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NEAR FULL-SCALE EXPERIMENTAL INVESTIGATION OF LOW-STANDARD RC FRAMES RETROFITTED WITH BUCKLING RESTRAINED BRACES

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Abstract

Existing Reinforced Concrete (RC) buildings designed according to outdated regulations and codes may lack seismic performance (strength, stiffness, and ductility) to meet the current codes' requirements. Especially older public buildings like schools or hospitals, typically require retrofitting to ensure safety during and after a major seismic event. While retrofit methods using conventional (i.e. buckling) braces in a concentric or eccentric configuration have been implemented for decades, the unbalanced hysteretic behavior of such braces tends to yield damage concentration in certain stories. Buckling Restrained Braces (BRBs), as a new generation bracing system, provide an increase of structural integrity and reduce seismic demands through energy dissipation. However, during a strong seismic event, maximum story drifts may exceed the yielding point of the RC frame, causing degradation in horizontal stiffness in all structural elements including BRBs. This phenomenon eventually results in damages and residual deformation at a specific story. In actual applications, these reductions could be prevented when BRBs are used in connection with an elastically designed closed steel frame (SF).

Although seismic retrofit of steel buildings using BRBs have been well studied to date, limited experimental work is present for retrofitting of RC buildings using BRBs. Connection details of BRBs to the perimeter RC elements are of major concern for an effective retrofit. To address this problem and possibly attain useful results and design recommendations, near full-scale three cyclic loading tests were conducted. One RC bare frame (R), one RC frame retrofitted with a closed steel frame (RS), and one RC frame retrofitted with a closed steel frame and a single diagonal BRB (RSB) were designed, constructed, and tested. BRB core material was a LYP225 steel and the BRB was attached to the SF with welded end connections at the gusset plates. RSB showed stable hysteretic behavior without fracture or buckling until up to 1/150 story drift, designated as a target retrofit drift for damage controlled design. Behavioral values such as load-displacement hysteretic curves, effective damping ratios, and total dissipated hysteretic energies are calculated and compared. The tests show that the proposed retrofit method is feasible and increases strength as well as ductility to an adequate seismic performance level. Also, damage distribution in both RC and steel members and self-centering functions of the elastic steel frames that connect BRBs to RC elements are reported and discussed.

Keywords: seismic retrofit; buckling-restrained brace; RC frame; composite structure; cyclic loading test

1. Introduction

In recent earthquakes, RC buildings that were poorly designed and constructed before modern seismic codes have suffered great damages or totally collapsed. Innovative and effective seismic retrofitting methods for existing RC buildings has become one of the main focus of earthquake engineering research and practice. For this reason, seismic performances of existing RC buildings are needed to be re-assessed for determining structural measures to be taken and thus to improve their behavioral values such as lateral strength, stiffness, ductility, and damping values. Although there are several methods to improve this poor behavior developed up to date, addition of shear walls or conventional steel braces are assumed as widely used retrofitting solutions since experiences gained over the course of time are significant [1].

Figure 1 shows that various retrofit solutions for deficient RC frames have different impacts with regard to strength, stiffness, and ductility. Among numerous retrofit solutions, steel braces have remarkable advantages compared to other retrofitting options. Braces can be prefabricated, allowing manual transportation and fast installation or enabling architectural flexibilities such as allowing openings that provide access and light. Additionally, steel braces are lighter when compared to RC shear walls and also strength and ductility can be adjusted specifically for each project following the project specific constraints.

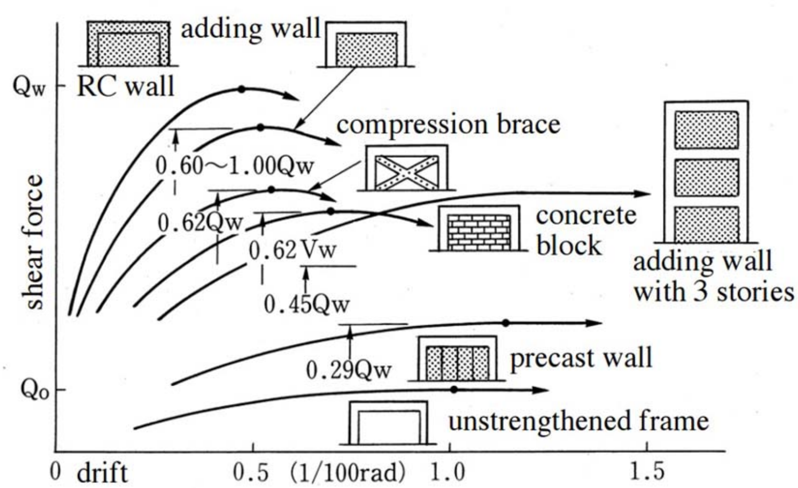


Figure 1. Retrofitting methods for seismically deficient RC frames [1]

In many practical applications, steel braces are attached to RC frames through a steel frame, which is connected with post-installed anchors to the existing RC frame. Also, there are retrofit schemes in which steel braces are directly connected to RC members (beams, columns, or beam-to-column connections). Retrofitting RC frames with steel braces together with a closed steel frame is practical and provides a larger increase in lateral force capacity and collapse resistances compared to RC jacketing of vertical members or adding low-strength shear walls. Moreover, elastic range of steel frame is generally larger compared to a retrofitted RC frame which would provide self-centering capabilities for the overall system. If sufficient anchorage and properly designed connection detail is provided between the RC and steel frames, the retrofitted system would ultimately fail by yielding or buckling of the brace, column shear mechanism, or welding failure [2].

Conventional buckling braces consist of a single steel member, with diverse cross-sections, which is designed to sustain both compressive and tensile forces. Buckling in these members is controlled by the slenderness ratio and usually, it is necessary to specify large cross sections in order to avoid buckling failure. Flexural buckling, a failure mode in which the member deforms laterally and loses its stiffness and load carrying capacity, is the most common problems associated with compression elements. When this failure occurs, lateral stiffness drops, frame stability decreases significantly, causing severe damage to the structural and non-structural elements and in some events taking the structure to collapse. It is believed that conventional (i.e. buckling) braces have limited deformation ductility capacity, and exhibit unsymmetrical hysteretic cycles, with a significant strength deterioration when loaded in compression (Fig. 2-a). However, when properly designed and constructed, buckling braces of certain types (for example tubular braces having compact sections) could dissipate significant amount of hysteretic energy even in the post buckling range [3].

Meanwhile, buckling restrained braces (BRBs) were developed in Japan in early 1980's and the first application in an actual building was reported in 1990 [4]. These braces are designed such that buckling is restrained to occur, exhibiting adequate behavior and fairly symmetrical hysteretic curves under the action of both tensile and compressive cycles, produced by the action of seismic forces. In the case of BRB retrofitted frames, the frame exhibits a stable behavior provided by the fairly symmetrical hysteretic character of BRBs (Fig. 2-b). BRBs have a steel core that sustains the lateral forces acting on the frame. The encasing member, formed by mortar (low or high strength) and steel tubes surrounding the inner core, acts as a restraining element that provides lateral stiffness when the inner core tends to buckle and deform.

BRBs represent an ideal combination of structural retrofit member as yielding dampers that function as structural fuses. The basic principles and working mechanism of BRBs have been well documented [5, 6]. Recent studies investigated BRBs in detail, both analytically and experimentally at the component level [7, 8]. Moreover the sub-assemblage level investigation of BRBs is also handled in detail [9, 10, and 11].

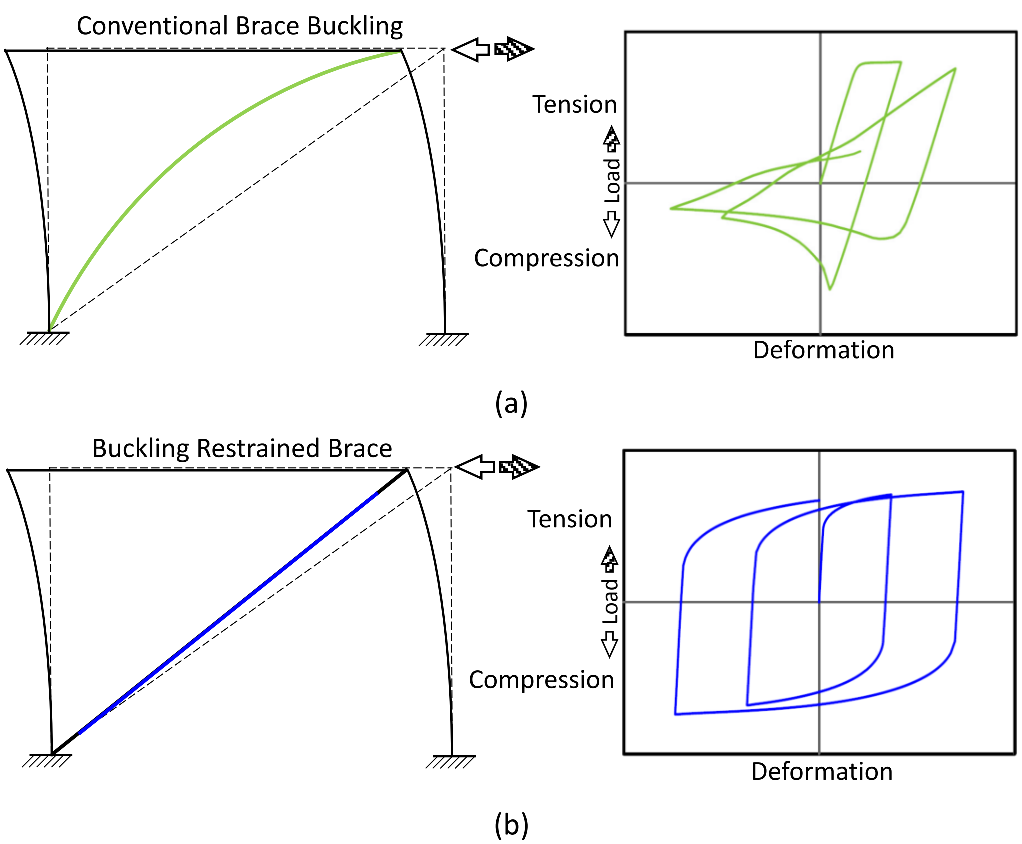


Fig. 2. Seismic behavior of frame with conventional steel brace (a) and BRB (b)

Up to date, research on BRBs has mainly focused on the application to steel structures. Moreover, very limited research has been reported on retrofitting of RC structures with BRBs. Analytical simulation of BRB strengthened RC frame buildings and bridges have been conducted [12, 13, and 14]. In experimental studies, buckling resistant bracings connected to an RC frame without implementing a steel frame, and instead using post installed connection details such as pre-loaded ties or anchors is investigated as a solution for seismic retrofitting [15, 16 and 17]. One of the earliest applications of BRBs for retrofitting an existing RC building is reported in 2006 [18]. In summary, BRBs appear to be a convenient retrofit solution for low-standard RC structures as they protect the structural integrity and allow inspections, repairs and replacements after earthquakes.

To investigate the validity of such a retrofit scheme and provide some experimental data, this paper represents near full-scale cyclic tests on RC frames retrofitted with BRBs. Special emphasis is paid on a sub-standard school building in Turkey. The proposed retrofit method requires an elastically designed closed steel frame installed in the RC frame and then BRBs are attached through the steel frame. The tests show that the proposed retrofit method is feasible and increases strength as well as ductility to an adequate seismic performance level. The paper also discusses the damage distribution in both RC and steel members and self-centering functions of the elastic steel frames that connect BRBs to RC elements.

2. Outline of Experiments

For the experimental part of this work, near full-scale RC frames have been manufactured in Turkey representing a low-standard school building. It is aimed that such a retrofit scheme would be an effective way of structural improvement and could be easily implemented in such school buildings. Both BRBs and steel frames are used for response control retrofit purposes. These members used in the tests in this work have been manufactured in Japan and shipped to Turkey. The proposed retrofit method requires an elastically designed closed steel frame installed in the RC frame and then BRBs are attached through the steel frame (Fig. 3 and 4). Column axial loads to account for the existence of upper stories are taken into consideration by using a specially designed and constructed axial loading setup. All tests are carried out in the Earthquake and Structural Engineering Laboratory (STEEL) of Istanbul Technical University (ITU). The performance target was to obtain a more ductile RC frame behavior with minimum seismic damage.

This experimental program includes three specimens as follows: R model (RC bare frame), RS model (RC frame with inner steel frame only) and RSB model (RC frame with a concentrically attached BRB and steel frame). In Fig. 4, structural details of R model and RSB model are given. Many older RC school buildings in Turkey have concrete frames (especially in their perimeter frames) with a framing configuration of story girders and columns resulting in an eccentric load transfer. In other words, axes of the frame girders and columns do not intersect. Although this seems as a negative impact on overall behavior, this geometric condition could be positively used for an appropriate retrofit scheme especially for a retrofit scheme developed herein. RS model is composed of R model and the steel frame shown in RSB model with identical connection details. For the connection of the steel frame and RC frame, post-installed anchors are used on RC frame members. The steel frame has shear studs on the relevant interface (Fig. 4). In the connection section, two layers of ladder type stirrups and mortar are used and the whole connection section is designed based on the Japanese retrofit design guidance [1].

3. General view of test set-up

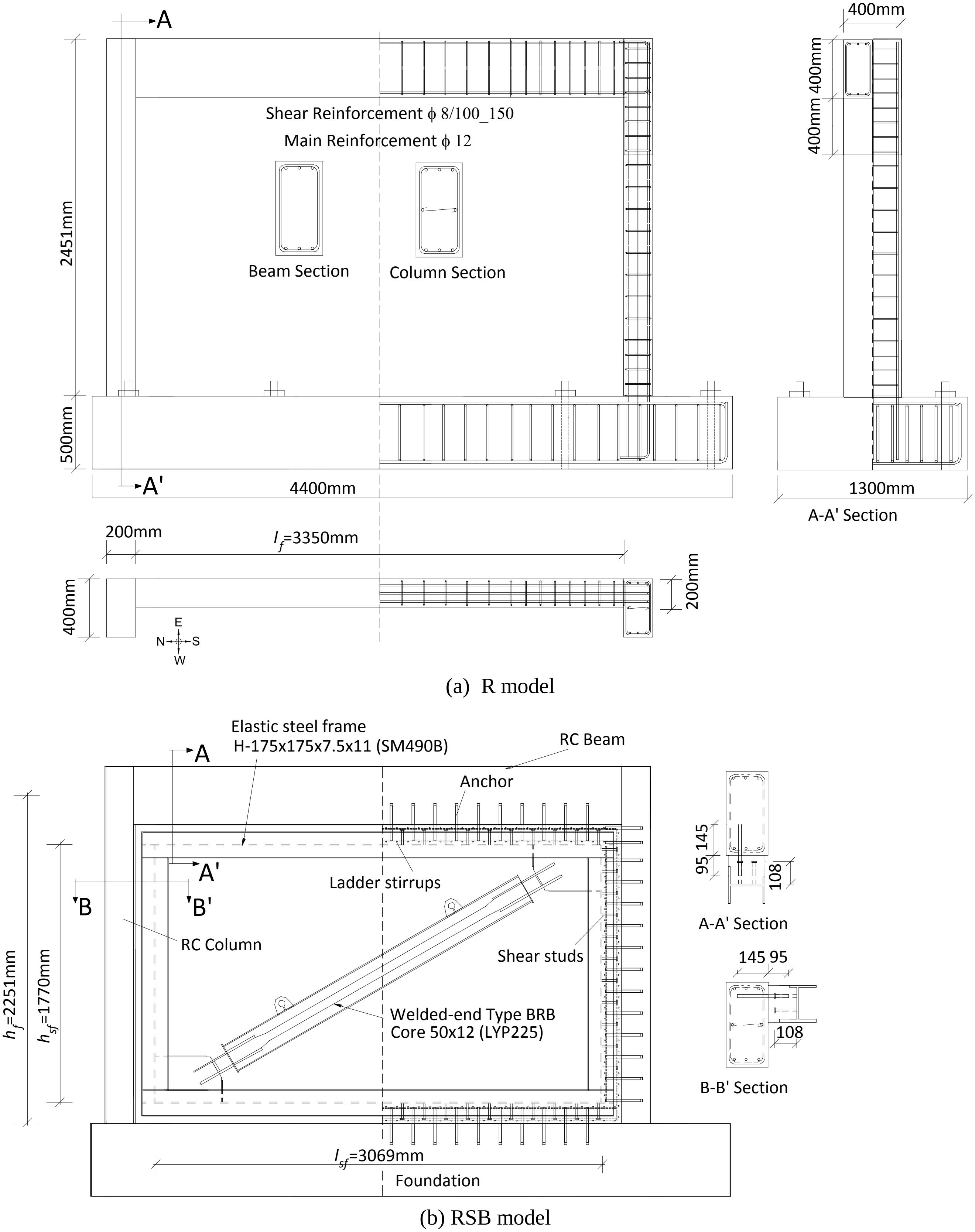


Fig. 4. Structural details of R model (a) and RSB model (b).

The RC frame is designed based on an existing school building stock representing the design of 1990's in Turkey where the scaling factor is approximately 80%. In other words, a RC frame taken from a well-engineered building is assumed. The scaling is used to fit the test facility dimension and load capacity limits. Material qualities for RC frame concrete and rebars are C20 (f_{ck}≈20MPa) and S420 (f_{yk}≈420MPa) respectively. High strength mortar with a characteristic strength of 80MPa was used in connecting the steel and RC frames. Design of the RC frame, re-bar ratios and placement in RC frame follows the seismic code effective in 1990's [19, 20]. Material Properties for the BRB and the steel frame are given in Table 1.

Table.1 Material characteristic of steel frame, BRB core, and restrainer tube.

Steel Member	Type of Material	Yield Stress (MPa)	Tension Stress (MPa)
BRB Core Plate	LYP225	235	305
Restrainer Tube	STKR400	381	467
Steel Frame H-175×175×7.5×11	SM490	402	529

A special displacement based loading protocol for this test program is developed and shown in Fig.5. A gradually increasing reversed cyclic protocol is adopted. Displacement control based on story drift angle of specimens is carried out under constant axial force representing the upper stories (250kN on each column during the early stages of the testing, 15% of the axial capacity of the column). Note that axial load level on the columns varies during the horizontal loading and the difference between the column axial loads increases with increase in drift values.

In the first 2 stages of loading, 1/3 and 2/3 of the estimated RC frame yielding displacement is applied (0.15% and 0.30%). Next, a story drift angle of 1/225 (0.44%) which is the estimated RC frame yielding displacement is performed. Note that a story drift angle of 1/150 (0.67%) is the target drift of this retrofit research. Also, a story drift angle of 1/100 (1.0%) is a drift limitation given in the current Turkish Seismic Code which corresponds to life safety performance level [21]. Finally, 2.0% and 3.0% story drift angles are included in the loading protocol to observe the behavior of specimens under exceeding horizontal displacements within the limits of test setup. For each level, 3 cycles are applied as shown in Fig. 5. Not all specimens were subjected to the whole loading protocol as in RSB specimen the testing device has reached its maximum capacity in 1% story drift level.

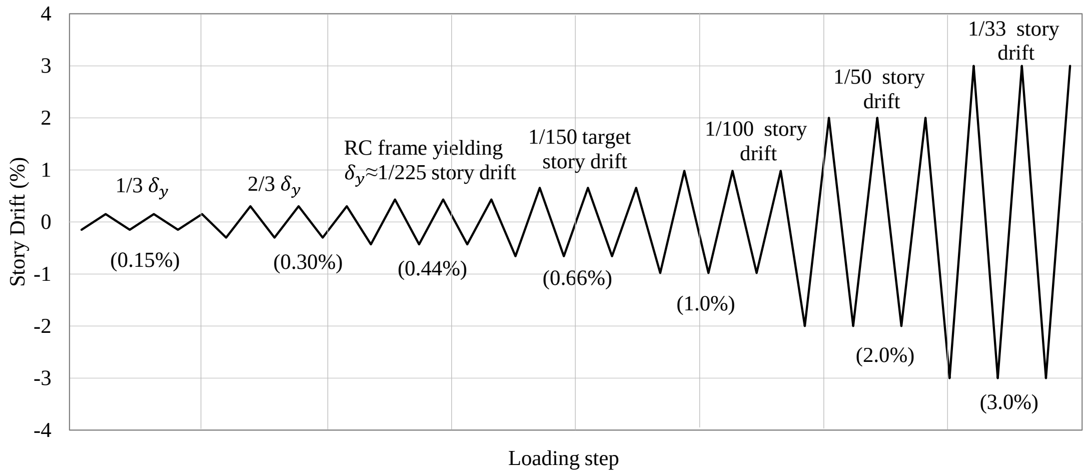


Fig.5 Loading Protocol

In the beginning, as stated before, the axial force applied on columns represents approximately 15% of the load bearing capacity of the columns. The cyclic loading and axial loading system details are shown in Fig. 6.

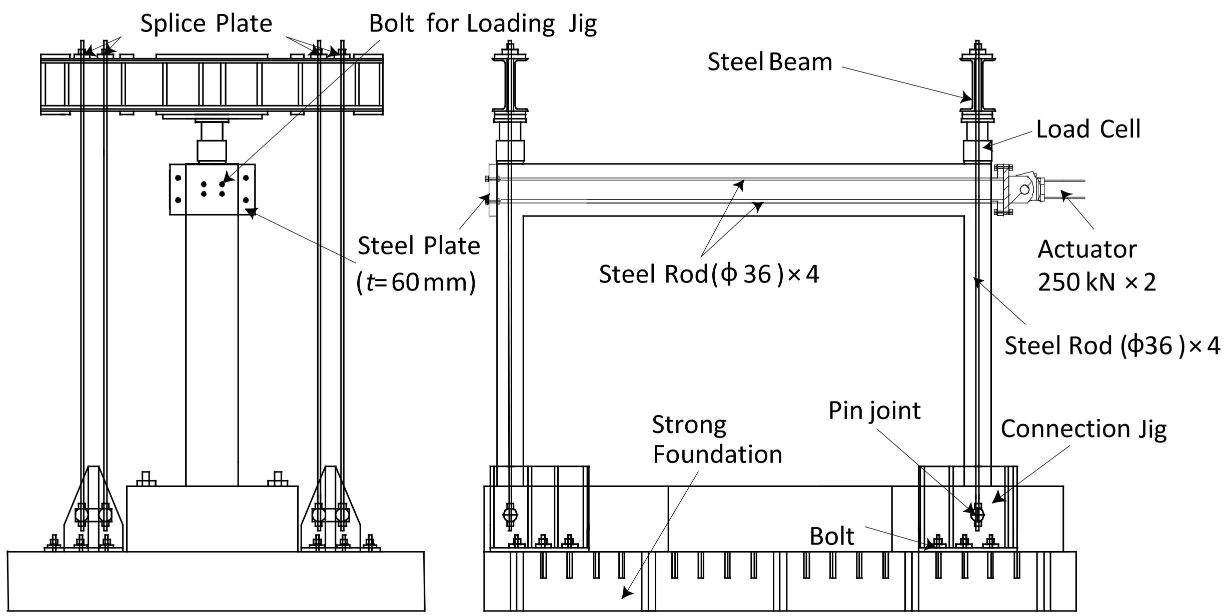


Fig. 6. Horizontal Cyclic and Axial Load System

3. Experimental Behavior of Specimens

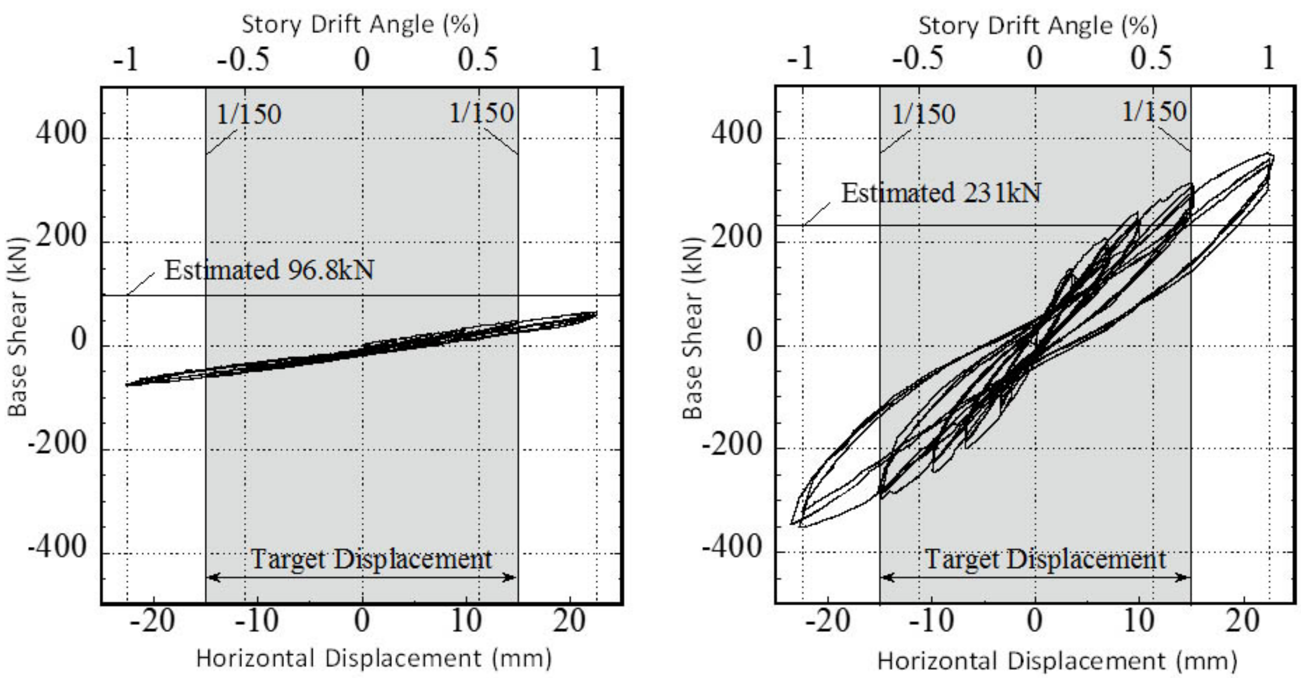
The cyclic test results for 3 specimens up to 1% drift level is shown in Fig. 7 in terms of horizontal load versus displacement (and story drift angle). Fig. 8 shows the observed damage at North column bottom end at target story drift of 1/150.

Figure 7-a shows the experimental results of R model (RC frame only), where the RC frame showed highly ductile behavior and the observed cracks were quite small in width and length No significant cracks were observed at the retrofit target story drift angle of 1/150 (Maximum crack width: 0.75mm). Maximum horizontal force was observed at story drift angle of 3%. During the testing, after 9 full-cycles of 3% story drift angle, additional 4% story drift angle was conducted and finally testing was terminated because of a stability problem

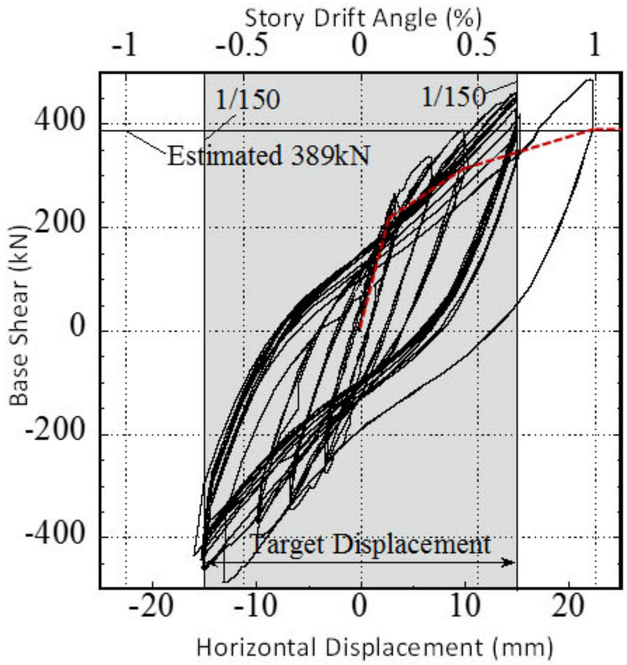
arose in the axial loading system. Maximum loading capacity is quite close to the estimated results obtained from pushover analyses using the material tests performed prior to system testing. Bending failure was observed with the exposure of rebars on the bottom part of RC columns after loading.

Experimental results of RS model (RC frame + steel frame) is depicted in Figure 7-b. RS specimen showed high ductility and the observed cracks were below acceptable limits in width and amount (Maximum crack width: 0.4mm). In the mortar part connecting the RC frame and steel frame, no significant crack was observed until retrofit target drift angle 1/150 (Maximum crack width: 1mm). Small vertical cracks were observed on surface of RC column nearby the steel frame. At 2% story drift angle, significant cracks developed on mortar connection. Bending failure occurred with exposure of rebars at the bottom end of RC columns at ultimate deformation. On the steel frame, tearing of flange welding was observed near the upper and lower corner. Maximum horizontal force was 1.7 times of the estimated result and this could be attributed to the fact of a strong (much stronger than estimated) composite interaction between RC frame and steel frame provided by the connection zone.

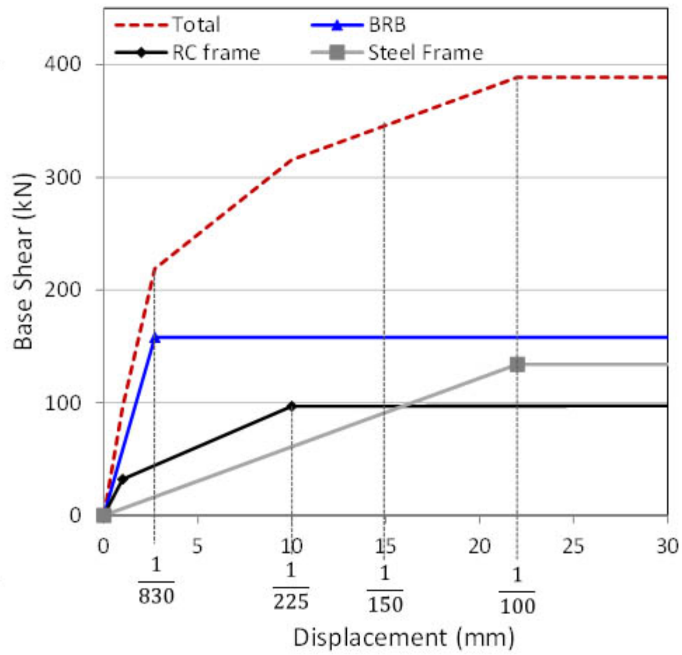
Base shear vs. horizontal drift/displacement hysteretic response of RSB model (RC frame + steel frame + BRB) is illustrated in Figure 7-c and estimated push-over behavior of RSB model including individual components are shown on Figure 7-d. Estimated total behavior plot given in Figure 7-d is also shown on Figure 7-c for comparison. Similar to RS model estimated force neglects the composite interaction and slight disagreement between test results and estimations have occurred. In RSB model, BRB core yielded around 0.15% story drift angle and stable energy dissipation was observed at retrofit target story drift angle 1/150. The energy dissipation performance of RSB model was higher than that of RS model. At story drift angle of 0.3%, cracks occurred around the surface of RC columns near the BRB connection zone (Maximum width: 0.7mm) and also on the mortar connection at retrofit target drift angle 1/150 (Maximum width: 0.9mm) although the observed cracks were not significant. Horizontal load bearing capacity of specimen reached approximately to 90% of actuator capacity at 1/150 loading level, therefore, repetitive cycles at target story drift angle were continued and a reliable performance of energy dissipation was observed until 9th cycle at this drift level. Testing was terminated at 1% story drift level as the actuator loading capacity was exceeded.



(a) (b)



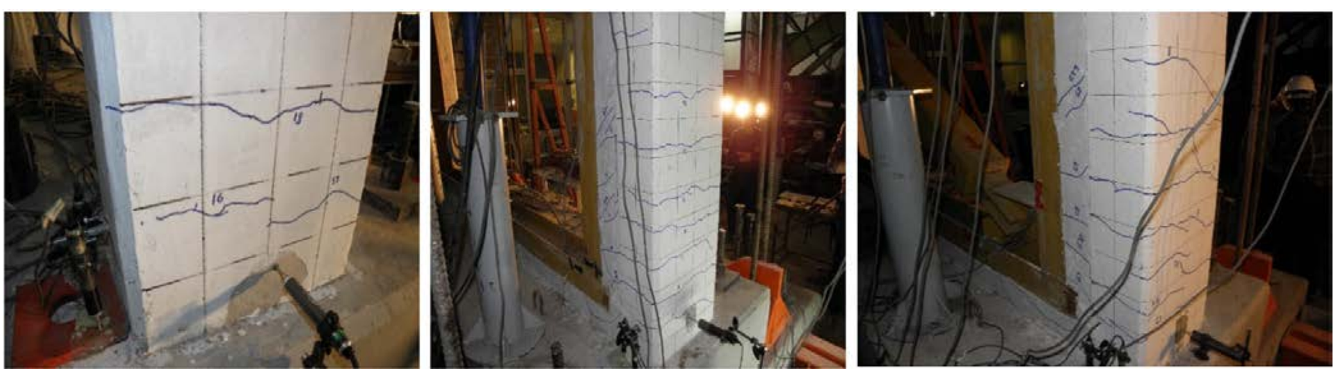
(c)



(d)

Fig. 7. Load versus drift responses of (a) R model: Bare RC frame (b)RS model: RC frame with steel frame (c) RSB model: RC frame with steel frame and BRB (d) Estimated push-over behavior of RSB model.

Photos in Fig. 8 show the observed damage at North column bottom end at target story drift of 1/150. While concrete spalling is observed and some concentrated cracks were visible on R specimen, the distributed plastic hinge (or distributed plasticity) on RC members of RS and RSB models is obvious. Also, increase in lateral strength of the retrofitted frames for the same story drift levels is also clearly shown in Fig. 7.



(a) R specimen (b) RS specimen (c) RSB specimen

Fig. 8. Damage at North column bottom end at retrofit target story drift angle (1/150)

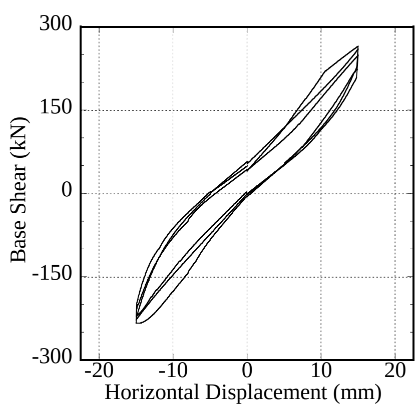
4. Dissipated Energies and Comparison

Dissipated energies give useful information about hysteretic performance of the tested specimens. A bare RC frame is supposed to dissipate energy with two potential mechanisms. The first mechanism is the structural inherent damping (or structural viscous damping) and the second is the hysteretically damped energy. In this test program, the cyclic loading was quasi-static and due to lack of velocity, structural inherent damping is not observed. However, the hysteretically damped energy is the simple mechanism derived from the stiffness degradation of frame and the applied displacement. Hysteretically damped energy which is the enclosed area in the cyclic behavior is simple visible in the R specimen test results (Fig. 7-a).

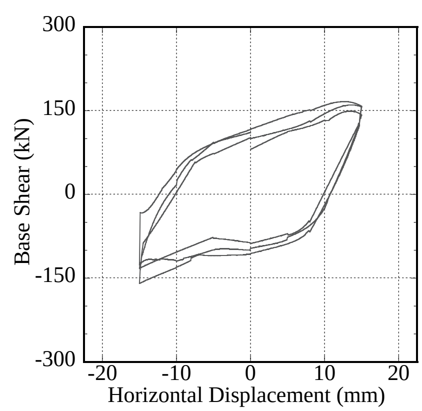
The steel frames used in RS and RSB specimens are designed to remain elastic, however, this is an ideal condition and there will be energy dissipation in the mortar interface connecting the steel frame and the RC frame as well as the steel frame itself. Although it is quite difficult to evaluate the amount of dissipated energy in the connection zone through mortar cracks and possible yielding in the studs and ladder re-bars, the specimens designed for this study allow to determine the dissipated energy in the mortar by simply calculating the difference between RS and R specimens. Fig. 9-a shows the load-displacement behavior of mortar connection and steel frame which is obtained by simply subtracting the behavior of R specimen from RS specimen for three cycles of 1/150 story drift. By using a similar approach, the load displacement behavior and therefore the hysteretically dissipated energy by the BRB can be evaluated by differentiating the RS and RSB specimen test results (Fig. 9-b).

The results obtained in Fig. 9-a shows that the mortar connecting RC frame and steel frame displays a stable behavior and dissipates energy constantly. These results can be used in the design of the mortar connection zone and to define the composite behavior of RC and steel frame analytically. Authors of this paper intend to develop a method for the analytical design of RSB model including the composite effect. The results shown in Fig. 9-b shows good correlation between the designed BRB behavior and the observed results.

The dissipated hysteretic energies in each cycle and the cumulative energy dissipation up to the retrofit target story drift is shown in Fig. 10-a and 10-b. As presented in the figures and as expected, the amount of dissipated hysteretic energy is the largest in RSB model compared to RS and R models at same drift levels. For example, the cumulative dissipated energy for RSB model is 3 times and 20 times larger than that of RS model and R model, respectively.

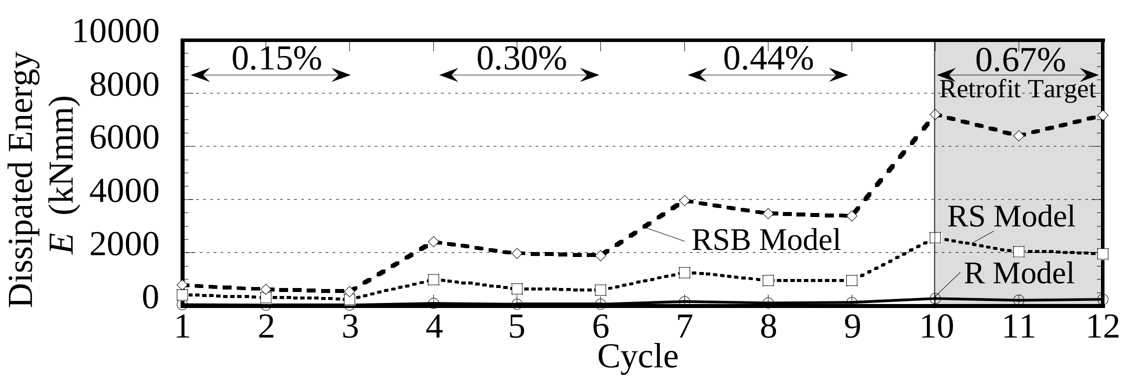


(a) Steel Frame + Mortar Connection (=RS – R)

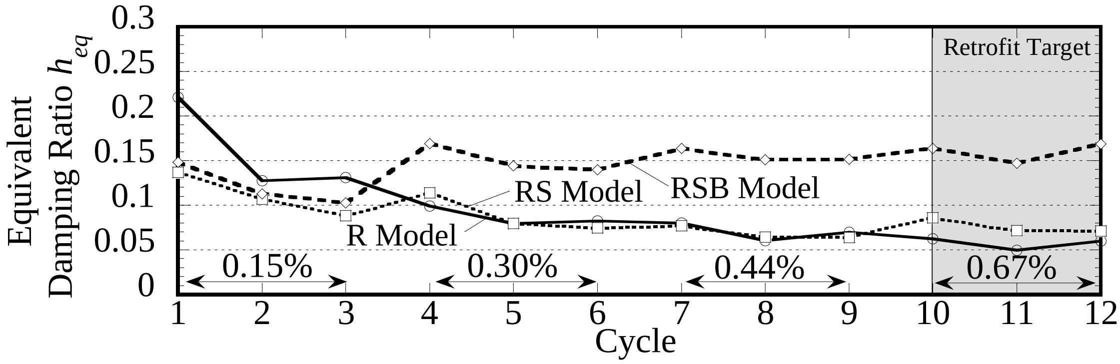


(b) BRB (=RSB – RS)

Fig. 9. Load-displacement relationships of steel frame and BRB at target story drift cycles (1/150)



(a)



(b)

Fig. 10. Comparison of energy dissipation (until retrofit target story drift angle of 1/150)

Equivalent damping ratio, h_{eq} is also a useful information for evaluating the seismic effectiveness of a retrofit scheme and calculated for each cycle of tests up to the retrofit target story drift level as shown in Fig. 11. Equivalent damping ratio can be defined with the widely used following equation:

$$h_{eq} = \frac{E_p}{4\pi E_e} \tag{1}$$

where E_p is the energy dissipated by the hysteretic behavior and calculated from the loop area of each cycle and E_e is the elastic strain energy of each cycle that is obtained at the maximum displacement of that cycle (Fig. 11). Evaluation of equivalent damping ratio is not stable for relatively small story drift ratios as the hysteretic energy is almost zero during small drifts, however after 0.30% story drift (3/1000) h_{eq} is stable. h_{eq} for RSB model is approximately 17% which is almost 3 times that of RS and R models.

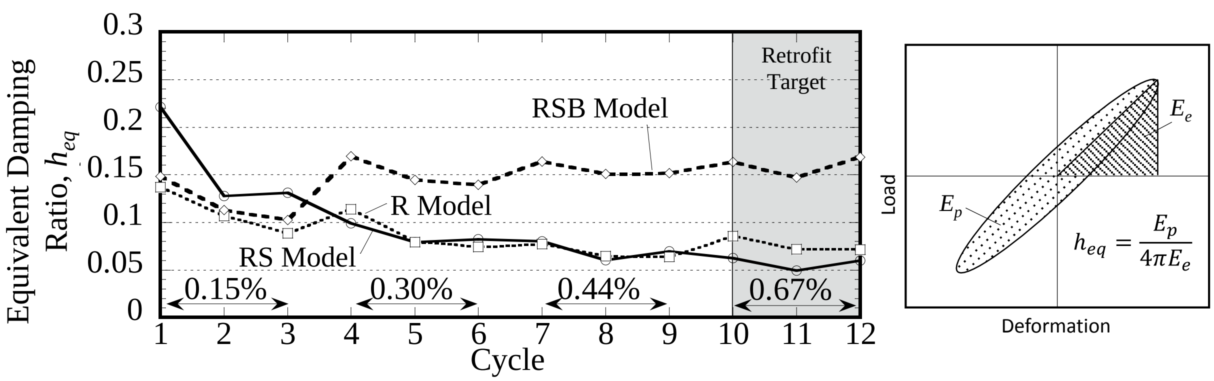


Fig. 11. Comparison of equivalent damping ratio (until retrofit target story drift angle of 1/150)

5. Conclusions

The following conclusions can be drawn from this experimental work:

1) Observed strength of the RC bare frame (R specimen) was almost the same as the estimated value. The RC frame displayed a very ductile behavior until 4% story drift angle. Collapse mechanism was determined by the bending failure of columns as estimated.

2) The retrofit target story drift angle was taken as 1/150. It was shown that the addition of steel frame to RC frame (RS) improved the structural performance significantly. At the retrofit target story drift, no significant structural damage was observed on RSB specimen. The lateral strength of RS and RSB specimens has increased by 6 and 9 times when compared to the bare frame’s values.

3) At the retrofit target story drift angle, the amount of energy dissipation of the RSB specimen was about 3 times higher than that of the R and RS specimens. No global or local buckling occurred in the BRB used in RSB.

4) Until retrofit target story drift, strain levels on the most parts of the steel frame was less than the yield strain. This proves that the closed steel frame remained elastic within the target limits as designed.

5) The strains on re-bars of RC frame were also monitored during the tests. Although some readings have exceeded the yield limits, the structural integrity was kept with minimum cracks and the specimen displayed very ductile behavior.

6) The tests show that the proposed retrofit method is feasible and increases strength as well as ductility to an adequate seismic performance level. These tests have also proven that the steel frame remains elastic up to a target retrofit level which may enhance the self-centering properties of such a retrofit scheme after a major earthquake.

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