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EXPERIMENTAL ANALYSIS OF BUCKLING RESTRAINED BRACE UNDER CYCLIC LOADNG

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Abstract - *It isn't the earthquake that causes damage to the community and society but it is the unfit structures that do. To minimize the effects of Earthquake and lateral forces on the structure, bracing system is one of the systems which plays an effective role in resisting the lateral forces in buildings. In most conventional cases, steel frame structures which have insufficient strength or stiffness against lateral forces can be rehabilitated by bracing systems. Braces could be added without substantially increasing the mass of the structures while the structures could be considerably strengthened and stiffened. New type of bracing system, called Buckling Restrained bracing system, has many advantages over conventional bracing system, hence can be employed in the structure. In the present study, fabrication of models of Buckling Restrained Brace (BRB) was done for analysing the performance of the models under dynamic loading. The study focuses on the behaviour of steel under tensile loading and compression loading and utilization of steel for the fabrication of models of BRB. One model was tested to determine the ultimate strength of BRB and another model was used to conduct static ultimate and cycling test. The behaviour of the model under static ultimate and cycling test was studied and graph was plotted.*

***Key Words*: Buckling Restrained Brace, Hysteresis Loop, Unbonded Brace, Tensile Loading, Compressive Loading,**

1. INTRODUCTION

Food, clothing and shelter are basic needs of human beings right from civilizations. Shelters are no longer simple structures, but are towering high-rise buildings that are usually constructed with either concrete or steel. A major innovation is the development of the steel frame as a structural element. Reinforced concrete, where steel rods are combined with concrete, is also a developed construction method. However, these high-rise buildings constructed with concrete or steel are not immune against natural calamities like Earthquake and tsunami and these calamities have adverse effects on the buildings or structures which result in death of a large number of people. The level of damage done to a structure depends on the amplitude and the duration of shaking. When the ground shakes, buildings respond to the accelerations transmitted from the ground through the structure's foundation. The inertia of the building (it wants to stay at rest) can cause shearing of the structure which can concentrate stresses on the weak walls or joints in the structure resulting in failure or perhaps total collapse. The type of shaking and the frequency of shaking depend upon the structure. Tall buildings tend to amplify the motions of longer period motions when compared with small buildings. Taller buildings also tend to shake longer than short buildings, which can make them relatively more susceptible to damage.

Steel concentric braced frame (CBF) is one of the efficient and commonly used lateral load resisting systems, especially in the structures of high seismic regions (or moderate to high seismic prone zone). The work lines of CBFs essentially intersect at points [FEMA, 2000]. The steel braces improve the lateral strength and the stiffness by inelastic deformation during an earthquake that leads to seismic energy dissipation. Studies show that the lateral response of CBFs is mainly dominated by inelastic behavior of bracing members; hence these members are subjected to alternating tension and compression loads once CBFs are exposed to the earthquake loading. It is through the post-buckling hysteresis behavior of bracing members and upon cyclic loading that the braced frames yield and dissipate energy. However, the energy dissipation capacity of a steel braced structure is limited due to the buckling of the braces. Considering this limitation, efforts have been made to develop new CBF systems with stable hysteretic behavior, significant ductility as well as large energy dissipation capacity. One such CBF system with an improved seismic behavior is the buckling restrained braced frame (BRBF) that enhances not only the energy dissipation capacity of a structure rather decreases the demand for inelastic deformation of the main structural members.

A Buckling Restrained Brace (BRB) is a structural brace in a building, designed to allow the building to withstand cyclical lateral loadings, typically earthquake-induced loading. BRB frames have the advantages of exhibiting a more stable hysteretic response and to impose reduced forces on the foundations and the adjacent structural elements that must be capacity protected. Compared to conventional tension-compression CBFs, the BRB system typically is laterally more flexible due to higher brace axial design stresses but this shortcoming can be overcome by reducing the length of the yielding core segment of the braces. The use of Buckling Restrained Braced (BRB) frames in lieu of conventional concentrically braced steel frames (CBFs) is gaining popularity both for new construction and for rehabilitation projects [Tremblay and Poncet, 2004]. The idea of buckling restrained brace (BRB) frames was borne out of need to enhance the compressive capacity of braces without affecting its stronger tensile capacity in order to produce a symmetric hysteretic response. BRB is a structural member in building, which uses the plastic strength of steel by such design which yields a stable hysteresis loops and energy is efficiently dissipated in event of dynamic loads such as earthquake or wind load. It was first introduced and developed by Nippon steel organization in Japan, at the end of 1980s and was trademark under name “Unbonded brace”. In 1999, it was first installed in the United States, in the plant and environmental building in U.C Davis. Nippon steel were able to install BRB successfully in various parts of earthquake prone zones [Black and Makris, 2002]. BRB usage is currently accepted, with its design regulated in current standards, throughout the world.

1.1 Components

The BRB is composed of a ductile steel core, designed to yield during tension and compression both. To prevent the buckling phenomenon, the steel core is first placed inside a steel casing before it is being filled with mortar or concrete. Prior to mortar casting, an unbinding material (bond preventing layer) or a very small air gap is left over between the core and mortar to minimize or possibly eliminate the transfer of axial force from steel core to mortar and the hollowness of structural section components of BRB. The casing is concrete filled tube, which restrains buckling of steel core through its flexural rigidity. Its design criterion is to provide adequate lateral support to steel core through its rigidity. Thus, the core in BRB can undergo a considerable yielding under both tension and compression, and absorb energy unlike conventional bracing. On the other hand, the basic structural framework in BRBF is designed to remain elastic and all of the seismic damage occurs within the braces.

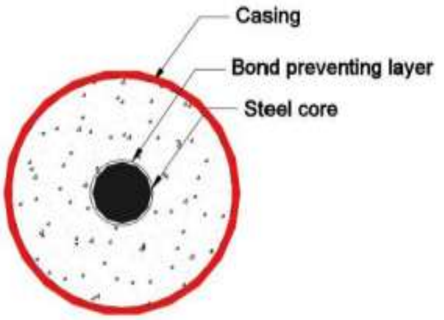

Fig -1: Cross section of BRB

Fig -2: Side view of BRB

1.2 Steel under tensile loading

If tensile force is applied to a steel bar it will have some extension. If the force is small, the ratio of the stress and strain will remain proportional. And the graph will be a straight line (up to point A). So the 0 to point A is the limit of proportionality.

If the force is considerably large the material will experience elastic deformation but the ratio of stress and strain will not be proportional (point A to B). This is the elastic limit. Beyond that point the material will experience plastic deformation. The point where plastic deformations starts is the yield point which is show in the figure as point B. B is the upper yield point. Resulting graph will not be straight line anymore. C is the lower yield point. D is the maximum ultimate stress. E is the breaking stress.

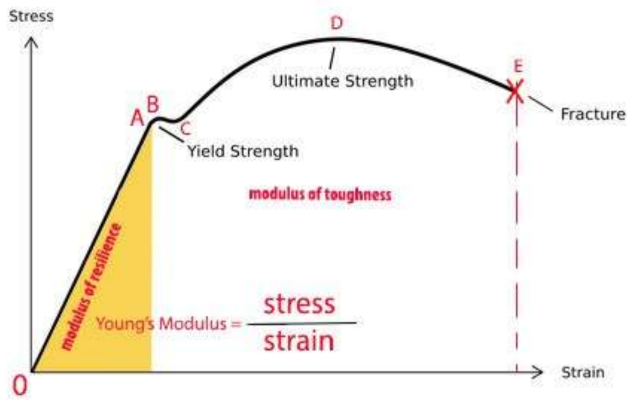

Fig -3: Standard stress-strain curve for mild steel (*courtesy*: The Chicago Curve)

1.3 Loading and unloading of steel

Figure 4 shows the behavior of a circular steel bar when tensile loads are applied, released and again applied. The specimen is first loaded monotonically to some value beyond the initial yield point and then completely unloaded. When unloaded, the strain decreases along the line AB which is parallel to the initial linear region of the curve. But a permanent irrecoverable strain BC is obtained. This is known as plastic strain or permanent set. Whereas the recoverable strain BC is known as elastic strain. If this specimen is reloaded, the curve follows the path BA, which is identical to the unloading path.

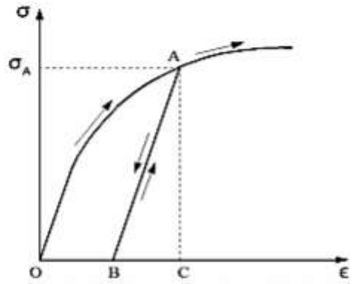

Fig -4: Loading, Unloading and Reloading

1.4 Reverse Loading

Figure 5 shows the response that would be obtained if a steel specimen is tested so as to yield in compression. On applying simple compression load on the specimen, a graph almost identical to the tensile stress-strain curve but occurring in the third quadrant is obtained. On applying plastic pre-straining in tension prior to applying compressive load, the curve varies as shown. For preloading σy" in tension, a corresponding compressive yield occurs at σy". Bauchinger effect and strain hardening affect the path followed by these curves. Here, it must be noted that the specimen yields in compression. If the specimen is slender enough to buckle before reaching yield stress, the response obtained wouldn't be identical. It is well established that as the l/r ratio i.e. the slenderness ratio increases, the specimen becomes more susceptible to buckling (where l represents effective length and r represents minimum radius of gyration of the specimen). The graph will break abruptly once the specimen buckles.

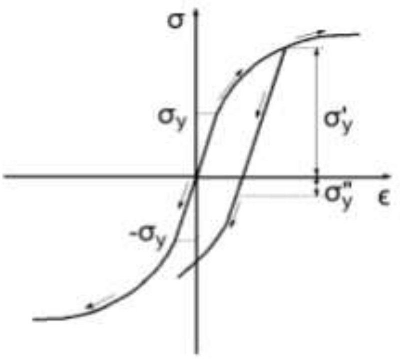

Fig -5: Reverse Loading

1.5 Hysteresis

Hysteresis in essence is the property of a system such that an output value is not strict function of the corresponding input, but also incorporates some lag, delay, or history dependence. Assuming arrangements are made that the specimens that is tested is prevented from buckling, on such specimen if cyclic loads are applied such that it yields in tension as well as compression, ideally, a curve as shown in Figure 6 is obtained. Such a curve is termed "stable hysteresis curve". The stress - strain relation in the curve is interpreted and it is observed that energy dissipation increases with increase in number of loading cycles. It is also noticed that the area inside curve goes on increasing with the number of cycles. Therefore to obtain maximum energy dissipation, it is advantageous to obtain stable hysteresis characteristics for as much number of cycles as possible.

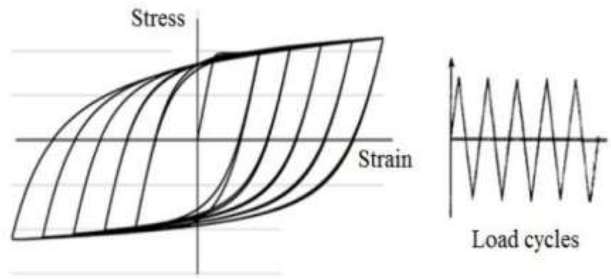

Fig -6: Stable hysteresis curve

1.6 Earthquakes

When seismic waves reach the Earth's surface, they cause the ground, and anything sitting on it, to vibrate at certain frequencies. During an earthquake, a building will tend to vibrate around one particular frequency known as its natural, or fundamental, frequency. When the building and ground share the building's natural frequency, they're said to be in resonance. Resonance amplifies the effects of an earthquake, causing buildings to suffer more damage. BRBs are used as devices to dissipate energy and dampen lateral movements of structures during earthquake. As such it is necessary to investigate the effect of earthquake loads on BRBs.

1.6.1 Effect of earthquakes on structures

To understand the effect of earthquake on structures, an example of a simple single storied single bay frame is taken as shown in figure 7 (a). A BRB is also fitted in the frame as shown. Assuming the first effect of an earthquake was to move the frame towards right as shown in figure 7 (b). Due to the ground movement, the base does move towards right, but the top portion tries to resist the motion due to inertia resulting in experience of a leftward push. All these factors in sum cause deformation of the frame as shown, resulting in action of tensile load on the BRB. In the consequent effect, the ground moves towards left causing leftward movement of the base and rightward deflection of the top due to inertia with overall deflection as shown in figure 7 (c). Here now, the BRB is in compression. Looking at the larger picture thus, we may infer that the BRBs must be designed for cyclic loads. And in general, the design loads in both cases, i.e. in tension and compression are kept equal.

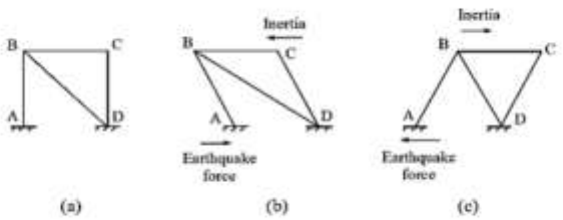

Fig -7: Earthquake forces on a single storey frame

2. PROJECT DESCRIPTION

The project focuses on three main aspects which are designing a BRB, fabricating models of BRB and testing a model of BRB for dynamic loading. Earlier works and study done related to design and fabrication of BRBs considered the core to be a rectangular plate or a cruciform shaped cross section. The design and fabrication process for the same is quite well defined. Here, we have attempted to design, fabricate and test a BRB with a core which has a circular cross section. The major disadvantage of using a circular cross section for the core is that for a given area, the radius of gyration and hence the moment of inertia cannot be played with. In cruciform cross section, for a given cross sectional area, the radius of gyration is quite large as compared to a circular one; while when a rectangular plate is used, the orientation can be suitably altered according to other design criteria. But, as the number of Buckling restrained braces required for the project were small, use of circular cores proved to be economical, owing to their easy availability. Thus, by fabricating and testing a BRB with circular core, the project aimed to obtain a stable hysteresis curve. In course, it is also established whether the parameters that define the design of BRB with cruciform core can be used effectively for circular ones or not. The project's aim was to obtain hysteresis curve when the BRB was subjected to cyclic loads which would indicate that the BRB would not buckle in compression before yielding.

2.1 Design of buckling restrained brace

The brace is the most important element in earthquake proof and wind proof steel structures. Braces not only help in structural reinforcement but also used for adding special aesthetic to the steel structures. It is generally known that brace frames have adequate horizontal resistance and structural rigidity. For heavily earthquake ridden countries like Japan, where design of buildings is according to the elastic-plastic design, buckling of braces is difficult to handle with plastic design because their yield stress falls after yielding under compressive loading. If the slenderness ratio of braces is increased to take advantage of their tensile strength only, they do not afford much energy absorption because of their slip type hysteresis characteristic. If cross section is increased to avoid buckling, greater stress concentration results, and building appearance looks bulky. We have fabricated two specimens for experimental analysis. A 6.5 mm diameter mild steel bar was used as a core. The core was encased in hollow steel pipe with inner diameter 28mm and outer diameter 30mm and was filled with cement mortar for avoiding buckling of braces. The length of the steel core was 950mm and effective buckling length that is the length of steel encasing is 650mm (buckling length = 0.7L).

2.2 Components of buckling restrained brace and their fabrication

2.2.1 Circular Core

The core consisted of 6.5 mm diameter, perfectly straight mild steel rod of length 650 mm with 150 mm free on both sides. During the experiment, the core is expected to take the complete external force. Buckling of the core is avoided by the encasing assembly. Hence it yields in tension as well as compression. The bond between the core and concrete is suitably broken so that load is not transferred to the concrete via bond or friction.

2.2.2 Concrete

The gap between the core and the pipe was filled with concrete. The main purpose of concrete in this assembly was to act like a layer of numerous continuously disposed elastic springs between the core and the outer part. Hence the composition of concrete was decided based on convenience and suitability rather than on strength required. The final proportions used were – The maximum size of aggregate used was 4.36 mm restricted by the gap available between the core and the outer pipe. Efforts were inclined towards obtaining well graded mixers. Thus the proportion of aggregate passing through 4.6 mm and retained on 2.36 mm: passing through 2.36 mm and retained on 1.18mm: passing through 1.18 mm was kept 2:1:1.

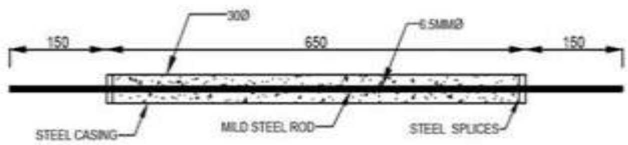

Fig -8: Components of fabricated buckling restrained brace

2.2.3 Casing pipe

A mild steel circular pipe of inner diameter 28 mm and thickness 2 mm and length 650 mm was used to encase the complete assembly. The main function of this pipe was to prevent the bursting of inner concrete and global buckling of the inner assembly.

2.2.4 Bond breaking layer

A single layer of PVC insulation tape was applied to the inner circular core so as to break the bond at the concrete-core interface and prevent transmission of load via shear. In classic example of BRB testing, a thick layer of expandable materials like polystyrenes were used to eliminate shear as well as to accommodate lateral expansion and contraction of the core during loading. Here, the project tested whether a single layer of PVC insulation tape could effectively provide the above mentioned things. The advantage of using this tape lied in its availability and ease of application to the core.

2.2.5 Steel splices

A few thin circular steel slices of inner diameter 7 mm which was almost equal to the diameter of the circular core were fabricated. These were used in essence to maintain verticality of circular core as to avoid getting eccentric during casting. Since these were placed at both the ends and at the centre of the casing they played a role in eliminating local buckling in the transmission zone.

Photo-1: Cicular steel core rod wrapped in bond breaking layer and splice placed at the centre of the rod.

Photo-2: Casing pipe filled with concrete during the fabrication process of buckling restrained brace

3. TEST PROGRAMS

Two models of the similar dimensions and properties were separately tested in the project. In the first test, model one of BRB was tested to determine the ultimate strength of the BRB. In the second test, static ultimate and cyclic test was conducted on the model two of BRB at ARAI (Automotive Research Association of India)

3.1 Ultimate strength test of BRB

Before the static ultimate and cyclic test, test was conducted to check the ultimate strength of BRB and feasibility of project. To ensure the cyclic loading limits, this test was carried out on first model of BRB by applying tensile load under Universal Testing Machine. The results of this test were plotted graphically and explained below.

3.1.1 The specimen

An inner steel core of circular cross-section of 6.5mm diameter mild steel rod was encased in a circular pipe of inner diameter of 28mm and outer diameter 30mm via concrete. The length of core was 820mm and the length of pipe was 650mm. The core was covered with a PVC layer to prevent bonding. The specifications of cement used were: cement grade OPC 43, cement-aggregate ratio-1:3 and water-cement-0.5.

3.1.2 Test and result

The test was carried out under UTM 5582. The model was tested for tensile loading and it was observed that the failure occurred due to yielding of steel core at 18.34 KN with a deflection of 18.2mm. Thus, it was decided that cyclic loading for the model two should be ±17 KN.

Photo-3: Model one of BRB under universal testing machine

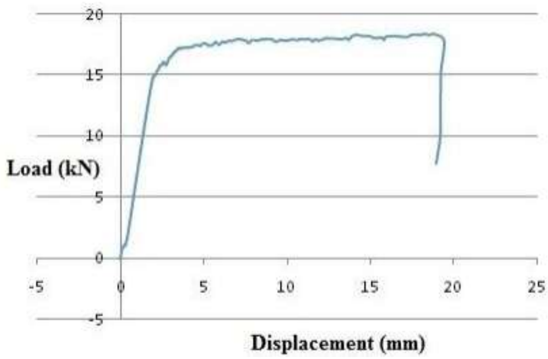

Fig -9: Load (kN) vs.Displacement (mm) for model one

3.2 Static ultimate and cyclic test of BRB

3.2.1 Experimental setup

Test Instrument: INSTRON 1343

Test Objective: To conduct static ultimate and cyclic test on structural specimen model two using servo hydraulic test facility.

Test Requirement and Specifications:

1. To prepare mechanical and servo hydraulic test setup for specimen testing.

2. Conduct cyclic test on specimen with sinusoidal cyclic load of 0 ± 17 KN for 10 cycles. Data of load and deflection was obtained.

Test Equipment Used:

1. Servo Hydraulic Actuator, ± 250 KN capacity

2. Load Cell, ±250 KN capacity

3. Controller.

3.2.2 Procedure

Mechanical and servo hydraulic set up was prepared. Model of BRB was held rigidly in upper and lower hydraulic grip in test frame. Cyclic load of 0 ± 17 kN was applied for 10 cycles. Data of load and deflection was acquired.

3.2.3 Testing

The BRB model no. 2 was tested under a cyclic load of 17 KN under the instrument INSTRON 1343 at ARAI. The cyclic load was of sinusoidal nature and was applied with a frequency of 0.029 Hz. The load frequency came out to be 2 KN per second. A total of 10 cycles of cyclic loading were applied of the model. Model two was attached to the apparatus with the help of hydraulic grips as shown in figure 10. Thus the cyclic load was transferred to the core through these grips and a small portion of the core of 10mm was left unbraced for deflection purpose. The values for deflection (mm) and load (KN) were observed during the test.

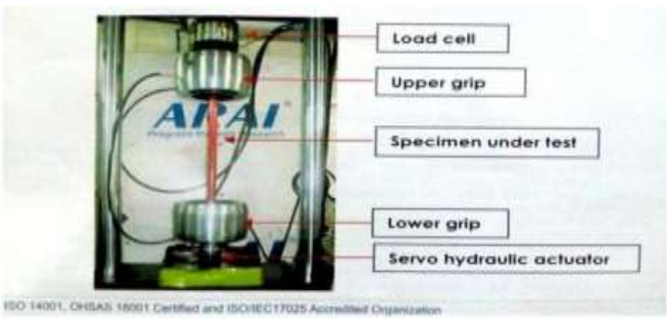

Fig -10: Model two of BRB under cyclic loading test at ARAI

3.3 Stability analysis of the model of BRB

1. Defining design load:

Let P1 be the load at which the core yields in tension. Hence, when yield stress of mild steel is taken as 250 MPa,

$P_1 = (\pi/4)$ (d) (F_y)

$P_1 = (\pi/4)$ (6.52) (250) = 8.29 KN

Since we wished to record the performance of the brace after yielding of the model, we considered application of 10 KN in both tension and compression.

2. Check of the section for global flexural buckling:

Data –

Ai = cross sectional area of the yielding portion of the brace i.e. the core cross section

Ai=(π/4) (d)

= (π/4) (6.52) = 33.19 mm2

I = Moment of Inertia of the outer tube

= (π/64) [304 - 284] = 9600 mm^4

KL = Effective buckling length of the brace

= 650 mm

E = Young"s modulus of the outer tube

= 2 x 105 N/m^2

We have,

Pcr = π 2 EI/$(KL)^2$

= π 2 x 2 x 105 x 9600/6502

= 44,851 N

= 44kN > 17kN

Hence the brace is safe for these criteria.

3. Check for buckling of inner core in higher modes:

Data –

β = Distributed spring constant 25

= 0.55 $tons/cm^2$

= 55 N/m^2

Et= Tangent elongation modulus

= 2 x 105

Ii = Moment of inertia of the inner core

= (π/4) (6.54) = 87.62 mm^4

We have,

$P_{cr} = 2\sqrt{\beta E}\mathrm{I}$

= 2 x $\sqrt{55x87.62x2x10^5}$

= 62.09 KN > 17 KN

Hence the brace is safe against buckling of inner core in high modes.

3.3 Test results

3.3.1 Sample readings of the test

The testing machine was connected to a computer setup to collect and observe the data during testing. Load range for this test was set as ± 17 KN i.e. 17 KN in tension as well as compression. The data for load and deflection was monitored continuously throughout the testing.

3.3.2 Force vs. Displacement curve

The graph of the data collected by the computer is shown below

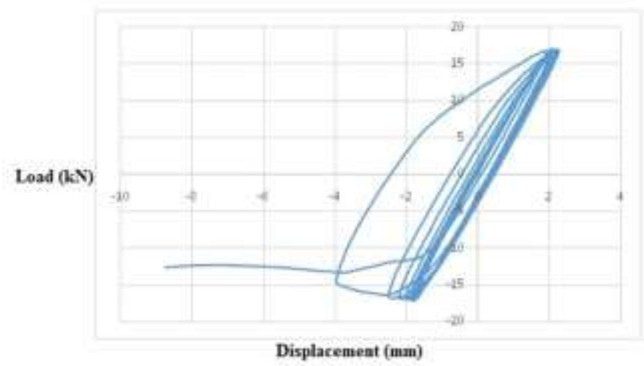

Fig -11: Force vs. Displacement curve of the test

Specimen was loaded cyclically so as to alternate between tension and compression which exhibited hysteresis loops when the loads were high enough to induce plastic flow. The enclosed area in the loop seen in figure 11 is the strain energy per unit volume released as heat in each loading cycle. This is the tendency of the specimen's core that is being bent back and forth to become quite hot at the region of plastic bending. The temperature of the specimen had risen according to the magnitude of this internal heat generated and the rate at which the heat was removed by conduction within the material and convection from the specimen surface.

3.3.2 Condition of the model after the test

After the test, layer by layer disintegration was done. First the steel pipe was cut longitudinally and concrete was removed so that the effects on steel could be observed. The yielding core of the BRB did not buckle even beyond yield loads in compression.

Photo-4: Condition of the model of BRB after cyclic testing

4. CONCLUSION

First and foremost, buckling was effectively prevented even beyond yield loads in compression. Thus, it can be inferred that the concrete and the outer casing played their role well in preventing buckling of the central core. From the cyclic test, it can be observed that the graph of force vs. displacement obtained was similar to the theoretical hysteresis loop. Initially the graph follows an elastic path starting from the origin and then yields when load applied goes excess than the yield strength. The graph also shows that for every cycle some permanent deformation was observed when the loads exceed yield strength. Thus the graph was of hysteresis nature. In the final cycle the structure fails in compression due to the buckling. From the observation of the disintegrated specimen after the testing, it was observed that the specimen buckled at the unsupported length beyond the splices. Rest of the core was completely undamaged except for the bend in central length. Failure occurred in the transition zone beyond the length which was supported by the splices. It is proposed that the specimen can handle more cycles if the unsupported length is kept less. Also it can be advantageous to keep a smoother transition zone to avoid buckling of the unsupported length. No lateral or transverse cracks were observed in concrete after disintegration, not even in the area where the rod underwent bending. Thus, it can be concluded that the concrete effectively acted as a bed of numerous continuously disposed elastic springs. The material used to prevent the bonding of the core-concrete interface was undamaged and completely adherent to the core even after the test. Thus we can infer that PVC electrical tapes can be effectively used instead of a polystyrene material, since the former is easily and cheaply available. Moreover, the application of these tapes to the core is also very easy. The stable hysteresis loop obtained proves that the BRB can be effectively used as a load damping structure. Thus, when installed in structures, they can handle the lateral loads generated due to earthquakes without buckling during compression.

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