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EXPERIMENTAL EVALUATION OF A BUCKLING RESTRAINED BRACE USING A NON-TRADITIONAL MATERIAL

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Abstract

Steel braced frames include braces to provide lateral resistance and stiffness. Conventional steel braces may buckle in compression and break after a few cycles when subjected to seismic loads. In order to provide adequate seismic resistance, larger sections of the braces must be used than those required purely from the level of tensile stresses. As an alternative, Buckling Restrained Braces (BRBs) are increasingly being used as seismic protection elements.

This research aims to experimentally study the behaviour of buckling restrained braces constructed using a non-traditional material, subjected to monotonic and cyclic loads. It is expected that the use of this material will simplify the fabrication process, the transportation, and the installation in the structure, as compared to currently available BRBs, without loss of strength and deformation capacity. Four specimens 2-meter long are manufactured using a square outer steel tube (200mmx200mmx5mm), a rectangular steel core (100mmx10mm), and a rubber-like material as confining material. The steel used is ASTM A36. The specimens consider variation of parameters such as the level of bond between the steel core and the confining material, the type of loading (monotonic versus cyclic), and the presence of steel end caps to restrict the longitudinal movement of the confining material.

Constitutive relations of the confining material are determined from cyclic tests of material coupons under tension and direct shear loading. The brace specimens are subjected to displacement controlled tension/compression cycles of increasing amplitude, according to AISC 341-10. Stable hysteresis cycles with slight strength degradation are obtained, showing that using this material in BRBs is an appropriate solution that can be manufactured with local technology.

Keywords: Buckling restrained brace, cyclic loading tests, steel structures, ductility demand, energy dissipation

1. Introduction

Following the behavior of building structures during earthquakes, it has been recognized that increased strength and stable energy dissipation capability are the most desirable mechanical characteristics needed to maintain interstory drift and overall displacements within tolerable levels.

Using buckling restrained braces for seismic resistance design of building structures has been popular in Japan since the 1995 Kobe earthquake. With the idea of preventing brace buckling under compression, one form of BRB comprises a yielding steel core, which is encased in a concrete filled steel hollow structural section (HSS), Fig. 1 shows this configuration. The BRB system is also gaining acceptance in the United States since the 1994 Northridge, California, earthquake (Clark et al. [1], Lopez [2], Shuhaibar et al. [3]), and a number of buildings have been constructed with BRBs in the past few years.

Fig. 1 – BRB Components

One such buckling restrained brace is the Unbonded Brace, manufactured by Nippon Steel Corporation. The unbonded brace consists of a steel core plate encased in a steel tube filled with concrete. The steel core carries the axial load while the outer steel tube provides lateral support to the core and prevents global buckling. A material placed between the steel core and the encasing concrete eliminates shear transfer during the elongation and contraction of the steel core and also accommodates its lateral expansion when in compression, hence the name unbonded brace.

Another type of BRB that was developed by Corebrace, LLC in the United States has been experimentally investigated at the University of Utah (Staker and Reaveley [4]); the study was limited to uniaxial testing of the braces.

This research aims to experimentally study the behaviour of buckling restrained braces constructed using a non-traditional material, subjected to monotonic and cyclic loads. It is expected that the use of this material will simplify the fabrication process, the transportation, and the installation in the structure, as compared to currently available BRBs, without loss of strength and deformation capacity.

2. Test Specimens

Four full-scale buckling restrained brace (BRB) specimens were tested. Each specimen was composed of a central rectangular core plate (100mmx10mm), which was confined in a rubber-filled square outer steel tube (200mmx200mmx5mm). The specimens consider variation of parameters such as the level of bond between the steel core and the confining material, the type of loading (monotonic versus cyclic), and the presence of steel end caps to restrict the longitudinal movement of the confining material. Specimens detail were

- Prototype BRB1 consists of a steel core brace, square outer steel tube, unbonded interface between steel core and confining material, monotonic load.

- Prototype BRB2 consists of a steel core brace, square outer steel tube, unbonded interface between steel core and confining material, cyclic load.

- Prototype BRB3 consists of a steel core brace, square outer steel tube, bonded interface between steel core and confining material, cyclic load.

- Prototype BRB4 consists of a steel core brace, square outer steel tube, end plates, unbonded interface between steel core and confining material, cyclic load.

Fig. 2 shows the overall geometry and dimensions of the test specimens.

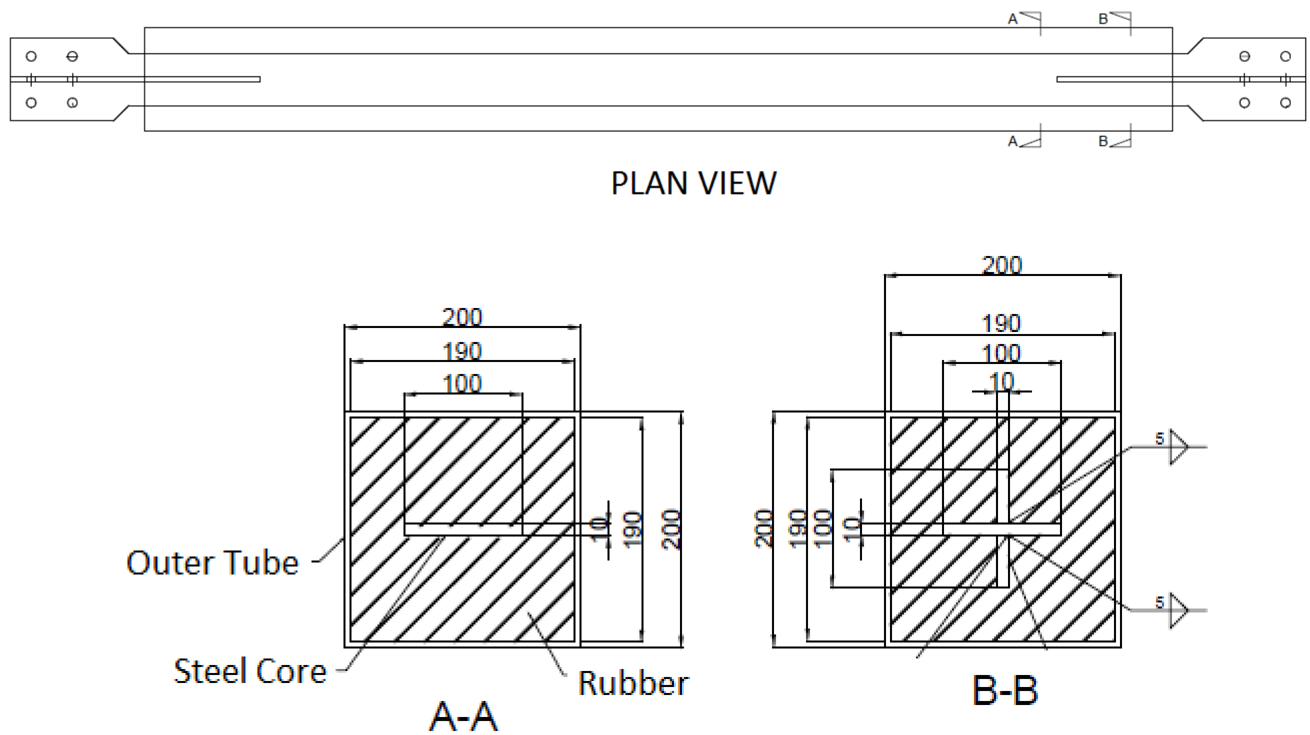

Fig. 2 – Overall Geometry

3. Material Properties

The core plate material is A36 steel, with a nominal yield strength, f_y, of 250 MPa. The outer steel tube is made of A500 Grade B steel. Confining material corresponds to a 70° ShA neoprene, black color, high shear modulus and low damping coefficient.

Tensile coupon tests of the core plates were conducted at the Structures Laboratory of the Department of Civil Engineering, University of Chile, to obtain the actual material properties. Four coupons were tested following ASTM E8/E8M – 15a [5]; the results are summarized in Table 1.

Table 1 – Mechanical Properties of Core Plates

	fy [MPa]	fu [MPa]	E [MPa]
Coupon 1	293	459	211.215
Coupon 2	309	474	231.605
Coupon 3	315	478	220.167
Coupon 4	304	469	223.417

Constitutive relations of the confining material (shear modulus, damping coefficient) are determined from cyclic tests of material coupons under tension and direct shear loading.

Tensile coupon tests of the confining material were conducted by IDIEM to obtain the actual material properties According to ASTM D412 – 06a [6], five dumbbell specimens were prepared for testing each of the rubber sheets (15 specimens); the test results are the median of three individual test measurement value, the test results are summarized in Tables 2, 3, and 4.

Table 2 – Mechanical Properties of Confining Material – Sheet 1

Coupon		Dimensions [mm]		Gage Distance [mm]		Load [N]	Tensile [MPa]	Elongation [%]
		Thickness	Width	Initial	Final			
M1	1	2,34	6,31	25	130	252	17,07	420
	2	2,30	6,39	25	130	266	18,10	420
	4	2,20	6,28	25	130	244	17,66	420
Average		2,28	6,33	25	130	254	17,61	420
Standard Deviation		0,07	0,06	0	0	11	0,52	0

Table 3 – Mechanical Properties of Confining Material – Sheet 2

Coupon		Dimensions [mm]		Gage Distance [mm]		Load [N]	Tensile [MPa]	Elongation [%]
		Thickness	Width	Initial	Final			
M2	1	2,25	6,24	25	125	240	17,09	400
	2	2,30	6,34	25	125	242	17,35	400
	4	2,34	6,37	25	125	252	16,91	400
Average		2,26	6,32	25	125	254	17,12	400
Standard Deviation		0,07	0,07	0	0	11	0,22	0

Table 4 – Mechanical Properties of Confining Material – Sheet 3

Coupon		Dimensions [mm]		Gage Distance [mm]		Load [N]	Tensile [MPa]	Elongation [%]
		Thickness	Width	Initial	Final			
M3	1	2,32	6,23	25	120	244	16,88	380
	2	2,26	6,23	25	120	234	16,62	380
	4	2,17	5,90	25	120	204	15,93	380
Average		2,25	6,12	25	120	227	16,48	380
Standard Deviation		0,08	0,19	0	0	21	0,49	0

Direct shear tests of the confining material were conducted at the Structures Laboratory of the Department of Civil Engineering, University of Chile, to obtain the actual material properties. According to Herrera [7], three specimens were tested at differents deformations (50%, 75%, 100% and 115%); the results are summarized in Tables 5, 6, 7, and 8.

Table 5 – Dynamic Properties of Confining Material – Deformation 50%

	Specimen 1	Specimen 2	Specimen 3
G [kgf/cm2]	15,70	15,20	15,35
	15,60	15,13	15,35
	15,52	15,09	15,30
β [%]	6,14	5,86	5,90
	6,14	5,85	5,90
	6,11	5,87	5,78

Table 6 – Dynamic Properties of Confining Material – Deformation 75%

	Specimen 1	Specimen 2	Specimen 3
G [kgf/cm2]	14,33	14,38	14,85
	14,32	14,36	14,78
	14,29	14,29	14,76
β [%]	5,82	5,54	5,56
	5,87	5,50	5,55
	5,83	5,54	5,62

Table 7 – Dynamic Properties of Confining Material – Deformation 100%

	Specimen 1	Specimen 2	Specimen 3
G [kgf/cm2]	13,84	13,49	14,00
	13,82	13,43	13,96
	13,77	13,37	13,88
β [%]	5,64	5,44	5,43
	5,65	5,38	5,39
	5,66	5,42	5,45

Table 8 – Dynamic Properties of Confining Material – Deformation 115%

	Specimen 1	Specimen 2	Specimen 3
G [kgf/cm2]	12,77	12,98	13,08
	12,71	12,91	13,04
	12,66	12,88	13,01
β [%]	5,81	5,64	5,48
	5,81	5,63	5,47
	5,80	5,66	5,45

4. Loading Protocol

According to Appendix T of the AISC Seismic Provisions [8], the following loading sequence shall be applied to the test specimens, where the deformation is the steel core axial deformation of the test specimen:

(1) 2 cycles of loading at the deformation corresponding to $\Delta_b = 1.0\Delta_{by}$,
(2) 2 cycles of loading at the deformation corresponding to $\Delta_b = 0.5\Delta_{bm}$,
(3) 2 cycles of loading at the deformation corresponding to $\Delta_b = 1.0\Delta_{bm}$,
(4) 2 cycles of loading at the deformation corresponding to $\Delta_b = 1.5\Delta_{bm}$,
(5) 2 cycles of loading at the deformation corresponding to $\Delta_b = 2.0\Delta_{bm}$,
(6) Additional complete cycles of loading at the deformation corresponding to $\Delta_b = 1.5\Delta_{bm}$ as required for the brace test specimen to archieve acumulative inelastic axial deformation of at least 200 times the yield deformation.

The above loading sequence requires two quantities: Δ_{by} and Δ_{bm}. Δ_{by} is defined as the axial deformation at first significant yield of the specimen, and Δ_{bm} corresponds to the axial deformation of the specimen at the design story drift. Fig 3, shows the loading protocol used for the tests.

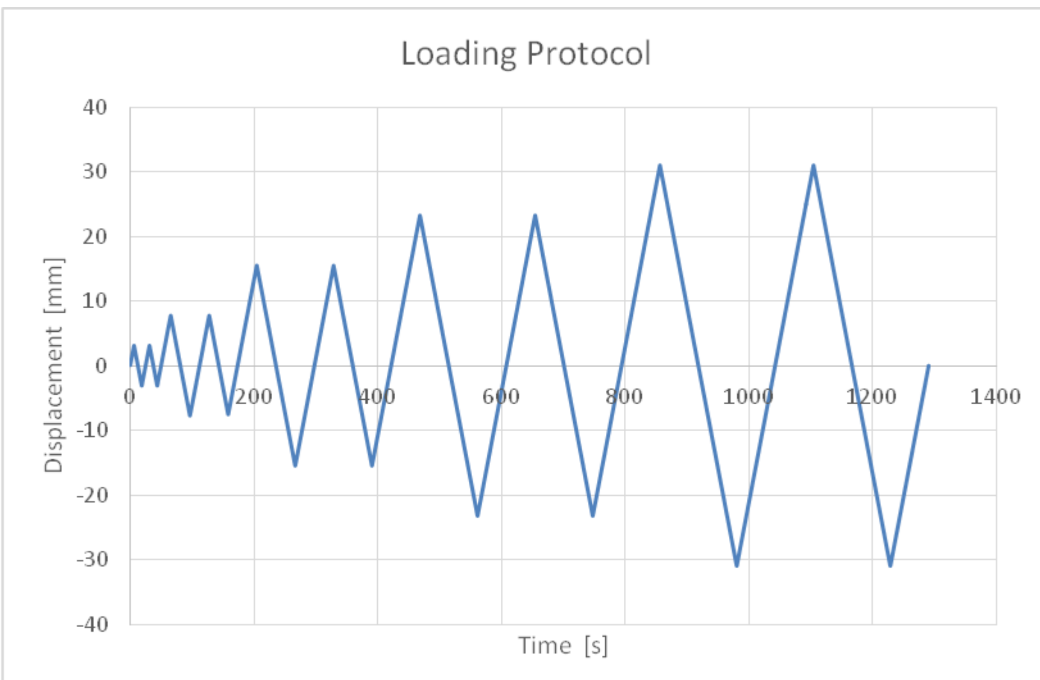

Fig. 3 – Loading Protocol.

This loading protocol was applied under displacement control using a PI servocontroller, which took the measurement of the actuator displacement from a linear variable differential transducer (LVDT) installed in the actuator, compare it with required displacement signal, and adjust accordingly.

5. Instrumentation

The force and displacement quantities of interest were measured with a digital data acquisition system. The force was measured by the load cell in the actuator and the nine displacements of interest were measured with linear variable differential transformers (LVDT). Fig. 4, shows a schematic diagram of the displacement instrumentation. It consists of

- One LVDT in the actuator, to measure the displacement and control the loading protocol.
- Two LVDTs, one on each side of the brace in a horizontal plane, to measure the relative displacement between the two ends of the steel core.
- Four LVDTs, two at each end of the specimen in a horizontal plane, to measure the relative displacement between the steel core and the end of the outer steel tube.
- Two LVDTs located at the mid-point of the specimen, one horizontally and one vertically, to measure the out-of-plane movement of the outer tube during loading.

The specimens were also instrumented with strain gages on the outer steel tube. Twelve gages were installed, four on each section at the quarter points. At the top and bottom side all gages were installed in the longitudinal direction, while on the sides the gage in the middle was installed in longitudinal direction and the other two were installed in the transverse direction of the brace.

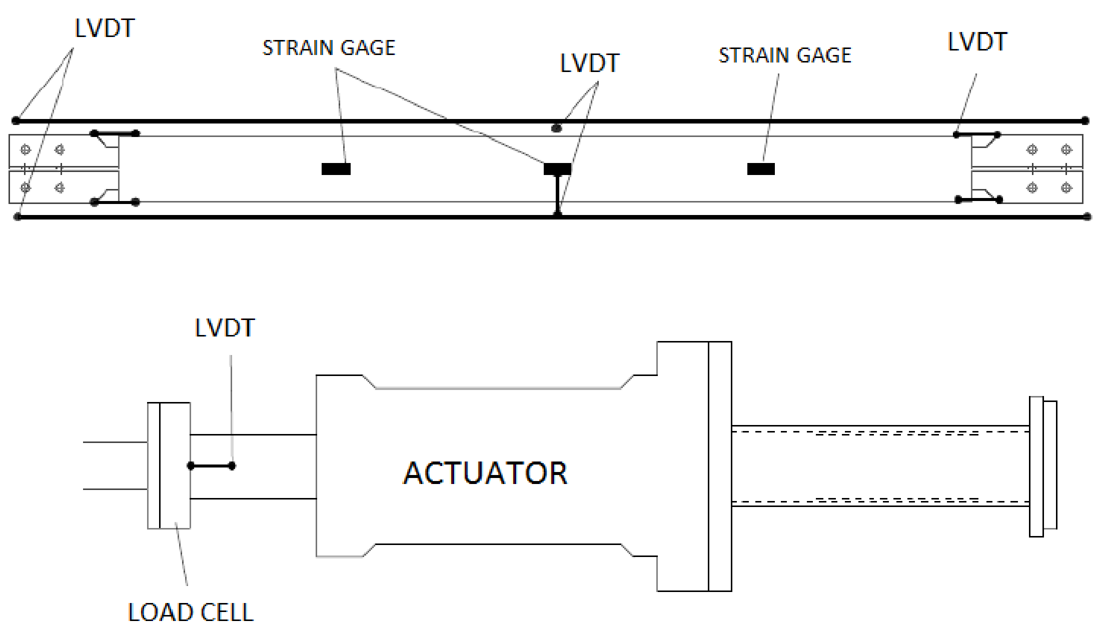

Fig. 4 – Location of linear variable differential transformers and strain gages

6. Test Setup

The four specimens tests were conducted at the Structures Laboratory of the Department of Civil Engineering, University of Chile. The experimental setup consisted in two fixed column at the ends and one sliding support in the middle, as seen in Fig. 5 and 6. The monotonic and cyclic load was applied by a 1000 kN actuator driven by a displacement control software, following Appendix T of the AISC Seismic Provisions loading protocol.

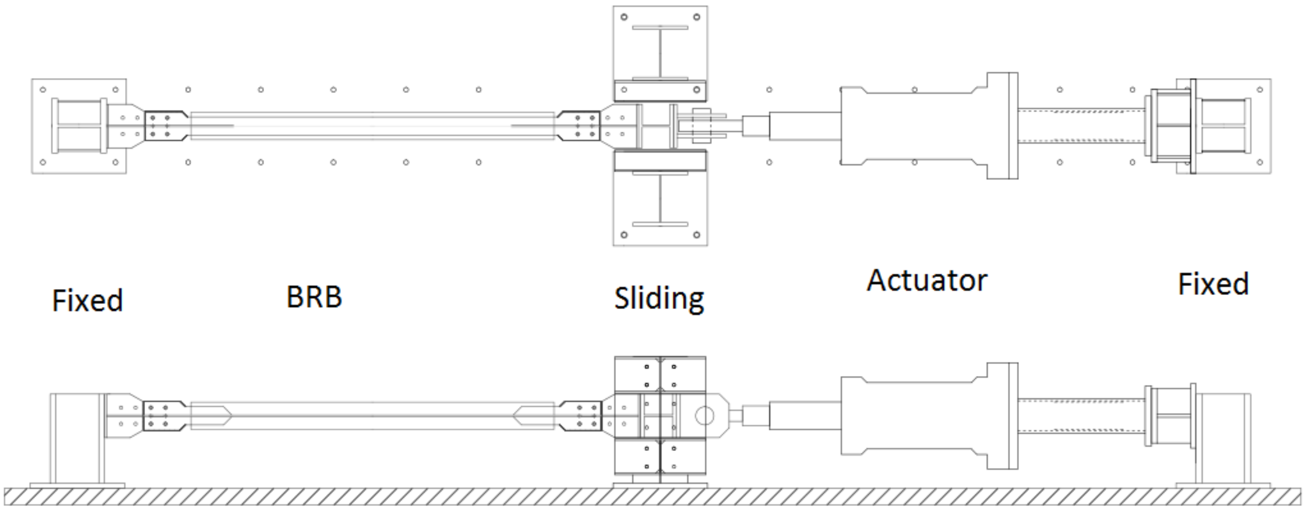

Fig. 5 - Test Setup Scheme

Fig. 6 – Test Setup Picture

7. Test Results

Specimen BRB1 was tested twice, first under monotonically increasing compression load and then under cyclic load at constant amplitude, equal to the maximum deformation reached in the monotonic test. Results from Specimen A monotonic test are presented in Fig 7. It shows the recorded force in the brace versus the total displacements measured across the yielding portion which was calculated by averaging the displacements recorded by the longitudinal LVDTs.

Specimens BRB2, BRB3 and BRB4 were tested under cyclic load at increasing amplitude following loading protocol.

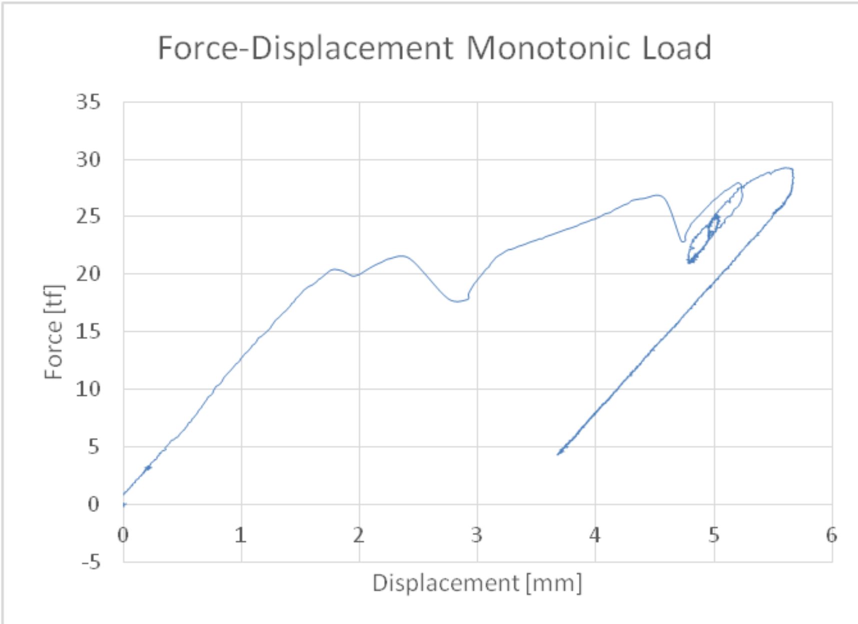

Fig. 7 – Recorded Force-Displacement Monotonic Load

Fig 8 shows the recorded force in the brace versus the control load protocol displacements measured by the longitudinal LVDT in the actuator for the four BRB. The red line correspond to the yield tensile stress.

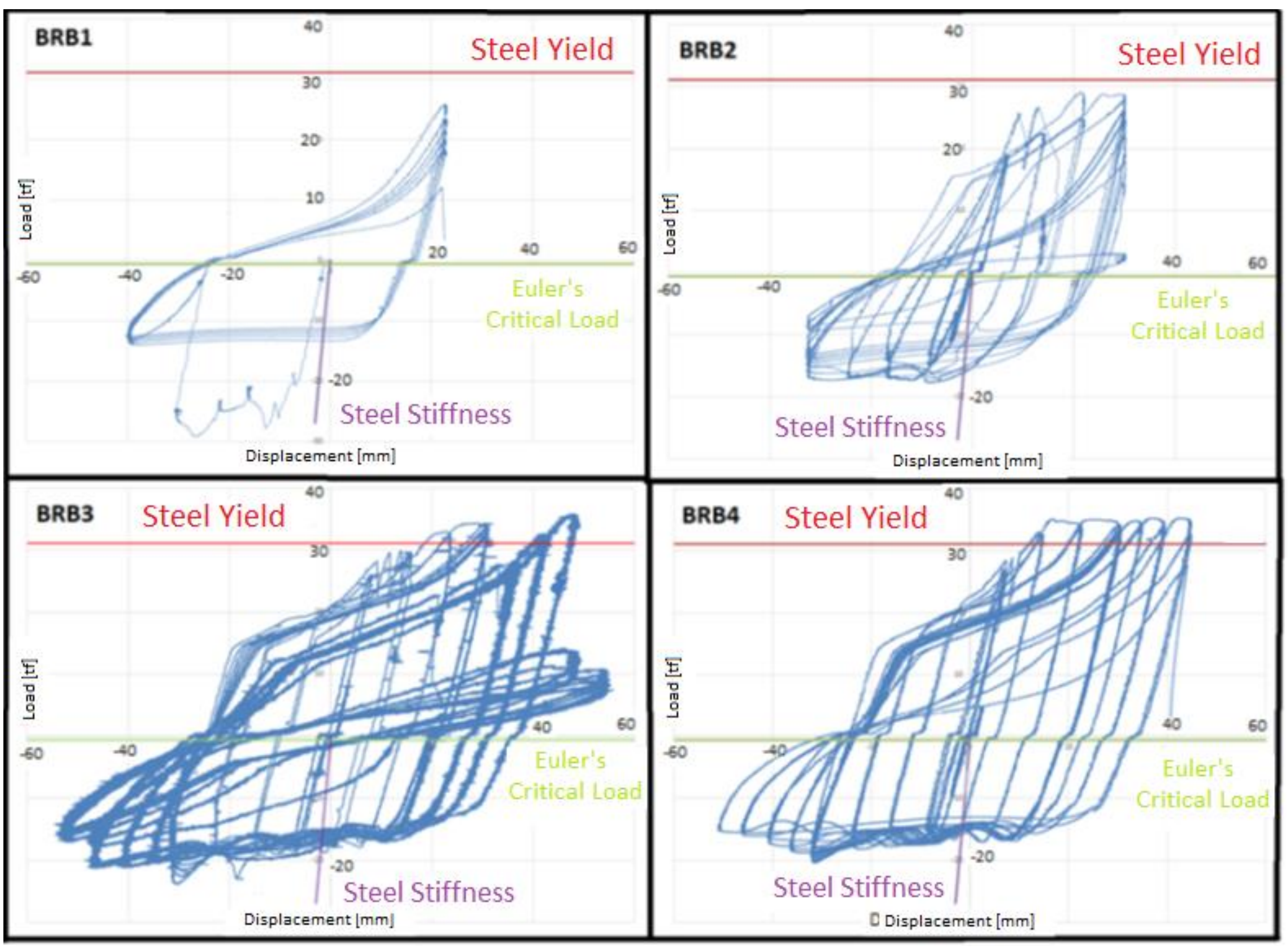

Fig. 8 – Recorded Force-Displacement Cyclic Load

The confinement is effective in avoiding buckling and maximum compression stresseses reach to about half of tensile yielding stresses. Cycles are stable specially for BRB3 and BRB4. In the first one the plate is bonded to the rubber-like material and the second one has steel plates at the ends. Fig 9 shows fractured plate BRB1.

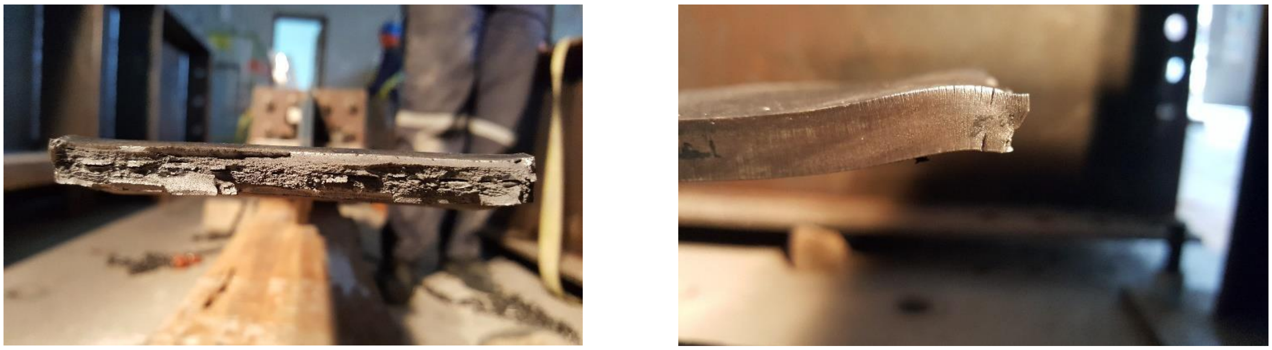

Fig. 9 Fractured Steel Plate, BRB1

Fig. 10 Fractured Steel Plate, BRB4

8. Conclusions

Based on the results, the following conclusion can be made

- Specimen BRB1 performed well under monotonic load, and no fracture was observed.
- Specimen BRB1 eventually fractured during 7th cycle of the cyclic fatigue testing. Prior to fracture, the hysteresis behavior was very stable.
- Specimen BRB2 eventually fractured during 8th cycle of the cyclic fatigue testing. Prior to fracture, the hysteresis behavior was very stable.
- Specimens BRB3 and BRB4 eventually fractured during increasing amplitud at 50 [mm]. Prior to fracture, the hysteresis behavior was very stable.

- The maximum compressive force under monotonic compression is greater than the maximun tension force of the cyclic loading phase. However, the latter is greater than the maximun compressive force from the following cycles. There seems to be a degree of buckling occurring, but the residual strength is significant and stable.

- Compressive and tensile maximum forces and energy dissipation for bonded specimen are larger than for unbonded specimens.

9. Acknowledgments

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