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The Development of a Compression-Free Energy Dissipative Brace

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ABSTRACT: This paper introduces a Compression-Free Device (CFD) for energy dissipative braces which comprises two major components, namely a sacrificial steel coupon for energy dissipation and a compression releasing device. The embedded mechanism in CFDs was designed to engage a steel coupon under tension and detach under compression to prevent coupon buckling. The energy dissipation by ductile steel occurs only in tension yielding. Without compressive force, only a light-weight coupon stabilizer is required instead of a bulky and heavy mortar with steel casing which is normally required in a Buckling Restrained Brace (BRB). Unlike BRBs, the CFD brace system offers ease of installation due to its light weight and ability to replace the yielded sacrificial steel coupon after the occurrence of an earthquake. The experiments were conducted by applying a reversed cyclic story drift in the sub-assemblage of a steel frame, equipped with a CFD brace. Test results exhibited sufficient tension gripping capacity to develop yielding in the steel coupon under the stretching cycle, and compressive force releasing behaviour was observed immediately at the beginning of the brace shortening cycle.

1 INTRODUCTION

Suppression of structural responses under earthquake ground motion is crucial for buildings in terms of the safety aspect, serviceability, and economics of construction. To do so, engineers can modify dynamic characteristics of structures, e.g. prolonging a vibration period using base-isolation techniques and suppression of peak responses, resulting from fundamental vibration modes, with a tuned-mass or tuned-liquid damper. Additionally, seismic dampers or energy dissipative devices can be employed to help reduce vibration. Various types of damping devices have been invented with different levels of suitability to ground motion characteristics, structural systems, and cost-performance preferences. The fundamental concept of all energy dissipative devices is to transform kinetic energy from structural motion into other forms of energy, namely heat, plastic strain energy, energy of friction, and energy of viscous flow.

The focus of this paper is on the improvement of the existing energy dissipative brace systems. There are two widely used systems which are the Fluid Viscous Damped Brace (FVDB) and the Buckling-Restrained Brace (BRB), sometimes called the un-bonded brace. FVDB is very efficient as it produces force in the orthogonal phase to displacement under earthquake motion. Thus, the maximum brace force will not concur with the maximum restoring force, as a result of frame deformation. However, due to high-precision manufacturing and high material cost (stainless steel), the price of a fluid viscous damper is considerably high. Moreover, the ambient vibration of structures wears out the cylinder and the O-ring of a fluid viscous damping device, causing fluid leakages at the seals and performance degradation (Graziotti 2010). Regular maintenance and monitoring of a fluid viscous damper is necessary to ensure safety of structures.

The buckling-restrained brace is considered a low-maintenance system, yet, highly practical. The energy dissipation via the BRB system occurs through plastic strain energy, i.e. hysteresis. The ductile steel core would incur yielding in both tension and compression. To prevent core buckling under compression, generally, encasing steel tubes with mortar grout or concrete (Watanabe et al. 1988) are provided as buckling restraint in commercial BRBs. Due to the fact the restraint has to be flexurally stiff, most BRBs are weighty and require heavy equipment during installation.

Developments on removable restraining member were made by using steel (Usami et al. 2009) and steel-concrete composite (Chou & Chen 2010). Instead of using a single-piece buckling restraint, two separated confining members were sandwiched around a steel coupon and secured together by bolts and nuts. Satisfactory energy dissipation was observed. However, to achieve stable hysteresis loops without brace buckling, sufficient flexural rigidity of restraining members is compulsory which implies its heavy self-weight. In practice, lifting equipment may still be required for disassembling, replacement, and reassembling.

Despite of BRB's effectiveness and durability, two major disadvantages are still present. First, the post-earthquake state of the core material (cumulative plastic strain) cannot be determined explicitly. This obstructs the planning of the maintenance of BRBs. Additionally, due to its weighty restraining case, the replacement of BRBs is nearly impossible since lifting equipment cannot access inside the building. Repair and replacement or seismic retrofit with installation of BRBs after construction is nearly impossible. In short, the concern over whether the remaining ductility can withstand future earthquake ground motion cannot be addressed clearly. Besides, replacement is unlikely. Due to the afore-mentioned facts, the light-weight hysteretic brace system is developed in this research to help enable brace replacement and structural retrofit in buildings.

2 DEVELOPMENT OF COMPRESSION-FREE DEVICE

To reduce weight of buckling restraint in order to make replacement and maintenance possible, this research attempted to avoid the compression force in the steel core by introducing a Compression-Free Device (CFD) into the energy dissipative brace system. A CFD, depicted in Figure 1, is a simple mechanism, which employs two rotatable cams to grip the sacrificial steel coupon in tension and release it under compression. Energy loss will occur only in tension yielding, while the zero internal force in the steel coupon is expected when steel coupon motion is towards the CFD. The inclined forces, produced by two cams, resist downward displacement (in the negative y-axis) of the steel coupon. Considering components of inclined forces in the x and y-axis, the ratio between the horizontal gripping force and the coupon motion resistance was designed to be 5. The inverse of such ratio implies that the minimum workable static friction coefficient between the steel cam and the steel coupon is 0.2, whereas the typical steel-to-steel friction coefficient is in the range of 0.5 to 0.8. Thus, slippage between the cam and the coupon is unlikely.

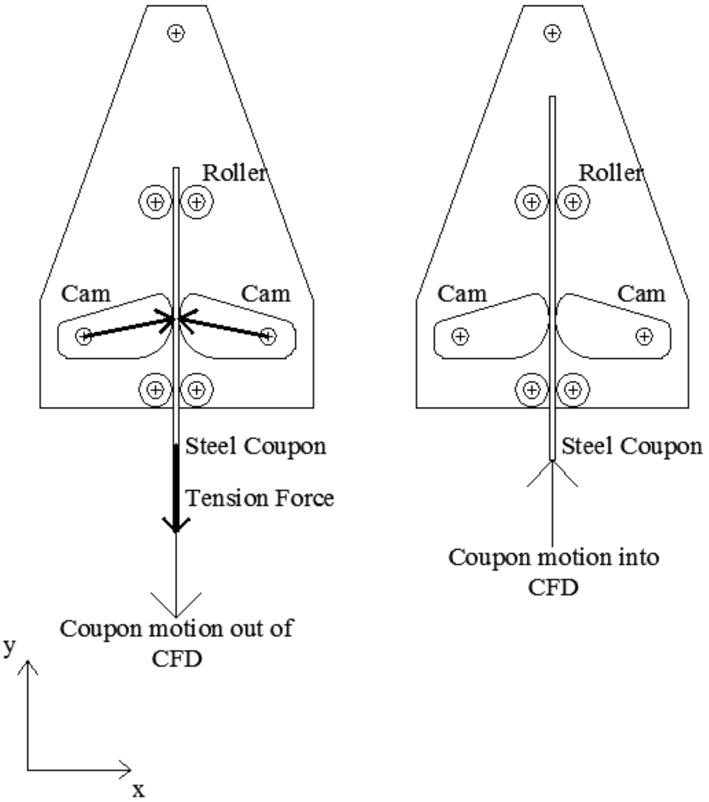

Figure 1 Compression-Free Device with Steel Coupon under Motion towards CFD (left) and away from CFD

(right)

The pins used to secure cams were designed to resist double shear which is caused by cam forces, transferred through the pins into the steel sandwich plates (outer body of the CFD). To prevent cams from snap-through, a solid steel is used with generous dimensions to ensure high axial and flexural rigidities. A performance test on the compression-free device alone in a universal testing machine as shown in Figure 2 was conducted under reversed cyclic displacement. Under the displacement cycle which caused tension in the steel coupon, the cam grip engaged tension properly without slippage, while free-sliding through cams was observed during the displacement cycle which caused shortening (coupon motion into the CFD). Compressive strain and core steel buckling were not detected during the test.

Figure 2 Test setup of CFD (located on top of universal testing machine) over reversed cyclic displacement

3 EXPERIMENTS

The experiment was made in a scaled steel-frame sub-assemblage, representing the storey height of 2000 mm, equipped with the CFD brace system, illustrated in Figures 3 and 4. Sacrificial steel coupons were 2400 mm long and 62 mm wide with reduced width section of 40 mm to confine yielding, of 1800 mm long. The horizontal push/pull force was applied with a double-action hydraulic jack with a load cell installed at the piston end. Displacement transducers were installed to measure horizontal displacement (storey drift) at the actuator level. Furthermore, shortening and elongation of the steel coupon relative to the CFD were also collected.

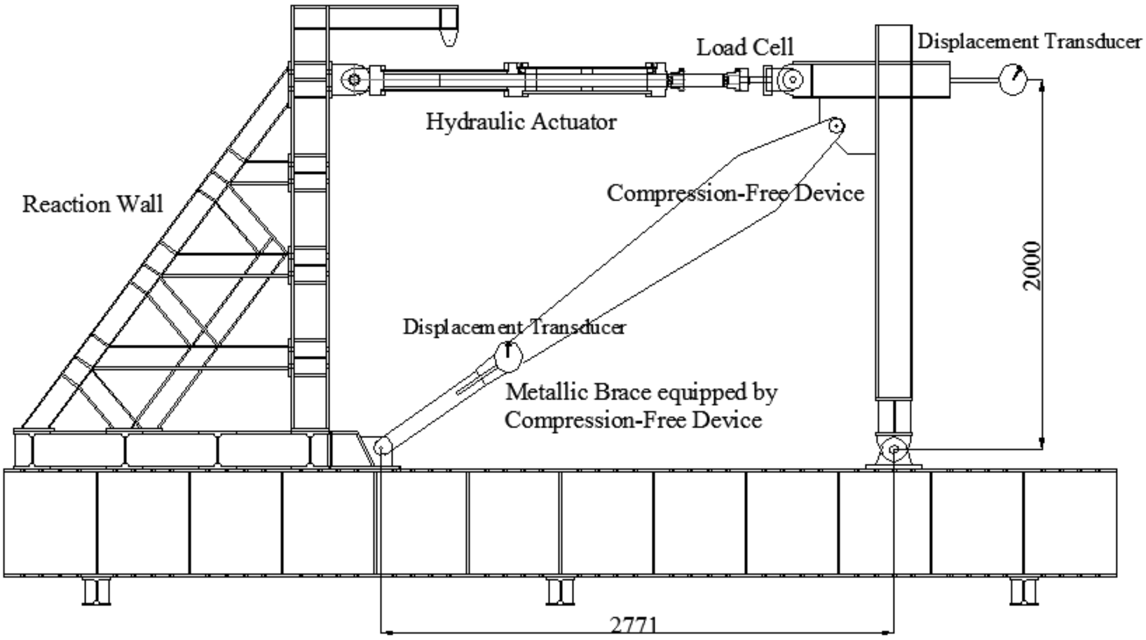

Figure 3 Experiment setup of steel frame sub-assemblage equipped with the CFD brace system (dimension in mm)

Figure 4 Picture of the experiment setup of the steel-frame sub-assemblage equipped with the CFD brace system

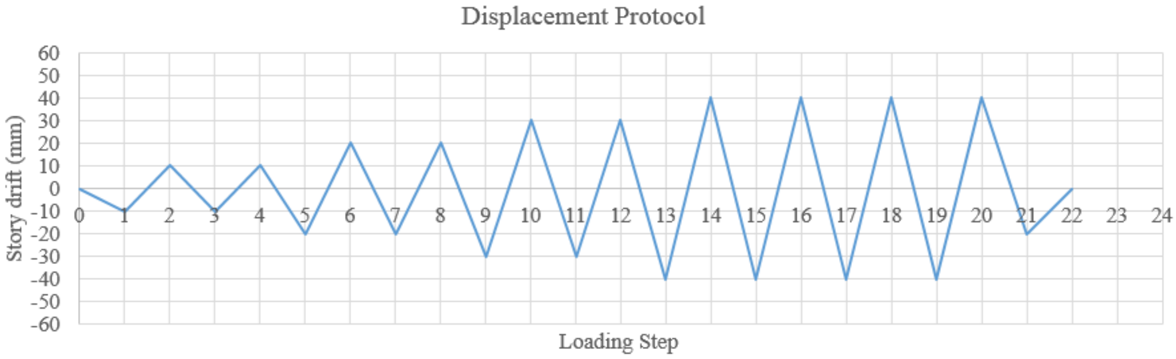

Figure 5 Displacement protocol for specimen 1

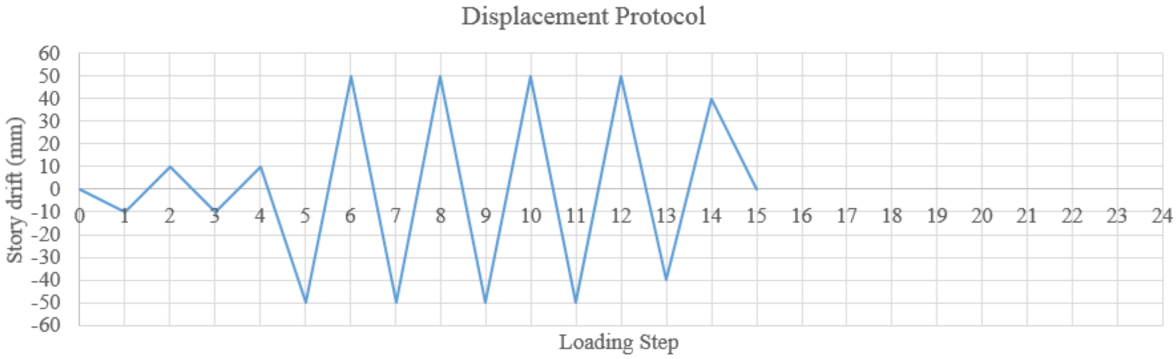

Figure 6 Displacement protocol for specimen 2

In this research, two steel coupon specimens were examined by using the same CFD since yielding damage occured only in coupons. After completion of one test, the yielded core plate was removed from the CFD and replaced by a new one. Two displacement-controlled loading protocols were used as shown in Figures 5 and 6. Specimen 1 was subjected to two cycles of each storey drift, which were 0.5% (10mm), 1.0% (20mm), and 1.5% (30mm), and the sustained maximum storey drift of 2.0% (40 mm) for 4 cycles. For specimen 2, two cycles of 0.5% storey drift were applied, followed by 4 cycles of 2.5% storey drift (50 mm) and 1 cycle of 2.0% storey drift.

4 RESULTS AND DISCUSSION

Plots of the applied load, measured by the load cell, versus horizontal displacement (storey drift) are shown in Figures 7 and 8. As clearly shown in both plots, the resisting force to horizontal displacement only occurred during brace elongation. In contrast, horizontal displacement, which caused brace shortening, did not produce any force resistance. The steel core yielded in the first few cycles, indicated by constant force resistance, and later underwent strain hardening as hysteresis loop expanded in force direction.

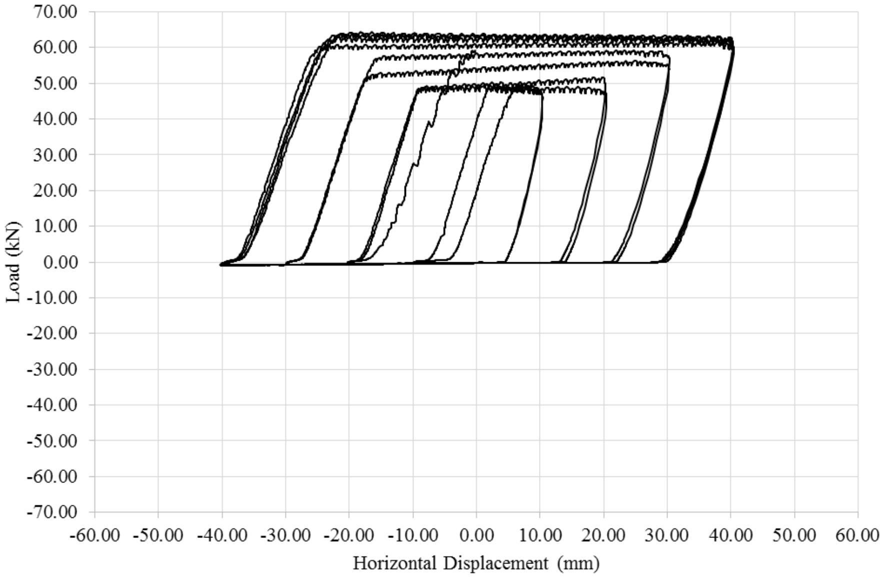

Figure 7 Load vs horizontal displacement from specimen 1

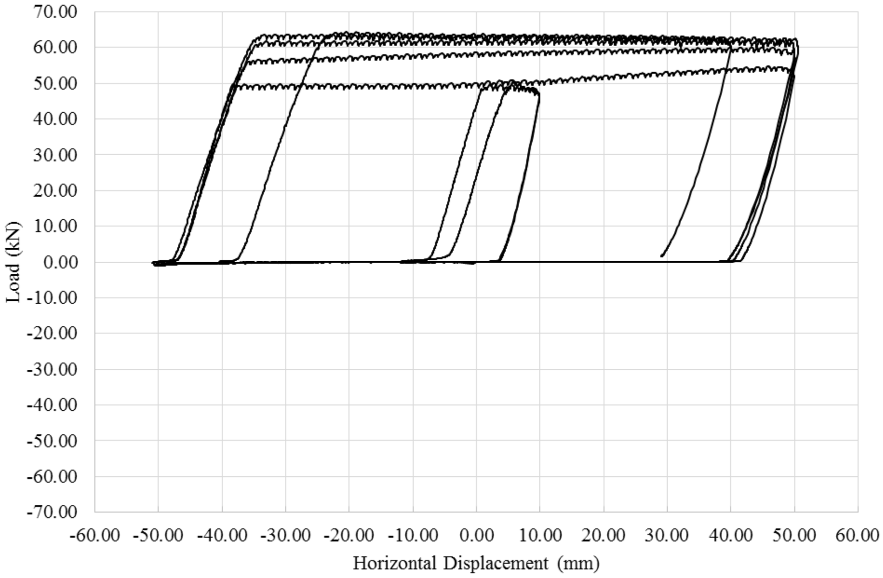

Figure 8 Load vs horizontal displacement from specimen 2

Figure 9 shows the measured strain in the steel core from 2 strain gauges, installed in specimen 2 versus horizontal displacement at the top of the column. The solid line and the dotted line represent results from two strain gauges on the reduced-width section of the same specimen. Over brace shortening (displacing to negative displacement direction), strain dropped from elastic unloading and remained unchanged due to free-sliding between the steel core and the cams. During brace elongation (displacing to positive displacement direction), strain increased with displacement. However, it took roughly 4 mm to mobilize strain due to gaps between the cams, the pins, and the steel sandwich plates, which may be minimized through a high-precision manufacturing process. This grip settling mechanism can also be observed in Figures 7 and 8.

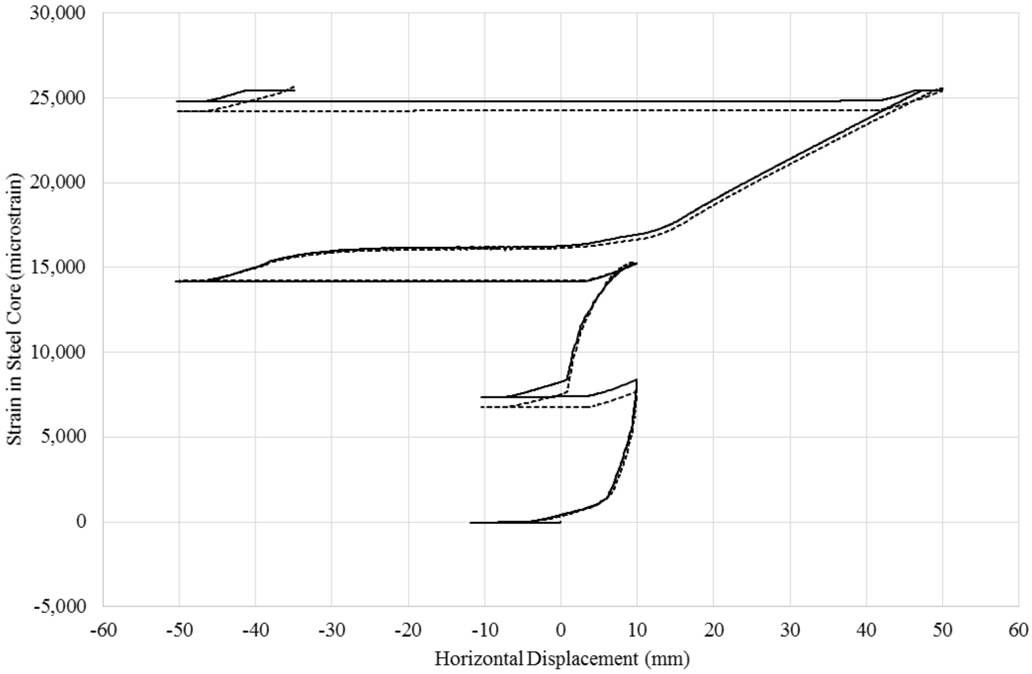

Figure 9 Strain in steel core versus horizontal displacement (story drift) from specimen 2

The experiments were not designed to reach failures (core plate fractures) due to safety concerns on measuring instruments. Test termination criteria were from the measured steel core elongation which was limited to 360 mm accounting for 20% of the original length of reduced width section. The computed cumulative plastic strain of Specimen 1 and Specimen 2 were 36.2 and 42.3, respectively. Although more than twice as much cumulative plastic strain was expected from BRBs, the results show that the CFD brace would be ductile enough to withstand major earthquakes.

5 CONCLUSION

The energy dissipative brace system equipped with a compression-free device showed satisfactory performance in absorbing energy of a steel-frame sub-assemblage. The CFD functioned properly such that compressive force was not present in the sacrificial steel coupon. The absence of compression helps reduce core plate buckling restraint drastically from steel casing with grouted mortar in BRBs to simply a core stabilizer. The significant reduction of weight of the CFD brace will make maintenance possible. Moreover, structural retrofit for the higher earthquake resisting capacity can be exploited via the CFD brace system due to its manoeuvrable dimensions and weight.

The significant improvement found in the CFD brace is the ability to re-juvenile the brace’s ductility back to its original condition, which is impossible when BRBs are used. After an earthquake, building maintenance personnel will simply replace the yielded steel coupon, and the structure will be ready for the next earthquake without any concerns of any partial damage to the bracing system.

Thus far, due to the single-direction force resisting behaviour, the installation of the CFD brace must be in symmetric configuration to provide equal energy dissipative capability in both positive and negative motion.

6 ACKNOWLEDGEMENT

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