due to their increased use as a building material and lack of information on their performance.