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In-Plane Quasi Static Cyclic Testing of Reinforced Concrete Frames Retrofitted with Eccentric Steel Braces

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Abstract—*Steel bracing is an effective and economical retrofitting technique for upgrading deficient reinforced concrete moment resisting frames typically found in the developing countries. Steel bracing not only increases the strength, stiffness and energy dissipation capacity of the system but also provide sufficient ductility under an earthquake event. This paper numerically investigates the seismic performance of eccentric steel braces connected diagonally to reinforced concrete beam at a distance of $L_{beam}/6$ from the face of the column. Static time history analysis was performed on a single story reinforced concrete bare frame and eccentric steel brace retrofitted frame using a finite element program. Results showed that frame retrofitted with eccentric steel brace changes the lateral load transfer path and reduces the demands on the most crucial zone beam-column joint and as a result increases the strength, stiffness and energy dissipation capacity of the frame as opposed to bare frame.*

Keywords: *Eccentric steel brace, Seismic upgrade, RC frames, Energy dissipation, Joint damageability.*

I. INTRODUCTION

Reinforced concrete moment resisting frames (RC MRF) are used throughout the world because of the easy availability of concrete ingredients as well as its low cost. However, on the other hand various construction deficiencies exist in RC MRF especially in the developing countries such as low strength concrete than the design strength, providing of reinforcement at larger spacing than the design etc. Various experimental and numerical studies have highlighted the vulnerability of RC MRF structures subjected to earthquake loading [1-5]. Therefore, reinforced concrete structures if not properly design and detailed can lead to damages and even collapse under a major shaking. Thus, it is necessary to retrofit and propose an effective and economical strengthening technique to seismically upgrade deficient RC frames.

In the past various retrofitting techniques have been proposed by researchers for various structural elements such as FRP strengthening, column jacketing, steel haunches. Steel braces are also one of the technique use to enhance the lateral strength, stiffness, ductility and energy dissipation capacity of the system [6-9]. However, studies have been carried out in the past mostly focusing on the concentric inverted V steel braces or X steel braces with very limited research available on the eccentric steel braces (ESB). ESB has some advantages over concentric steel braces such as it provides openings for doors, windows and provides more spacing as compared to X or inverted V type bracing. Similarly, Eccentric steel bracing provides adequate ductility as opposed to other bracing types [10]. Therefore, the objective of this study was to evaluate the seismic performance of deficient RC frames strengthened with eccentric steel braces.

II. DESCRIPTION OF FRAME

Three story reinforced concrete moment resisting frame was considered for the study. Concrete of compressive strength 3000 psi and reinforcement having yield strength of 60,000 psi was considered for both longitudinal and transverse reinforcement. The ground story was selected for retrofitting technique because of being the soft story. The ground story was extracted for non-linear analysis as shown in figure 1. The beam and column cross sections and their reinforcement details are also shown in figure 1.

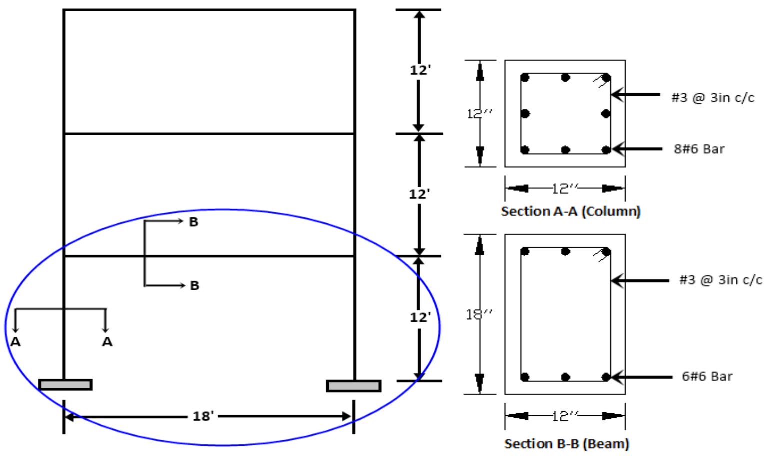

Figure 1. Considered frame geometric and reinforcement details

The selected ground story was retrofitted using rectangular hollow A36 steel section having width and depth (height) of 4 inches and thickness 0.2 inches. The yield strength of the brace was chosen as 36,000 psi. The brace was attached to the beam at a distance of $L_{beam}/6$ i.e. the centerline of brace intersects the beam at a distance of $1/6^{th}$ of beam length from the face of the column as shown in figure 2.

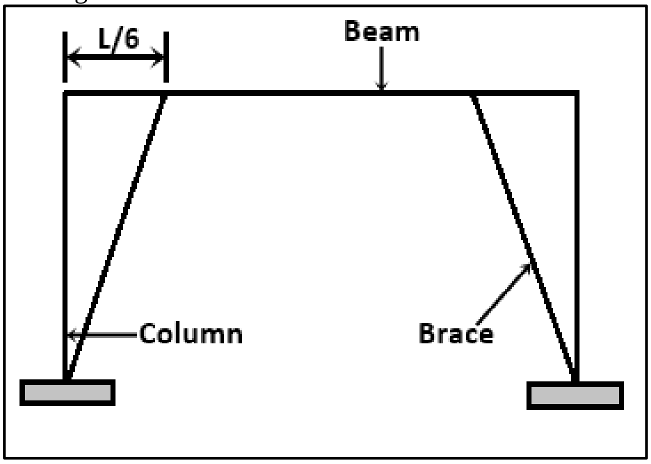

Figure 2. Eccentric steel brace configuration

III. NON-LINEAR MODELING

The finite element software SeismoStruct was used for simulations. The non-linear concrete model proposed by Mander et al., [11] was used for modeling behaviour of confined/unconfined concrete while reinforcing rebars were modeled following the constitutive relationships proposed by Menegotto and Pinto [12]. The steel brace was modeled following a bi-linear constitutive relationship available in the program. The structural elements were modeled using the distributed plasticity fiber type force-based formulations capable of modeling members with geometric and material non-linearities.

The beam-column joint was modeled using the modeling technique proposed by the authors [13]. The multi-linear hysteretic constitutive relationship proposed by [14] was used for the beam-column joint shear hinge defined at the center-line of beam and column elements. The main objective of assigning a hysteretic rule to the beam-column joint was to know the moment demands on the beam-column joint as well as the deformations (shear-strains) for both bare as well as ESB frame under lateral loading. The different parameters needed to be defined for the hysteretic constitutive relationship was defined same for both bare frame as well as ESB frame. The different parameters needed to be defined using analytical formulations however, the objective of this study was to evaluate the performance of ESB frame and to assess its importance on how it reduces the demand on the crucial zone i.e. beam-column joint so the values were decided to be chosen same for both frames.

IV. STATIC TIME HISTORY ANALYSIS

A displacement loading protocol with an increasing drift was prepared (figure 3) and applied on the considered frames at the beam-column joint level. The frames were subjected to two cycles at each level of story drifts. Static time history analysis was performed using the finite element program SeismoStruct version 2020.

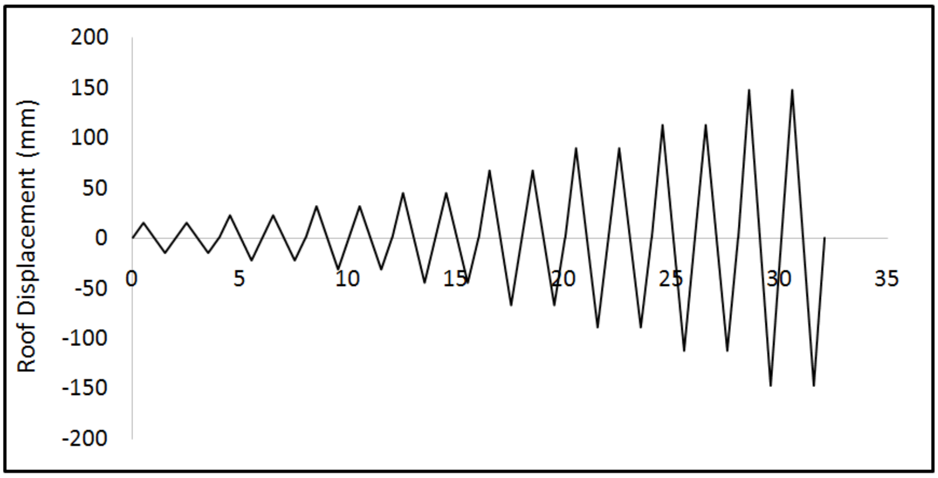

Figure 3. Loading protocol

V. RESULTS AND DISCUSSION

5.1. Hysteretic Response Curves

The hysteretic response curves of both bare frame as well as ESB frame is shown in figure 4. The ESB frame offered a maximum lateral resistance of 196 kN, which on the other hand in the case of bare frame reduced to a value of 115 kN. The ESB frame increased the lateral load taking ability of the frame to approximately 1.7 times as opposed to bare frame. Moreover, the bare frame showed a more pinched behaviour as compared to a more stable hysteretic response curves in the case of ESB frame. The reason behind this is the more damage of beam-column joint in the case of bare frame. A comparison of both frames is also shown in figure 5. The ESB frame significantly increases the lateral strength, stiffness and energy dissipation capacity of the system as compared to bare frame.

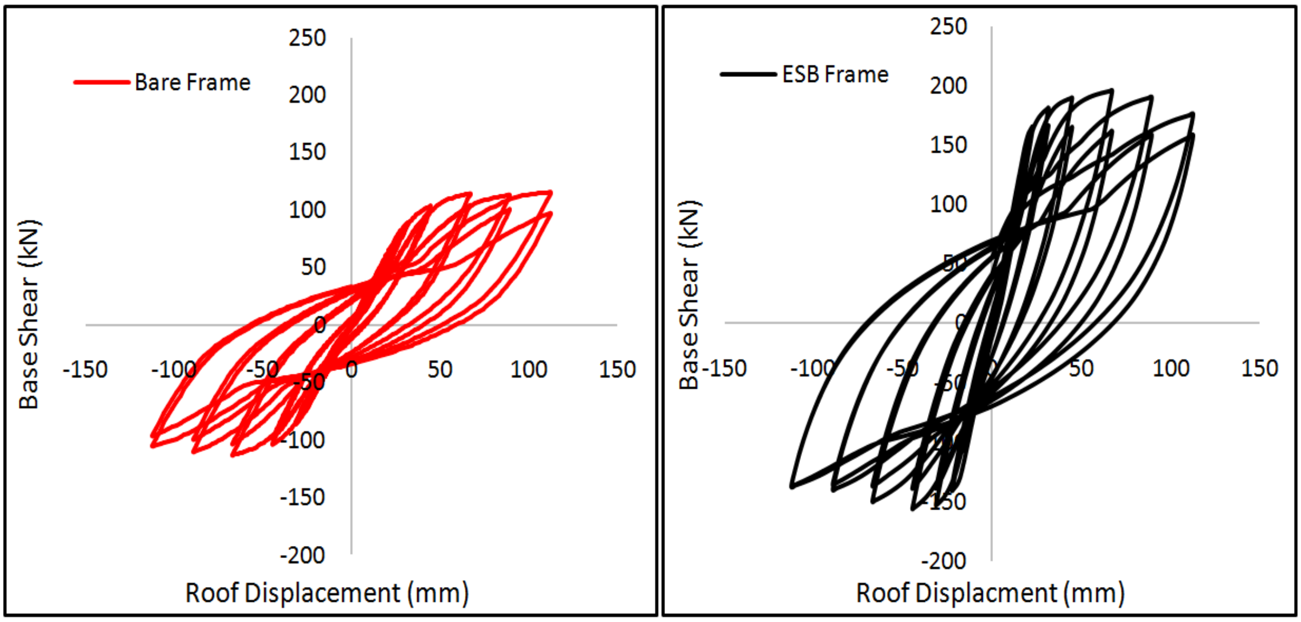

Figure 4. Hysteretic response curves (left; bare frame and right; ESB frame)

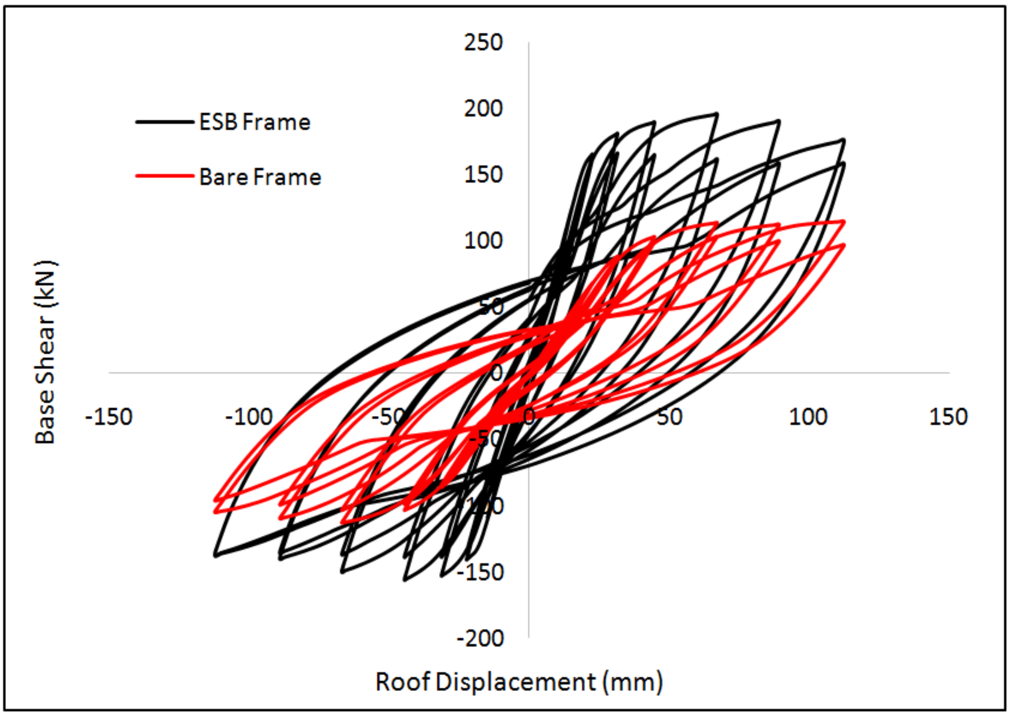

Figure. 5 Hysteretic response curves comparison

5.2. Backbone Envelope

The peak roof displacement and the corresponding base shear load for frame under both push and pull were identified, and were averaged in order to derive the average backbone capacity curve. Figure 6 represents the comparison of both bare frame and ESB frame. The maximum lateral resistance offered by bare frame was approximately 114 kN, which on the other hand in the case of ESB frame increased to approximately 173 kN. From the figure 6, it can be observe that the ESB frame significantly enhanced the stiffness of the frame as opposed to the bare frame.

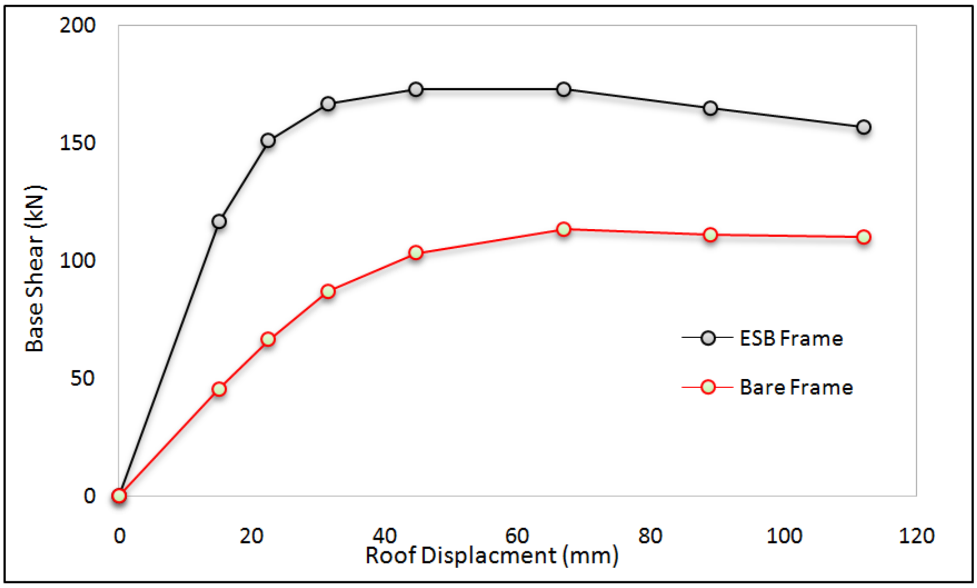

Figure 6. Average backbone comparison

5.3. Moment-Rotation Demand on the Joint

The moment-rotation demands on the joints were assessed for both bare frame and ESB frame by comparing the shear hinge hysteretic curves defined for the beam-column joint. The maximum moment demand on the beam-column joint was 86 kN-m and the corresponding shear strain was 0.00012 Rad in the case of ESB frame. On the other hand, the bare frame increased the moment demand on the joint to a value of approximately 110 kN-m and the corresponding shear strain was 0.00028 Rad. The demands on the ESB frame beam-column joint is less as compared to bare frame, this is due to the load transfer path which changes in the case of ESB frame. Thus ESB frame also decreases the demand on the most crucial zone i.e. beam-column joint.

VI. CONCLUSION

This paper evaluated the performance of RC bare frame and ESB frame under cyclic loading protocol. On the basis of the results presented, the following conclusions are summarized;

- ESB retrofitted technique is an effective and economical strengthening technique and significantly increases the lateral strength, stiffness and energy dissipation capacity of the system.
- ESB frame offered a more stable hysteretic response curves as compared to a more pinched hysteretic response curves in the case of RC bare frame. The reason behind this is the joint damage/deformations and more moment demands on the joint in case of RC bare frame. On the other hand, ESB frame reduces the moment demands on the joint and changes the lateral load transfer path.
- ESB frame increased the lateral load taking ability to approximately 1.7 times as compared to RC bare frame.
- ESB retrofitting technique can be used to upgrade deficient RC frames typically found in high seismic zones. However, an extensive experimental study is necessary in order to evaluate the performance of various ESB connected to different lengths of beam diagonally.

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