CHAPTER 5

5. Cyclic Shear Wall Test Results

5.1 Introduction

Cyclic shear wall tests were performed on four wall configurations. A fifth wall configuration was tested as a variation of Wall D, the wall with tie-down anchors at the bottom of the wall. Wall E was tested with tie-down anchors at the top of the walls, but was found to behave similarly to wall configuration Wall D. In all, 11 cyclic tests were performed on 8 ft by 8 ft walls. This chapter discusses the load-deflection, equivalent elastic-plastic, cyclic, and the qualitative behaviors of the walls. Load resistance and elastic stiffness of the walls are investigated. An equivalent elastic-plastic curve analysis is used to determine the yield point and ductility of the walls. Cyclic load-deflection hysteresis is investigated to determine the cyclic stiffness and energy damping characteristics of the walls. The overall wall qualitative behavior and failure modes are also discussed.

5.2 Results

5.2.1 Envelope Curve Data

The following values were obtained from analyzing the maximum points of load and displacement for the initial and stabilized cycles of the hysteresis. Individual envelope curves can be found in Appendix B. Values obtained from analysis of each individual wall can be found in Appendix C. Values presented in this chapter represent average values from positive and negative envelope curves obtained for each wall configuration.

5.2.1.1 Strength and Deflection

Values of strength and deflection at the point of yield, failure, and maximum load resistance are presented in Table 5.1 and Table 5.2 for the initial and stabilized cycles of testing. It can be seen that the additional tie-down anchors provided in Wall E provided no significant increase in strength over Wall D. This configuration was tested in an attempt to prevent failure of the wall along the top plate as occurred in the first test of Wall D. The second test of Wall D, however, did not fail solely along the top plate (see Section 5.3.2). Deflections are greater at all points for Wall E because of problems with the test specimens. On one of the tests of Wall E, the tie-down anchors at the base were not properly tightened leading to unrealistic deflections. The other test of Wall E had a LVDT slip off the fixture causing unrealistic values for slip at the base of the wall. For this reason, the values at yield as well as the cyclic analysis of Wall E are not discussed any further than to say its strength and behavior was similar to Wall D with tie-down anchors only at the bottom of the wall.

Some variability existed between tests of similar wall configurations, mainly in the drifts experienced during each cycle. They differed slightly due to the fact that the carriage bolts being used to anchor the walls to the test frame sometimes crushed the bottom and top plates that they were mounted to, causing additional slip at the interface of the test frame and the wall. Two tests were performed for each wall unless the maximum load resistance and stiffnesses differed more than 15%. A third test was performed if a difference of 15% or more was experienced. A third test was needed only for Wall configuration A. Due to the differences in slip and the displacement-controlled nature of the test, values of displacement at maximum load resistance, failure, and yield vary slightly among each wall configuration.

In all of the walls, the load resistance of the initial cycle is greater than that of the stabilized cycle. For values of F_{max}, F_{yield}, and $F_{failure}$, the stabilized load resistance is approximately 80% of the initial load resistance. Percentages ranged from 77% to 85% of the initial cycle load resistance for the stabilized cycle. Values of maximum load resistance (capacity) ranged from 2550 lb to 6950 lb for the initial cycles and 2000 lb to 5750 lb for the stabilized cycle. Values of load resistance at failure ranged from 2400 lb to 6950 lb and 1900 lb to 5750 lb for the initial and stabilized cycles respectively. Values of load resistance at yield ranged from 2150 lb to 6600 lb and 1800 lb to 5350 lb for the initial and stabilized cycles.

Table 5.1 - Initial Cycle Values for Load Resistance, Drift, Elastic Stiffness, and Ductility at Maximum, Failure, and Yield.

Initial	Wall A	Wall B	Wall C	Wall D	Wall E
F_{max} (lb)	2550	2550	4300	6650	6950
Δ_{max} (in)	0.75	0.63	0.87	0.52	0.82
$F_{failure}$ (lb)	2500	2400	4300	6450	6950
$\Delta_{failure}$ (in)	0.85	0.72	0.87	0.60	0.86
F_{yield} (lb)	2200	2150	3600	5900	6600
Δ_{yield} (in)	0.21	0.19	0.21	0.27	0.48
k_e (lb/in)	10200	11300	17200	21900	14900
Ductility	3.8	3.8	4.0	2.2	1.9

Table 5.2 - Stabilized Cycle Values for Load Resistance, Drift, Elastic Stiffness, and Ductility at Maximum, Failure, and Yield.

Stabilized	Wall A	Wall B	Wall C	Wall D	Wall E
F_{max} (lb)	2050	2000	3500	5500	5750
Δ_{max} (in)	0.54	0.54	0.69	0.51	0.65
$F_{failure}$ (lb)	2000	1900	3500	5500	5750
$\Delta_{failure}$ (in)	0.66	0.69	0.74	0.51	0.67
F_{yield} (lb)	1750	1800	3000	4900	5350
Δ_{yield} (in)	0.18	0.17	0.18	0.22	0.41
k_e (lb/in)	10000	10800	16600	23000	14900
Ductility	3.8	4.1	4.1	2.4	1.8

As shown in Figure 5.1, no significant difference in wall capacity exists between wall configurations A and B. Load resistance at yield and failure also agree closely between these two wall configurations. Since the failure mechanism occurred at the bottom plate of these two walls and not the vertical connecting members, this would be expected. Wall C, the wall with two bottom plates, showed an increase in capacity over the walls with only one bottom plate and no tie-down anchors (Walls A and B). The capacity of the wall systems increased approximately 70% with the addition of a second bottom plate. Failure loads increased approximately 75%, and the yield loads increased approximately 60% with the addition of another bottom plate.

The highest capacity was obtained for Wall D. This is due to the tie-down anchors on Wall D preventing separation at the bottom plate, thus increasing capacity. The bottom plate was no longer the element which had to resist the overturning moment, and the tie-down anchors allowed for the overturning moment to be resisted by the end studs and 5/8 in. diameter bolts. Capacity, as well as load resistance at failure and yield, are approximately 160-170% higher for wall configuration D than for wall configurations A and B. This is the added strength provided by the addition of tie-down anchors. The capacity of wall configuration D and load resistance at failure is approximately 55% higher than that of Wall C with two bottom plates. Load resistance at yield is increased by approximately 65% when tie-down anchors are used instead of a second bottom plate.

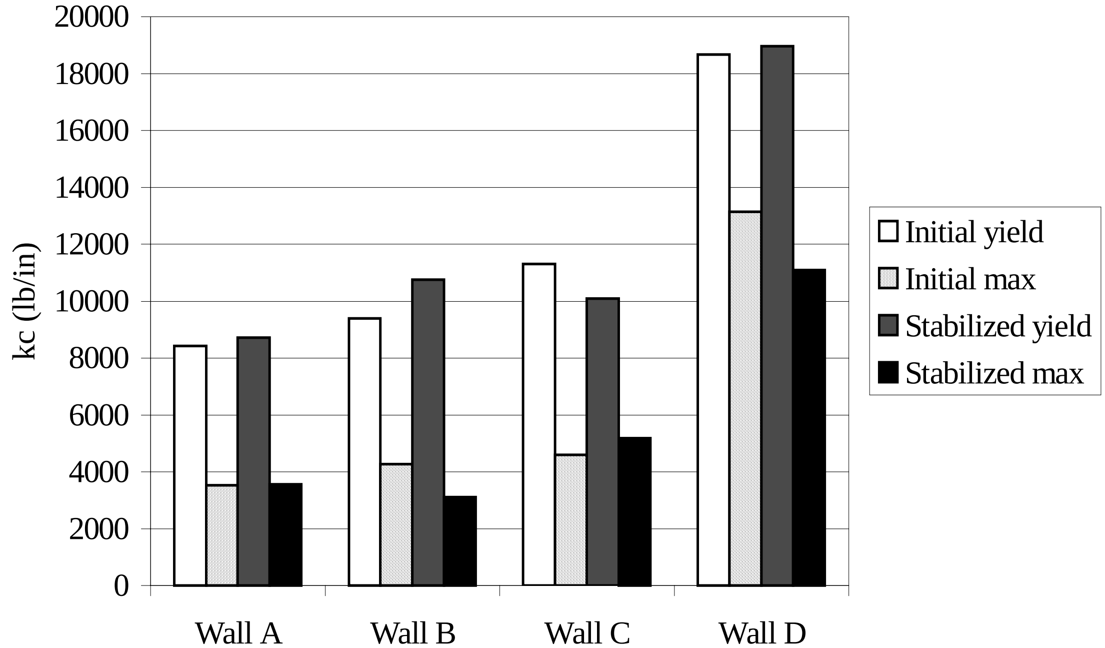


Figure 5.1 – Average Initial and Stabilized Capacities for Walls.

Values for drift at maximum load resistance, failure, and yield can be seen in Tables 5.1 and 5.2 for the initial and stabilized cycles respectively. Drifts at each of these loads are less for the stabilized cycle than for the initial cycle. This is expected because the wall will reach maximum load and failure on an initial cycle of a phase, not a stabilized one, resulting in stabilized drift equal to or less than the drift corresponding to the initial values.

Average values of drift for Wall A are greater than those for Wall B. They vary by approximately 0.1 in. As discussed previously, this may be due to the fact that the carriage bolts crushed into the wood, allowing deflections and slip to vary slightly. Values of drift at maximum load resistance, failure, and yield agree relatively well for all the wall configurations without tie-down anchors (Wall A, B, C). This implies that each of the wall configurations failed at approximately the same drift and time in the test. Wall D, however, has lower values of drift at failure than the other tests. This indicates that tie-down anchors cause the wall to fail at lower drifts due to its higher stiffness than the walls without tie-down anchors.

5.2.1.2 Elastic Stiffness

Values obtained for elastic stiffness for the initial and stabilized cycles are presented in Tables 5.1 and 5.2. As shown in Figure 5.2, there is no significant difference in elastic stiffness for the initial and stabilized cycles. All of the stabilized elastic stiffness values are within 5% of the initial elastic stiffness values. Values of stiffness are lower for the stabilized cycles of Walls A, B, and C but higher for the stabilized cycles of Wall D on average. However, these results could go either way for individual tests. This is expected because of the fact that at loads of 0.4 F_{max} or less, where k_e is defined, the initial and stabilized curves are nearly linear elastic and almost identical. Values of k_e ranged from 10,200 lb/in. to 21,900 lb/in. for the initial cycles and from 10,000 lb/in. to 23,000 lb/in. for the stabilized cycles.

As can be seen in Figure 5.2, there is no significant difference in the values of elastic stiffness between Wall A and Wall B. This confirms the earlier conclusion that in these walls, the bottom plate connections, not the vertical connecting elements, govern the behavior of the walls. The addition of a second bottom plate in Wall C increased stiffness approximately 60% from that of Walls A and B due to the addition of another row of screws and adhesive. Tie-down anchors in Wall D increased stiffness 100% over the initial stiffness of Walls A and B and 120% for the stabilized stiffness. Wall D is approximately 27% stiffer than Wall C for the initial cycles and 38% stiffer for the stabilized cycles.

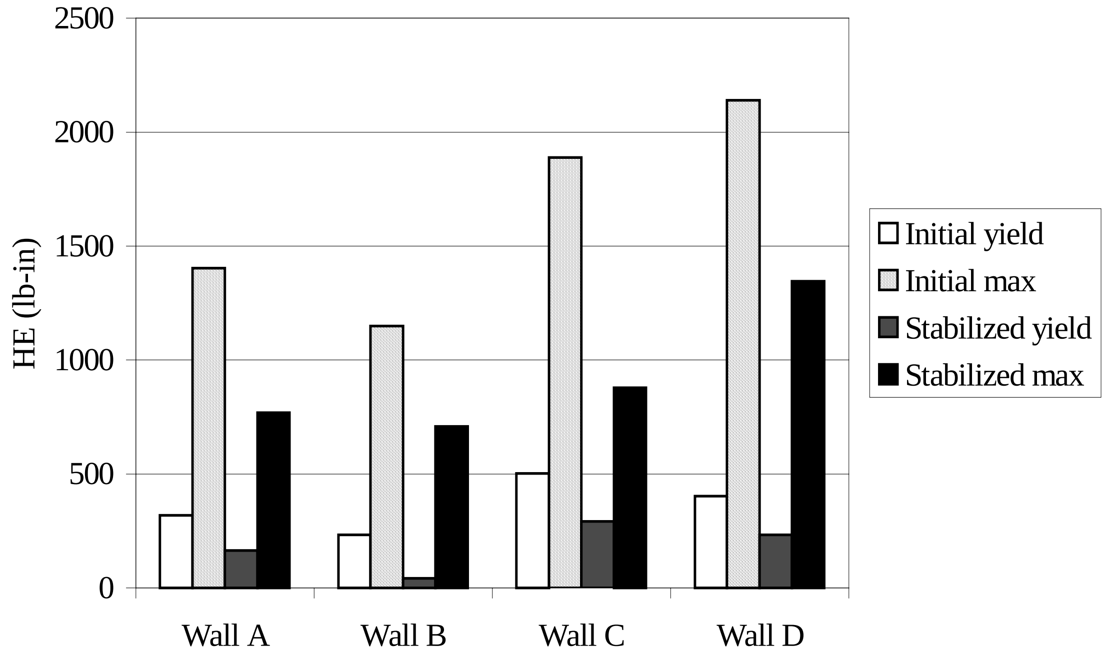


Figure 5.2 – Average Initial and Stabilized Elastic Stiffness Values for Walls.

5.2.1.3 Ductility

Values of ductility for the initial and stabilized envelope curves are presented in Tables 5.1 and 5.2. As shown in Figure 5.3, ductility ratios for the stabilized cycles were, for the most part, higher than the initial ductility ratios. In a few instances, however, ductility ratios were slightly lower for the stabilized cycles. This is due to the nature of the definition of failure. A sudden drop in load resistance could have been experienced in the stabilized cycle envelope curve on a cycle previous to the drop in load resistance in the initial cycle envelope curve. This occurred in a few cases and explains why, for Wall A, the stabilized ductility ratio is lower than the initial ductility ratio.

The only trend found between different wall configurations is that the ductility ratio of the wall with tie-down anchors (Wall D), is lower than the other walls. This indicates that the wall with tie-down anchors is a more brittle system and indicates that the tie-down anchors prevent the wall from deflecting an excessive amount before failure.

This is due to the bottom plate not deflecting as much. Ductility in itself is not a good measure of cyclic performance but must be viewed in conjuncture with other properties.

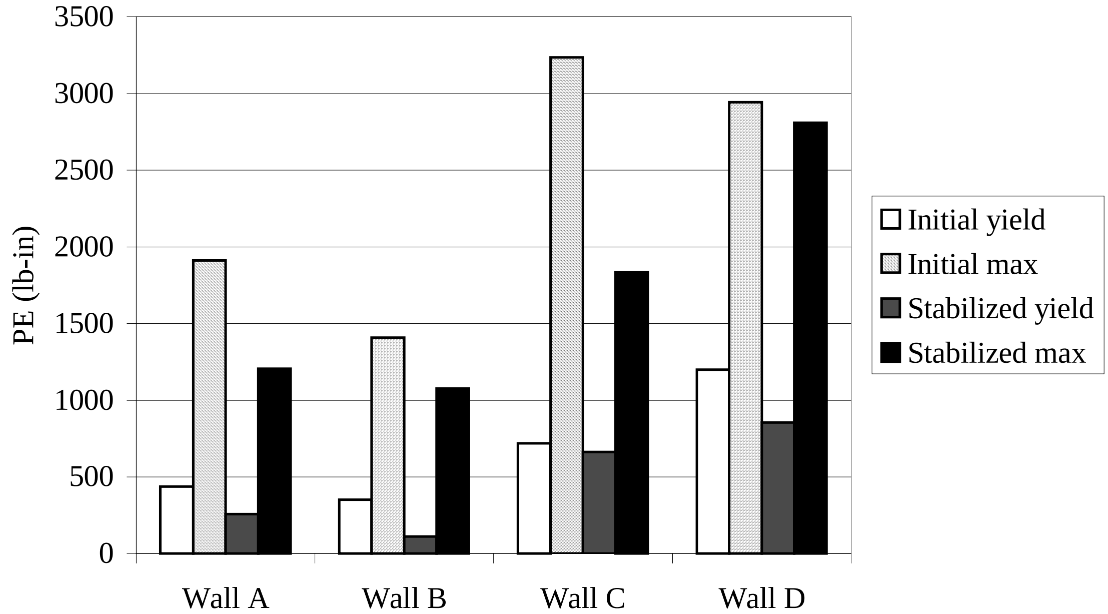


Figure 5.3 – Average Initial and Stabilized Ductility Ratios for Walls.

5.2.2 Cyclic Data

Initial and stabilized hysteresis curves were analyzed to determine properties of cyclic stiffness, hysteretic energy, potential energy, and equivalent viscous damping ratio. Results of this analysis for each cycle of both the initial and stabilized cycle of each test can be found in Appendix D. Results presented here represent average results for each configuration tested.

5.2.2.1 Cyclic Stiffness

Values of cyclic stiffness at or near yield and at or near maximum load resistance are presented in Tables 5.3 and 5.4 for the initial and stabilized cycles respectively. As shown in Figure 5.4, the cyclic stiffness at yield is higher than that at maximum load resistance. As can be shown in Figures 5.5 and 5.6, this trend follows the wall throughout testing with a high initial cyclic stiffness that degrades as more cycles are applied. There is a small difference between the initial and stabilized cycle values of cyclic stiffness. The differences between the initial and stabilized cycles follow no pattern. The values of k_c ranged from 8400 lb/in. to 18700 lb/in. at yield for the initial cycles and 8700 lb/in. to 19000 lb/in. for the stabilized cycles at or near yield. Values ranged from 3500 lb/in. to 13100 lb/in. for the initial cycles at maximum load resistance and 3600 lb/in. to 11100 lb/in. for the stabilized cycles at maximum load resistance.

As shown in Figure 5.4, cyclic stiffness does not change significantly between Walls A, B, and C. Wall C has a slightly higher cyclic stiffness than Walls A and B, as was the case with elastic stiffness. Also, consistent with elastic stiffness trends, Wall D has a much higher cyclic stiffness than the other wall configurations. Since there is no appreciable difference in the values obtained for cyclic stiffness between Walls A and B, the vertical connecting elements in a structurally insulated panel don't affect the cyclic stiffness. This is once again a function of the bottom plate. The addition of a second bottom plate to the wall does not increase the stiffness of the wall nearly as much as the addition of tie-down anchors.

Table 5.3 - Initial Values of Load Resistance, Cyclic Stiffness, Hysteretic Energy, Potential Energy, and Equivalent Viscous Damping Ratio at Yield and Max.

Initial	Wall A	Wall B	Wall C	Wall D
Δ_{yield} (in.)	0.24	0.20	0.21	0.27
k_c (lb/in.)	8400	9400	11300	18700
HE (lb-in.)	319	233	503	403
PE (lb-in.)	438	352	718	1200
EVDR at yield	0.11	0.09	0.11	0.05
Δ_{max} (in.)	0.75	0.63	0.88	0.52
k_c (lb/in.)	3500	4300	4600	13100
HE (lb-in.)	1400	1150	3240	2140
PE (lb-in.)	1910	1410	3240	2940
EVDR at max	0.11	0.13	0.09	0.10

Table 5.4 - Stabilized Values of Load Resistance, Cyclic Stiffness, Hysteretic Energy, Potential Energy, and equivalent Viscous Damping Ratio at Yield and Max.

Stabilized	Wall A	Wall B	Wall C	Wall D
Δ_{yield} (in.)	0.18	0.17	0.18	0.22
k_c (lb/in.)	8700	10800	10100	19000
HE (lb-in.)	165	43	291	234
PE (lb-in.)	258	111	664	854
EVDR at yield	0.09	0.06	0.07	0.04
Δ_{max} (in.)	0.54	0.54	0.69	0.51
k_c (lb/in.)	3600	3100	5200	11100
HE (lb-in.)	770	708	878	1350
PE (lb-in.)	1210	1080	1830	2810
EVDR at max	0.10	0.11	0.08	0.07

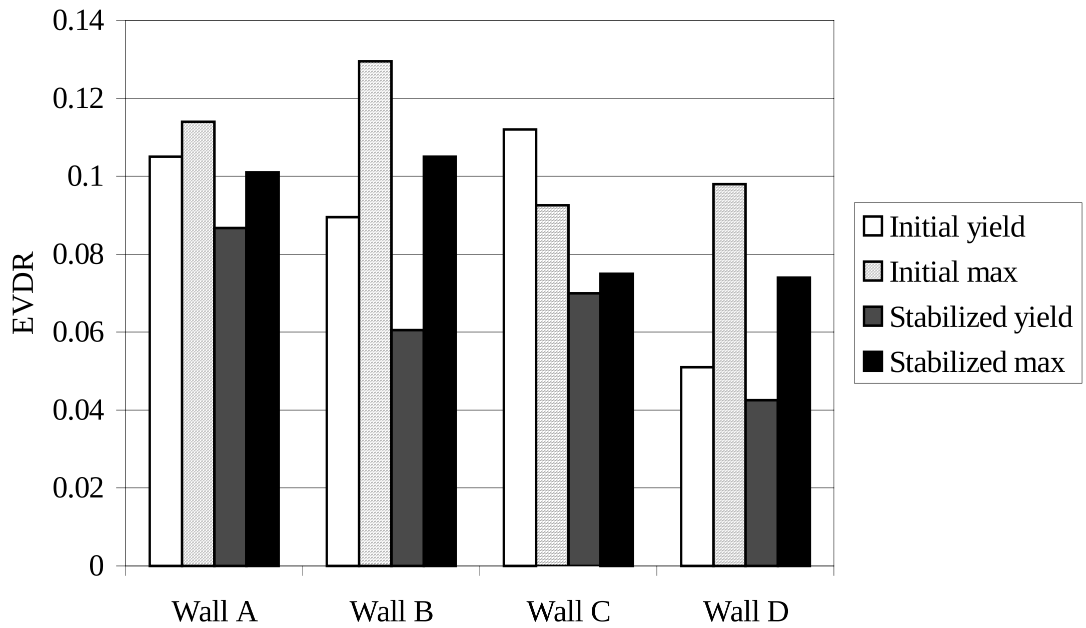
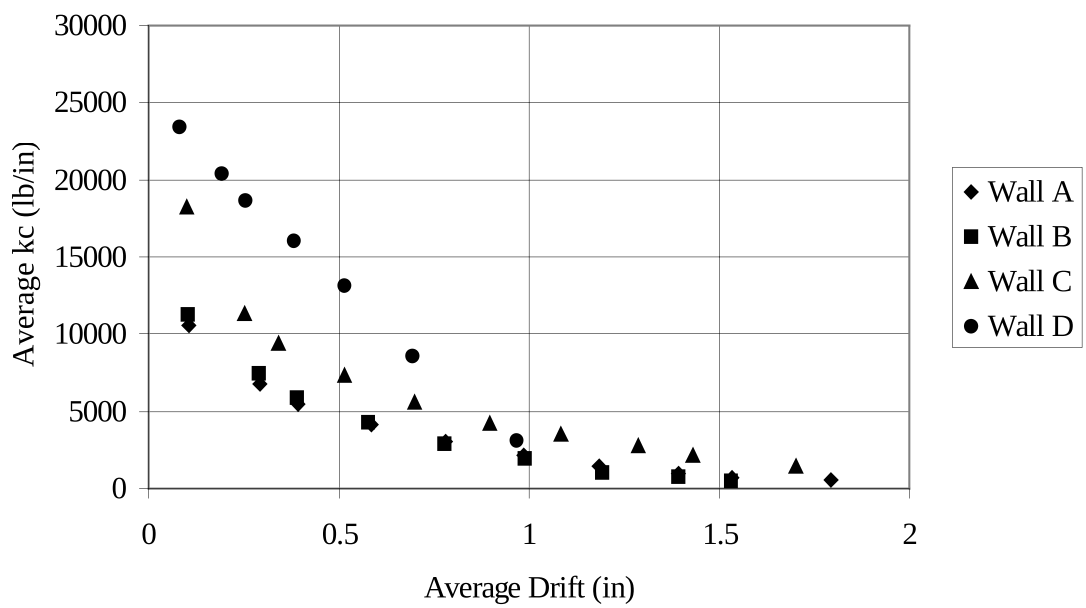


Figure 5.4 – Average Initial and Stabilized Cyclic Stiffness Values at Yield and



Maximum Load Resistance for Walls.

Figure 5.5 – Average Initial Cyclic Stiffness at Average Interstory Drifts for the Four Wall Configurations.

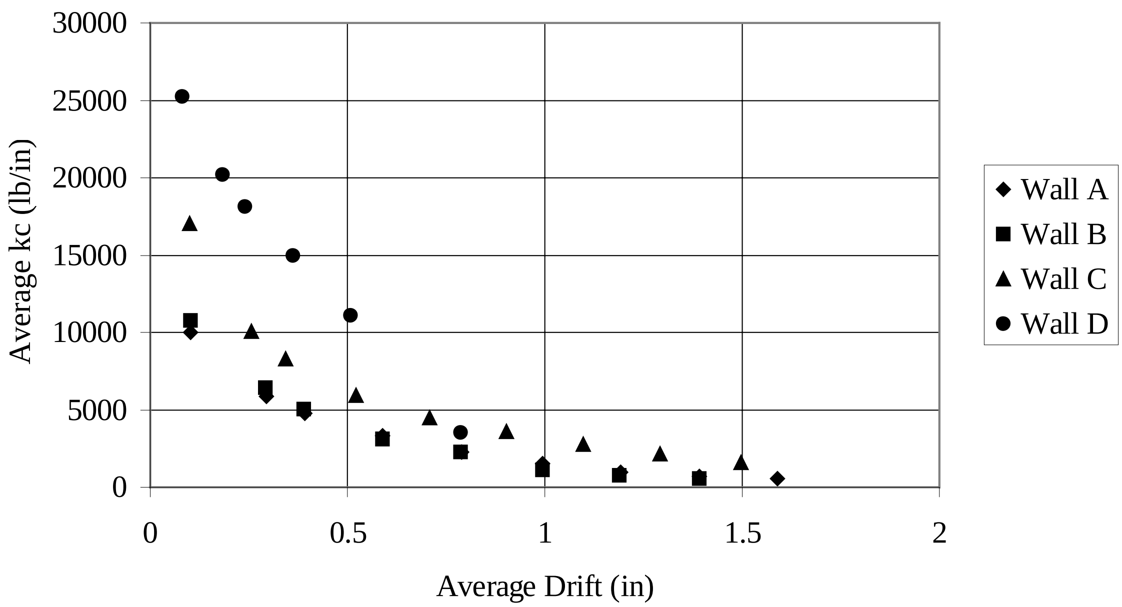


Figure 5.6 – Average Stabilized Cyclic Stiffness At Average Interstory Drifts for the Four Wall Configurations.

5.2.2.2 Hysteretic Energy

The values obtained for hysteretic energy at or near yield and at or near maximum load resistance are presented in Tables 5.3 and 5.4 for the initial and stabilized cycles. As shown in Figure 5.7, there is a significant drop in the hysteretic energy between the initial and the stabilized cycles. At yield and maximum load resistance, a drop in hysteretic energy of 40% or more occurred between the initial and stabilized cycles. This is also evident in the shapes of the initial and stabilized hysteresis loops shown in Appendix B. Stabilized hysteresis loops are much more pinched and tight, so the area enclosed by the hysteresis loops is smaller resulting in lower values of HE. As shown in Figures 5.8 and 5.9, HE increases as more cycles are applied. Values of HE range from 233 lb-in. to 503 lb-in. for the initial cycle at yield and from 43 lb-in. to 291 lb-in. for the stabilized cycle at yield. The values of HE ranged from 1150 lb-in. to 2140 lb-in. for the initial cycle and 708 lb-in. to 1350 lb-in. for the stabilized cycle at maximum load resistance.

There is a small difference between the two walls (Wall A and B) which have different vertical connecting elements. This difference, however, is not significant; therefore, the two systems can be considered to have the same hysteretic damping characteristics. As shown in Figure 5.7, Walls C and D have higher values of HE at yield and maximum load resistance than do Walls A and B. Wall D, with tie-down anchors, exhibited the highest stabilized values of hysteretic energy. The addition of tie-down anchors or a second bottom plate improves the system's ability to dissipate energy. Addition of tie-down anchors, however, will improve the energy dissipation ability of structurally insulated panel wall system the most effectively for cyclic loading.

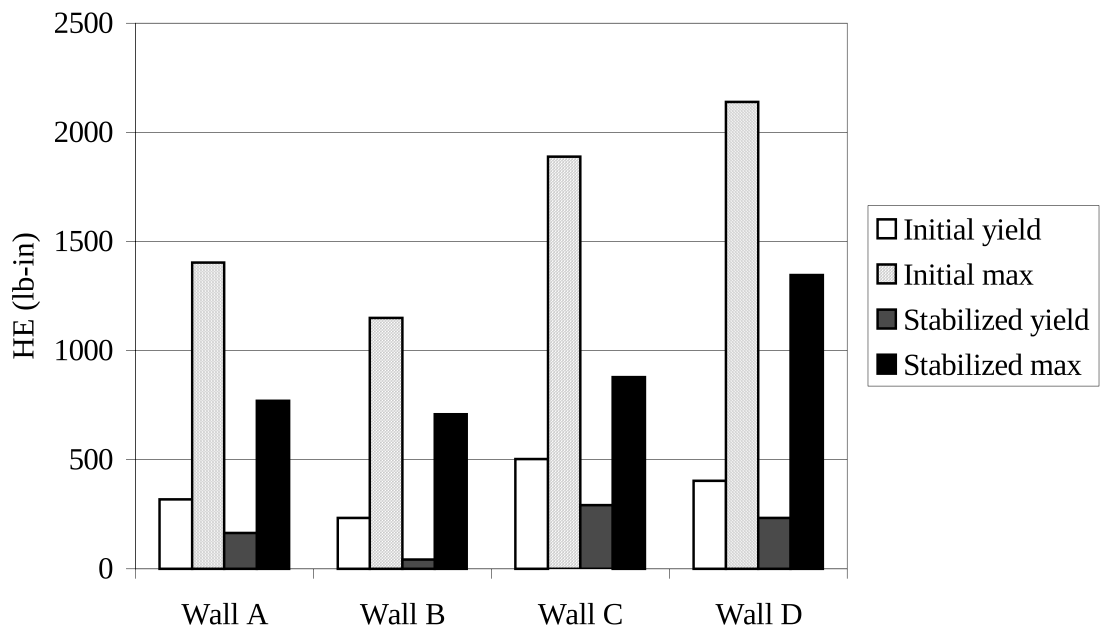


Figure 5.7 – Average Initial and Stabilized Hysteretic Energy Values at Yield and Maximum Load Resistance for Walls.

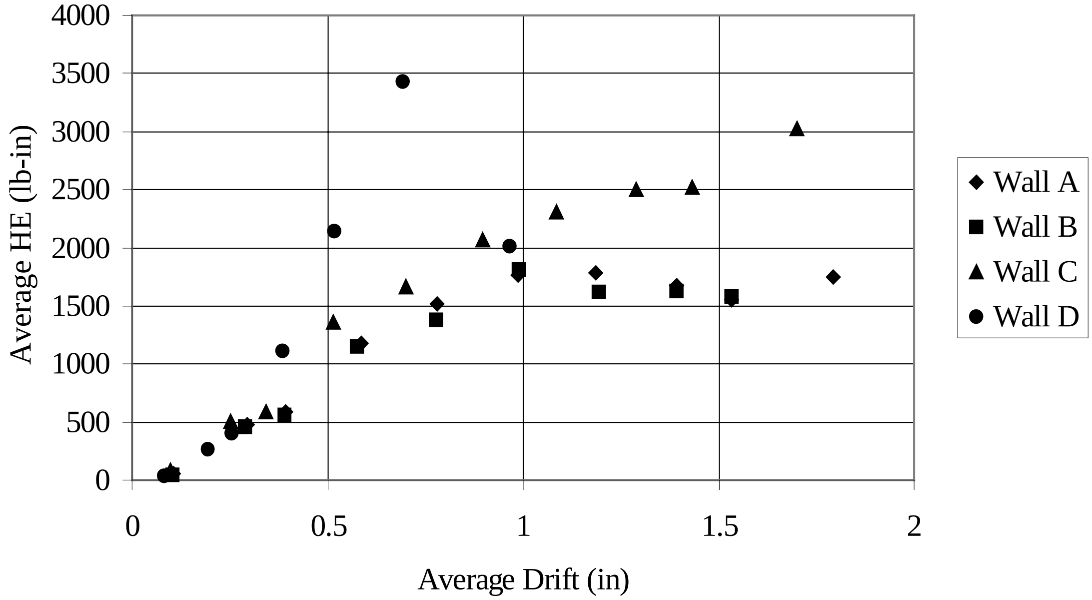


Figure 5.8 – Average Initial Hysteretic Energies at Average Interstory Drift for the Four Wall Configurations.

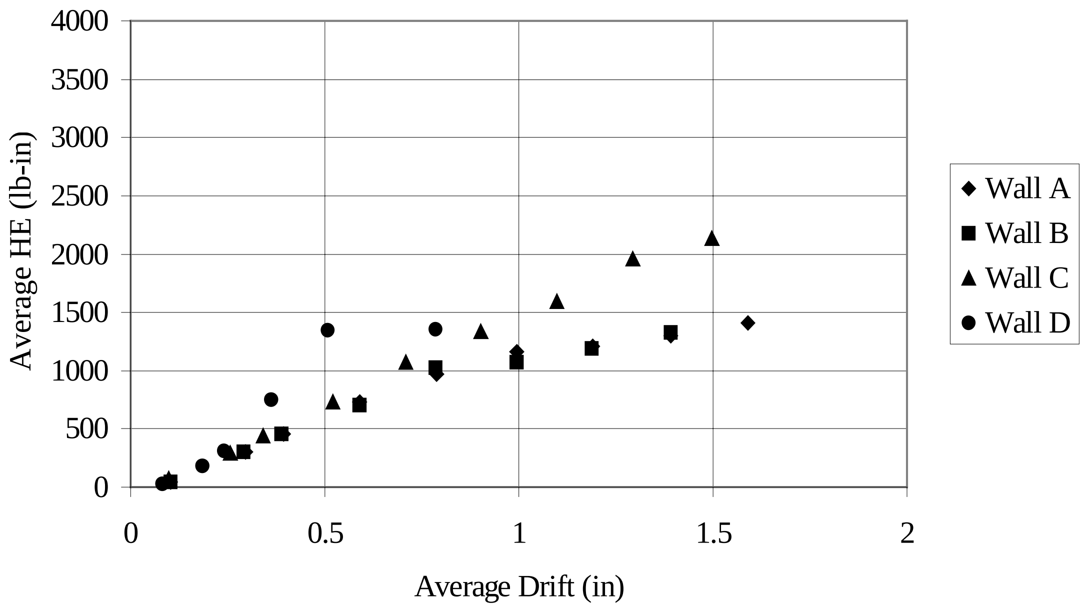


Figure 5.9 – Average Stabilized Hysteretic Energies at Average Interstory Drift for the Four Wall Configurations.

5.2.2.3 Potential Energy

Values obtained for potential energy at or near yield and at or near maximum load are presented in Tables 5.3 and 5.4 for the initial and stabilized cycles respectively. As shown in Figure 5.10, a drop in PE from the initial to the stabilized cycle was observed. This drop, however, is not as pronounced as it was with HE. This drop in potential energy can be explained by the fact that for the stabilized cycles, the same drift is experienced with a lower load resistance. Values of PE range from 352 lb-in. to 1200 lb-in. for the initial cycle at yield and from 111 lb-in. to 854 lb-in. for the stabilized cycle at yield. Values of PE ranged from 1410 lb-in. to 2940 lb-in. for the initial cycle and 1080 lb-in. to 2810 lb-in. for the stabilized cycle at maximum load resistance.

Potential energies for Walls A and B are relatively close. The PE values for Wall A are slightly higher due to one high value of PE for an individual test. This was the first test specimen to be tested and the slip at the top of the wall was not measured. This would result in the drifts to be overestimated, resulting in the values of potential energy to be slightly higher. The initial maximum PE of Wall C is larger than that of Wall D for the same reason. The carriage bolts crushed excessively into the bottom plate of Wall CC-2, causing the wall to reach maximum load at a larger drift than the other wall of the same configuration. Since PE increases with drift until a few cycles after failure, Wall C would exhibit higher values of PE than Wall D, though this may not be expected. For the most part, the trends of PE follow those of HE.

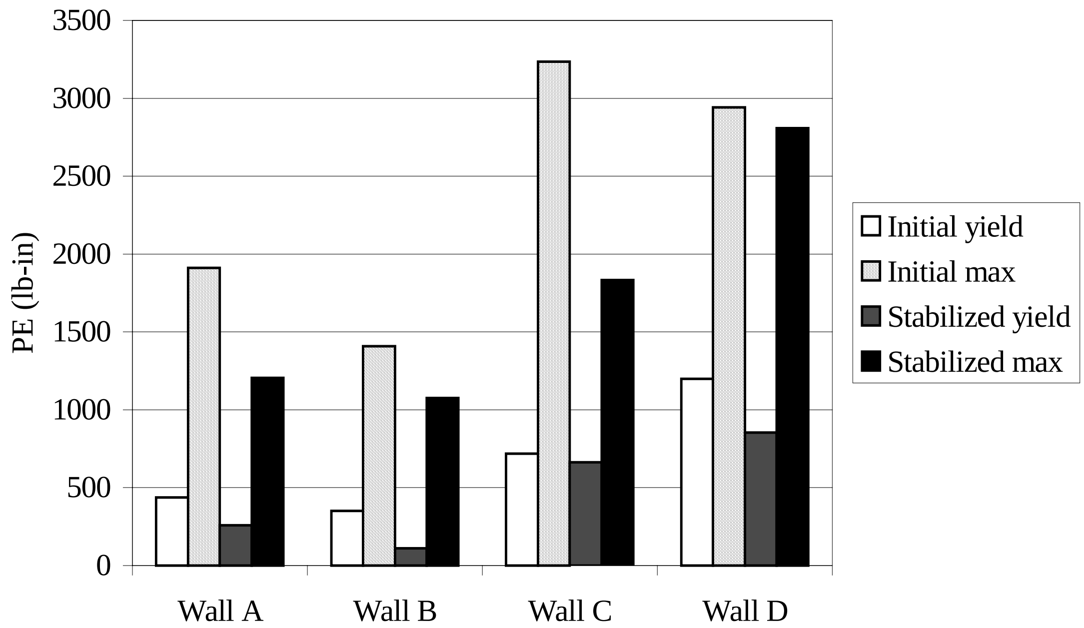


Figure 5.10 – Average Initial and Stabilized Potential Energy Values at Yield and Maximum Load Resistance for Walls.

5.2.2.4 Equivalent Viscous Damping Ratio

Values of EVDR at or near yield and maximum load resistance are presented in Tables 5.3 and 5.4 for the initial and stabilized cycles of each wall configuration. As shown in Figure 5.11, most specimens followed the trend of initial EVDR values being higher than stabilized EVDR values and EVDR values at max being higher than EVDR values at yield. As shown in Figures 5.12 and 5.13, the EVDR follows a trend of increasing as the number of loading cycles the wall experiences increases. Walls C and D have lower values of EVDR than do Walls A and B. This difference, however, is small.

Wall D is the only wall that exhibited a significantly different EVDR. Even though more energy was dissipated by Wall D, it did so with tighter hysteresis loops at greater loads near the beginning of the displacement history. As shown in Figures 5.12 and 5.13, as the amount of loading cycles the wall experienced increased, Wall D began to behave more like Walls A, B, and C. Wall C experiences lower EVDR values than the rest of the walls at higher values of drift (more cycles). Values of potential energy, PE, were high for Wall C (as discussed in the Section 5.3.2.3) which would reduce the EVDR. It should also be noted that the derivation of the EVDR equation assumes that the structure is elastic, which is not the case at higher values of drift.

EVDR can be used for modeling purposes. From this limited amount of data, only an estimate can be made for values to use in models. It is assumed in the derivation of EVDR that the wall acts linearly or is within the elastic range. Values for EVDR at maximum load resistance should be viewed with this in mind. Values at yield are a better indication of the elastic behavior of the wall. This is the point at which the wall would still be assumed to be behaving elastically and would provide useful values of the EVDR. The EVDR for walls without tie-down anchors (Walls A, B, C) can be estimated to be 0.1 for the initial behavior and 0.07 for the stabilized behavior. For walls with tie-down anchors (Wall D), the EVDR can be estimated to be 0.05 for the initial behavior and 0.04 for stabilized behavior. More accurate estimates of the EVDR could be found with forced vibration tests performed on the walls near their natural frequencies.

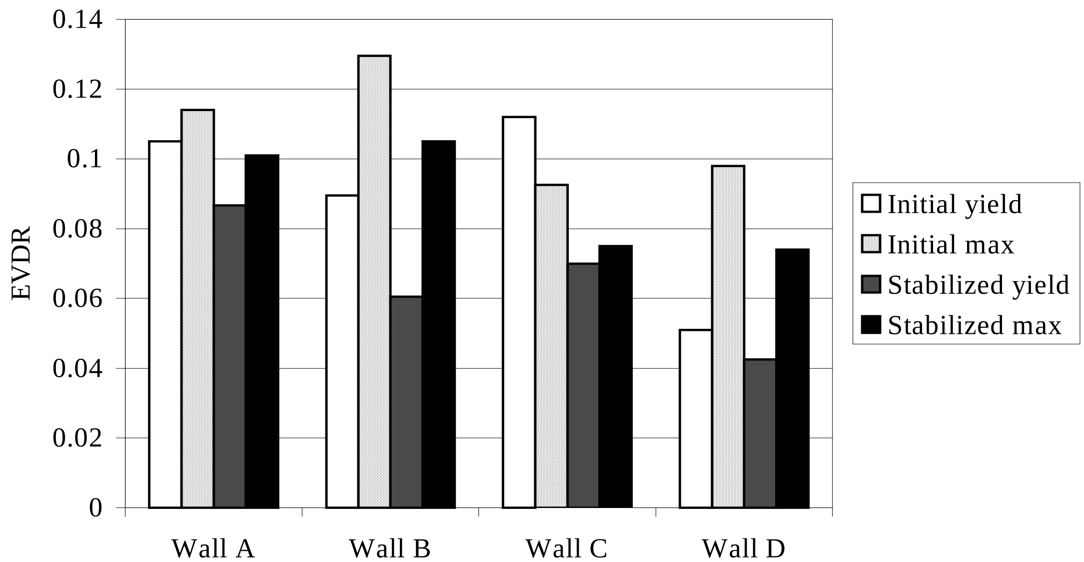


Figure 5.11 – Average Initial and Stabilized Equivalent Viscous Damping Ratios at Yield and Maximum Load Resistance for Walls.

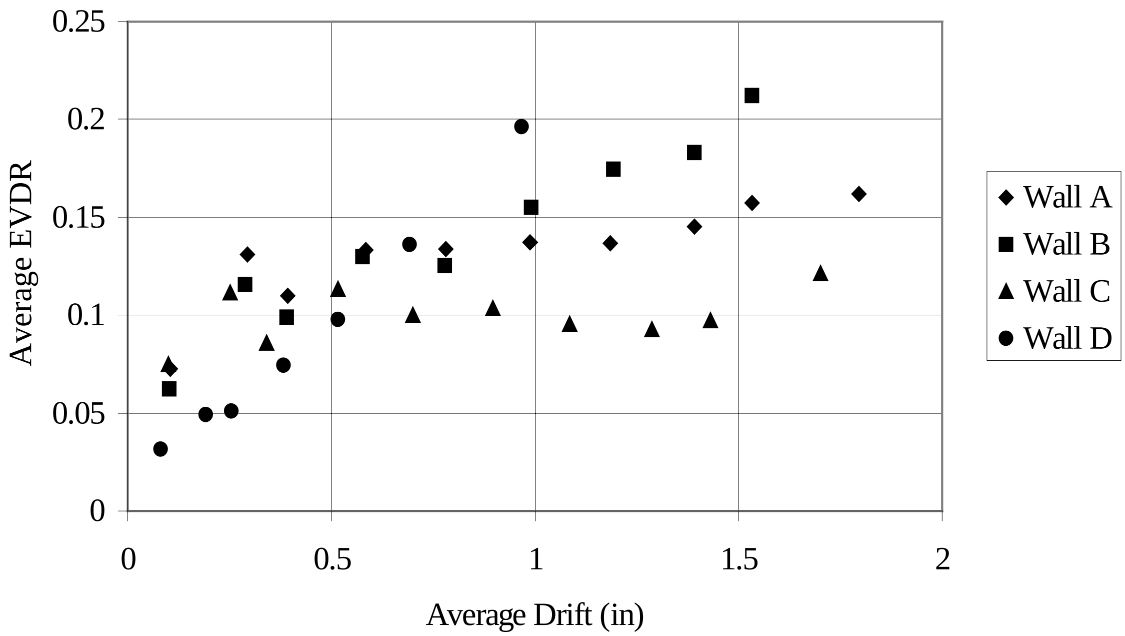


Figure 5.12 – Average Equivalent Viscous Damping Ratio at Average Interstory Drifts for the Four Wall Configurations.

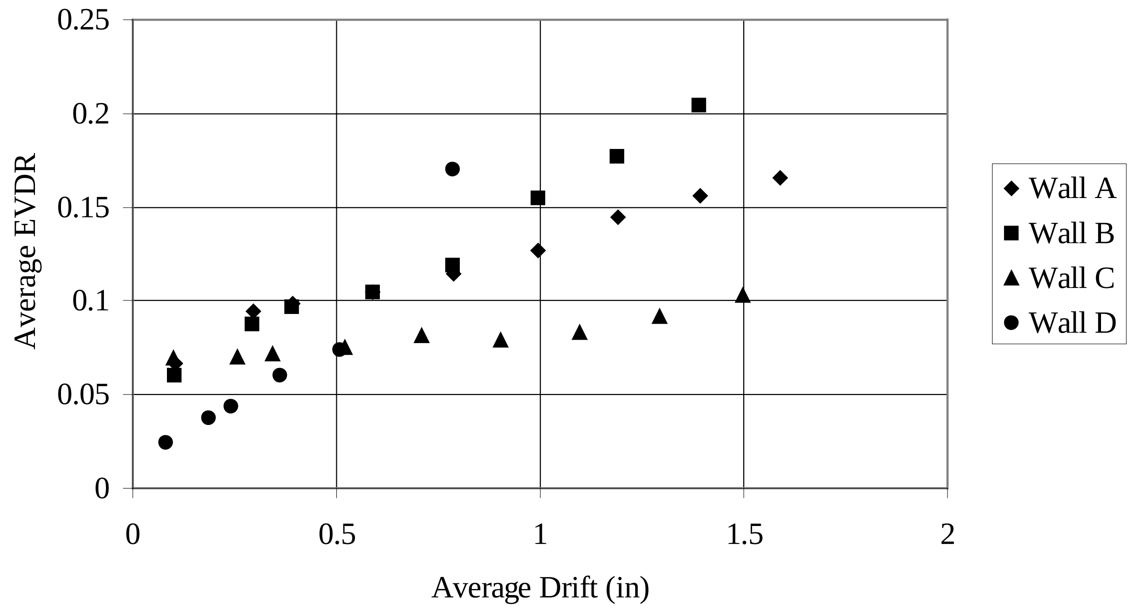


Figure 5.13 – Average Stabilized Equivalent Viscous Damping Ratio At Average Interstory Drifts for the Four Wall Configurations.

5.3 Wall Behavior

During each test, with the exception of Wall AC-1, the slip at the bottom and top of the wall relative to the test frame and the uplift of the ends of each wall were monitored. Wall AC-1 did not have an LVDT to monitor the slip of the top plate relative to the test frame. Values of slip were used to determine correct values of drift for each test. Values of wall ends uplift and wall failure modes are discussed in this section.

5.3.1 Uplift of Wall Ends

Uplift of the ends of the walls was measured with two LVDT's as discussed in Chapter 3. For discussion purposes, the right side of the wall is defined as the side of the wall that was attached to the hydraulic actuator and the left, the opposite. Average maximum values of uplift experienced before failure of the walls are presented in Table 5.5. A negative number indicates that the end of the wall was crushing into the bottom plate of the wall. A positive number indicates that the end of the wall was lifting away from the bottom plate or the test frame. It was noticed that initial positive uplift was characterized by bending of the base plate at the ends, separating from the rigid steel tube frame until an initial failure of the drywall screw connection at the corner of the wall. After this initial failure, uplift consisted of the wall separating from the base plate.

It should be noted that some values of uplift are significant. This is due to the walls having already experienced localized failures at the corners of the walls before failure of the entire wall or before the maximum load resistance is reached. Positive values of uplift, indicating separation of the wall from the base, are larger than the negative values indicating crushing. Also all uplift values are smaller for Wall D due to the presence of tie-down anchors.

Table 5.5 - Maximum Wall End Displacements Through Failure of Wall.

	Wall A	Wall B	Wall C	Wall D
Δ_{right} uplift (in)	0.62	0.55	0.76	0.17
Δ_{right} crushing (in)	-0.19	-0.24	-0.31	-0.10
Δ_{left} uplift (in)	0.78	0.49	1.00	0.33
Δ_{left} crushing (in)	-0.30	-0.26	-0.30	-0.15

5.3.2 Failure Modes

Failure of Walls A, B, and C occurred at the bottom plate of the wall. The wall appeared to rock under rigid body rotation about the base of the wall. For this reason, failure started at either side of the ends of the bottom plate. Drywall screws were specified by the manufacturer of the panels and are very brittle. Drywall screws failed in shear along the bottom plate/OSB interface and either ripped through the Fiberboard or failed in shear along the bottom plate/Fiberboard interface on the other side of the panel. This occurred in every wall that did not have tie-down anchorage. A break in the Fiberboard panel was also present in two of the tests in which the Fiberboard failed in tension along the four foot length of a single panel, along the bottom plate, with the small strip of Fiberboard left screwed to the bottom plate.

Addition of tie-down anchors moved the failure mechanism away from the bottom plate as well as changed the behavior of the wall. The wall appeared to perform in more of a racking fashion than a rigid body rotation when anchors were used. For Wall D, failure was experienced in the middle vertical connecting element and top plate. The top plate separated from the wall in a manner similar to the bottom plate for the other testing configurations. For one of the two tests of this configuration, the vertical connection at the center of the wall experienced some screws tearing through the Fiberboard and failing in shear. The ultimate failure mechanism in both of the Wall D specimens occurred when the top plate separated from the wall.

5.4 Conclusions

The following conclusions can be drawn from the cyclic data presented.

- Vertical connecting elements between panels and on panel ends have no significant effect on the performance of structurally insulated panels if the same spacing of screws is used. The bottom plate connection of the wall is critical to performance.
- Addition of a second bottom plate to a structurally insulated panel wall system can significantly increase the capacity of the wall system. Addition of a second base plate also creates a stiffer wall system that can dissipate slightly more energy than a wall system with one bottom plate.
- Addition of tie-down anchors to a structurally insulated panel wall system will greatly increase the capacity as well as stiffness and energy dissipation capability. This would be the best option for a wall being built in a seismic or high wind area.
- The predominant mode of failure in structurally insulated panel wall systems occurs at the bottom plate. The addition of a second base plate will not move the failure mechanism away from the bottom but the addition of tie-down anchors will.

5.5 Summary

The load-deflection behavior of four different wall configurations of structurally insulated panels tested under cyclic, quasi-static loading was discussed in this chapter. Different parameters were defined and values were presented for load resistance and drift at yield, maximum load resistance and failure, elastic stiffness, ductility ratio, cyclic stiffness, hysteretic energy, potential energy, and equivalent viscous damping ratio. Qualitative behavior of the walls and comparisons of the four different wall configurations against each other have been presented.