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Shaking Table Test of BRB Strengthened RC Frame

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Executive Summary

Seismically deficient reinforced concrete (RC) frame structures exist in different parts of the world. Although various methods of seismic retrofitting of frames structures are available, buckling restrained bracing (BRB) provide a convenient alternative method. The application of BRB for RC frame structures is not investigated thoroughly in the existing literature. This report presents the details of shaking table tests of a seismic resistant BRB strengthened RC frame. A 1/3rd model of the prototype frame was employed for this testing programme. A similar frame without retrofit was used as a control specimen. The objective of these tests was to observe and compare the performances of both types of frames after they were subjected to varying levels of earthquake ground excitations. The model frames were subjected sequentially to ground motions corresponding to different levels of the 1988 Kobe earthquake acceleration time history. These levels were varied from 25% to 500% in increment of 25% of Kobe ground motion. The performances of the models were monitored after the application of each earthquake event.

The observed performance of the BRB strengthened frame was found satisfactory. The frame was able to withstand earthquake forces up to 500% of Kobe ground motion with minor level of damage. In contrast, the control frame was heavily damaged and was near collapse at this level of earthquake excitation.

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1 Introduction

A significant building stock in Pakistan and other parts of the world consists of seismically deficient building structures. These buildings pose a serious threat to human lives. Life and property losses have been witnessed after recent earthquakes in Pakistan such as 2005 Kashmir earthquake, 2013 Mashkel earthquake, 2013 Awaran earthquake and 2015 Afghanistan earthquake. Being a natural hazard, earthquakes cannot be prevented or controlled. However, the risk to damages can be reduced by effective mitigation efforts. A resilient built infrastructure helps great deal in achieving this objective.

Reinforced concrete (RC) frame construction is a prevalent construction type in different parts of Pakistan and elsewhere. These buildings are long lasting in many conditions and in conducive environment, and are considered a better construction type in seismic regions. In some cases, the resistance of these buildings may fall short of that required by the design codes. The reasons may include change in occupancy, faulty design or increased force demand suggested by the revisions in the prevalent building codes. These instances require that the capacity of the existing structures is increased by carrying out retrofit which could be designed based on the conditions and requirements of the capacity enhancement.

Concentrically and eccentrically braced frames are used widely for steel construction in seismic regions in different parts of the world. These diagonal bracing members deform inelastically during a moderate to severe earthquake excitation. The capacity of conventional braced frames is controlled by the buckling of bracing in compression which significantly reduces energy dissipation capacity and strength of the frame in compression. As a result, large cross sectional areas are needed to allow the bracing members to yield in compression (without buckling), similar to their behaviours in tension.

Buckling restrained bracing (BRB) provides an alternate of the conventional braces. The development of BRB started in Japan with the work of Watanabe et al. in 1988. These were employed for the seismic strengthening of buildings in Japan after the 1995 Kobe earthquake. The application of BRB in Japan was followed by their use in building retrofitting in USA. BRBs act as hysteretic dampers. The main concept of buckling restraining is to decouple stress resistance of main yielding steel member from the flexural buckling resistance. As a result, BRB reinforced frames yield in both tension and compression without buckling. Main characteristics of BRBs include enhanced energy dissipation, excellent ductility and symmetrical hysteretic response.

The existing designs of BRBs were studied by the University of Ottawa, Canada and an improved design was provided. The development of this design was carried out by Steel Canada Limited (SCL), Canada. In order to assess the dynamic performance of this design scheme, the Department of Earthquake at NED University of Engineering and Technology was engaged by SCL to test the performance of a BRB strengthened RC frame and to compare its performance with a control frame without BRB. The shaking table in the Department of Earthquake Engineering was used to conduct dynamic testing of these frames. The testing of the frames was carried out on 13 May 2017.

2 Construction of Model

One-third scaled models of both types of frames were employed. The design of the frames was provided by University of Ottawa, Canada. The details of the frame are shown in Figures 1-4. The construction of the model followed scientific principles of similitude and dimension analysis. Figures 5-8 show different stages of the model construction.

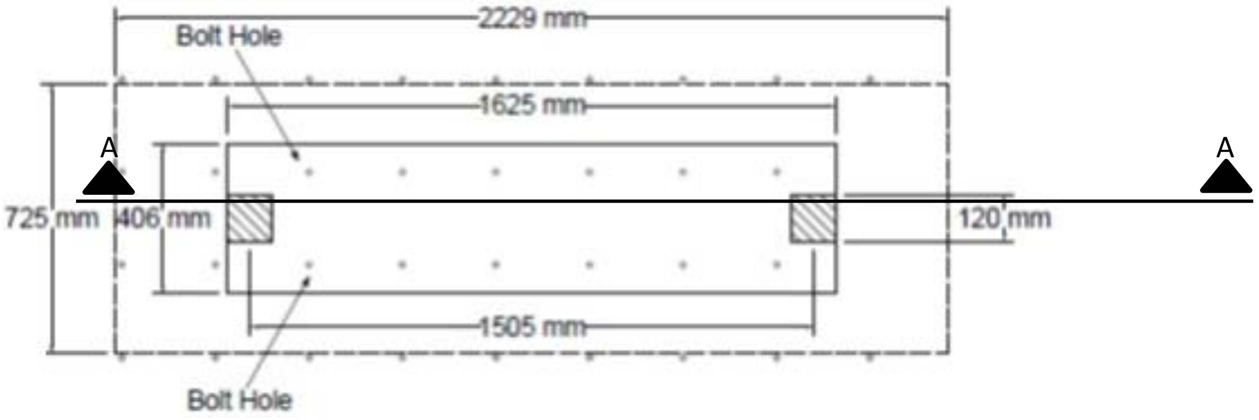

Fig. 1 Plan of typical frame

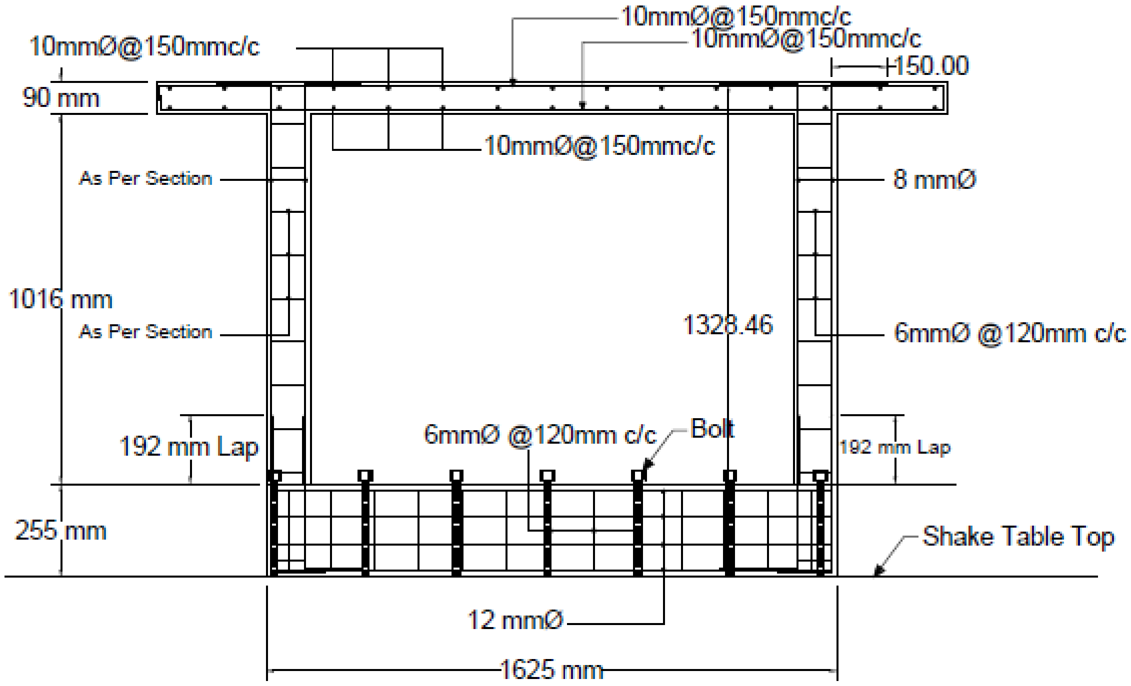

Fig. 2 Sectional elevation of frame (A-A)

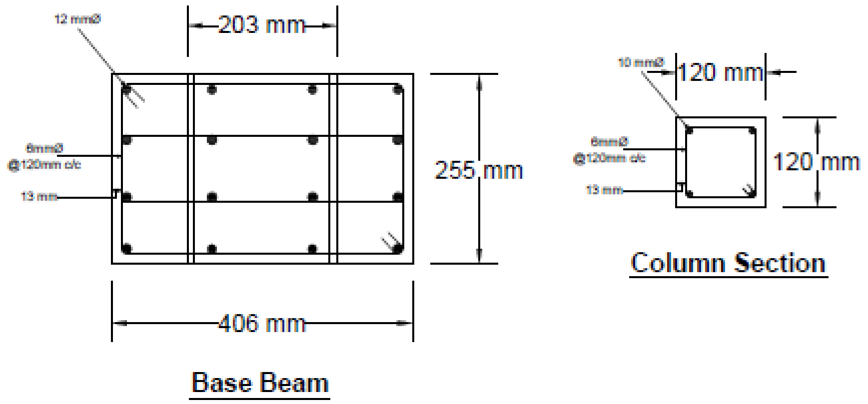

Fig. 3 Reinforcement detail for base beam and column

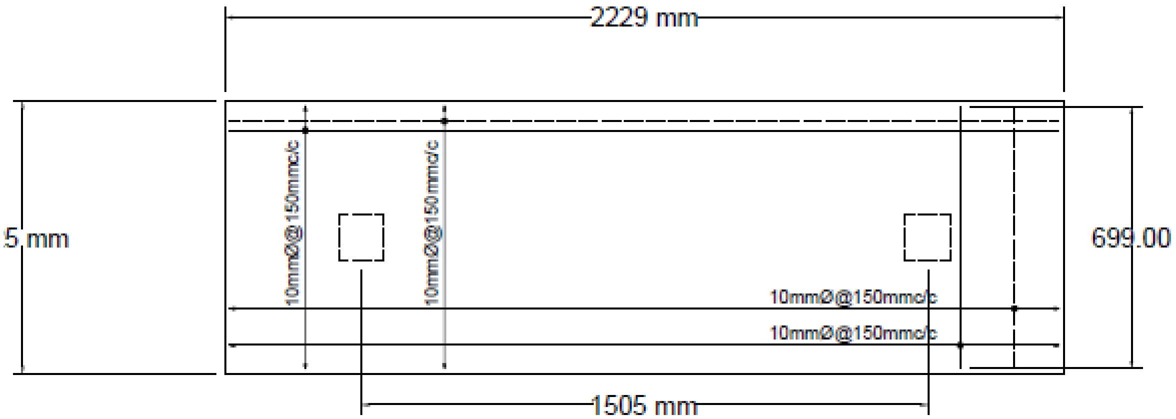

Fig. 4 Reinforcement detail for top slab

Fig. 5 Cutting and bending of steel for frames

Fig. 6 Casting of foundation beam

Fig. 7 Concreting of columns

Fig. 8 Casting of top slab of frames

3 Testing Protocols

The peak ground acceleration record for the 1988 Kobe earthquake was employed to simulate the earthquake ground motion for the models. The duration of this earthquake is 40.9 sec with peak ground acceleration (PGA) 0.34g. Fig. 9 demonstrates ground acceleration (a_g) record and response spectra at 5 percent critical damping of this earthquake. The acceleration record was scaled for the testing of model. The model was subjected to different intensities of a seismic excitation in an incremental fashion. The intensities were varied from 25-500 percent in increment of 25 percent. These records were calibrated prior to the test so that the machine output matches closely with the input time-history record. At the end of each sequence of seismic excitation physical inspection of the model was carried out to assess the damage pattern and photographs were taken. The videos of the tests were continuously recorded from two different angles. PGA values for each dynamic excitation are summarised in Table 1.

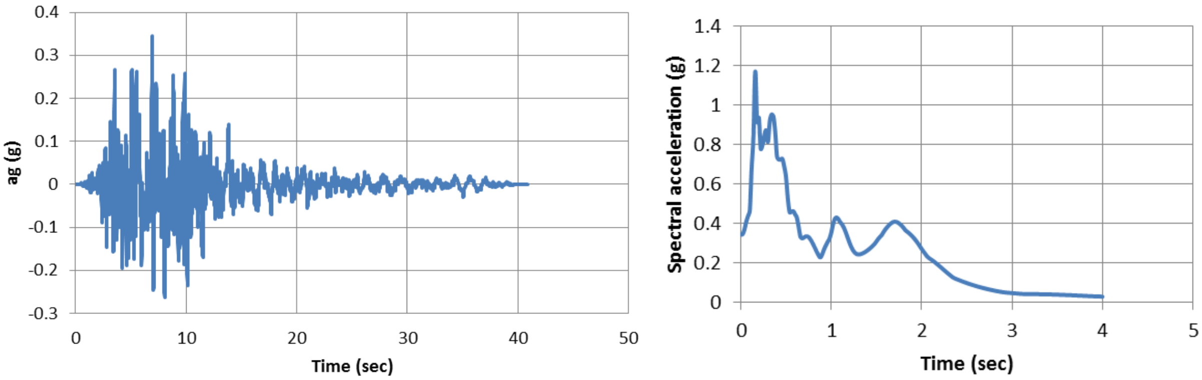

Fig. 9 Acceleration time history record of Kobe earthquake and response spectra at 5 percent critical damping

Table 1. PGA for different test runs

Test run	PGA (g)	Test run	PGA (g)	Test run	PGA (g)
25%	0.076	200%	0.679	375%	1.197
50%	0.177	225%	0.779	400%	1.368
75%	0.221	250%	0.838	425%	1.452
100%	0.324	275%	0.927	450%	1.529
125%	0.418	300%	1.019	475%	1.628
150%	0.516	325%	1.050	500%	1.748
175%	0.631	350%	1.151		1.197

4 Observation and Records

1) No damage occurred to the frames up to 250% level of earthquake and both frames were intact.

2) First crack in the columns appeared at 275% level of earthquake excitation. For the control frame, the flexural crack appeared at the connection of column with the base beam (Fig. 10). A shear crack also appeared in one of the columns of the BRB strengthened frame above the plate of clevis used to connect the BRB end with the column (Fig. 11).

2) A crack in the junction of column and base beam appeared in the BRB strengthened frame in the column where BRB was connected in the top of the column (Fig. 12).

3) The cracks in the columns of the control frame increased with the increase in PGAs of the calibrated records. These cracks concentrated the top and bottom regions of the columns (Fig. 13).

4) The shear crack in the BRB strengthened column opened up with the application of higher PGAs. New cracks, however, were not seen in this frame until 350% level of earthquake excitation when a crack appeared in the column top region where BRB end was connected (Fig. 14). This was the column opposite the column with the shear crack. Another crack in the same column appeared on its opposite face at 375% level of earthquake (Fig. 15).

5) The bars in the columns of the control fame appeared to yield at 350% level of earthquake excitation.

6) A crack in the bottom of the overhanging part of the slab of the control frame appeared at 450% level of earthquake.

7) Another crack appeared with the application of 475% level of dynamic excitation (Fig. 16).

A large piece of concrete in the bottom of the overhanging part of the slab of the control frame broke at 475% level of earthquake (Fig. 17).

7) The control frame appeared to be damaged badly at 500% level of earthquake excitation of the table. Consequently, the testing was stopped at this stage to avoid collapse of the control frame. BRB strengthened frame appeared intact and in good shape at this stage.

Fig. 10 First level crack in the column of control frame

Fig. 11Shear crack in the column of BRB strengthened frame at top of end plate

Fig. 12 Crack at the column-base beam junction in BRB strengthened frame

Fig. 13 Damage zones in column of control frame

Fig. 14 Crack in the column of BRB strengthened frame at 350% earthquake excitation

Fig. 15 Crack in the column of BRB strengthened frame at 375% level of test run

Fig. 16 Cracks in the overhanging part of top slab in control frame

Fig. 17 Damaged portion of top slab for control frame

5 Conclusions

The shaking table test of an earthquake resistant BRB strengthened frame was conducted using the 1988 Kobe earthquake ground motion time history. A similar frame without strengthening was used as control specimen. One-third models of the frames were employed which were simultaneously subjected to increasing levels of the employed time history. The levels applied were varied from 25% to 500% in increment of 25%. At the end of application of each time history, the structure was inspected to observe the damages. No damage to the structure was observed until 250% level of earthquake. Structural cracks in the columns of the frames appeared at 275% level of test run as first sign of damage. The cracks increased with the increase in PGA of earthquake excitation which were concentrated in the top and bottom regions of the columns. The rebars in the columns of the control frame appeared to yield at 350% level of earthquake ground shaking. The control frame became heavily damaged at 500% level of dynamic excitation. On the other hand, BRB strengthened frame appeared to be intact with adequate residual strength and stiffness.

Based on the observations made during the test, it can be concluded that the BRB strengthened frame was able to perform satisfactorily up to an earthquake as large as 500% of the Kobe earthquake.