EVALUATION OF SEISMIC RETROFITS FOR POST AND PIER FOUNDATION SYSTEMS

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Abstract

A research study was performed to evaluate two seismic retrofit schemes proposed to improve the lateral resistance of post and pier foundation homes in Hawaii. The retrofit designs are based on a FEMA funded report by UH Manoa and Martin & Chock, Inc. developed after the Kiholo Bay Earthquake on Hawaii Island in October 2006. The first retrofit scheme involved anchoring the posts to the pier foundation and installing metal plate connectors at all joints in the post and pier framing. The second retrofit scheme involved adding new shear walls, using 2x4 studs with plywood sheathing, and a new plywood sub diaphragm to the existing floor system, and pouring new cast-in-place concrete footings. The retrofitted post and pier foundations were subjected to cyclic lateral loading simulating seismic ground shaking to compare their performance with that of an un-retrofitted control specimen. In addition to validating the two retrofit designs, this project will develop a video tool to encourage implementation of these retrofits by homeowners. The video will be posted on appropriate websites and combined with an assisting web-based expert system for selection of the retrofit system.

Each test specimen represented a 6 foot by 12 foot, 1 bay wide by 2 bay long post and pier floor system on isolated footings. The specimens were loaded laterally using a hydraulic actuator to apply 10 cycles at various displacement amplitudes at a frequency of 1Hz. The displacement amplitude was increased each time the frame was loaded until a structural failure of the specimen was observed.

When loaded with approximately the same cyclic lateral loading as the failure load of the un-retrofitted frame, both retrofit option 1 and retrofit option 2 showed no signs of failure. Retrofit 1 with the hold-downs, ties and straps installed at all the foundation blocks, posts, and braces performed as designed, as did retrofit 2 with plywood shear walls and sub diaphragm. Based on the performance of a partially retrofitted foundation, it was determined that a partial retrofit anchoring only the post to the foundation blocks appeared to be detrimental to the seismic performance of the assembly.

Acknowledgements

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1. Introduction

1.1 Background

The October 15th, 2006 earthquakes off the Northwest coast of Hawaii Island with a maximum recorded moment magnitude of 6.7 highlighted the vulnerability of post and pier residential construction to major damage during an earthquake (USGS 2006). Approximately 30% of the total housing inventory of the County of Hawaii, or about 15,000 residences, utilizes a post and pier supported elevated first floor (Robertson and Chock 2009). Many of these buildings are also single wall construction, where the bottom of the exterior wallboard is nailed to a rim joist or sill beam, transferring the roof and wall load by vertical shear through the nails, rather than by bearing. The first floor framing is supported by individual posts, commonly spaced between 8 and 12 feet on center in both directions. Each individual post is supported on unanchored small concrete blocks locally known as “tofu blocks” which in turn rest on 16”x16”x7” unreinforced concrete foundation blocks that have little or no embedment into the soil. The soft-story lateral resisting “system” below the first floor consists of toe-nailed 2x4 braces in each direction from the posts to the main floor framing members. In more recent construction, conventional wood stud and light-gage steel double wall framed homes are often still elevated on post and pier foundations for economy and convenience. Connections between the post and pier framing members typically have minimal uplift and lateral capacity. Based on Hawaii’s historic building code provisions and property tax records, less than 10% of post and pier homes are estimated to have utilized metal plate connectors and straps for lateral resistance; the remainder are framed using only toe-nails (Robertson and Chock 2009).

1.2 Objectives

The objective of this study was to evaluate the seismic performance of two retrofit schemes proposed in the report titled, “Structural Seismic Retrofits for Hawaii Single

Family Residences with Post and Pier Foundations” by Robertson and Chock (2009). The first retrofit scheme involves adding metal straps and hold down connectors to an existing post and pier system to form a complete load path from the existing floor system down to the foundation. The second retrofit scheme involves adding plywood shear walls below the first floor with new cast-in-place concrete spread footings, and a new sub-diaphragm below the floor system to transfer lateral loads to the shear walls.

1.3 Project Scope

Three timber frames were built to test the performance of the post and pier retrofit schemes. A control specimen was constructed and subjected to lateral loads to simulate a typical post and pier foundation. The two retrofitted post and pier foundations were subjected to cyclic lateral loading simulating seismic ground shaking to evaluate their performance. The performance of the two retrofitted post and pier specimens were compared against the performance of the control specimen.

2. Literature Review

Robertson and Chock (2009) researched the effects of two earthquakes on October 15th, 2006 off the Northwest coast of the island of Hawaii, namely the Kiholo bay earthquake, and the Mahukona earthquake. Based on their analysis of 53 homes on the island of Hawaii, three retrofit schemes were created. The retrofits are presented in a general format that can be applied to a wide range of houses without specific input from a structural engineer, except in special cases. Retrofit Option 1 is primarily a strengthening of connections using the existing post and pier foundation system, applicable in regions of low to moderate seismic hazard and for houses with moderate differential post heights. Retrofit option 2 uses additional plywood shear walls between the ground and first floor of the house to provide additional lateral strength and stiffness to the foundation system. Retrofit option 3 uses additional masonry shear walls between the ground and first floor of the house to provide additional lateral strength and stiffness to the foundation system. Retrofit option 3 provides the most strength out of the 3 proposed retrofit schemes, however is the most expensive and difficult to install.

Based on the report by Robertson and Chock (2009) with the aid of UH Hilo's ICS department in 2010, a website called the "Retrofit Expert System" has been created to help homeowners determine which of the three retrofit options are applicable to their home. The homeowner will follow some basic steps, such as counting the number of posts on their homes, the post height and spacing, and enter the information into the program. Based on the information entered, the Retrofit Expert System will provide the homeowner with the applicable retrofit schemes, construction drawings to follow, as well as a list of items that are required to complete the retrofit. Due to the difficulty of installing some of the retrofits, a contractor may be required to assist the homeowner.

3. Project Description

3.1 Test Specimens

3.1.1 Specimen 1 - Control

The control specimen was a 12 foot long by 6 foot wide floor system (Figure 1). Six 16”x16”x7” thick standard concrete foundation blocks with smaller 7”x7”x4” concrete blocks (“tofu” blocks) placed on top were used as the main foundation (Figure 2). The foundation blocks were embedded 4 inches into a 10 foot x 4 foot x 6 inch deep soil bed. The soil was compacted using a pneumatic pole tamper or a “pogo” stick. Metal termite barriers were placed on top of the smaller “tofu” block (Figure 2). The 4x4 posts were placed on the termite shields with no connection to the precast concrete foundation blocks below. This is typical of existing post and pier foundations in Hawaii. The top of the posts were toe-nailed to the 4x10 girders with 3-16d (0.162” diameter by 3½” long) common box nails. The floor was framed with 2x10 joists spaced at 24 inches on center placed on top of the three main 4x10 girders with 4x10 perimeter beams and a 2x10 fascia. The 2x10 joists and the 4x10 perimeter beams were toe-nailed to the 4x10 girders with 2-16d common box nails. The 2x10 fascia was face nailed to the 4x10 perimeter beams and the 2x10 joists with 3-16d common box nails. All posts were braced in all directions by 2x4 diagonal braces toe-nailed to the 4x10 girder and perimeter beams using two 16d common box nails at each end of the brace (Figure 3). The floor diaphragm consisted of 3/4” thick plywood sheathing with 10d (0.148” diameter by 3” long) common box nails at 4 inches on center around the panel edges and 12 inches on center along the joists. See Figure 4 for typical fasteners used in construction of the test specimens.

Figure 1: Control Specimen

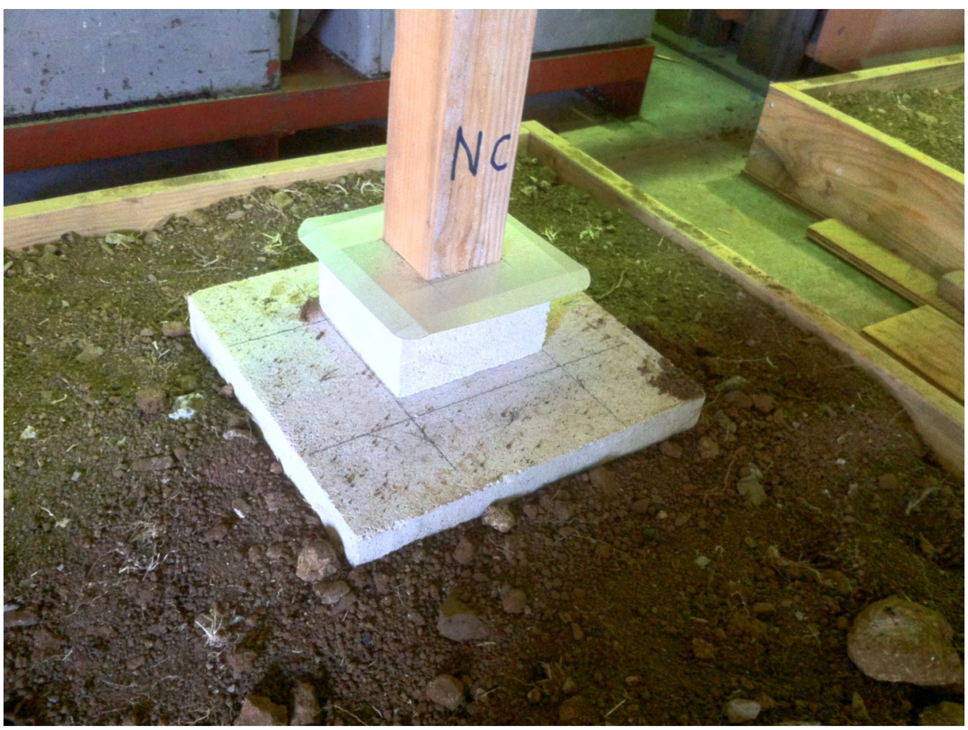

Figure 2: Typical Un-Retrofitted Tofu Block Foundation

Figure 3: Typical 2x4 Diagonal Brace with toe-nail connections

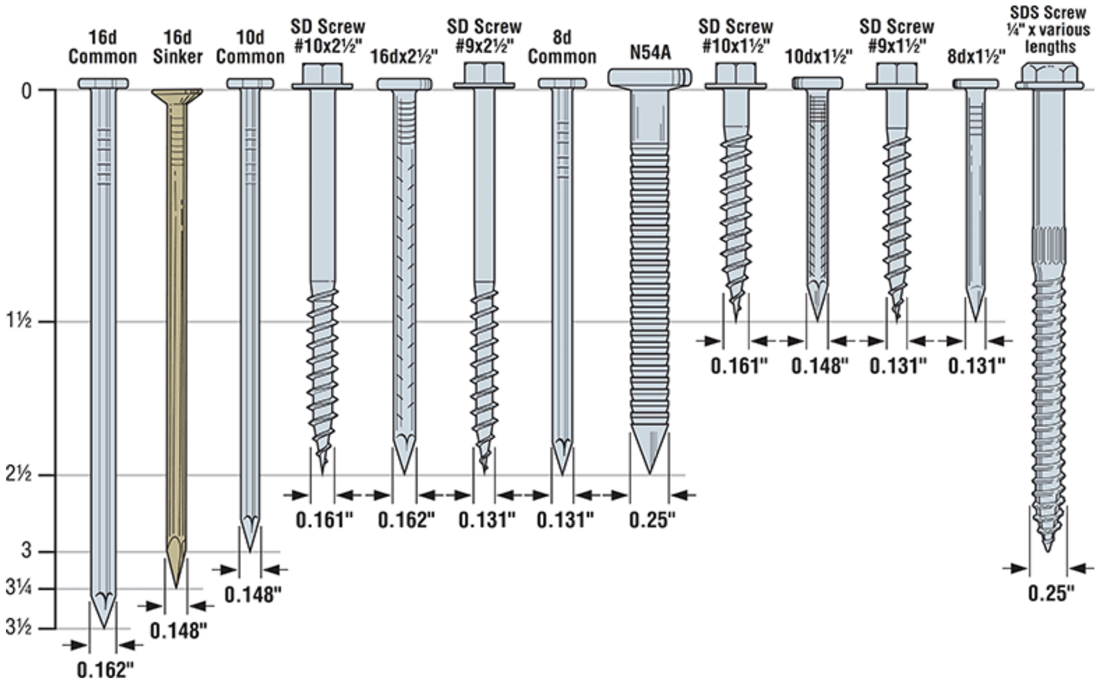

Figure 4: Typical Fastener Types and Sizes

3.2 Specimen 2 – Partial Retrofit

After testing, the control specimen was retrofitted with Simpson HDU5 hold-downs on each side of the 4x4 posts to connect the posts to the foundation blocks (Figure 5, Figure 6 and Figure 7). Simpson H2.5A hurricane ties were installed at each joist to beam connection (Figure 8). The Simpson HDU5 connectors were installed per the manufacturer's recommendations with a 5/8" diameter threaded rod drilled and epoxied with a 4 inch embedment into the 16" x 16" masonry foundation blocks with Hilti HY-150 Max. Spacers made from 2x4 blocking were installed on either side of the 4x4 post with 4-10d common box nails, so that the HDU5 hold-down would clear the "tofu" block. Due to the dimension of the smaller tofu block, on one side of the 4x4 post an additional ½" thick piece of plywood was added in addition to the 2x4 blocking. The HDU5 hold-down was connected to the 2x4 blocking and the 4x4 post with 14- ¼" diameter by 2 ½" long Simpson SDS screws. The braces were left with toe-nail connections at both ends. The post to beam connection was left with the original toe-nail connection. Everything else remained the same as in the un-retrofitted control specimen.

Figure 5: Partial Retrofit Specimen

Figure 6: Typical Partial Retrofit 1 Specimen Tofu Block Foundation

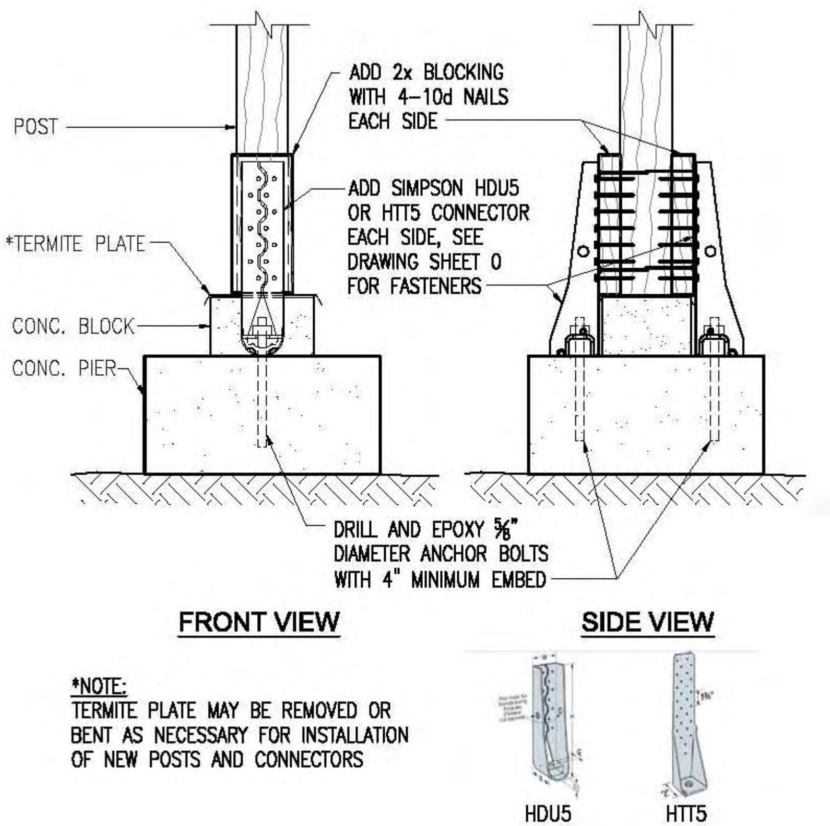

Figure 7: Simpson HDU Hold-down Connection

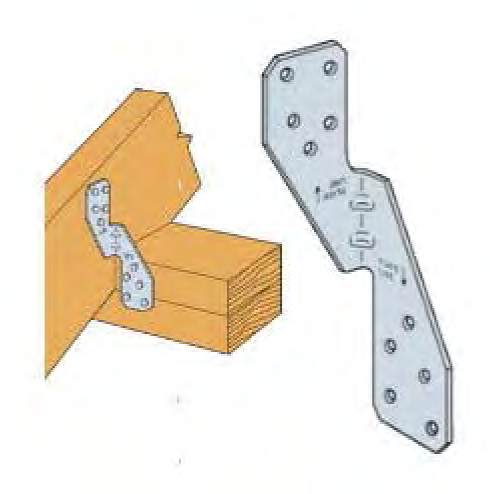

Figure 8: Simpson H2.5A Hurricane Tie

3.3 Specimen 3 - Retrofit Scheme 1

After testing the partial retrofit, the specimen was retrofitted with the complete retrofit scheme 1 (Figure 9). Simpson Strongtie connectors were installed to connect the 4x4 posts to the 4x10 girder and perimeter beams and at both ends of the 2x4 diagonal knee braces. Simpson 88L straps were added on both sides of the interior brace to post connections (Figure 10 and Figure 11). In order to accommodate nailing for the 88L straps, 2x4 blocking was added to the end of the braces near the post connection with 4-10d nails by 3 inches long (Figure 10 and Figure 11). At interior diagonal bracing conditions, the added 2x4 blocking could not be installed without completely removing both of the braces as shown in Figure 10.

Simpson HRS12 straps were added to both sides of the brace where the brace was only in one direction (Figure 12 and Figure 13) and at the brace to beam connections (Figure 14). Simpson LCE4 post caps were installed on both sides at all 4x4 post to 4x10 beam connections (

Figure 15 and

Figure 16). All other connections not mentioned above remained the same as in the partial retrofit specimen.

Figure 9: Retrofit Scheme 1 Specimen

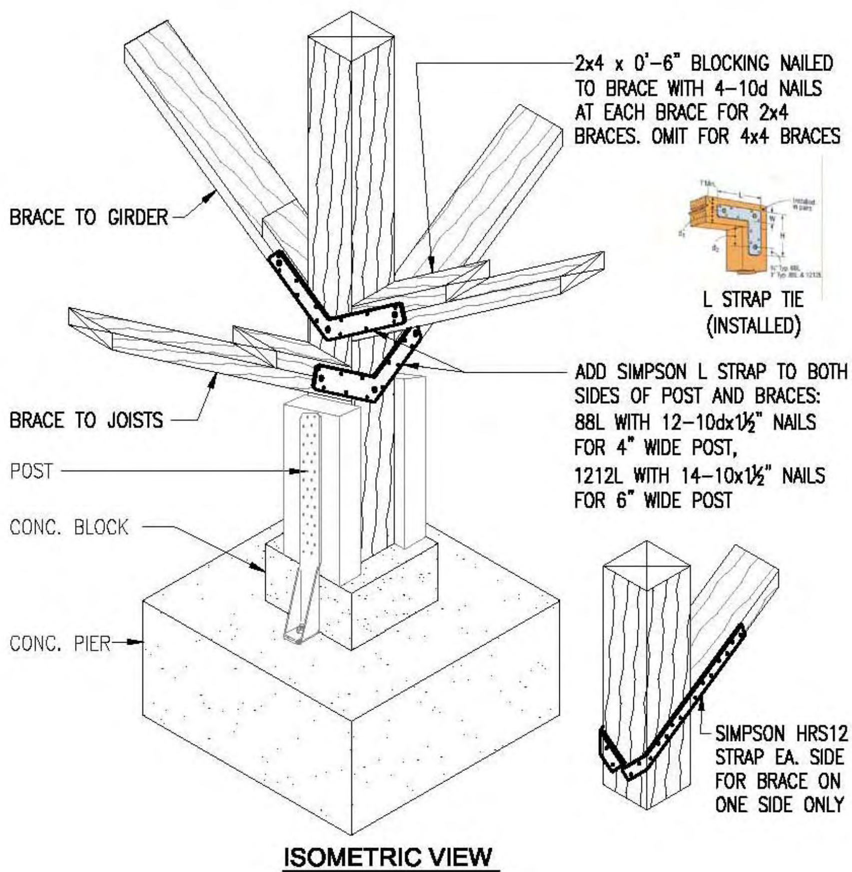

Figure 10: Simpson 88L Strap installation

Figure 11: Typical Retrofit Scheme 1 center post with Simpson 88L strap installed

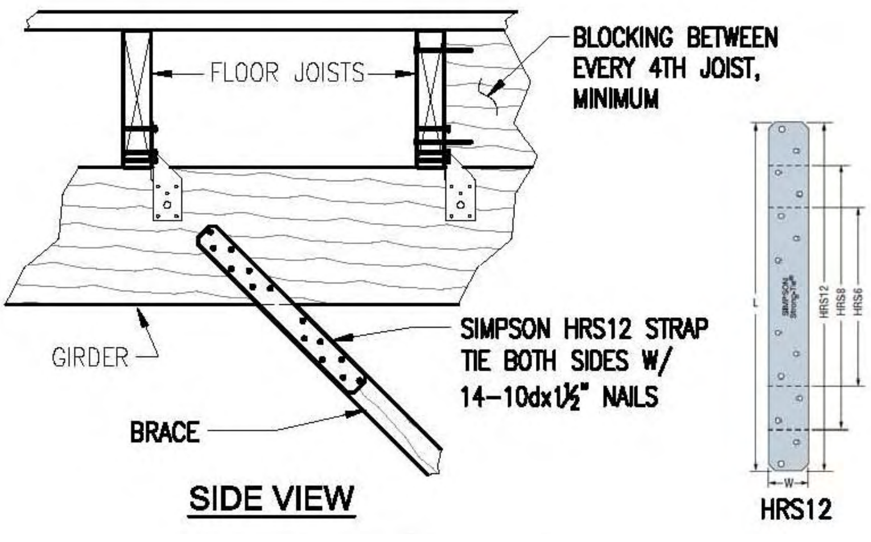

Figure 12: Simpson HRS12 Strap installation

Figure 13: Typical Retrofit 1 corner post with HRS12 straps installed

Figure 14: Typical 2x4 diagonal brace retrofit with HRS12 straps installed

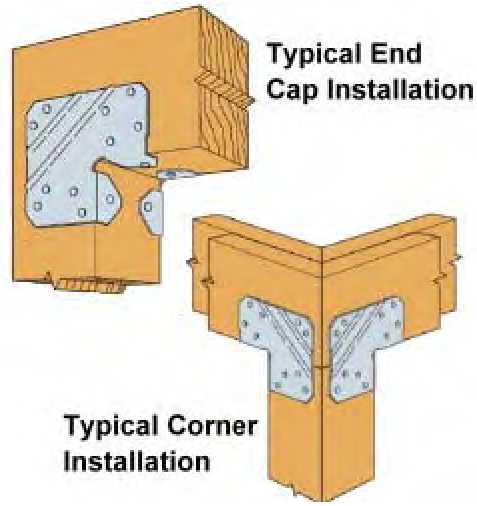

Figure 15: Simpson LCE4 Post Cap

Figure 16:LCE4 Post Cap Installed on 4x4 Post

3.4 Specimen 4 - Retrofit Scheme 2

A new test specimen was constructed similar to the control specimen. This specimen was retrofitted with scheme 2 (Figure 17). Two out of the six foundation blocks remained the same “tofu” block set up, while the other four were replaced with new 2 foot square by 12 inch thick concrete footings with 4 No. 3 reinforcing steel bars in each direction. Retrofit 2 specimen was retrained at the base to prevent the sliding to simulate the soil resistance by being embedded deeper in the soil when constructed in the field. A Simpson CBSQ44 post base connector (

Figure 18) was cast in place in each of the four concrete footings. Plywood sheathing using ½” plywood was attached to a 2x4 at 16 inches on center stud wall added in the longitudinal direction of each bay farthest from the actuator replacing the diagonal bracing used in the previous specimens. The plywood was nailed with 8d nails at 4” on center along the panel edges and at 12” on center along the studs. Diagonal braces were only installed in the transverse direction and the bay nearest to the loading actuator in the longitudinal direction. Each brace was toe-nailed to the 4x girder with two 16d common nails. The ¾” plywood floor sheathing was nailed with the same nailing pattern as the previous specimens. A ½ inch thick plywood sub diaphragm was installed below the joists with 8d nails at 4 inches on center along panel edges and at 12 inches on center along the joists. Full depth blocking using 2 x 10 sections was installed around all panel edges to allow for nailing around all edges of the plywood sheets. Simpson MSTA36 straps were installed to connect the bottom chord of the plywood shear walls to the end posts (Figure 19 and Figure 20). The completed retrofit 2 is shown in Figure 21.

Figure 17: Specimen 4 with Retrofit Scheme 2 Installed

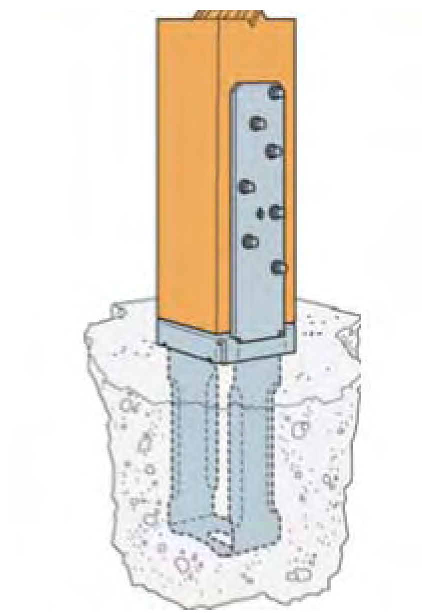

Figure 18: Simpson CBSQ44 Post Base Connector

Figure 19: Typical Retrofit 2 Footing

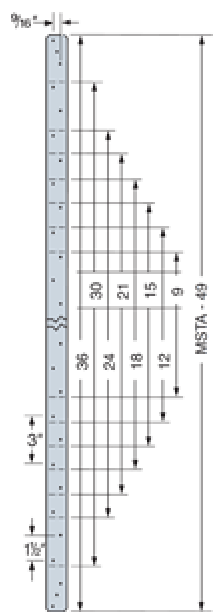

Figure 20: Simpson MSTA Strap

Figure 21: Retrofit 2 Specimen Plywood Shearwall and Plywood Sub Diaphragm

3.5 Test Set up

3.5.1 Gravity Loading

To simulate dead loads applied to the post and pier foundation system from the weight of the walls, floors and roof above, structural steel wide flange beams weighing a total of 2,364 pounds were added to the top of the test specimens. The beams were secured to the floor framing using straps to avoid movement when the lateral loading was applied. The equivalent loading on the 6 foot by 12 foot floor was approximately 33 pounds per square foot (psf). This represents a reasonable dead weight of a single family residence.

3.5.2 Lateral Loading

A 30,000 pound hydraulic actuator was used to apply cyclic displacements to each test specimen. The actuator applied 10 cycles of each amplitude displacement at 1Hz, increasing the amplitude after each test until failure. After each series of 10 cycles the specimens were inspected for any visible signs of structural damage before increasing the lateral displacement. During each segment the applied load and lateral displacement at the load application point were recorded by a load cell and displacement transducer in the load actuator. Cycling amplitudes for each of the specimens are shown in Table 1. Actual displacement versus time graphs were compared to the theoretical displacement time graphs for the typical 1.0 inch cyclic lateral loading for each test specimen to ensure that the hydraulic actuator was providing the correct amount of displacement to the specimens (Figure 23, Figure 24, Figure 25 and Figure 26).

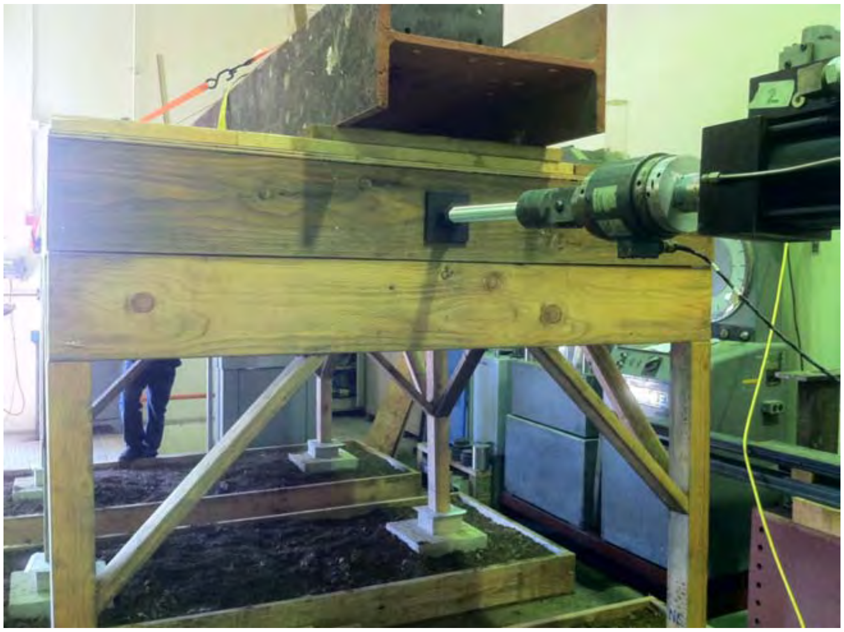

Figure 22: Typical Test Specimen Lateral Loading Set Up

Test Series	Control Specimen Disp (in)	Partial Retrofit Specimen Disp (in)	Retrofit Specimen 1 Disp (in)	Retrofit Specimen 2 Disp (in)
1	0.25	0.25	0.25	0.25
2	0.5	0.35	0.35	0.1
3	1	0.5	0.5	0.15
4	1.5	0.75	0.75	0.2
5	2	1	1	0.3
6		1.25	1.25	0.35
7		1.5	1.5	0.4
8				0.5
9				0.6
10				0.75
11				0.875
12				1
13				1.125
14				1.25
15				1.375
16				1.5
17				1.75
18				2
19				2.5

Table 1: Displacement Amplitudes for Cyclic Tests

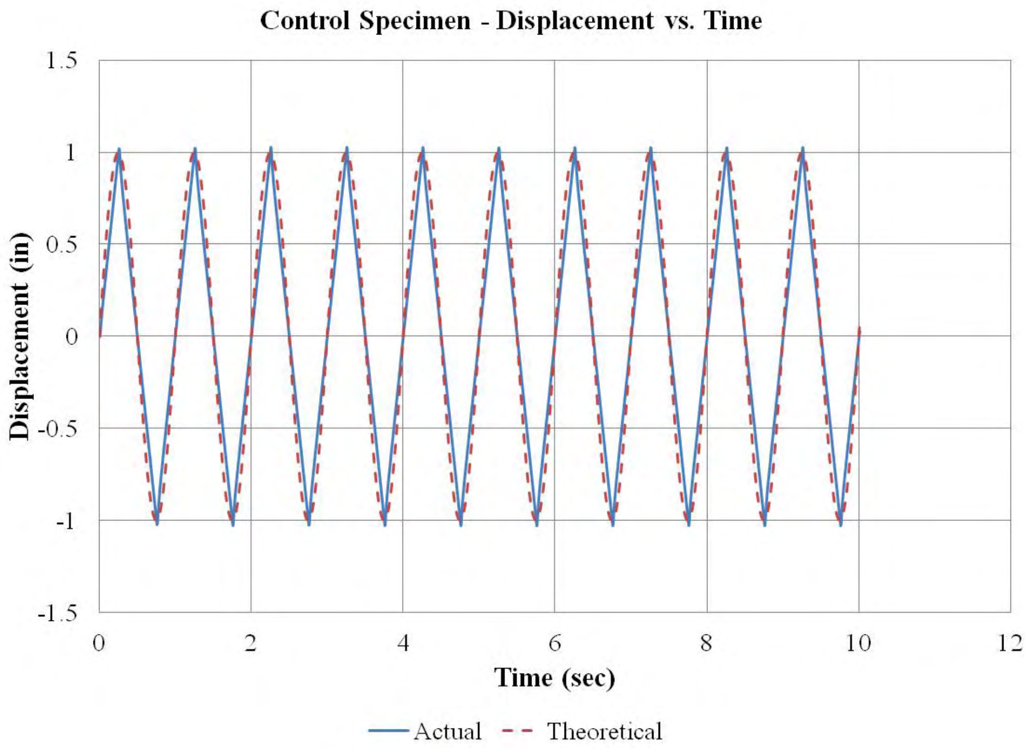

Figure 23: Control Specimen - Displacement vs. Time

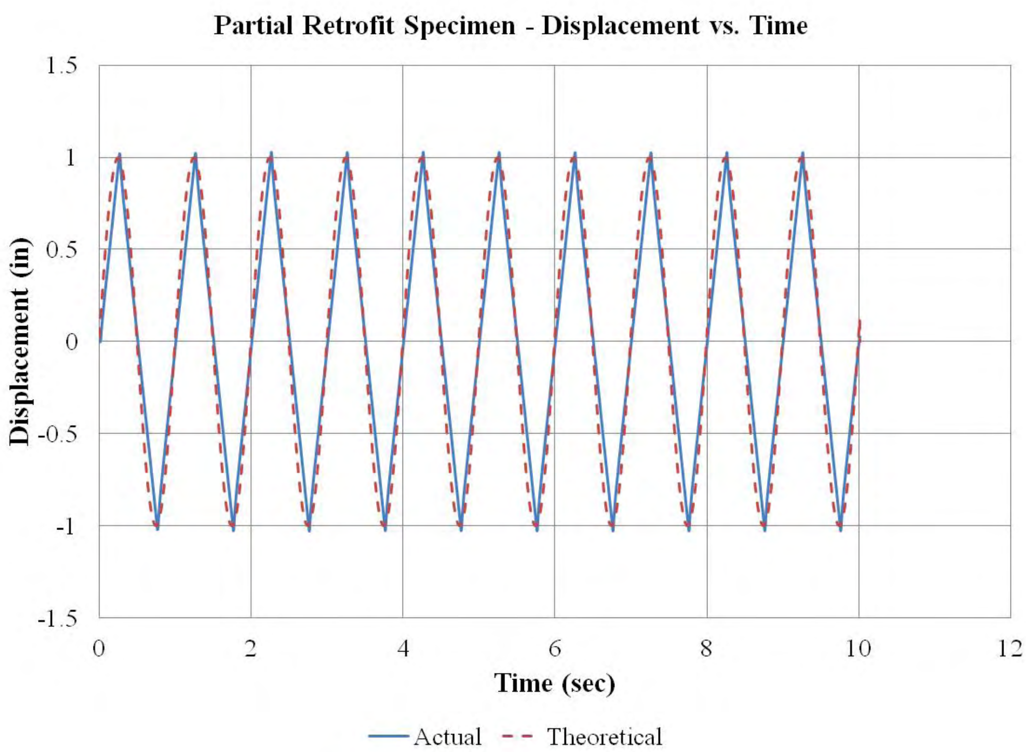

Figure 24: Partial Retrofit Specimen - Displacement vs. Time

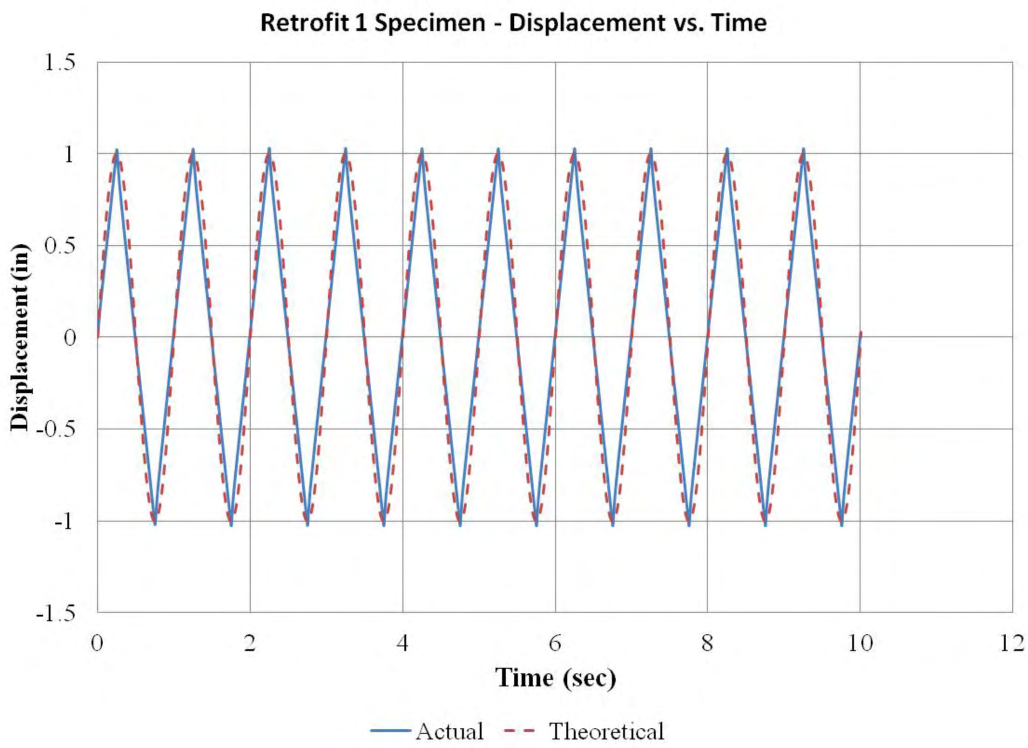

Figure 25: Retrofit 1 Specimen - Displacement vs. Time

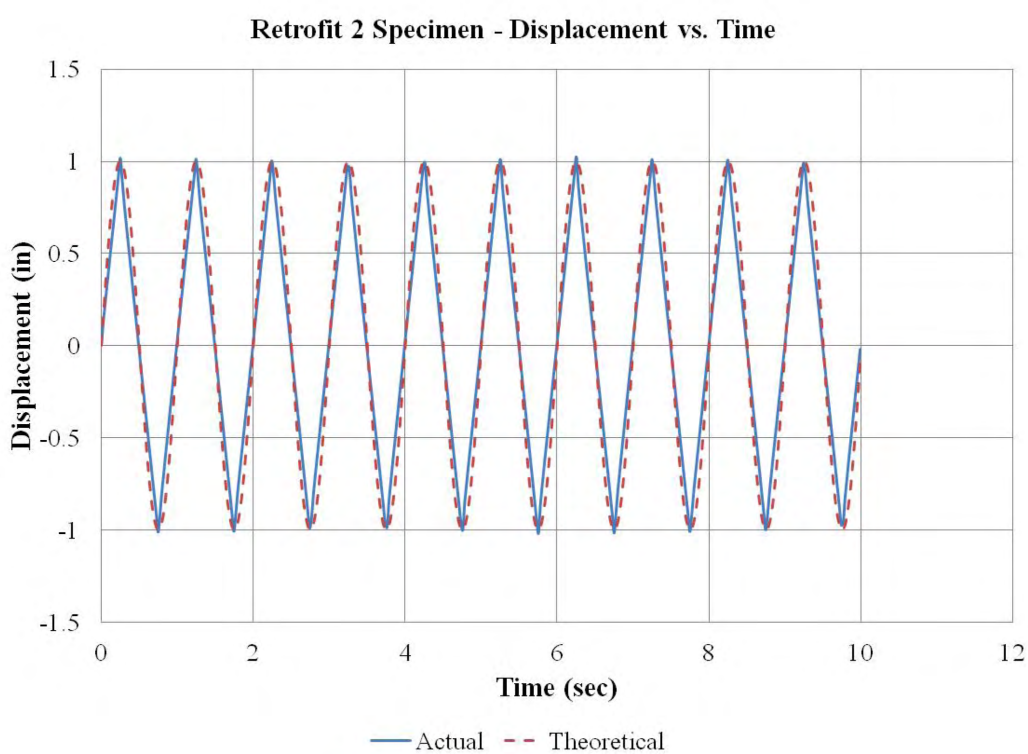

Figure 26: Retrofit 2 Specimen - Displacement vs. Time

4. Results

4.1 Control Specimen

When loaded laterally, the control specimen appeared to slide back and forth within the foundation on the metal termite shield. When the post began to slip off the termite shield it created an oscillation in the force displacement plot curve which can be seen in Figure 27 and Figure 28. The oscillation is caused by the vibration of the posts as they slip on the foundation. The graphs represent the hysteric response of the specimen. Hysteric plots for all levels of cycling are included in the appendix. Stiffness is the relationship of the applied lateral displacement and the lateral force experienced by the specimen. The initial and effective stiffness of the control specimen and maximum resisted load, are shown in Table 2 for each of the cyclic tests.

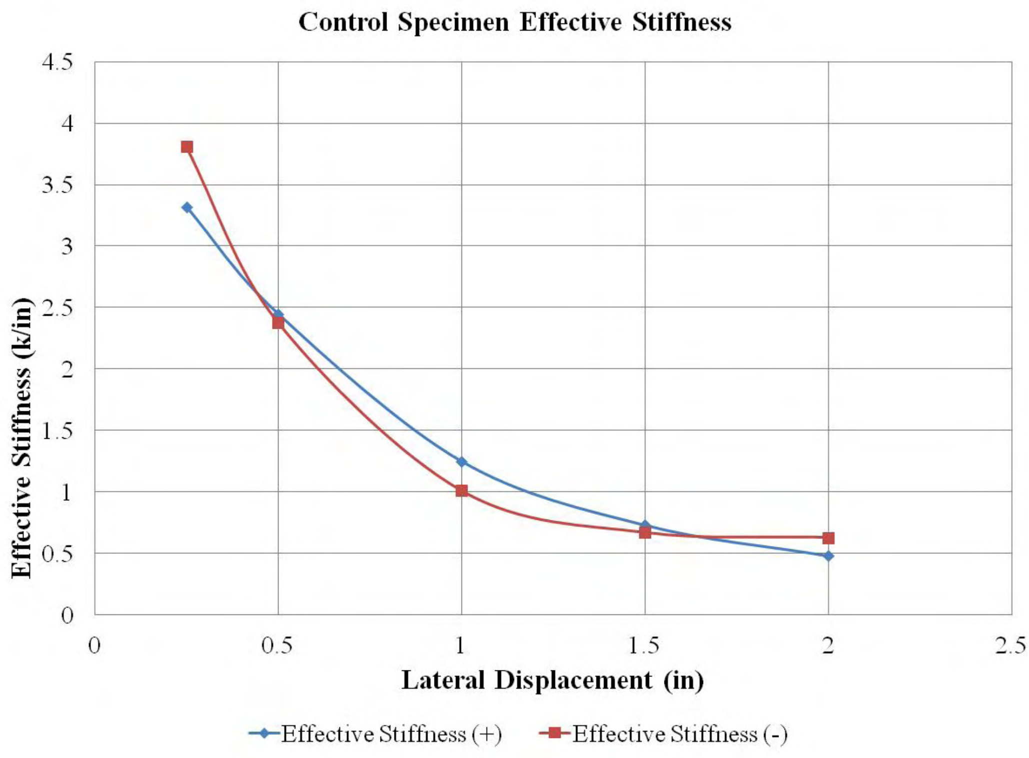

Figure 29 shows the decay of the effective stiffness of the specimen as the lateral displacement is increased. Figure 30 shows the maximum lateral load resisted by the foundation system during each set of 10cycles at increasing displacements.

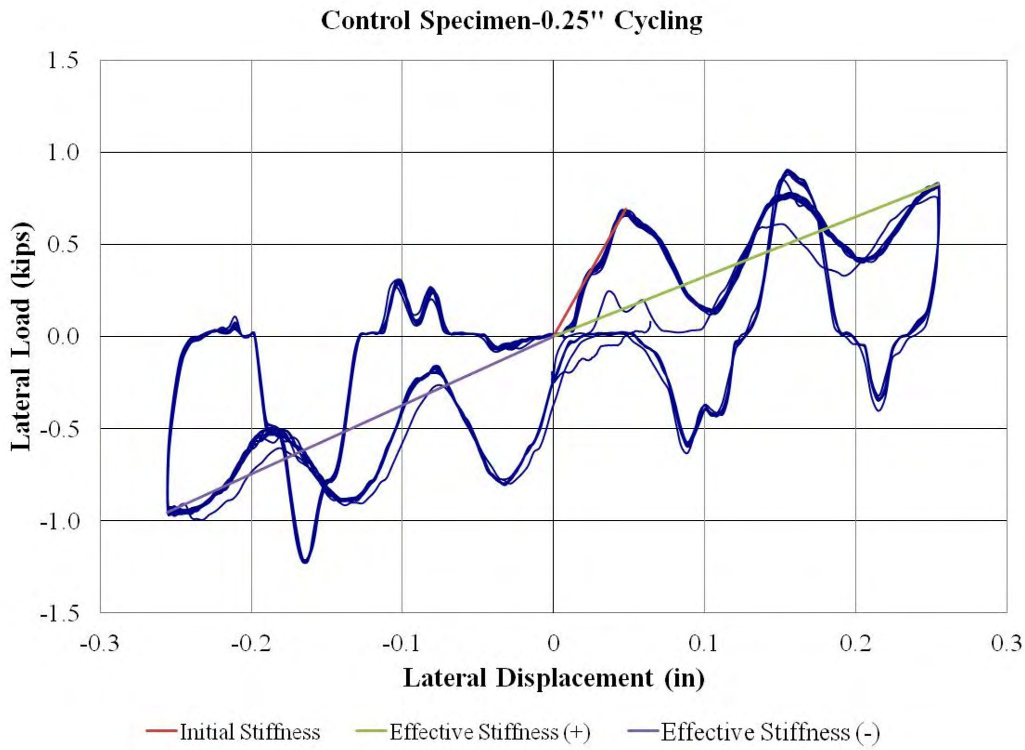

Figure 27: Control Specimen - 0.25" Cycling

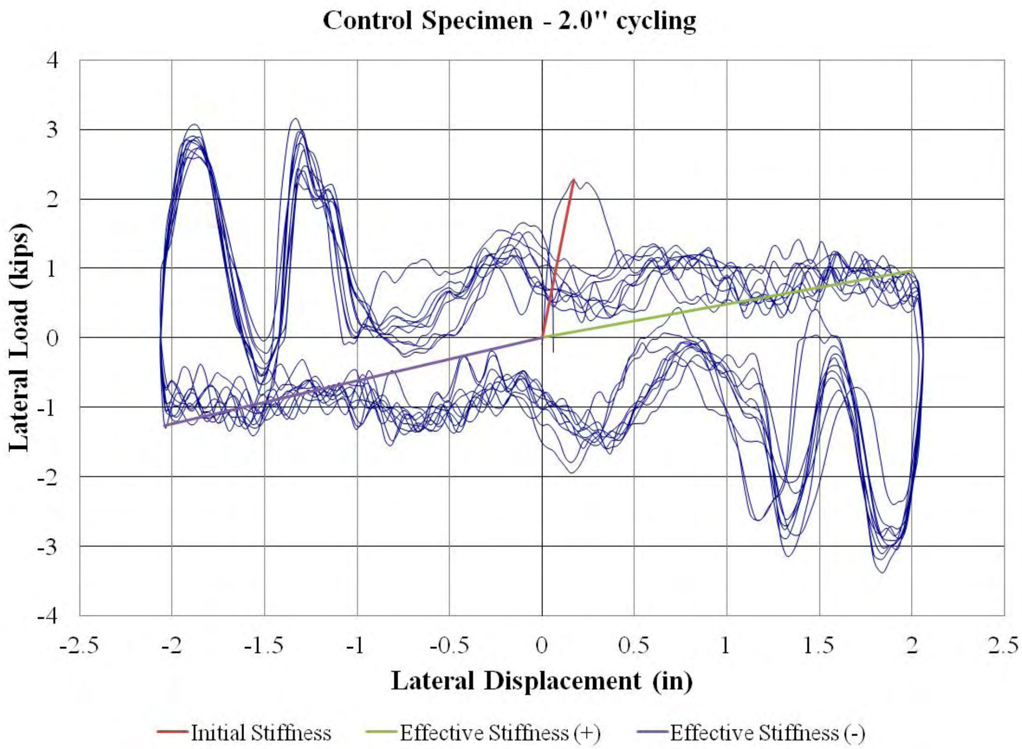

Figure 28: Control Specimen - 2.0" Cycling

Control Specimen		Stiffness			Max Lateral Load		Lateral Load / Approximate Weight	
Test	Displacement Amplitude (in)	Initial (k/in)	Effective (+) (k/in)	Effective (-) (k/in)	+ (kip)	- (kip)	+	-
1	0.25	14.41	3.32	-3.81	0.91	-1.22	0.30	0.41
2	0.5	17.58	2.45	-2.38	1.25	-1.19	0.42	0.40
3	1	23.8	1.25	-1.01	1.64	-1.73	0.55	0.58
4	1.5	16.15	0.73	-0.67	3.00	-2.59	1.00	0.86
5	2	13.37	0.48	-0.63	3.16	-3.38	1.05	1.13

Table 2: Control Specimen Stiffness

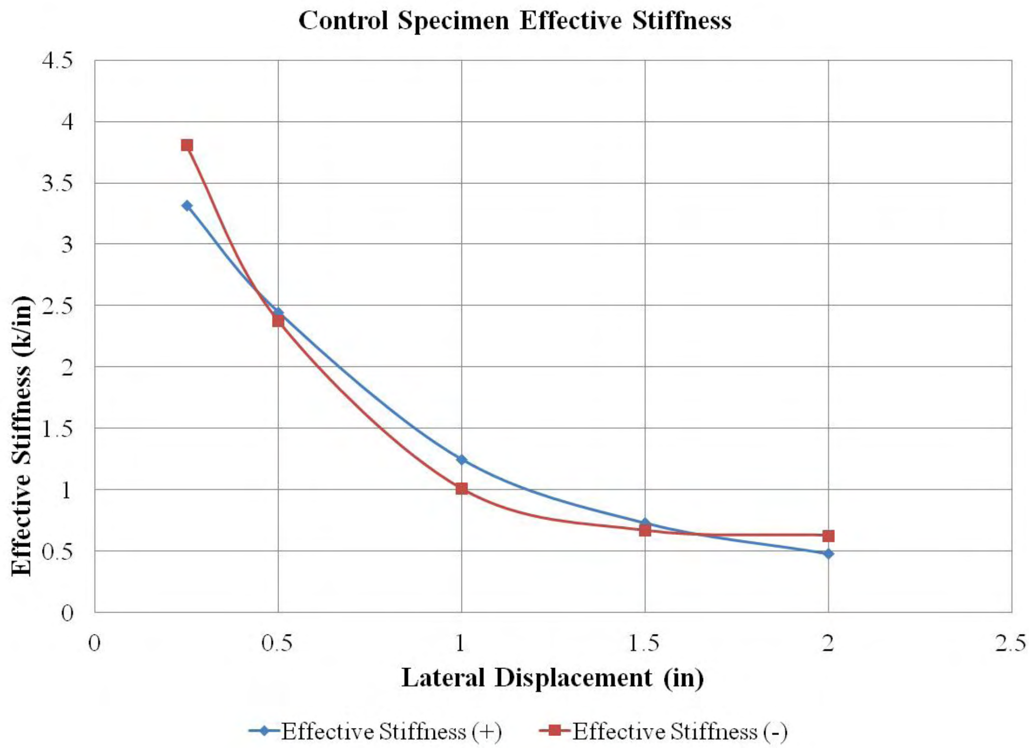

Figure 29: Control Specimen Effective Stiffness

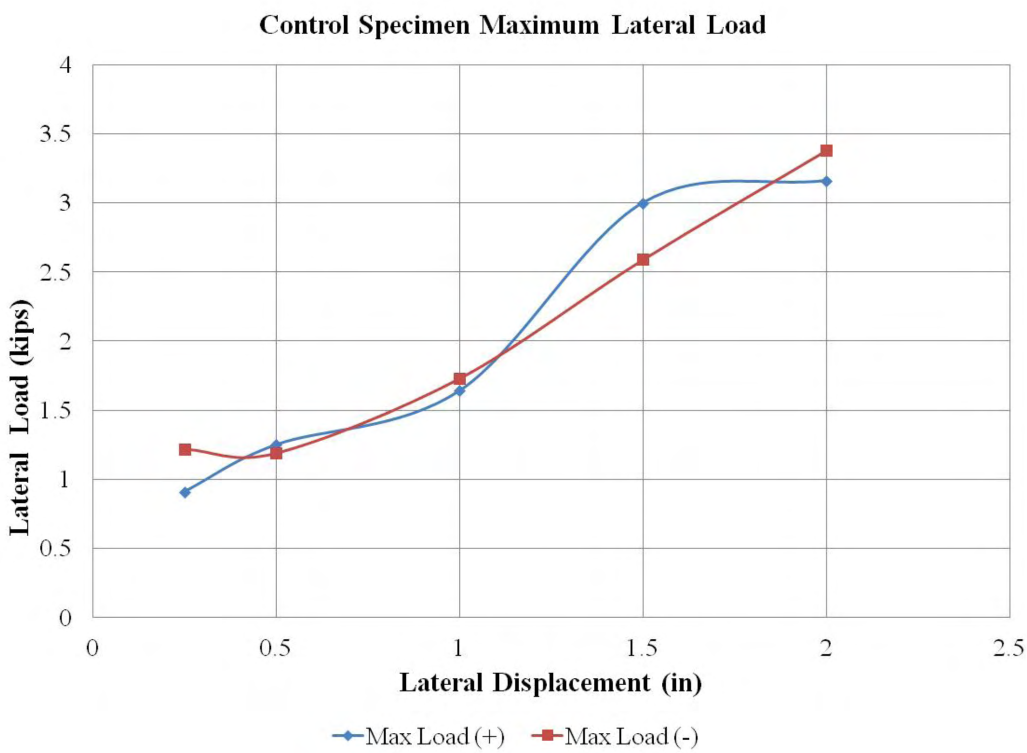

Figure 30: Control Specimen Maximum Lateral Load

When cycling to +/- 2” amplitude, the posts migrated off the foundation blocks as shown in Figure 31. The max load sustained during the 2” cycling was 3.38 kips. The failure mechanism of the control specimen was the slipping of the wood post and the termite shield as well as the pulling out of the 16d toe-nails from the diagonal brace to beam connection. Figure 31 shows the failure at the post to foundation location in which the post and metal termite shield slipped off the tofu block foundation. Figure 32 and Figure 33 show the toe-nail pullout failures of the control specimen.

Figure 31: Control Specimen Post Failure

Figure 32: Control Specimen Nail Pullout Failure at 2x4 Brace

Figure 33: 4x10 Perimeter Beam to 4x10 Girder Nail Pullout

4.2 Partial Retrofit Specimen

The partial retrofit specimen modified with only the Simpson HDU5 hold downs and the Simpson H2.5A ties appeared to perform worse than the control specimen. When loading the frame, the max sustained load was approximately 2.5 kips during 1.5” cycling at 1Hz. The frame was not loaded beyond 1.5” so as to prevent additional damage to the specimen as it needed to be modified for retrofit specimen 1. There was a significant decrease in the amount of movement in the frame due to the HDU5 hold downs which prevented the 4x4 posts from sliding on the foundation blocks. The oscillation seen in Figure 34 and Figure 35 can be attributed to movement of the foundation blocks in the soil. Under the cycling lateral loading, the soil was displaced, therefore providing very little passive lateral resistance. The shifting of the footing caused a reduction in the lateral load applied to the specimen by the actuator. The effective stiffness compared to the control specimen was slightly higher due to the added hold-downs restraining the slipping of the 4x4 posts from the tofu block foundation. The initial and effective stiffness of the partial retrofit specimen are shown in

Partial Retrofit Specimen		**Stiffness**			**Max Lateral Load**		**Lateral Load / Approximate Weight**	
Test	Displacement Amplitude (in)	Initial (k/in)	Effective (+) (k/in)	Effective (-) (k/in)	+ (kip)	- (kip)	+	-
1	0.25	37.32	4.07	-2.86	1.02	-0.71	0.34	0.24
2	0.35	44.91	3.87	-2.89	1.35	-1.01	0.45	0.34
3	0.5	66.4	3.49	-2.57	1.75	-1.29	0.58	0.43
4	0.75	50.7	2.94	-2.28	2.21	-1.71	0.74	0.57
5	1	28.52	2.42	-2.07	2.42	-2.07	0.81	0.69
6	1.25	27.59	2.02	-1.81	2.53	-2.26	0.84	0.75
7	1.5	18.45	1.55	-1.49	2.32	-2.23	0.77	0.74

Table 3 along with the maximum lateral load resisted during each set of cycling. Figure 36 shows the decay in effective stiffness as the cycling amplitude increases, while Figure 37 shows the change in maximum resisted load. The drop in lateral load capacity during the 1.5” cycling was attributed to the pull-out of the toe-nails.

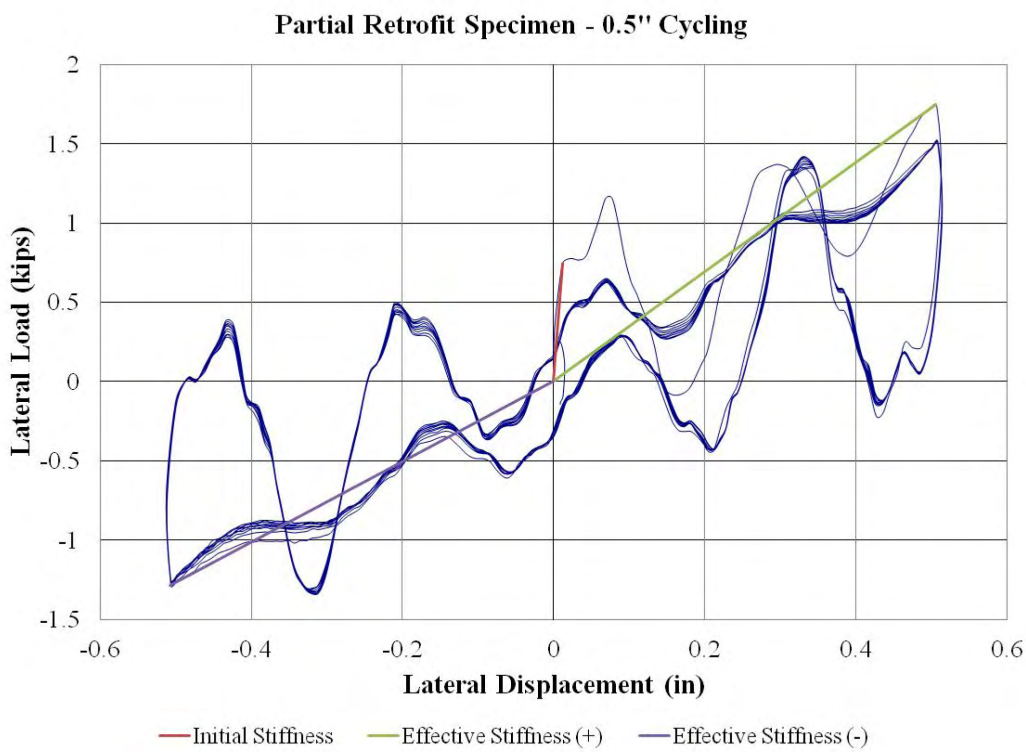

Figure 34: Partial Retrofit Specimen – 0.5” Cycling

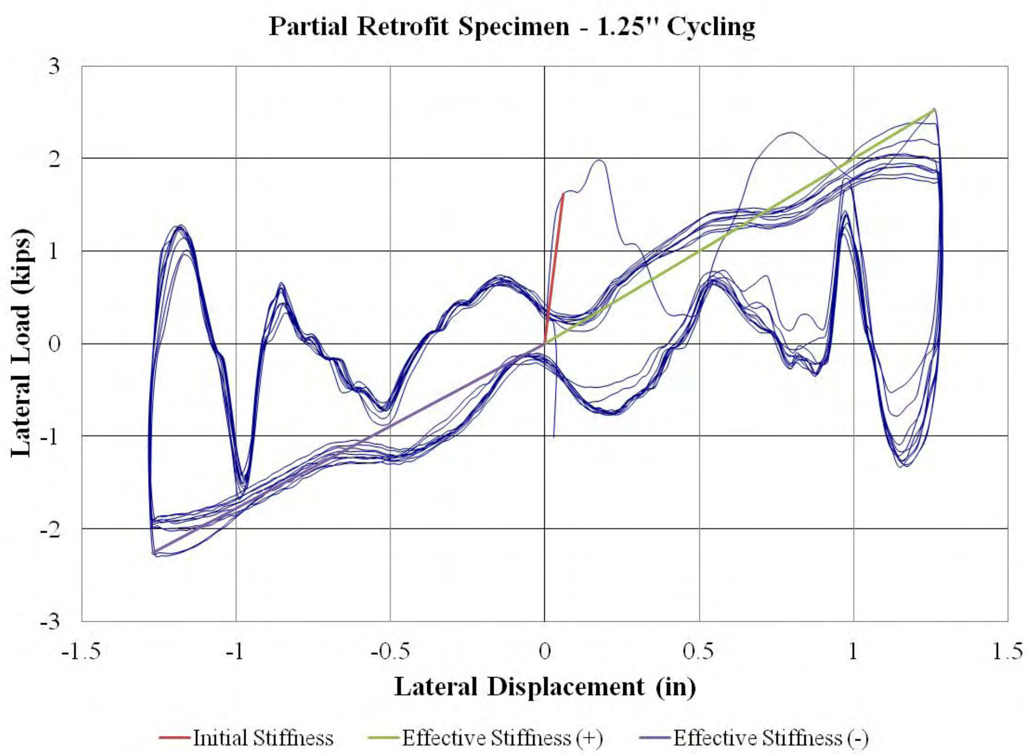

Figure 35: Partial Retrofit Specimen – 1.25” Cycling

Partial Retrofit Specimen		Stiffness			Max Lateral Load		Lateral Load / Approximate Weight	
Test	Displacement Amplitude (in)	Initial (k/in)	Effective (+) (k/in)	Effective (-) (k/in)	+ (kip)	- (kip)	+	-
1	0.25	37.32	4.07	-2.86	1.02	-0.71	0.34	0.24
2	0.35	44.91	3.87	-2.89	1.35	-1.01	0.45	0.34
3	0.5	66.4	3.49	-2.57	1.75	-1.29	0.58	0.43
4	0.75	50.7	2.94	-2.28	2.21	-1.71	0.74	0.57
5	1	28.52	2.42	-2.07	2.42	-2.07	0.81	0.69
6	1.25	27.59	2.02	-1.81	2.53	-2.26	0.84	0.75
7	1.5	18.45	1.55	-1.49	2.32	-2.23	0.77	0.74

Table 3: Partial Retrofit Specimen Stiffness

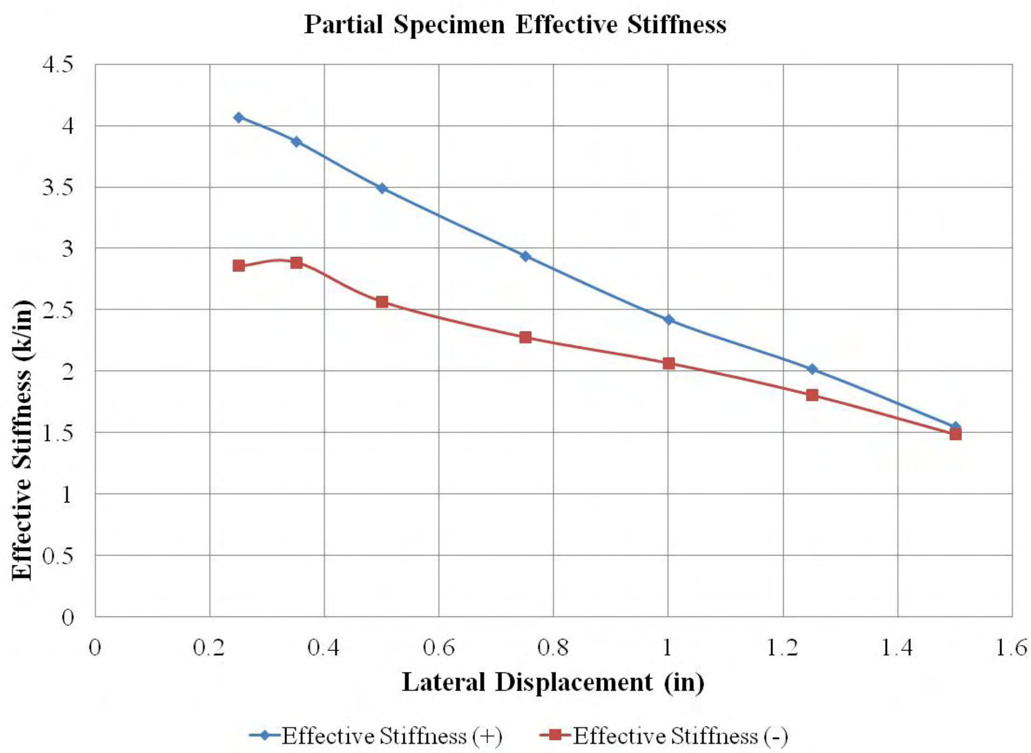

Figure 36: Partial Retrofit Effective Stiffness

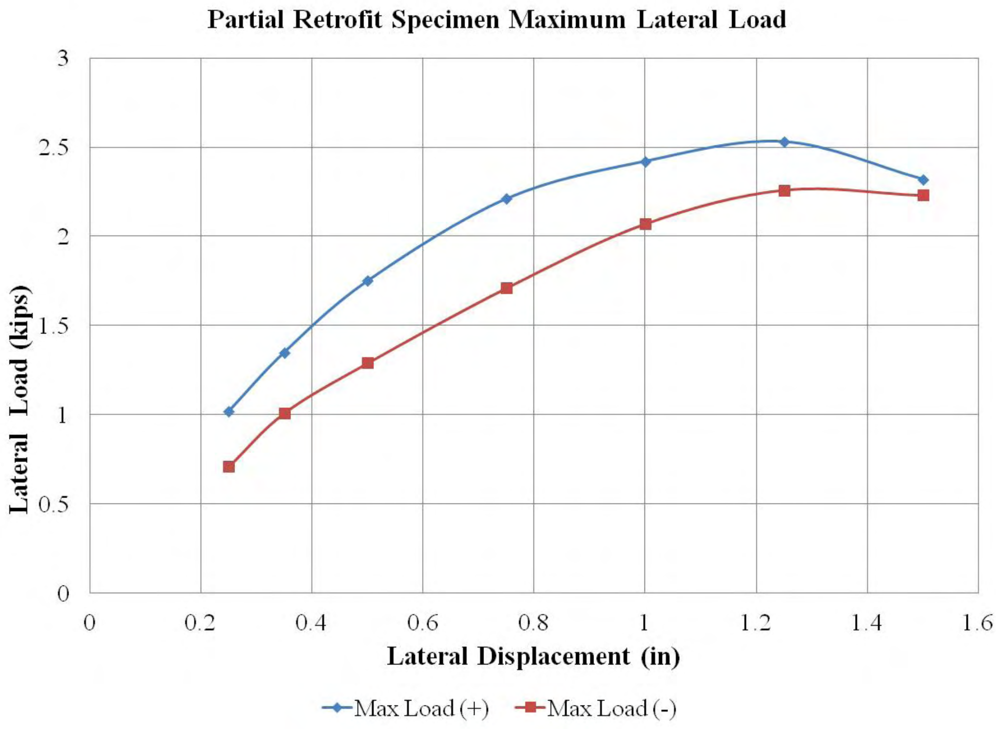

Figure 37: Partial Retrofit Specimen Maximum Lateral Load

The main failure mode of this specimen was the pull out of the toe-nails connecting the 2x4 diagonal knee braces to the 4x10 perimeter beams (Figure 38). Another failure observed was the pull out of the toe-nails connecting the 4x10 perimeter beams to the 4x10 girder beams (Figure 39).

Figure 38: Partial Retrofit Specimen Nail Pullout

Figure 39: 4x10 Perimeter Beam to 4x10 Girder Toe-nail Pull Out

4.3 Retrofit 1 Specimen

Retrofit 1 specimen appeared to perform significantly better than both the control specimen and the partial retrofit 1 specimen. When loading the frame, the max sustained load was approximately 3.8 kips during 1.5” cycling at 1Hz. The oscillation seen in Figure 40 and Figure 41 can be attributed to the sliding of the foundation blocks due to insufficient embedment depth in the soil bed. Under the cycling lateral loading, the soil was displaced, therefore providing very little passive lateral resistance. The shifting of the footing caused a reduction in the lateral load applied to the specimen by the actuator. The effective stiffness of the retrofit specimen was significantly higher than both the control specimen and the partial retrofit 1 specimen due to the added straps and connectors at all joint locations. The initial and effective stiffness values of retrofit specimen 1 are shown in Table 4 and Figure 42. The maximum lateral loads resisted during each set of cycling are shown in Table 4 and Figure 43.

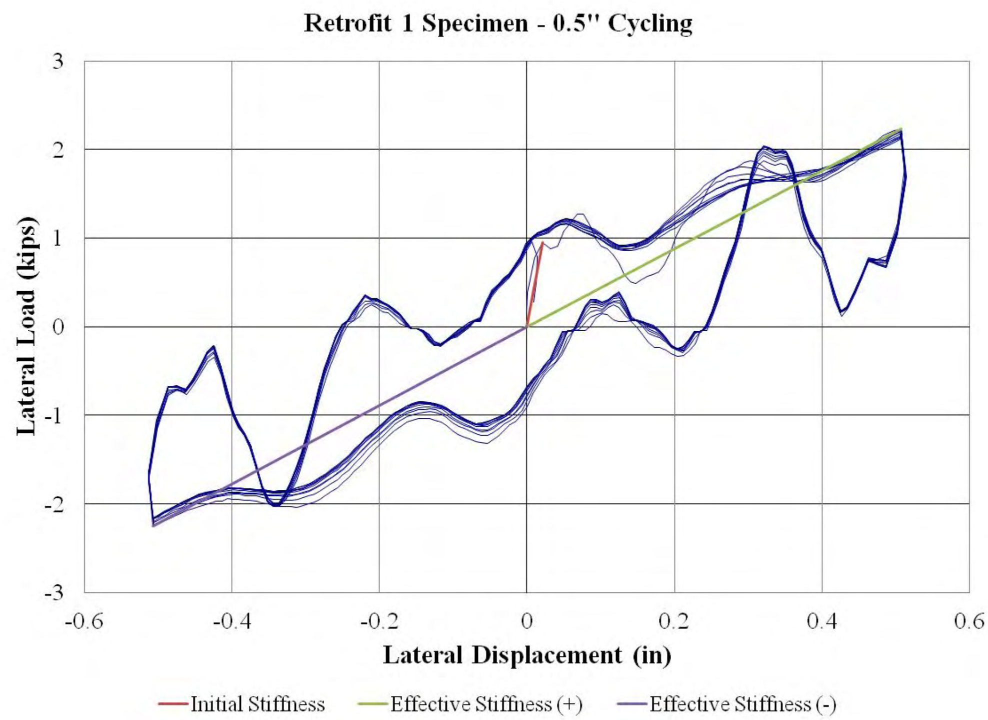

Figure 40: Retrofit 1 Specimen – 0.5" Cycling

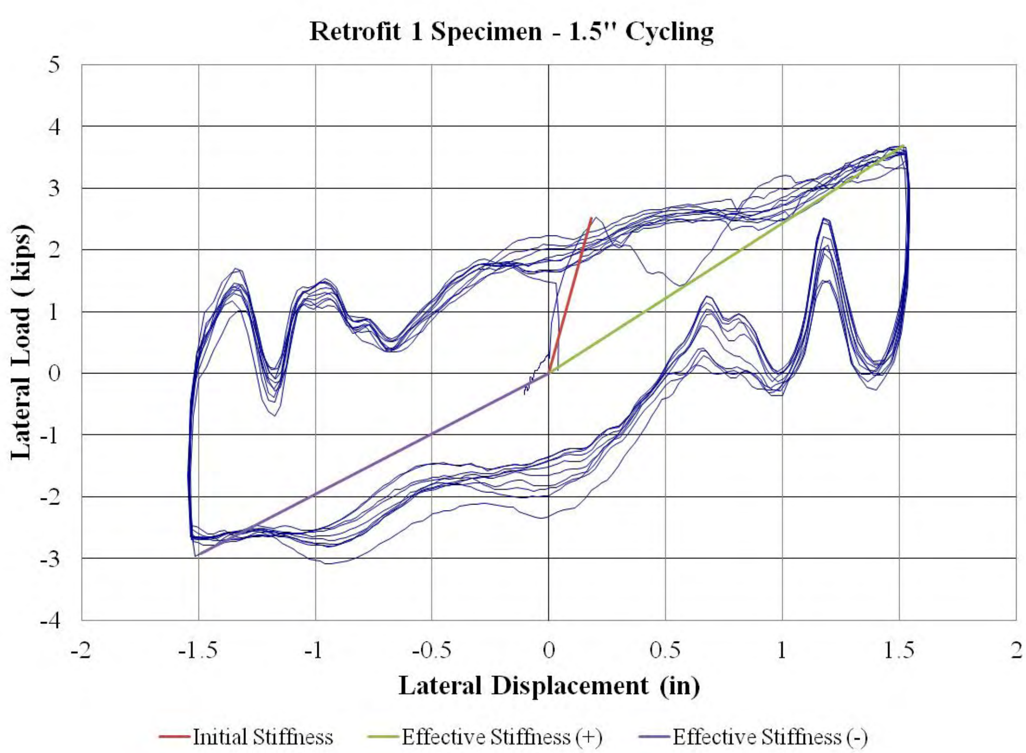

Figure 41: Retrofit 1 Specimen – 1.5" Cycling

Retrofit 1 Specimen		Stiffness			Max Lateral Load		Lateral Load / Approximate Weight	
Test	Displacement Amplitude (in)	Initial (k/in)	Effective (+) (k/in)	Effective (-) (k/in)	+ (kip)	- (kip)	+	-
1	0.25	37.81	6	-6.44	1.5	-1.61	0.50	0.54
2	0.35	68.51	5.46	-5.95	1.91	-2.08	0.64	0.69
3	0.5	44.31	4.47	-4.49	2.23	-2.25	0.74	0.75
4	0.75	65.73	3.59	-3.21	2.69	-2.41	0.90	0.80
5	1	59.06	3.01	-2.77	3.01	-2.77	1.00	0.92
6	1.25	42.03	2.58	-2.21	3.23	-2.77	1.08	0.92
7	1.5	13.98	2.46	-1.95	3.69	-2.92	1.23	0.97

Table 4: Retrofit 1 Specimen Stiffness

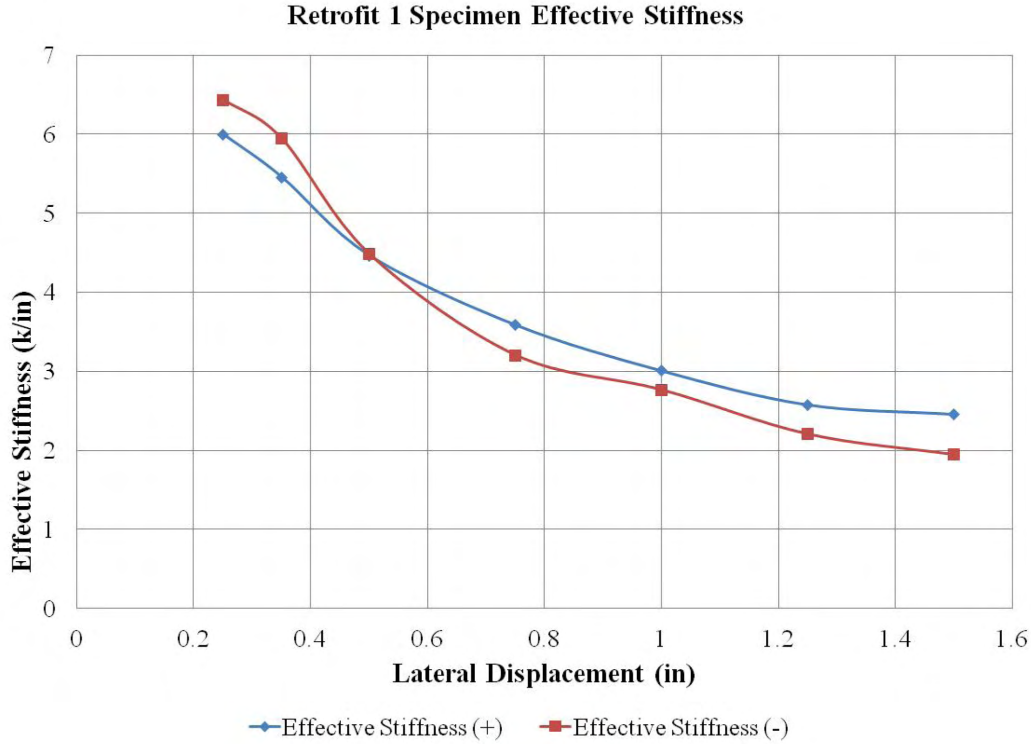

Figure 42: Retrofit 1 Specimen Effective Stiffness

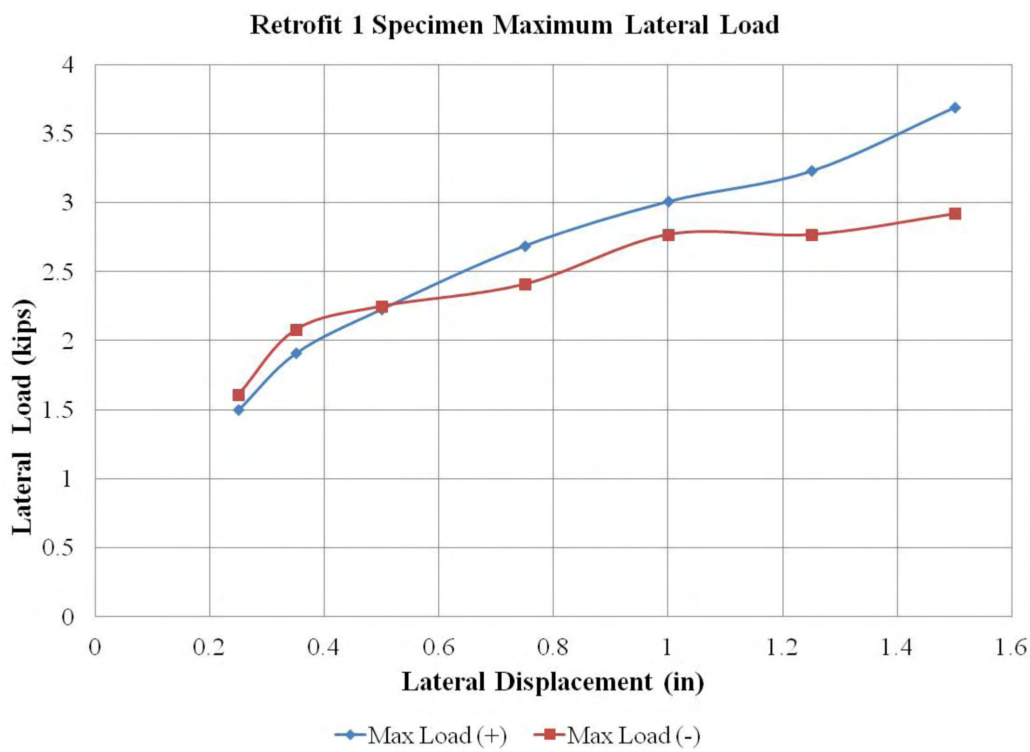

Figure 43: Retrofit 1 Specimen Maximum Lateral Load

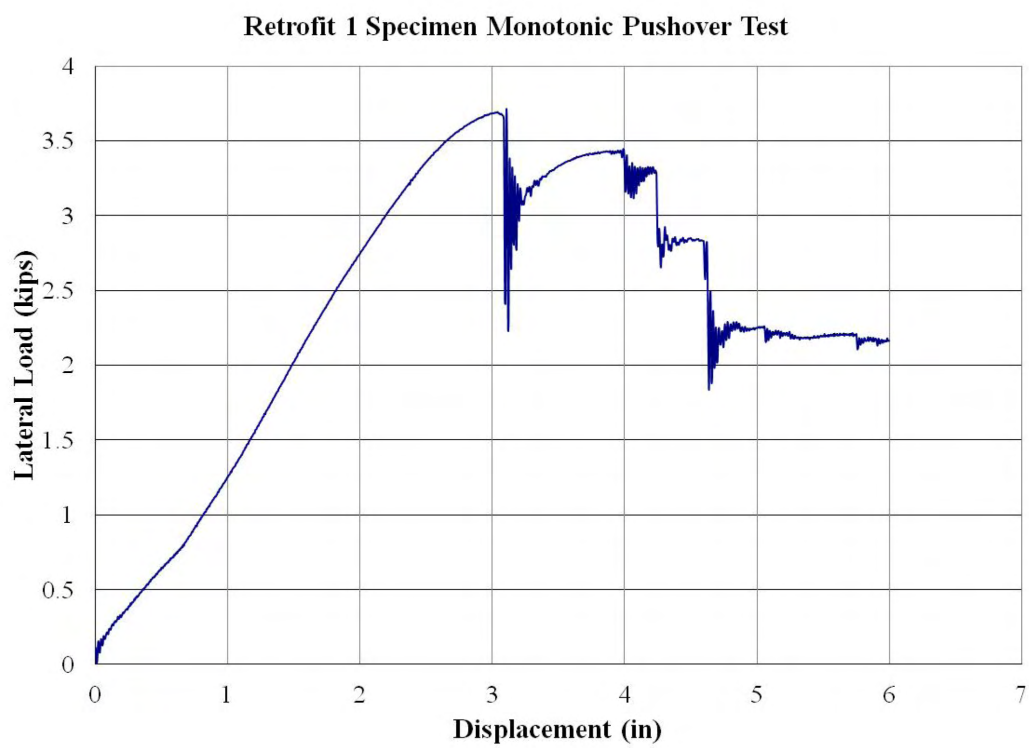

Figure 44: Retrofit 1 Specimen Monotonic Pushover Test

Retrofit 1 showed no signs of structural failure during cyclic lateral load testing. To determine the maximum resisted strength of the specimen, a monotonic pushover test was performed (Figure 44). The main failure mode of retrofit 1 specimen during the monotonic push over test was the failure of the connection between the HDU5 hold downs and the 4x4 post with the added 2x4 blocking. The 2 ½” long SDS screws were inadequate to connect the HDU5 through the 2x4 and ½” plywood spacers (Figure 45). Another failure observed was the pull out of the toe-nails connecting the 4x10 perimeter beams to the 4x10 girder beams (Figure 46).

Figure 45: HDU5 separation from 2x4 Blocking Separation From 4x4 Posts

Figure 46: 4x10 Perimeter Beam to 4x10 Girder Nail Pullout

4.4 Retrofit 2 Specimen

Retrofit 2 specimen was modified with plywood shear walls and new cast-in-place concrete footings. When loading the frame, the maximum sustained load recorded was approximately 7 kips during 2.5” cycling at 1Hz. The force displacement hysteretic response for retrofit specimen 2 appears to have little to no oscillation at all displacements (Figure 47 and Figure 48). The new concrete footings appear to provide better resistance to sliding than the retrofitted “tofu” block foundation used in the retrofit scheme 1. Retrofit 2 appeared to be much more rigid than the other specimens. A similar load to the max load achieved from the control specimen of 3.1 kips was obtained with 0.35” cyclic loading at 1 Hz as opposed to 2” cyclic loading for the control specimen. Retrofit 2 specimen had a significantly higher effective stiffness than the other test specimens due to the new foundation and added shear walls. The initial and effective stiffness values and the maximum lateral load values for retrofit specimen 2 are shown in Table 5 and plotted in Figure 49 and Figure 50.

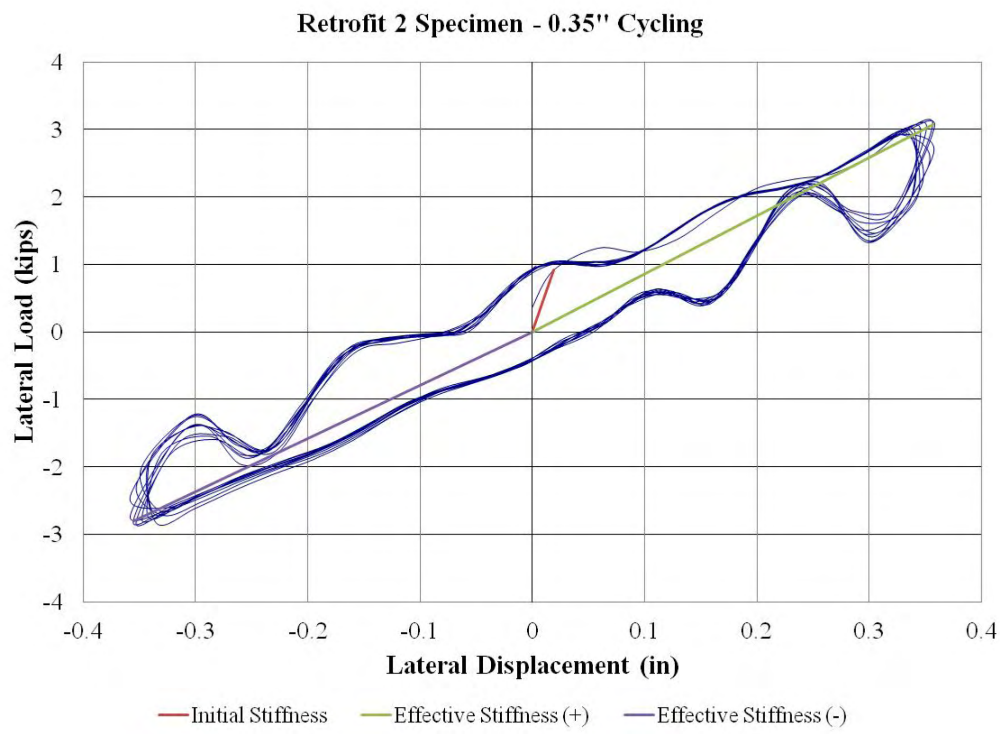

Figure 47: Retrofit 2 Specimen – 0.35” Cycling

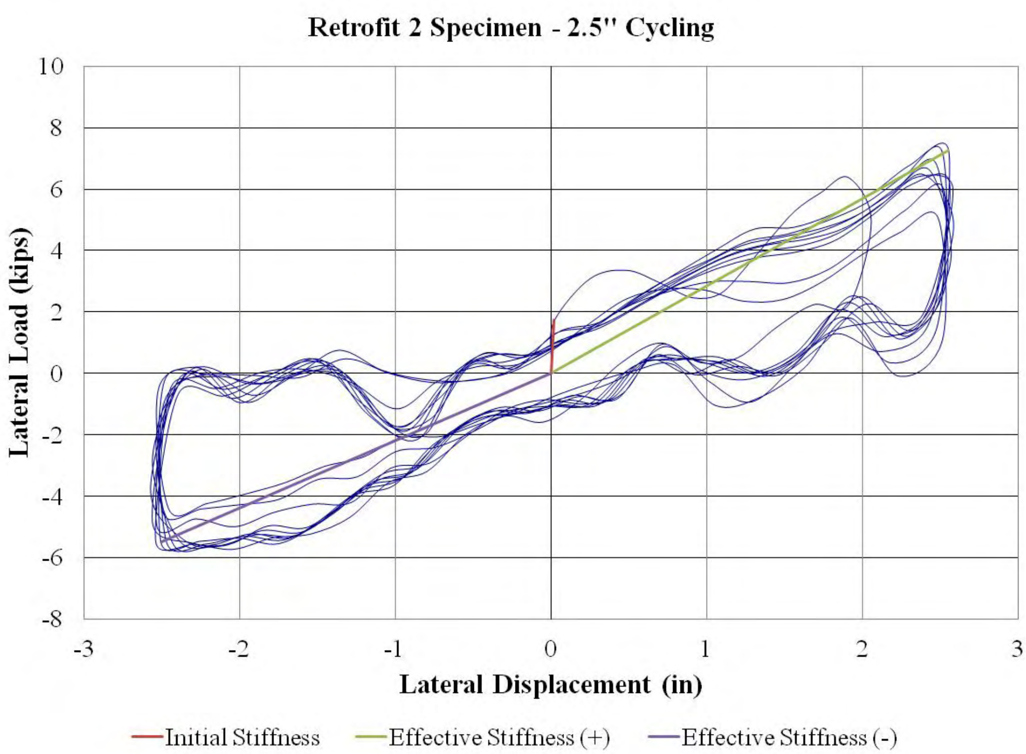

Figure 48: Retrofit 2 Specimen – 2.5” Cycling

Retrofit 2 Specimen		Stiffness			Max Lateral Load		Lateral Load / Approximate Weight	
Test	Displacement Amplitude (in)	Initial (k/in)	Effective (+) (k/in)	Effective (-) (k/in)	+ (kip)	- (kip)	+	-
1	0.1	73.23	12.99	-8.84	1.3	-0.88	0.43	0.29
2	0.15	44.65	11.43	-9.53	1.71	-1.43	0.57	0.48
3	0.2	41.08	10.54	-9.27	2.11	-1.85	0.70	0.62
4	0.25	20.21	9.57	-9.44	2.39	-2.36	0.80	0.79
5	0.3	28.07	9.54	-8.88	2.86	-2.66	0.95	0.89
6	0.35	48.47	8.79	-8	3.08	-2.8	1.03	0.93
7	0.4	47.17	8.34	-7.41	3.34	-2.96	1.11	0.99
8	0.5	25.4	7.62	-6.78	3.81	-3.39	1.27	1.13
9	0.6	28.79	6.65	-5.95	3.99	-3.57	1.33	1.19
10	0.75	36.46	5.81	-5.28	4.35	-3.96	1.45	1.32
11	0.88	20.81	5.32	-4.82	4.66	-4.22	1.55	1.41
12	1	19.69	4.92	-4.47	4.92	-4.47	1.64	1.49
13	1.13	16.13	4.47	-4.09	5.03	-4.6	1.68	1.53
14	1.25	24.18	4.14	-3.59	5.17	-4.49	1.72	1.50
15	1.38	19.71	3.9	-3.6	5.36	-4.95	1.79	1.65
16	1.5	15.13	3.81	-3.43	5.71	-5.15	1.90	1.72
17	1.75	17.77	3.49	-2.91	6.11	-5.09	2.04	1.70
18	2	18.62	3.2	-2.59	6.4	-5.18	2.13	1.73
19	2.5	83.39	2.91	-2.2	7.27	-5.49	2.42	1.83

Table 5: Retrofit 2 Specimen Stiffness

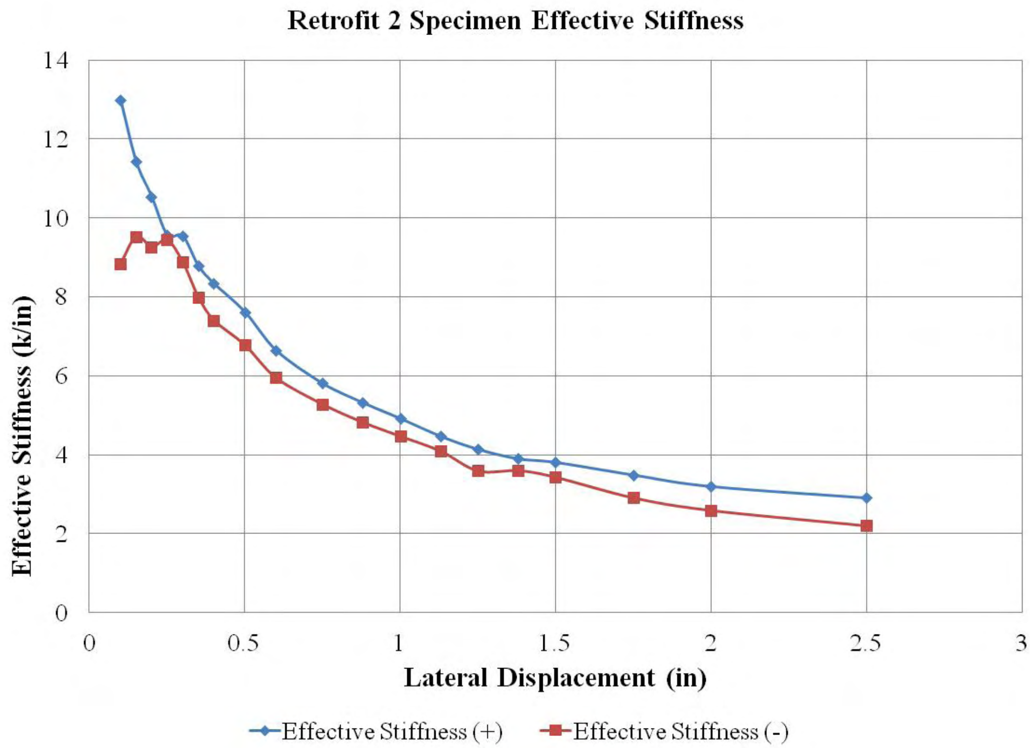

Figure 49: Retrofit 2 Specimen Effective Stiffness

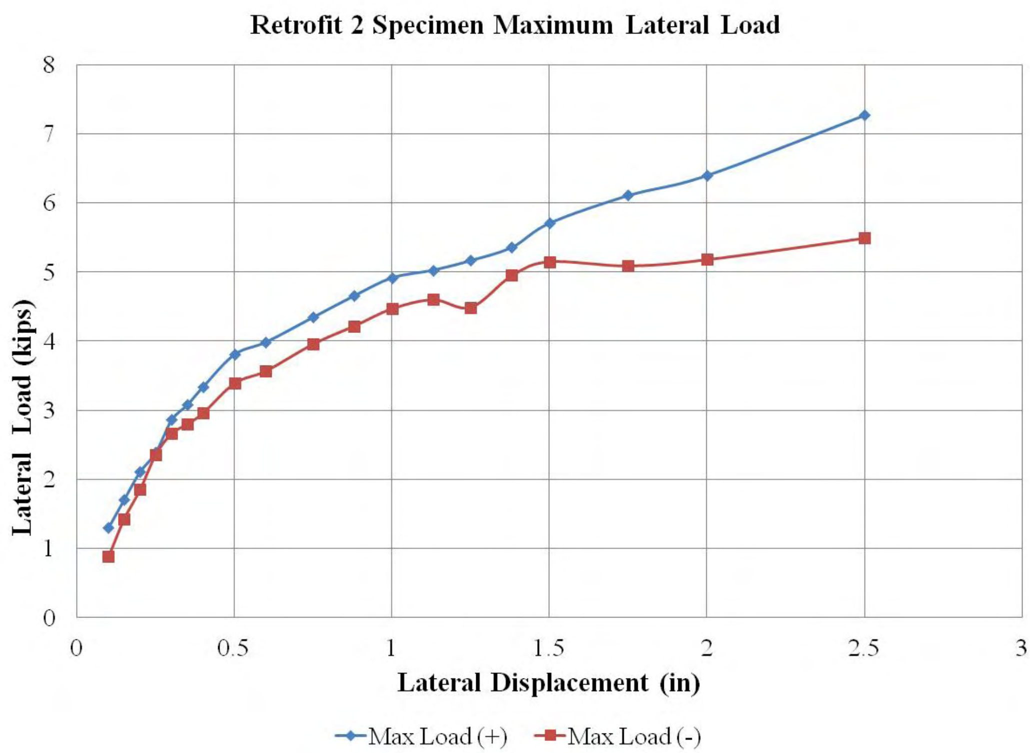

Figure 50: Retrofit 2 Specimen Maximum Lateral Load

The main failure mode of the retrofit 2 specimen was the failure of the 8d nails connecting the plywood shear walls to the 2x4 studs. During the 2.5” cyclic lateral loading, the 8d by 2 ½” long common nails sheared off along the lower panel edges (Figure 51).

Figure 51: Plywood Shearwall Edge Nailing Shear Failure

4.5 Specimen Comparison

Figure 52 and Figure 53 show typical single cyclic responses of each of the specimens super imposed on one another to compare their overall relative performance. The behaviors of the control, partial retrofit, and retrofit 1 specimens all appear to have similar force displacement curves. They all share the same oscillations in the curve due to the slipping of the foundation blocks under the cyclic lateral loading. Retrofit 2 does not show the same oscillations as it was retrained at the base to prevent the sliding to simulate the soil resistance by being embedded deeper in the soil when constructed in the field.   Figure 54 and Figure 55 show the effective stiffness of each of the specimens to compare their overall relative performance. Each specimen's effective stiffness decreased as lateral displacement was increased. Retrofit specimen 2 provided the greatest increase in effective stiffness when compared to the un-retrofitted control specimen. Figure 56 and Figure 57 show the maximum resisted lateral load of each of the specimens to compare their overall relative performance. Each specimen's maximum resisted lateral load increased as lateral displacement was increased. Retrofit specimen 2 provided the greatest increase in maximum lateral load resisted when compared to the un-retrofitted control specimen.

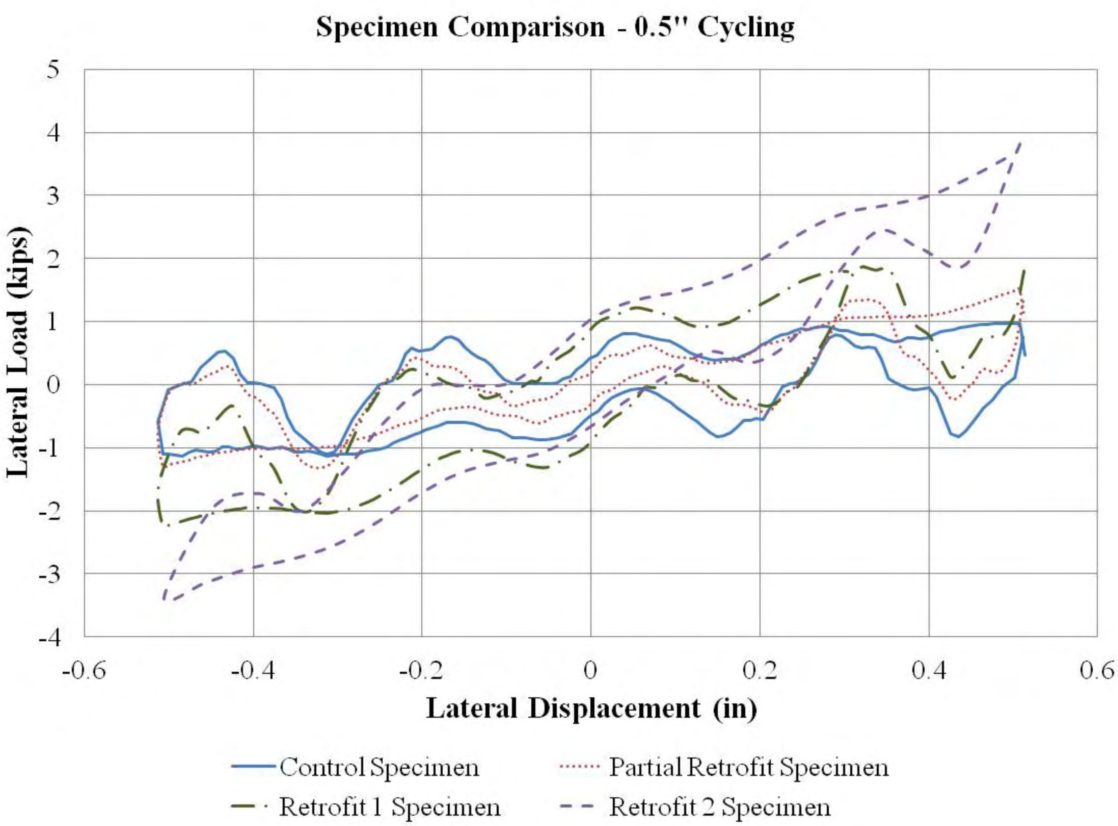

Figure 52: Specimen Comparison – 0.5" Cycling

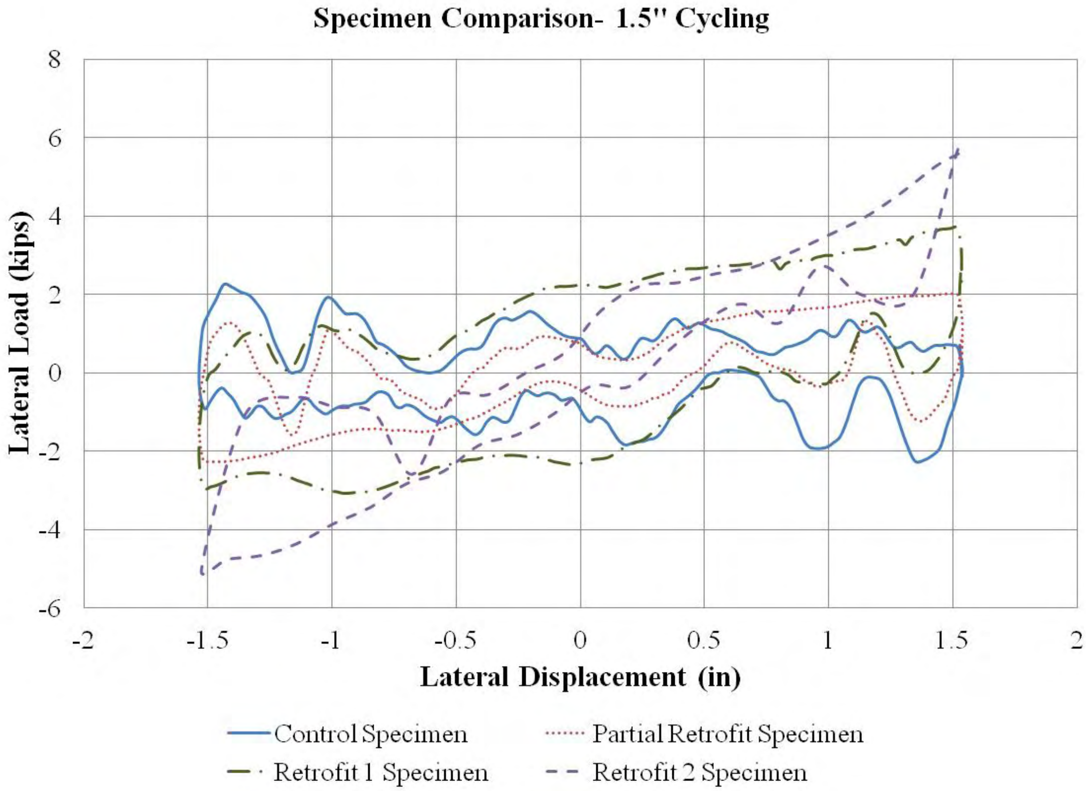

Figure 53: Specimen Comparison – 1.5" Cycling

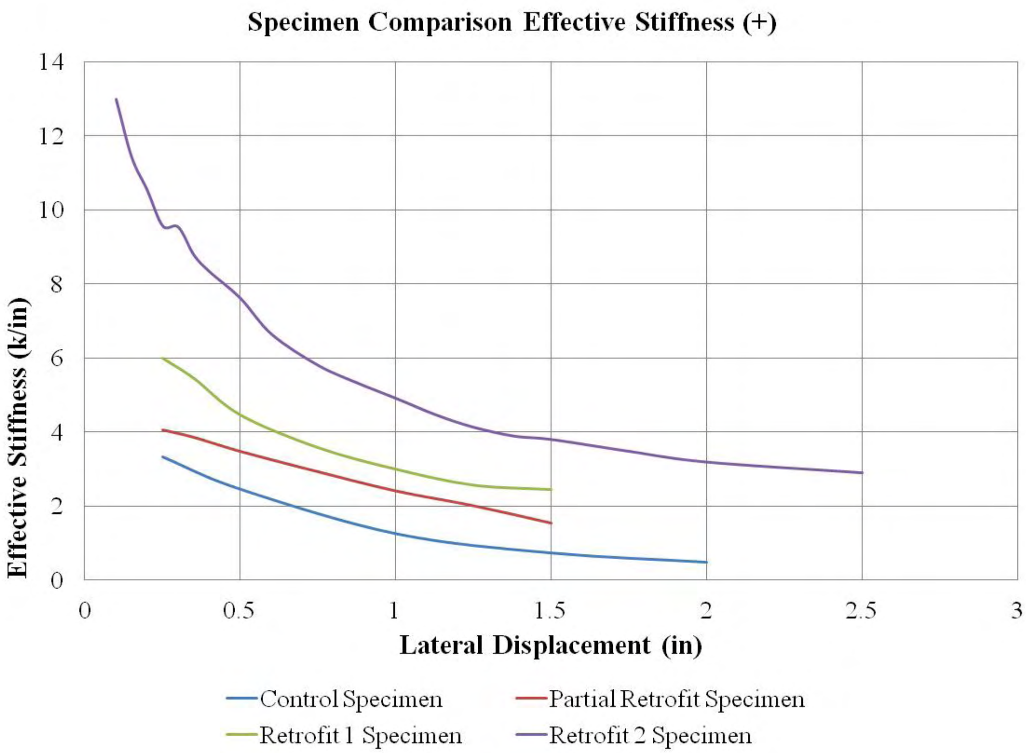

Figure 54: Specimen Comparison Effective Stiffness (+)

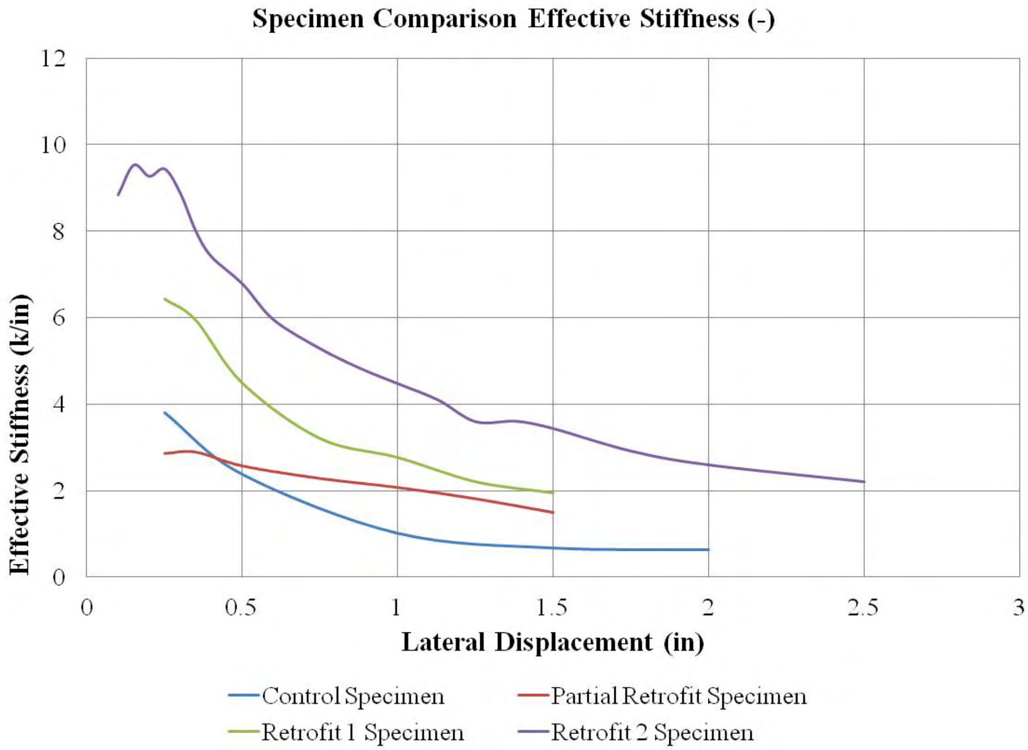

Figure 55: Specimen Comparison Effective Stiffness (-)

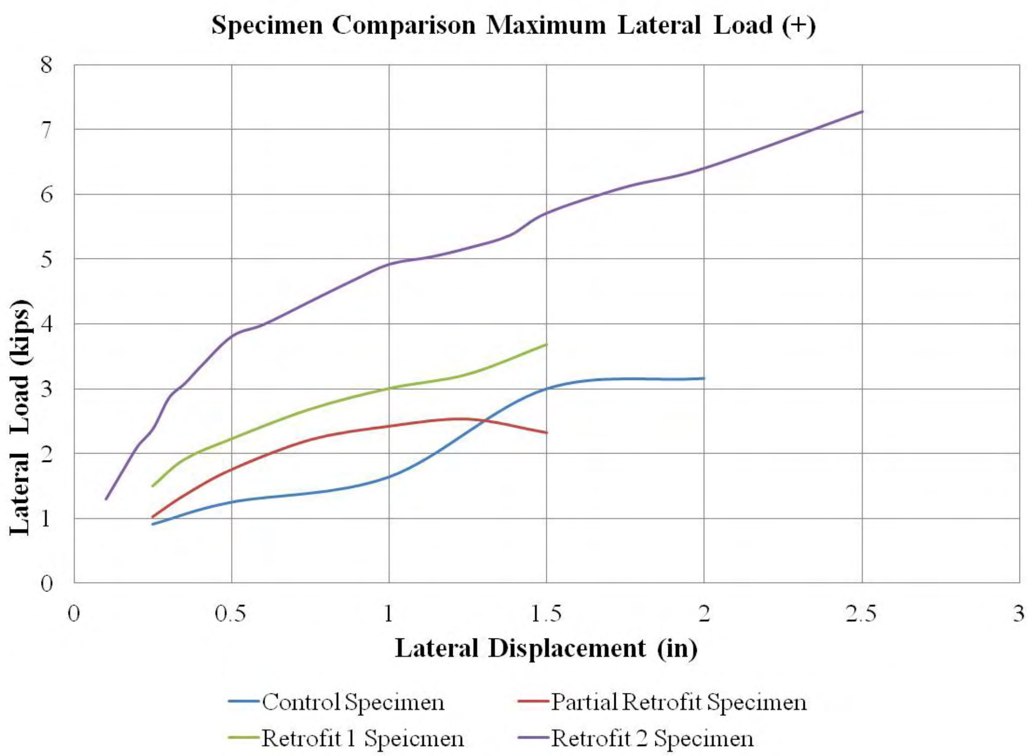

Figure 56: Specimen Comparison Maximum Lateral Load (+)

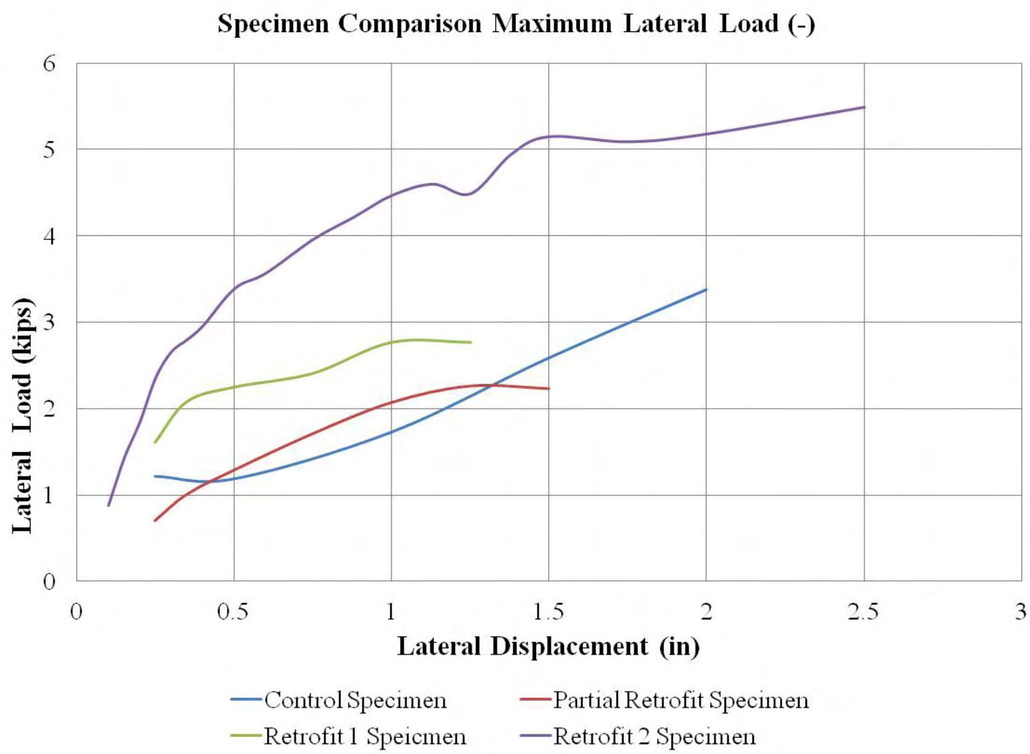

Figure 57: Specimen Comparison Maximum Lateral Load (-)

5. Summary and Conclusions

A research study was performed to evaluate two seismic retrofit schemes proposed to improve the lateral resistance of post and pier foundation homes in Hawaii. The first retrofit scheme involved anchoring the posts to the foundation and installing metal plate connectors at all joints in the post and pier framing. The second retrofit scheme involved adding a new 2x4 stud wall plywood shearwall and a new plywood sub diaphragm to an existing floor system and pouring new cast-in-place concrete footings. The retrofitted post and pier foundations when subjected to cyclic lateral loading simulating seismic ground shaking to compare their performance with that of an un-retrofitted control specimen. In addition to validating the two retrofit designs, this project will provide a video tool to encourage implementation of these retrofits by homeowners. The video will be posted on appropriate websites and combined with an assisting web-based expert system for selection of the retrofit system.

Based on the cyclic lateral loading tests performed in this study, the following conclusions were drawn:

1) When loaded with approximately the same cyclic lateral loading as the failure load of the un-retrofitted frame, both retrofit option 1 and retrofit option 2 showed no signs of failure. Retrofit 1 with the hold-downs, ties and straps installed at all the foundation blocks, posts, and braces performed as designed, as did retrofit 2 with plywood shear walls and sub diaphragm.
2) Based on the performance of a partially retrofitted foundation, it was determined that a partial retrofit anchoring only the post to the foundation blocks appeared to be detrimental to the overall seismic performance of the assembly.
3) The effective stiffness of the retrofit 1 specimen was approximately double that of the control specimen at all levels of cycling. The effective stiffness of the retrofit 2 specimen was approximately four times that of the control specimen.
4) The strength of the retrofit 1 specimen was approximately double that of the control specimen at all levels of cycling. The strength of the retrofit 2 specimen was approximately three times that of the control specimen.

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Robertson, Ian N. and Chock, Gary (2009). "Structural Seismic Retrofits For Single Family Residences With Post and Pier Foundations", Honolulu, HI.

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Simpson Strong-Tie (2011). Retrieved September 2011, from http://www.strongtie.com/.

USGS (2006). "Magnitude 6.7 – Hawaii Region, Hawaii". Retrieved September 2011 from http://earthquake.usgs.gov/earthquakes/eqinthenews/2006/ustwbh/

Appendix

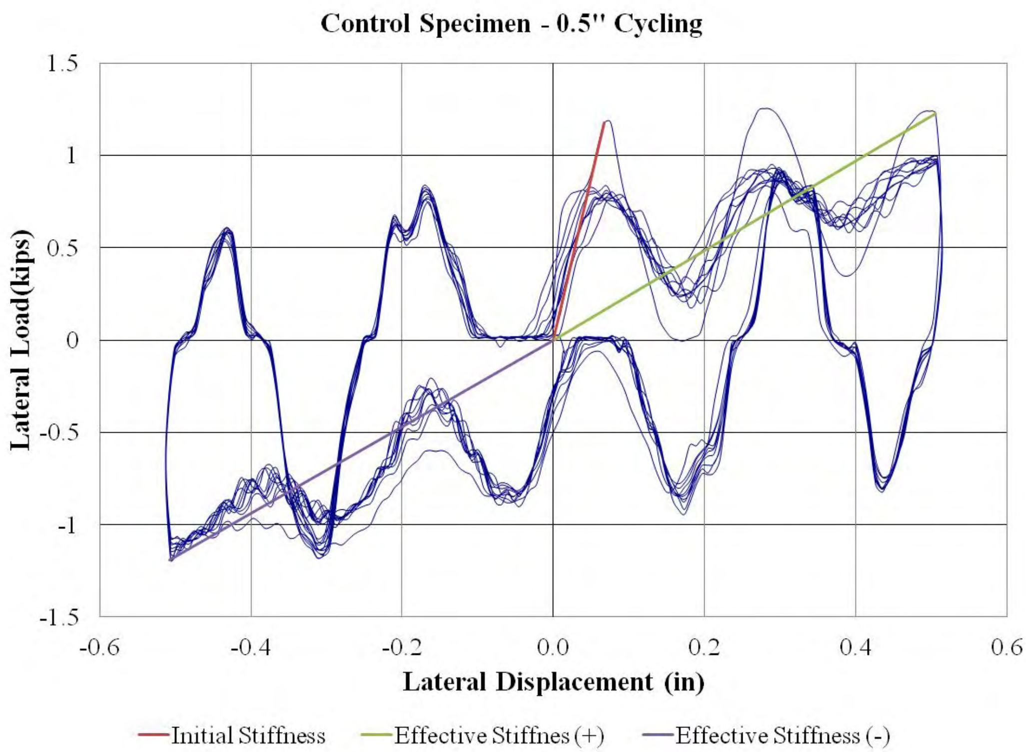

Figure 58: Control Specimen – 0.5” Cycling

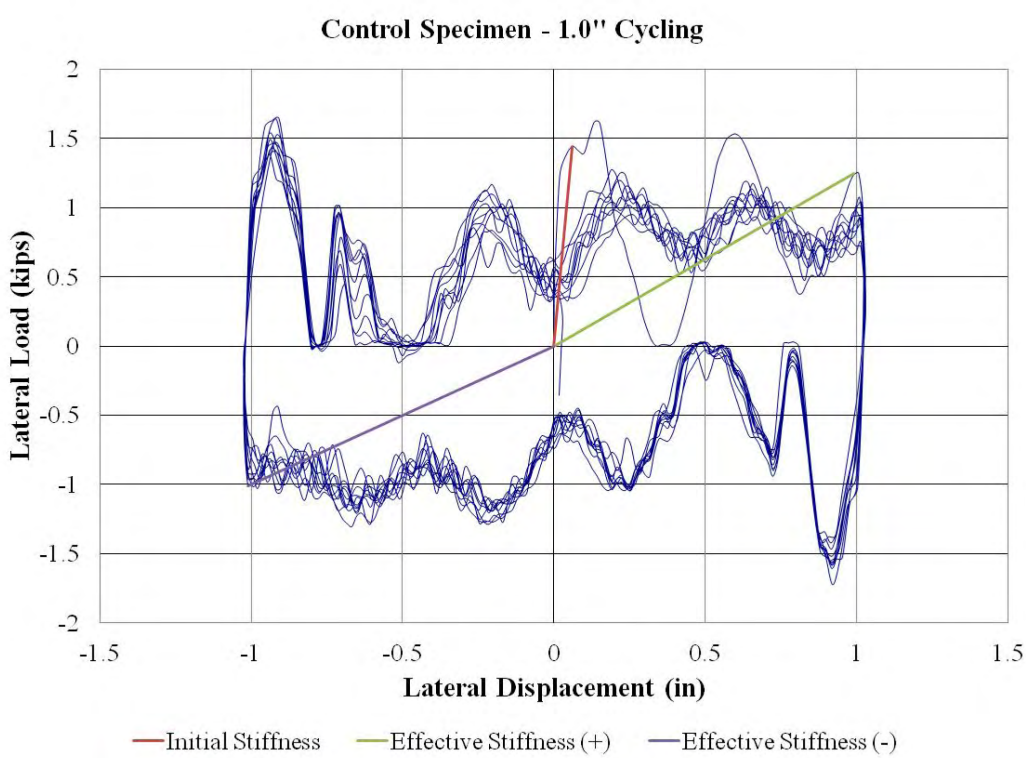

Figure 59: Control Specimen – 1.0” Cycling

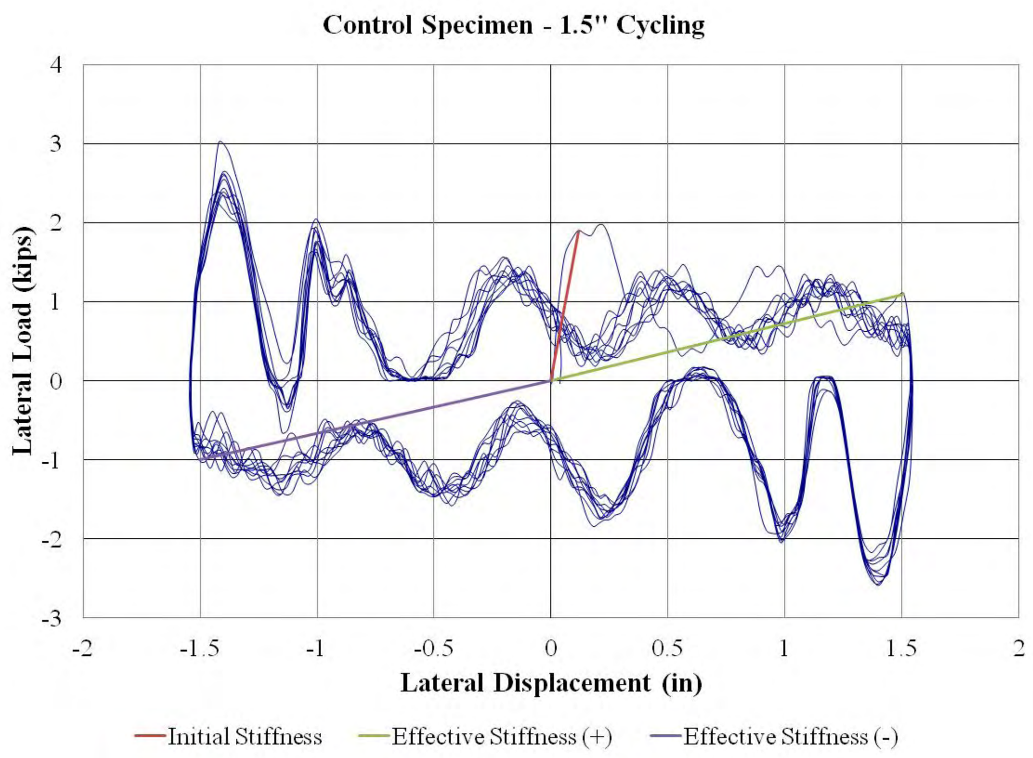

Figure 60: Control Specimen - 1.5” Cycling

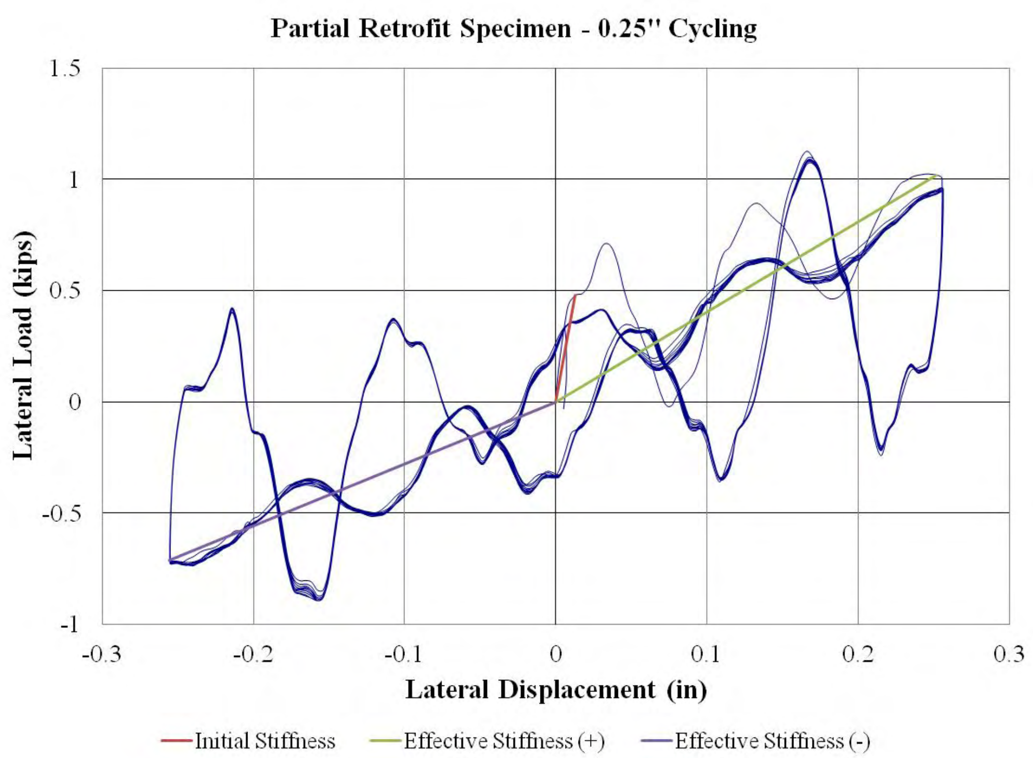

Figure 61: Partial Retrofit Specimen - 0.25” Cycling

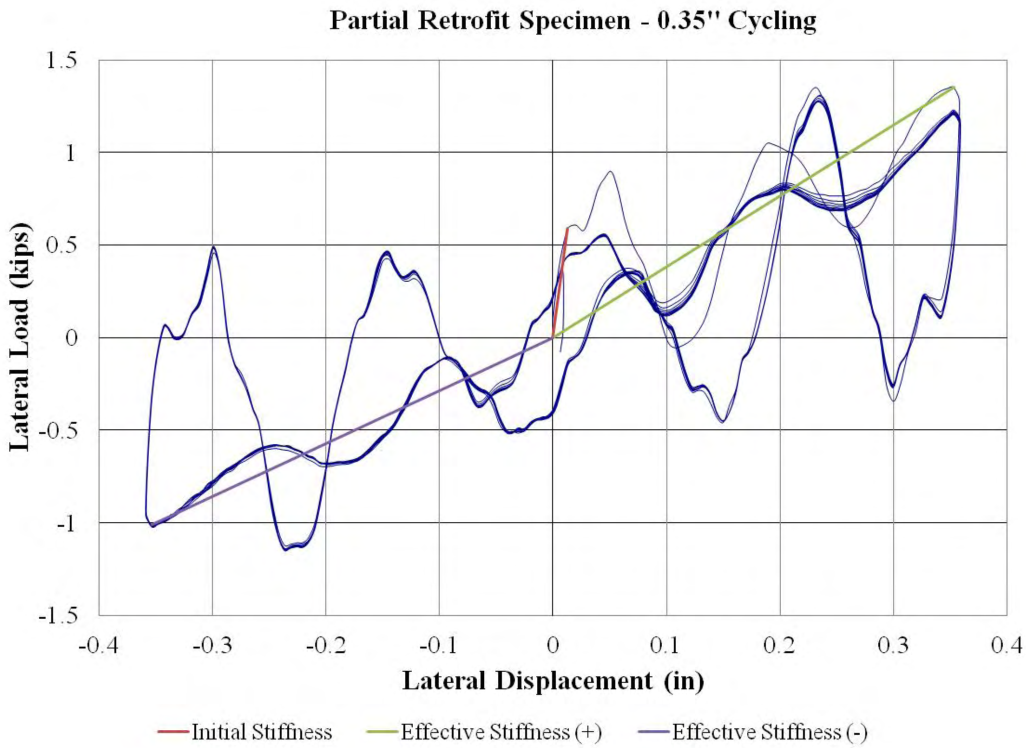

Figure 62: Partial Retrofit Specimen – 0.35” Cycling

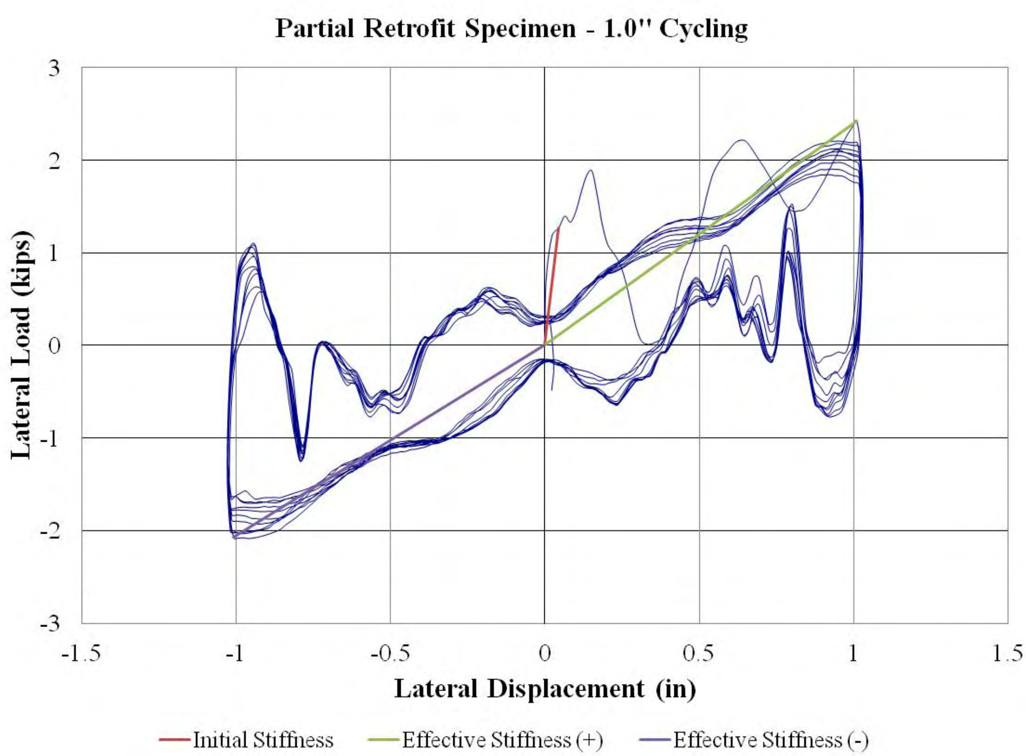

Figure 63: Partial Retrofit Specimen – 1.0” Cycling

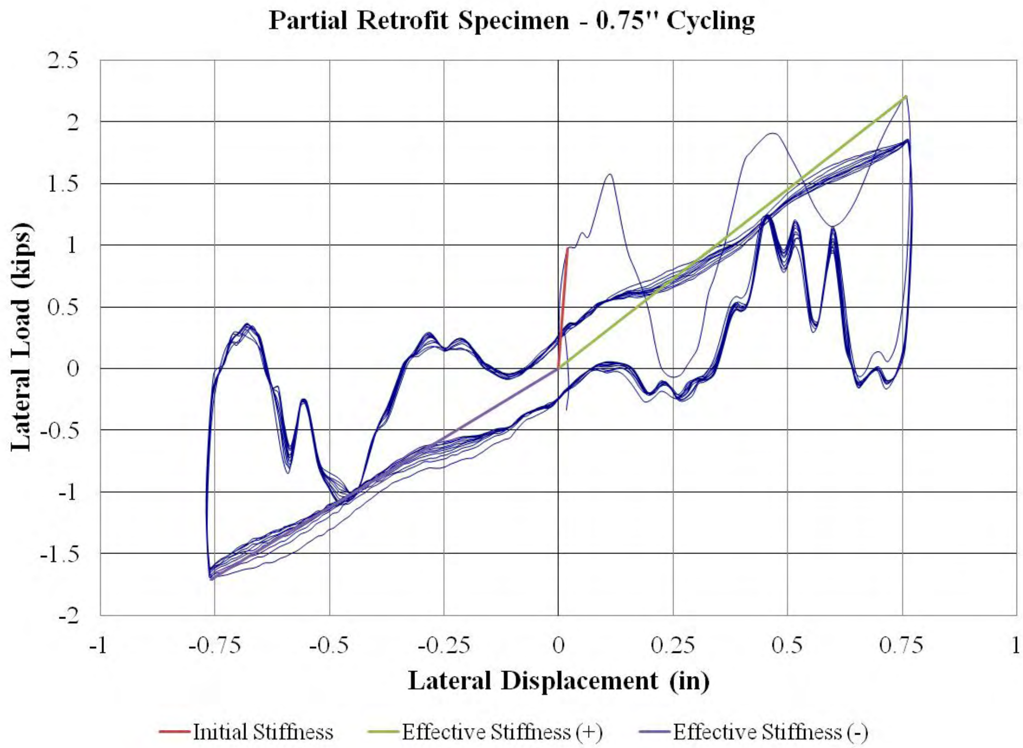

Figure 64: Partial Retrofit Specimen – 0.75” Cycling

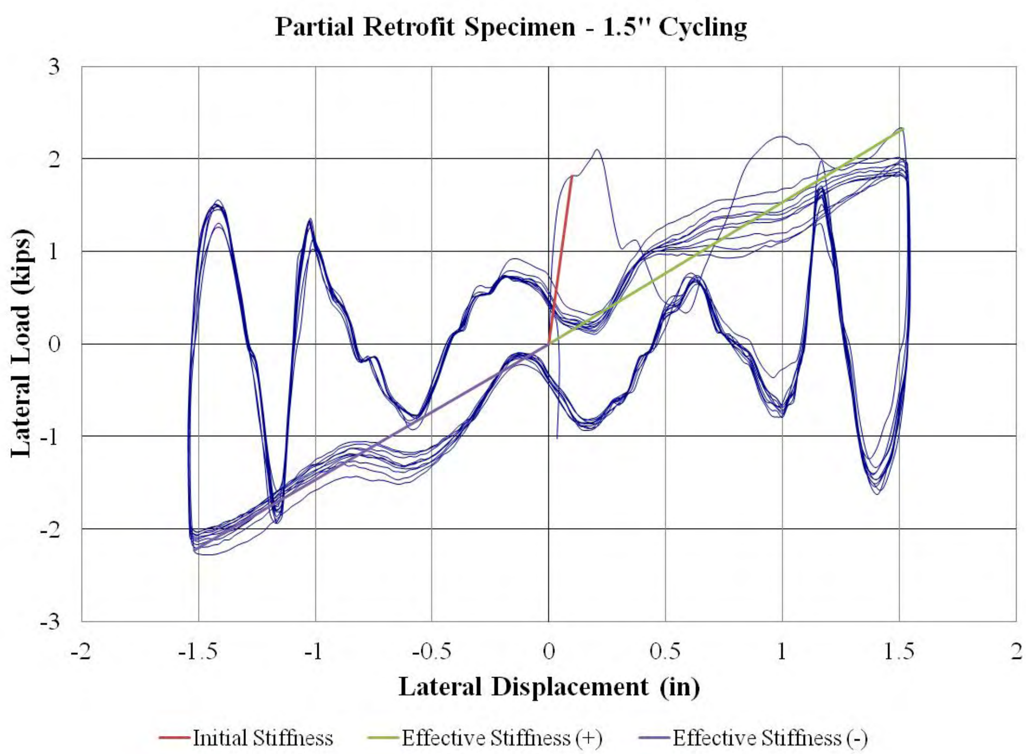

Figure 65: Partial Retrofit Specimen – 1.5” Cycling

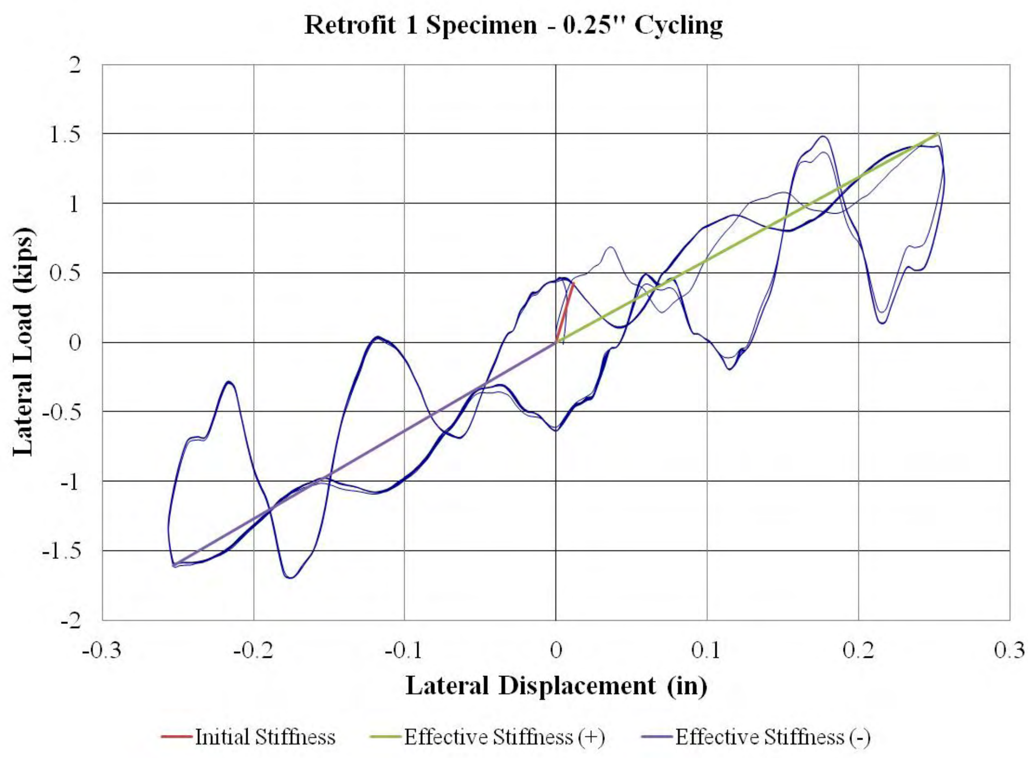

Figure 66: Retrofit 1 Specimen – 0.25" Cycling

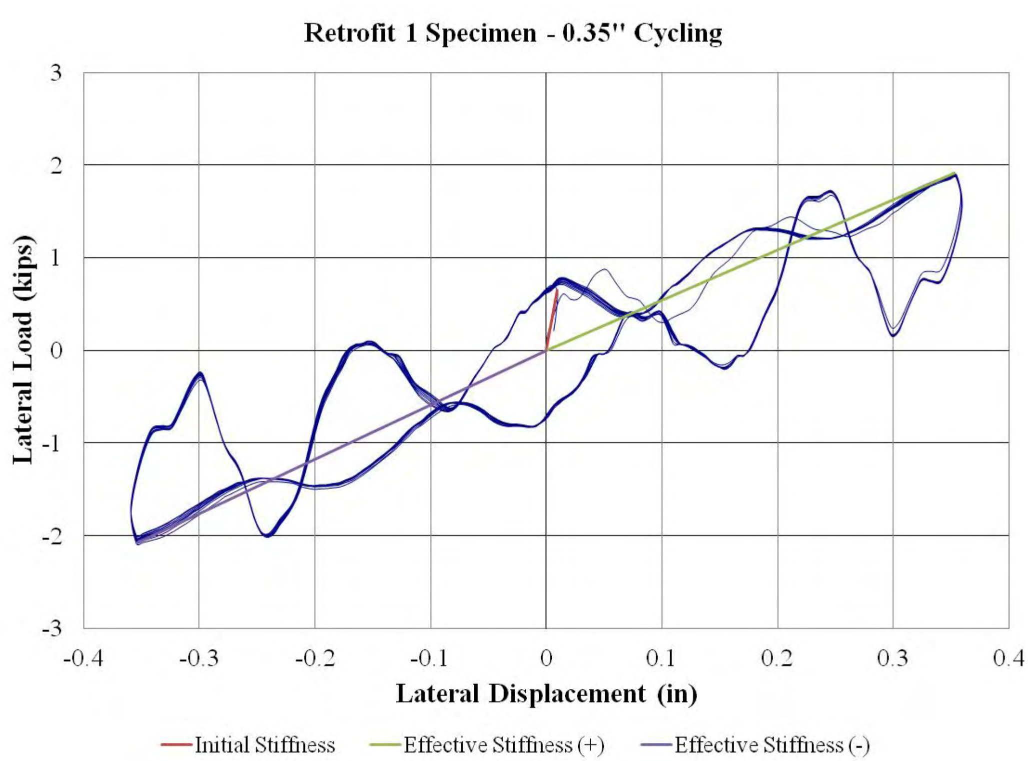

Figure 67: Retrofit 1 Specimen – 0.35" Cycling

Figure 68: Retrofit 1 Specimen – 0.75” Cycling

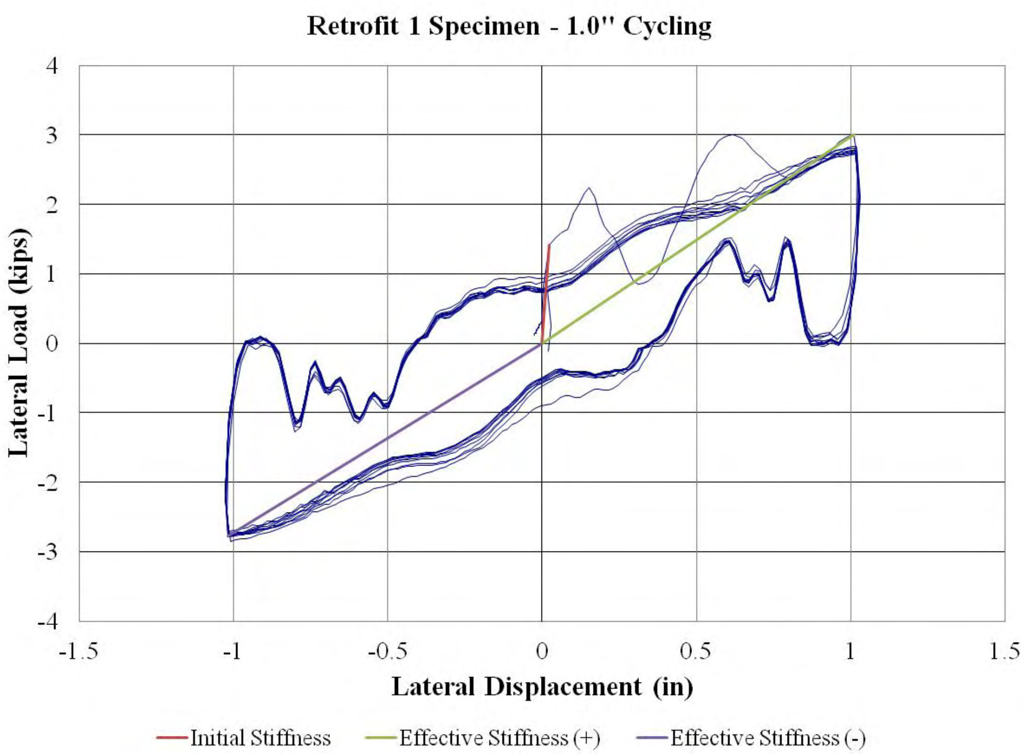

Figure 69: Retrofit 1 Specimen – 1.0” Cycling

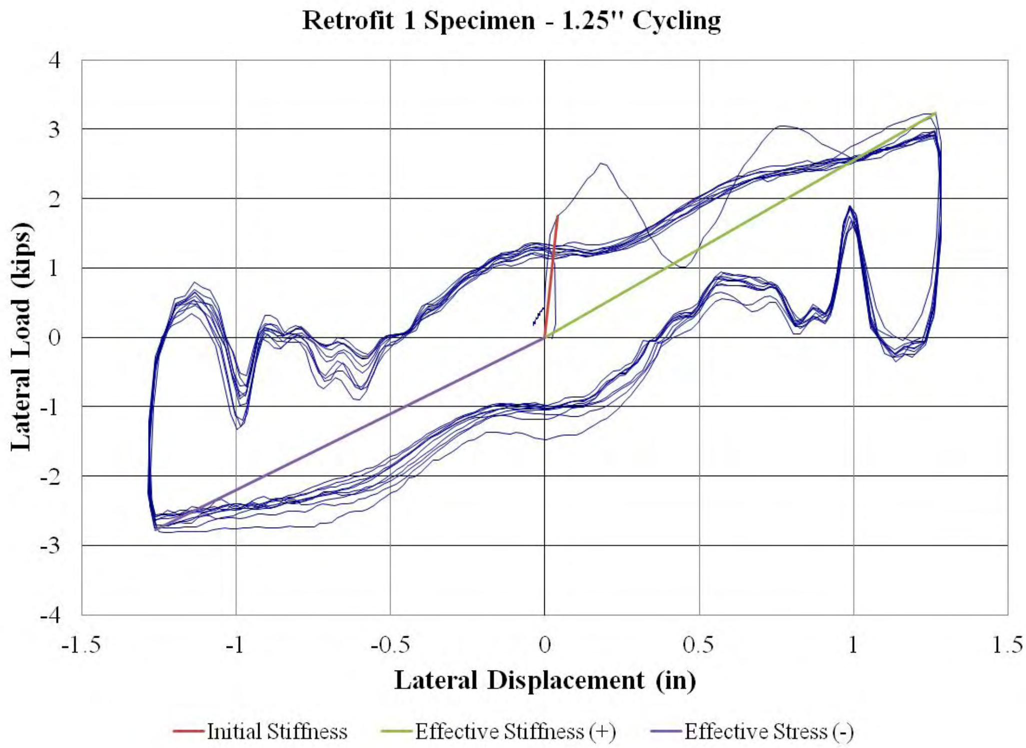

Figure 70: Retrofit 1 Specimen – 1.25” Cycling

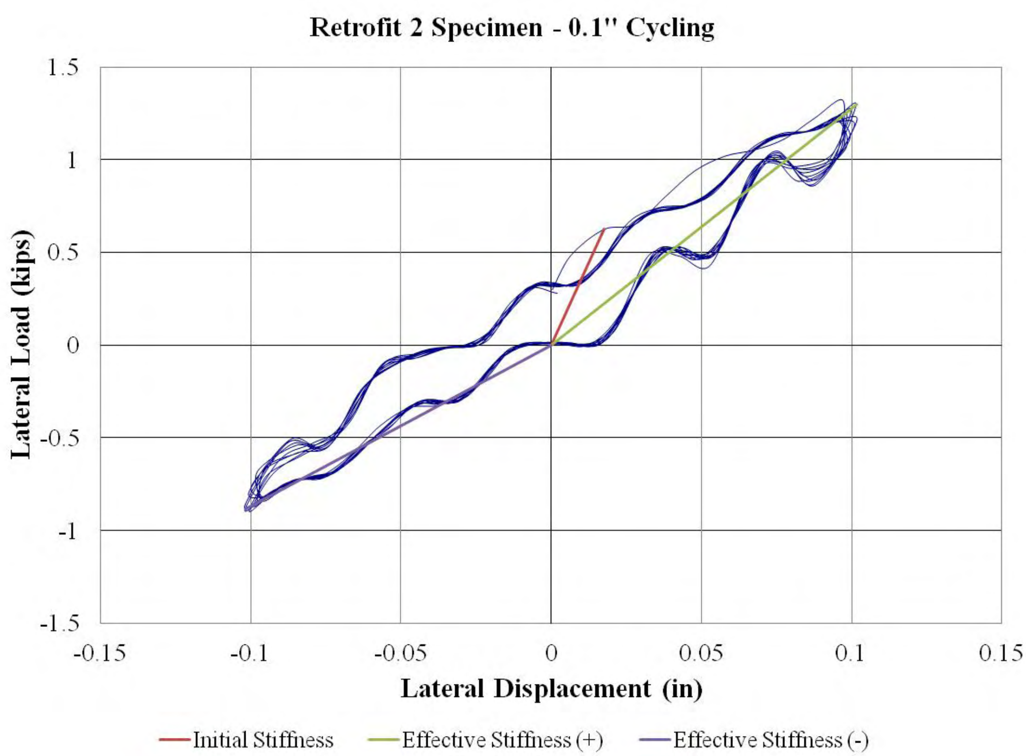

Figure 71: Retrofit 2 Specimen – 0.1” Cycling

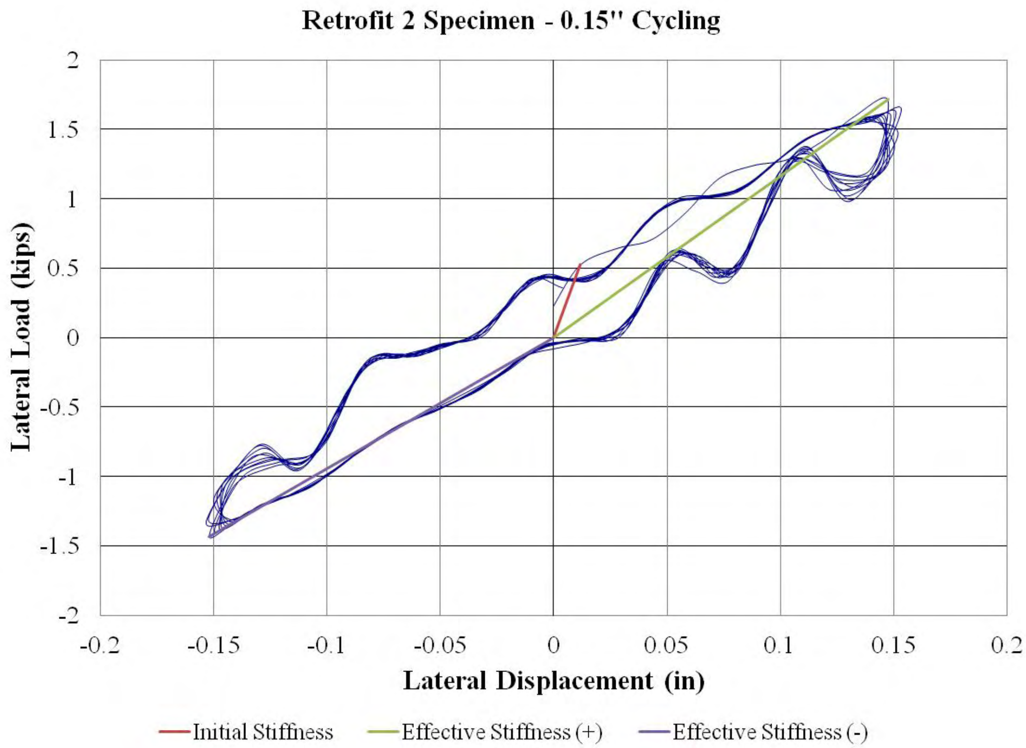

Figure 72: Retrofit 2 Specimen – 0.15” Cycling

Figure 73: Retrofit 2 Specimen – 0.2” Cycling

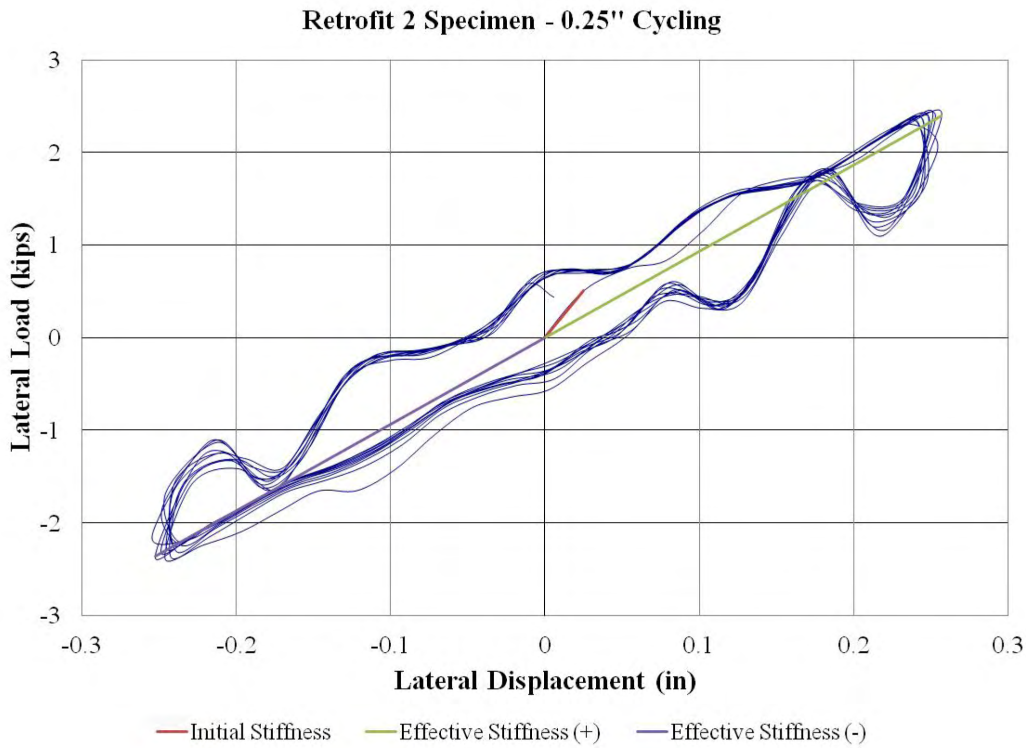

Figure 74: Retrofit 2 Specimen – 0.25" Cycling

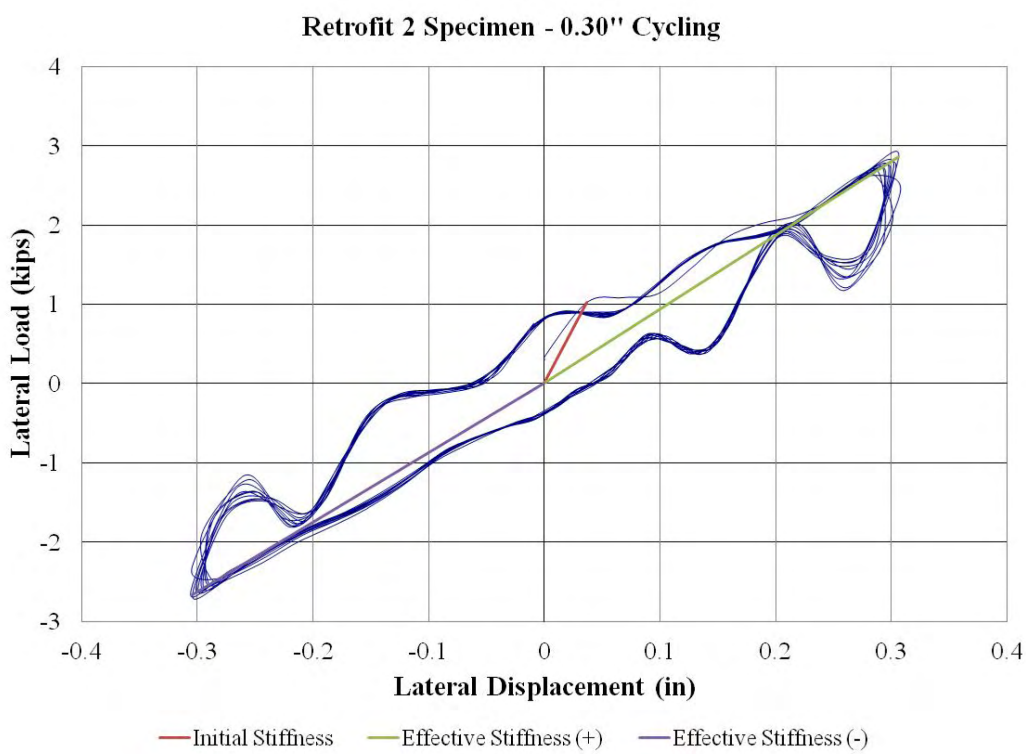

Figure 75: Retrofit 2 Specimen – 0.30" Cycling

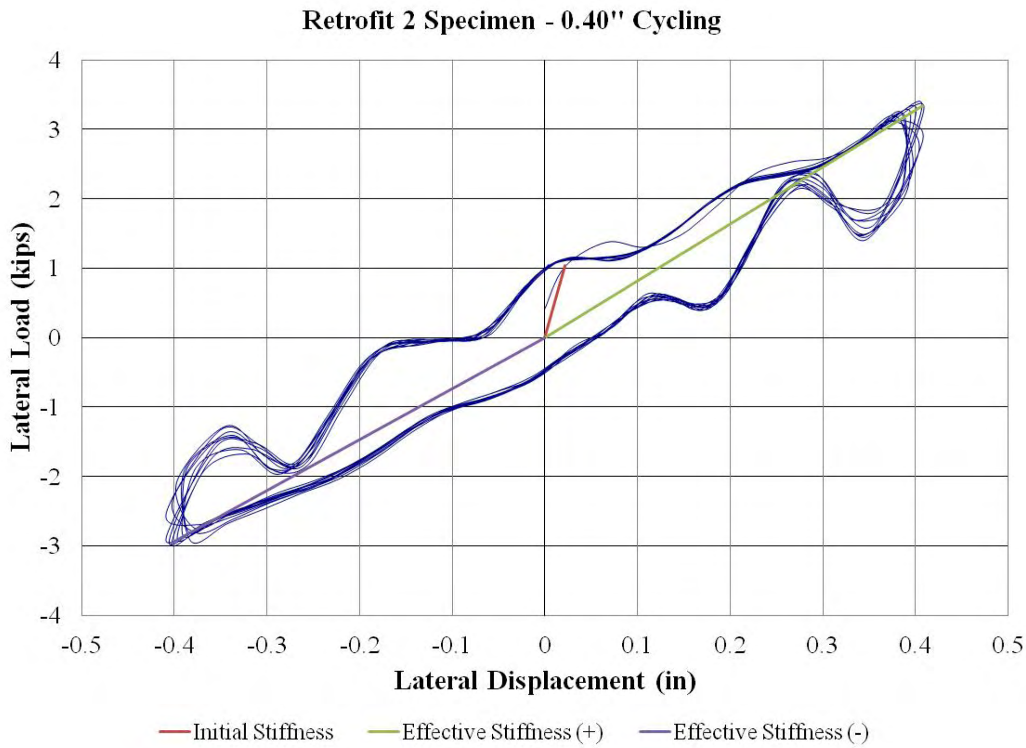

Figure 76: Retrofit 2 Specimen – 0.40” Cycling

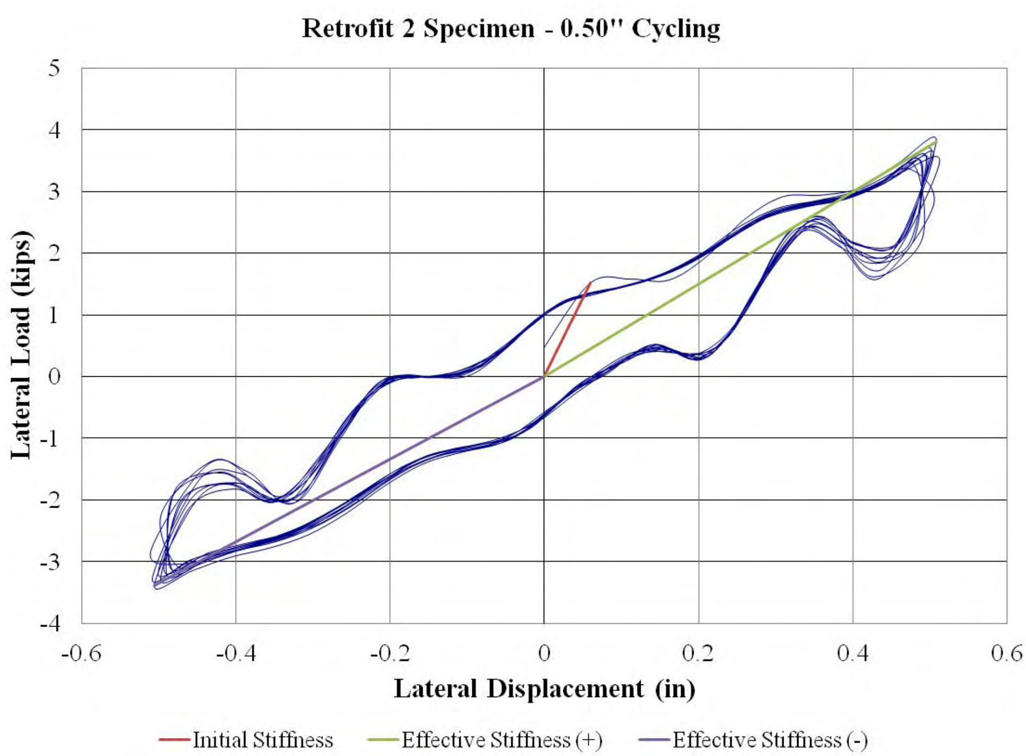

Figure 77: Retrofit 2 Specimen- 0.50” Cycling

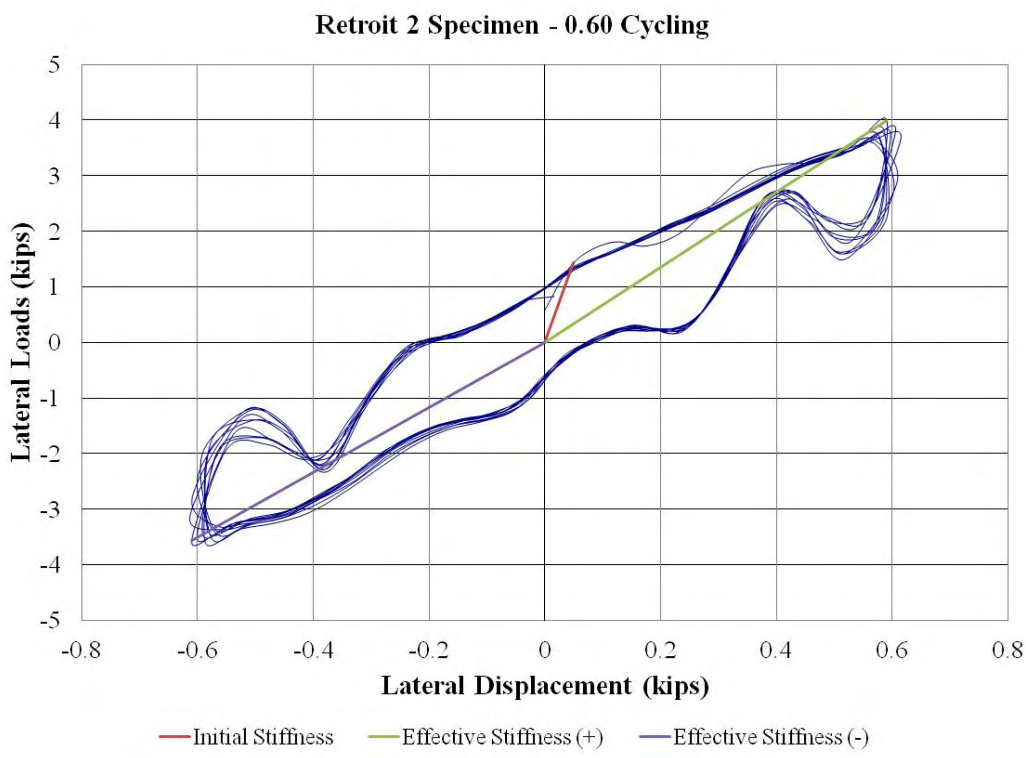

Figure 78: Retrofit 2 Specimen – 0.60” Cycling

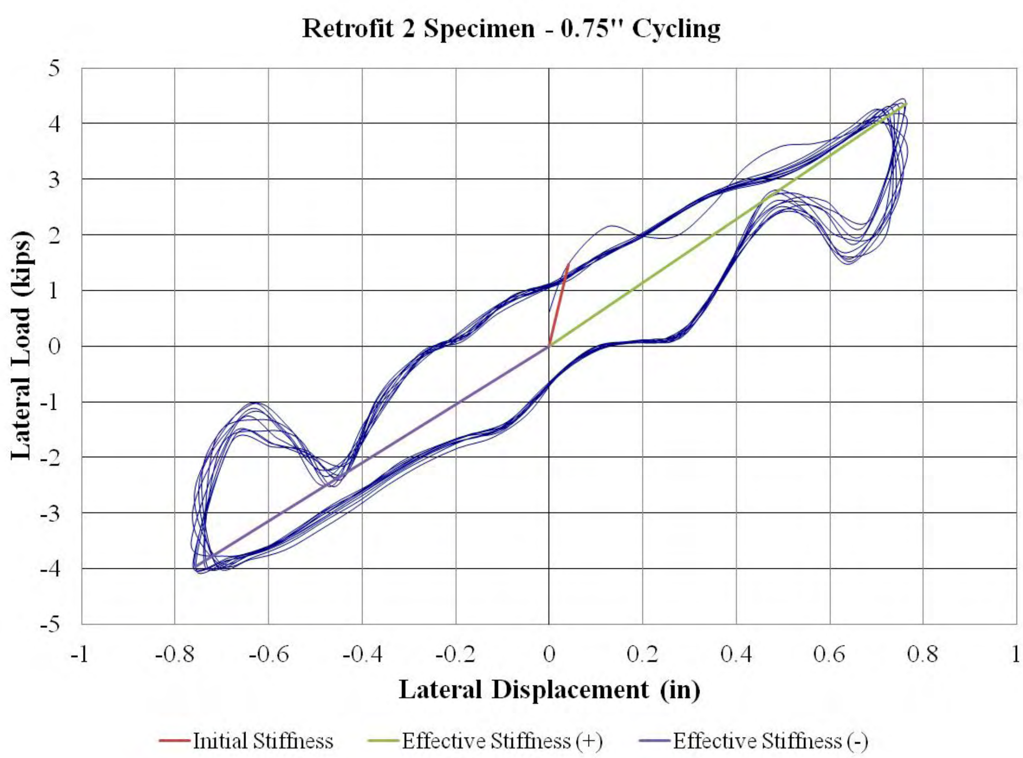

Figure 79: Retrofit 2 Specimen – 0.75” Cycling

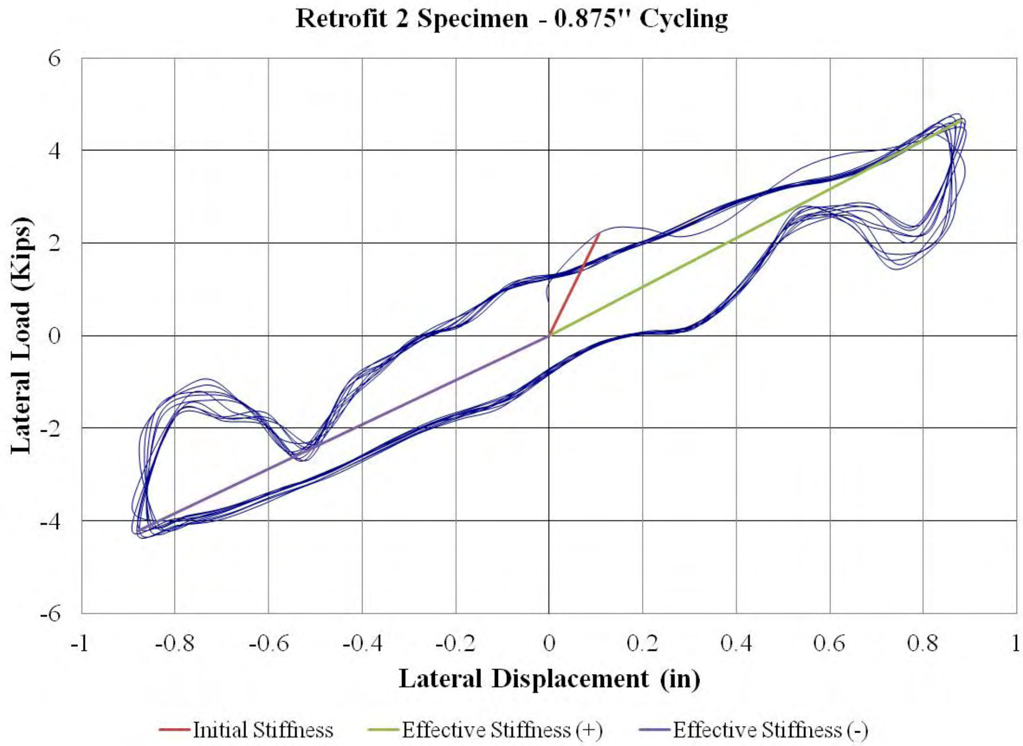

Figure 80: Retrofit 2 Specimen – 0.875” Cycling

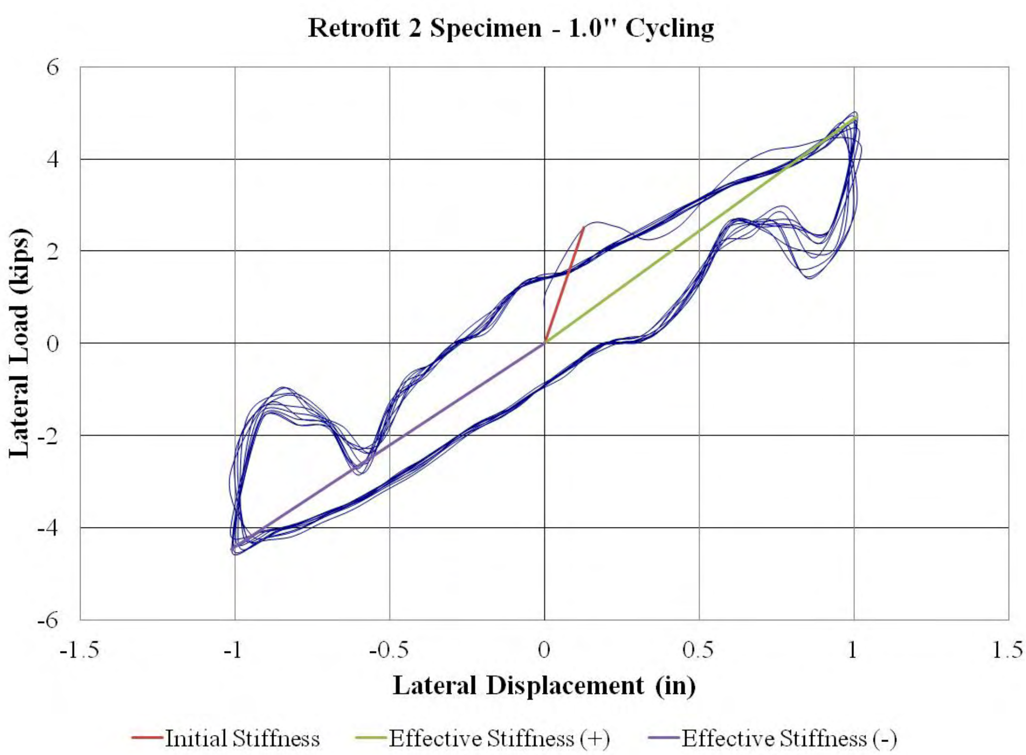

Figure 81: Retrofit 2 Specimen – 1.0” Cycling

Figure 82: Retrofit 2 Specimen – 1.125” Cycling

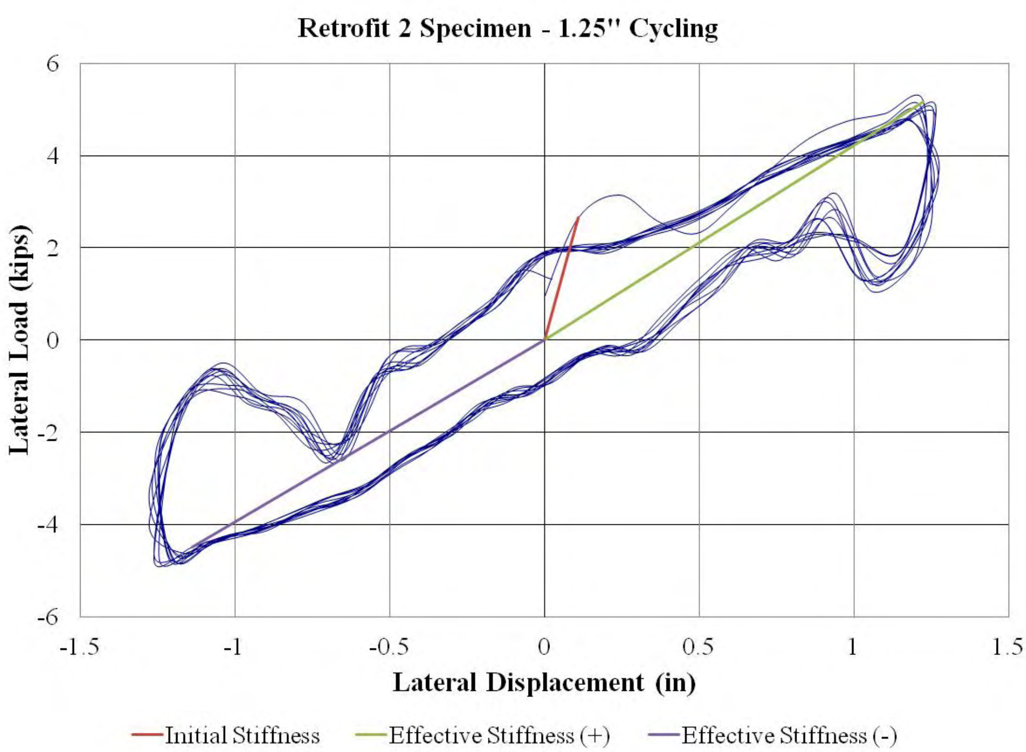

Figure 83: Retrofit 2 Specimen – 1.25” Cycling

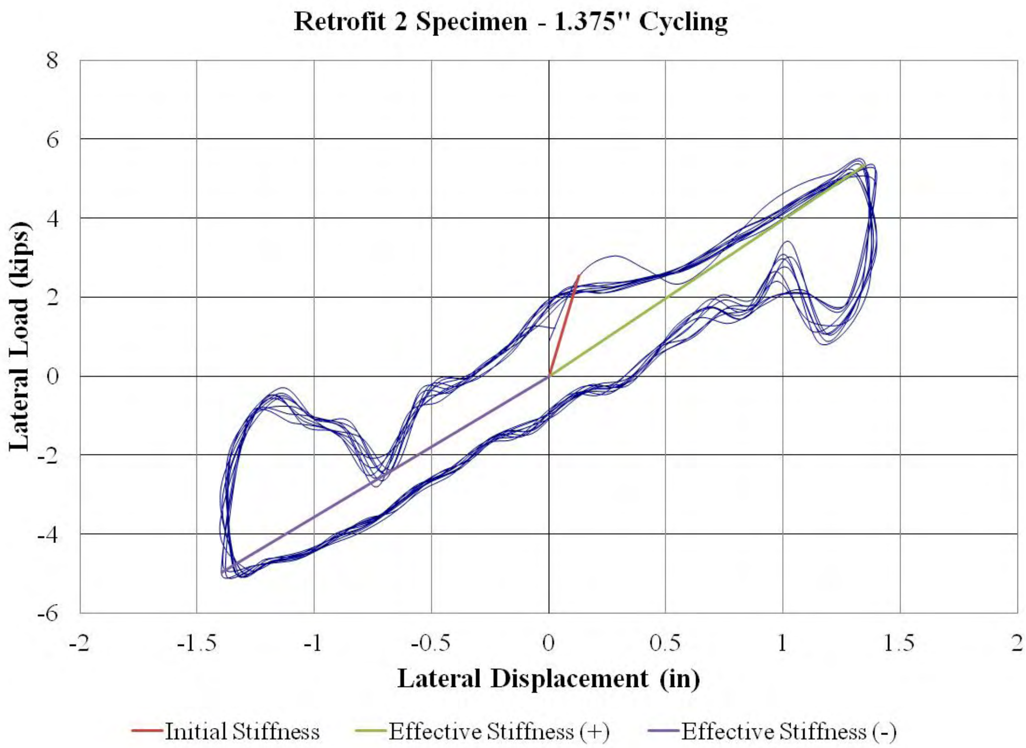

Figure 84: Retrofit 2 Specimen – 1.375” Cycling

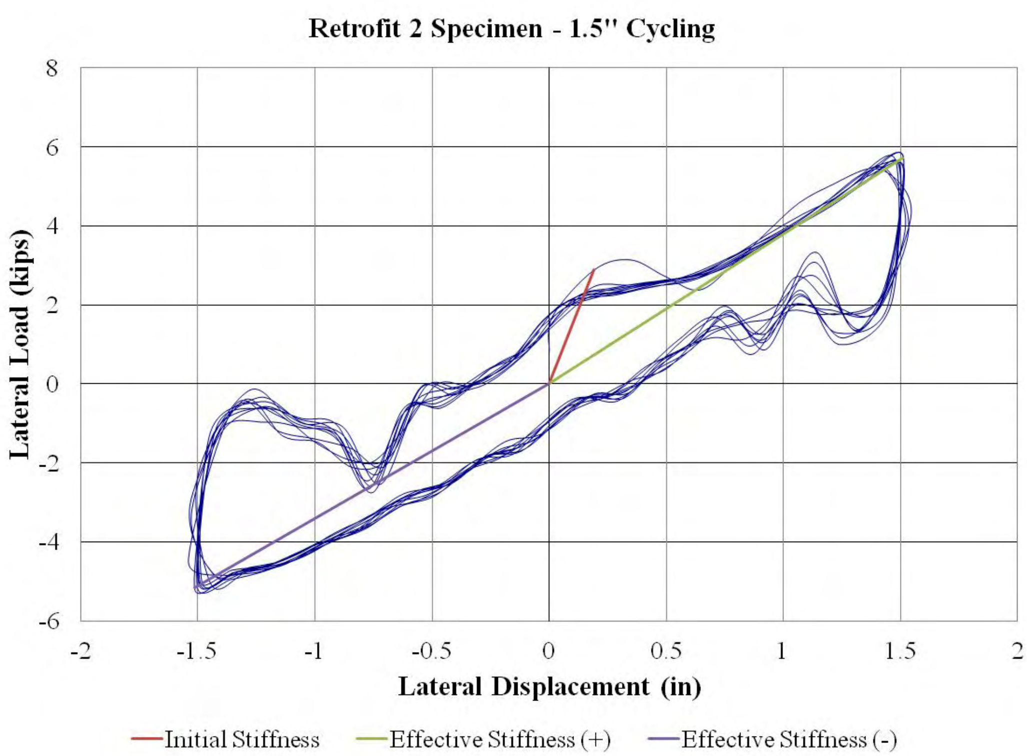

Figure 85: Retrofit 2 Specimen – 1.5” Cycling

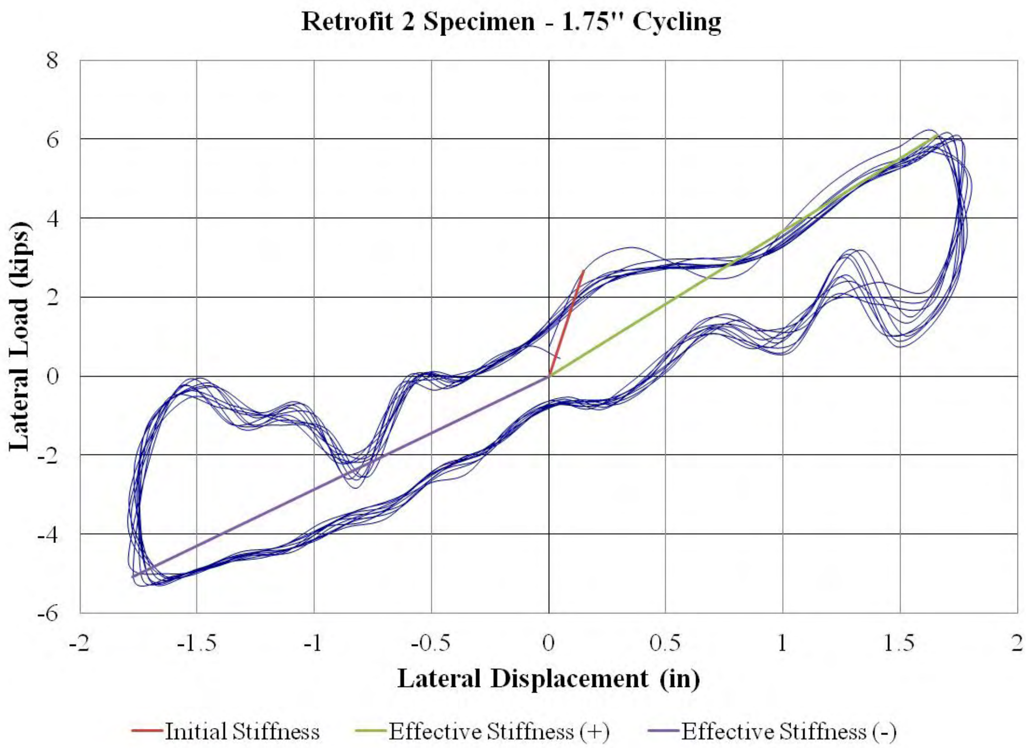

Figure 86: Retrofit 2 Specimen – 1.75" Cycling

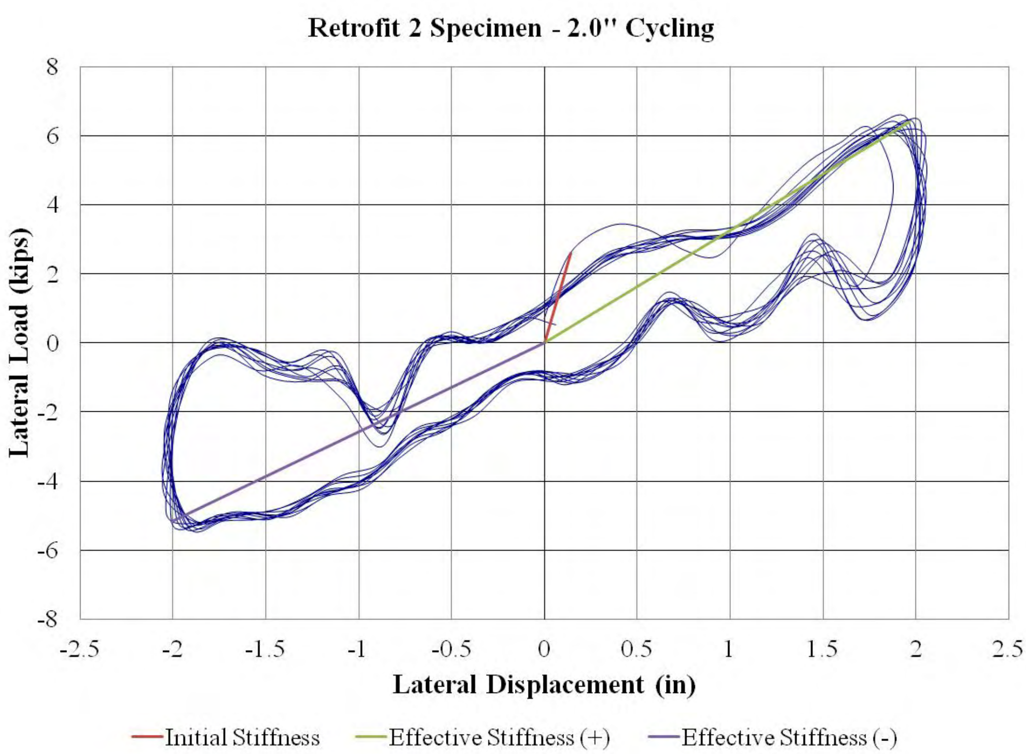

Figure 87: Retrofit 2 Specimen – 2.0" Cycling