Vol.5, No.1 EARTHQUAKE ENGINEERING AND ENGINEERING VIBRATION June, 2006

Article ID: 1671-3664(2006)01-0151-08

Mechanical compression release device in steel bracing system for retrofitting RC frames

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Abstract: The development of an innovative structural system with satisfactory seismic performance of braced systems is an important and challenging area of interest in structural engineering. In this paper, a device that can release the compressive force in the bracing members is developed, and its performance is evaluated. For comparison, four steel braced RC frames were constructed and tested under reverse cyclic loads. Two of them had different amounts of bracing and the other two had the same amount of bracing but incorporated different type of device, called compression release device, which is developed and described in this paper. It can be concluded from the test results that the newly developed device can effectively be used in steel braced systems to prevent buckling failure of the bracing members. Therefore, the device enhances the ductility of brace-framed systems by allowing an adequate capacity for energy dissipation.

Key words: reinforced concrete; steel bracing; cyclic load; buckling; ductility, testing

1 Introduction

Braced steel frames are commonly used to resist seismic loads. Their seismic behavior was extensively studied during the past decades (Bertero *et al.*., 1989; Roeder, 1989; Jain, 1978). Their design is governed by the buckling behavior of the bracing members (ASCE, 1994, 2002; CSA, 1994). To prevent or delay the seismic buckling of compressive members in concentrically braced frames in steel structures, a great number of methods have been proposed. These include the use of special brace members with composite sections (Isabella *et al.*, 2003; Jinkoo and Youngil, 2004; Watanabe *et al.*, 1989; Liu and Goel, 1987), added hysteresis damper (Watanabe, 1996; Kamura *et al.*, 2000; Aiken *et al.*, 1992), or devices made from high performance materials (Ohi *et al.*, 2001). During the past three decades, steel bracing has been widely used to upgrade the seismic resistance of existing RC structures. This was required to address the observed unsatisfactory performance of RC structures during recent strong earthquakes such as: San Fernando Earthquake in 1971, Mexico City Earthquake in 1985, Whittier Narrows Earthquake in 1987, Loma Prieta Earthquake in 1989, Northridge Earthquake in 1994, Kobe Earthquake in 1995, Izmit Earthquake in 1999, and Chi-Chi Earthquake in 1999. Steel bracing was chosen over RC shear walls because of its architectural flexibility, lesser weight, and increased ductility. A number of researchers (Badoux *et al.*, 1990; Bush *et al.*, 1987; Sesigur *et al.*, 2002, Tasnimi and Maasumi, 1999) have demonstrated the efficiency of this retrofitting technique. Abou-Elfath and Ghobarah (2000), through analysis, showed that existing non-ductile buildings could be retrofitted effectively by using brace members. They also highlighted the need for experimental studies to define the behavior of RC braced frames.

The use of steel bracing in newly built RC structures is still in its infancy. Maheri and Sahebi (1995) and Maheri *et al*. (2003) conducted pushover tests on steel braced RC frames. Test results indicated that the yield and strength capacities of the steel braced RC frame increased while its global displacement decreased when compared with RC frames. In the present study, the performance of braced RC frames is investigated experimentally. Also, a compression release device (CRD) device, which is able to release the compressive force in the brace member, is developed, and its performance is evaluated. For comparison purposes, four steel braced RC frames were constructed and tested under reverse cyclic loads. Two of them had different amounts of bracing and the other two had the same amount of bracing but each incorporated a different type of CRD device. The comparison provides an improved understanding of the performance of the braced RC frames. It also allows the effectiveness of the new CRD device to be evaluated.

2 Construction and basic function of the CRD

The proposed CRD is shown in Fig. 1. It is composed

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Received April 25, 2006; **Accepted** May 29, 2006

of two steel plates separated by a gap. The two plates are connected together by a maximum of four bars. A cylindrical steel pipe (cylinder) is attached to one of the plates. A steel rod (piston) is attached to the nother. The cylinder is padded with rubber material.

A typical brace member can be divided into two pieces; each is welded to one of the CRD steel plates. When the member is subjected to a compressive displacement, the piston will slide inside the cylinder and thus the member will not have any compressive stresses. When it is subjected to a tensile displacement, the bars will transfer the tensile force between the two brace pieces. The bars should be chosen such that the sum of their yield resistance is less than the yield resistance of the brace member. Following a strong earthquake, the brace member is expected to be easily retrofitted by replacing the bars.

3 Experimental program

An experimental study was conducted to evaluate the effectiveness of the CRD. A four-story residential building of 12.4 m by 15.4 m in plane shown in Fig. 2 was considered for this study. The building was assumed to be located in a highly seismic area. Braced RC frames were utilized to resist lateral loads.

A unit of the braced RC frame was selected and isolated from the third floor of the building (see Fig. 2). The unit was assumed to be supported by two hinged supports located at the ends of the bottom beam. To duplicate the distribution of the bending moments in the actual RC frame, the unit frame was subjected to two concentrated vertical loads acting on the columns and a concentrated lateral load acting at the level of the top beam. The gravity and lateral loads acting on this unit were calculated using linear elastic analysis.

Scaled models of the unit frame were experimentally investigated in this study. Their overall dimensions were 1.76 m by 1.36 m. The loads acting on the models were obtained by scaling down the loads acting on the actual unit frame. This resulted in a lateral load of 22 kN and two vertical loads of 38 kN.

3.1 Test specimens

Four braced RC specimens were designed using the gravity and lateral loads obtained in the previous section. The design and detailing of the RC frames were conducted according to the general requirements of ACI 318-02 (ACI Committee 318, 2002). Special seismic provisions were not enforced as the bracing was expected to highly reduce the seismic demand on the beams, columns, and beam-column joints of the RC frames. Details of the reinforcement are given in Fig. 3.

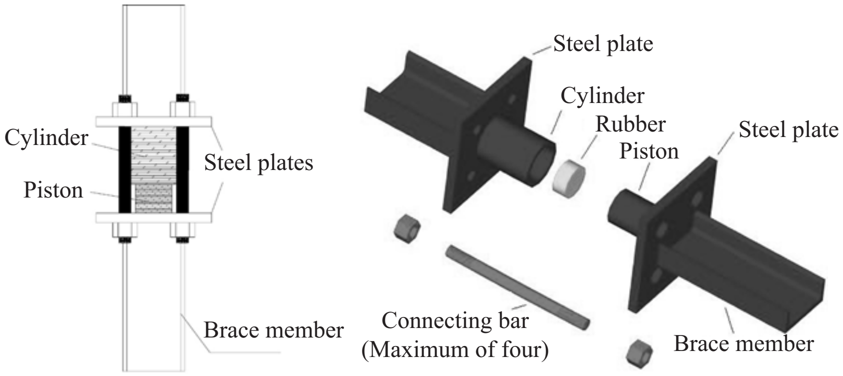


Fig. 1 Compression release device (CRD)

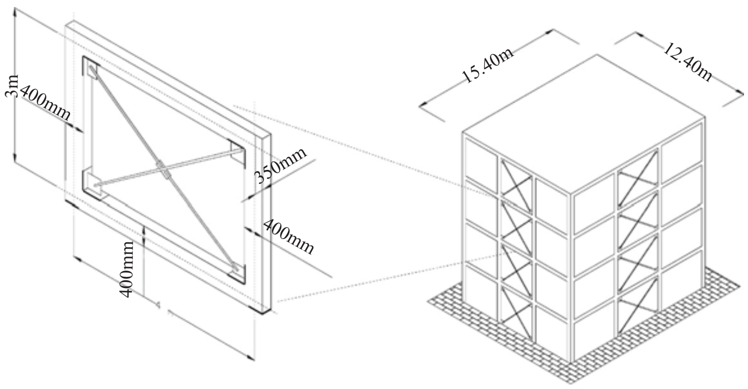
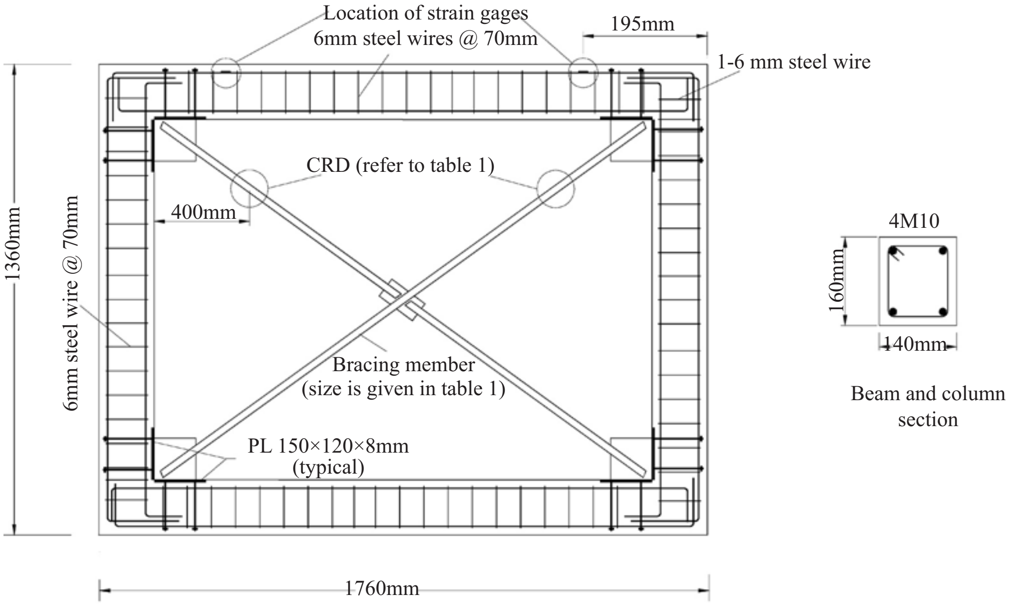


Fig. 2 Isolation of a unit braced RC frame from the considered RC building

Two 150mm × 150mm × 8 mm steel plates were placed at each of the four inner corners of the RC frames prior to casting the specimens. Each plate was anchored to the RC frame using four-5/8 inch (1 inch = 2.54cm) headed studs as shown in Fig. 3. Self-consolidated concrete with 28-days compressive strength of 55 MPa was used to cast the specimens. Bracing members were then installed by welding their gusset plates to the previously anchored steel plates.

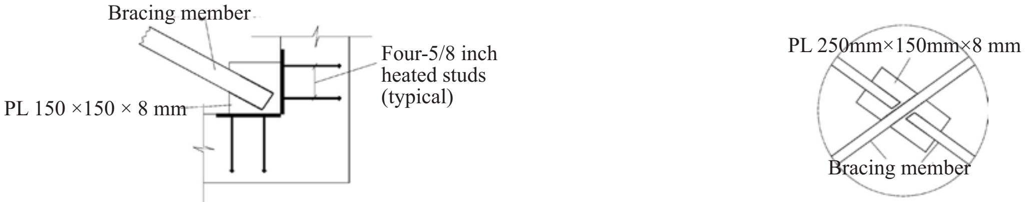
Table 1 summarizes the differences between the four specimens. The bracing members in specimens FX1 and FX2 were two 25×25×3.2 angles and C 3×3.5, respectively. For specimens FXS1 and FXS2, C 3×3.5 bracing members with CRD were installed. The CRD can be installed anywhere along the brace member. For the tested specimens, it was decided to install the CRD at the location shown in Fig. 3.

The size of the steel plates in the CRD was chosen to be 120mm × 120mm × 10 mm. The expected axial deformation in the brace members was calculated with consideration of achieving a 135 mm gap between the steel plates of the CRD. To create this gap, the length of the cylinder and the piston was chosen to be 135 mm. The inner diameter and wall thickness of the cylinder were chosen to be 40 mm and 5 mm, respectively. The piston was chosen to be a 35 mm steel rod. The bars connecting



Beam and column section

Braced RC frame



Brace to Gusset plate connection

Bracing connection at the center

Fig. 3 Detailing of braced RC frame

Table 1 Specification of test specimens

Test specimen	Bracing member section
FX1	2 L 25 × 25 × 3.2 mm (Double angle shape cross section)
FX2	C 3 × 3.5 (Channel cross section)
FXS1	C 3 × 3.5 + CRD with 2–12.7 mm Rods (Channel cross section)
FXS2	C 3 × 3.5 + CRD with 2–16.0 mm Rods (Channel cross section)

the steel plates were different in specimen FXS1 from those in specimen FXS2. They were two-12.7 mm and two-16 mm in diameter steel bars in specimens FXS1 and FXS2, respectively. Tensile load tests on the steel rods revealed that their yield stress is 350 MPa.

Note that the dimensions chosen for the CRD are for the tested frames. For other frames, modifications are needed depending on the brace member size and its expected deformation.

3.2 Test setup

The test setup is shown in Figs. 4 and 5. The specimens were pin-jointed at the two ends of the bottom beam. They were subjected to gravity loads generated by two hydraulic jacks. A special roller was developed to allow these jacks to slide on the concrete surface while testing. An actuator with a capacity of 245 kN and maximum stroke of 150 mm was used to apply several cycles of loads using a displacement-controlled approach. In each cycle, the actuator was first pulled to a displacement d_1 of 5 mm then pushed to the same displacement. Then d_1 was increased in the following cycles by an increment of 5 mm. A photo of an installed CRD is shown in Fig. 6.

The behavior of the test specimens was monitored by using electrical and mechanical instrumentations as shown in Figs. 3 and 4. The data were recorded at intervals of one second.

4 Experimental observations and results

The present study focuses on the performance of the CRD in preventing buckling of compressive brace members. The seismic parameters evaluated from the test results include: stiffness degradation, energy dissipation capacity (toughness) and ductility. The performance of specimens with CRD is also compared with the other specimens.

4.1 Behavior of the tested specimens

The lateral force-drift relationship for specimen FX1 is shown in Fig. 7. At a drift of 1.8% (load of 105 kN), yielding of the double-angle bracing member initiated the plastic response. A significant drop in the lateral load capacity was observed at a load of 140 kN (drift of 3.5%). This was mainly due to buckling of brace members. Following this, the lateral load capacity was mainly provided by the RC frame, which failed when plastic hinges were formed at the ends of the bottom and top beams. Figure 8 shows the variation in the strain of the longitudinal reinforcement in the beam of specimen FX1 with the lateral load. It shows that under a load of about 105 kN, the reinforcement reached the yield strain.

The lateral force-drift relationship for specimen FX2 is shown in Fig. 9. The specimen behavior was almost linear. The measured strain of the longitudinal reinforcement in the beam (Fig. 10) shows that the yielding occurred under a load of about 140 kN. The corresponding yielding strain is 0.18%. The lateral capacity of the frame was not affected due to the reinforcement yielding because the bracing members were still acting in the elastic range. Testing was terminated at a load of 200 kN as the capacity of the

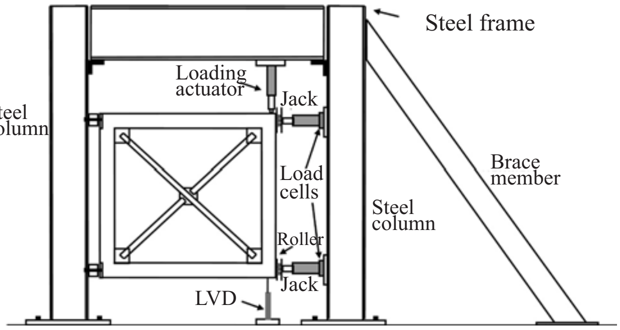


Fig. 5 Schematic of the test setup

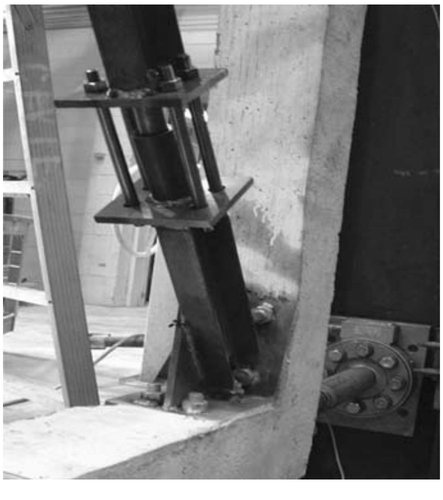


Fig. 4 Photo of the CRD (specimen FXS1)

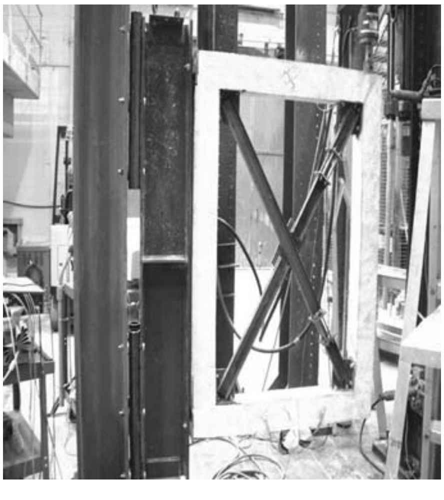


Fig. 6 Photo of the test setup

actuator was reached.

The lateral load-deformation response for specimen FXS1 (Fig. 11) indicates the formation of the first plastic hinge at a drift level of 1.2%. This was due to the yielding of the two-12.7 mm steel bars joining the steel plates of the CRD. This happened at a lateral load of 65 kN. It can be seen in Fig. 11 that there is a load drop at 65 kN. Meanwhile, the calculated yield load confirms that first yielding is expected at the same level of loading. The frame failed at a drift of 4.8% corresponding to a lateral load of 182 kN due to a tensile failure of the two-12.7 mm in diameter bars. Variation of strain of the top reinforcement of the top beam is illustrated in Fig. 12.

The behavior of specimen FXS2 was similar to specimen FXS1. The force-displacement for this specimen is shown in Fig. 13. Yielding of two-16 mm in diameter steel bars in the CRD occurred at a drift of 2.5% (lateral load of 140 kN). By increasing drift, cracks became visible. Strains in the top reinforcement of the top beam (Fig. 14) indicate that steel yielded at a drift

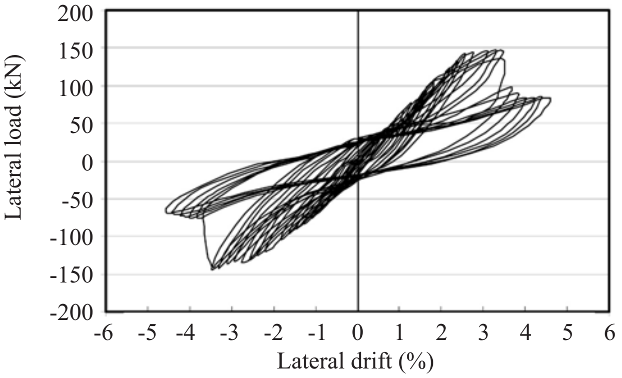


Fig. 7 Lateral load-drift curve for specimen FX1

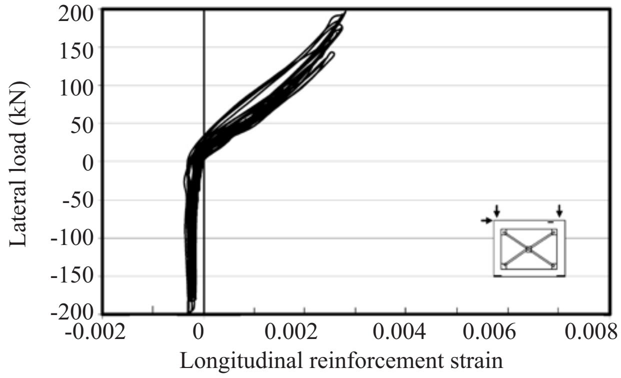


Fig. 10 Strain variation in the top beam reinforcement for specimen FX2

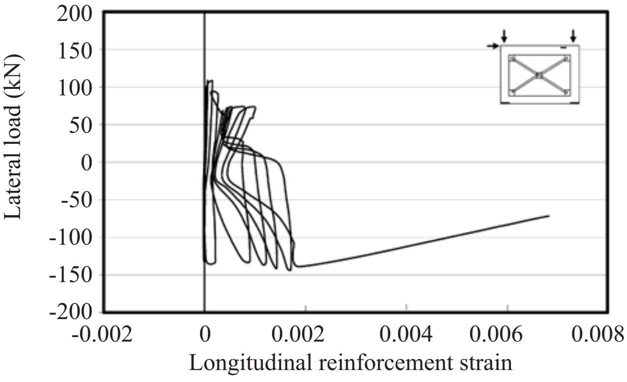


Fig. 8 Strain variation in the top beam reinforcement for specimen FX1

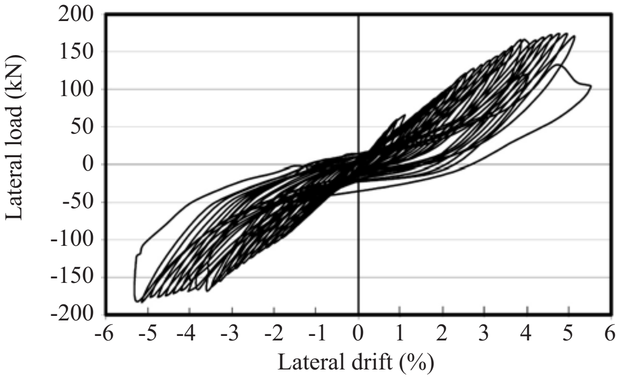


Fig. 11 Lateral load-drift curve for specimen FXS1 (equipped with CRD)

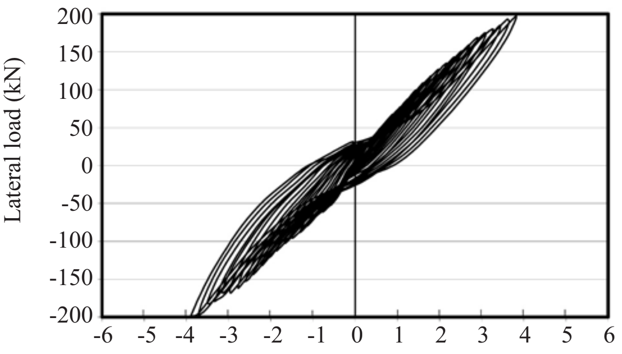


Fig. 9 Lateral load-drift curve for specimen FX2

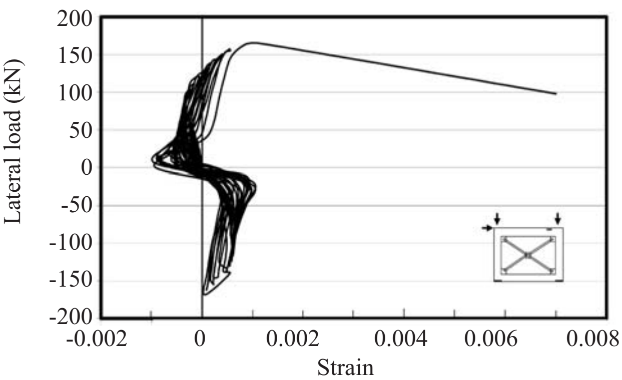


Fig. 12 Strain variation in the top beam reinforcement for specimen FXS1

of 3.4%. The measured strain at this level of drift was 0.18%, which related to a lateral load of 150 kN. The test was terminated because of localized concrete failure in the vicinity of the supports.

The overall response of all specimens was evaluated by comparing the load-drift envelopes shown in Fig. 15. A sudden load drop in the load-drift curve of the specimen FX1 indicates the buckling of the compressive member. Buckling for the specimen FX2 was as expected during the test, but it did not fail because of the restriction in the maximum capacity of the actuator. The failure of specimens FXS1 and FXS2 was because of yielding in the CRD. Buckling phenomenon was not seen for these tested specimens and the installed CRD was efficient in prohibiting compression buckling.

4.2 Stiffness degradation

Figure 16 shows the stiffness degradation of the test specimens with increasing lateral drift. The stiffness was evaluated by the applied peak lateral load divided by the associated displacement measured at each cycle. It can be observed that the initial stiffness of specimens FX1 and FX2 was higher than that of specimens FXS1 and FXS2. This is a direct result from the lower elastic stiffness of bracing members equipped with CRD. The steeper degradation in the lateral stiffness observed in specimens FX1 and FX2 indicates that using the CRD minimized the cracking in the RC frame and kept the lateral stiffness of the frame almost constant.

4.3 Energy dissipation capacity (toughness)

The ability of a structure to dissipate energy has a strong influence on its response to dynamic loading. In this study, the energy dissipated by each specimen during the reversed cyclic load test (also known as toughness) was estimated by calculating the area enclosed by the corresponding load-displacement hysteretic loop. Fig. 17 shows a plot of the energy dissipated during a load cycle versus the applied displacement for this cycle. The cumulative energy dissipated by the frames after 5, 10, 15, 20 and 25 cycles is also calculated and presented in Table 2. Note that in this table, at lower displacements, the energy dissipated by the braced frames with CRD (specimens FXS1 and FXS2) is somewhat less than for braced frames without CRD (specimens FX1 and FX2). With increasing displacements and as the bars in the CRD yield, the energy dissipated by the frames with CRD increases to levels higher than those of the frames without CRD. This reveals that the incorporation of the CRD did not, by and large, affect the energy dissipation

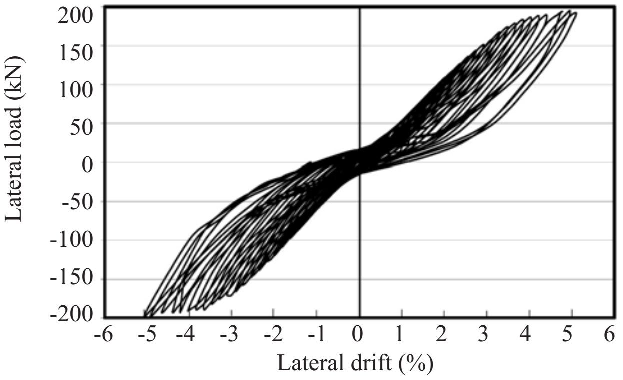


Fig. 13 Lateral load-drift curve for specimen FXS2 (equipped with CRD)

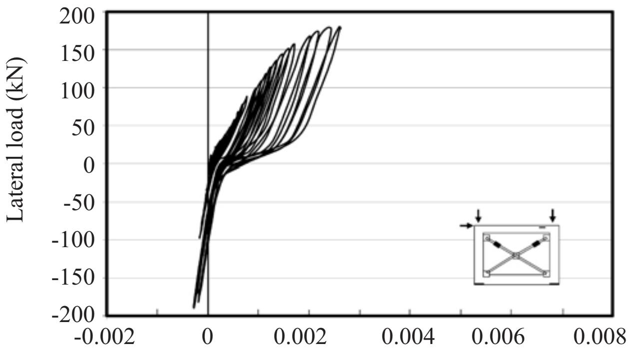


Fig. 14 Strain variation in the top beam reinforcement for specimen FXS2

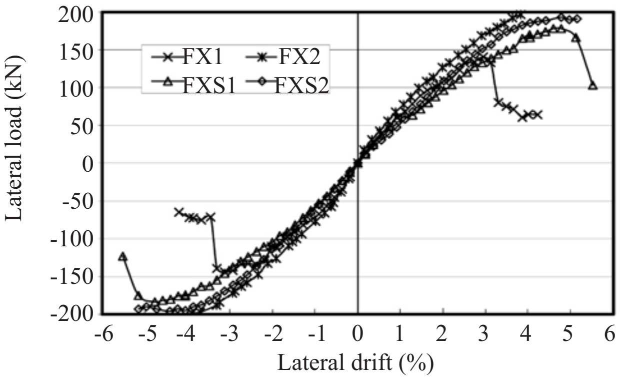


Fig. 15 Comparison of the lateral load-drift envelopes for the tested specimens

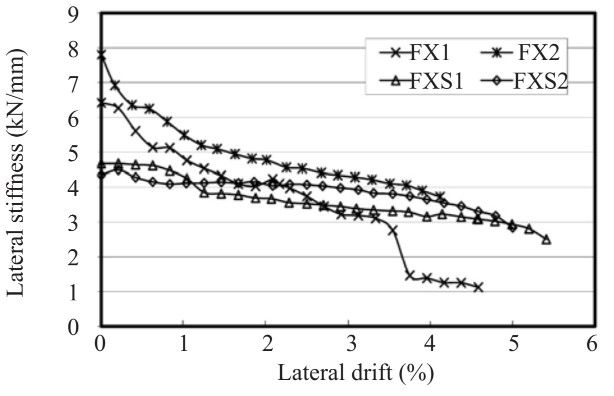


Fig. 16 Degradation of lateral stiffness for the tested specimens

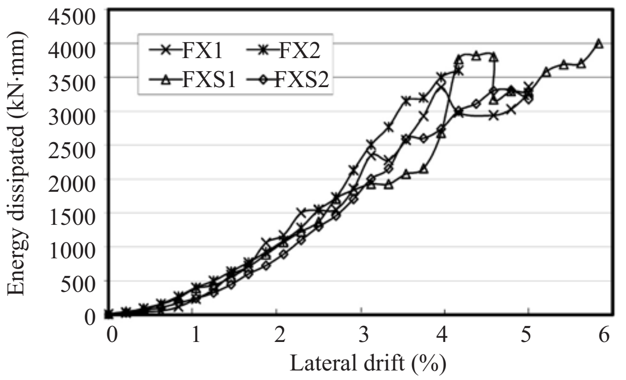


Fig. 17 Variation of energy dissipation with lateral drift for the tested specimens

capacity of the braced frames.

4.4 Ductility

Displacement ductility is an important factor in the seismic design of structures. In this study, ductility is measured as the ratio of the maximum available displacement capacity to the displacement pertaining to the yield point of the specimens. The available ductility of the four specimens is given in Table 3. It can be observed from this table and Fig. 16 that the overall behavior of the specimen with CRD (specimen FXS1) is more ductile when compared with specimen FX1 without CRD. A sudden drop in the load-drift response curve of specimen FX1 after buckling of the compression brace indicates a brittle behavior. However, the specimen FXS1, in which buckling was inhibited and failure happened by yielding of steel bars of the CRD, exhibited more ductile behavior (almost twice as much). This shows the effectiveness of the CRD in increasing the ductility of the braced frame.

Table 2 Energy dissipation capacity of the test specimens

Test specimen	Cumulative energy dissipated (kN·mm)				
	Cycle 5	Cycle 10	Cycle 15	Cycle 20	Cycle 25
FX1	450.9	4366.7	13163.5	27275.8	32875.1
FX2	570.5	3807.1	11540.1	26714.7	-
FXS1	550.5	3524.3	10730.2	28497.0	36647.1
FXS2	390.5	2735.0	9188.5	27275.1	35256.2

Table 3 Ductility of the test specimens

Test specimen	Δ_y (mm)	$\Delta_{\text{available}}$ (mm)	μ
FX1	22.5	47.5	2.11
FX2	33.0	51.5	1.56
FXS1	17.5	71.5	4.08
FXS2	35.0	75	2.15

By comparing the results of the stronger braced frames without CRD (specimen FX2) and with CRD (specimen FXS2), the favorable effect of the CRD on the ductility of the frame can also be noted. The increase in ductility due to CRD for specimen FXS2 would be even higher if the test on FXS2 had not been terminated prematurely due to some local support failure.

5 Conclusions

In this paper, a compression release device (CRD) for steel braces in RC frames is proposed and its behavior is experimentally investigated. The CRD can be incorporated in any brace member to relieve the compressive stresses and thus prevent buckling, an undesirable mode of failure. For comparison purposes, four steel braced RC frames were constructed and tested under reverse cyclic loads. Two of them had different amounts of bracing and the other two had the same amount of bracing but each incorporated a different type of CRD device. From the test results, the following conclusions can be drawn.

- Buckling failure of compressive brace members greatly reduces the lateral capacity and ductility of braced RC frames.
- The proposed CRD can be used effectively in steel braced systems to prevent buckling failure. Also allows an adequate energy dissipation capacity for the brace-framed system.
- The inclusion of CRD can greatly enhance the ductility of the braced frame. The desired level of ductility can be achieved by an appropriate design of the CRD bars.
- Following an earthquake, the damaged CRD can be easily retrofitted by replacing the bars. The possible minor cracking in the concrete frame can be easily repaired by using epoxy grouting, or any other appropriate method.

References

Abou-Elfath A and Ghobarah A (2000), “Behavior of Reinforced Concrete Frames Rehabilitated with Concentric Steel Bracing,” *Canadian Journal of Civil Engineering*, **27**: 433-444.

ACI Committee 318 (2002), *Building Code Requirements for Reinforced Concrete (ACI 318-02) and Commentary (ACI 318R-02)*. American Concrete Institute, Detroit, Michigan.

Aiken I *et al*. (1992), “Comparative Study of Four Passive Energy Dissipation Systems,” *Bulletin of the New Zealand National Society for Earthquake Engineering*, **25**(3): 175-192.

ASCE (2002), *Seismic Provisions for Structural Steel Buildings,* American Institute of Steel Construction, Chicago, Illinois.

ASCE (1994), *Manual of Steel Construction, Load and Resistance Factor Design,* 2nd edition, American Institute of Steel Construction, Chicago, Illinois.

Badoux M and Jirsa J (1990), “Steel Bracing of RC Frame for Seismic Retrofitting,” *Journal of Structural Engineering*, ASCE, **116**(1): 55-74.

Bertero VV, Uang C, Llopiz CR and Igarashi K (1989), “Earthquake Simulator Testing of Concentric Braced Dual System,” *Journal of Structural Engineering*, ASCE, **115**(8): 1877-1893.

Bush TD, Jones EA and Jirsa JO (1987), “Behavior of RC frame strengthened using steel bracing,” *Journal of Structural Engineering*, ASCE, **117**(4): 1115-1126.

CSA (1994), *Limit State Design of Steel Structures,* Standard CAN/CSA-S16, Canadian Standards Association, Rexdale, Ontario, 1-94.

Isabella R, Mahin S and Chang C (2003), “Seismic Demands on Steel Braced Frame Build ings with Buckling-restrained Braces,” *Engineering Structures*, **25**(5): 655-666.

Jain AK (1978), “Histeresis Behaviour of Bracing Members and Seismic Response Of Braced Frames with Different Proportions,” *Ph. D. Thesis*, University of Michigan, Ann Arbor, MI.

Jinkoo K and Youngil S (2004), “Seismic Design of Low-rise Steel Frames with Buckling-restrained Braces,” *Engineering Structures*, **26**(5): 543-551.

Kamura H, Katayama T, Shimokawa H, and Okamoto H (2000), “Energy Dissipation Characteristics of Hysteretic Dampers with Low Yield Strength Steel,” *U.S.-Japan Joint Meeting for Advanced Steel Structures*, Building Research Institute, Tokyo.

Liu Z and Goel S (1987), “Investigation of Concrete-filled Steel Tubes Under Cyclic Bending and Buckling,” *Research Report UMCE 87-3*, Dept. of Civil Engineering, University of Michigan, Ann Arbor.

Maheri, MR, Kousari R and Razazan M (2003), “Pushover Tests on Steel X-braced and Knee-braced RC Frames,” *Engineering Structures*, **25**: 1697-1705.

Maheri MR and Sahebi A (1995), “Use of Steel Bracing in Reinforced Concrete Frames,” *Engineering Structures*, **9**: 112-120.

Ohi K, Shimawaki Y, Lee S and Otsuka H (2001), “Pseudo-dynamic Tests on Pseudo-Elastic Bracing System Made From Shape Memory Alloy,” *Bulletin of Earthquake Resistant Structure Research Center*, No. 34: 21-28.

Roeder CW (1989), “Seismic Behaviour of Concentrically Braced Frame,” *Journal of Structural Engineering*, ASCE, **115**(8): 1837-1855.

Sesigur H, Celik OC and Cili F (2002), “Seismic Retrofitting of RC Framed Buildings by Vertical Steel Bracing: Case Studies After Last Turkey Earthquakes,” *12th European Conference on Earthquake Engineering*, London, Paper No. 336.

Tasnimi AA and Maasumi A (1999), “Behavior of RC Frames Strengthened by Steel X-Bracing,” *Proceedings of the Third International Conference on Seismology and Earthquake Engineering*, Tehran, I.R. Iran.

Watanabe A (1996), “Some Damage Control Criteria for a Steel Building with Added Hysteresis Damper,” *Eleventh World Conference on Earthquake Engineering*, Pergamon, Elsevier Science Ltd., Disc 1, Paper No. 449

Watanabe A *et al*. (1989), “Properties of Brace Encased in Buckling-restraining Concrete and Steel Tube,” *Ninth World Conference on Earthquake Engineering*, Organizing Committee, Japan Assn. for Earthquake Disaster Prevention, Tokyo, Vol. IV, Paper 6-7-4, pp.719-724.