CHAPTER 3

3. Test Descriptions and Procedures

3.1 Introduction

The different types of wall specimens tested, materials used in the construction of the specimens, equipment, and testing procedures followed for testing the structurally insulated panel shear walls are described in this chapter. Parameters used in subsequent chapters to describe the behavior of the shear walls are also presented.

3.2 Test Specimens

Four different wall configurations, described in Table 3.1, were tested both monotonically and cyclically. All wall specimens were 8 ft tall by 8 ft wide. Types of connections between the panels and the anchorage details were varied between panels. The same fastener schedule and amount of adhesive was used on all of the walls.

<table>
<thead>
<tr>
<th>Wall A</th>
<th>Wall B</th>
<th>Wall C</th>
<th>Wall D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edge Vertical Members</td>
<td>1x4</td>
<td>½ in. OSB spline</td>
<td>1x4</td>
</tr>
<tr>
<td>Middle Vertical Members</td>
<td>2x4</td>
<td>½ in. OSB spline</td>
<td>2x4</td>
</tr>
<tr>
<td>Top Plate</td>
<td>2x4</td>
<td>2x4</td>
<td>2x4</td>
</tr>
<tr>
<td>Bottom Plate</td>
<td>2x4</td>
<td>2x4</td>
<td>2 – 2x4</td>
</tr>
<tr>
<td>Tie-down Anchors</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

Four different wall configurations, illustrated in Figure 3.1, were tested. Wall A consisted of a single 2x4 top and 2x4 bottom plate, 1 x 4 end studs, and a 2 x 4 middle stud. No tie-down anchors were used for this wall configuration. Wall B consisted of a
single 2x4 top and bottom plate, but used \( \frac{1}{2} \) in. thick OSB as a spline connection between wall panels. The middle stud of this wall consisted of two 5 in. splines while the end studs consisted of two 2 \( \frac{1}{2} \) in. splines. Wall C was the same as wall configuration A except that it contained two 2x4 bottom plates with two rows of adhesive and two rows of screws, one for each bottom plate. Wall configuration D consisted of a single 2x4 top and bottom plate, 2 x 4 end studs, a 2 x 4 middle stud, and tie-down anchors connected to the bottom of the end studs. Two specimens for wall configuration D were also tested cyclically with tie-down anchors at the top of the specimen in addition to the tie-down anchors at the bottom to simulate strapping tying multiple building stories together.
Figure 3.1 – Boundary Conditions of Four Different Wall Configurations.
3.3 Materials

The materials used in the construction of the structurally insulated panel walls, as well as the construction details, are presented in this section. Individual panels, consisting of the insulation foam and sheathing, were fabricated by the manufacturer, Advanced Construction Systems International, in Richmond, Virginia, and were delivered to the testing facility. Wall panels consisted of 7/16 in. OSB and ½ in. Fiberbond structural sheetrock facings separated by 3-1/2 in. Expanded Polystyrene Insulation with a density of 1.0 pcf. Individual panels measured 4 ft by 8 ft and were oriented vertically. The walls were then constructed by inserting end members, a connecting member between panels, and top and bottom plates according to the type of specimen desired. The walls were not tested for 24 hours after construction to allow the construction adhesive to cure.

Framing lumber used in the construction of the walls were Stud grade or better, Spruce-Pine-Fir obtained from a local lumberyard. The actual dimension of the core of the panels was 3-3/8 in. instead of 3-½ in for the cyclic and strait ramp monotonic tests. For this reason, 1/8 in. was removed from all the 2 x 4’s and 1 x 4’s used in these tests in order to assemble the walls. Wall specimens used for the ASTM E564 tests did not require resizing because the panels were delivered with 3-1/2 in. cores.

Connections between the panels and framing members or top and bottom plates consisted of a construction adhesive and drywall screws. The construction adhesive used was either Liquid Nails for Projects and Construction or Sub-floor and Construction adhesive. The screws used throughout testing were 1-5/8 in. coarse thread drywall screws as specified for testing by the manufacturer of the panels.

The connection of the panels to the end studs, middle studs, and top and bottom plates all consisted of a ¼ in. bead of construction adhesive and drywall screws placed 6 in. o.c. All wall sections had a single top and had either a double or single bottom plate as needed. End studs consisted of either 1 x 4’s or 2-1/2 in. wide pieces of 7/16 in. OSB to represent a typical 8 ft section of wall if tie-down anchors were not being used or 2 x 4’s if tie-down anchors were being used to represent the end of a wall.
Tie-down anchors were used for some of the wall specimens being tested. The anchors were located on the outside of the end studs of both ends of the wall section to facilitate construction of the wall. In practice, the tie-downs would be placed on the inside of the end studs. Simpson tie-down model HT22 anchors with 5/8 in. anchor bolts were used for the tests, and were attached to the end studs with 32-16d sinker nails (0.147 in. diameter and 3.25 in. length), then anchored to the steel structural tube test frame using 5/8 in. bolts.

In all of the tests, the bottom and top plates were attached to the steel structural tube test frame with 5/8 in. diameter carriage bolts spaced 24 in. on center. The carriage bolts were anchored into the top and bottom plates prior to the construction of the wall.

### 3.4 Test Apparatus

Specimens were tested in a horizontal position similar to what is prescribed in ASTM E564. This type of test frame was decided upon over the ASTM E72 recommendation because the tie-down rod in the ASTM E 72 test resists all of the overturning moment that the wall anchorage should resist.

Each wall was mounted to a rigid foundation at its base using four 5/8 in. diameter carriage bolts as seen in Figure 3.2. The first bolt was located 12 in. from the end of the wall and subsequent bolts were placed every 24 in. o.c. along the bottom plate. Tie-down anchors were also attached to the rigid foundation if applicable. A hydraulic actuator with a 12 in. travel was attached to the distributor beam and attached to allow movement in both a positive and negative direction. The tops of the walls were connected to a 3 x 5 in. steel tube distributor beam with casters in the same manner. The steel tube allowed the more or less uniform distribution of the load from the hydraulic actuator to the top plate of the wall. Casters were aligned parallel to the loading tube to allow the tube to move in the plane of the load. The amount of friction created by the casters was measured and all test data was corrected for this error. Friction was not significant when compared with the magnitude of actual test loads.
3.5 Instrumentation

Four LVDT’s were used to measure the displacement at various locations on the wall in a similar fashion to that prescribed in ASTM E564. In addition to the LVDT’s, the hydraulic actuator contained a load cell and displacement transducer that were monitored. A personal computer was used to record data continuously from the six instruments. These displacement measurements allow the racking deflection, as well as the rigid-body rotation of the wall to be calculated. The locations of the measurement devices are shown in Figure 3.3, and are defined as:

**Ch 0**: LVDT that measured the slip between the top plate of the wall and the steel load distributor beam for the ramp monotonic and cyclic tests. Ch 0 measured the drift of the top of the wall relative to the ground for the ASTM E564 tests.

**Ch 1**: LVDT that measured the vertical uplift of the base of the wall on the end away from the load application point.

**Ch 2**: LVDT that measured the vertical uplift of the base of the wall on the side of the wall to which the load was applied.

**Ch 3**: LVDT that measured the horizontal slip between the bottom plate of the wall and the rigid foundation.
**Ch 6:** Displacement of the end of the hydraulic actuator attached to the steel tube recorded internally.

**Ch 7:** Load cell that measured the load applied to the top of the wall.

![Figure 3.3 – Location of 6 Channels of Data Collection.](image)

Uplift of the ends of the walls was measured using two LVDT’s. Actual uplift of the wall ends was not measured due to constraints involved with the test configuration. Instead, LVDT stops were used to measure uplift 4-¹/₄ in. from the outside face of the wall and 9-¹/₂ in. up from the base of the wall. Values of actual uplift for the ends of the walls were obtained by correcting the data recorded for the geometrical distortions of the LVDT stops assuming the majority of drift came from rigid body rotations.
3.6 Monotonic Tests

3.6.1 Monotonic Testing Procedures

Two types of monotonic tests were performed. The first type of monotonic test was a static one-directional ramp test, with a rate of displacement of 0.01 in. per second. Data was continuously recorded at a frequency of 10 samples per second. In addition to these tests, 8 tests were performed as specified by ASTM E564. These tests are one-directional static load-controlled tests except that a pre-load of 10% of the estimated ultimate load was applied for 5 min and removed for 5 min before the instruments are zeroed. At each increment of load, the load level was maintained for at least 1 min before displacement readings are taken. In addition, after 1/3 and 2/3 the ultimate load is reached, the load was removed and the specimen allowed to relax for 5 min in order to measure the displacement recovery or set of the wall. Two tests were performed for each wall configuration unless the load-displacement behavior of the walls differed more than 15%. If necessary, a third test was performed as required by ASTM E564.

3.6.2 Definition of Properties

3.6.2.1 Load-Deflection Parameters

The data collected during the monotonic tests were used to create the load-deflection plots that are included in Section 4.2 for each wall configuration. The following parameters were determined from direct examination of the load-deflection plots.

Maximum load resistance is designated $F_{\text{max}}$ and is defined as the peak load a wall experiences during testing. The corresponding drift experienced at maximum load resistance is defined as $\Delta_{\text{max}}$. The load resistance at failure is defined as $F_{\text{failure}}$. Failure is defined as either the point at which a sharp decrease in load resistance is experienced or the point after the wall has experienced the maximum load resistance, $F_{\text{max}}$, and decreases to a value of 0.8 $F_{\text{max}}$. The elastic stiffness, $k_e$, of the wall is defined as the
3.6.2.2 Equivalent Elastic-Plastic Curve Analysis

In order to make comparisons between tests performed on different materials, an equivalent elastic-plastic curve (EEPC), as illustrated Figure 3.4, is determined for the load-displacement curve of a test.

![Figure 3.4 – Equivalent Elastic Plastic Curve Analysis.](image-url)

The point of yield can be defined for an equivalent elastic plastic curve using different procedures (Foliente, 1996). For this study, to remain consistent with studies performed by Johnson (1997) and Heine (1997), the equivalent elastic-plastic curve is defined as an elastic-plastic curve in which the energy is equal to the energy of the original load-deflection curve through failure. This essentially states that the area under the EEPC is equal to the area under the load-deflection curve through the point of failure. Load resistance at yield, $F_{\text{yield}}$, is defined as the point at which this equivalent energy
curve becomes plastic such that, by definition, $F_{\text{yield}} \geq 0.8 F_{\text{max}}$. The corresponding deflection on this curve at that point, or $F_{\text{yield}} / k_e$ is defined as $\Delta_{\text{yield}}$. Ductility ratio, $D$, is defined as the ratio of displacement at failure to displacement at yield.

$$D = \frac{\Delta_{\text{failure}}}{\Delta_{\text{yield}}} \quad (6-1)$$

### 3.7 Cyclic Tests

#### 3.7.1 Cyclic Testing Procedure

Each of the four wall configurations was also tested cyclically in a manner similar to the Sequential Phased Displacement (SPD) procedure, a fully-reversed triangular, sinusoidal cyclic ramp function. The SPD procedure begins with at least three incremental levels of three cycles each, within the elastic displacement region of the material being tested up to the First Major Event (FME) of the material. The FME is defined as a major crack, first limit state, or connection yielding or degradation. For this study, three increments of displacement of three cycles were applied at 25%, 50%, and 75% the FME. Yielding of the walls was anticipated to occur around 0.1 in. For this reason, 0.1 in. was chosen as the FME for the tests.

Following the initial three sets of cycles, the SPD displacement pattern is initiated. The SPD displacement pattern consists of phases of cycles in the pattern starting at some peak displacement (the FME for the first phase) as can be seen in Figure 3.5. The first (peak displacement) cycle is followed by three degradation cycles of 75%, 50%, and 25% of displacement of the initial cycle. The three degradation cycles are followed by three or more cycles at the initial displacement in order to stabilize the hysteretic response of the wall. Stabilized response is defined as when the decrease in resistance between two successive stabilization cycles is less than 5%. If the decrease in resistance is greater than 5%, additional stabilization cycles are required. The walls tested in this study stabilized in three cycles.
The second phase of the cycles started after the three stabilization cycles of the previous phase. The procedure followed the same pattern of cycles for later phases as the first FME phase, except for a higher initial cycle displacement was used. The SPD procedure recommends using 200% of the FME as the displacement increment for each phase for flexible or ductile systems. Walls tested as part of this system may seem to be brittle systems, but ductility ratios of greater than three were not uncommon so the walls were tested as though they were ductile systems. In this study, three times the FME was used as the initial displacement of the second phase. The SPD third phase used 400% the FME as the initial cycle displacement. The initial displacements for the remaining phases were increased by 200% the FME until the wall experienced catastrophic failure.

Data was recorded continuously during the tests at a rate of 20 samples per second. The frequency of the cycles in the test was nominally 0.4 Hz.

Figure 3.5 – Displacement History for Cyclic Loading Procedure.
3.7.2 Definition of Properties

3.7.2.1 Test Parameters

The SPD testing procedure was used to conduct the cyclic tests performed on the different wall configurations. There are two specific cycles within each phase of the procedure which are of interest. The initial cycle is the first cycle of each phase characterized by an initial peak displacement as can be seen in Figure 3.6. The stabilized cycle is the third stabilization cycle and final cycle in each phase of the testing procedure.

![Initial and Stabilized Cycles from Displacement History](image)

The initial cycle is used to predict the behavior of a wall under a one-time peak load event such as a high gust of wind load. The stabilized cycle is meant to represent the behavior of the wall under sustained cyclic loading such as a seismic event or any other type of repetitive cyclic loading. This information can be used to help predict the behavior of the wall under different circumstances.
The same information was obtained for both the initial and stabilized cycles of the wall hysteresis. Maximum load resistance is designated $F_{\text{max}}$ and is defined as the average of the peak positive and negative loads a wall experiences during testing. The corresponding average maximum positive and negative drifts experienced during the cycle of maximum load resistance is defined as $\Delta_{\text{max}}$. Average positive and negative load resistance at failure is defined as $F_{\text{failure}}$. Failure is defined as either the point at which a sharp decrease in load resistance is experienced or the point at which the wall has already experienced the maximum load resistance, $F_{\text{max}}$, and decreases to a point of 0.8 $F_{\text{max}}$. Elastic stiffness, $k_e$, of the wall is defined as the slope of a line between the origin and a point corresponding to 0.4 $F_{\text{max}}$ on the load-displacement envelope (or backbone) curve developed from points of maximum load and displacement of either the initial or stabilized cycles of a test.

3.7.2.2 Equivalent Elastic-Plastic Curve Analysis

In order to make comparisons between tests performed on different materials tested in a racking behavior, an equivalent elastic-plastic curve is utilized. An equivalent elastic-plastic curve is determined from the load-displacement envelope (backbone) curve for each test.

The envelope curve is created by choosing points of maximum positive and negative load resistance and positive and negative maximum drift for each initial and stabilized cycle of a test as illustrated in Figure 3.7. An envelope curve is obtained for both the positive and negative cycles of a test; and from these, separate equivalent elastic-plastic curves are obtained and analyzed.
The same definition of elastic-plastic curve is used for the cyclic test envelope curves as was used for the monotonic load-drift curves. Ductility ratio, $D$, is defined as the ratio of displacement at failure to displacement at yield.

$$D = \frac{\Delta_{\text{failure}}}{\Delta_{\text{yield}}}$$ \hspace{1cm} (6-2)

Ductility is the ability of a system to sustain inelastic deformations, without significant loss of load resistance, before failure. Porter (1987) notes that ductility alone is not a good indicator of cyclic performance because it does not indicate the decrease in resistance and stiffness of the system near failure and should be viewed in conjuncture with other variables. Ductility is the ability of the wall to yield and become less stiff so that lower loads will be attracted to the system under earthquake excitation.

**Figure 3.7 – Typical Hysteretic Response and Initial and Stabilized Envelope Curves.**
The values presented in this report represent an average of the properties obtained from analysis of both the positive and negative equivalent elastic-plastic curves for each test.

3.7.2.3 Cyclic Energy Analysis

From each test, the hysteretic behavior of the wall was summarized in a plot of load vs. inter-story drift. The data from all of the initial and stabilized cycles were also extracted and used to create hysteresis loops for both initial and stabilized cycles of each test. Typical hysteretic response as well as typical initial and stabilized envelope curves can be seen in Figure 3.7. These plots for each test can be found in Appendix B. A typical individual hysteresis loop can be seen in Figure 3.8. Walls start to display this hysteretic behavior as inelastic deformations are achieved. Each of the individual hysteresis loops were analyzed to find values for cyclic stiffness, hysteretic energy, potential energy, and equivalent viscous damping ratio.

Figure 3.8 - Typical Hysteresis Loop.
Cyclic stiffness, \( k_c \), is defined as the average of the slopes for secant lines from the origin to the points of maximum positive and negative load and displacement on the hysteresis loop. This can be defined as the average slope of line OA and OB in Figure 3.8. Cyclic stiffness is a measure of the stiffness of the wall at different points in its load history. The change in cyclic stiffness provides a measure of how much the wall degrades throughout the load cycles of the test.

Hysteretic energy, \( HE \), is defined as the amount of energy dissipated by the shear wall in one displacement cycle. Energy is dissipated due to the inelastic behavior of the wall. This energy is equivalent to the area enclosed by the load-displacement curve during one displacement cycle.

Potential energy, \( PE \), is defined as strain energy present in the wall during one cycle. This is equal to the energy of the system if it were a perfect linear spring (or elastic). Potential energy is defined, for either the positive or negative half of a cycle, by one half the maximum load times the maximum displacement. This is equivalent to the sum of the areas of the triangles formed with the origin, the displacement axis, and the maximum points (points A and B) of the hysteresis loop (see Figure 3.8).

Equivalent viscous damping ratio, \( EVDR \), is a useful tool for modeling a structure's response to load. Many times it is useful to approximate damping in a structure with a viscous damper. This can be accomplished with the EVDR. The EVDR is chosen so that the total energy dissipated in the system is equal to the vibrational energy the equivalent viscous damper would dissipate. The hysteretic behavior of the structure should be found at the natural frequency to define the EVDR because this is where the structure is most affected by damping (Chopra, 1995). However, Chopra says that the equation below would still provide a good estimate for other excitation frequencies. The derivation of the equation for EVDR below can be found in Medaris and Young (1964), and is given as.

\[
EVDR = \frac{HE}{2\pi PE} \quad (6-3)
\]
3.8 Summary

The four different wall configurations tested and the materials used to construct them were discussed in this chapter. The test apparatus, testing instrumentation, and testing procedures for both monotonic and cyclic tests were presented.