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DEVELOPMENT, AND TESTING OF CAM-GRIP TYPE, COMPRESSION-FREE ENERGY DISSIPATIVE BRACE

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Abstract

A newly developed hysteretic-type energy dissipative brace for suppression of structural responses under earthquake ground motions, namely Compression-Free Braces (CFBs), is introduced herein. Resembling to Buckling Restrained Braces (BRBs), CFBs transform kinetic energy in buildings under earthquake into plastic strain energy in a mild steel core. However, in contrast with BRBs, the energy dissipation in a steel core in CFBs occurs only under tension whereas zero-stiffness and zero-resistance behavior occurs under compression as a result of compression-free mechanism. Two rotary cams, pinned to the body of CFBs, are used to grip a mild steel core by friction force only under tension and disengage a core readily at the mobilization of compression. The resulting near-zero compression force in a steel core in CFBs benefits majorly in very minimal requirement in steel core restraint, unlike the BRB system that depends upon a weighty casing (steel tube filled with mortar) to maintain a steel core's compressive force. As a result of an extermination of restraining casing in CFBs, the light weight CFB system promotes ease of installation and replacement of a plastically-deformed steel core after the earthquake. Furthermore, retrofit and strengthening for earthquake of existing buildings is much easier than the counterpart system. In this research, the pseudo-static experiments were performed in steel frame sub-assemblage, equipped with CFD, under different level of story drifts. We obtained stable and predictable hysteretic loops which appear only in tension force side from a number of tests under different loading protocols. In the experiments, steel core replacements were carried out conveniently.

Keywords: brace; seismic damper; energy dissipative device; earthquake; compression-free mechanism

1. Introduction

Buckling-Restrained Brace (BRB) is a highly efficient energy dissipative system for buildings which make use of hysteresis of ductile steel to transform kinetic energy of vibrating building into plastic strain energy. Under reversed cyclic loading from earthquake ground motion, the bracing element is subjected to both compression and tension which affect braces differently. Tension causes yielding of steel core whereas compression induces buckling which is unfavorable due to the brittle behavior. The development of restraint for brace was initialized in 1970's and the optimum restraint stiffness was studied and reported by Watanabe et al. [1]. Generally, the brace restraint is made of steel tube, filled with concrete or mortar to control the deformation of steel core against lateral motion. Further numerical study by Watanabe & Nakamura [2] using low-yield strength steel as a core was conducted and satisfactory reduction of structural response was obtained.

In last few decades, numerous investigations on BRBs have been conducted. Black et al. [3] conducted component testing of BRBs and the experimental results indicated that BRBs possessed stable and repeatable hysteretic behavior and high ductility. Moreover, the sub-assemblage test carried out by Nishimoto et al. [4] proved that BRB also had high fatigue resistance. Because of the satisfactory behavior of BRB, Fahnestock et al. [5] conducted large scale tests of a steel frame with BRBs under pseudo-dynamic earthquake simulations and a quasi-static cyclic test. A frame, equipped with BRBs, can maintain large story drift without stiffness degradation and hence an excellent performance of BRBs frame was observed under the simulation.

Furthermore, BRBs were also aimed to use for structural retrofit of non-ductile structures (Gravity Load Designed, GLD). To investigate the performance in retrofit, Di Sarno & Manfredi [6] tested full-scale GLD reinforced concrete frames strengthened with BRBs. Besides, Usami et al. [7] also studied the influence of BRBs in upgrading the steel arch bridges by numerical analysis. From their experimental and numerical results, it can be concluded that BRB is an effective and reliable solution in structural retrofit.

Due to the fact that restraining elements in BRBs have to be flexurally-rigid enough to prevent steel core from buckling failure, the overall weight of BRBs is majorly contributed by casing. The weight of BRBs may not be a serious concern during installation since most of the area inside buildings are still accessible by heavy lifting equipment during the construction. However, BRBs' weight is a serious issue in the case where the structural retrofit or strengthening has to be performed in existing buildings. Furthermore, in the case when BRBs suffer from strong ground motion and the remaining service life is questionable, which may end up in replacement, maneuverability of heavy BRBs should be a serious concern.

Since the root cause of the need for a restraint is for stabilization of a brace under compression, the mechanism that embrace only tension and disengage compression will help eliminate such need. As a consequence, mobility of a brace without restraint make it possible for retrofit operation and damaged brace replacement. Efforts to construct compression-free bracing system were proposed in [8, 9] where researchers proposed wedge and beveled-washer mechanism at the end of brace rod. The wedge works by filling up the gap, caused by permanent elongation and frame displacement in compression cycle. The brace with wedge device exhibits perfect elasto-plastic behavior of steel brace rod. However, such mechanism cannot handle very large wedge slip due to the dimension of the device that will be proportional to slip length.

2. Development and Description of Compression-free Brace

The design of CFB, shown in Fig. 1 and Fig. 2, utilizes a simple mechanical friction-gripping technique which produce firm gripping force resistance to motion downward only and demobilize gripping force suddenly when a steel core move into upward direction. The mechanism of CFD comprises two symmetric eccentric pear-shape cams and a mild steel core (sacrificial/yielding element) which locate at the middle between two cams. Fig. 3 illustrates the assembly of compression free mechanism to the brace. Cam grip is installed and secured to the upper end of a brace by steel pin and steel sandwich jacket plates whereas steel core is hinged to the lower end. The friction gripping mechanism between cams and a steel core functions conditionally upon their relative motion. Under the attempt to displace cams and a steel core apart (leftward motion in gripping mechanism and rightward for a steel core), denoted by "tension motion", cams will grip a steel core tightly which allow the mobilization of tension and tensile yielding. The longitudinal-to-gripping force ratio is set to 0.20 by the design of cams' geometry, which implies that as long as friction coefficient between cam surface and a steel core is not lower than 0.20, the slippage at the cam-core interfaces will not occur. Generally, friction coefficient between steel and steel is exceedingly higher than 0.20 ratio.

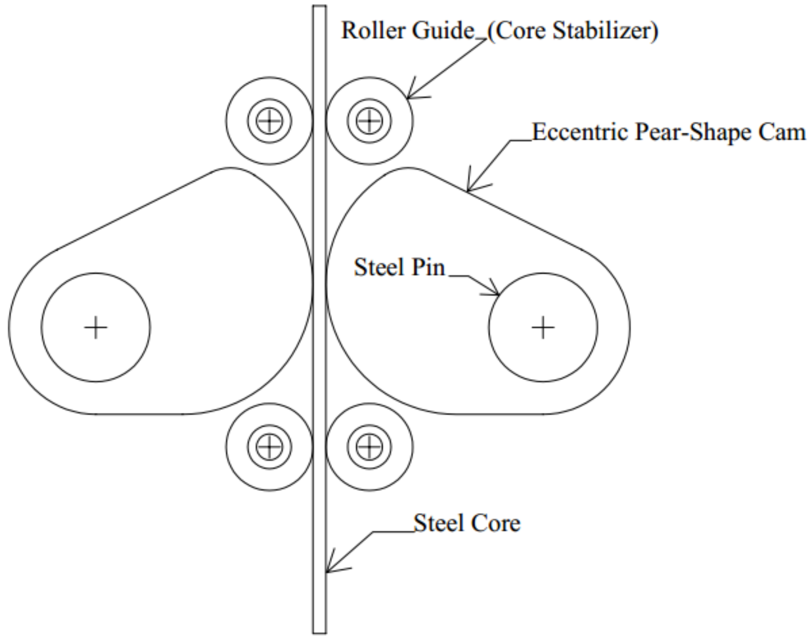


Fig. 1 – Cam-Grip Mechanisms

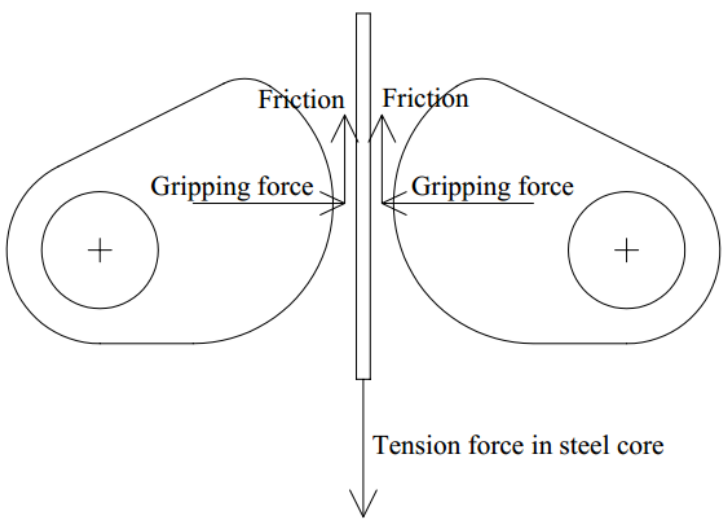


Fig. 2 – Force Diagrams of Griping Mechanism under Tension

In contrast, if the cam grip and core are pushed into another (gripping mechanism moves rightward and a steel core moves leftward), denoted by "compression motion", free slippage at the cam-core interfaces will occur which cause immediate demobilization of axial force in the core.

In conclusion, CFBs provide bracing force resistance conditionally only under tension motion. As a result, a rigid and heavy restraining element (concrete/mortar-filled steel casing) for compression force is not necessary for CFB but the much lighter weight core stabilizer is required to prevent sagging of a long slender core.

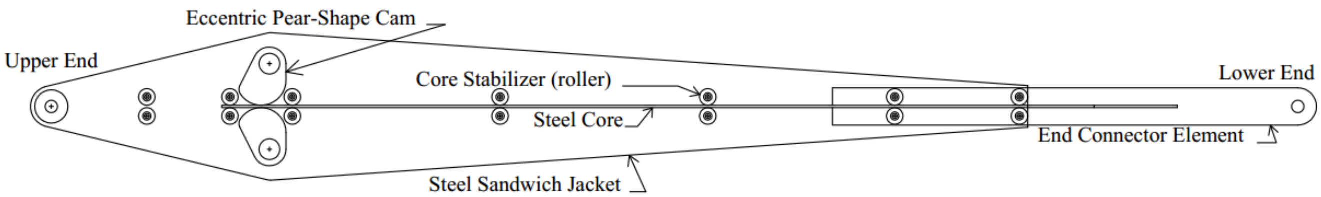


Fig. 3 – Compression-Free Brace Mechanism

A steel core is made of 6 mm thick (JIS SS400 grade, f_y = 330 MPa), 60 mm wide, and 2400 mm long steel strip. In the middle part, assigned to be a yielding portion, the width is reduced from 60 mm to 30 mm over 1700 mm long segment to confine inelastic effects within this region as shown in Fig. 4. The left end is to be gripped and released by cam mechanism and the right end is welded to rigid connector plate and hinged with structural frame.

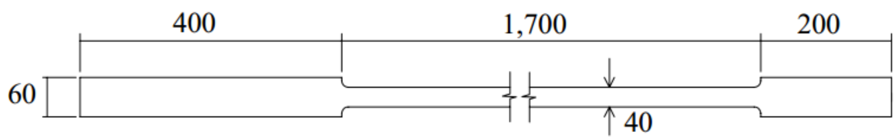


Fig. 4 – Steel Coupon

3. Experimental setup

The experiments were performed in a steel frame sub-assemblage as shown in Fig. 5. All experiments were conducted by using the same compression free device, including cams and jacket plates, to highlight its reusability. Only steel cores are replaced after completion of test under each loading protocol. The column is hinged at the base such that the horizontal force resistance is contributed by compression-free brace only. Reversed cyclic load tests were conducted in the same CFB with 10 identical steel cores (same material properties and dimensions), designated by S-01 to S-10. After the test, there was no damage observed in any part of the gripping device.

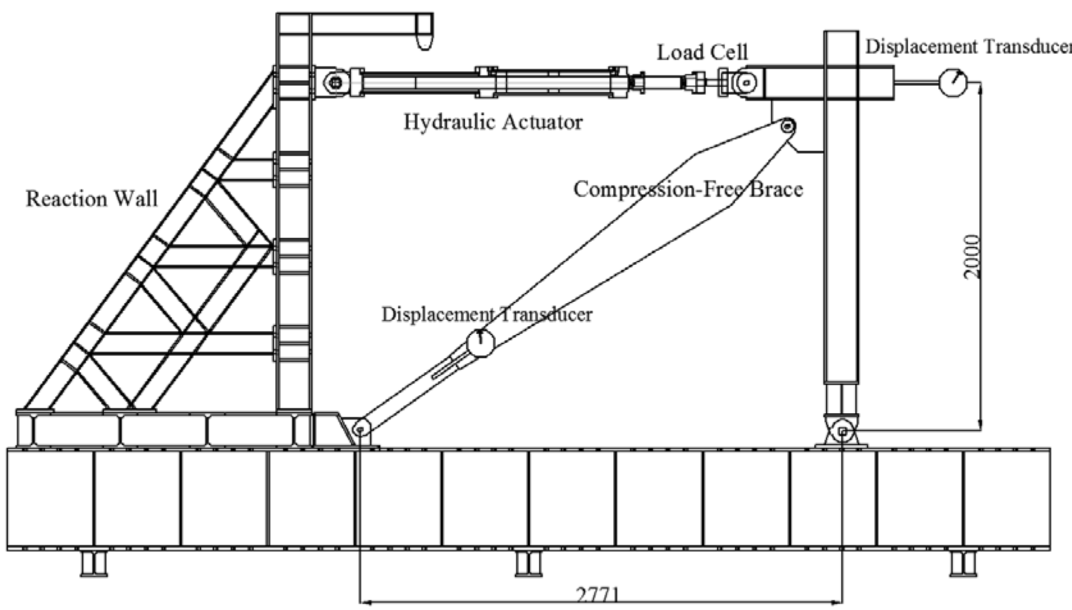


Fig. 5 – Schematic Diagrams of Test Setup of Compression-Free Brace in Steel Frame Sub-assemblage (dimension in mm)

Displacement transducer was installed in the same alignment to the actuator rod to measure inter-story drift. Another displacement transducer was installed on the brace to measure relative displacement between its upper part (including cams and sandwich jacket) and lower part (steel coupon and connector plate) which implies the elongation of a steel core. High-elongation strain gauges were installed at two different locations on each steel core. 24-bit analog-to-digital dynamic data acquisition system was exploited here.

CFB specimens were loaded by applying reversed-cyclic constant displacement amplitude, encompassing inter-story drift ratio of 0.75%, 1.00%, 1.25%, 1.50%, 1.75%, and 2.00% which are assigned to specimen S-01 to Specimen S-06 respectively. In order to understand the effect of very small displacement amplitude loading to CFB, Specimen S-07 was subjected to 15 cycles of 0.3% and 63 cycles of 0.5% inter-story drift. Similarly, Specimen S-08 was subjected constant amplitude of 2.5% inter-story drift. The loading protocol for Specimen S-09 and Specimen S-10 were adopt from AISC Recommended Provisions for Buckling-Restrained Braced Frames. The design story drift for this test was assumed to be 1.5%, thus, a loading protocol for Specimen S-09 and S-10 became two cycles of 0.53%, 0.75%, 1.50%, 2.25% and 3.0% inter-story drift. All specimens were tested up to failure (fracture of a steel core). However, only Specimen S-07 was tested up to 63 cycles of 0.5% drift and stop without steel core fracture.

4. Results

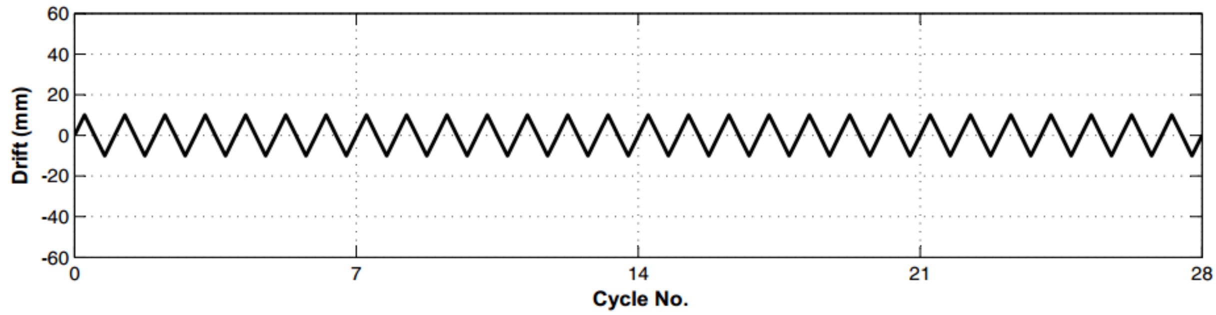
4.1 Relationship between Load and Deformations

The results have shown that, all specimens have similar behaviors in terms of lateral load resistance, hysteretic characteristic and energy dissipation. Thus, three specimens namely S-01, S-03 and S-10 have been selected to represent testing results.

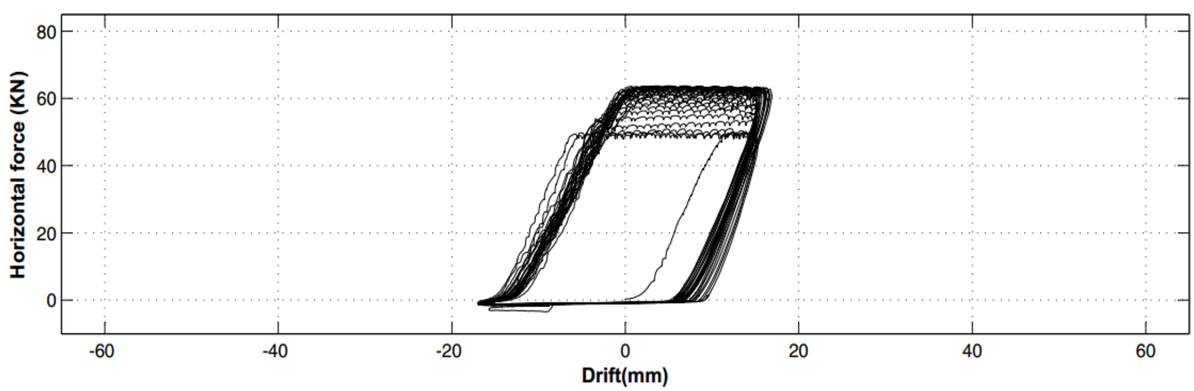
Loading protocols and hysteresis loops from 3 selected specimens are shown in Fig. 6 to 8. Horizontal force versus drift plots are constituted by force resistance, measured by load cell attached to the hydraulic actuator, and inter-story drift (the displacement of an actuator rod). The positive sign convention for both drift and horizontal force are in line with tension motion of a CFB (force and displacement, pointing to the right-hand-side referring to Fig. 5). The one-directional load-carrying behavior of CFB can be observed in all three specimens. In other words, the graphs show that CFBs mobilized positive force whenever the sub-assemblage of braced frame was subjected to tension motions. Besides, there are negligible magnitude of negative force readings (maximum value of 1.4 KN) which might be caused by internal friction of CFB mechanism and a test system during the compression motion.

The initial slopes in every loading cycle of hysteresis plots are lower than predecessor slopes as a result from grip settling and tolerances from CFB fabrication & assembly. Due to the tension only behavior of CFB, unlike BRBs, longitudinal strain reversal did not occur in a steel core. If horizontal forces are plotted versus cumulative displacement under tension motion, the behavior, which is resemble to stress-strain relationship of mild steel, will be observed as shown in Fig. 9. Constant size hysteresis loops were noticed as long as a steel core is under yielding condition. Once strain hardening occurs in a core, a hysteresis loop grows in the vertical direction and the size was controlled by the ultimate strength of steel.

All test results exhibited repeatable and stable hysteretic behavior for different loading protocols without any strength and stiffness degradation. The ductility of CFB is equivalent to that of steel under uniaxial tension. Moreover, no buckling of the yielding part of a steel core was observed as expected initially.

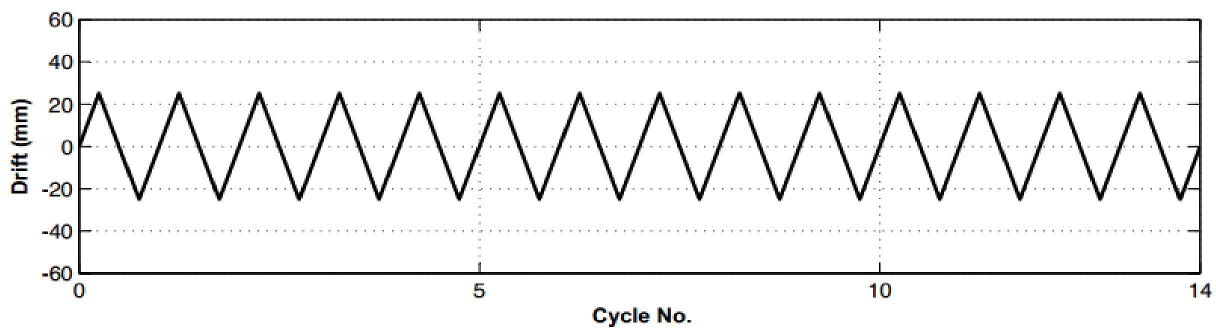


(a) Loading protocol (28 cycles of 10mm- drift)

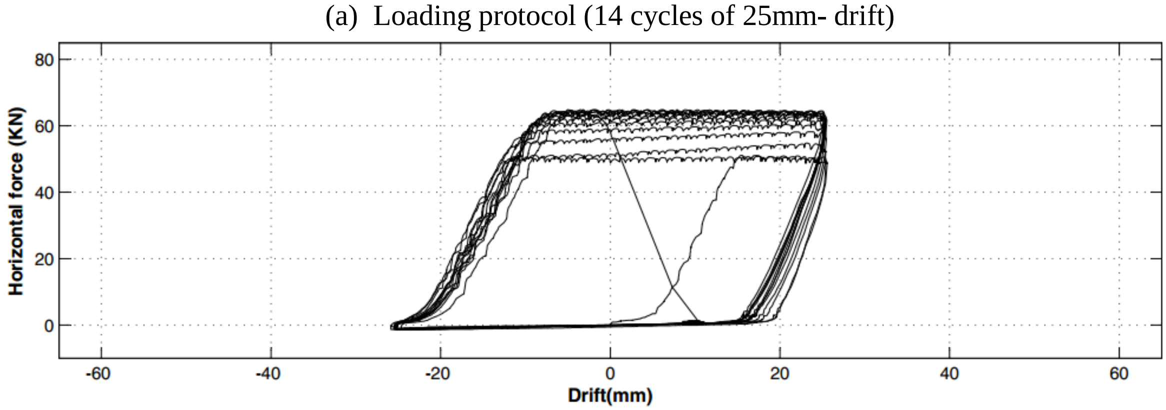


(b) Hysteretic loop

Fig. 6 – Loading protocol and Hysteretic behavior of Specimen S-01

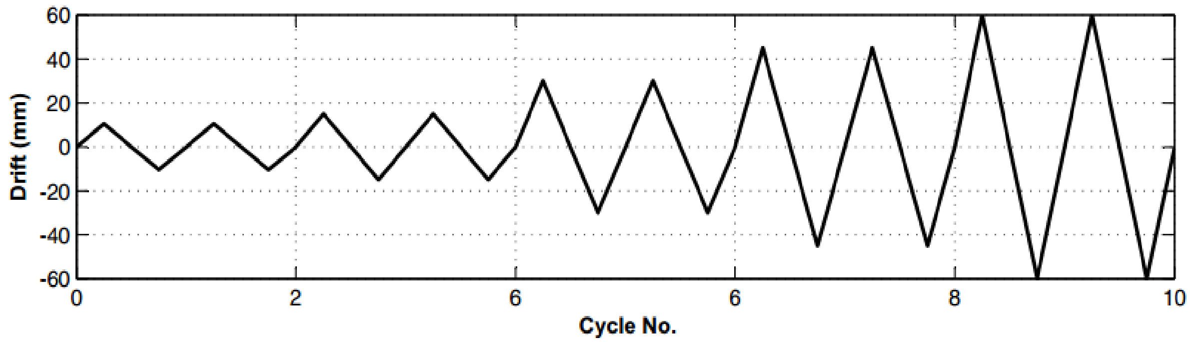


(a) Loading protocol (14 cycles of 25mm- drift)

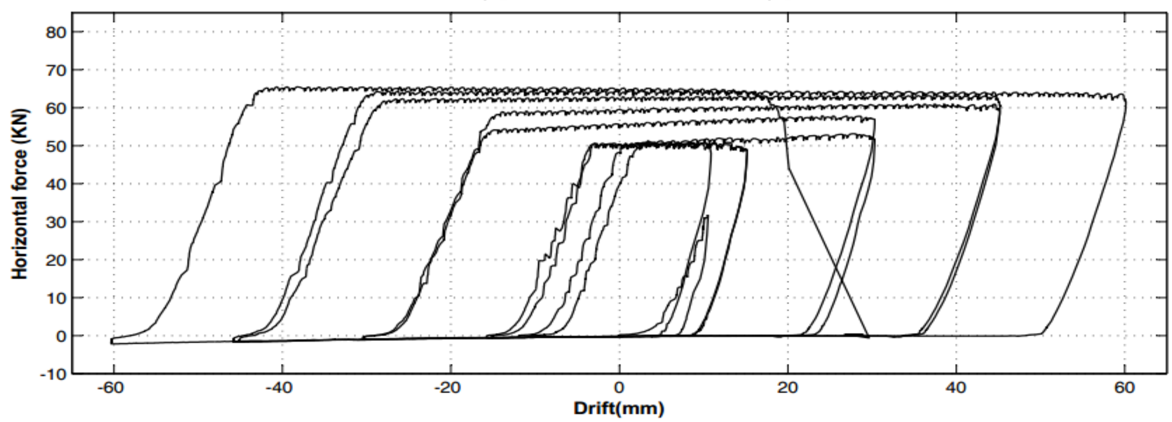


(b) Hysteretic loop

Fig. 7 – Loading protocol and Hysteretic behavior of Specimen S-03



(a) Loading protocol (AISC loading protocol)



(b) Hysteretic loop

Fig. 8 – Loading protocol and Hysteretic behavior of Specimen S-10

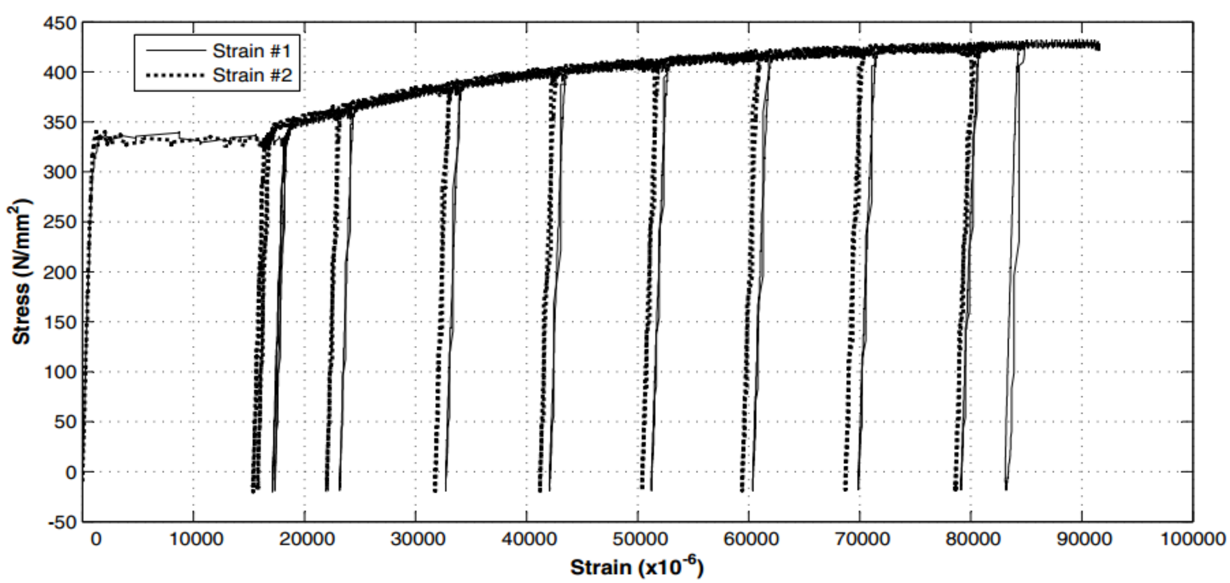
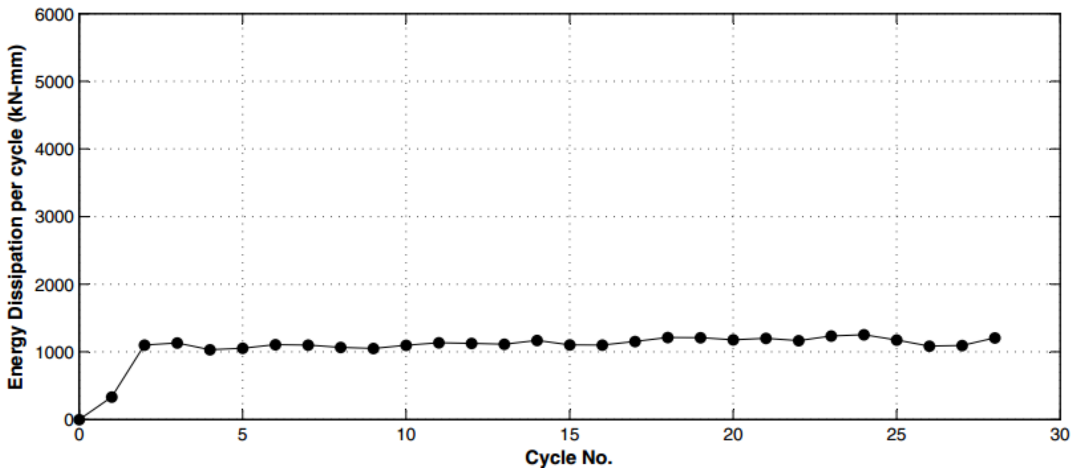


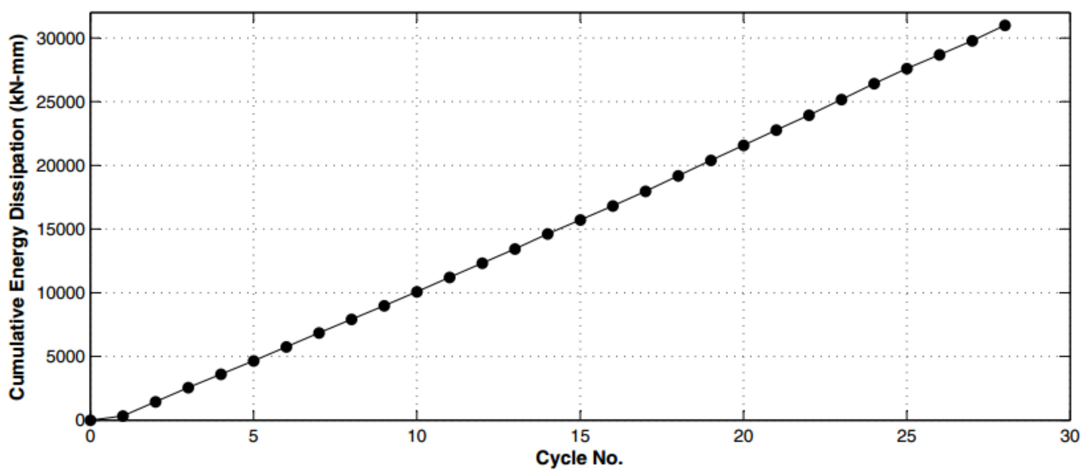
Fig. 9 – Stress and strain relationship of Specimen S-03

4.2 Energy dissipation

Hysteresis loops for all specimens are very stable and repeatable as observed from Fig. 10 to 12. For constant displacement amplitude loadings, energy dissipation per cycle is quite constant. Increasing drift in specimen S-10 caused the increasing energy dissipation per cycle.

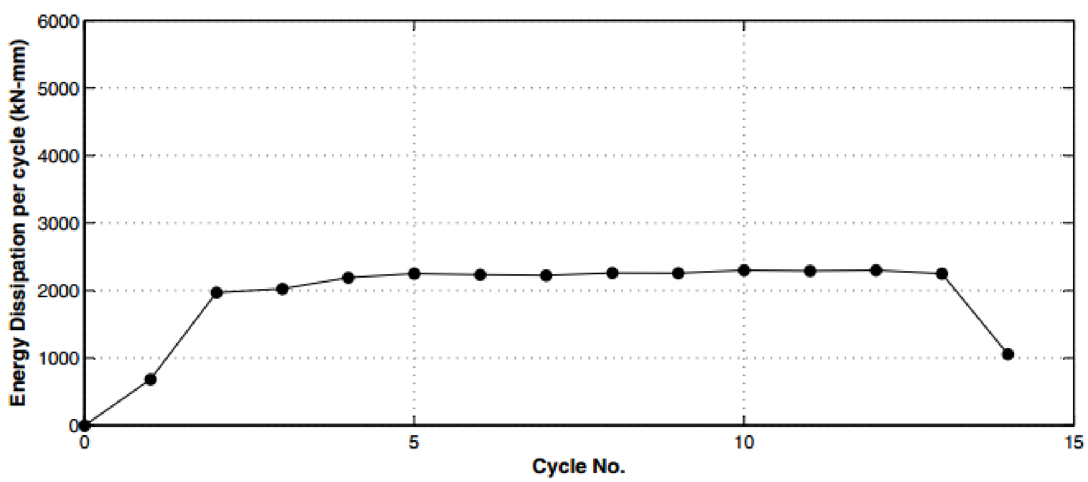


(a) Energy dissipation per cycle

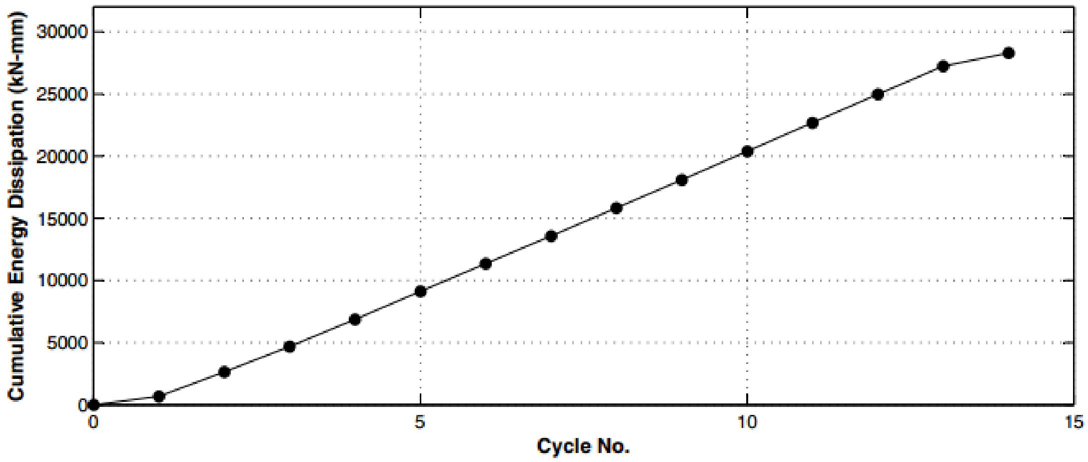


(b) Cumulative energy dissipation

Fig. 10 – Energy Dissipation capacity of Specimen S-01

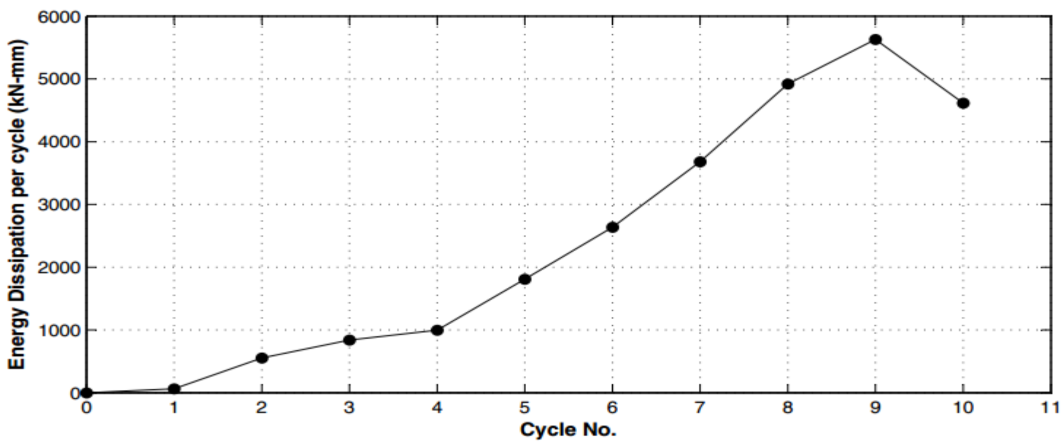


(a) Energy dissipation per cycle

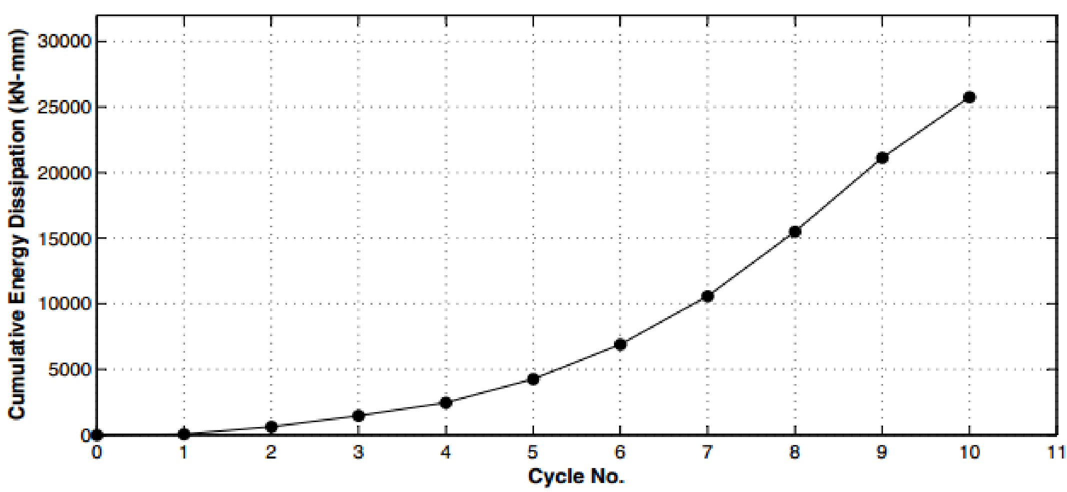


(b) Cumulative energy dissipation

Fig. 11 – Energy Dissipation capacity of Specimen S-03



(a) Energy dissipation per cycle



(b) Cumulative energy dissipation

Fig. 12 – Energy Dissipation capacity of Specimen S-10

4.3 Relationship between strain versus story drift and strain versus brace elongation

Two high-elongation strain gages were installed on each steel core to capture longitudinal strain during cyclic loading. Plots between strain and drift are shown in Fig. 13 and 14. Positive drift and positive brace elongation represent tension motion and vice versa for compression motion. The observation from these plots verifies that a compression-free mechanism performed properly. As story drifts increase, core strain does not increase immediately due to grip settling. The tension force mobilization took roughly 7-10 mm of story drift and strain increase was then detected. During compression motion, designated by decreases of drift and brace elongation, insignificant decrease of strain is observed which attests that the gripping mechanism disengaged steel cores perfectly.

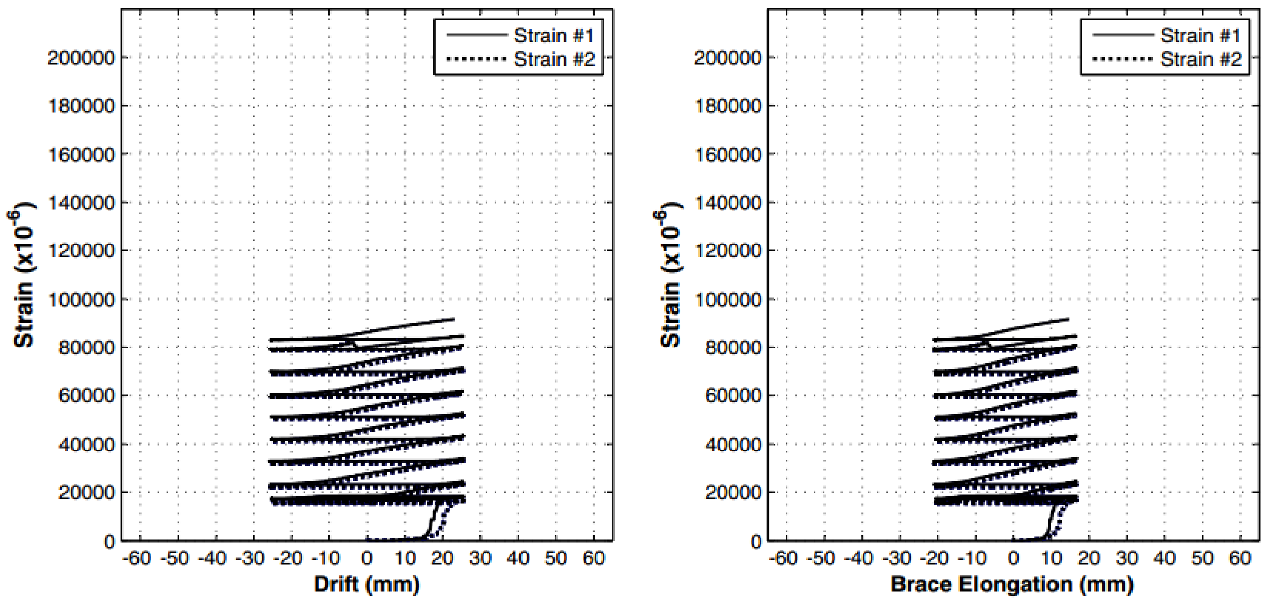


Fig. 13 – Specimen S-03: (a) Plot strain versus drift; (b) Plot of strain versus brace elongation

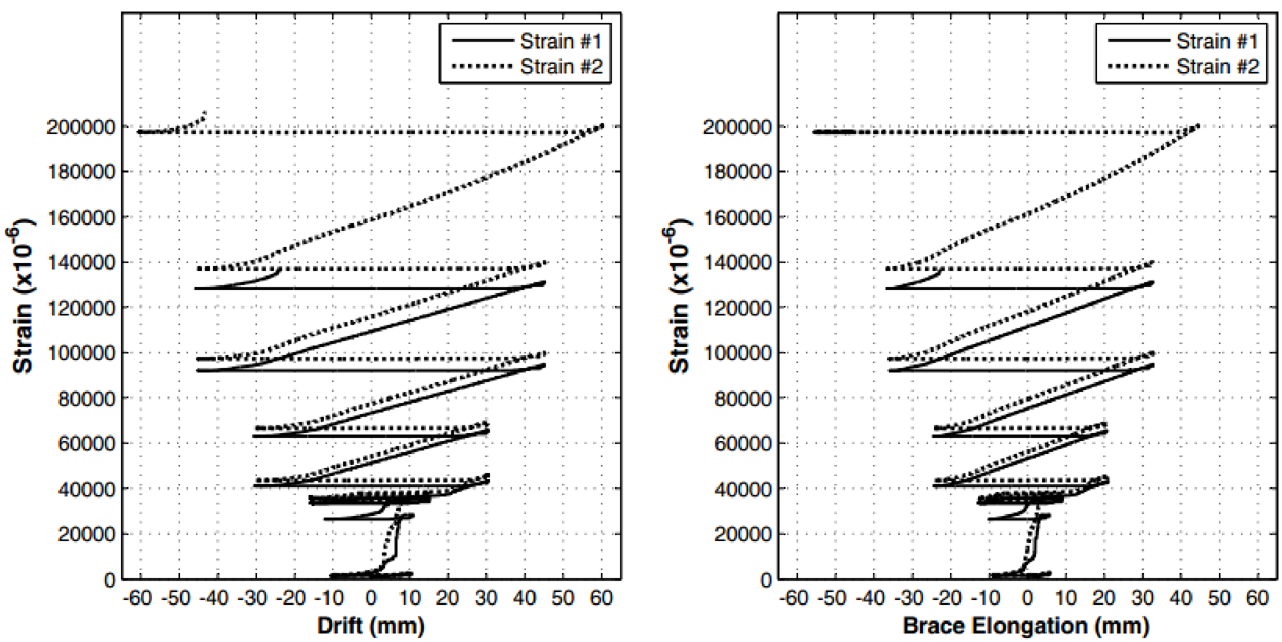


Fig. 14 – Specimen S-10: (a) Plot strain versus drift; (b) Plot of strain versus brace elongation

5. Conclusion

A compression-free mechanism, using rotating cam grip, was newly developed in this research for bracing system in structural frame. A series of experiments were conducted to investigate the performance of CFBs under reversed-cyclic loading using the same compression-free mechanism with 10 steel cores to point out the reusability of a CFB's mechanism and the ease of steel core replacement. CFBs were tested under different displacement-controlled loading protocols which result in the following observations.

1. The CFB exhibited the desired response in load resistance versus story drift. CFB produced force resistance only under tension motion whereas steel cores were released freely under compression motion which results in a negligible magnitude of compressive force in a steel core.

2. Due to the low compression force level in a steel core, a buckling restraint is not necessary. However, a steel core stabilizer, much lighter than a buckling restraint, is required in CFBs.

3. Hysteresis loops, produced by CFBs under different loading protocols, are stable and repeatable. The loops expanded in the force direction with the increasing loading cycle (which implies the increasing cumulative plastic strain in steel cores) due to strain hardening effect in steel cores.

4. All components in compression-free mechanism were not damaged as they are designed to behave elastically. The compression-free mechanism was reusable and steel cores were replaced easily within short time. This character helps promote rapid maintenance of CFBs after the earthquake.

7. References

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