論文 / 著書情報
Article / Book Information

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Pub. date	2020, 9
Citation	2020 17WCEE Proceedings

Comparing Hysteretic Behavior of RC Frames Retrofitted with Low-Yield-Point (LYP) Steel Core BRB and Perforated Steel Plate Shear Wall (PSPSW)

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Abstract

This paper aims to compare effective retrofitting methods for existing reinforced concrete (RC) buildings using updated response control techniques. The study presents results of a near full-scale experimental study of sub-standard RC frames retrofitted with both steel core buckling restrained braces (BRBs) and thin perforated steel plate shear walls (PSPSWs). Older public buildings with higher importance factors like schools and hospitals do not satisfy the up-to-date code requirements generally lack strength, stiffness, and ductility and typically require retrofitting to enhance their seismic performance. BRBs functioning as metallic hysteretic dampers are new generation bracing systems developed both for existing or new buildings and bridges, and provide an increase in structural integrity and reduce seismic demands through stable energy dissipation until core fracture. Closed steel frames (SF) designed to remain elastic within the target limits are preferred to provide an efficient/distributed load transfer between the BRBs and RC frame. The proposed solution helps preserve the lateral stiffness while enhancing self-centering capability of the frame especially at inelastic cycles. As an alternative method and for comparison, this paper also investigates a possible retrofit concept, which features a combination of PSPSW and closed steel frames.

In the experimental program, the RSB specimen which is an RC frame retrofitted by BRB with the core material having a low yield point steel (LYP225) is investigated firstly. The BRB is attached to the SF with welded end connections at the gusset plates. Steel frame is connected to the RC frame by using a specially designed joint consisting of chemical anchors on RC frame, shear studs on SF, and ladder stirrups for controlling cracks in the grout. The joint between the SF and RC frame is finally filled with high strength grout to provide a strong composite action for the full transfer of loads caused by the yielding of the BRB core. RSP specimen, which implements PSPSW as retrofit member, used the same joint detail with RSB specimen for a better comparison. In the RSP specimen, PSPSW with circular perforations having a diameter of D=300mm spaced at 400mm diagonal distance were designed to develop an appropriate tension field action in the specimen. Both specimens showed stable hysteretic behavior without fracture up to 1/150 story drift (0.67%), designated as the 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 for both specimens. Dissipated energies per volumetric steel material used and inelastic demands placed on the RC frame for both specimens are also given for a better comparison. These tests show that PSPSWs and BRBs increase ductility to an adequate seismic performance level while controlling damage at a minimum.

Keywords: Buckling restrained braces; seismic retrofit; perforated steel plate shear wall; composite action; cyclic loading tests

1. Introduction

Effective seismic retrofitting methods for existing RC buildings have become one of the main focus of earthquake engineering research and practice. There are many existing RC buildings that do not provide sufficient conditions for the current code requirements as these buildings have insufficient strength, stiffness, and ductility. Especially, older public buildings like schools and hospitals typically require retrofitting to enhance structural performance during an earthquake. For this reason, seismic performances of existing RC buildings need to be re-assessed for determining structural measures to be taken and thus to improve their behavioral values. While retrofit methods using conventional steel 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. Some improvements in cyclic behavior of round HSS steel braces could be obtained when carbon fiber reinforced polymer (CFRP) sheets are used to delay local buckling [1]. Retrofitting with Buckling Restrained Braces (BRBs), as a new generation bracing system, provide an increase in structural integrity and reduce seismic demands through energy dissipation [2]. 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. Furthermore, steel braces are lighter when compared to RC shear walls and strength and ductility can be adjusted specifically for each project following the project specific constraints. As an alternative method to others, this paper additionally investigates a retrofit concept, which features a combination of perforated thin steel plate shear wall (PSPSW) and elastically designed closed steel frame where PSPSW is expected to reduce seismic demands in existing frames through energy dissipation.

Once sufficient anchorage and properly designed connection detail are 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 [3]. Conventional (i.e 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 global and local slenderness ratios and usually it is necessary to specify large cross sections in order to avoid/delay buckling failure. 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 [4]. Meanwhile, BRBs were developed in Japan in early 1980's and the first application in an actual building was reported in 1990 [5]. BRBs represent an ideal combination of structural retrofit member as axially yielding dampers that function as structural fuses. The basic principles and working mechanism of BRBs have been well documented [6, 7]. Recent studies investigated BRBs in detail, both analytically and experimentally at the component level [8, 9]. Moreover, the sub-assemblage level investigation of BRBs is also handled in detail [10, 11, and 12]. To date, research on BRBs has mainly focused on the application to steel structures while 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 [13, 14, and 15]. In some experimental studies, BRBs are directly connected to RC frames without implementing a steel frame. Post installed connection details such as pre-loaded ties or anchors are used in such retrofit applications [16, 17 and 18]. One of the earliest applications of BRBs for retrofitting an existing RC building is reported in 2006 [19]. 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 presents near full-scale cyclic tests on RC frames retrofitted with BRBs and PSPSW. Special emphasis is paid on sub-standard school buildings in Turkey. The proposed retrofit method requires an elastically designed closed steel frame installed in the RC frame. Subsequently, the infill such as BRB or PSPSW is attached through this steel frame. The performed cyclic 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 BRB or PSPSW to RC elements.

2. Outline of Experiments

This experimental program includes two specimens as follows: RSB model (RC frame with attached BRB and steel frame) and RSP model (RC frame with attached PSPSW and steel frame). In Figs. 2 and 3, structural details of RSB and RSP models are shown.

Near full-scale RC frames have been manufactured in Turkey representing a low-standard school building. The RC frame is designed based on the existing school building stock representing the design of 1990's in Turkey where the scaling factor is approximately 80%. The scaling is used to fit the test facility dimensions and load capacity limits. Material grades for RC frame concrete and rebars are C20 (fc≈20MPa) and S420 (fy≈420MPa), respectively.

BRB members used in the tests have been manufactured in Japan and transported to Turkey while the perforated steel plate infill has been produced locally in Turkey. 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 as shown in Fig.1. The performance target was to obtain a more ductile RC frame behavior with minimum (or controlled) seismic damage.

(a) (b)

Fig. 1 - General view of (a) RSB model and (b) RSP model test set-up.

The proposed retrofit method requires an elastically designed closed steel frame installed in the RC frame and then BRB or PSPSW is attached to the system through the steel frame (Figs. 1, 2 and 3). For the connection of the steel frame and RC frame, post-installed chemical anchors are used on RC frame members. The steel frame has headed shear studs on the relevant interface (Fig. 2). 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 [20]. High strength mortar with a characteristic strength of 80MPa was used in connecting the steel and RC frames. Design of the RC frame, rebar ratios, and placement in RC frame follow the seismic code effective in 1990's [21,22].

Design of the BRB used for RSB specimen follows an equivalent linearization method where the spectral response is modified according to the stiffness and equivalent damping. The BRB design is considered in terms of the ratio of BRB stiffness to the initial stiffness of RC frame (K^{BRB}/K_0^{RC}) although the final design depends on the stiffness of each component at the target displacement, which is extensively explained in previous publications by Sutcu et al. [23] and Takeuchi et al. [24]. As for reference, in this study, the K^{BRB}/K_0^{RC} ratios for RSB specimen is 2.6. The BRBs used in the experiments are composed of a 50mm x 12mm, LYP225 grade steel core and 175x175x4mm STKR400 grade steel square restrainer tube.

RSP specimen includes retrofitting with PSPSW infill. The yield strength of a solid panel V_{yp} is calculated as

$$V_{yp} = \frac{1}{2} F_{yp} \cdot t \cdot W_{panel}\, Sin2\alpha \tag{1}$$

where F_{yp} is panel yield strength; t is panel thickness; W_{panel} is panel width, and α is inclination angle of the tension field force with respect to the vertical. Perforation is expected to decrease the yield strength and stiffness of the panel while reducing seismic demands in the RC frame. It had earlier been proposed that the strength of a perforated panel $V_{yp.perf}$ could be conservatively approximated by applying a linear reduction factor to the strength of a solid panel V_{yp}, with same overall dimensions [25]. The proposed reduction was developed from a single holed panel.

Purba and Bruneau [26] performed experimental and numerical analyses on the yield strength of diagonally multi-perforated steel panels. For simplicity, linear regression was applied on a new proposed equation as follows:

$$V_{yp.perf} = \left[1 - \alpha \frac{D}{S_{diag}}\right] V_{yp} \tag{2}$$

where α is a proposed regression factor that is equal to 0.70. Other parameters are $V_{yp.perf}$: strength of the perforated panel, V_{yp}: strength of the solid panel, S_{diag}: diagonal band width, D: diameter of perforation. The equation matches within 5% on average the actual data series. This proposed equation is only valid for a wall with a regular grid of uniformly distributed holes covering the entire plate surfaces, as shown in Fig. 3. The equation has been validated for geometries having D/S = 0.12 to 0.71. Meanwhile the stiffness of PSPSW is also reduced by the perforations compared to solid panels. The ratio of stiffness reduction is obtained by the following equation, which is proposed by Vian et al. [27]:

$$\frac{K_{perf}}{K_{panel}} = \frac{w_{eff}}{S_{diag}} = \frac{1 - \frac{\pi}{4} \cdot \left(\frac{D}{S_{diag}}\right)}{1 - \frac{\pi}{4} \cdot \left(\frac{D}{S_{diag}}\right) \cdot \left(1 - \frac{N_r \cdot D \cdot Sin\theta}{H_{panel}}\right)} \tag{3}$$

in which K_{perf}/K_{panel} is the effective panel stiffness reduction, w_{eff} is effective width of a perforated diagonal infill panel strip, H_{panel} is the total height of steel panel, N_r is the number of rows, and θ is orientation angle of a perforated strip with respect to the horizontal. The PSPSW used for the experimental studies of this paper is designed by Eqs.1 and 2 in order to stay within the test set-up limits. A regular perforation pattern having D=300mm diameter circular openings spaced at 400mm diagonal distance is used. Thickness of the unstiffened thin plate manufactured from S235JR steel is taken as t=0.8mm. The specimen having multiple openings specially laid out in the steel panel, has also the characteristic of reduced panel strength and stiffness compared to the corresponding a solid panel that would have created larger seismic demands on the existing frame. Material Properties for the BRB and the steel frame are given in Table 1.

Table.1 Material characteristics of BRB core, restrainer tube, steel plate shear wall, and steel frame.

Steel Member	Type of Material	Yield Stress (MPa)	Tension Stress (MPa)
BRB Core Plate	LYP225	235	305
Restrainer Tube	STKR400	381	467
Panel (t=0.8mm)	S235JR	235	360
Steel Frame H-175×175×7.5×11	SM490	402	529

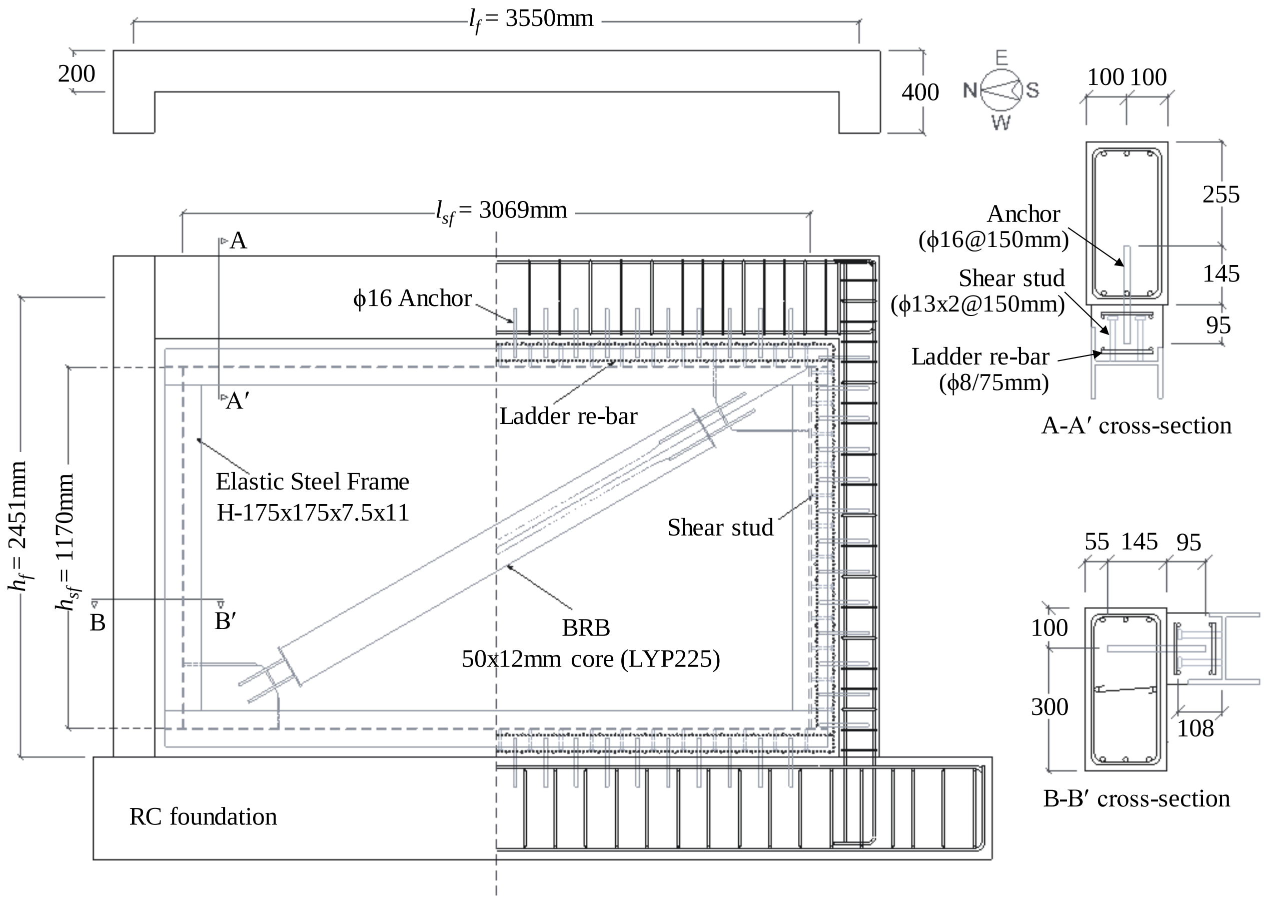


Fig. 2- Structural details of RSB model.

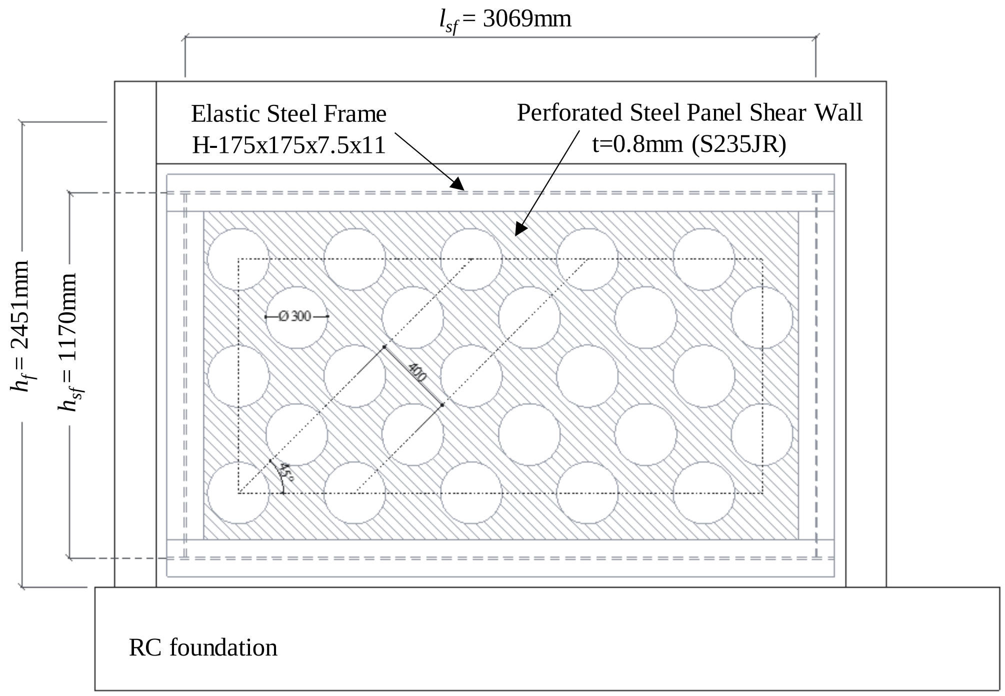


Fig. 3- Structural details of RSP model and perforation layout.

Production stages of RSP specimen are shown in Fig. 4.

(a) (b) (c)

Fig. 4 – Production of RSP specimen (a) Spot welding of segments (b) Horizontal configuration (c) Vertical configuration before grouting

All specimens were instrumented using many LVDTs and strain gauges for detailed measuring of the tests. Fig.5 and Fig.6 show the layout of the instrumentation. A special displacement based, increasing reversed cyclic loading protocol is developed for this test program and shown in Fig.7. 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). 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 added since this drift limitation is proposed in many international seismic codes which corresponds to life safety (LS) performance level for such buildings. 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.

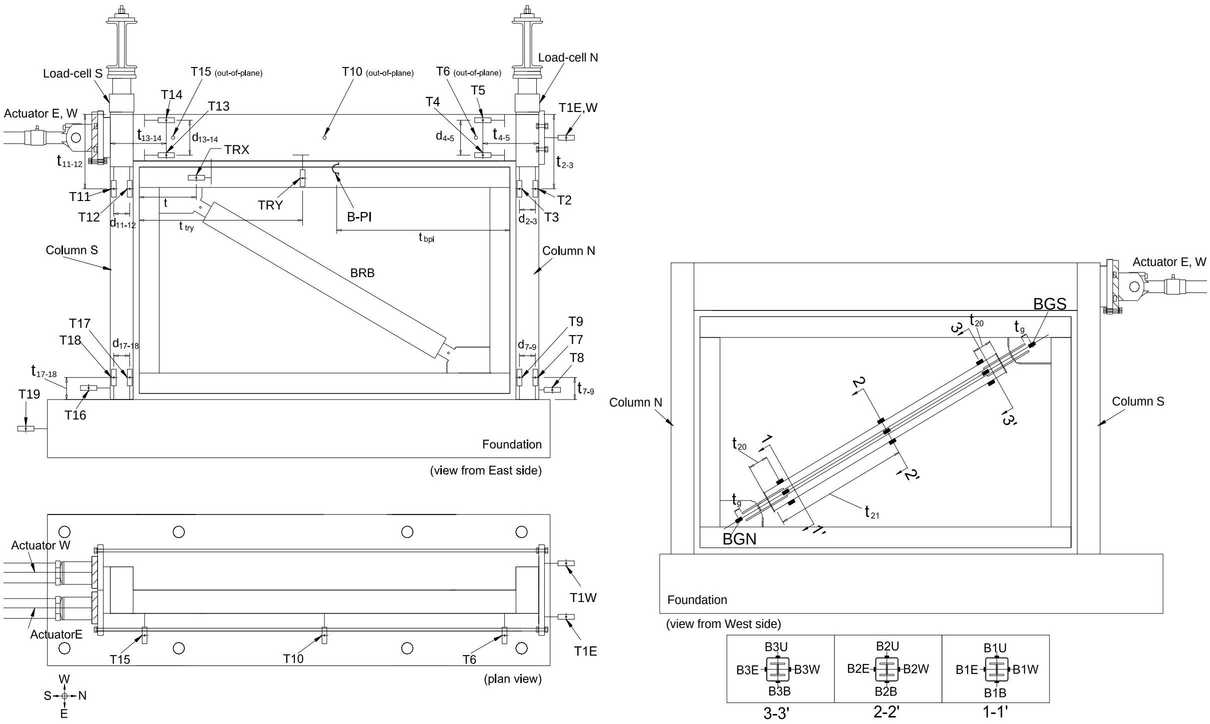


Fig. 5- Instrumentation for RSB specimen including the devices for RC frame (strain-gauges and LVDTs).

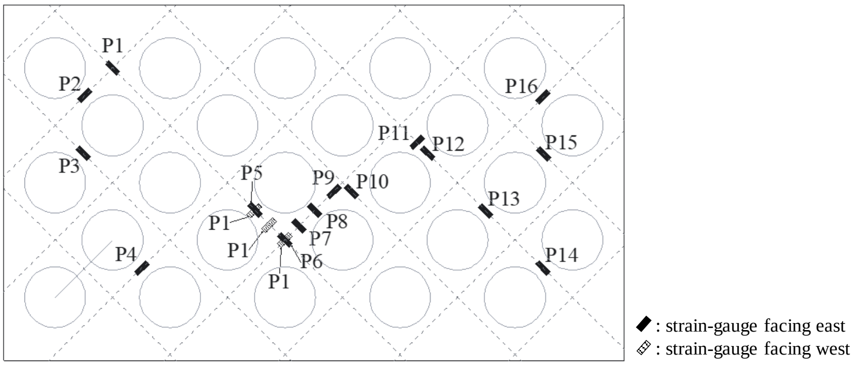


Fig. 6- Instrumentation for the perforated panel shear wall of RSP specimen (strain gauges).

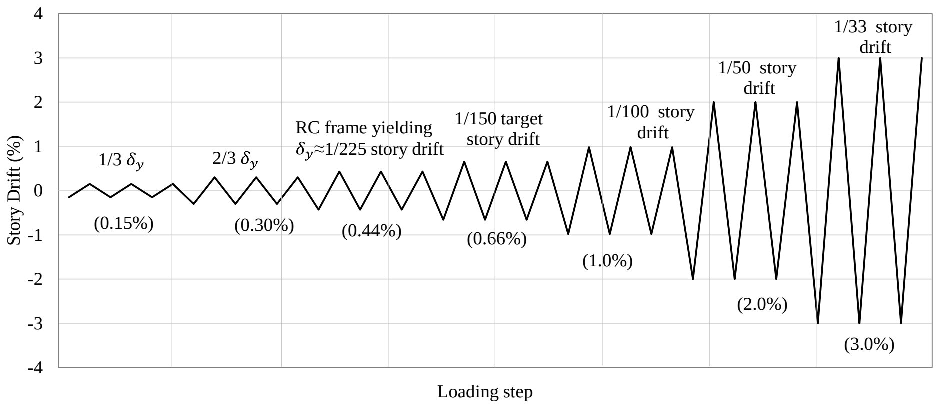


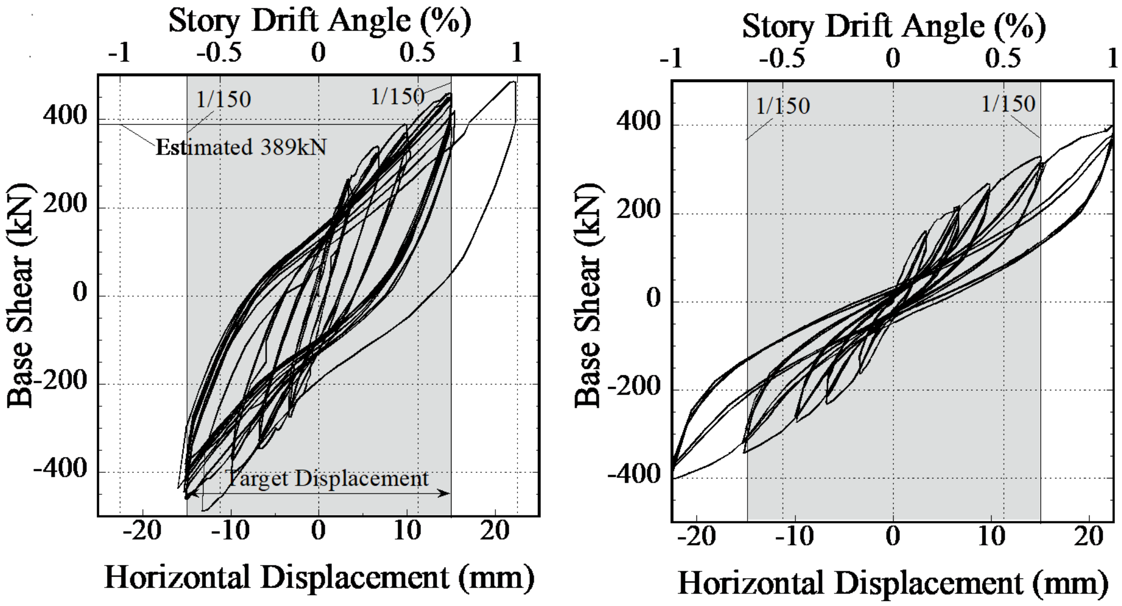
Fig. 7 - Loading Protocol

3. Experimental Behavior of Specimens

Test results for both specimens up to 1% drift level are shown in Fig. 8 in terms of horizontal load versus displacement (and story drift angle). Base shear vs. horizontal drift/displacement hysteretic responses of RSB and RSP models reveal that RSB possesses fuller hysteretic response with higher stiffness and strength when compared with RSP. More pinching is observed in the hystereses of RSP although the curves are stable and symmetrical.

Figure 8(a) shows the hysteretic response of RSB model. The BRB core yielded at around 0.15% story drift and exhibited stable energy dissipation through the retrofit target of 1/150 story drift. Energy dissipation was significantly enhanced compared to a bare RC frame behavior. Small cracks were observed at the surface of the RC columns near the BRB connection zone at 0.3% drift (Maximum width: 0.7mm) and at the mortar connection at 1/150 drift, (Maximum width: 0.9mm). As the horizontal shear reached 90% of the actuator capacity at 1/150 drift, testing was continued at this level to reach a total of 9 cycles at the target story drift, confirming stable energy dissipation. The actuator capacity was exceeded during the first cycle at 1% drift. The strength exceeded the estimated capacity due to strong composite interaction between the RC and steel frames.

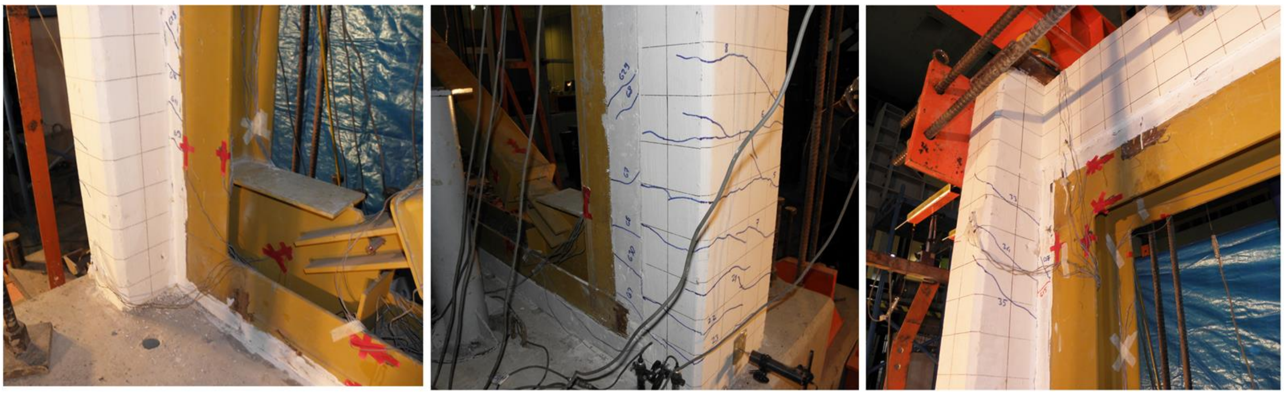
Base shear vs. horizontal drift/displacement hysteretic response of RSP model is illustrated in Fig. 8(b). In RSP model, according to the strain gauge readings, the steel panel yielded at 0.30% story drift angle and stable energy dissipation was obtained until the target story drift angle of 1/150. At target retrofit story drift angle of 0.67%, cracks of approximately 0.8mm width occurred around the surface of RC columns near the column-to-foundation connection zone. In addition, some minor cracks were observed on the mortar/interface connection. Tests were carried up to 2% story drift angle where the cracks opened up to 3mm in width although no tearing was observed in the panel and its welded connections.



(a) (b)

Fig. 8 – Load versus drift responses of (a) RSB, (b) RSP specimens.

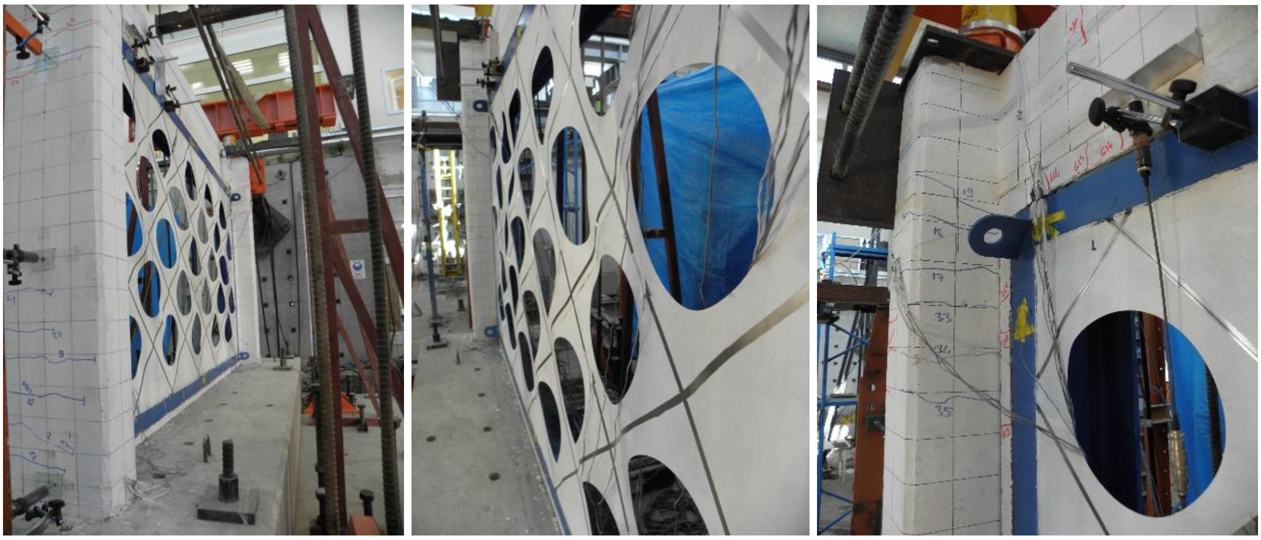
Photos in Fig. 10 show the observed damage in RSB specimen at target story drift of 1/150. Some cracks were visible on RSB specimen, the distributed plastic hinge (or distributed plasticity) on RC members of RSB models is obvious.



(a) (b) (c)

Fig. 10 - Damage in RSB specimen at retrofit target story drift angle (1/150) (a,b) Column-foundation connection regions (c) Beam-to-column connection region

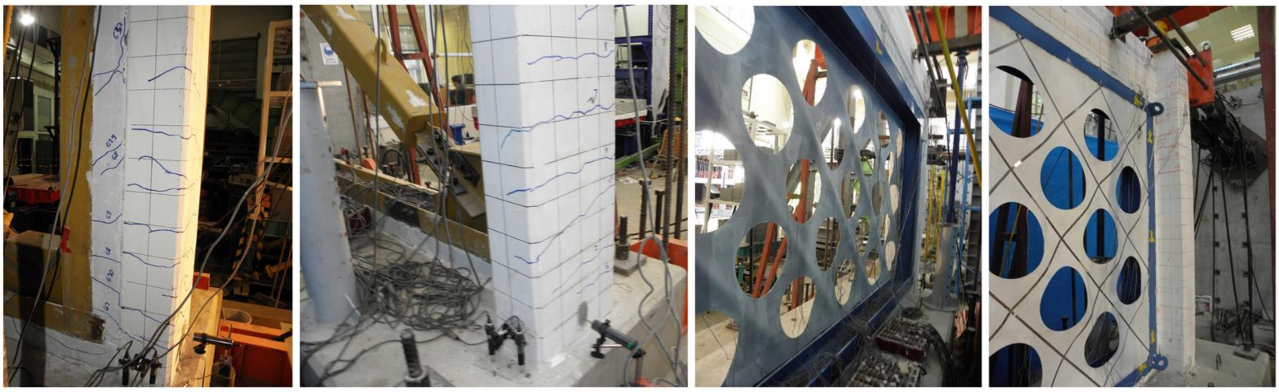
Photos in Fig. 11 show the observed damage of RSP specimen at target story drift of 1/150. Cracks were visible on the columns of the RSP specimen. Similar to the RSB specimen, the distributed plastic hinge on RC members of RSP models is also observed although the cracks were a bit narrower mainly from reduced demands on the RC columns. As per the design intent, the infill buckled significantly in one direction while developing a tension field in the other.



(a) (b) (c)

Fig. 11 – Observed damage in RSP specimen at retrofit target story drift angle (1/150) (a) Column-foundation connection region (b) Buckled shape of infill plate (c) Beam-to-column connection region

Fig. 12a shows the damage state and crack patterns at column ends in RSB specimen at story drift of 1%. No significant cracks were detected at the retrofit target story drift angle of 1/150 (maximum crack width: 0.75mm). Fig. 12b shows the observed damage in RSP specimen at story drift of 1%.



(a) (b)

Fig. 12 - Damage at (a) RSB and (b) RSP specimens at %1 drift

Dissipated energies provide useful information about hysteretic performance of the tested specimens. A RC frame is supposed to dissipate energy with two potential mechanisms: The first one is the structural inherent 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 was not observed. However, the hysteretically damped energy is the simple mechanism derived from the stiffness degradation of frame and the applied displacement. The dissipated hysteretic energies and the equivalent damping ratios in each loading cycle up to the retrofit target story drift is shown for RSB and RSP specimens in Figs. 13 and 14, respectively. As presented in the figures and as expected, the amount of energy dissipation of the RSB specimen was about 2 times higher than that of the RSP specimen.

Although, if the amount of dissipated energy per volumetric steel materials is calculated, BRB and PSPSW yields similar results. This result is obtained considering all steel components of BRB including gussets and restrainer tube, and in energy calculation, the energy dissipated by RC frame and the mortar zone is deducted [2].

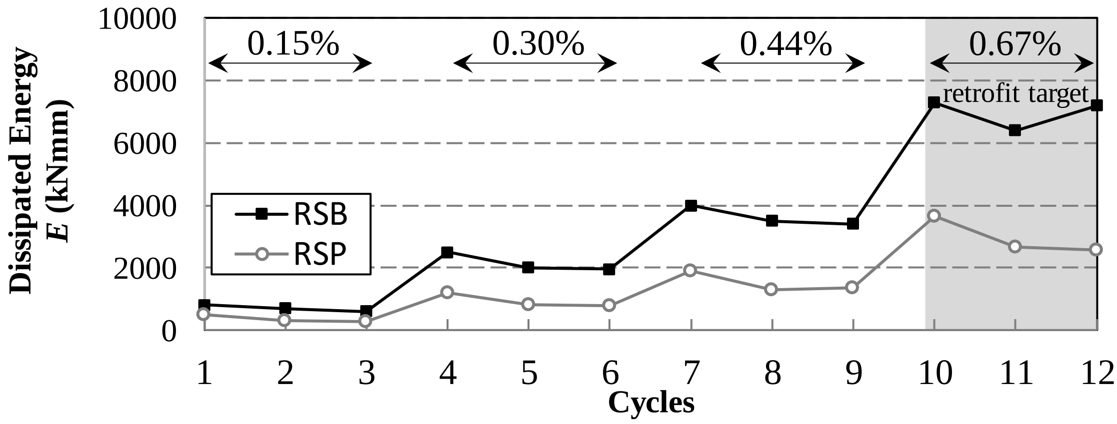


Fig. 13 - Dissipated Energy at each cycle for RSB and RSP specimens

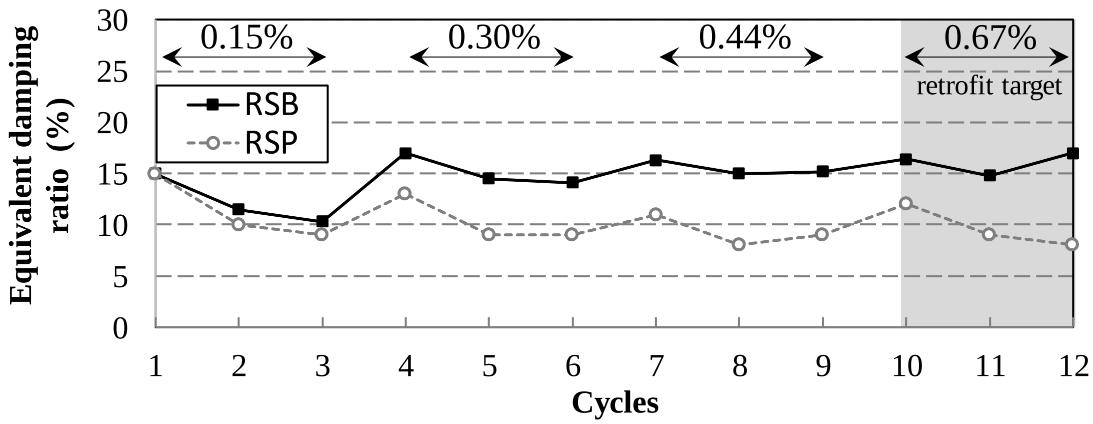


Fig. 14 - Equivalent Damping Ratio at each cycle for RSB and RSP specimens

4. Conclusions

The following conclusions can be drawn from this comparative experimental work:

1- The retrofit target story drift angle was taken to be 1/150 as proposed in the Japanese Code. At the retrofit target story drift, no significant (i.e. reparable) structural damage was observed both on RSB and RSP specimens.

2- The lateral strength of RSB and RSP specimens are very close to each other as per the design intent. At the retrofit target story drift angle, the amount of energy dissipation of the RSB specimen was about 2 times higher than that of the RSP specimen. However, the amount of dissipated energy per volumetric steel material is quite similar. No global or local buckling occurred in the BRB used in RSB specimen.

3- At inelastic cycles, hysteretic damping values are obtained to be around 15% and 10% for RSB and RSP specimens, respectively. More pinching is observed in the hystereses of RSP although the curves are stable and symmetrical.

4- Demands placed on RC frame are smaller in RSP specimen than the ones in RSB specimen.

5- Cyclic test results of the specimens with BRB and PSPSW infills show that the both proposed retrofit methods are feasible and increase strength as well as ductility to an adequate seismic performance level.

6- According to strain-gauge readings, these near full-scale 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.

5. Acknowledgments

The invaluable assistance of ITU-STEEL laboratory personnel is greatly appreciated. BRB specimens and steel frames were kindly donated by Nippon Steel & Sumikin Engineering (Japan). RSP and RSB frames are constructed by Emek Prefabrik Yapi Elemanlari Sanayi (Turkey). HILTI kindly provided anchor bars used in the RC frames. However, any opinions, findings, conclusions, and recommendations presented in this paper are those of the authors and do not necessarily reflect the views of the sponsors and other people.

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