Chapter 6 Monotonic and Cyclic Comparisons

6.1 Introduction

Chapters Four and Five have dealt with the monotonic and cyclic data on an individual basis. The purpose of this chapter is to draw comparisons between the wall behavior under the two loading conditions so inferences can be made of cyclic performance based on monotonic performance.

Due to time and cost, only one test of each wall configuration and load pattern could be done. Even though all materials were of the same grade, variability of material properties will cause no two walls of the same configuration and materials to have identical performance. However, when one considers that wall performance is principally governed by the sheathing nails, and that there is a high number of nails per wall, the average response can be expected from this size of specimen. From a large number of tests of one configuration and loading pattern, the long term average and variability could be found. With this knowledge true inferences can be found.

6.2 Parameters

6.2.1 Strength

This section refers to monotonic data presented in Section 4.3.1 and cyclic data presented in Section 5.4.1.

Capacity of monotonic and cyclic tests are presented in Table 6.1 and illustrated against sheathing area ratio in Figure 6.1. The best fit third order equation of monotonic capacity as a function of sheathing area ratio for the wall configurations examined in this thesis is:

$$F_{max} = 33.476 \cdot r - 37.061 \cdot r^2 + 42.483 \cdot r^3 \tag{4.2}$$

The best fit equation for initial cycle capacity is:

$$F_{max} = 29.458 \cdot r - 23.090 \cdot r^2 + 25.633 \cdot r^3 \tag{5.3}$$

The best fit equation for stabilized cycle capacity is:

$$F_{max} = 26.543 \cdot r - 22.932 \cdot r^2 + 23.889 \cdot r^3 \tag{5.4}$$

where F_{max} is capacity and r is sheathing area ratio.

As discussed in Chapter One, it is desirable to be able to determine cyclic capacity based on monotonic capacity. The ratios of initial to monotonic capacity and stabilized to monotonic capacity are presented in Table 6.1 and illustrated in Figure 6.2. The ratio of initial to monotonic capacity ranged from 82% to 99% with Wall A having the lowest relative capacity and Wall C having the highest. The ratio of stabilized to monotonic capacity ranged from 71% to 86% with Wall A having the lowest relative capacity and Wall C having the highest.

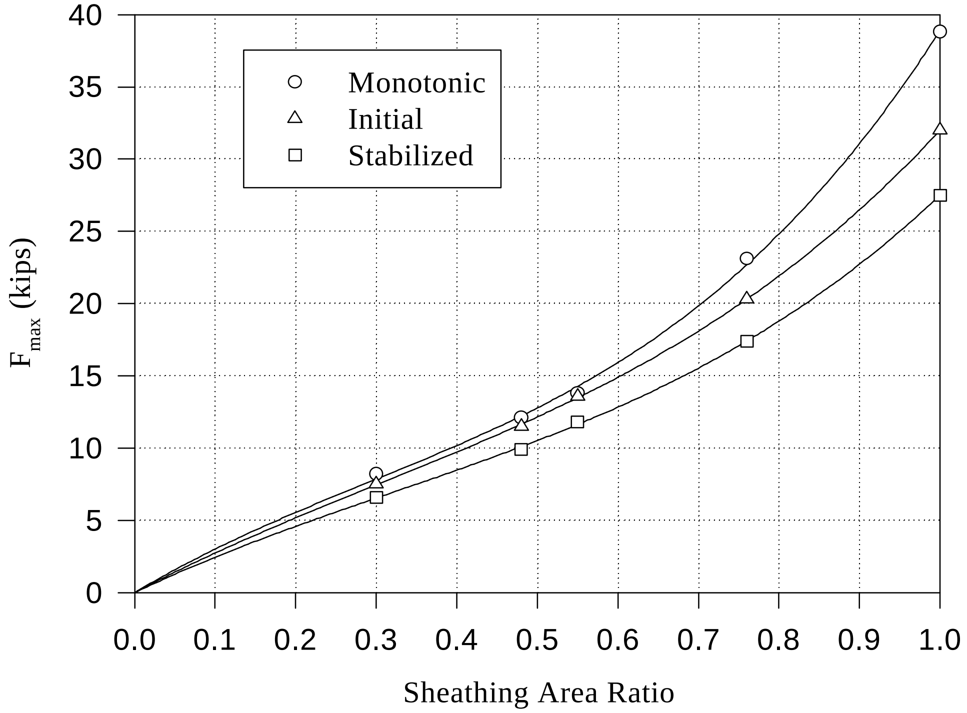

Figure 6. 1- Monotonic and cyclic capacity of the five shear wall configurations examined plotted against sheathing area ratio

The two walls with the least amount of openings (Walls A and B) had the largest percent degrade between the cyclic and monotonic capacity. Both walls had initial to monotonic capacity ratios under 90%. Walls C, D, and E, which contained large openings, all had initial to monotonic capacity ratios greater than 90%. There tends to be less difference between monotonic and cyclic capacity for shear walls with large openings (less stiffness). Based on the limited data determined in this thesis, no direct correlation between cyclic capacity relative to monotonic capacity and sheathing area ratio was found.

6.2.2 Yield Load

The ratios of initial to monotonic F_{yield} and stabilized to monotonic F_{yield} are given in Table 6.1 and illustrated in Figure 6.3. The ratio of initial to monotonic F_{yield} ranged from 90% to 115% with Wall A having the lowest relative capacity and Wall C having the highest. The ratio of stabilized to monotonic F_{yield} ranged from 77% to 100% with Wall A having the lowest relative capacity and Wall C having the highest. Initially, it seems illogical that monotonic F_{yield} would be higher than cyclic F_{yield}. However, differences in the shapes of the monotonic load displacement and cyclic load-envelope curves, such as the magnitude of $\Delta_{failure}$ and the rate of load degredation after capacity

Table 6. 1: Comparison of monotonic and cyclic parameters of the five shear wall configurations examined

	Wall A r = 1.0	Wall B r = 0.76	Wall C r = 0.55	Wall D r = 0.48	Wall E r = 0.30
Capacity:					
Monotonic (kips)	38.8	23.1	13.8	12.1	8.2
Initial Cyclic (kips)	32.0	20.3	13.6	11.5	7.5
Stabilized Cyclic (kips)	27.5	17.4	11.8	9.9	6.6
Initial / Monotonic	0.82	0.88	0.99	0.95	0.91
Stabilized / Monotonic	0.71	0.75	0.86	0.82	0.80
F_{yield}:					
Monotonic (kips)	35.6	20.9	11.8	10.6	7.5
Initial Cyclic (kips)	29.9	18.4	12.4	10.4	6.8
Stabilized Cyclic (kips)	25.9	15.6	10.7	8.8	5.8
Initial / Monotonic	0.84	0.88	1.05	0.98	0.91
Stabilized / Monotonic	0.73	0.75	0.91	0.83	0.77
Mono. F_{yield} / Mono. F_{max}	0.92	0.90	0.86	0.88	0.91
Initial F_{yield} / Initial F_{max}	0.93	0.91	0.92	0.90	0.91
Stab. F_{yield} / Stab. F_{max}	0.94	0.90	0.91	0.89	0.88
$F_{failure}$:					
Monotonic (kips)	31.0	18.7	8.6	7.9	6.6
Initial Cyclic (kips)	29.1	17.6	12.2	9.8	6.6
Stabilized Cyclic (kips)	23.6	14.1	9.8	5.7	4.7
Initial / Monotonic $F_{failure}$	0.94	0.94	1.42	1.24	1.00
Stab. / Monotonic $F_{failure}$	0.76	0.75	1.14	0.72	0.71
Mono. $F_{failure}$ / Mono F_{max}	0.80	0.81	0.62	0.65	0.80
Initial $F_{failure}$ / Initial F_{max}	0.91	0.87	0.90	0.85	0.80
Stab. $F_{failure}$ / Stab. F_{max}	0.86	0.81	0.83	0.58	0.71

has been reached, result in F_{yield} being a lower percentage of capacity for monotonic tests than cyclic tests for Walls A - D. For Walls C and D, which had the highest percentage of initial to cyclic capacity, F_{yield} of the initial cycle was higher than monotonic. Wall E had identical monotonic and initial cyclic F_{yield}. F_{yield} / F_{max} values for monotonic and cyclic tests are given in Table 6.1.

If the yield load for the three conditions is compared to the capacity for the same conditions, the yield load is approcimately a constant percentage of the capacity. As shown is Figure 6.1, the ratio of F_{yield} / F_{max} for each of the conditions ranges from 0.86 to 0.94 with an average of 0.90.

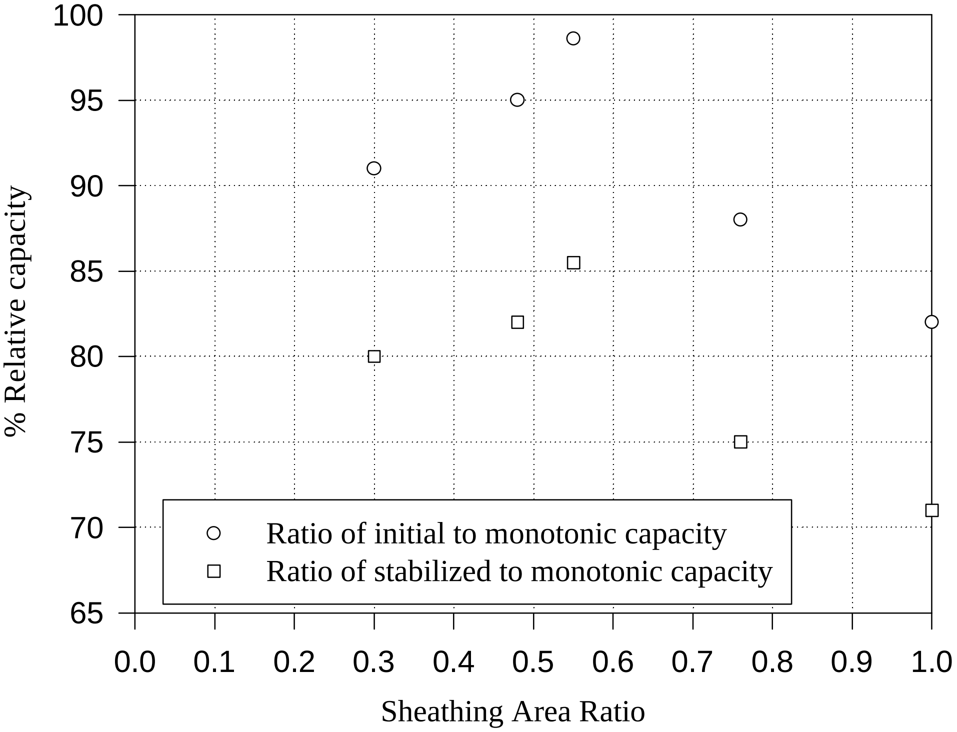

Figure 6. 2- Ratio of cyclic to monotonic capacity of the five shear wall configurations examined plotted against sheathing area ratio

6.2.3 Load at Failure

Monotonic and cyclic load at failure is compared in Table 6.1. Walls with less stiffness tend to have higher drifts at failure when monotonically loaded, and as a result the load resistance at failure is a smaller percentage of capacity. Drift at failure for cyclically tested walls occurred closer to drift at capacity than monotonically tested walls, resulting in load resistance at failure to be a higher percentage of capacity than monotonically tested walls. Walls A and B were the only monotonic shear wall tests with a catastrophic drop in load resistance at failure. Only Walls A and B had initial to monotonic $F_{failure}$ ratios less than 1.0. For the monotonic tests of Walls C - E, load resistance slowly decreased after capacity was reached and the ratio of initial to monotonic load resistance at failure ranges from 1.0 to 1.42. Only Wall C had a stabilized to monotonic $F_{failure}$ ratio greater than 1.0. The ratio of stabilized to monotonic $F_{failure}$ ranged from 0.71 to 1.14 for the five walls.

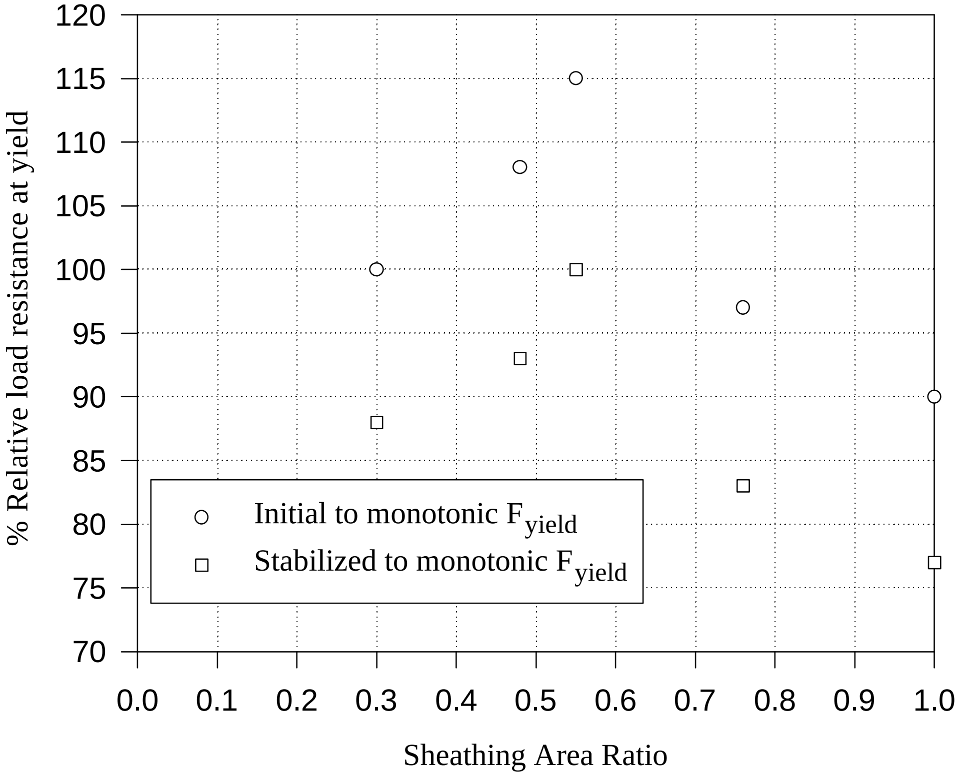

Figure 6. 3- Ratio of cyclic to monotonic load resistance at yield of five wall configurations examined plotted against sheathing area ratio

6.2.4 Drift Comparison

Table 6.2 presents monotonic and cyclic drifts at yield, capacity and failure. Also included in Table 6.2 are the ratios of cyclic to monotonic drift.

At capacity, the ratio of initial to monotonic drift ranged from 0.43 to 0.84. The ratio of stabilized to monotonic drift at capacity ranged from 0.43 to 0.97. In both cases, Wall E had the lowest relative drift and Wall D had the highest. Figure 6. 4 is a bar chart of monotonic, initial and stabilized drift at capacity. Peak load is usually sustained for several phases and depending on which phase maximum load resistance was obtained, differences between initial and stabilized drift at capacity occurred. Figure 6. 4 shows driftat capacity occurred at higher interstory drifts for monotonic tests than cyclic tests in all cases. This difference between monotonic and cyclic performance is due to the difference in failure modes. Monotonic failures were characterized by nail withdrawal and pull through, while cyclic failures were characterized by nail fatigue. Wall D (r = 0.48) had the least difference between monotonic and cyclic drift at capacity.

Table 6. 2- Comparison of monotonic and cyclic drifts at yield, capacity, and failure of the five shear wall configurations examined

	Wall A r = 1.0	Wall B r = 0.76	Wall C r = 0.55	Wall D r = 0.48	Wall E r = 0.30
Δ_{yield}:					
Monotonic (in)	0.56	0.48	0.55	0.57	0.98
Initial Cyclic (in)	0.43	0.47	0.62	0.58	0.37
Stabilized Cyclic (in)	0.37	0.38	0.53	0.49	0.32
Initial / Monotonic	0.77	0.98	1.13	1.02	0.38
Stabilized / Monotonic	0.66	0.79	0.96	0.86	0.33
Δ_{max}:					
Monotonic (in)	2.0	2.2	1.9	1.6	2.7
Initial Cyclic (in)	1.13	1.18	1.38	1.35	1.15
Stabilized Cyclic (in)	1.12	1.19	1.37	1.55	1.15
Initial / Monotonic	0.57	0.54	0.73	0.84	0.43
Stabilized / Monotonic	0.56	0.54	0.72	0.97	0.43
$\Delta_{failure}$:					
Monotonic (in)	4.14	4.18	4.00	5.04	5.05
Initial Cyclic (in)	1.93	2.0	2.19	1.94	1.97
Stabilized Cyclic (in)	1.93	1.98	2.17	1.95	1.98
Initial / Monotonic	0.47	0.48	0.55	0.38	0.39
Stabilized / Monotonic	0.47	0.47	0.54	0.39	0.39

However, Wall E (r = 0.30) had the largest difference. Wall E, which contained only three fully sheathed panels, was able to sustain capacity at high interstory drifts when a racking load was slowly applied, but not under an earthquake or hurricane type load.

Determination of Δ_{yield} is based on the shape of the load-drift curves. From Table 6.2, the ratio of initial to monotonic drift at yield for the five wall configurations ranged from 0.38 to 1.13. The ratio of stabilized to monotonic drift ranged from 0.33 to 0.96. In both cases Wall E had the lowest ratio and Wall C had the highest. Figure 6. 5 is a bar chart of monotonic and cyclic drift at yield. As shown, Walls A, B and E had higher monotonic Δ_{yield} than initial cyclic Δ_{yield}.

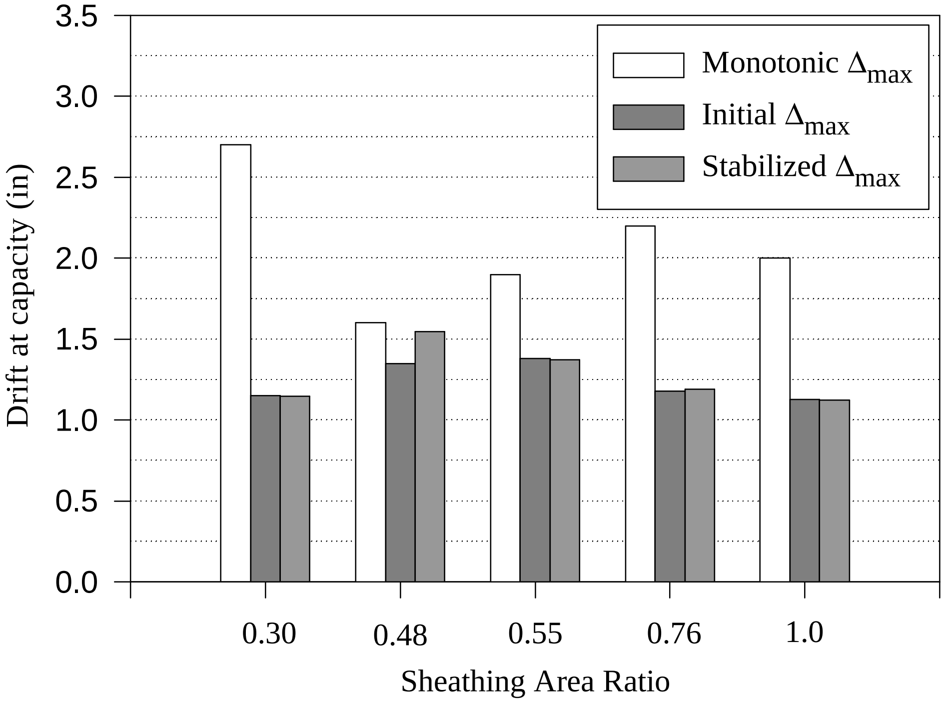

Figure 6. 4- Monotonic and cyclic drift at capacity of the five shear wall configurations examined

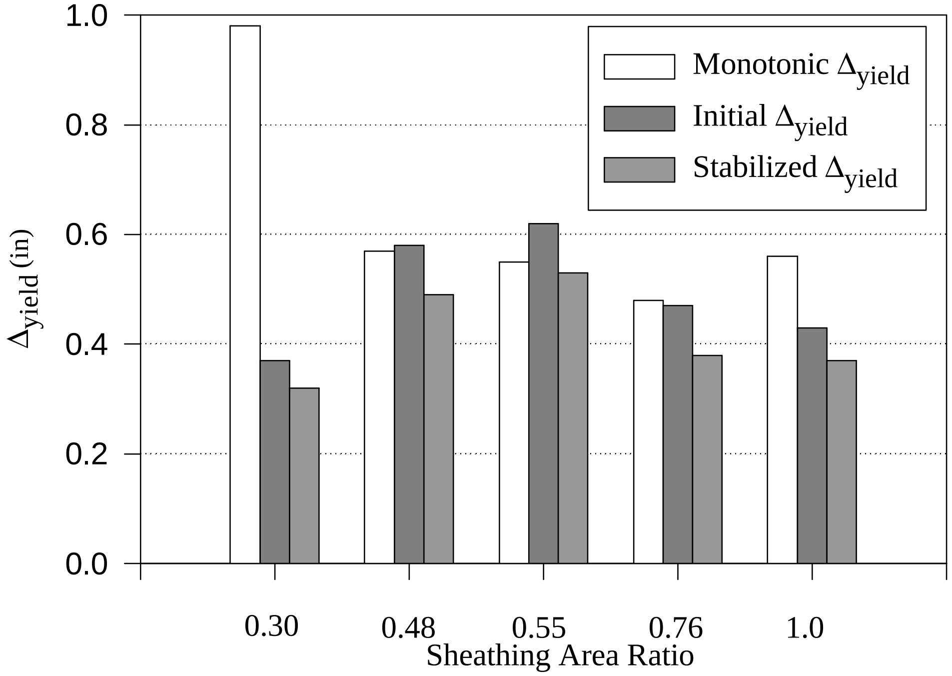

Figure 6. 5- Monotonic and cyclic drift at yield of the five shear wall configurations examined

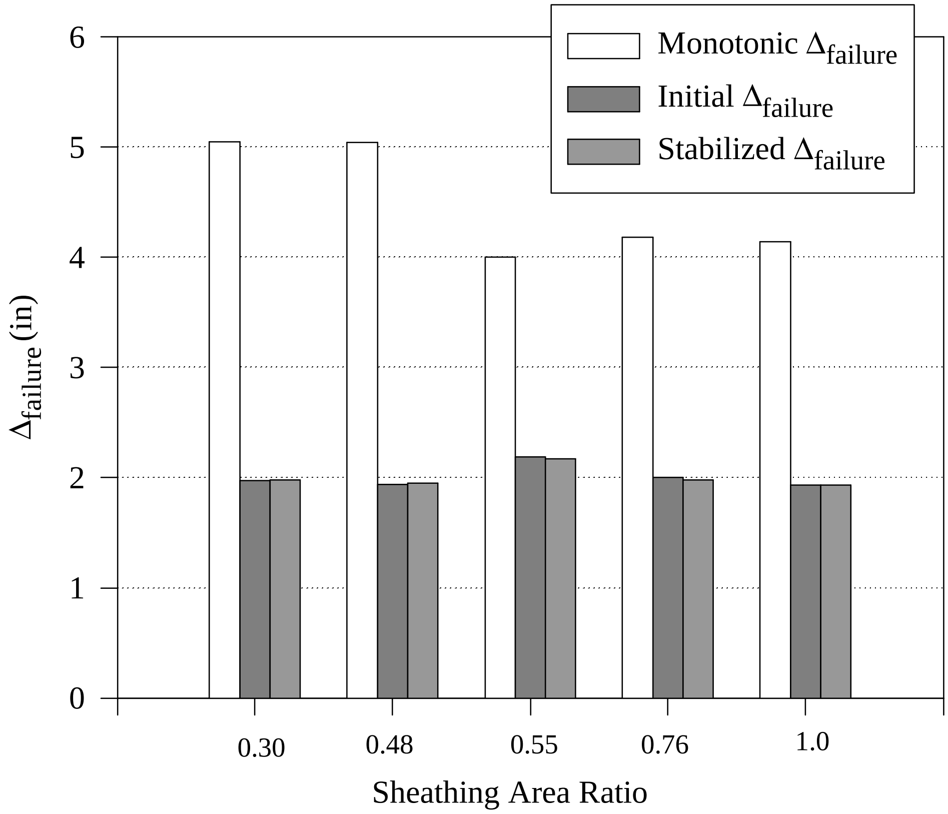

Figure 6. 6- Monotonic and cyclic drift at failure of the five shear wall configurations examined

For Walls C and D, cyclic Δ_{yield} was higher than monotonic Δ_{yield}. Wall E had the largest difference between monotonic and initial cyclic Δ_{yield}. Only considering Walls A - D, monotonic and initial cyclic Δ_{yield} ranged between 0.43” (11 mm) to 0.62” (16 mm). For the shear walls examined with a sheathing area ratio of at least 0.48, Δ_{yield} can be estimated as 0.50” (13 mm).

Figure 6.6 is a bar chart illustrating drift at failure for the five wall configurations. Table 6.2 tabulates the ratio of initial to monotonic drift at failure. For the initial cycle, the ratio ranged from 0.39 to 0.68. For the stabilized cycle, the ratio ranged from 0.40 to 0.68. Monotonically loaded shear walls are capable of resisting load at least twice the drift of cyclically loaded shear walls. This is due to fatigue failure of sheathing nails under repetitive cyclic loading.

6.2.5 Elastic Stiffness

The relationship between monotonic and cyclic elastic stiffness, as determined from the equivalent elastic plastic curves, is compared. Monotonic elastic stiffness was discussed in Section 4.3.2 and cyclic elastic stiffness was discussed in Section 5.4.2.

Table 6.3 presents the values and Figure 6.7 illustrates elastic stiffness for the five wall configurations examined when loaded monotonically and cyclically. Relative cyclic to

Table 6. 3: Comparison of monotonic and cyclic elastic stiffness of the five shear wall configurations examined

	Wall A	Wall B	Wall C	Wall D	Wall E
	r = 1.0	r = 0.76	r = 0.55	r = 0.48	r = 0.30
Elastic Stiffness (kips/in):					
Monotonic	63.7	43.7	22.2	19.4	7.8
Initial cyclic	69.7	40.0	19.9	18.1	18.2
Stabilized cyclic	69.2	41.8	20.3	18.2	18.0
Relative elastic stiffness:					
Initial to monotonic	1.09	0.92	0.90	0.93	2.33
Stabilized to monotonic	1.09	0.96	0.91	0.94	2.31

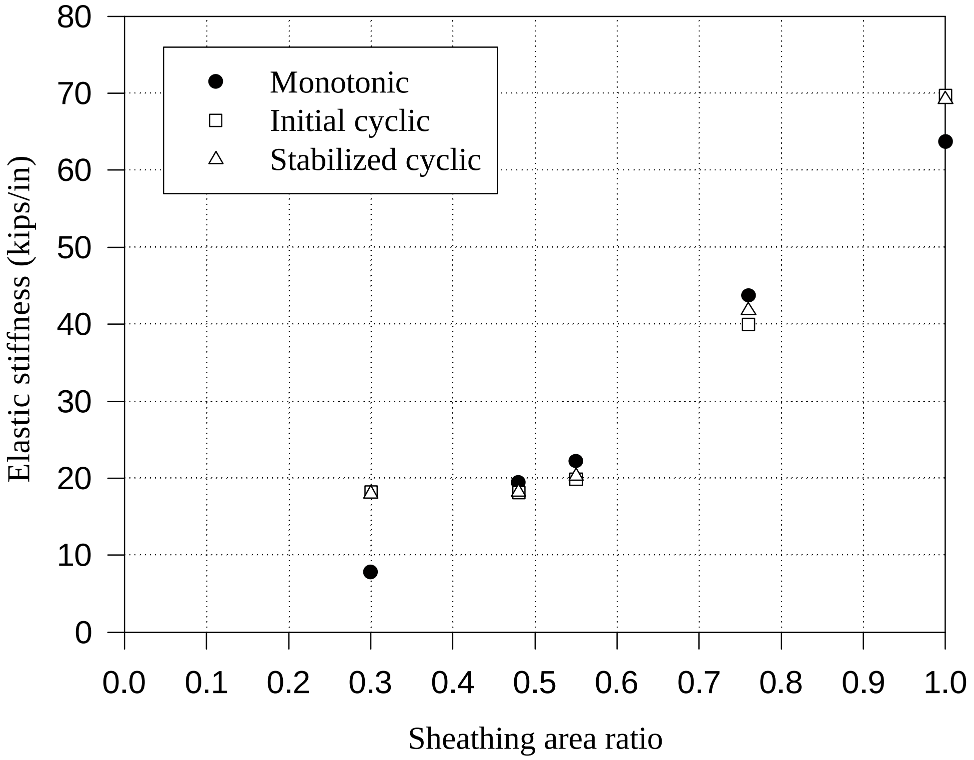

Figure 6. 7- Monotonic and cyclic elastic stiffness of the five shear wall configurations examined plotted against sheathing area ratio

monotonic stiffness is presented in Table 6.3. The ratio of initial to monotonic elastic stiffness ranged from 0.90 to 2.33 and stabilized to monotonic elastic stiffness ranged from 0.91 to 2.31. Wall E (r = 0.30) is an outlier in the previous two ranges of elastic stiffness. Without Wall E, initial to monotonic elastic stiffness ranged from 0.90 to 1.09 and stabilized to monotonic elastic stiffness ranged from 0.91 to 1.09.

It was expected that monotonic stiffness would be higher than cyclic stiffness for all wall configurations. This was not the case for Walls A and E. No explanation for this was determined, but the difference may be due to the inherent variability of materials. Based on the cyclic tests of the other four wall configurations when tested cyclically, it was expected that Wall E would have a lower elastic stiffness. Cyclic elastic stiffness of Wall A is 9% higher than the corresponding monotonic elastic stiffness. Cyclic elastic stiffness of Wall E is 133% higher than monotonic elastic stiffness.

A larger number of shear wall tests need to be conducted to get a better understanding of the relationship between cyclic and monotonic elastic stiffness.

6.2.6 Ductility

The relationship between monotonic and cyclic ductility, as determined from the equivalent elastic plastic curves, is examined. Monotonic ductility was discussed in Section 4.3.3 and cyclic ductility was discussed in Section 5.4.3.

Table 6.4 presents monotonic, initial cyclic and stabilized cyclic ductility, as well as the ratios of initial to monotonic ductility and stabilized to monotonic ductility of the five wall configurations examined. The ratio of initial to monotonic ductility ranged from 0.38 to 1.02 and the ratio of stabilized to monotonic ductility ranged from 0.45 to 1.19.

Table 6. 4: Comparison of monotonic and cyclic ductility of the five shear wall configurations examined

	Wall A	Wall B	Wall C	Wall D	Wall E
	r = 1.0	r = 0.76	r = 0.55	r = 0.48	r = 0.30
Ductility (kips/in):					
Monotonic	7.4	8.7	7.3	8.8	5.2
Initial cyclic	4.5	4.3	3.5	3.3	5.3
Stabilized cyclic	5.2	5.2	4.1	4.0	6.2
Relative Ductility:					
Initial to monotonic	0.61	0.49	0.48	0.38	1.02
Stabilized to monotonic	0.70	0.60	0.56	0.45	1.19

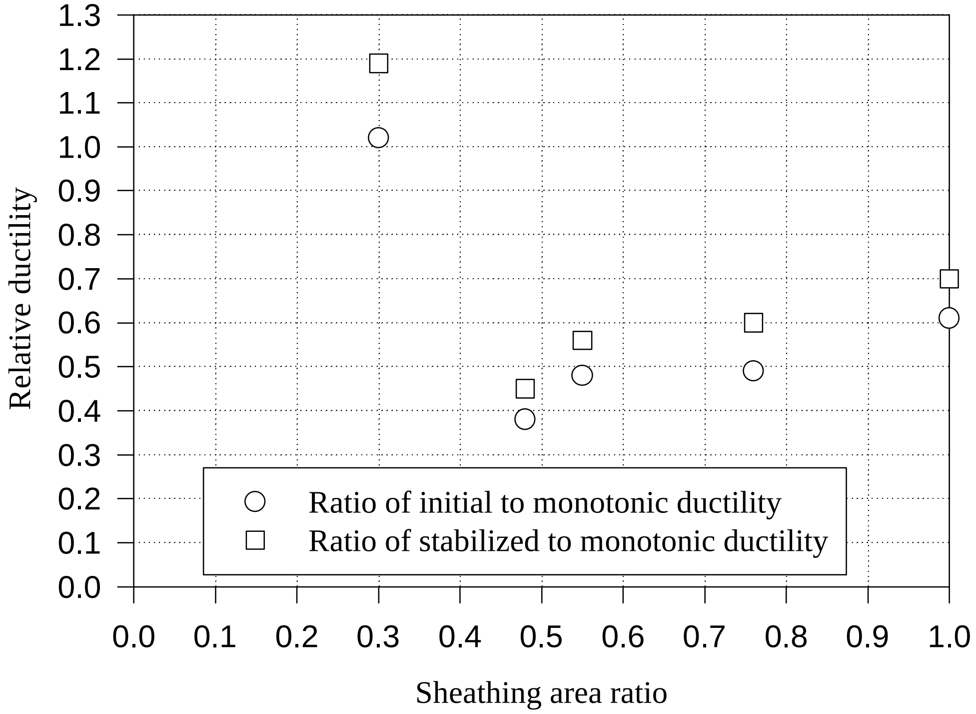

Figure 6. 8- Ratio of cyclic to monotonic ductility of the five shear wall configurations examined plotted against sheathing area ratio

It was expected that monotonic ductility would be higher than cyclic ductility for all wall configurations. As with elastic stiffness, Wall E behaves differently than the other four walls. As explained in Section 4.3.1, monotonic Δ_{yield} of Wall E was roughly twice as

high as the other four walls, resulting in a low ductility. For the other four walls, initial to monotonic ductility ranged from 0.38 to 0.61 and stabilized to monotonic ductility ranged from 0.45 to 0.70. Figure 6.8 plots the ductility ratios as a function of sheathing area ratio. Based on Walls A - D, the ranges of cyclic to monotonic ductility found in thisthesis can be used to give designers good estimates of cyclic ductility based on monotonic ductility for walls with similar sheathing area ratios.

For prediction purposes, a larger number of shear wall tests needs to be done to get a better understanding of the relationship between cyclic and monotonic ductility.

6.3 Conclusions

The data obtained in this thesis is a good portrayal of typical shear wall performance, but for prediction purposes, larger numbers of each shear wall test need to be conducted to account for variability in test specimens.

Conclusions that were drawn from comparison of monotonic and cyclic data are:

- Capacity is reached at lower interstory drifts for cyclic tests than monotonic tests. Failure at lower interstory drifts is due to fatigue failures of the plywood sheathing nailing under repetitive cyclic displacements.
- Larger drops in load resistance are experienced during cyclic loading when compared to monotonic loading. Load resistance at failure is a higher percentage of capacity for cyclic test data than monotonic test data. This is also due to fatigue failure of sheathing nails at lower interstory drifts under cyclic loading.
- Based on the data from this thesis, no direct correlation between monotonic and cyclic capacity was found. Walls with larger openings (less stiffness) had monotonic capacity's that were 90% or greater than monotonic capacity. Walls with little or no openings (higher stiffness) had cyclic capacity's less than 90% of monotonic capacity.

6.4 Summary

Chapter Six has presented data concerning load resistance, elastic stiffness, and ductility from the monotonic and cyclic shear wall tests and drawn comparisons between the effects of the two loading patterns.