Full Scale Testing of WC Series Buckling-Restrained Braces

Final Report

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Executive Summary

This report describes the results and analysis of tests performed on seven buckling-restrained braces manufactured by Star Seismic, LLC. The test were performed and the Structures and Materials Laboratory of the Department of Civil Engineering at the University of Utah during the spring of 2006.

The cores of the test specimens were all made of structural steel and range in yield force size from 150 kips to 780 kips. The testing protocol was designed to exceed the criteria found in Appendix T of the *March 2005 AISC-SEAOC Seismic Provisions for Structural Steel Buildings* and the ICC Acceptance Criteria for Buckling Restrained Braces, (AC238 effective Nov 1, 2003).

All specimens had inelastic deformation greater than 10 times the deformation at first significant yield of the steel core. All of the seven test specimens were able to meet the other requirements found in these documents. The final results are summarized below.

Specimen	Maximum Deformation in yielding section of steel core As a ratio of deformation at first yield	Maximum Cumulative Inelastic Displacement	Maximum Compression to Tension Ratio
WC150 Brace 1	12.8	511	1.10
WC150 Brace 2	19.2	810	1.29
WC250 Brace 1	17.8	725	1.18
WC250 Brace 2	17.8	715	1.17
WC500 Brace 1	10.2	246	1.06
WC500 Brace 2	13.4	351	1.04
WC780	13.6	393	0.98

Disclaimer

The role of The University of Utah is limited to testing and reporting results. It is the responsibility of Star Seismic LLC to determine, from the information provided as stated in this document, the capabilities of their brace to function in a manner consistent with any applicable standards. Star Seismic LLC maintains the responsibility of interpreting the statistical appropriateness of the use of the data. The University of Utah (Department of Civil and Environmental Engineering) is limited in this project to serving as a testing agency.

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E	Modulus of elasticity of steel, 29,000 ksi
F_y	Specified minimum yield strength of steel used in brace cores, ksi
P_y	Axial yield strength of steel core, kips
L_x	Length of steel member x, inches
b_x	Width of steel member x, inches
t_x	Thickness of steel member x, inches
A_x	Area of steel section x (b_x*t_x), squared inches
K_x	Stiffness of member x, kips per inch
β	Compression strength adjustment factor
ε	Strain, percent
ω	Tension strength adjustment factor
Δ_b	Deformation quantity used to control loading of test specimen. In this report it refers to the steel core axial deformation, inches
Δ_{bm}	Value of deformation quantity Δ_b corresponding to the design story drift, in this report it was taken to be 5.0Δ_{by}, inches
Δ_{by}	Value of deformation quantity Δ_b at first significant yield of the steel core, inches
Δ_{tz}	Value of deformation of the steel core within the transition zone, inches
Δ_{yz}	Value of deformation of the steel core within the yielding zone, inches

Introduction

This report contains the results of axial tests conducted during the Spring of 2006 on a series of buckling-restrained braces (BRBs). The tests were performed at the Structures and Materials Laboratory (SML) of the University of Utah Department of Civil and Environmental Engineering and were witness by a representative from Smith Emery, LLC. A total of seven test specimens were provided by Star Seismic, LLC to be cyclically tested using the south frame of the SML. Star Seismic, LLC also furnished the top and bottom connection substructures used during this test. Material tests and quality control/assurance were not performed by the University of Utah and are not included herein. Connection details, member sizes, grades of steel, and other specifics on the BRB specimens is proprietary information and it is also excluded from this report.

Test Specimen Information

Seven buckling-restrained braces (BRBs) were provided by Star Seismic LLC for testing. Duplicate braces were designated as WC150, WC250, WC500, and a single brace was designated as WC780. This designation corresponded to their expected yield force in kips.

The BRBs were approximately 18 feet long. This included the top and bottom portions that were welded to the loading frame connection. A picture of a brace inside the loading frame is shown in Figure 1.

Figure 1 – Buckling Restrained Brace attached to the loading frame

Two sketches of the setup are shown in Figure 2. The dimensions of the steel core at different locations within the brace are shown on Table 1. The drawings for each set of brace are shown in Appendix B. This information was provided by Star Seismic LLC.

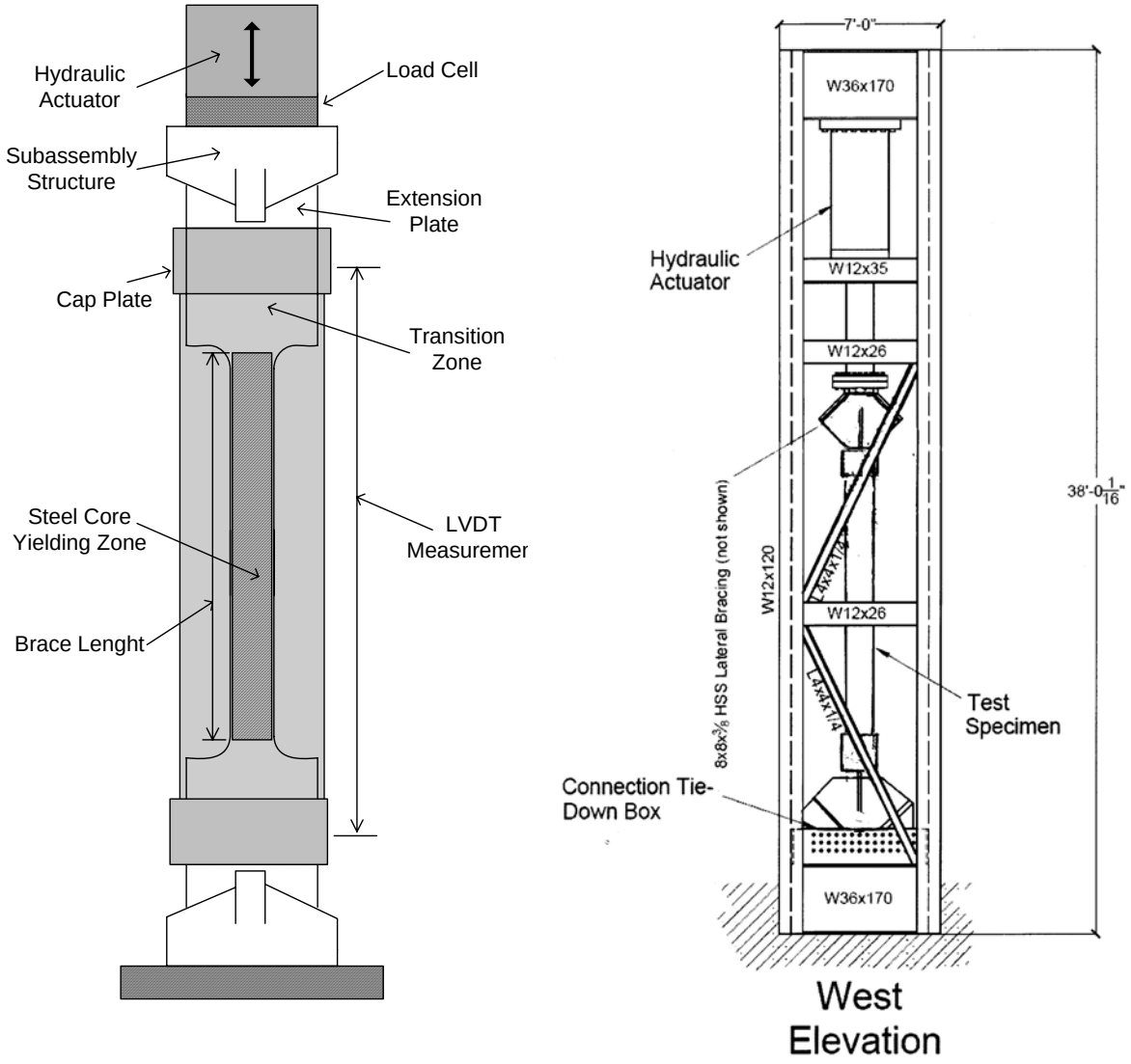


Figure 2 – Sketches of Buckling Restrained Brace testing setup

Table 1 – Dimensions of steel core for the braces

			Brace Designation			
			WC150	**WC250**	**WC500**	**WC780**
Specified yield strength, F_y, ksi			41.4	39.9	39.9	39.9
Extension Plate (KP)		Thickness t_{KP}, in	0.75	2	2	4
		Width b_{kp}, in	9	9	9	18.5
		Length L_{kp}, in	13	19	23	23
		Stiffness K_{KP}, kip/in	15,058	27,474	22,696	93,304
Core Plate	# of Plates		1	1	2	4
		Thickness t_p, in	0.75	1	1	1
		Total Thickness t_T, in	0.75	1	2	4
	Transition Zone (TZ)	Width b_{TZ}, in	10	10	10	10
		Length L_{TZ}, in	14	14	14	14
		Stiffness K_{TZ}, kip/in	15,536	20,714	41,429	82,857
	Yielding Zone (YZ)	Width b_{YZ}, in	4.90	5.75	5.75	4.88
		Length L_{YZ}, in	152.7	134.7	134.7	132.6
		Stiffness K_{YZ}, kip/in	698	1,238	2,476	4,269

Notes: All values provided by Star Seismic LLC.
Stiffness calculated as AE/L.

Test Setup and Loading Protocols

Installation and Physical Setup

The braces were attached vertically to the South Loading frame by welding the core extension into the subassembly gusset plate that was previously bolted to the loading frame actuator.

To facilitate the installation, the ram was retraced to its maximum position. The braces were then hosted by chainfalls into its vertical position and the core extensions knifed onto the gusset plates. Before extending the ram, the upper welds were made, gap filling wedges installed, and the chainfalls removed. This left the brace in its natural plumb position. The brace was then lowered by the ram into its relative position on the lower gusset plate. A 1 inch gap was left between the edge of the gusset and the collar end plate.

To simulate rotation of the brace in a frame, the braces were pulled out of plumb by displacing them 4 inches at the bottom. This meets the requirement of ANSI/AISC 3421 Appendix T4. By rotating the brace out of plumb once the top is fixed, the condition of Loading the Brace with Constant Imposed Rotation shown in CT4 page 6.1-245 is met.

The targeted deformation of the braces was to be 4”. If the braces are installed in a frame at 45 degrees the deformation perpendicular to the axis of the braces would also be 4”. Pulling the braces out of plumb by 4” simulates the rotation the braces would see if axially deformed 4”.

Two Linear Variable Differential Transducers (LVDTs) were externally mounted to the east and west side of the brace. The LVDT’s were welded against the cap plates at the top and bottom of the brace. This ensured that the movement recorded by these devices corresponded to the deformation of the steel core within the brace. A picture of the LVDT setup is shown in Figure 3, with a closer look at the welded connection in Figure 4.

Figure 3 – Buckling Restrained Brace with LVDTs. The braces were installed 4" out of plum to simulate frame drift. The LVDTs were welded to the brace.

Figure 4 – Welded connection

Determination of Yield Deformation

The brace deformation that corresponds to the first significant yield of the core, Δ_{by}, was determined based on the elastic deformation that occurs in both the transition zone and the yielding zone of the steel core. The core was modeled as three springs in series (two transition zones and one yield zone) each with a stiffness K. The yield deformation Δ_{by} was determined as the sum of these three deformations ($2\Delta_{TZ} + \Delta_{YZ}$).

$$\Delta_{by} = P_y\left(\frac{2}{K_{TZ}} + \frac{1}{K_{YZ}}\right)$$

The yield deformation for each brace is shown on Table 2.

Table 2 – Yield deformation for braces

Brace Designation	Yield Force P_y, kips	Deformation at first significant yield, inches		
		Transition Zones, Δ_{TZ}	Yielding Zone, Δ_{YZ}	Total Brace Δ_{by}
WC150	152.1	0.020	0.218	0.238
WC250	229.4	0.022	0.185	0.207
WC500	458.9	0.022	0.185	0.207
WC780	778.8	0.019	0.182	0.201

Note: Yield force determined as F_yA_{YZ}

Test Controls

The testing of the braces was done using a servo-hydraulic actuator with digital control (MTS TestStar IIm). All tests were displacement controlled. Force readings were acquired from a load cell mounted between the hydraulic ram and the top substructure as shown in Figure 2. The displacements readings were acquired using two externally mounted LVDT's, one of which controlled the movement of the ram. All the data was collected in an electronic file and was later processed to arrive at the results shown on the next section.

Test Loading Protocols

The test loading protocols were programmed into the system so that precise displacements were obtained from the hydraulic ram. The deformations used in the test protocols were based on the brace deformation at first significant yield as defined in Appendix T, Section T6.3 of the 2005 AISC Seismic Provisions for Structural Steel Buildings as well as the 2003 Acceptance Criteria for Buckling-Restrained Braced Frame Subassemblages, AC238 from ICC Evaluation Services.

The actual deformations used in the tests were larger than those required in both documents to ensure greater severity in terms of inelastic deformation. This is permitted under section T6.3 of the AISC Provisions. The requirements listed on those documents are shown on the top of Table 3 for comparison purposes.

The loading sequence was applied to the test specimen at a rate of approximately 0.025 inches per second.

Table 3 – Test Protocols for each specimen

	Step	1	2	3	4	5	6	7
AISC	Cycles	2	2	2	2	2	As needed	--
	Δ_b/Δ_{by}[1]	1.00	2.50	5.00	7.50	10.0	7.5	
ICC	Cycles	6	4	4	2	As needed		
	Δ_b/Δ_{by}	1.00	2.50	5.00	7.50	5.00	--	--
WC150	Cycles	6	4	6	4	2	2	2
	Δ_b	0.30	0.75	1.50	2.20	2.80	3.50	4.20
	Δ_b/Δ_{by}	1.26	3.15	6.30	9.24	11.76	14.71	17.64
	$\frac{\Delta_b-\Delta_{TZ}}{\Delta_{YZ}}$[2]	1.28	3.35	6.79	10.00	12.75	15.96	19.17
WC250	Cycles	6	4	6	4	2	4	2
	Δ_b	0.30	0.70	1.40	2.00	2.60	3.30	3.90
	Δ_b/Δ_{by}	1.45	3.38	6.76	9.60	12.56	15.94	18.84
	$\frac{\Delta_b-\Delta_{TZ}}{\Delta_{YZ}}$	1.50	3.66	7.45	10.69	13.94	17.72	20.96
WC500 Brace 1	Cycles	9	4	4	2	2	2	2
	Δ_b	0.30	0.65	1.30	1.90	2.50	3.10	3.75
	Δ_b/Δ_{by}	1.45	3.14	6.28	9.18	12.08	14.98	18.12
	$\frac{\Delta_b-\Delta_{TZ}}{\Delta_{YZ}}$	1.50	3.39	6.91	10.15	13.39	16.64	20.15
WC500 Brace 2	Cycles	6	4	4	2	2	2	2
	Δ_b	0.25	0.65	1.30	1.90	1.30	1.90	2.50
	Δ_b/Δ_{by}	1.21	3.14	6.28	9.18	6.28	9.18	12.08
	$\frac{\Delta_b-\Delta_{TZ}}{\Delta_{YZ}}$	1.23	3.39	6.91	10.15	6.91	10.15	13.39
WC780	Cycles	6	4	6	4	2	2	2
	Δ_b	0.25	0.70	1.30	1.90	2.50	3.20	3.70
	Δ_b/Δ_{by}	1.24	3.48	6.46	9.45	12.44	15.92	18.41
	$\frac{\Delta_b-\Delta_{TZ}}{\Delta_{YZ}}$	1.27	3.74	7.04	10.34	13.63	17.48	20.23

Note: (1) The requirements are listed in terms of Δ_{bm}. For this work $\Delta_{by} = 5.0\Delta_{bm}$
(2) This quantity represents the ratio of Δ_b/Δ_{by} when Δ_{by} is considered the yielded core of the specimen only.

Test Results

The results for each set of braces include the number of deformation cycles to failure, the corresponding deformation as a function of the specimen yield, the maximum cumulative inelastic displacement (CID) and the maximum compression to tension (C/T) ratio within a given cycle. The ICC 238 criterion requires 4 steps with a maximum deformation of 7.5 Δ_b/Δ_{by} and a CID of at least 140 at the end of the test. The ANSI/AISC criteria requires 5 steps with a maximum deformation of 10.0 Δ_b/Δ_{by} and a CID of at least 200 at the end of the test. Both documents require a maximum compression to tension ratio of 1.3 for each cycle greater than $\Delta_b = \Delta_{by}$.

These results are summarized in Table 4. Plots showing the applied load history and applied load versus deformation are found in Appendix A.

Table 4 – Summary of results for each brace

Specimen	Cycle at failure	Maximum Deformation		Maximum CID	Maximum C/T Ratio
		Δ_b/Δ_{by}	Δ_b-Δ_{TZ}/Δ_{YZ}		
WC150 Brace 1	1st cycle at step 6	>11.7	>12.8	511	1.10
WC150 Brace 2	1st cycle after step 7	>17.6	>19.2	810	1.29
WC250 Brace 1	2nd cycle at step 7	>15.9	>17.8	725	1.18
WC250 Brace 2	2nd cycle at step 7	>15.9	>17.8	715	1.17
WC500 Brace 1	1st cycle at step 5	>9.2	>10.2	246	1.07
WC500 Brace 2	2nd cycle after step 7	>12.1	>13.4	351	1.04
WC780	1st cycle at step 6	>12.4	>13.6	393	0.98

Test Specimen Failure Observations

Two modes of failure were observed; one consisted in bulging of the outer tube and eventual failure of the wall and the second one was rupture of the yielding core. In one specimen the gusset plate weld failed. Bulging occurred at the top of the brace, closer to the hydraulic actuator. Tensile rupture was accompanied with a loud noise. Table 5 describes the failure mode for each brace tested.

Table 5 – Failure Modes of Each Specimen Tested

Specimen	Failure Mode
WC150 Brace 1	Tension Failure of Core
WC150 Brace 2	Tension Failure of Core
WC250 Brace 1	Tension Failure of Core
WC250 Brace 2	Tension Failure of Core
WC500 Brace 1	Bottom Gusset Plate Weld Failure
WC500 Brace 2	Bent Collar and Failed Wall at Top
WC780	Bent Collar and Failed Wall at Top

Test Analysis

Backbone Curve

The backbone curve was developed from the data for all braces based on the load at maximum deformation normalized to the yield load. This curve resulted in the following formulas. For tension, the regression equation is:

$$\omega = 26.80\varepsilon + 1.033$$

For compression, the regression equation is

$$\omega\beta = 45.19\varepsilon - 0.77.$$

where ω is hardening and ε is strain.

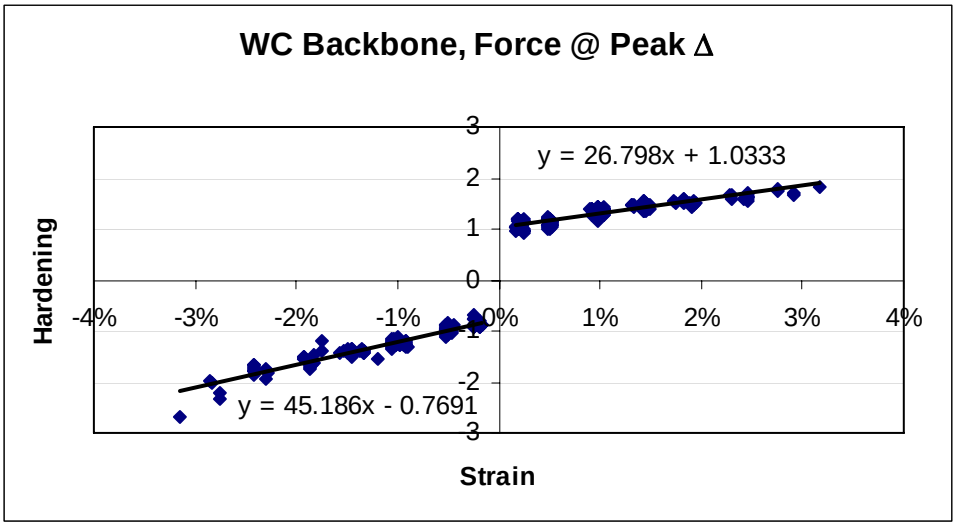


Figure 5 – WC backbone curve

Comparisons to Acceptance Criteria

The requirements of the AISC-SEAOC criteria are as follows:

- Load vs. displacement history shall exhibit stable, repeatable behavior with positive incremental stiffness.
- There shall be no fracture, brace instability or brace end connection failure.
- For brace tests, each cycle to a deformation greater than Δ_{by} the maximum tension and compression forces shall not be less than the nominal strength of the core.
- For brace tests, each cycle to a deformation greater than Δ_{by} the ratio of the maximum compression force to the maximum tension force shall not exceed 1.3.

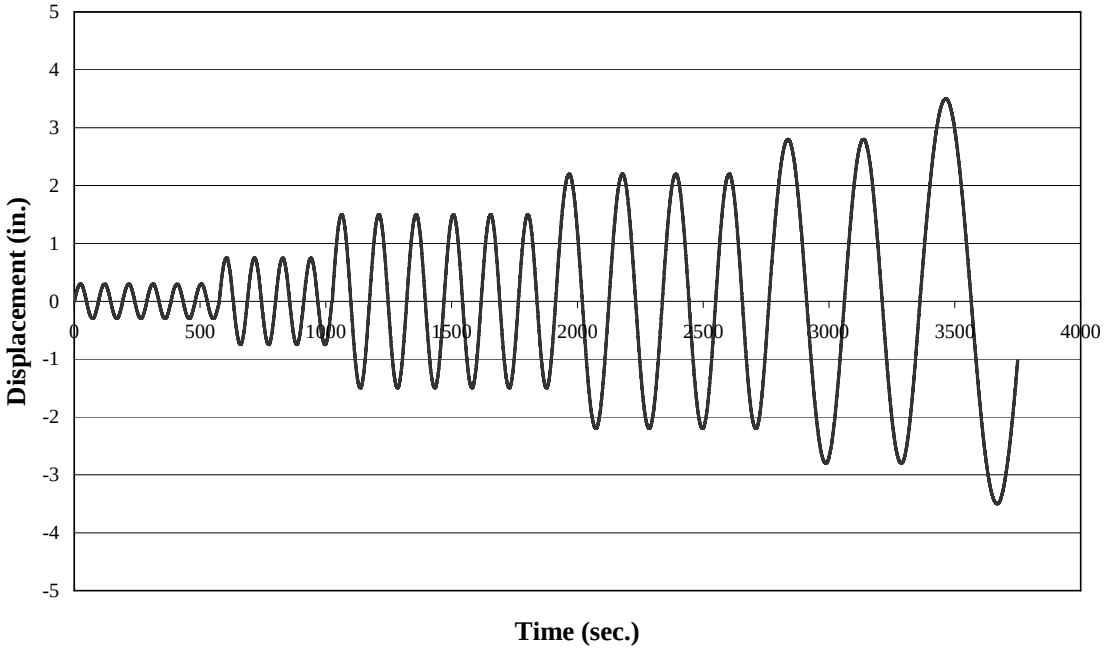
All of the seven braces conform to these criteria.

Appendix A: Test Results

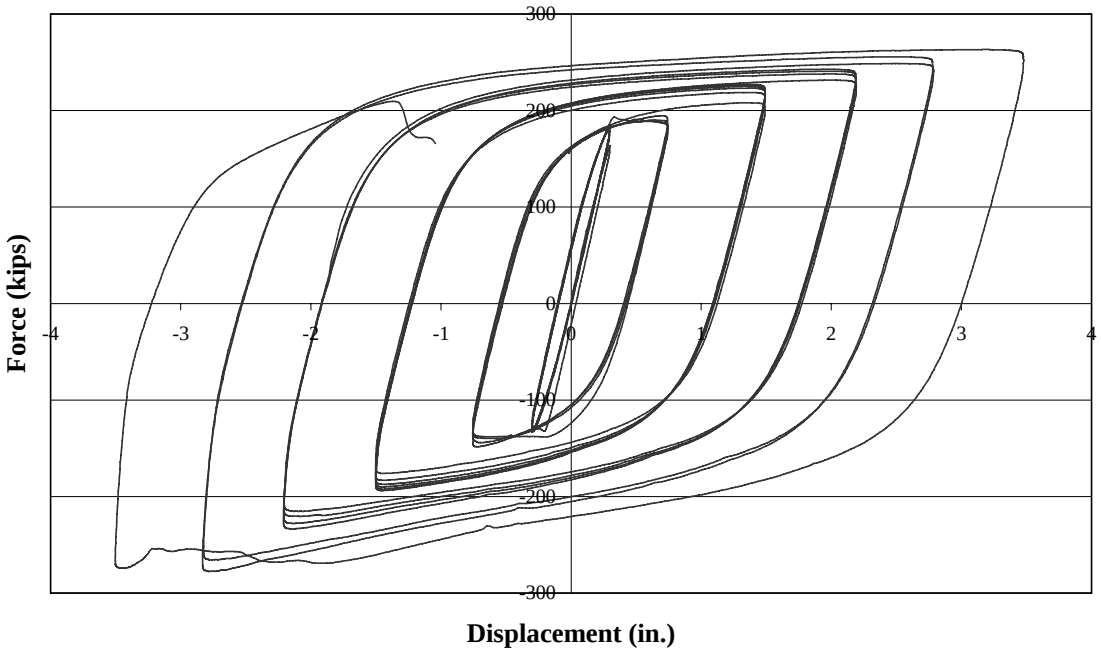
WC150 Brace 1 Results

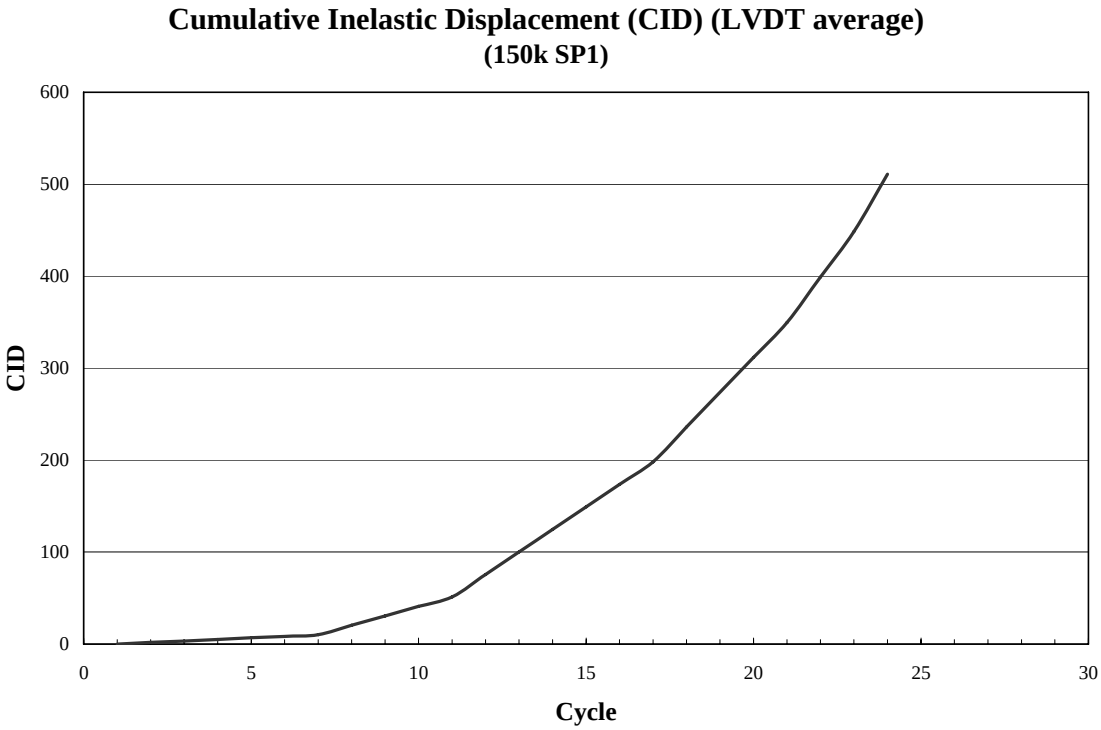
(150K S1)		CID (LVDTavg)				C/T	Tension Force
Step	Cycle	per cycle	per step	Cum.	per step		Kips
	0			0.00			
1	1	1.683	10.09	1.68	10.09	0.766	163.33
	2	1.687		3.37		0.723	177.86
	3	1.676		5.05		0.725	179.66
	4	1.676		6.72		0.717	180.94
	5	1.686		8.41		0.732	179.17
	6	1.677		10.09		0.741	179.16
2	7	10.287	41.07	20.37	51.16	0.726	182.09
	8	10.263		30.64		0.717	182.05
	9	10.266		40.90		0.737	182.85
	10	10.257		51.16		0.783	185.01
3	11	24.494	146.96	75.65	198.12	0.857	198.34
	12	24.506		100.16		0.825	212.74
	13	24.506		124.66		0.826	217.09
	14	24.486		149.15		0.834	220.38
	15	24.485		173.64		0.855	218.72
	16	24.485		198.12		0.865	217.01
4	17	37.884	151.50	236.00	349.62	0.908	224.28
	18	37.855		273.86		0.918	231.65
	19	37.883		311.74		0.942	234.51
	20	37.876		349.62		0.947	238.17
5	21	49.431	98.87	399.05	448.49	1.077	241.10
	22	49.443		448.49		1.103	242.41
6	23	62.476	62.48	510.97	510.97	1.054	251.49
	Σ	510.97	510.97		**Max**	**1.103**	

Displacement Time History (East LVDT)
(150k SP1)



Force-Displacement (LVDT average)
(150k SP1)

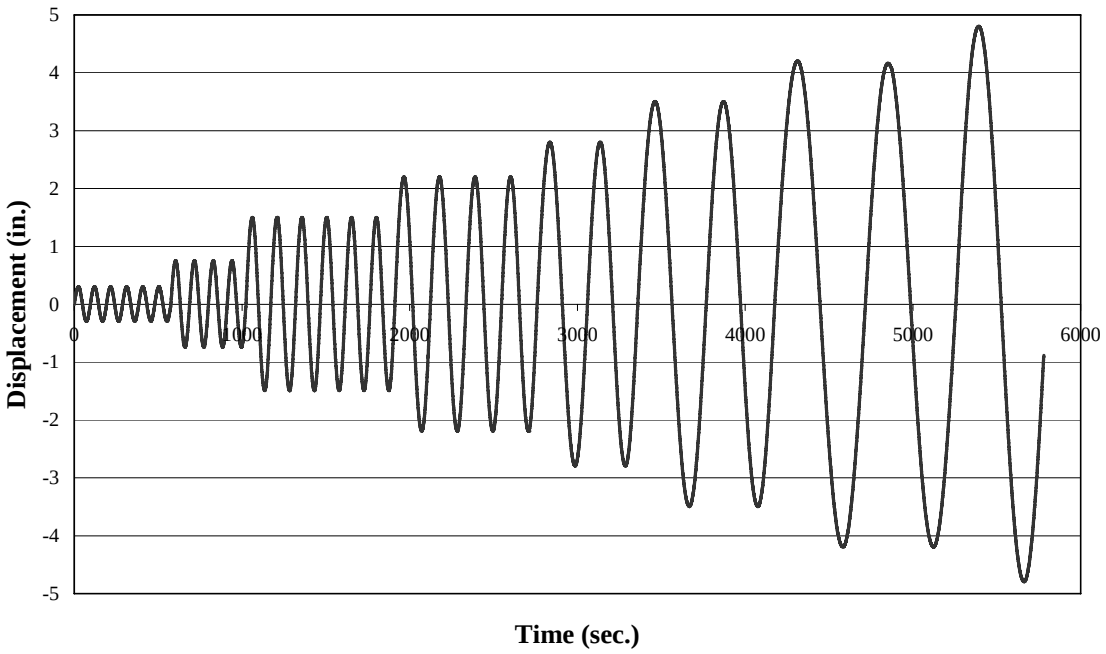



Cumulative Inelastic Displacement (CID) (LVDT average)
(150k SP1)
CID
600
500
400
300
200
100
0
0
5
10
15
20
25
30
Cycle

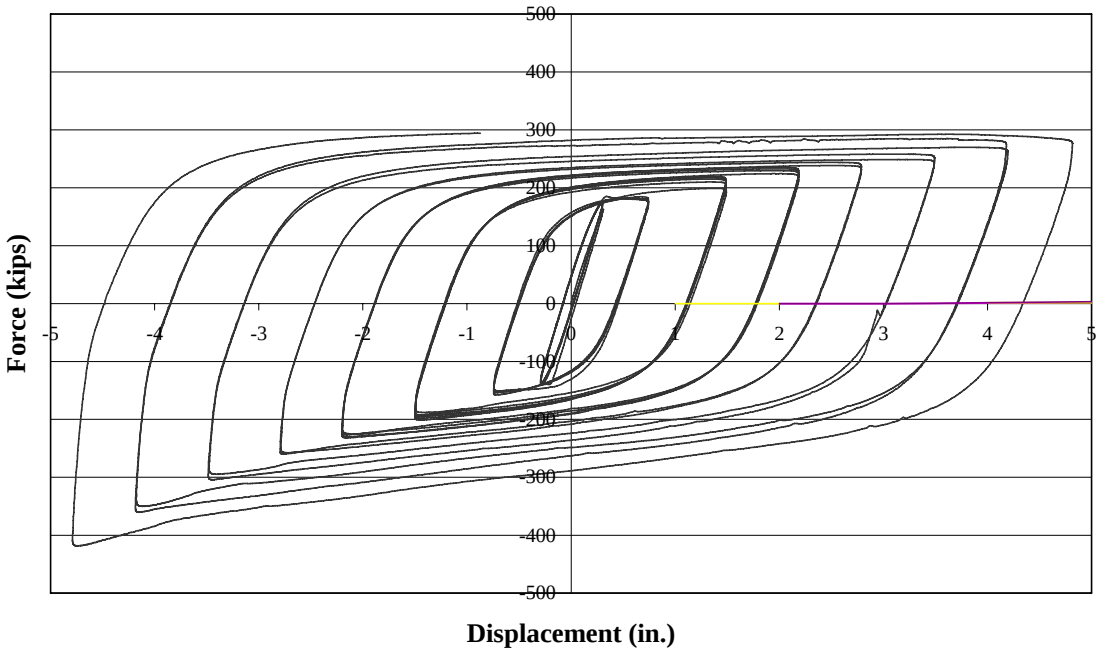
WC150 Brace 2 Results

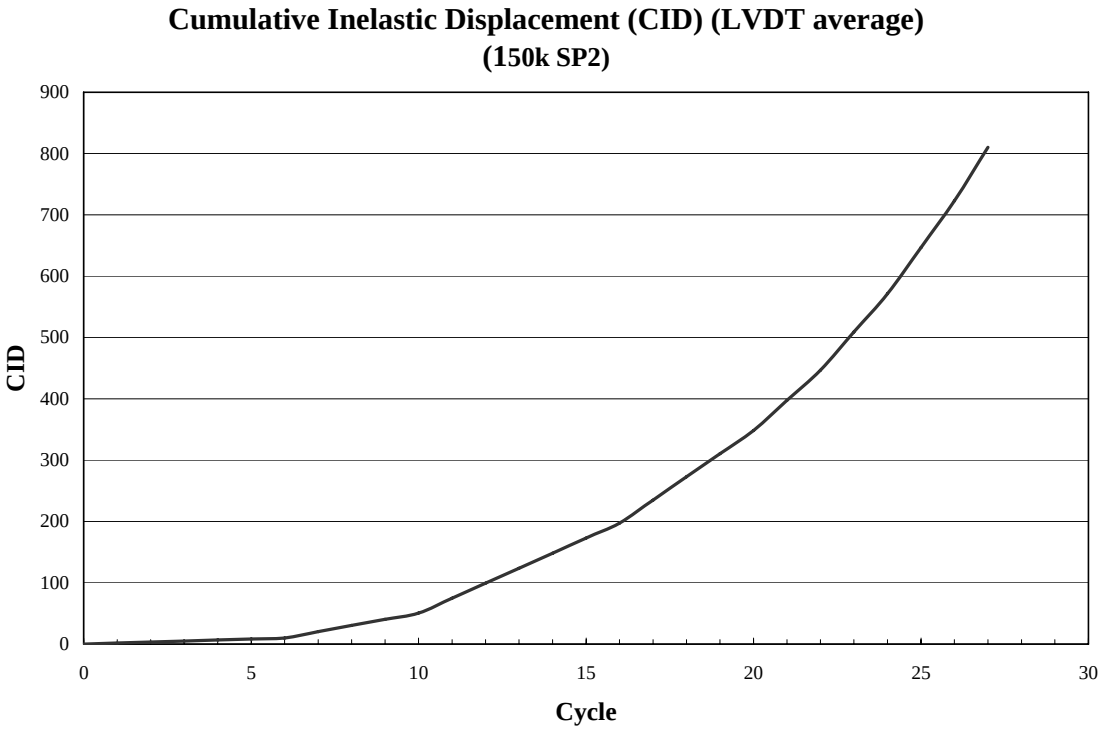
(150K S2)		CID (LVDTavg)				C/T	Tension Force
Step	Cycle	per cycle	per step	Cum.	per step		Kips
	0			0.00			
1	1	1.649	9.97	1.65	9.97	0.822	162.06
	2	1.652		3.30		0.785	173.20
	3	1.670		4.97		0.791	173.54
	4	1.670		6.64		0.783	174.52
	5	1.664		8.31		0.792	173.70
	6	1.662		9.97		0.789	174.59
2	7	10.150	40.58	20.12	50.55	0.809	175.43
	8	10.119		30.24		0.843	173.78
	9	10.133		40.37		0.861	176.14
	10	10.176		50.55		0.861	179.14
3	11	24.428	146.64	74.97	197.19	0.945	192.38
	12	24.445		99.42		0.902	204.97
	13	24.405		123.83		0.898	207.78
	14	24.455		148.28		0.898	211.73
	15	24.452		172.73		0.904	213.50
	16	24.458		197.19		0.920	212.20
4	17	37.746	151.09	234.94	348.28	0.987	219.05
	18	37.778		272.72		0.973	223.23
	19	37.763		310.48		0.995	225.21
	20	37.800		348.28		0.996	227.64
5	21	49.120	98.30	397.40	446.57	1.083	230.59
	22	49.176		446.57		1.081	236.57
6	23	62.321	124.78	508.89	571.35	1.139	242.83
	24	62.456		571.35		1.176	251.96
7	25	75.720	151.41	647.07	722.77	1.289	263.27
	26	75.695		722.77		1.285	273.93
8	27	87.489	87.49	810.25	810.25	1.480	276.31
	Σ	810.25	810.25		**Max**	**1.289**	

Displacement Time History (East LVDT)
(150k SP2)



Force-Displacement (LVDT average)
(150k SP2)

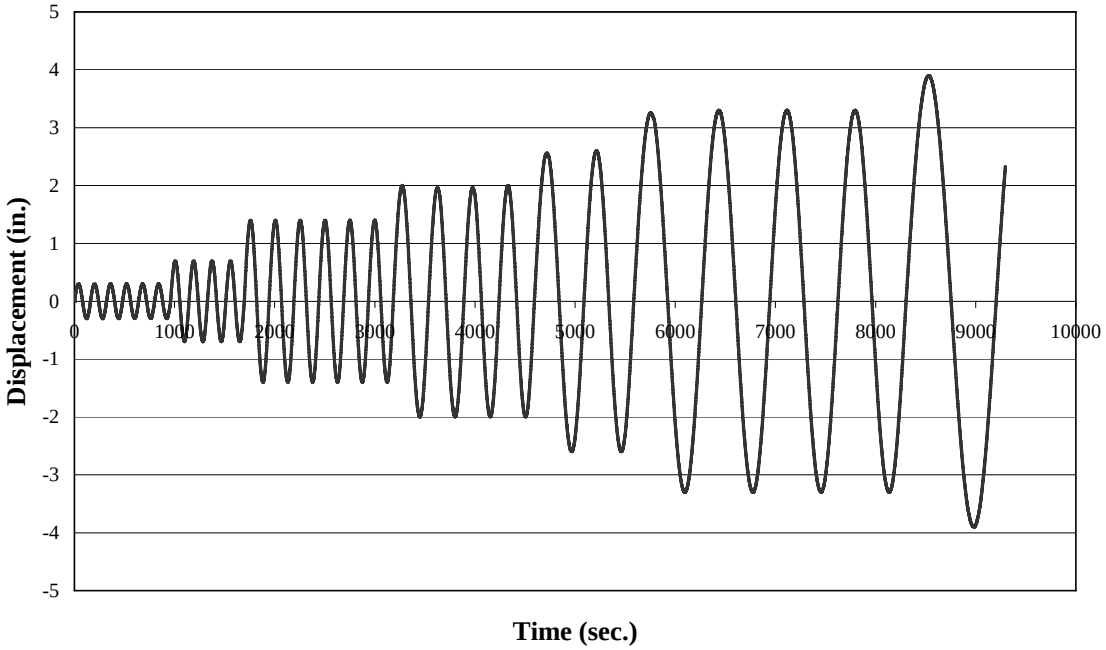



Cumulative Inelastic Displacement (CID) (LVDT average)
(150k SP2)
CID
900
800
700
600
500
400
300
200
100
0
0
5
10
15
20
25
30
Cycle

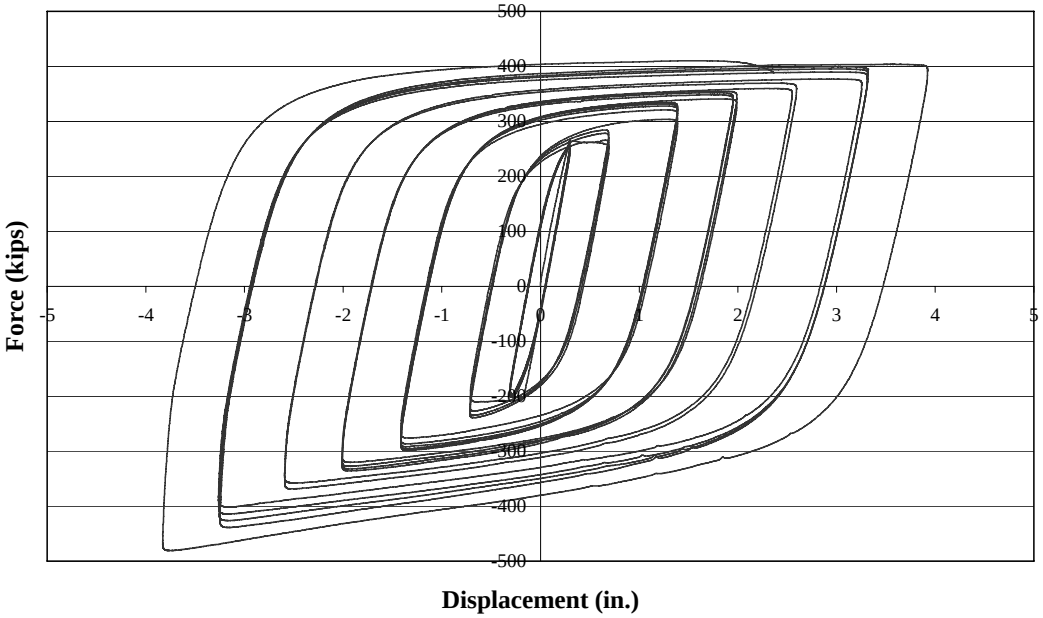
WC250 Brace 1 Results

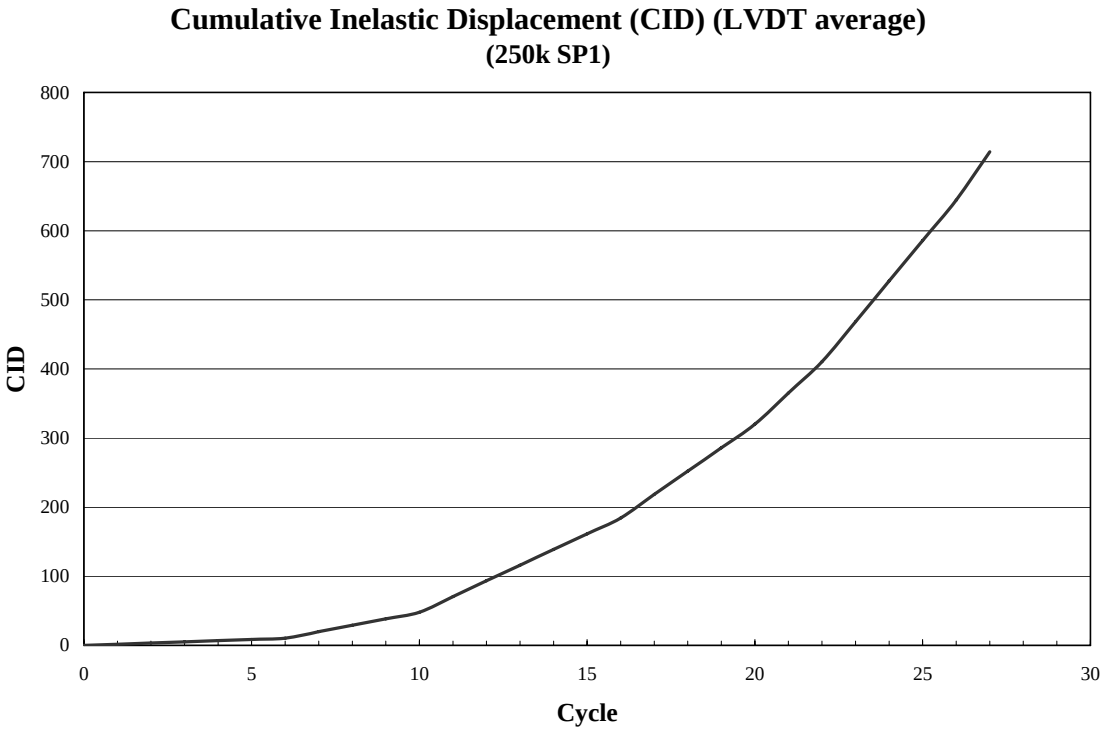
(250K S1)		CID (LVDTavg)				C/T	Tension Force
Step	Cycle	per cycle	per step	Cum.	per step		Kips
	0			0.00			
1	1	1.788	10.59	1.79	10.59	0.711	264.50
	2	1.760		3.55		0.783	248.53
	3	1.756		5.30		0.787	248.27
	4	1.748		7.05		0.806	246.26
	5	1.761		8.81		0.796	249.91
	6	1.774		10.59		0.786	249.90
2	7	9.371	37.55	19.96	48.13	0.815	251.18
	8	9.392		29.35		0.851	259.47
	9	9.387		38.74		0.834	270.68
	10	9.396		48.13		0.832	276.63
3	11	22.709	136.22	70.84	184.36	0.899	297.00
	12	22.727		93.57		0.883	310.57
	13	22.699		116.27		0.893	318.74
	14	22.702		138.97		0.896	319.61
	15	22.694		161.67		0.881	319.53
	16	22.692		184.36		0.897	325.27
4	17	34.094	135.69	218.45	320.05	0.944	331.73
	18	33.741		252.19		0.937	341.04
	19	33.739		285.93		0.939	344.38
	20	34.115		320.05		0.958	340.74
5	21	44.997	90.42	365.04	410.46	1.008	344.25
	22	45.420		410.46		0.993	358.75
6	23	58.118	233.91	468.58	644.38	1.040	367.69
	24	58.621		527.20		1.066	377.37
	25	58.607		585.81		1.071	386.35
	26	58.568		644.38		1.094	388.49
7	27	69.866	80.14	714.24	724.52	1.183	391.92
	28	10.275		724.52	**Max**	**1.183**	
	Σ	724.52	724.52				

Displacement Time History (East LVDT)
(250k SP1)



Force-Displacement (LVDT average)
(250k SP1)

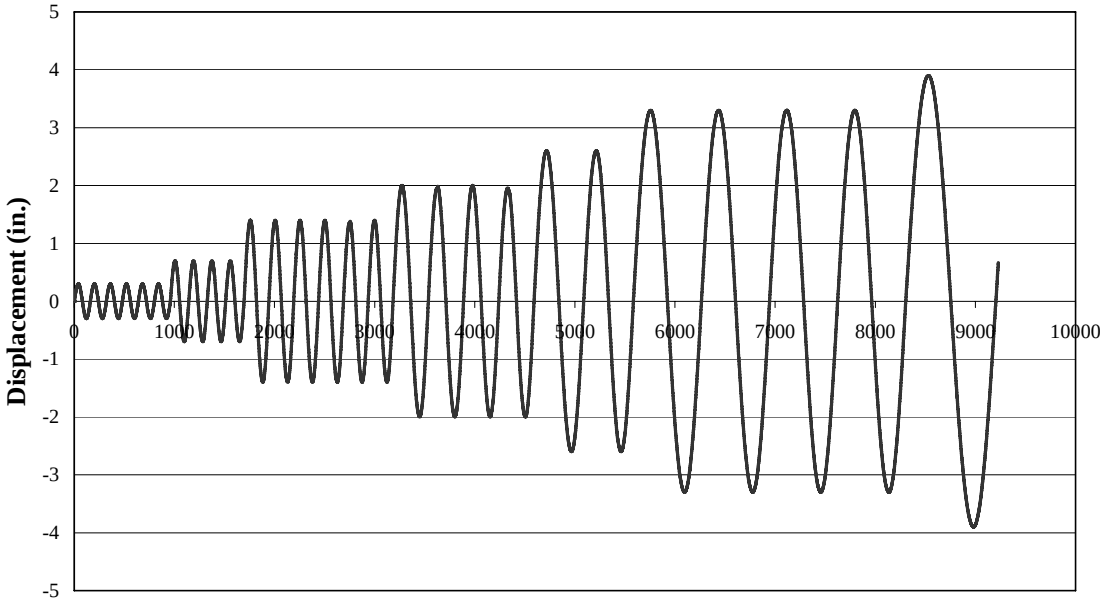



Cumulative Inelastic Displacement (CID) (LVDT average)
(250k SP1)
CID
800
700
600
500
400
300
200
100
0
0
5
10
15
20
25
30
Cycle

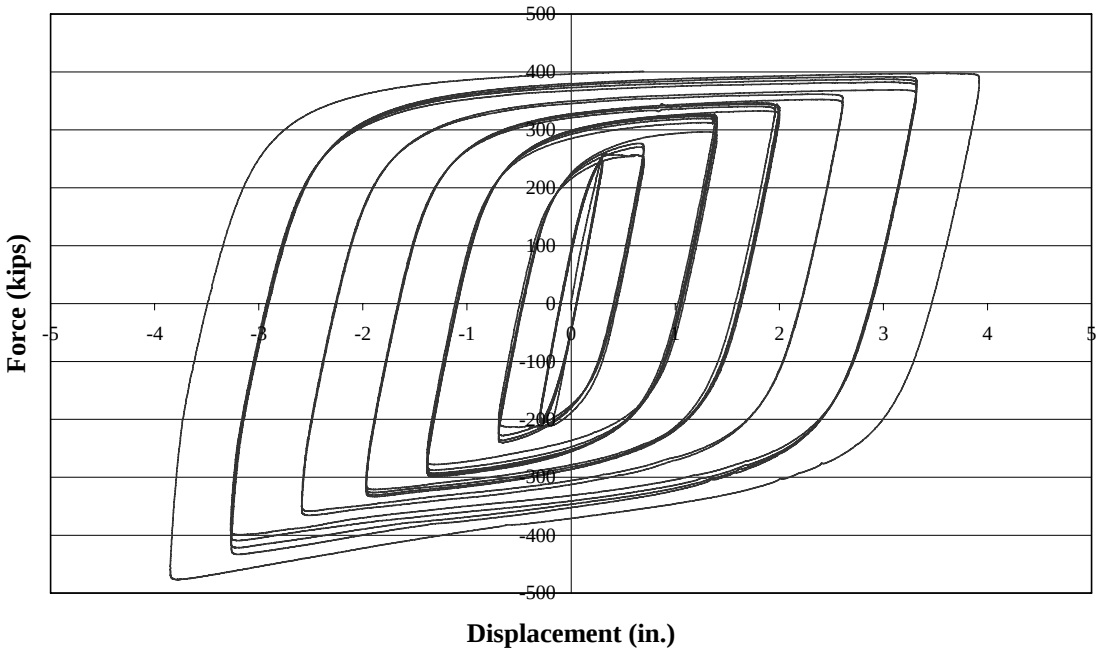
WC250 Brace 2 Results

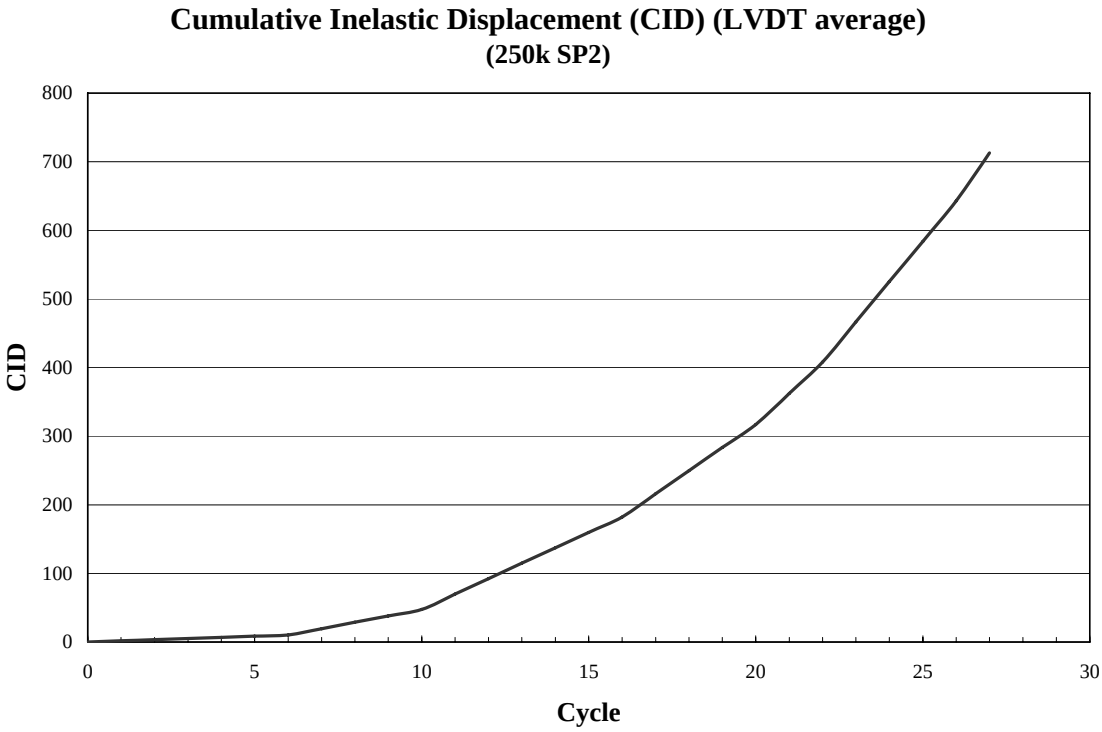
(250K S2)		CID (LVDTavg)				C/T	Tension Force
Step	Cycle	per cycle	per step	Cum.	per step		Kips
	0			0.00			
1	1	1.687	10.20	1.69	10.20	0.759	254.57
	2	1.708		3.40		0.815	243.79
	3	1.712		5.11		0.808	245.38
	4	1.701		6.81		0.830	242.60
	5	1.696		8.50		0.822	242.75
	6	1.693		10.20		0.830	243.57
2	7	9.289	37.14	19.49	47.34	0.820	244.33
	8	9.293		28.78		0.861	250.63
	9	9.275		38.05		0.846	265.61
	10	9.281		47.34		0.870	268.96
3	11	22.511	134.80	69.85	182.13	0.905	289.53
	12	22.488		92.33		0.898	303.78
	13	22.482		114.82		0.916	313.20
	14	22.493		137.31		0.912	313.18
	15	22.338		159.65		0.909	318.56
	16	22.487		182.13		0.906	319.58
4	17	33.816	134.76	215.95	316.90	0.968	321.55
	18	33.697		249.65		0.947	337.19
	19	33.835		283.48		0.969	334.16
	20	33.413		316.90		0.965	332.27
5	21	45.478	90.98	362.37	407.87	1.019	343.64
	22	45.497		407.87		1.025	348.65
6	23	58.708	234.88	466.58	642.75	1.068	356.86
	24	58.741		525.32		1.061	368.95
	25	58.735		584.05		1.088	375.20
	26	58.691		642.75		1.101	376.62
7	27	70.009	72.33	712.75	715.08	1.174	386.74
	28	2.323		715.08	**Max**	**1.174**	
	Σ	715.08	715.08				

Displacement Time History (East LVDT)
(250k SP2)



Force-Displacement (LVDT average)
(250k SP2)

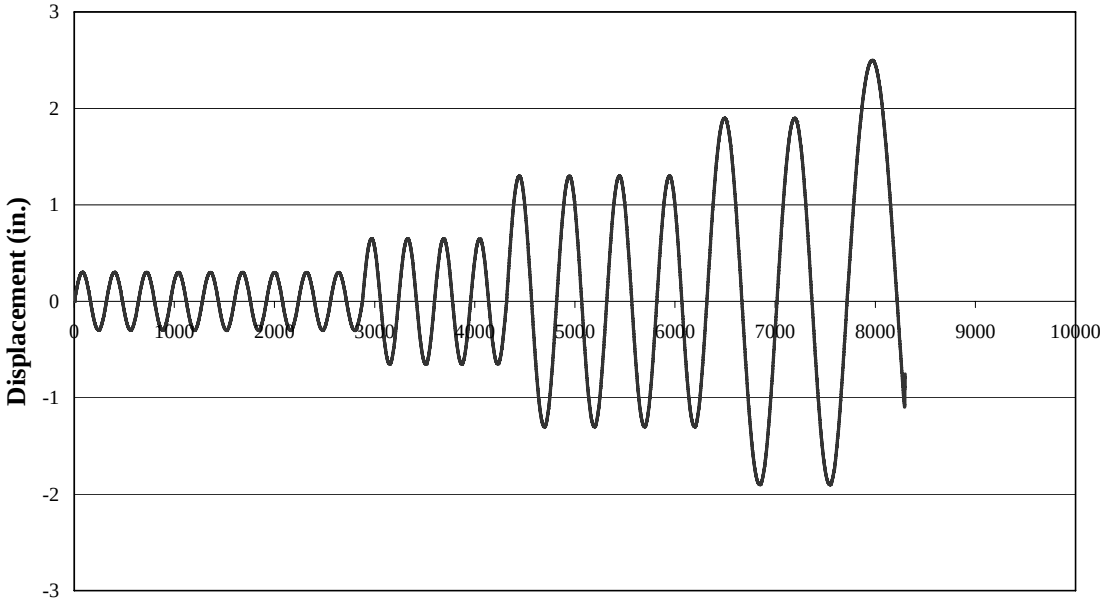



Cumulative Inelastic Displacement (CID) (LVDT average)
(250k SP2)
CID
800
700
600
500
400
300
200
100
0
0
5
10
15
20
25
30
Cycle

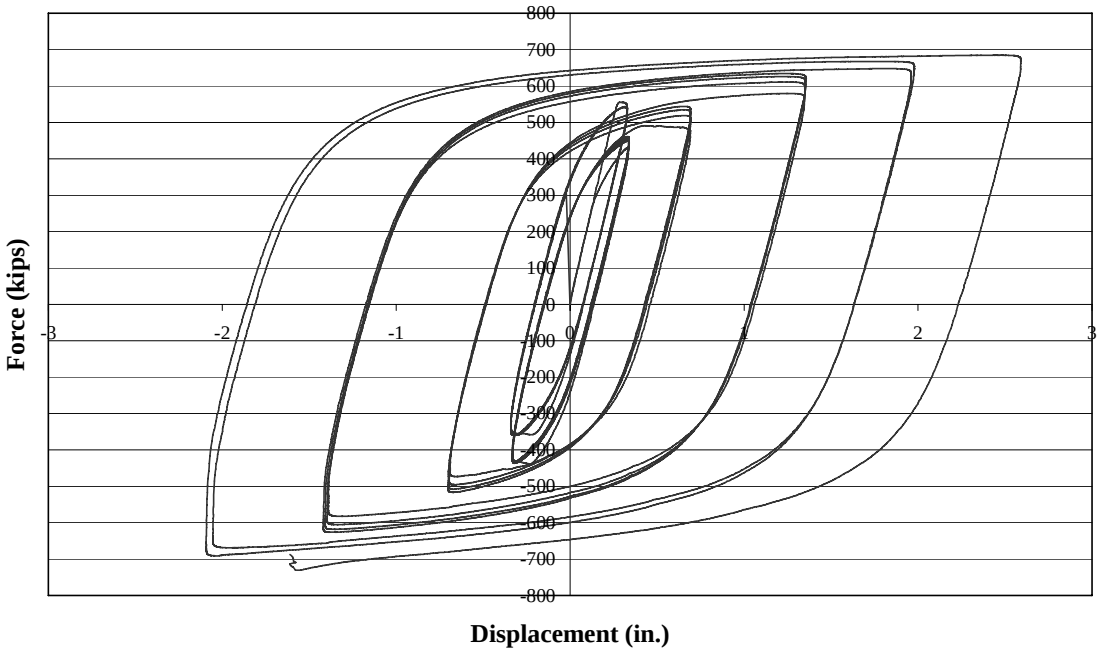
WC500 Brace 1 Results

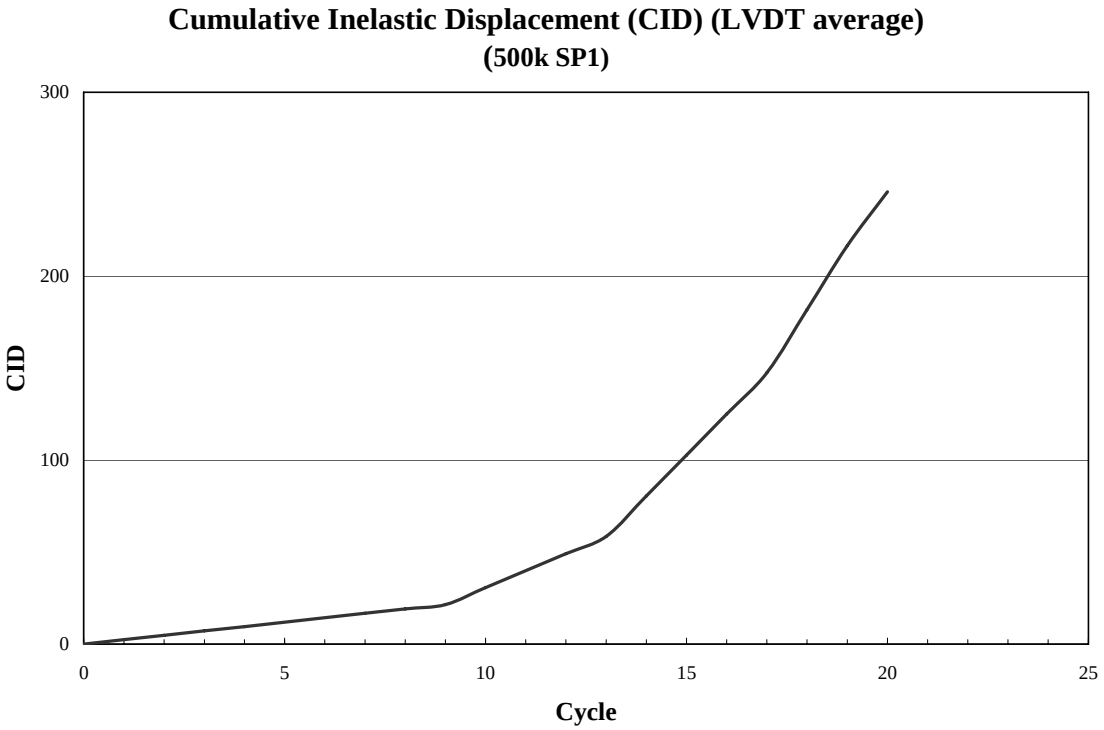
(500K S1)		CID (LVDTavg)				C/T	Tension Force
Step	Cycle	per cycle	per step	Cum.	per step		Kips
	0			0.00			
1	1	2.372	21.48	2.37	21.48	0.582	547.22
	2	2.374		4.75		0.654	530.89
	3	2.387		7.13		0.659	530.99
	4	2.374		9.51		0.968	424.63
	5	2.402		11.91		0.940	443.29
	6	2.409		14.32		0.952	443.85
	7	2.386		16.70		0.931	441.51
	8	2.380		19.08		0.952	447.44
	9	2.399		21.48		0.945	453.53
2	10	9.163	36.98	30.65	58.46	0.983	469.15
	11	9.246		39.89		0.944	508.76
	12	9.278		49.17		0.948	523.57
	13	9.289		58.46		0.947	536.75
3	14	22.083	89.03	80.54	147.49	0.969	567.46
	15	22.181		102.72		0.996	588.26
	16	22.318		125.04		0.997	608.95
	17	22.450		147.49		0.988	620.92
4	18	34.242	69.04	181.73	216.53	1.004	630.74
	19	34.794		216.53		1.027	646.51
5	20	29.355	29.36	245.88	245.88	1.066	669.19
	Σ	245.88	245.88		**Max**	**1.066**	

Displacement Time History (East LVDT)
(500k SP1)



Force-Displacement (LVDT average)
(500k SP1)

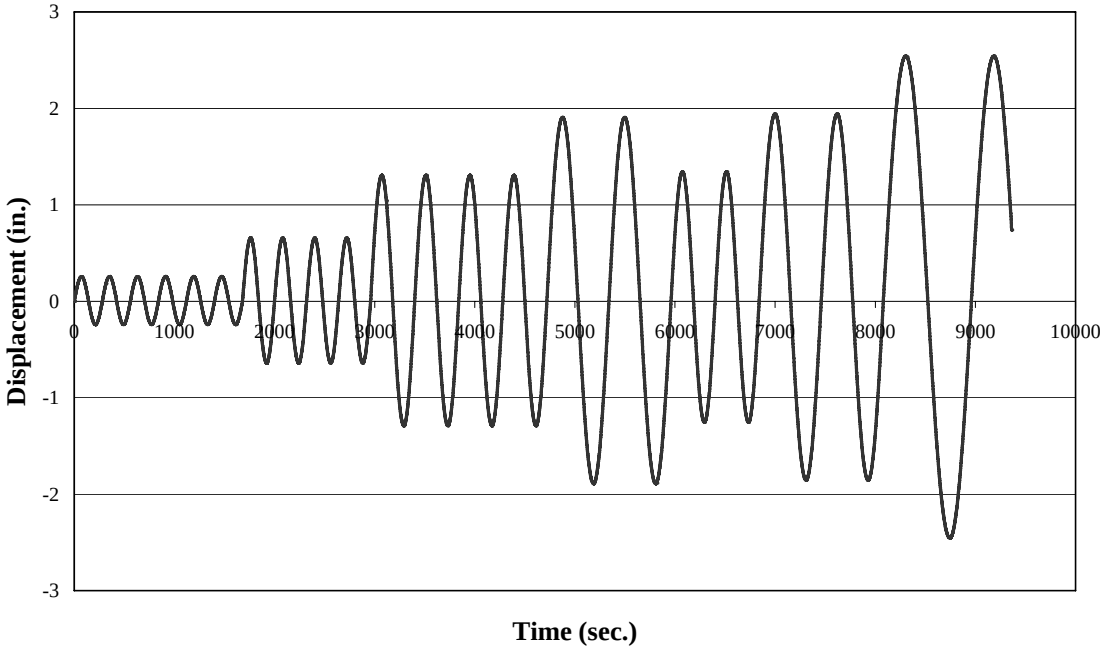



Cumulative Inelastic Displacement (CID) (LVDT average)
(500k SP1)
300
200
100
0
CID
0
5
10
15
20
25
Cycle

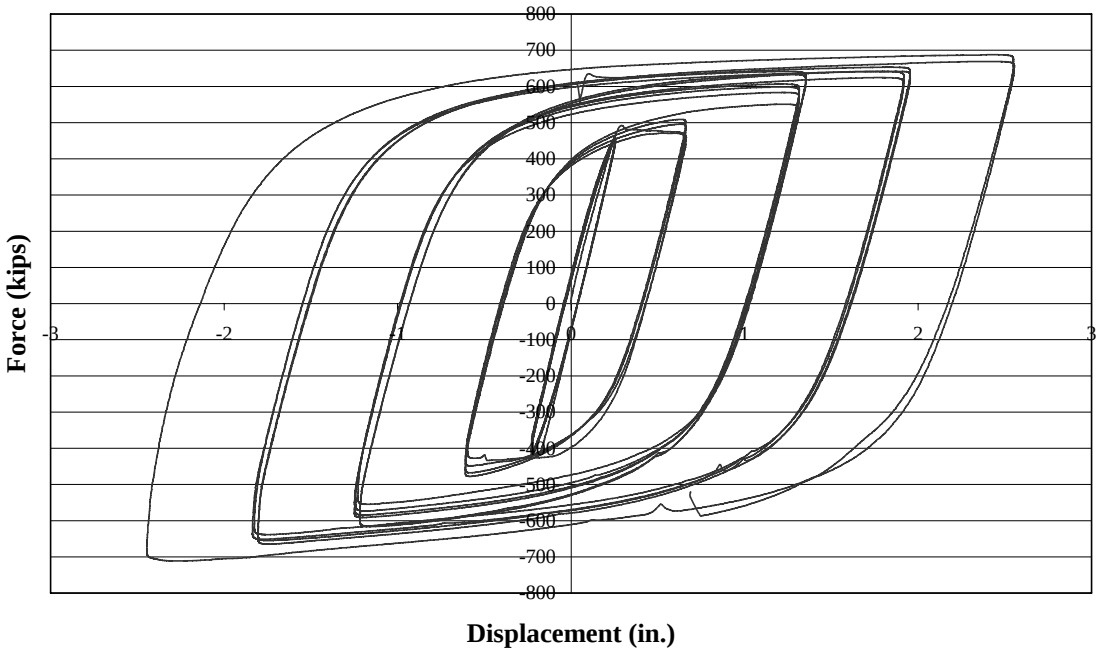
WC500 Brace 2 Results

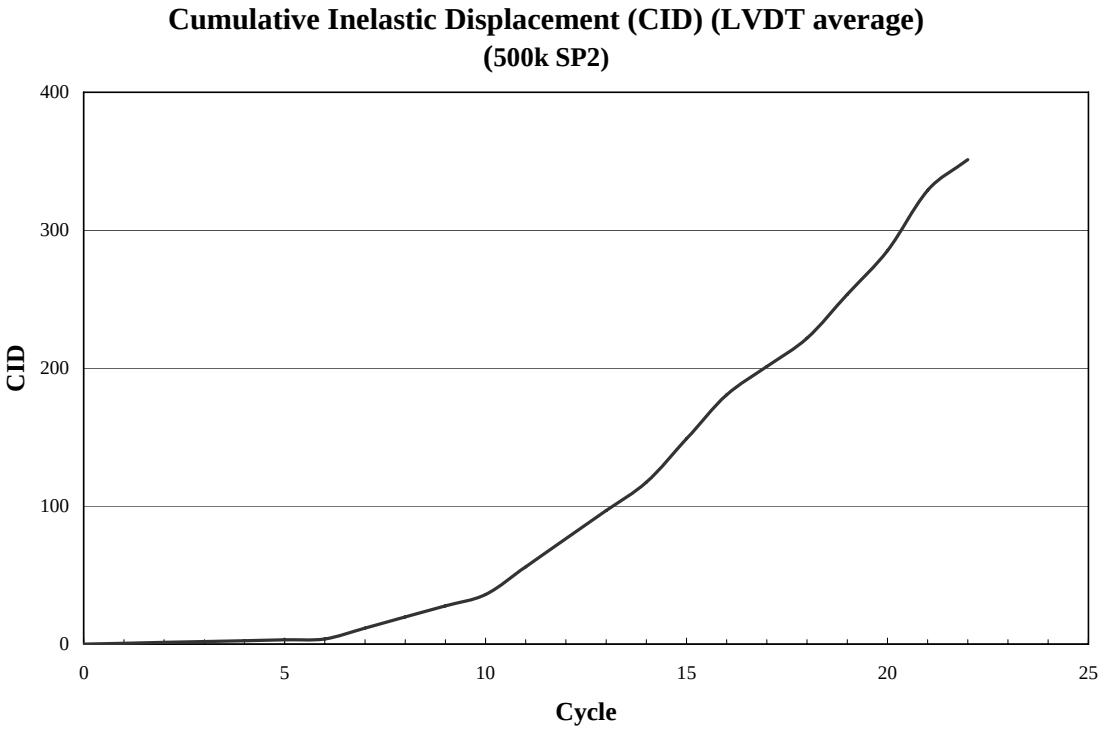
(500K S2)		CID (LVDTavg)				C/T	Tension Force
Step	Cycle	per cycle	per step	Cum.	per step		Kips
	0			0.00			
1	1	0.603	3.60	0.60	3.60	0.894	455.15
	2	0.608		1.21		0.910	450.56
	3	0.601		1.81		0.909	449.31
	4	0.602		2.41		0.909	453.22
	5	0.594		3.01		0.912	452.50
	6	0.596		3.60		0.890	455.71
2	7	7.946	32.29	11.55	35.89	0.882	458.29
	8	8.129		19.68		0.951	458.94
	9	8.105		27.78		0.954	479.67
	10	8.106		35.89		0.937	501.80
3	11	20.184	81.35	56.07	117.24	1.022	528.76
	12	20.357		76.43		0.979	571.79
	13	20.382		96.81		0.975	582.45
	14	20.426		117.24		0.979	592.28
4	15	31.653	63.43	148.89	180.67	1.020	613.30
	16	31.779		180.67		1.016	627.19
5	17	20.488	40.98	201.16	221.65	0.953	629.75
	18	20.494		221.65		0.947	622.24
6	19	31.804	63.61	253.46	285.26	1.032	622.04
	20	31.807		285.26		0.999	644.74
7	21	43.618	65.91	328.88	351.17	1.040	656.45
	22	22.294	351.17	351.17	**Max**	**1.040**	
	Σ	351.17					

Displacement Time History (East LVDT)
(500k SP2)



Force-Displacement (LVDT average)
(500k SP2)

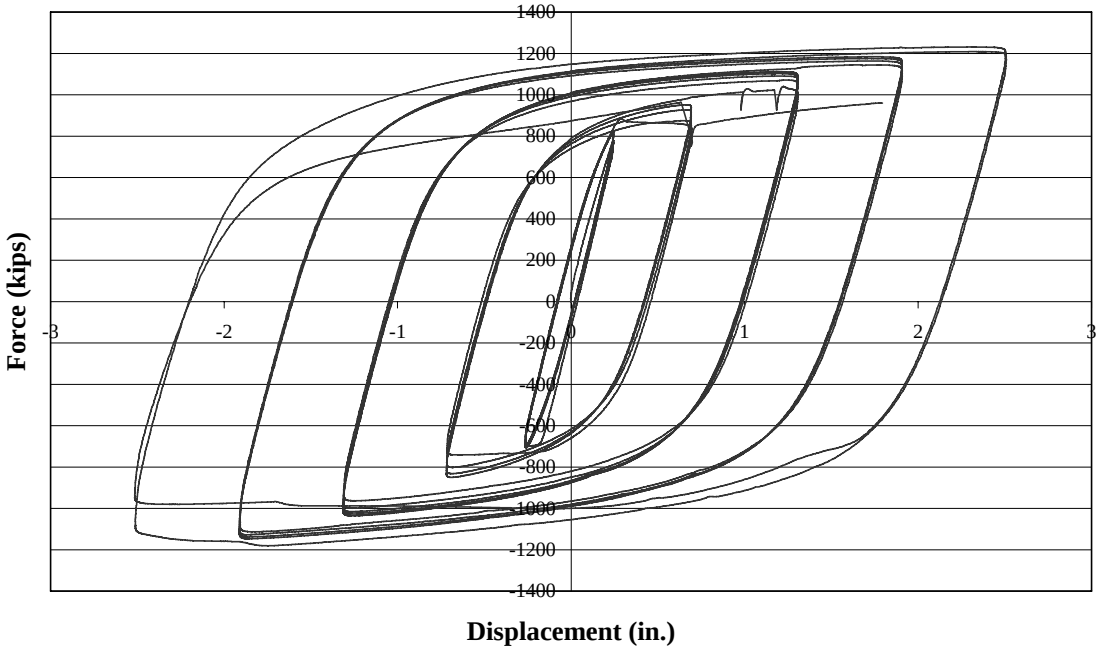



Cumulative Inelastic Displacement (CID) (LVDT average)
(500k SP2)
CID
400
300
200
100
0
0
5
10
15
20
25
Cycle

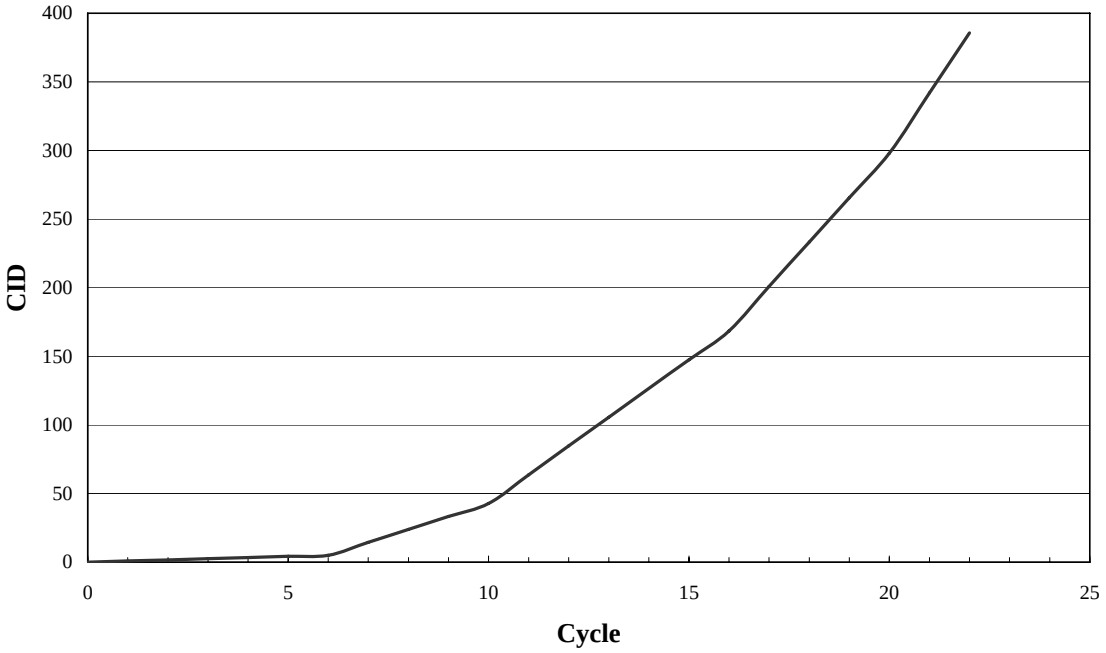
WC780 Brace Results

(780K S1)		CID (LVDTavg)				C/T	Tension Force
Step	Cycle	per cycle	per step	Cum.	per step		Kips
	0			0.00			
1	1	0.835	5.06	0.84	5.06	0.893	764.37
	2	0.855		1.69		0.869	799.69
	3	0.843		2.53		0.856	816.31
	4	0.848		3.38		0.841	817.29
	5	0.845		4.23		0.843	806.38
	6	0.833		5.06		0.847	816.96
2	7	9.429	37.74	14.49	42.80	0.854	829.81
	8	9.424		23.91		0.916	850.03
	9	9.437		33.35		0.904	895.59
	10	9.451		42.80		0.887	937.30
3	11	20.935	125.73	63.74	168.53	0.942	997.38
	12	20.943		84.68		0.916	1041.05
	13	20.959		105.64		0.923	1070.77
	14	20.960		126.60		0.926	1082.11
	15	20.967		147.57		0.918	1091.45
	16	20.963		168.53		0.943	1074.32
4	17	32.364	129.51	200.89	298.04	0.978	1111.23
	18	32.381		233.27		0.969	1135.02
	19	32.379		265.65		0.968	1148.09
	20	32.384		298.04		0.979	1145.70
5	21	43.824	87.63	341.86	385.67	0.929	1170.13
	22	43.808		385.67		0.787	1203.99
6	23	7.547	7.55	393.22	393.22		
	Σ	393.22	393.22		**Max**	**0.979**	

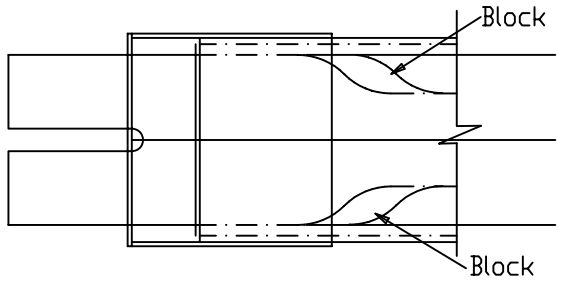
Force-Displacement (LVDT average)
(780k SP1)



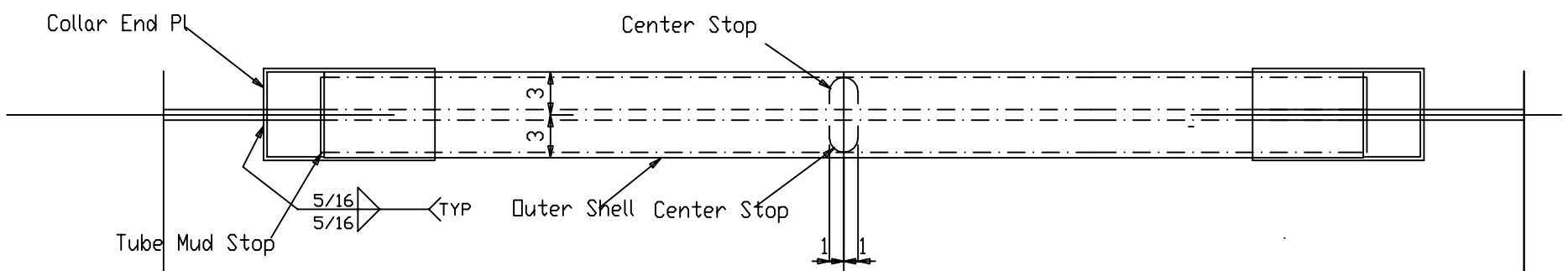
Cumulative Inelastic Displacement (CID) (LVDT average)
(780k SP1)

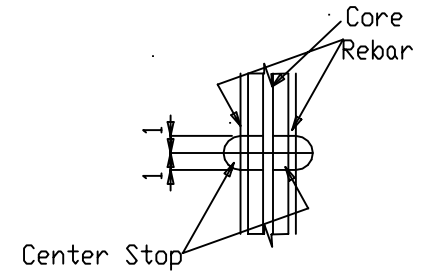


Appendix B: Brace Drawings

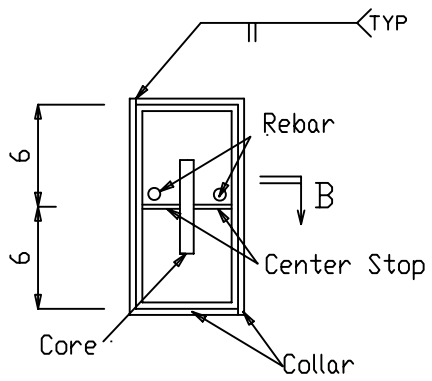


Compressable Block Placement

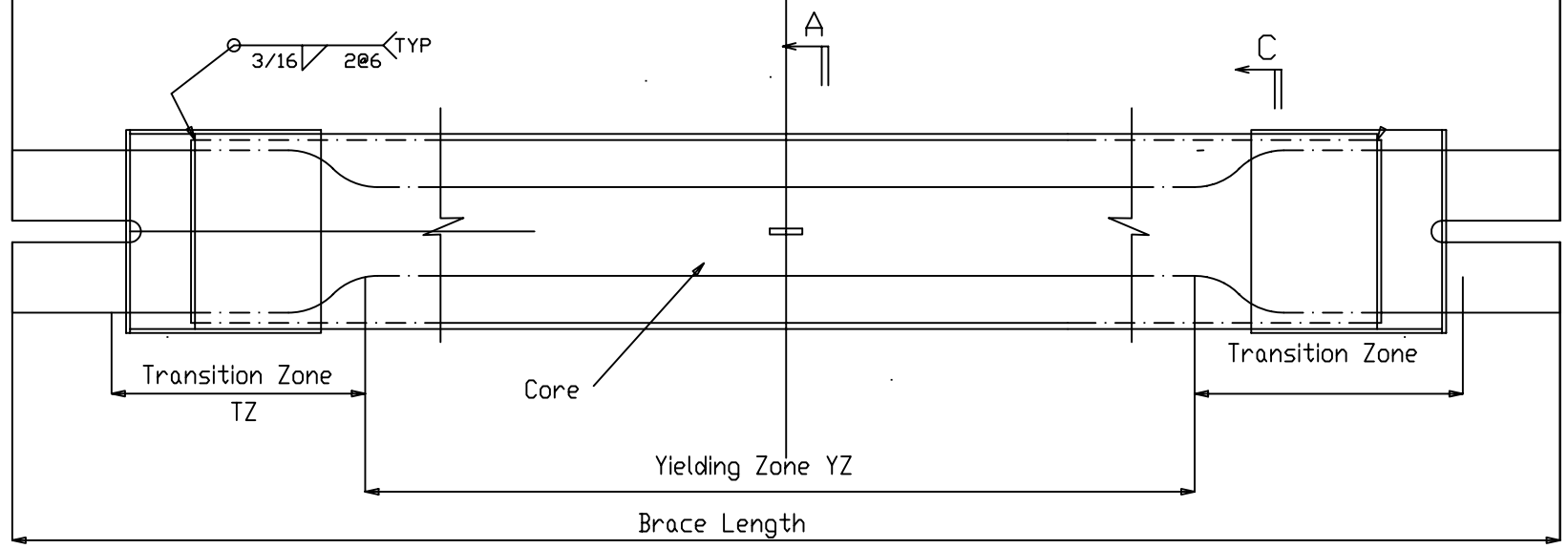




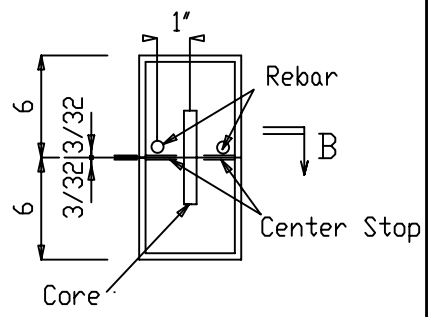
SECTION B



SECTION C



ONE BRACE Generic



SECTION A

BILL OF MATERIAL

NO.		LENGTH			
PCS.	DISCRIPTION	FT.	IN.	MARK	REMARKS

NO.	DATE AND CHECKED BY	DESCRIPTION OF REVISION			
△					
△					
△					
△					

SHOP PLACE PIECE MARK ON LEFT HAND END OF MEMBER AS DETAILED
ERECT MEMBER WITH PIECE MARK TO END SHOWN ON PLACING PLAN

FOR △ DATE

PRINTS ISSUED

MATERIAL A36 & AS NOTED

HOLES____–_____UNLESS NOTED

BOLTS_____–_____(U.N.)

SHOP PAINT _____

SURFACE PREPARATION _____

SUBJECT WC Generic

PROJECT Welded Testing

LOCATION University of Utah

CUSTOMER Star Seismic

ERECTION DWG REF Test ENGINEER DWG REF Test

DRAWN BY_____DATE_____CHECKED BY

STAR SEISMIC
3070 RAMUSSEN RD
SUITE 260
PARK CITY, UT 84098
www.starseismic.net
1-435-940-9222

JOB NO Test DWG NO_____

Appendix C: Material Test Report

SMITH-EMERY LABORATORIES
An Independent Commercial Testing Laboratory, Established 1904

To: ARGAN JOHNSON, JR
STAR SEIZMIC, LLC
3070 RASMUSSEN ROAD # 260
PARK CITY, UT 84098

Date: November 23, 2005
Project No.: 35366-1
Lab. Report No.: M05 - 336

STAR SEISMIC, LLC

TABLE I - ROOM-TEMPERATURE TENSION TEST RESULTS

		Tensile Property		
Size	Ht.#	Elon. 2-in Gage	Yield Point, psi	Ult.Tensile psi
¾-in Thick	400 - 9160	36 %	41, 380	66, 945
1.0-in Thick	400 - 9161	36 %	39, 910	66, 940
ASTM A 36	**--**	**21%min**	**36,000 min**	**58,000-80,000**

1. The stress-strain curves for specimens machined from the submitted samples identified in Table I exhibit a distinct yield point. The yield point is the first stress in a material, less than the maximum obtainable stress, at which an increase in strain occurs without an increase in stress.

2. The machined specimens from the material identified in Table I meets the tensile requirement for ASTM A 36 specification for Carbon Structural Steel.

Prepared By: _____

Praful P. Patel, P.E
Metallurgical Engineer

REGISTERED PROFESSIONAL ENGINEER
PRAFUL P. PATEL
MT 1933
Exp. 03/31/06
METALLURGICAL ENGINEER
STATE OF CALIFORNIA