

Numerical Investigation of the Failures Observed in Eccentrically-Braced Frames in the Aftermath of the Christchurch Earthquake Series (2010–2011)

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Abstract

Finite element analysis was used to investigate the effects of the misalignment of the brace flange-to-beam connection point with the link-end stiffener on the ductility of the EBF frames. The misalignment was speculated to be a possible reason for the unexpected EBF failures observed in the aftermath of the Christchurch earthquake series of 2010 and 2011. EBF models with different detailing at the offset area were analyzed under monotonic and cyclic displacements. Results showed severe stress and strain concentration in the offset area, preventing the EBF from developing its expected ductility, and suggested possible initiation of a failure from the part of link flange located in the offset area. Results from analyses on different detail configurations showed that removal of the offset by modifying the brace section to build an ideal case, or by a simple change in the location of the link stiffener, can mitigate the problem of possible premature failure, with the latter solution being slightly less effective but much easier to be used in practice.

INTRODUCTION AND BACKGROUND

A survey of damage caused by the Christchurch earthquake series of 2010 and 2011 on steel structures showed an unexpected failure type in a number of EBFs used in a parking garage in the city of Christchurch (Clifton, et al. 2011). This is considered to be the first observed failure of EBF systems during an earthquake worldwide. Despite the satisfactory seismic performance of the building due to the presence of six EBF frames in each of the structure's principal directions, the fractures were observed in two braced bays. A typical fracture is shown in Fig. 1. Clifton et al. speculated that

the cause of this fracture might be due to a local stress concentration resulting from the fact that the brace flange was connected to the beam at an offset from the link stiffener. This hypothesis was supported by the observation that fracture didn't occur in cases where the flanges of the brace lined-up with the stiffeners.



Fig. 1. Fracture in EBF Observed in the Aftermath of Christchurch Earthquake Series (Clifton, et al. 2011)

The reported EBF fractures were studied in a forensic examination by Kanvinde et al. (2012). Material samples were extracted from the fractured structures and subjected to Charpy-V notch toughness tests and tensile tests, to establish if potential deficiencies in material properties could explain the observed fractures. The material test results revealed satisfactory ductile behavior for the extracted coupons. Some finite element analyses on EBF models with detailing similar to the fractured structures were also conducted, showing stress concentrations at the eccentricity between the link stiffener and the brace flange.

According to the survey of damage, there were other EBF frames in the same building, which did not have the mentioned offset in the brace-to-beam connection and showed a significant amount of yielding in the link without any fractures (Clifton et al. 2011). Imani and Bruneau (2015) conducted detailed finite element analyses on EBF frames with different geometry details regarding the location of stiffener at the brace to beam connection area and assessed the effects of connection detail on local stress/strain distributions and overall behavior of the frame.

This paper summarizes the key findings from that study and concentrates on the factors contributing to the EBF failure reported from the Christchurch earthquake.

CONNECTION DETAIL ALTERNATIVES

Four connection detail alternatives (shown in Figure 2) were arbitrarily selected in this and investigated using finite element analysis when subjected to monotonic and cyclic displacements.

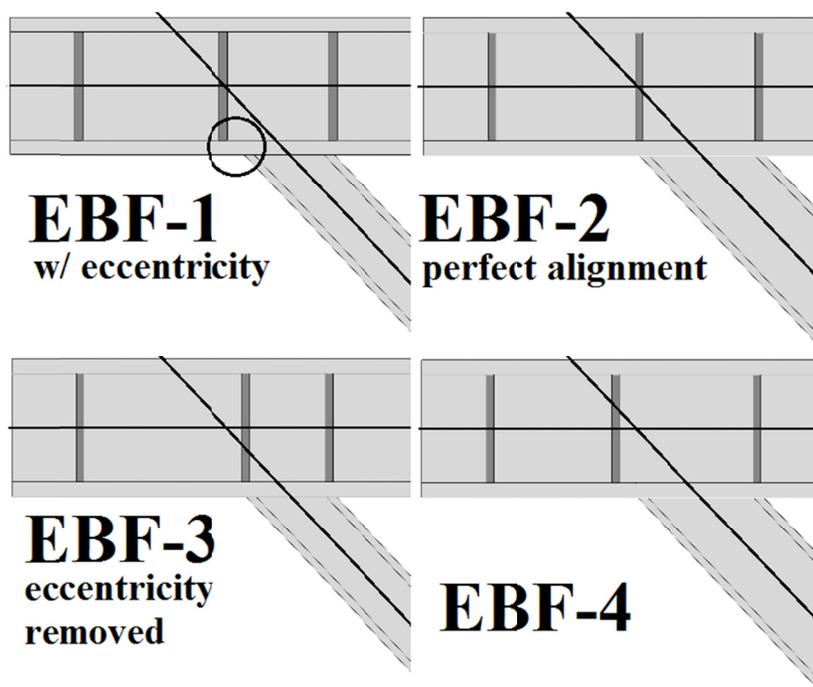


Fig. 2. Detailing alternatives for brace-to-beam connection

Case 1 is similar to the configuration used in the reported fractured EBFs in that the stiffener is placed at the intersection of the brace and beam centerlines but doesn't vertically line up with the edge of the brace flange; Case 2 represents the ideal configuration; The third case, EBF-3, is similar to EBF-1, except that the link end-stiffener has been moved to align vertically with the point where the flange of the brace is welded to the beam. Note that all four configurations are allowed per AISC 341-10.

Finite Element Modeling

General finite element software, ABAQUS, was used to study the behavior of the EBF frames with different connection details. The analysis model was built with 8-node 3D brick elements (C3D8R) and a non-uniform mesh pattern that was designed to be finer around the area of interest. Due to symmetry, only half of a typical EBF frame was modeled. To eliminate unnecessary complexities, the column and the brace were set to remain elastic throughout the analysis. The beam (including the link) and the stiffeners were modeled with a simple bilinear steel material with von-Mises yield criteria. Post-yield behavior was modeled with a linear strain hardening branch going to the strain value of 0.15 (hardening slope was defined to be 3% of the initial stiffness). The material was modeled to linearly lose strength from strain of 0.15 to 0.2 to crudely model damage in the elements at high strains. Assuming a simple connection at the base of the column, a cyclic lateral displacement was applied to the frame by pushing and pulling top of the column while its other end was simply supported. Fig. 3 shows different views of the finite element model.

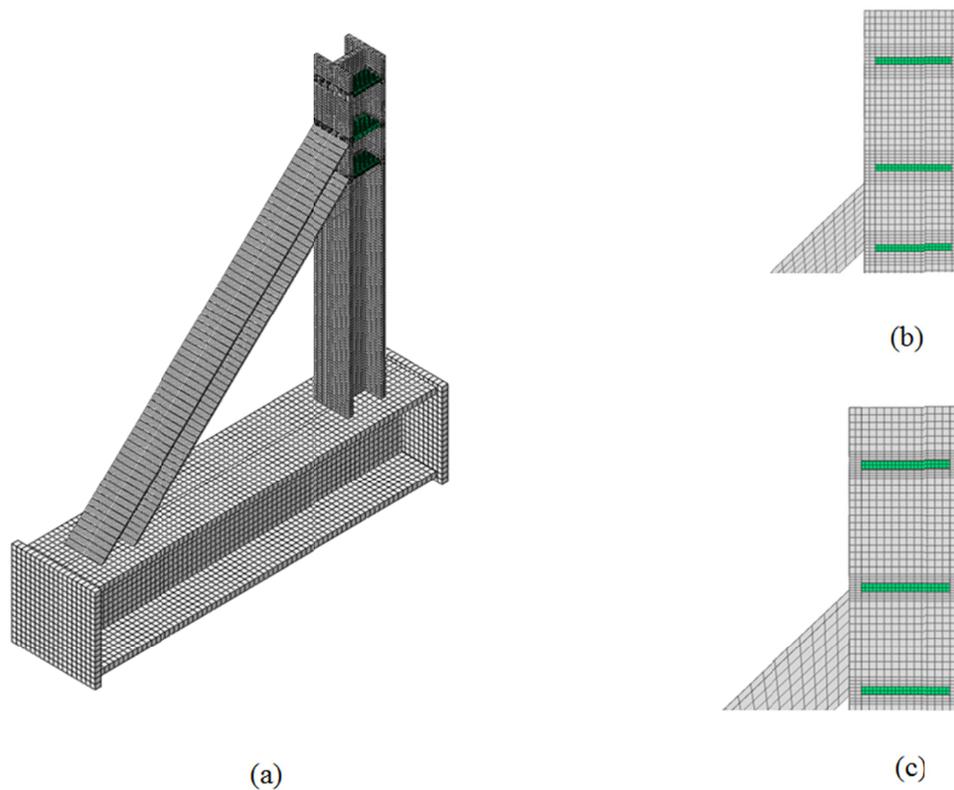


Fig. 3. Finite Element Modeling of The EBF System: (a) Complete Model; (b) Case 1 connection detail; (c) Case 2 connection detail.

FAILURE INVESTIGATION (CASE 1)

Fig. 4 shows the graphs of base shear versus plastic link rotation for EBF frame Case 1 under monotonic applied displacements in two opposite directions. Both of the curves show significant strength loss at plastic link rotation values in the range 0.15-0.2 rad (expected for properly stiffened EBF frames). Applying displacement in direction A causes tensile forces in the link bottom flange and applying displacement in direction B causes the opposite. Results show that EBF-1 loses strength at a relatively smaller plastic link rotation when monotonic loading is applied in the direction B.

Fig. 5 shows final deformation plots from the same analyses. Case A shows excessive deformations and element distortions in the web of the link close to one of the intermediate stiffener (typical behavior of EBF frames). On the other hand, Case B shows excessive distortions for a different group of elements which are located in the offset area which can be considered as a sign of improper behavior.

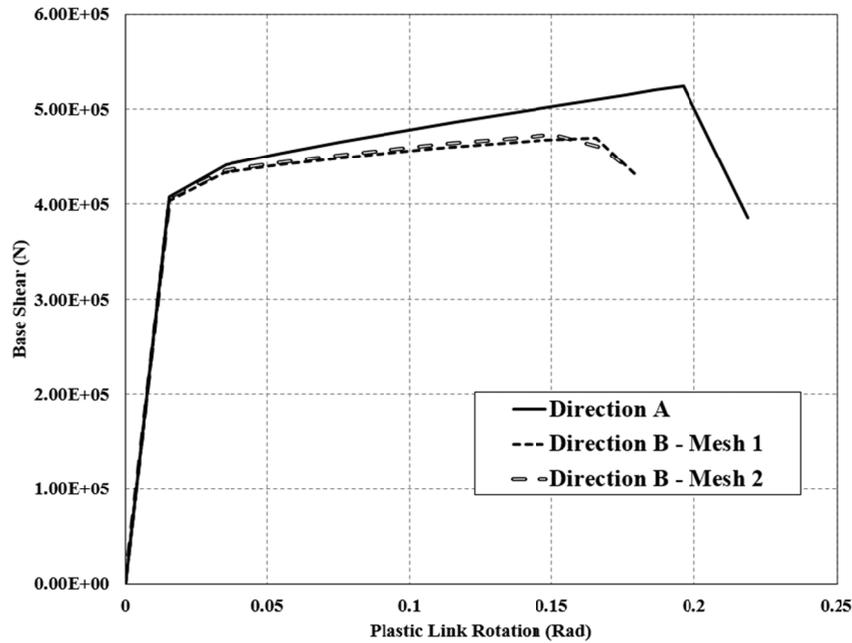


Fig. 4. Push-over analysis results for EBF-1 half frame under monotonic displacements in two opposite directions

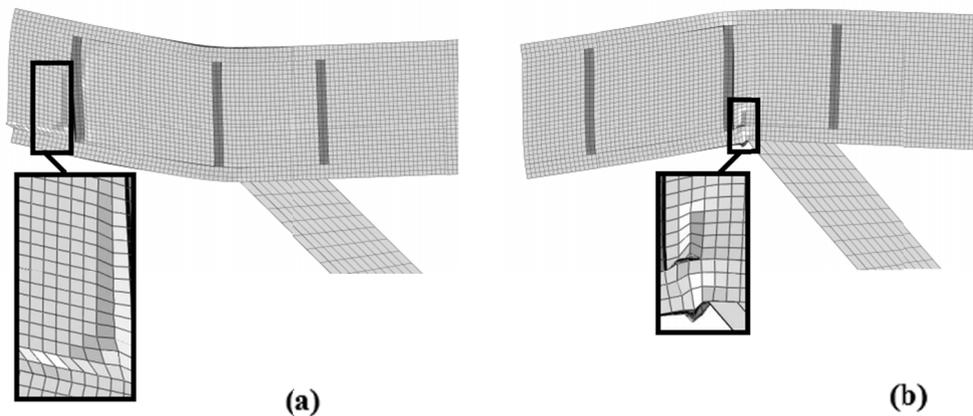


Fig. 5. Final deformation results from push-over analysis of EBF-1 in two opposite directions: a) direction A; b) direction B

The difference in the mechanisms leading to strength loss under loading from two opposite directions is due to the different stress and strain distributions in two cases. Fig. 6 shows the loads applied to the beam flange in the offset area for cases A and B. Looking into numerical solutions and Mohr circles of the two cases revealed that the combined axial and compression stresses in Case B pushed the elements in the offset area to surpass the Von Mises failure criteria leading to a sooner strength loss in the push over curve. For Case A, on the other hand, Von Mises stress values in the offset area remain below the failure limit until failure occurs in the web of the link.

Occurrence of failure in different location is also shown with plastic strain contours for both cases in Fig. 7.

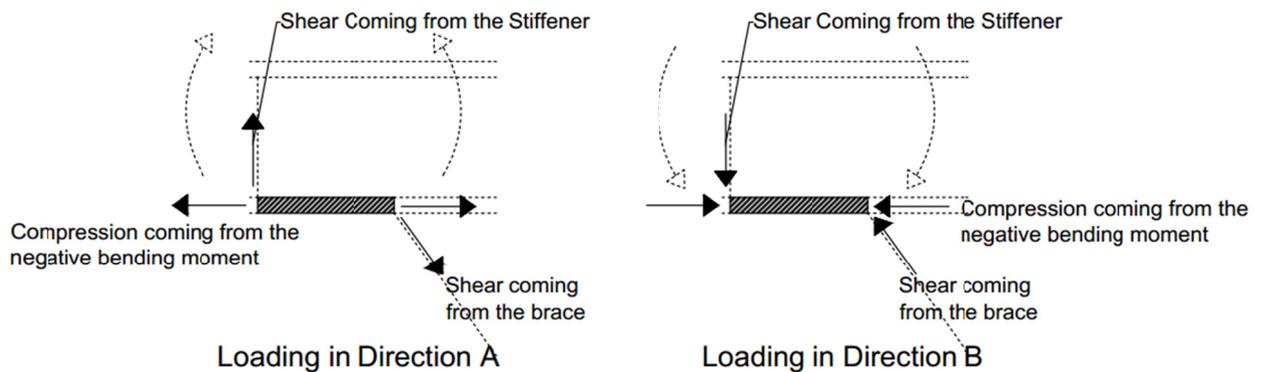


Fig. 6. Loads applied to the segment of the beam flange located at the offset

RESULTS FROM ALTERNATIVE DETAILS

Fig. 8 shows the resulting base shear versus plastic link rotation values from analyses of all four models subjected to cyclic displacements with increasing amplitudes. Cases 2 and 3 have reached the 0.08 rad plastic rotation limit (AISC 341-10 recommendation) without failure. However, cases 1 and 4 have reached failure at much lower plastic link rotation limits.

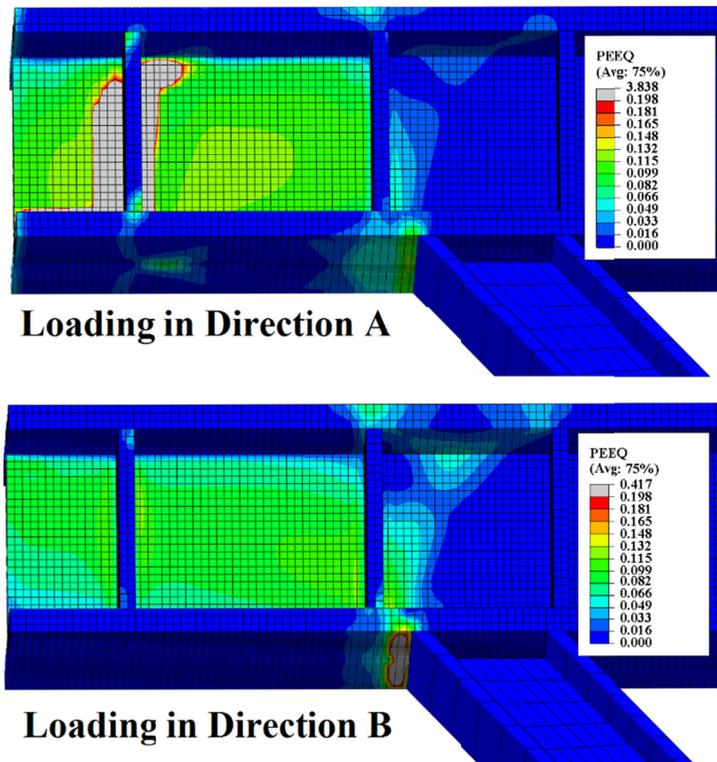


Fig. 7. Equivalent plastic strain distribution for EBF-1 under monotonic loading in two opposite directions

The superior behavior of cases 2 and 3 is due to proper distribution of plastic strain inside the EBF link, while cases 1 and 4 have severe stress and strain concentrations in the offset area, leading to a premature failure. Proper behavior of Case 3 shows that if the geometry of EBF-2 cannot be accomplished (due to limits in brace depth), satisfactory ductile behavior of the frame can still be ensured by locating the stiffener such as to eliminate the stiffener-to-brace flange offset.

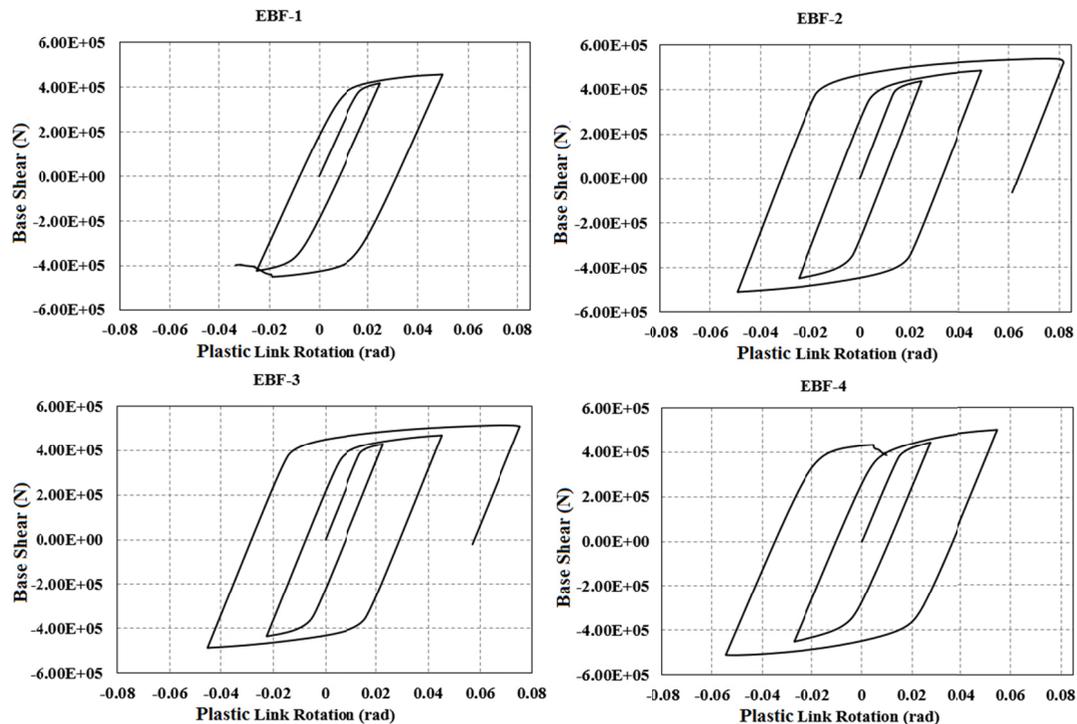


Fig. 8. Base shear versus plastic link rotation results from cyclic analyses

CONCLUSION

Eccentrically braced frames with different geometry configurations regarding the location of link end stiffener at the brace to beam connection area were modeled and analyzed with finite element method to study the effects of connection details on local and overall behavior of the frame. Special attention was paid to EBF failure reported following the Christchurch earthquake series of 2010 and 2011.

Results from limited monotonic and cyclic analyses showed that the eccentricity (misalignment) of link stiffeners with respect to the beam-to-brace flange connection point is responsible for the observed premature failures outside of the link. This is due to severe stress and strain concentrations in the offset area.

Modifying the section of the brace to achieve a condition in which the intersection of the beam and brace centerlines line up vertically with the edge of the brace flange as well as with the link-end stiffener was shown to be effective in solving the fracture

problem by properly distributing the plastic strain inside the link. Results showed that in case of geometric limitations to achieve the perfect alignment, simply moving the stiffener to remove the offset can also lead to an acceptable EBF behavior.

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