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Experimental Tests on X-Braced Frames Under Cyclic Loading and Behavior Improvement Using Lower Grade Steel and Internal Stiffeners

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Abstract

The behavior of X-braces in steel buildings depends on various parameters such as slenderness ratio of diagonals, details of gusset plates, middle connection and stitches configurations, material properties, beam to column connection and etc. Some innovative details used in three half-scale tests to verify different aspects of this system. The application of Lower-Grade Steel for design of braces implemented to absorb earthquake energy. In addition, Parallel stiffeners used inside diagonals in one of specimens to dissipate earthquake energy by accordion behavior. This test was repeated by oblique diagonals and analogous results presented. In addition, a new configuration introduced instead of conventional central plates at middle of diagonals to decrease the effective length factor of braces and increase the braces capacity in compression.

Brief demonstrations of specimens and failure modes during experimental cyclic tests presented and the critical seismic parameters compared and discussed. According to tested specimens, the considerable effects of proposed details and theories in energy dissipation capacity improvement of this system clarified.

Keywords: X-Brace, Lower Grade Steel, Cyclic Test, Seismic Behavior, Stiffener.

1. Introduction

Many researchers studied seismic behavior of X-braces in recent decades. Most of them concentrated on special parts of X-braces such as gusset plates, diagonals, connections and etc. In spite of various researches on X-Braces and the experience of recent earthquakes, there are many doubts on confident behavior of X-braces during moderate earthquakes. The need for more researches on X-bracing system leads the new researches on development and employment of new details to improve the seismic behavior of this system. In this paper, some innovative details discussed briefly and tested in three half-scale specimens. The seismic performance characteristics of X-bracing systems with new configurations studied and verified according to ATC-24 [1] guidelines.

Many researchers studied hysteresis behavior of steel X-braces [2, 3, 4, 5, 6, 7, 8, 9, 10, 11]. They found that, in general the slenderness ratio, boundary conditions, section type and width to thickness ratio are the most important and influential parameters on hysteresis behavior of braces.

Past tests on tubular braces under cyclic inelastic loading showed that these members fractured because of plastic hinge formation at the brace mid-length after buckling [12, 13, 14, 15, 16, 17, 18, 19, 20].

Tremblay (2008) showed that "Axial compressive strains that develop in rectangular steel tube braces subjected to cyclic inelastic loading can lead to local buckling and brace fracture. Fracture initiates when loading in tension, at the innermost fiber of the brace cross-section, typically shortly after local buckling of the tube walls has developed in a previous negative deformation excursion" [20].

Ebadi and Sabouri-Ghomi extended researches on premature buckling of brace in compression and its harmful effects on stability of system which leads to decreased energy absorption capacity of system. They also studied the effects of Lower Grade steel in X-Braces and developed theories for modelling the behavior of this system [21, 22, 23, 24, 25, 26, 27, 28, 29].

In this paper, three experiments on X-Braced frames with some innovative details explained. In this research, the idea of using Lower Grade Steel in steel X-Braces and the effects of new proposed configurations verified for three half-scale experimental tests and comparative diagrams presented and discussed.

2. Design of Specimens

Three half-scale specimens were tested under slow cyclic loading. These experiments were conducted at Iranian Building and Housing Research Center (BHRC) in spring 2009 [22, 26, 27, 28, 29]. Similar loading conditions and test setup were applied for all tests. All specimens were designed for equal nominal shear strength. The clear height and span width are equal to 1500 mm for each one of the tests.

The maximum applied lateral capacity of frame was limited to maximum hydraulic Jacks capacity considering appropriate safety factor.

First specimen (XBF1) didn't have any stiffeners. While internal parallel stiffeners were used in second specimen (XBF2) to limit the effects of local buckling and oblique transverse stiffeners used in third specimen (XBF3) to achieve more lateral stiffness and less lateral yield displacement along with uniform energy dissipation process [26]. The pictures of tested specimens are shown in Fig. 1.

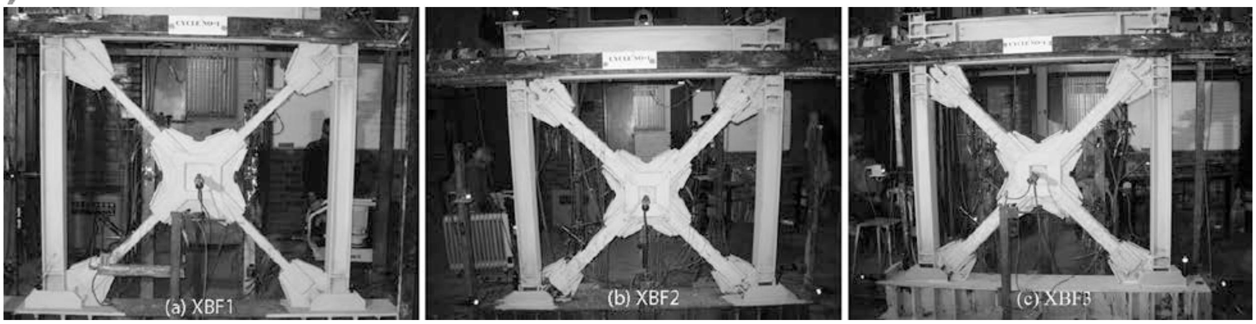

Fig. 1 – Tested specimens; a) XBF1, b) XBF2, c) XBF3

Everything in the test specimens was similar except braces. The columns, beams, gusset plates and central cores, all were made of high strength steel, while braces were made of steel with various steel grades (St52 in XBF1 and St12 in XBF2 and XBF3).

The requirements of ANSI/AISC360 and AISC341 specifications adapted in seismic design of diagonals, gusset plates, columns, stitches and width to thickness ratio of braces' sections [30, 31].

2.1 Diagonal's Stiffeners

Since the maximum thickness of available lower grade steel in Iron Market was limited to 3 mm, internal stiffeners were used to fulfill AISC341 requirements for preventing premature local buckling of sections in XBF2. The distances between the centers of stiffeners were considered equal to 30 mm. The new idea for X-braces as "Guided Local Buckling" [22, 29] for using the local buckling capacity of thin plates for energy absorption instead of limiting its capacity were employed in XBF3 using oblique transverse stiffeners inside braces. The stiffener configuration for XBF2 and XBF3 specimens are shown in Fig. 2.

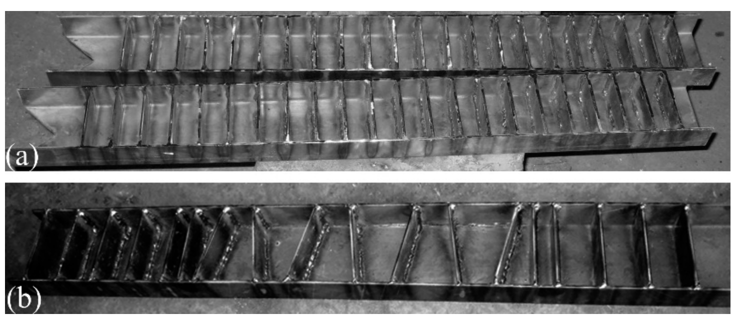

Fig. 2 – The stiffeners Configuration; a) XBF2, b) XBF3

2.2 Lower Grade Steel Theory for design of diagonals

The diagonal cross sections are designed for similar lateral loads using lower grade steel theory. According to this theory, the total capacity of system, assuming ideal non-buckling behavior of braces, can be evaluated. This theory is very useful for design of short braces with larger cross sections and little slenderness ratio. According to this theory, if both of the X-braced frames were designed for equal nominal shear strength, the relation between the cross section of braces and related yield point would be as follows:

$$A_{bs}\sigma_{ys} = A_{bl}\sigma_{yl} \tag{1}$$

where, A_{bs} and A_{bl} are cross sections of braces made of Structural Steel and Low Grade Steel, respectively. Also, σ_{ys} and σ_{yl} are yield point of Structural Steel and Low Grade Steel, respectively. The effects of buckling ignored for short braces.

2.3 Braces Section

According to AISC341 specifications, the brace section in XBF1 frame is seismically compact but this condition cannot be satisfied for XBF2 and XBF3 specimens because of small thickness of the brace section. The cross section of braces selected from double U channels with area equal to 640 for XBF1 and 1050 square millimeter for XBF2 and XBF3, respectively. The sections formed by hand working from plates.

2.4. Stitches

Stitches were designed according to section 13.2e specifications of AISC341 [31] in XBF1 and XBF2 specimens with maximum distance of 90 mm. But, because of development of local buckling in XBF1 test, longitudinal plates considered between stitches in XBF2 test to limit undesirable effects of local buckling in braces. In XBF3, Stitches were eliminated completely and longitudinal plates were used in free distances between channel sections to prevent unwanted local deflections at free edges of section. The stitches and longitudinal plates are shown in Fig. 3 for specimens.

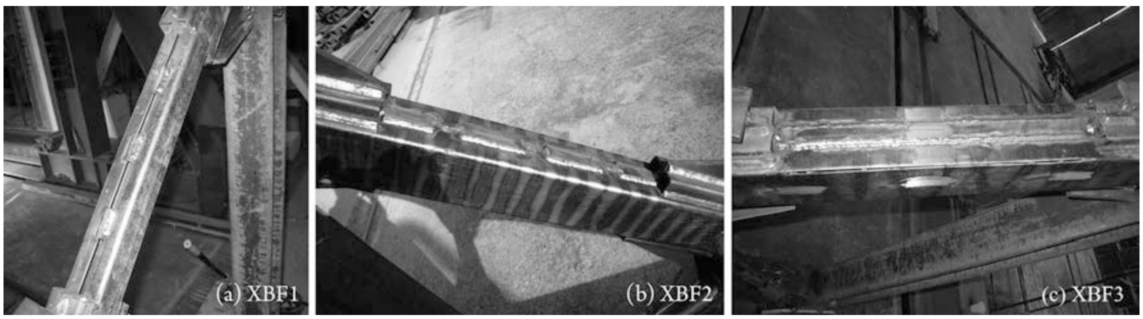

Fig. 3 – Stitches Configuration; a) XBF1, b) XBF2, c) XBF3

2.5. Gusset Plates

Gusset Plates were made of higher strength steel and fulfilled the seismic design specifications completely. The appropriate safety factor was considered to prevent any failure in gusset plates and their connections to beam, local buckling occurrence at edges and also block shear failure. Also, the Whitmore Area was considered and the gusset plates controlled for all combination of stresses. Also according to AISC341 [31] specifications, a free distance equal to 2t was observed at the end of brace (see Fig. 4).

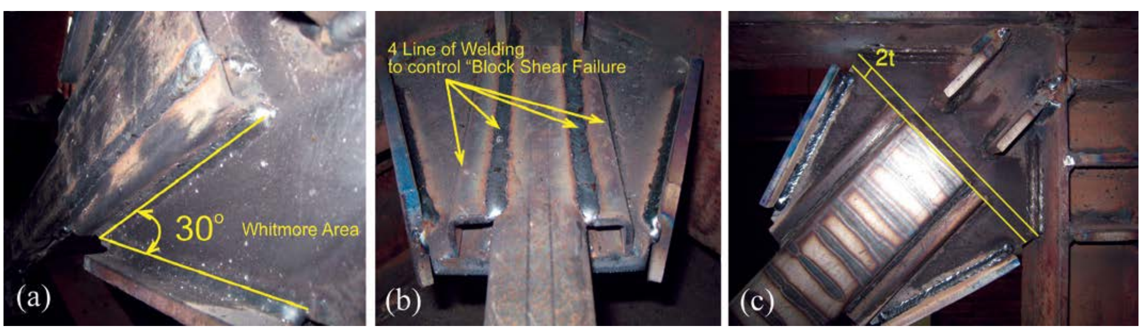

Fig. 4 – Gusset Plates Design Considerations, a) Whitmore Area, b) Block Shearing Failure, b) 2t distance at end of braces

2.6. Central Connection of Diagonals

The middle core at braces intersection plays an important role in braces buckling shape. Using special innovative central core at this experiment, not only the slenderness ratio of braces decreases because of reduction in braces unsupported length, but also the first buckling mode of braces moves from the first to the second mode. So, by using heavy central core, the effective length factor of braces was considered equal to 0.5 in both in-plane and out-of-plane directions. Finally, the short braces will have slenderness ratio equal to 50.8 for XBF1 and 27.9 for XBF2 and XBF3 specimens. The details of central core connections are shown in Fig. 5.

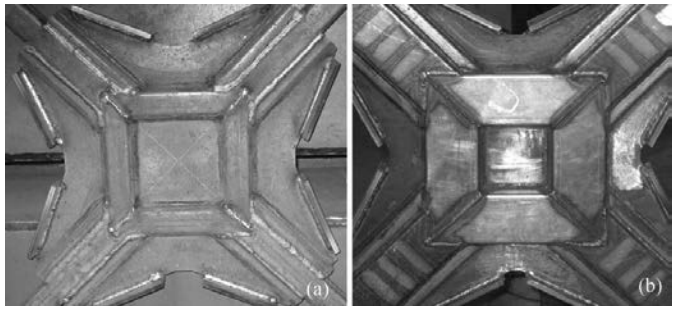

Fig. 5 – The central core details, a) XBF1, b) XBF2 & XBF3

2.7. Top Beam

Top beam was designed to transfer Jack forces to the system. This beam shall be able to transfer applied forces without failure. The beam to column connections are provided by using direct fillet welds around beam's web. The beam to column connection was designed as rigid to prevent gusset plates' zip failure in large rotations.

2.8. Columns

The columns were made of high strength steel with HEB-120 profile. They were designed to remain elastic in maximum transferred forces from braces. Also, the columns controlled for excessive shear forces caused by braces rupture.

2.9. Deep Beam

All applied forces by Jacks must ultimately be tolerated by deep beam beneath the frame connected to story floor. Its section was selected of HEB-280 profile and high strength steel. Some stiffeners provided at its web especially under columns locations.

2.10. Welding

The welded connections were designed according to AWSD1.1 [32] specifications. Appropriate safety factors were also considered for failure prevention of welds.

3. Loading Protocole

Slow multi-step cyclic loading was used for these experiments because of the desired goals and available hardware. The choice of a loading scheme is largely decided by the objective of the testing. Therefore, the proposed loading method by Krawinkler, known as ATC-24 [1], used for these experiments.

The loading and unloading process continued until cycles 24, 21 and 23 for XBF1, XBF2 and XBF3 specimens, respectively. The number of cycles with a peak deformation less than yield displacement (δ_y) was selected equal to six. Then, three cycles with peak deformation equal to δ_y were applied. The deflection increments equal to δ_y were considered for following steps. Each step contained three cycles until cycle 18. After that, each step was followed by two cycles. Since the rigid frames in all tests were similar and its Behaviour had been obtained in test XBF1, the loading operation was stopped for tests XBF2 and XBF3 immediately after the fracture of braces. The loading histories for specimens are shown in Fig. 6.

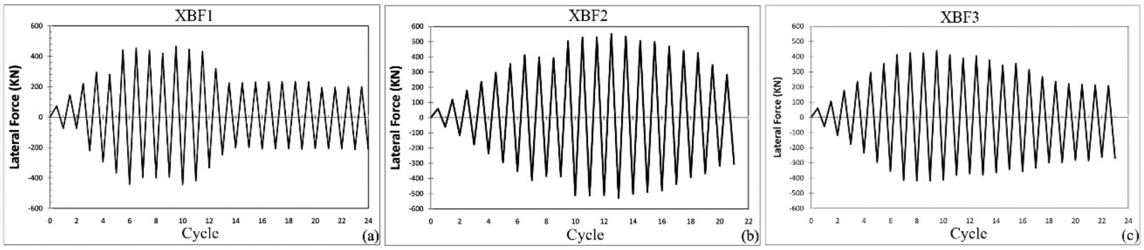

Fig. 6 – cyclic loading history, a) XBF1, b) XBF2, c) XBF3

4. Cyclic Behavior

The Behaviour of all specimens in first six cycles was linear and uniform. The Behaviours of specimens during other cycles are illustrated in following subsections.

4.1. XBF1 Specimen

XBF1 specimen entered the nonlinear zone at drift of 0.5%. The global buckling was initiated in diagonals in out of plane direction at drift of 1%. The gusset plates and central core also started to rotate in out of plane direction (buckling in second mode). Besides global buckling in diagonals, the local buckling developed, especially at the middle length of diagonals at each side of central core. So, intensive global buckling was observed at cycles 11 and 12. With increasing drift to 1.1%, intensive plastic hinge formed at middle part of compression diagonal. When the load direction changed at reverse cycle, the applied tensile force on this diagonal caused fracture at the location of plastic hinge because of necking action in the plate. With brittle fracture of one of diagonals in cycle 13, the load capacity of braces decreased considerably and the braces did not play any role on lateral stiffness, strength and energy absorption capacity of the system. The cyclic loading continued up to 3.8% drift in order to measure the contribution of frame and the role of rigid beam to column connection.

4.2. XBF2 Specimen

The XBF2 specimen entered the nonlinear zone at drift of 0.29%. With lateral drift increment, no global buckling was observed and no considerable deflection was noted in gusset plates, central core and diagonals at drift of 0.57%. A small global buckling was seen in compression diagonal in out of plane direction at drift of 0.87%. The local buckling added to global buckling at cycle 15. At this specimen, in contrary to XBF1, the start of local buckling was not accompanied by quick fracture of diagonals. First because of employing low grade steel with much more ductility and heavier section in braces and second because of the arrangement of stiffeners, close to each other, inside the braces which caused accordion shape local buckling which prevented strain concentration in some especial locations of the diagonals and therefore, the braces did not fracture under compression forces. With increment of plastic hinges due to local buckling in diagonals, small fractures occurred, especially at the middle length of diagonals at each side of central core and adjacent to gusset plates at drift of 1.07%. At following cycle, the fracture of diagonals at these locations developed and the lateral load capacity of system decreased gradually. At following cycles (until drift 1.76%) the local buckling and fracture developed. This phenomenon developed gradually which means more ductility of the system in comparison to XBF1. This type of gradually developed fractures in braces may result in the design of ductile X-Bracing system. Finally, the braces fractured completely at cycle 21.

4.3. XBF3 Specimen

The braces in XBF3 specimen entered nonlinear range at drift of 0.26% (cycle 7). No specific phenomena occurred in cycles 7, 8 and 9 and the braces had axial deformations. No global or local buckling took place in this load step. With drift increment, premature local buckling occurred suddenly at one of stiffeners intervals at drift of 0.43%. The local buckling effects intensified in following cycles. The local buckling developed quickly with drift increment and plastic hinge formed at middle length of each half brace. Therefore, the global buckling accompanied with existing deflections. In the other words, the local buckling extended to global buckling. The mid-length section of braces started to fracture at drift of 0.78% (cycle 15) because of cumulative buckling effects. At drift of 1.04%, local buckling increased in braces and led to fracture at each leg. Braces fracture reduced significantly the lateral capacity of the system and from now on, only peripheral frame resisted the applied loads. The rupture of braces completed at drift of 1.29% and actually, they didn't play any role on transformation of applied lateral forces. In following cycles, only the peripheral frame played a role on energy absorption and the stiffness of lateral load resisting system decreased significantly.

5. Cyclic and Envelope Curves

As definition, Envelope curves are the locus of extremities of the load-displacement hysteresis loops. The envelope curve contains the peak loads from the first cycle of each phase of the cyclic loading [33]. The full cyclic and envelope curves for tests are shown in Fig. 7.

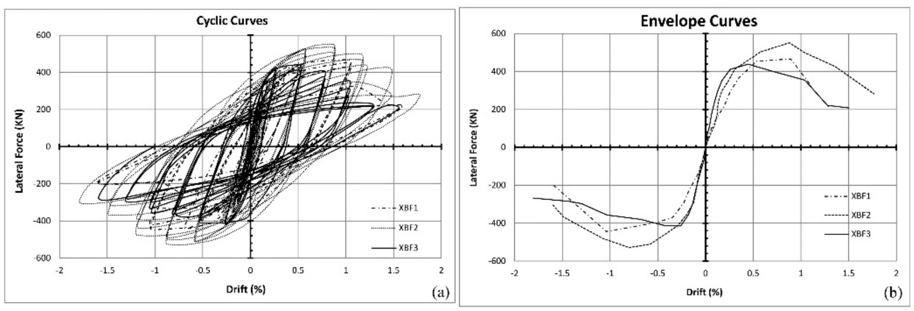

Fig. 7 – a) Cyclic curves, b) Envelope Curves

With comparison of cyclic and envelope curves in Fig. 7a, b, the following results can be observed:

1) The initial stiffness of XBF2 is more than XBF1 because of using Lower Grade Steel theory for design of braces. Also the initial stiffness of XBF3 is amplified by truss behaviour of oblique stiffeners.
2) The peak force of XBF2 is more than XBF1 because of delay in local buckling occurrence and more ductility of lower grade steel which leads to optimum use of ultimate capacity of steel. On the other hand, more capacity of steel is used. As expected, according to applied philosophy for design of XBF3, the peak force in XBF3 and XBF1 are similar.
3) The fracture drift of XBF2 is more than XBF1 because of more elongation of steel and dual effect of steel grade and internal stiffeners. This quantity is the same for XBF3 as XBF1 specimens. But because of more initial stiffness of XBF3 and its smaller yield displacement, its ductility is higher than XBF1.
4) XBF1 experienced brittle behaviour after peak force, while more ductility along with more stable behaviour considered in XBF2 and the load decreases with less slope. XBF3 presented almost uniform force level after peak load because of action of oblique stiffeners to absorb energy.

6. Equivalent Energy Elastic-Plastic

Equivalent Energy Elastic-Plastic (EEEP) is defined as an ideal elastic-plastic curve circumscribing an area equal to the area enclosed by the envelope curve between the origin, the ultimate displacement, and the displacement axis (ASTM-E2126, 2008). The Failure limit state was defined as the point on the envelope curve corresponding to the last data point with the absolute load equal or greater than |0.8 Ppeak|. EEEP curves are depicted in Fig. 8.

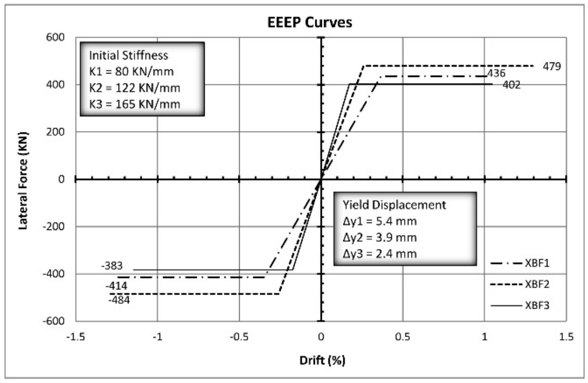

Fig. 8 – EEEP Curves for Tested Specimens

According to EEEP curves for specimens, the following results can be obtained:

1) Initial stiffness of XBF3 is higher than others because of truss Behaviour of oblique stiffeners and Lower Grade Steel Theory for design of braces. So its yield displacement is smaller and energy dissipation process starts sooner. Also the yield displacement of XBF2 is less than XBF1 because of using lower grade steel in braces and related design theory.

2) The energy dissipation of XBF2 is higher than others. This quantity for XBF1 and XBF3 are similar but the ductility of XBF3 is higher.

3) The yield force magnitude for XBF2 is higher because of confinement of braces by using stiffeners and the optimum use of lower grade steel capacity obtained. The premature local buckling and brittle Behaviour of high strength steel in XBF1 prevented increasing the force level. As mentioned before the force level was kept limited purposefully.

7. Energy Dissipation

The area under hysteresis curves indicates the energy dissipation capacity of the system. If the area under hysteresis curves is bigger, more dissipation capacity will be expected. The energy absorption capacity of tested specimens until defined ultimate point is shown in Fig. 9. In XBF1, the energy dissipation of the system increases uniformly with drift increment until reaching peak point. But it experienced premature decrease after peak point because of not-ductile Behaviour and fracture of braces because of induced moderate local buckling. It means that the sudden fracture of the braces prevented the system to dissipate energy completely. In XBF2, the decrease in energy absorption capacity decreases smoothly and more ductile Behaviour was observed. So, according to higher pick load, the energy absorption capacity is much higher than other specimens. In XBF3, the energy absorption continuous constantly after peak point because of accordion Behaviour plates between stiffeners. As though in the “Guided Local Buckling” theory the ideal Behaviour was related to complete action of all distances between oblique stiffeners, but in practical samples it is hard to obtain. According to obtained results, this specimen presented much more ductile Behaviour relative to XBF1 and there wasn’t monitored any sudden failure in the system.

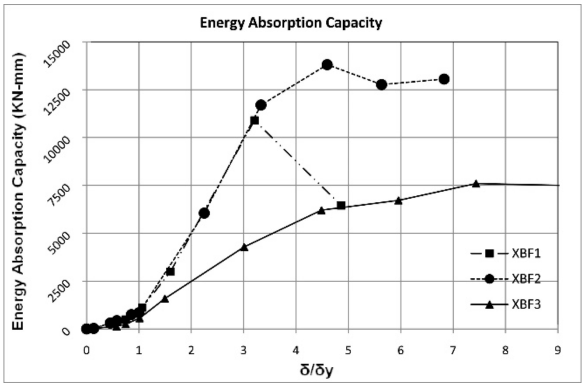

Fig. 9 – Energy Absorption Capacity of specimens

8. Conclusions

Three X-braced frames using various steel grades and different configurations for stiffeners inside braces were tested. Their Behaviour and failure modes during cyclic loading accompanied by cyclic curves and calculation of ductility and energy absorption parameters.

Using lower grade steel and internal stiffeners inside diagonals, seismic behaviour of X-Braced system improves. Accordion behaviour of diagonals' sections between internal stiffeners increased the energy absorption capacity and ductility of system.

The fracture life of braces increased and resulted into higher ductility. The system exhibited uniform energy absorption with more stability and more load cycles sustained. In addition, the over strength and maximum deformation of the system increased considerably by using parallel stiffeners. It was accompanied by decrease of elastic shear displacement and increase in the stiffness of the system. In other words, by employing lower grade steel in braces the hysteresis Behaviour was improved and resulted into much more energy absorption capacity of the system.

9. Acknowledgements

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