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(Research Article)

Enhancement of lateral load carrying capacity of reinforced concrete frames with improved eccentric steel brace retrofitting technique

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Abstract

The existing reinforced concrete (RC) buildings around the globe are at risk to earthquakes events due to various deficiencies arising for previous codes and construction execution. These vulnerable RC structures are retrofitted with different techniques to improve their seismic load carrying potential. One of the most used techniques, Eccentric Steel Bracing (ESB), has appeared as a favorable technique for enhancing the seismic strength of existing structures. In this study, the application of ESB along with the combination of epoxy is investigated. The ESB technique essentially involved attachment of steel plates to RC elements using epoxy and embedding the bolts. The study emphases the attachment of gusset plates to RC elements, utilizing the advantages of epoxy and embedding bolts to ensure a strong connection. A one-third scale RC Braced frame (M-model) is subjected to Quasi Static Loading Test (QSLT). The results of the M-model are compared with another identical braced frame (A-model) where epoxy and pedestals were not applied while external steel plates were connected solely with bolts. The results suggested that M-models showed an increase of 6.24% compared to 4.17% (A-model). However, the lateral load capacity of M-model reduced by 22.60% compared to A-model. The ultimate drift of M-Model enhanced by 8.62% whereas the same parameter recorded for A-Model was 3.39%. In conclusion, the ESB methodology applied in this research study showed a promising result to enhance the seismic performance of the existing structures at risk.

Keywords: Eccentric Steel Bracing; Lateral load capacity; Reinforced concrete frame; Retrofitting; Seismic

1. Introduction

In the standards, [1] has recorded few common retrofitting methods employed to seismically enhance the existing vulnerable reinforced concrete (RC) frame structures. The most used methods are adding reinforced masonry or concrete walls, steel braces, seismic isolation, RC or FRC jacketing of columns and beams, use of fiber reinforced polymers (FRP) composite wraps, and localized strengthening of beam-column joints. The selection of any of the methods is attributed to various considerations. For instance, the steel bracing system is favored because of its higher strength ratio (Strength to weight ratio), rapid construction, ease in installation without greater disruption, and the higher capability to improve the seismic performance of the RC structure in global perspective. Similarly, the installation of steel braced frame to the RC frame gives multiple options, for instance, it can be externally installed in the existing structure [2], [3], [4] or internally within the RC frame [5], [6]. The auspicious performance of the steel bracing system that consists of diagonal steel braces, directly connected to the RC frame [7], without any intermediary steel frame, thus it encouraged the application of internal steel braces for seismic retrofitting of the RC frame structures using concentric braces [8] or eccentric braces [9]. On the other hand, different techniques including dissipating and viscous dampers have also been recommended to brace the system for strengthening of the existing RC structures subjected to seismic forces [10], [11], [12].

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The RC frames having concentric braces, without providing eccentricity in the connections, tend to resist the lateral loads through a truss action where the diagonal braces (steel members) are subjected to axial stresses [13]. There are certain similarities in both types of frames. For instance, in the eccentric and non-eccentric frames, the diagonal steel is subjected to large axial stresses, however minimum or no bending stresses are experienced. On the contrary, in the concentric braced frames, the initial stiffness is higher thus favoring the response of frames to act elastically to control vibration and inelastic deformability varying from 0.30% to 0.50% story drift which is significantly lower than permitted i.e. 2.5% [13]. In the concentric braced frames, the steel members are designed to yield in tension while in compression, it buckles elastically to dissipate seismic energy [14]. However, a famous phenomenon known as pinching, where the steel braces buckled and thus reduces the lateral force-displacement capacity of the frame and leads to a soft-story mechanism. Therefore, the AISC seismic design provisions [13] have a stringent criterion to limit the slenderness of steel braces to avoid pinching and to ensure stabilized response during lateral loading. In addition, the quality and detailing of bracing system also play a significant role in altering the yielding mechanism of concentric braced frame [15]. During the previous earthquakes, it was discovered that concentric braces' poor performance is attributed to the improper design and poor construction, led to the collapse of frame structures [16].

When it comes to eccentric braced frames, by introducing an eccentricity intentionally, the lateral loads are resisted by a combination of actions, a truss action and bending mechanism, thus the eccentricity is utilized as beneficial [17]. In the eccentric braced frames, the diagonal steel member is connected to the beam, away from the center line of beam, to induce eccentricity. In between, the two diagonal braces, the segment of beam is called as link and subjected to a higher shear and bending stresses. The resisting mechanism of the system is such that; during elastic deformation, the resistance is provided by flexural or shear deformation of the link whereas during the yielding mechanism and in-elastic deformation, the moment – shear ratio of the link provides resistance to the external forces. It is worth noting that the initial stiffness of the frame depends on length of the link i.e frame with shorter links exhibit high initial stiffness and vice-versa [18]. A careful design ensures that flexural yielding of link beam and elastic response of braces, thus the frame system exhibits a high initial stiffness and deformation capacity. Furthermore, the eccentric braced frame offers accommodation of windows or doors in the frame panel. Similarly, it is experimentally verified that retrofitting with eccentric steel bracing technique enhances ductility of the frame system compared to the concentric bracing technique[19].

2. Experimental program

2.1. Reinforced concrete frame model

To test the RC frame while keeping in view the limitations of the structural testing laboratory, a one-third scaled model of the prototype was constructed. The RC frame model is essentially a single storey and single bay structure. The RC frame having a beam and columns of size of 4"x6" and 4"x4", respectively. Similarly, the longitudinal reinforcement in beam and column were 6#2 rebars and 8#2 rebars, respectively. The transverse reinforcement having dia of 1/8" were provided with a spacing of 1" between the reinforcement in beam and columns. The cross sections of beam and column along with reinforcement details are shown in Figure 1. Concrete with a ratio of 1:3.5:2.87 having compressive strength of 2000 psi and rebars with yield strength of 60 ksi were considered in beam and columns. The unit weight of concrete was 150 pcf and modulus of elasticity of steel & concrete was 29000000 psi & 2549117 psi respectively. To ensure stability the RC frame model (M-Model), a thick foundation with dimensions of 8' long, 1.67' wide, and 1' deep was constructed monolithically with the RC frame. The constructed RC model is shown in Figure 2.

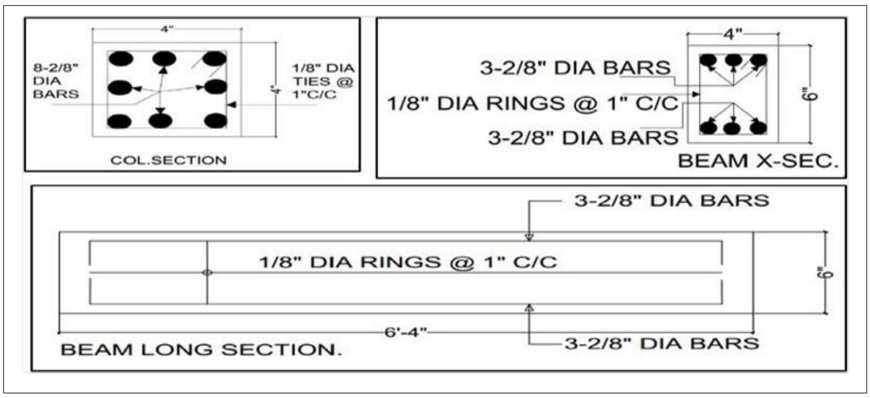


Figure 1 Reinforcement Details of the RC frame members

Figure 2 Constructed an RC frame model for testing

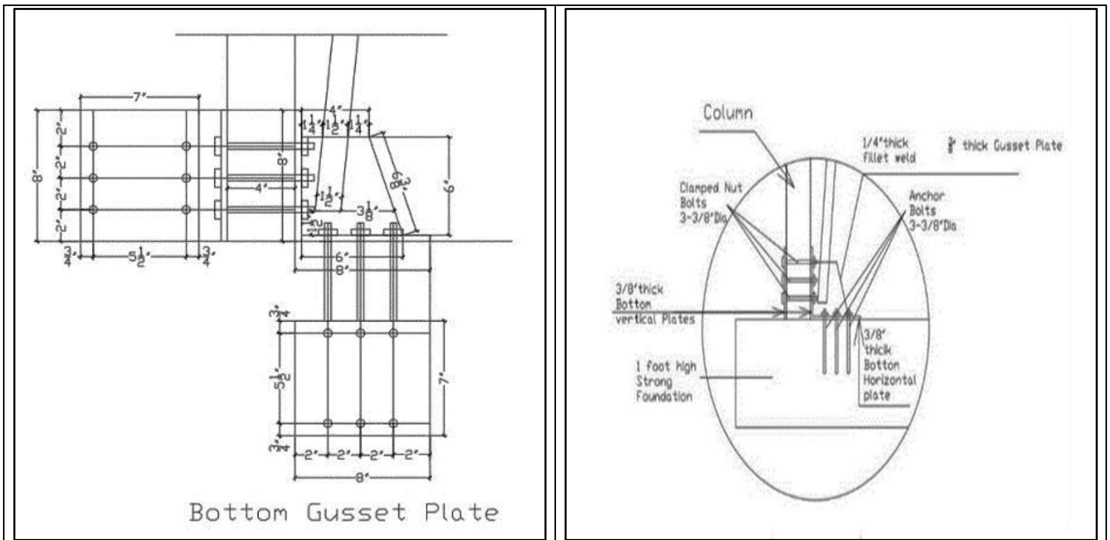
2.2. Design of eccentric steel bracing (ESB

2.2.1. Design of Steel Brace Section

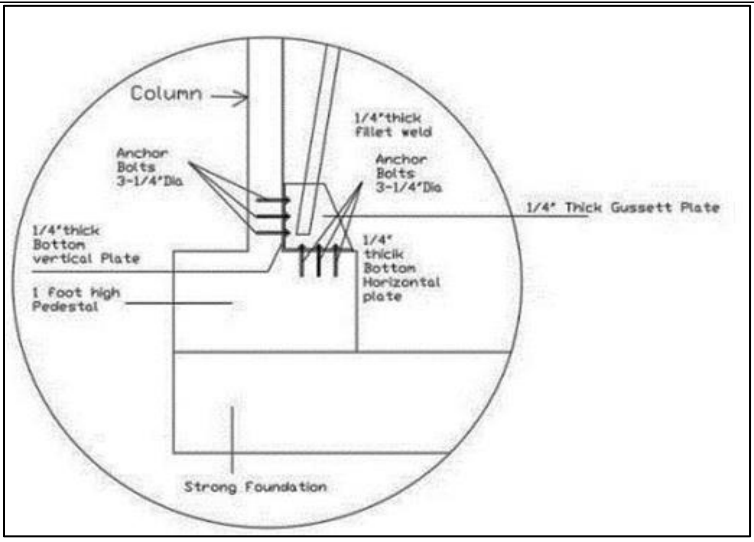
To brace the gusset plates, a steel bracer (SB) made up from HSS with the dimensions of 4.5”x4.5”x1/8” used in prototype was scale down to 1.5”x1.5”x1/24” for the model. In order to brace the gusset plates, an opening was produced in steel bracer of size to fit exactly with the gusset plates. The steel bracer was joined using a ¼” fillet longitudinal weld using an electrode with a 60 ksi strength. It is worth mentioning that the length of fillet weld was calculated using LRFD manual considering a factor of safety of 6 in the calculations.

2.2.2. Design of Gusset Plate

A gusset plate of yield strength of 36 ksi (A36) was used in this research study. The gusset plate of thickness equal to 0.23 inches was calculated using the basic equations of steel structure design, however due to availability of closely matched section of thickness 0.25 inches equal to ¼ “was utilized in the model. The details of gusset plate and its attachment with the reinforced concrete beam and columns are illustrated in Figure 3.



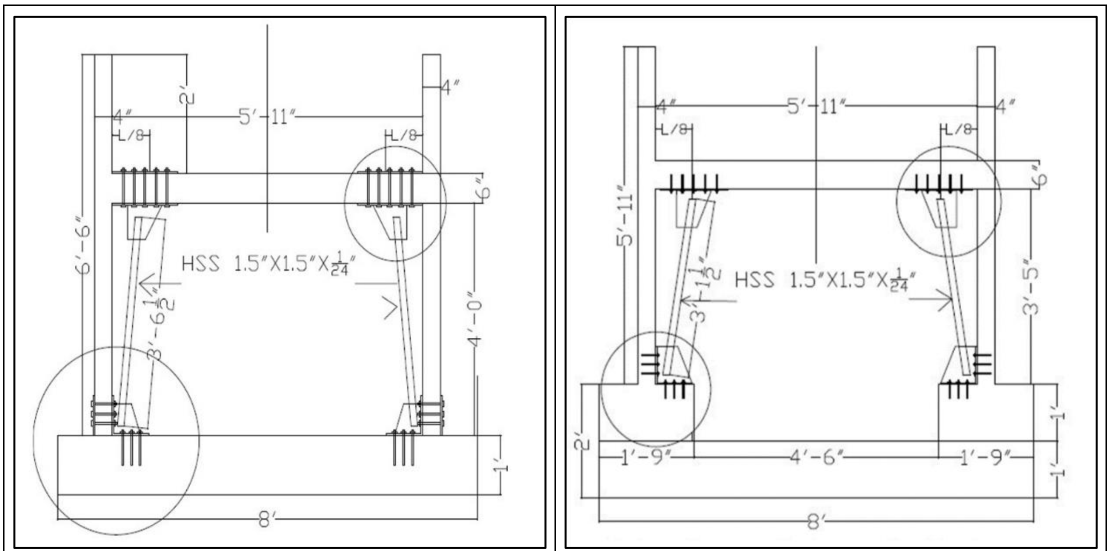
(a) (b)



(c)

Figure 3 (a &b) Bolts Clamped to A-Model and (c) Bolts Inserted to M-Model

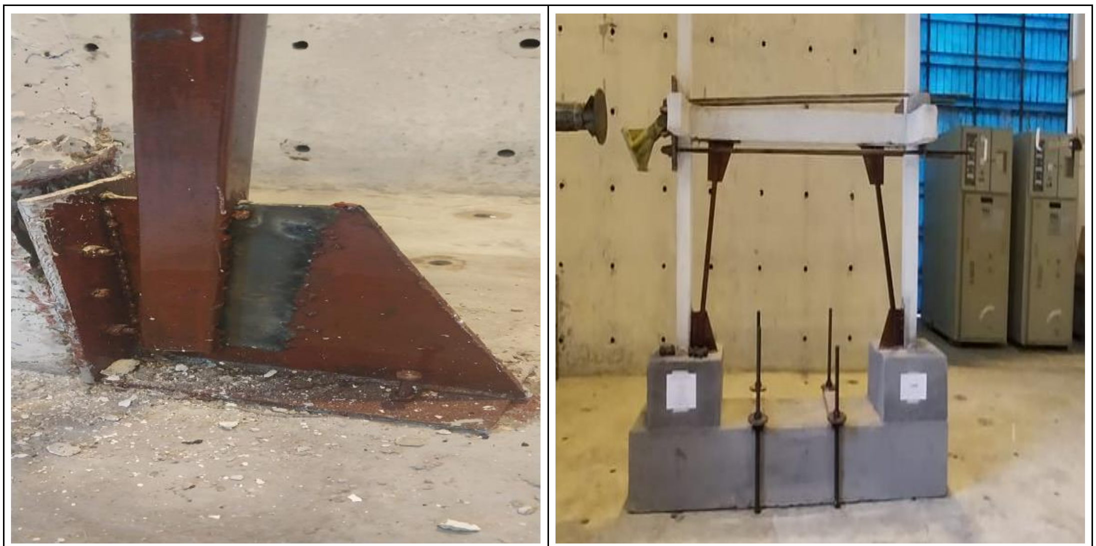
At the critical points below the columns, two pedestals 1.67'x1.83'x1' each were placed strategically as shown in Fig-3(a). The M-Model is almost similar to the B-Model; however, a main distinction is the addition of two pedestals and the insertion of bolts in RC elements. Moreover, the M-Model was further strengthened by applying an epoxy to the surface of steel plates and RC elements for boosting durability. The arrangement of Gusset plates and bolts are shown in Figure 3 (a-c) for both A-Model and M-Model. Similarly, an overview of the dimensions and bracing of both models are shown in Figure 4. The step-by-step application of the gusset plate to the concrete members and application of epoxy to attached bolts are illustrated in Figure 5.



(a) **(b)**

Figure 4 Dimensions of the Braced Frame Models (a) A- Model and (c) M-Model

	 (b)
 (c)	 (d)
 (e)	 (f)



(g) (h)

Figure 5 A complete procedure of installation of the gusset plate in M-Model (a-h)

2.3. Test setup for model

The RC frame was tested by applying a Quasi-Static Loading Testing (QSLT) protocols to capture a more realistic behaviour for a better seismic assessment. The attachment of hydraulic jack is to apply displacement control loading to the RC frame. The RC frame was fixed in the bottom to a strong floor and the top was freed whereas the quasi-static loading was applied on the joint. A displacement-controlled loading was applied in accordance with the FEMA Guidelines [20].

Prior to testing, Linear Variable Displacement Transducers (LVDTs) were installed in different critical locations to monitor RC frame structural responses such as displacement whereas the loadcell was installed to record the corresponding lateral load applied in each cycle of the quasi-statis loading. The LVDTs were installed in different locations. For instance, LVDT-1 and 2 were installed on both ends of the middle beam to record the horizontal displacement, and their average value was taken as control displacement whereas the LVDT-3 was used to record any horizontal movement or sliding of the foundation pad while applying load.

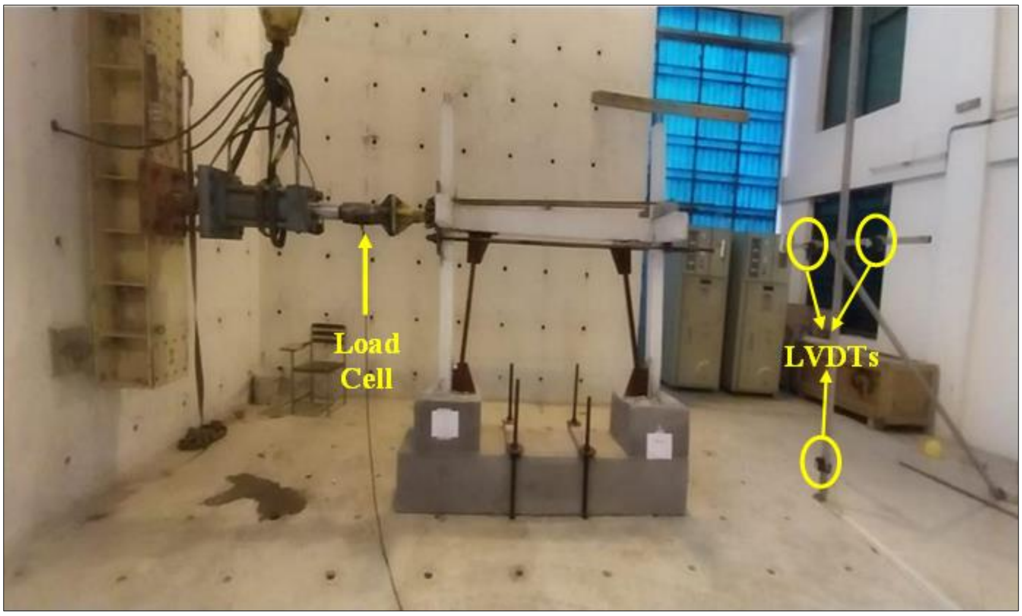


Figure 6 Test Setup and Instrumentation

Quasi-Static lateral loading was applied with the help of a hydraulic actuator which a displacement controlled. to the testing frame for multiple level story changes in displacement. The hydraulic actuator connected to the RC frame via a pin connection to prevent any accidental eccentricity. The pin connection includes a thick steel plate with a number of holes to pass the steel longitudinal rods for clamping both ends of the frame, in order to facilitate the push and pull of the RC frame. At the back end, the actuator was clamped to a rigid steel beam. The displacement-controlled loading was employed via the hydraulic actuator by giving three cycles of each level of story drift. The instrumentations and the quasi-static loading protocol applied to the RC frame are shown in Figure 6 and Figure 7, respectively.

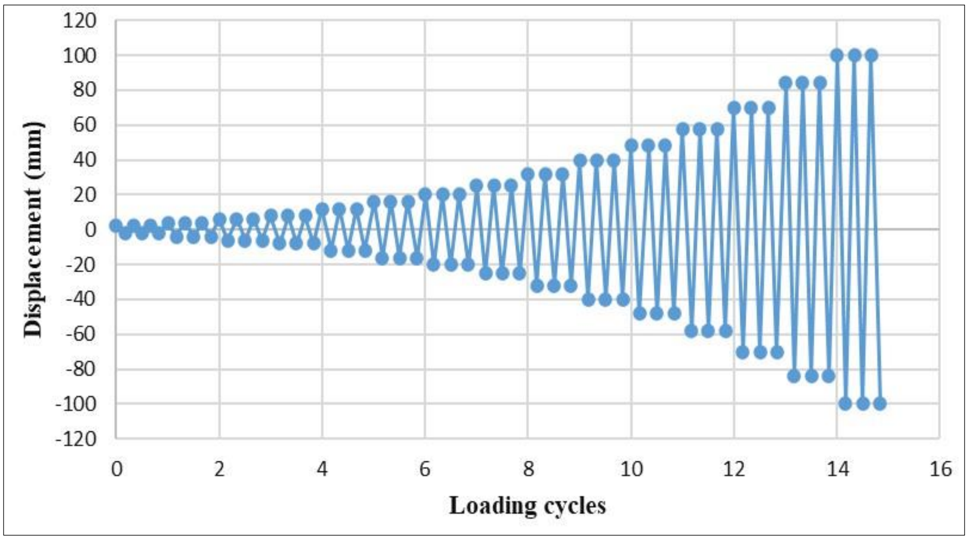


Figure 7 Displacement Loading Protocol applied to the RC frame

3. Experimental results

3.1. Hysteresis Loops of RC frames

The hysteresis loops or load-deformation curve show the response of a structure under testing with the intensity of load on the y-axis whereas the displacement of structure is plotted on x-axis. The Hysteresis loops of both the braced frame models, A-Model and M-Model, are shown in Figure 8. Lateral displacement was recorded at mid beam and the corresponding load force was recorded with a load cell

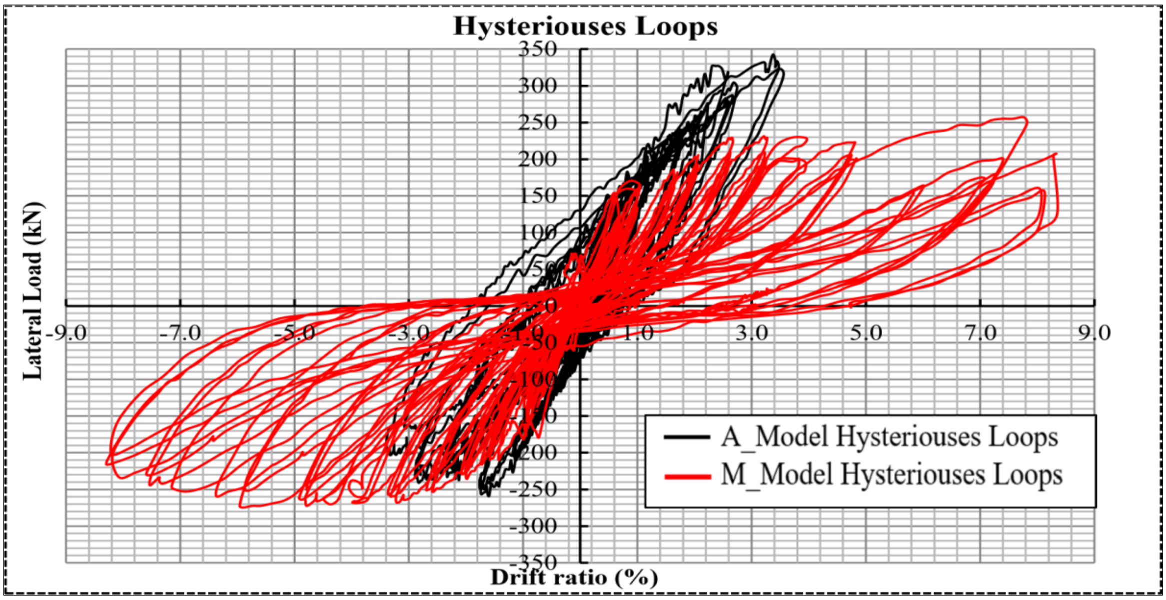


Figure 8 Load Deformation curves of A-Model Braced frame and M-Model Braced frame

Initially when lateral displacement is applied to the frame, the A-Model braced frame indicated an increase in initial stiffness while the M-Model braced frame exhibited a lower stiffness resistance. On the other hand, the ductility of the M-Model braced frame increases substantially. Nonetheless, A-Model showed a higher lateral load capacity of 323kN whereas M-Model achieved highest load of 250kN. Furthermore, up to the drift ratio of 3.4%, A-Model showed a steady increase in stiffness, however, less amount of energy dissipated as evident from the closed loops whereas the M-model dissipated a considerably higher amount of energy. Beyond 3.4% drift ratio, M-Model there was no considerable increase in lateral load capacity, however a significant amount of energy was dissipated.

3.2. Lateral Force-Deformation Capacity Curves

The maximum displacements and corresponding lateral forces from each hysteresis loops were connected to make a load-deformation curve, also known as back bone curve. The backbone curve of both of the braced frames is presented in Figure 9.

Initially, the stiffness of the A-Model and M-Model remains same, however at the higher drift ratios, the M-Model stiffness loss and the curve falls flat. This is due to the fact that cracks development led to significant loss in strength, thus, stiffness was degraded whereas the A-Model braced frame still maintains higher stiffness and is able to withstand further loads.

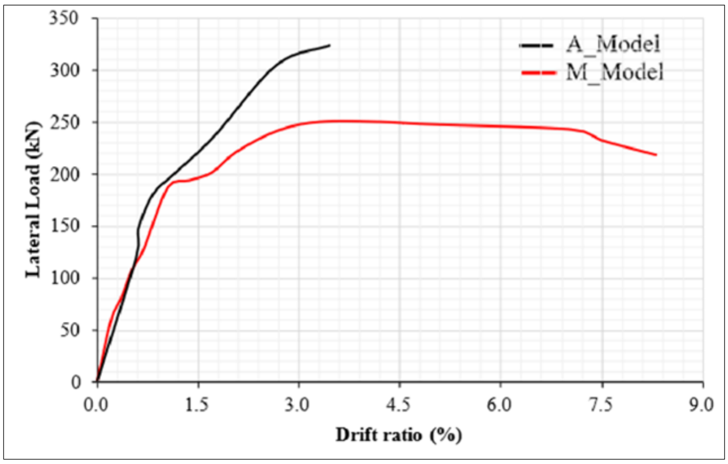


Figure 9 Backbone Curve of the A-Model and M-Model

4. Conclusion

This research study presented experimental testing to evaluate the performance of ESB along with the combination of epoxy and embedded bolts. The ESB technique involved attachment of steel plates to RC elements using epoxy and embedding the bolts. A one-third scale RC Braced frame (M-model) is subjected to Quasi Static Loading Test (QSLT). Based on the experimental tests results, the following conclusions can be drawn.

- Lateral Load Carrying Capacity of M-Model Braced Frame decreased by 22.6% as compared to A-Model Braced Frame (from 323KN to 250KN) & increased by 43% as compared to braced Frame A-Model (from 175KN to 250KN).
- From the data analysis, it is found that lateral stiffness of M-Model Braced Frame increased by 15%, as compared to A-Model Braced Frame (from 4.47KN/mm to 5.15KN/mm) & increased by 239% as compared to A-Model braced Frame (from 1.52KN/mm to 5.15KN/mm).
- The ductility of M-Model came out to 6.84 as compared to A-Model braced Frame.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare no conflicts of interest

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