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CYCLIC BEHAVIOR AND CRITICAL PART OF ECCENTRIC BRACED FRAMES WITH VERTICAL LINKS

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A vertical shear link-equipped reinforced concrete eccentric braced frame (RC-EBF) exhibits a unique behavior that has yet to receive much research. The vertical shear link is located separately from the main beam, so it does not interfere with its performance. Moreover, it gives structural retrofitting flexibility. To comprehend the structural strength of EBF compared to Concentric Braced Frames (CBF), the current work explored the cyclic deformation history of RC-EBF type Y (vertical shear links). It also sought to identify the critical frame components contributing to structural failure. The investigation involves nine specimens comprising CBF and EBF with 15 cm and 25 cm vertical linkages. Cyclic load-displacement histories revealed that the CBF configuration is the stiffest and most reliable one. The CBF structure exhibits equal deformation at higher cyclic loads than the EBF. Shear stress is the critical factor contributing to the structure's collapse, as demonstrated by the diagonal main crack in the current EBF samples.

Keywords: cyclic load, deformation, eccentrically braced frames, reinforced concrete, vertical shear link

1 INTRODUCTION

There are three types of frame structure according to the lateral load resisting frame systems that are Moment Resisting Frame (MRF), Concentric Braced Frame (CBF), and the one behaves between MRF and CBF, known as Eccentric Braced Frame (EBF). EBF provides moderate stiffness and absorbs more energy under lateral load than bare and braced frames [1]. Some types of bracing are commonly used and researched, including diagonal, V, inverted V, X, Y, inverted Y, and so on. A Comparison study on the EBF behavior examined diagonal, inverted-V, and combined braced frames to confirm that inverted-V frames with two braced bays provided better resilience for preventing progressive collapse [2]. Overall, the brace function to the frame structure includes enhanced structural performance, increased shear capacity, and decreased displacements and drifts. An investigation has reported that retrofitting an RC frame using steel-X bracing through time history studies resulted in the benefit of all frame’s performances [3]. Adding braces on a frame structure increases 58% of inter-story drift compared to a moment-resisting frame [4]. It should be noted that only a few studies have used RC as bracing material. This study investigated the performance of RC braces material.

Type-V bracing is well known for its seismic performance [5]. Eccentric installation of braces results in the appearance of a section called a link beam. Link beams are the most critical part of the Eccentric Braced Frame [6]. There are two different V-brace installation styles for EBF, including horizontal and vertical shear links. The link beam in an EBF structure significantly influences its behavior, especially in seismic events, by providing high ductility, rigidity, and energy dissipation capacity [7].

Horizontal link beams in Eccentrically Braced Frames (EBF) with a V-type arrangement (EBF-V) offer advantages in seismic resilience and structural performance. The spacing of the link beam’s stirrups is crucial, where smaller spacing can slightly increase the strength of the link beam but may reduce its ductility [8]. These beams, designed to yield primarily in shear, have a greater potential to dissipate energy during seismic events. The spacing of the stirrups is crucial for this shear-dominated yielding. EBFs with shear links exhibit excellent hysteretic behavior, making them a suitable substitute for concentrically braced buildings and moment-resisting frames [9]. On the other hand, when there is a horizontal shear link, the link beam is coupled to the main beam, endangering its ability to function in the event of a moderate or strong earthquake. Using a vertical shear link, the link beam can be replaced or retrofitted to increase the structural capacity of the building because it is situated apart from the main beam.

Bracing type-V with vertical shear link is also known as bracing type Y. Some previous studies investigated the behavior of frame structure using brace type Y. Vertical connections in eccentrically braced frames (EBF) have various advantages regarding structural design. They aid in shifting the area of plastic deformation to more bearable locations, preserving the beam's elasticity even in the face of powerful earthquakes. This design decision improves the structure's overall seismic performance by simplifying, replacing, or repairing damaged portions after an earthquake. Furthermore, it has been demonstrated that adding vertical linkages to EBF systems enhances the system's behavior analytically and experimentally, resulting in good convergence with experimental results and improving the structure's overall performance [9]. Although codified in Eurocode 8, eccentrically braced frames with vertical links (VL-EBFs), also known as inverted Y-schemes, have not been extensively studied regarding seismic response and design. As a result, design standards typically used for eccentrically braced frames with horizontal links (HL-EBFs) are used instead [10]. J. Liu et al. [11] found that the failure of the frame with Y-braced is caused by macro buckling on the shear link element. EBF-V with a horizontal link produces higher load-carrying capacity and ultimate angular rotation than EBF-V with a vertical link [12]. The eccentricity length also influences the performance of the structure. Excellent load-carrying capability and ductility are characteristics of EBF with a vertical shear link [13, 14]. However, some local damage is discovered after a high-intensity earthquake, particularly in the shear-link region [15]. The shear mechanism is primarily responsible for the plastic deformation for vertical shear-link installation [16].

There have been many studies on EBF behavior [2, 4, 7, 9, 10, 12, 13, 14, 15, 16]. All of these studies use steel as the material for the brace. This research's uniqueness is the use of reinforced concrete as the constituent material, whereas other studies rarely do the same. Reinforced concrete has a strength that is not as great as steel material because this research is intended for application in residential buildings as a solution to strengthen building structures against earthquake loads or repairs to post-earthquake structures. The structural load on residential buildings is not large, so they do not require a structure with high strength. However, in many earthquakes, residential buildings are usually the most severely damaged and cost many lives because they are often not designed by experts like high-rise buildings. The present study investigated RC-EBF's load-displacement history under cyclic load to confirm the previous study's results that conclude the critical part of EBF structure type Y is the link beam or shear link. The present study aimed to explore the cyclic deformation history of RC-EBF type Y (vertical shear link) to understand the structural strength of EBF compared to CBF and also to find out the critical part or location of the frame structures that lead to the structural failure. By understanding the deformation behavior, the effective retrofitting method can be decided.

2 MATERIALS AND METHODS

Reinforced concrete was the main component of this investigation's main frame and bracing. Residential house structures are an appropriate application field for the utilization of RC. RC is renowned for its effective resistance to tensile and compressive stresses. Using essential equipment, installing reinforcement and casting concrete can be installed effectively. The steel rebar diameters utilized are 6 mm for the primary reinforcement and 4 mm for the stirrups. A concrete grade target as K-275 (22.8 MPa) is also used. Beams, columns, and bracing with dimensions of 10 cm by 10 cm are employed on the scale of the structural model, and the stirrup space is 15 cm. Fig. 1 explains the structural cross-section in detail.

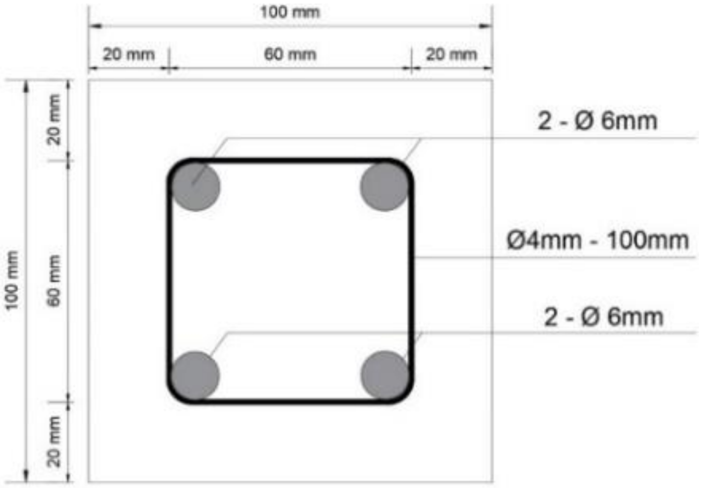

Fig. 1. Detail cross section’s dimension and rebar

The central dimension of the primary frame structures is 100 by 75 cm. The lengths of the shear links where bracing type Y is installed vary from 0 cm (CBF), 15 cm (EBF-Y-15), and 25 cm (EBF-Y-25). According to statistical requirements, the minimum number of samples is three, so if two results are significantly different, the third sample is the validator. Increasing the number of specimens and varying parameters such as material properties and geometric configurations provide more robust and generalizable conclusions. However, we have conducted many previous studies regarding this topic with good results and have confirmed each other [5], [6], [8], [20], [21], so this experimental research used three frame specimens for each variation. Fig. 2-4 shows specific frame dimensions for each sample.

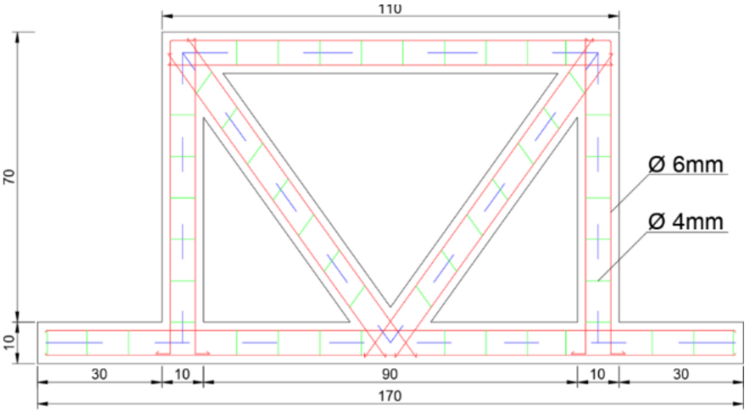

Fig. 2. RC-CBF

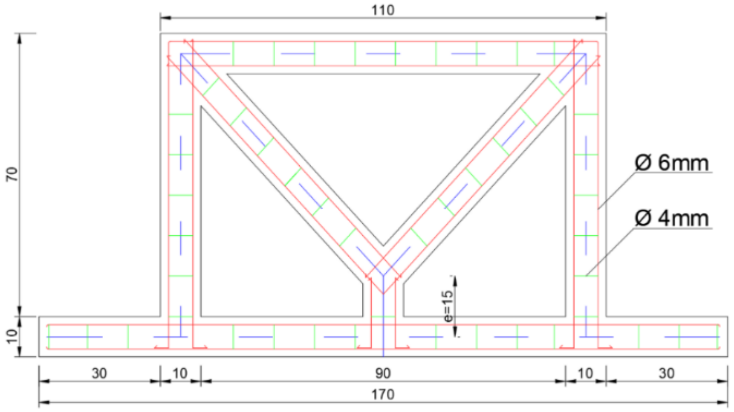

Fig. 3. RC-EBF with shear link of 15 cm

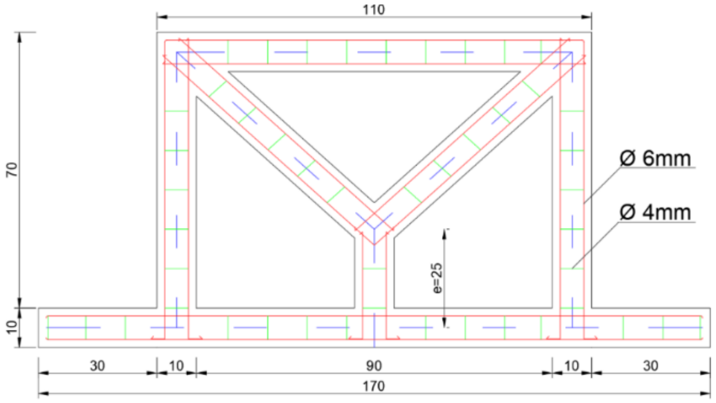

Fig. 4. RC-EBF with shear link of 25 cm

The structures are subjected to cyclical load with the load control method. The previous study's result [5], which was 5250 kg, determines the maximum load. There are four stages to this maximum load: 25, 50, 75, and 100% (1312 kg, 2625 kg, 3937 kg, and 5250 kg). Five cycles of bi-directional loads make up each stage. The cyclic stress is applied to the frame tests until they collapse. Table 1 provides cyclic load application details, and Fig. 5 shows a representative setup on the loading frame. Static lateral loads (pushover), cyclic loads, and full dynamic loads can all be used to represent lateral seismic loads. Since cyclic loads can account for fatigue effects and energy dissipation distribution, they represent better seismic load than static loads. Static loads are not as good at representing seismic loads as cyclic loads.

Table 1. Detail of cyclic load application

Stages	Load intensity (kg)	Frequency and direction
1	1312.5	5 (bi-direction)
2	2625	5 (bi-direction)
3	3937.5	5 (bi-direction)
4	5250	5 (bi-direction)

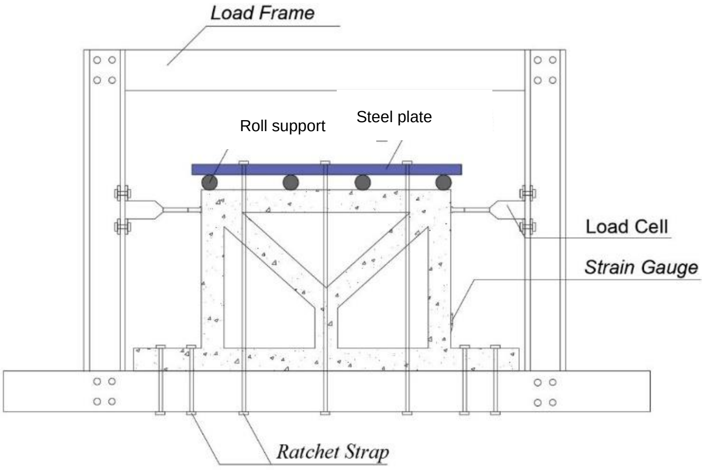

Fig. 5. Sample setting on the loading frame

The cyclic load-deformation history is the research output for the current study, and it helps to understand how the structural behavior of ECF and EBF differs and how the length of the shear link affects the strength of the frames. The vital components of the structure are also examined in this analysis, which is crucial for identifying the most effective and efficient structural retrofitting technique in subsequent investigations. Although by combining computational modeling with experimental studies, researchers can strengthen the validity and applicability of their findings in various fields of study [17], [18], the present study only conducted an experimental investigation because the authors have done some previous studies with a similar topic that resulted in a suitable output to increase the confidence of the present data result.

3 RESULT AND DISCUSSION

3.1 Cyclic load and displacement history

This experiment tested steel and concrete materials before evaluating the sample frames to validate the current concrete mix design results and determine the steel reinforcement's strength. The outcome showed that the concrete grade reached 25.3 MPa, while the primary steel reinforcement had a yield stress of 459.7 MPa and a maximum stress of 565.9 MPa. The stirrups steel grade's yield and maximum stress are 238.7 MPa and 318.3 MPa, respectively.

All samples underwent cyclic loading until they achieved their maximum carrying capacity, at which point collapse occurred. The load-deformation history of the CBF structure is shown in Figs. 6, 7, and 8 (there is no eccentricity). These three CBF structure samples showed a nearly identical response and maximum load, with all three CBF samples collapsing at stage 3 of cyclic load at a weight of 3937.5 kg. Each CBF sample exhibits a maximum deformation at this loading point of 22.58 mm, 23.7 mm, and 16.04 mm, with an average value of 20.77 mm. According to certain peculiar graphic lines, the CBF constructions are getting closer to their point of collapse.

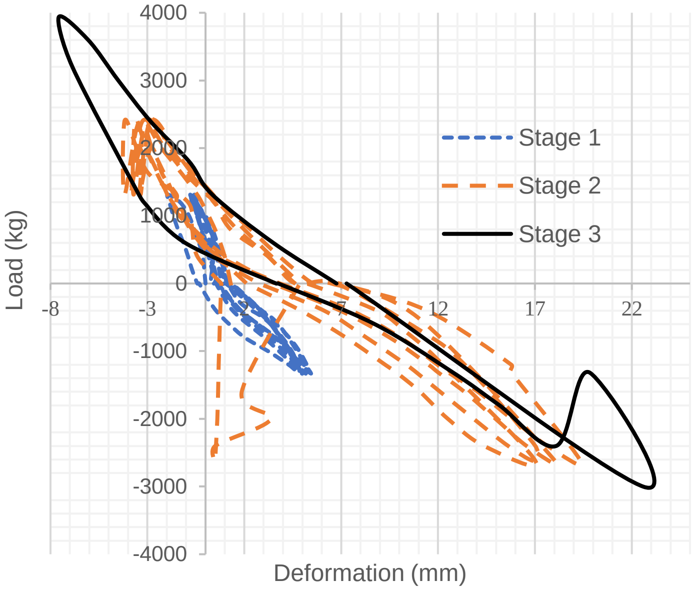

Fig. 6. Load-deformation history of CBF sample 1

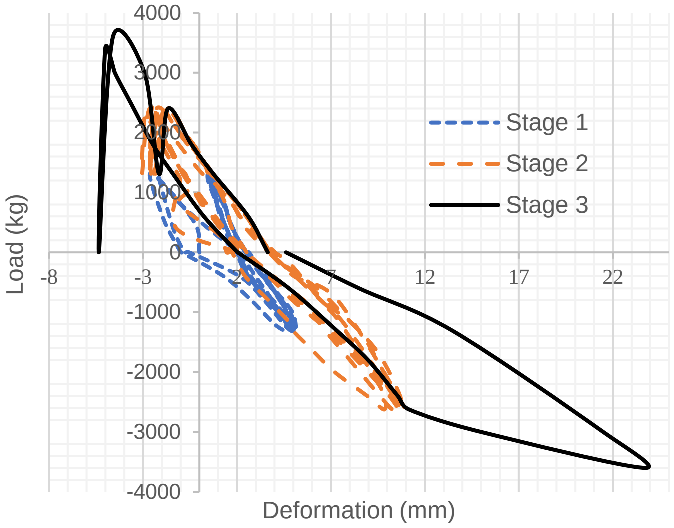

Fig. 7. Load-deformation history of CBF sample 2

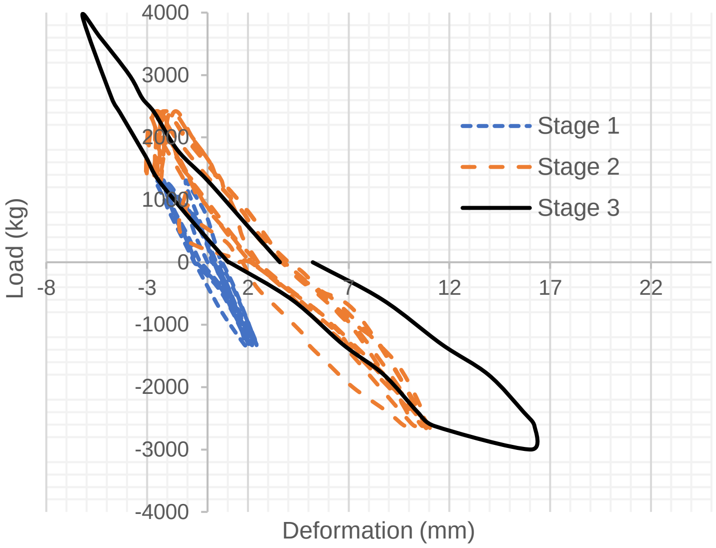

Fig. 8. Load-deformation history of CBF sample 3

With a shear link of 15 cm, the EBF structure could withstand a lower maximum cyclic stress (Figs. 9, 10, and 11). The maximum loads for Samples 1 through 3 (first cycle on stage 2) are 2625 kg, and their maximum deformations are 5.85 mm, 8.29 mm, and 10.75 mm, respectively. As a result, the mean deformation value is 8.30 mm. Compared to CBF samples, the EBF exhibits a 60% drop in deformation capacity and a more than 33% reduction in cycle load.

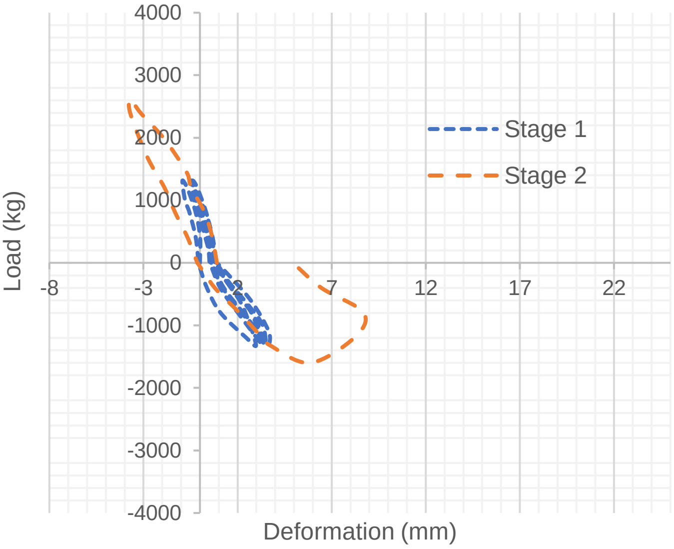

Fig. 9. Load-deformation history of EBF shear link of 15 cm sample 1

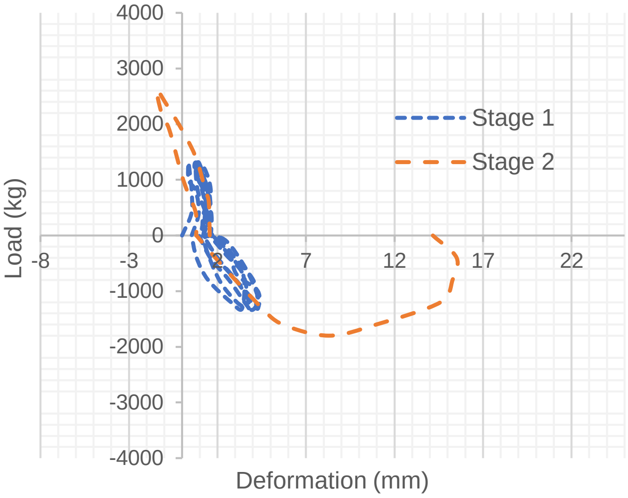

Fig. 10. Load-deformation history of EBF shear link of 15 cm sample 2

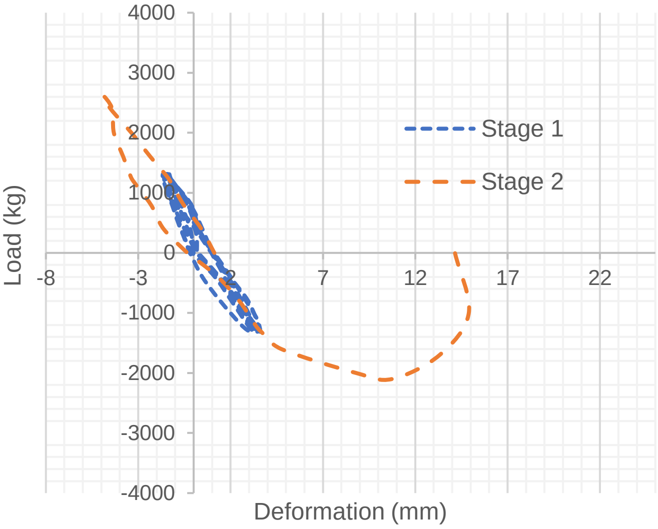

Fig. 11. Load-deformation history of EBF shear link of 15 cm sample 3

Figs. 12, 13, and 14 depict the load-deformation history of an EBF sample with a 25 cm shear link. A similar load stage was attained by the EBF - 25 cm of shear link in comparison to the EBF -15 cm as 2625 kg, with maximum cyclic deformations of 12.94 mm, 15.08 mm, and 9.07 mm for samples 1 through 3, respectively, and an average deformation of 12.36 mm. This finding supports the previous study result [5], [6], [8], [20], [21], that longer shear links led to more significant cyclic deformation but comparable load-bearing capability.

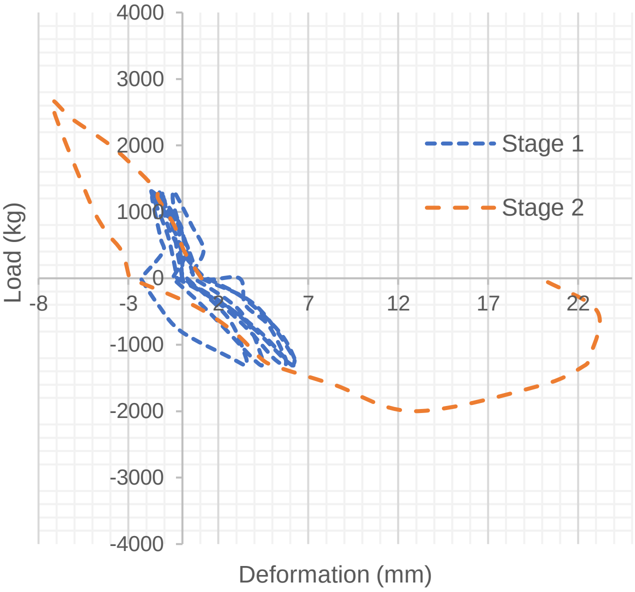

Fig. 12. Load-deformation history of EBF shear link of 15 cm sample 3

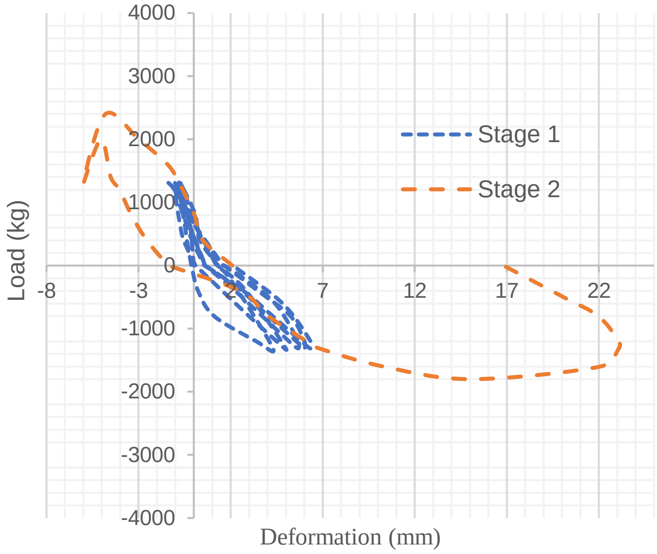

Fig. 13. Load-deformation history of EBF shear link of 15 cm sample 3

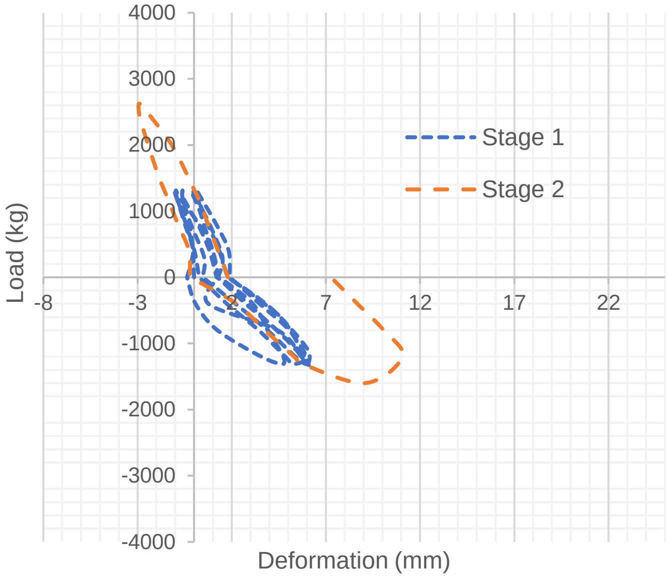

Fig. 14. Load-deformation history of EBF shear link of 15 cm sample 3

3.2 Critical location of the frames

Figs. 15, 16, and 17 display each sample's variation's after-test condition. Through Figure 15, the ECF's collapsed state showed that the left brace and the right and left main bottom beam-column joint were the primary sites for the critical components. The end and center portions of the brace are where cracks are most frequently detected. This circumstance demonstrated how effectively the brace function increases and safeguards the primary structure throughout the load cycle. In addition, the bottom beam-column joint requires additional treatment due to the cracks discovered there.

Fig. 15. Failure of CBF structure

Fig. 16. Failure of EBF shear link of 15 cm structure

Fig. 17. Failure of EBF shear link of 25 cm structure

The frame exhibits varied structural behavior due to the vertical shear linkages present because of the eccentricity that may appear due to specific architectural considerations. The crucial components at the brace seen in CBF structures were replaced with vertical shear linkages in EBF structures. Only little cracks were discovered in the EBF brace sections. All joint locations must be taken into consideration as a crucial component. Shear link element failure is the primary cause of collapse in EBF structures. Shear forces greater than the beam's ability to withstand them usually cause shear cracks in concrete beams. A diagonal cracking direction results from shear pressures acting parallel to the beam's cross-section, which causes the beam's various components to shift about one another. Shear fractures may appear along the beam when these shear pressures are greater than the shear capacity of the beam. Comprehending the shift between tensile, crushing, and diagonal tension failures is essential to understanding the behavior of shear cracks. Nonlinear fracture mechanics, cohesive crack models, and dual overlapping crack models are useful tools for analyzing the dynamics underlying shear crack behavior. These models take dissipated energy, strain localizations, and fracture nonlinearity into account. Because of the complex interactions between these collapse processes, numerical methods must be used for forecasting and assessment. This is especially important for determining the failure load and the principal collapse mechanisms, which depend on scale, slenderness, and variations in the amount of reinforcement steel.

Using longer shear links at some specific ranges resulted in similar load-carrying capacity but higher displacement. An almost identical collapse mechanism was found in EBF-15 and EBF 25 cm, but more severe cracks were found at the shear link location of EBF with an eccentricity of 25 cm.

Cyclic load-displacement histories generally showed that the CBF is the stiffest and most reliable configuration. It has the highest stiff behavior cyclic load-bearing capacity. Compared to the EBF arrangement, the CBF structure experiences equivalent deformation values at larger cyclic loads. Because every structural joint (beams, columns, and braces) comes together at one exact location, the CBF system has superior structural stiffness and integrity and can support more weight. Bracing can be the main frame's ideal stiffener, boosting structural stiffness. The CBF structure is universally acknowledged as the finest option.

The CBF structure may occasionally not be ideal for an opening placement or another flexible architectural consideration due to particular circumstances. Some factors should be considered for this circumstance, such as the frame using EBF with the vertical shear link. The strength of EBF with vertical shear linkages is lower than that of CBF. EBF is still appropriate for installation in small structures like dwellings. EBF with a horizontal link, where the shear link is connected to the main beam, will also make structural retrofitting challenging. The threat to the structures is not usually increased deformation. Increased ductility is typically linked to increased deformation. Ductility is essential in determining whether a structure can support a seismic load. The cyclic load-carrying capacity is unaffected by shear links (eccentricity) within a given range. However, the specific component of the structure suffered more severe damage due to the extended shear link.

The shear link element is where the EBF's vital component, which is a vertical link, is situated. This finding supports the findings of earlier studies [8], [12], and [13], which claimed that the vertical shear link collapse of the EBF was produced by buckling in at the position of the link beam as a result of the shear mechanism. The diagonal main crack in the current EBF sample shows that shear stress is the primary cause of the structure's collapse.

4 CONCLUSIONS

CBF constructions perform stiffer, deform more than EBF structures, and have a larger structural cyclic load capacity. CBF is the ideal option for constructions subject to heavy external loads. It should be determined that the seismic stress is of minor or moderate intensity if the current conditions call for eccentric bracing placement. Because they have a high dissipative capacity, good elastic stiffness, and the potential to survive powerful seismic events without suffering a sizable loss of bearing capacity, eccentrically braced frames, or EBFs, offer several advantages in seismically active places. EBFs are the best structural option for areas where low to moderate earthquakes occur because they can also prevent damage to non-structural components. Additionally, a simplified technique for assessing the demand for plastic rotation has been developed for EBFs equipped with short links, allowing for predicting the eventual plastic rotation required based on the structure's capacity for plastic redistribution. This method improves buildings' seismic safety and structural performance, demonstrating the many advantages of applying EBFs to certain applications. Indeed, CBF offers high stiffness but has limitations regarding architectural considerations. EBF is the solution because of its high structural design flexibility. The behavior of link beams significantly impacts stiffness, ductility, and energy absorption in different structural scenarios. In reinforced concrete structures, shorter link beams exhibit better performance, providing more energy dissipation and ductility than longer link beams, with shear behavior as a crucial ductile component.

A crucial component of the construction for EBF with the vertical shear link (EBF-Y) is found in the shear link element. Some treatment must be applied to ensure the shear link has greater structural capacity than other elements. EBFs composed of reinforced concrete structural materials produce different structural repair method mechanisms than steel materials. The shear capacity of steel structures can be increased using stiffening steel plates [19]. In that case, EBF vertical links that use reinforced concrete materials can be repaired, one of which is with the external reinforcement method. Following the damage, external stirrup reinforcement must be given to link beams with failures due to shear forces. In contrast, adding external longitudinal reinforcement can repair link beams with failures caused by bending forces. Similar to the repair method, the improvement capacity of the link beam area can be carried out according to the dominant cause of damage. Improvement in flexural capacity is made by adding longitudinal reinforcement while increasing the shear capacity, which is conducted by increasing the space of stirrups.

Regarding the practical implications of the findings, some benefits are obtained, namely more economical construction costs, because using reinforced concrete materials can reduce construction costs compared to steel materials. Installing connections between the ends of the braces, link beams, and the main structure is easier because it can be done only by making bends in the reinforcement. In the use of steel materials, the connection becomes more complicated to implement. Finally, adopting the EBF structure in the real field is not complex. Reinforced concrete materials are well-known for their resistance to fire and extreme environments, and they are easy and cheap to maintain compared to steel materials, so long-term applications are very promising.

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