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Investigation of innovative steel concentrically braced frame connections using advanced analytical models

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ABSTRACT

Moderately ductile concentrically braced frame (MDCBF) is a highly stiff and efficient seismic force resisting system. Hollow Structural Steel (HSS) members are commonly used as the structural steel brace for MDCBF. They have demonstrated good performance in past earthquakes. A common connection for this type of braces to use slotted hole where the HSS is welded to a gusset plate. Due to the lower cross sectional area around the slotted connection, steel cover plates are welded to both side of the HSS to prevent net section failure. In this paper, an advanced finite element model is developed to simulate the monotonic and cyclic behaviour MDCBF. The numerical model is validated against experimental results. The results show that the numerical model is capable of simulating the cyclic hardening, fracture, and buckling of the HSS braces. The validated numerical model is then used to investigate the performance of HSS braces with side plates with different HSS compactness and slenderness ratios. The results show the compactness and slenderness ratios of HSS could have a significant impact to the failure mode when the HSS is connected to the slotted gusset plates and reinforced with side cover plates.

Keywords: Concentrically braced frames; HSS; Side cover plate;

1 INTRODUCTION

Moderately ductile concentrically brace frame system (MDCBF) using Hollow Structural Steel (HSS) brace is a simple and economical way to provide the stiffness and energy dissipation capacity needed for earthquake loads. There have been many numerical and experimental studies that have been conducted to investigate the behaviour of the braces and connections of MDCBFs [1-17]. In these studies, various failure modes, such as fracture along the welded connections between the HSS and the gusset plate and between the gusset plate and the column, fracture in the brace due to out-of-plane buckling, and net area fracture of the HSS, have been observed. Many different variables, such as material properties, frame detailing, initial imperfections, stiffness of the braces, beams, columns and gusset plate have significant influence on the failure modes. Fig. 1 shows some of the failure modes observed from past experimental tests. Fig.1a shows the section failed through local buckling follow by net section fracture. Fig.1b shows the HSS failed through net section fracture.Fig.1c shows when side plates are added to the HSS, the net section fracture cannot occur, but the initial crack around the net section results to eccentric loading to the brace, which eventuallyrupture the welds. Fig.1d shows out of plane buckling of the HSS brace.

In general, side cover plates are added to the HSS to eliminate the net section failure. To examine the failure modes of HSS elements with side cover plates, an advanced finite element model (FEM) was developed. The model was verified against experimental data [21-22]. The result showed the developed model is capable of simulating the localized stress and strain distribution, until the member fractured under monotonic and cyclic loads. Using this model, the cyclic response of typical HSS connected using slotted gusset plate connections was investigated. The results showed that when two side plates are welded to the HSS, the axial stiffness of the brace increases significantly around that

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cover plate area, this leads to high stress concentrations in the HSS under compression load. With different slenderness and compactness ratios, the brace could local buckle (see Fig. 1a) or global buckle (see Fig. 1d). A detailed parameter study was conducted to examine the different failure modes of the HSS brace with side cover plates.

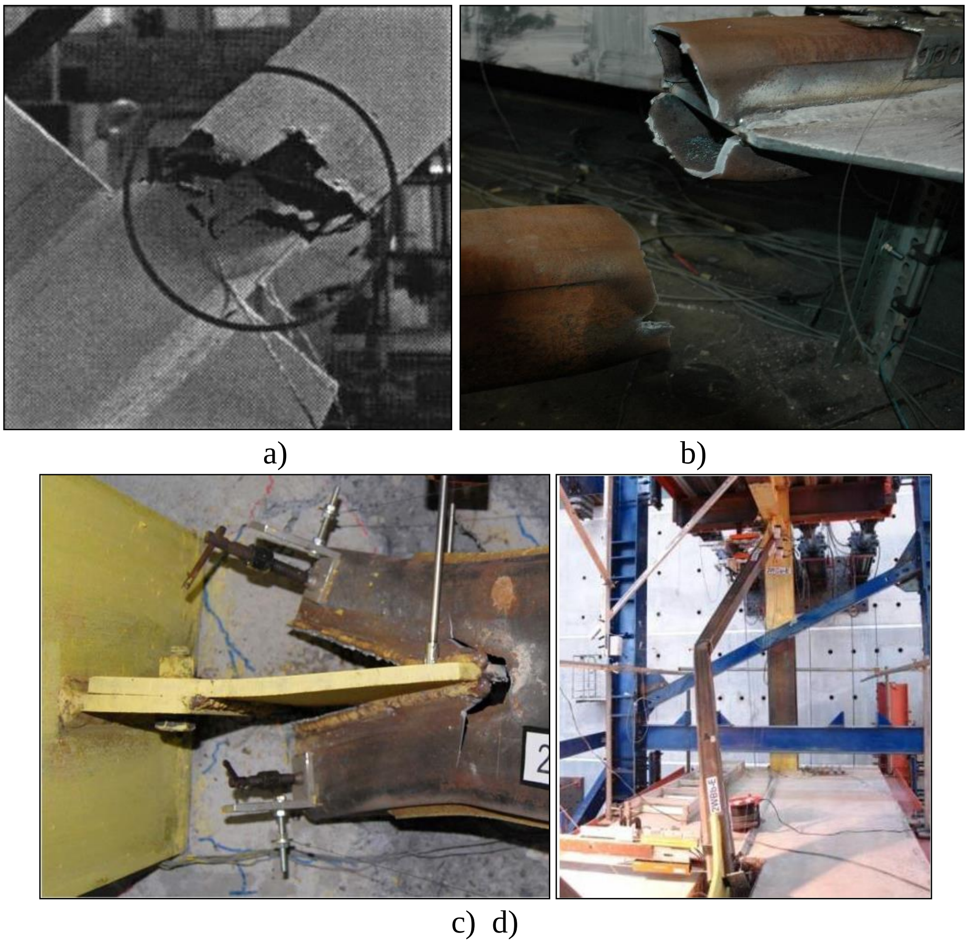


FIG. 1: A) SLOTTED END CONNECTION FRACTURE OF UNREINFORCED HSS ELEMENT [18]; B) TENSION FRACTURE OF UNREINFORCED HSS ELEMENT [19]; C) TENSION FRACTURE OF REINFORCED HSS ELEMENTS [20]; D) OUT OF PLANE BUCKLING OF THE BRACE [22]

2 DEVELOPMENT OF FINITE ELEMENT MODEL

Previous researchers have developed numerical models to simulate the nonlinear behaviour of concentrically braced frame [23-24]. However, these studies were focused on the overall frame behaviour not the detailed localized stress-strain distribution of HSS with slotted connections. In this paper, an advanced modeling approach which is capable of modeling the fracture behaviour of the HSS was developed using Abaqus6.10.1[25].In this modelling technique, deformable solid 8-noded elements with reduced integration (C3D8R) was used to model the beam, column, brace, gusset plate and weld. The C3D8R element has the ability to utilise the reduced integration and hourglass control, which is ideal modeling the fracture behaviour of steel material. Different mesh sizes were studied and it was determined that a mesh size of 10 mm is suitable to simulate the fracture response of full size HSS with slotted gusset plat connections. The anchor bolts were modelled with the 4 node 3D bilinear rigid quadrilateral discrete rigid element (R3D4in Abaqus). The material property was calibrated using material property obtained from notched bar specimen [21]. The material was modelled using the true stress-strain relationship, where the fracture strain was obtained from test data. Special element removal technique was implemented when the element reached the fracture strain. The loads were then redistributed among the remaining elements.

Fig. 2 shows the fracture behavior of the specimen observed from the analytical and experimental studies. Fig. 3 shows the force-deformation relation comparison between the analytical and experimental studies.

In addition to the verification on the component level, the same modelling approach was verified on the system level using the experimental test, as shown in Fig. 4, conducted by Roeder et al. [22]. The experimental test was a part of an experimental program which conducted at the NCREE facility in Taiwan based on a two-story, two-bay special concentrically braced frames (SCBF). It should be note that MDCBF used in Canada is intended to have similar performance as the SCBF in the United States. Fig. 5 shows the comparison of the force-deformation response of the frame observed and simulated from the experimental and numerical studies. The displacement time history from the experiential data was applied to the frame at the location of the actuator. The results showed that the frame sustained 21 cycles of loads before the brace at the first and second story fractured.

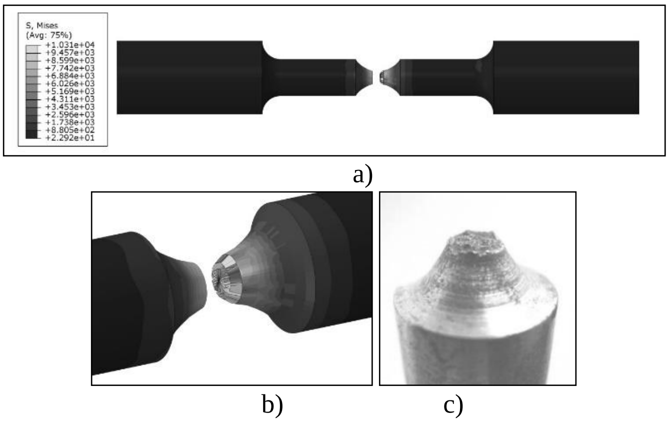


Fig.2: a) Stress in steel specimen applying tension force; b) Fracture in finite element model; c) Fracture in experimental model [21].

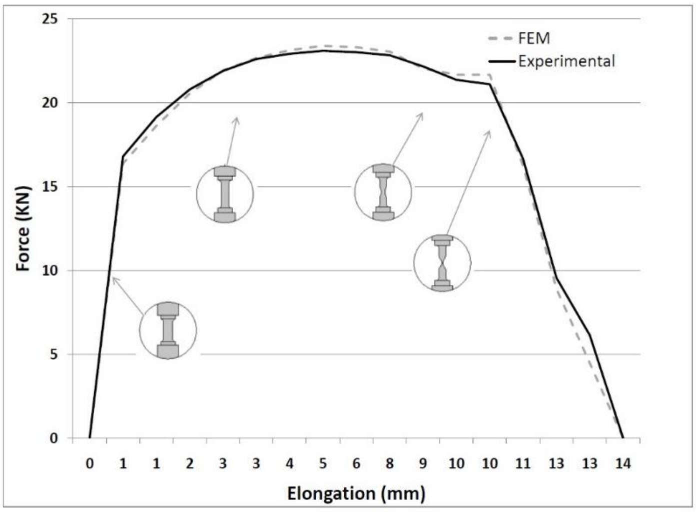


Fig. 3: Force-Elongation diagram from experimental data [21] and FEM results.

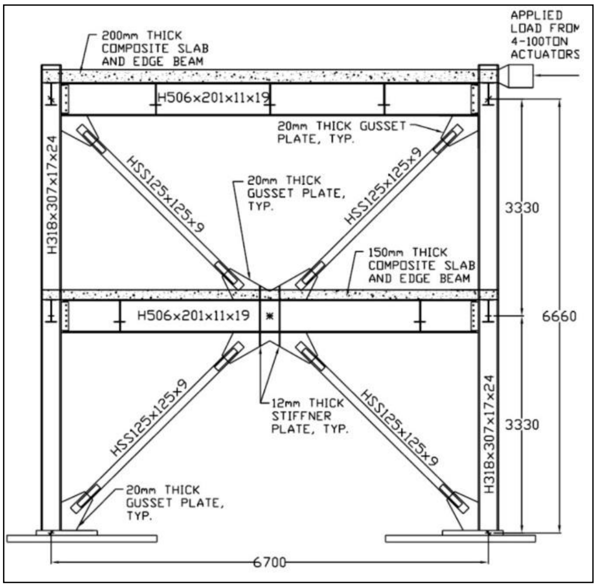


Fig. 4: Elevation of the model and the profiles type [22].

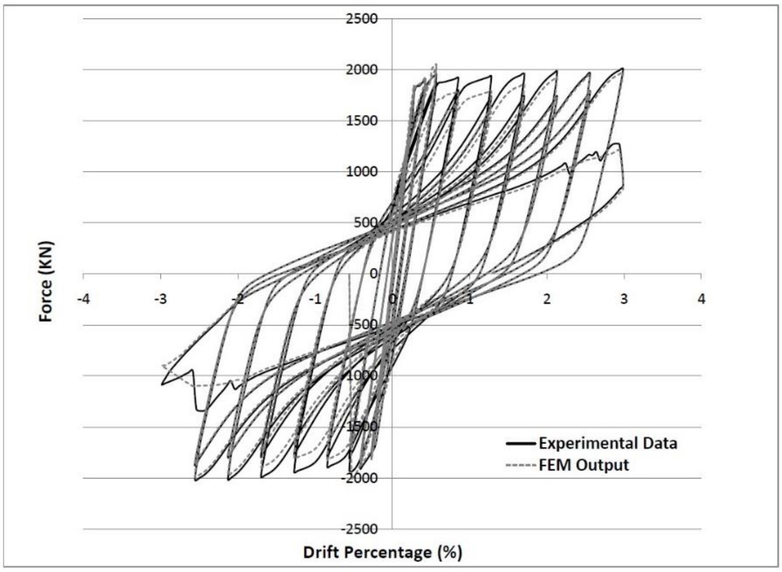


Fig. 5: Hysteresis loop comparison between the experimental [22] and FEM simulations.

Fig. 6 and Fig. 7 show the FEM deformation and test deformation in gusset plates and braces. The result shows that the FEM is capable of modeling the nonlinear response of the frame.

Fig. 6: Deformation between the experimental [22] and FEM simulations.

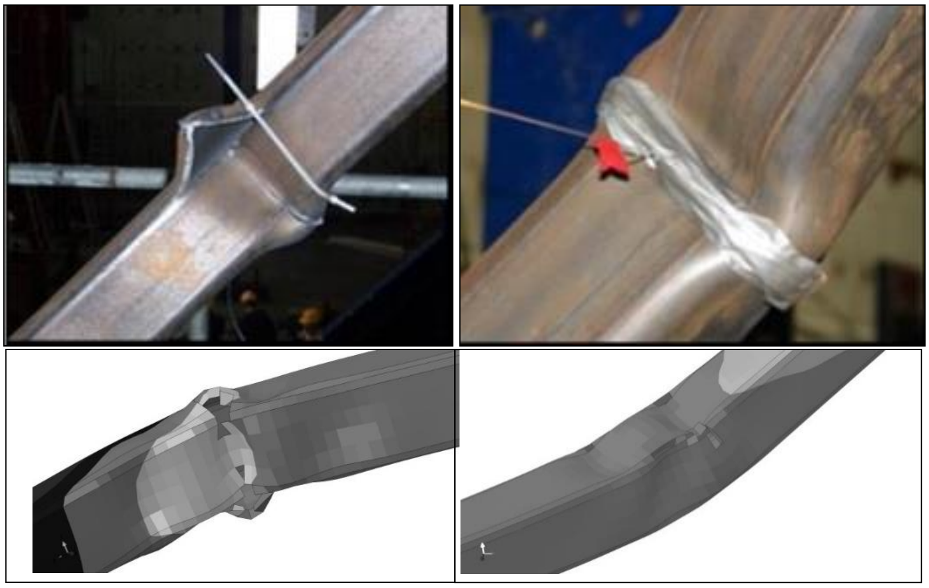


Fig. 7: Local buckling mode between the experimental [22] and FEM simulations.

3 NUMERICAL STUDIES

To systematically examine the failure modes of HSS brace elements with side cover plates, 47 finite element models with different HSS compactness (w/t) ratios and slenderness ratios (kl/r) were investigated. To limit the scope of the study, the simulation assumed the gusset plates were rigid, where it will not have buckled out of plane nor fracture within the plate or at the interface of the column and beam connection. In addition, the side plates were assumed to be rigid as well. Uniform monotonically increasing displacements were applied to the brace until the brace buckled locally or globally. Fig. 8 shows the finite element model developed for this study.

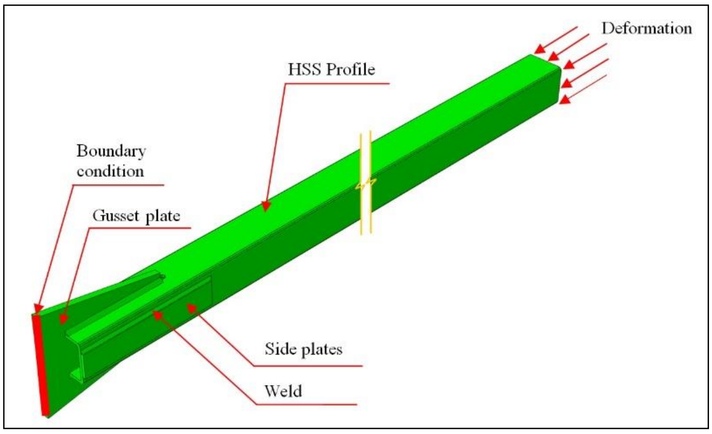
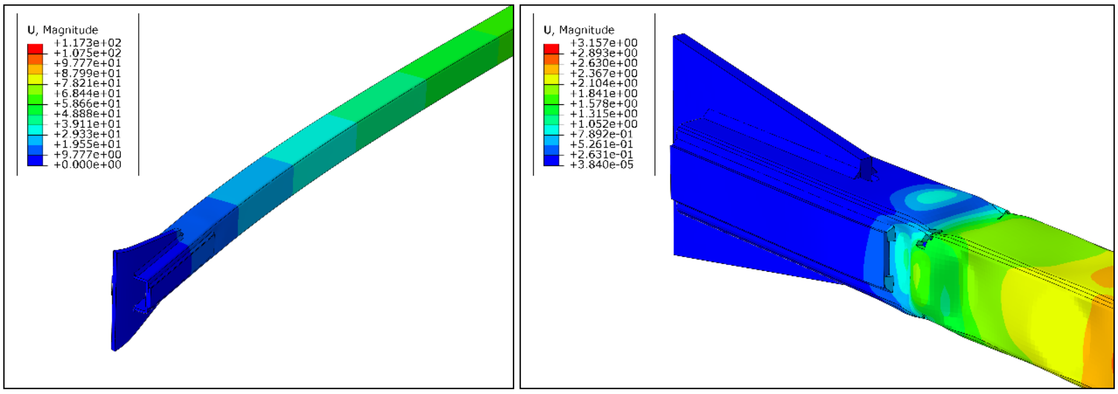


Fig. 8: Developed FEM for HSS with different compactness and slenderness ratios.

Slenderness ratios of the braces between 40 to 120were included in this study. Compactness ratio (w/t) of the braces was limited to 22.6 which is consistent with the limit set by CSA-S16 [26] for MDCBF. Depending on the slenderness ratio and compactness ratio one of two failure modes were observed: brace buckle out of plane or brace local buckle near the side plate connections. Fig. 9a and Fig. 9b show the out of plane buckling of the HSS brace and local buckling of the brace around the connection, respectively.



a) b)

Fig. 9: a) Out-of-plane buckling of the brace; b) Local buckling of the HSS near the connection of the side plates

Fig. 10 shows the results of the parameter study. In addition, 3 experimental data were included in the plot [17, 20]. The result shows as the slenderness ratio (kl/r) increases, the failure mode changes from local buckling to global buckling. The limit increases as compactness (w/t) ratio increases. An equation, Equation 1, as shown in line A is derived.

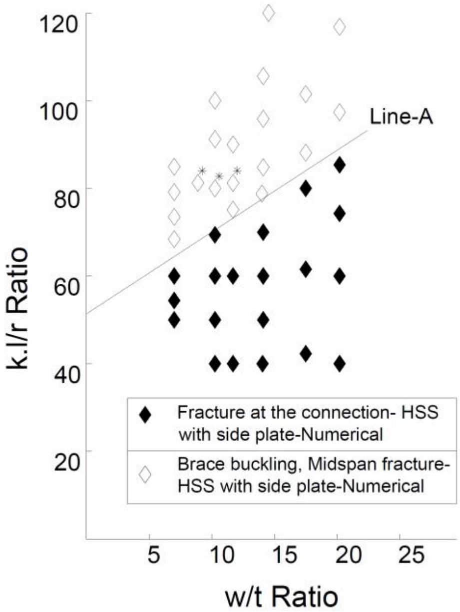


Fig.10: Different failure mode of HSS with different wall to thickness and slenderness ratios. ('*' shows the experimental data)

$$\left(\frac{k.l}{r}\right) = 51 + 1.87\left(\frac{w}{t}\right) \qquad (1)$$

In addition to the change in failure model as observed in Figure 10, the failure displacement for the above mentioned parameters were calculated. This displacement was normalized using the life safety limit of the HSS braces in compression as presented in ASCE-SEI 41-13 [27]. Fig. 11 shows the normalized ratio for the HSS sections with different compactness and slenderness ratios. The results show as the compactness ratio (w/t) decreases the failure displacement increases. Similarly, as the slenderness (kl/r) ratio increases, the failure displacement increases.

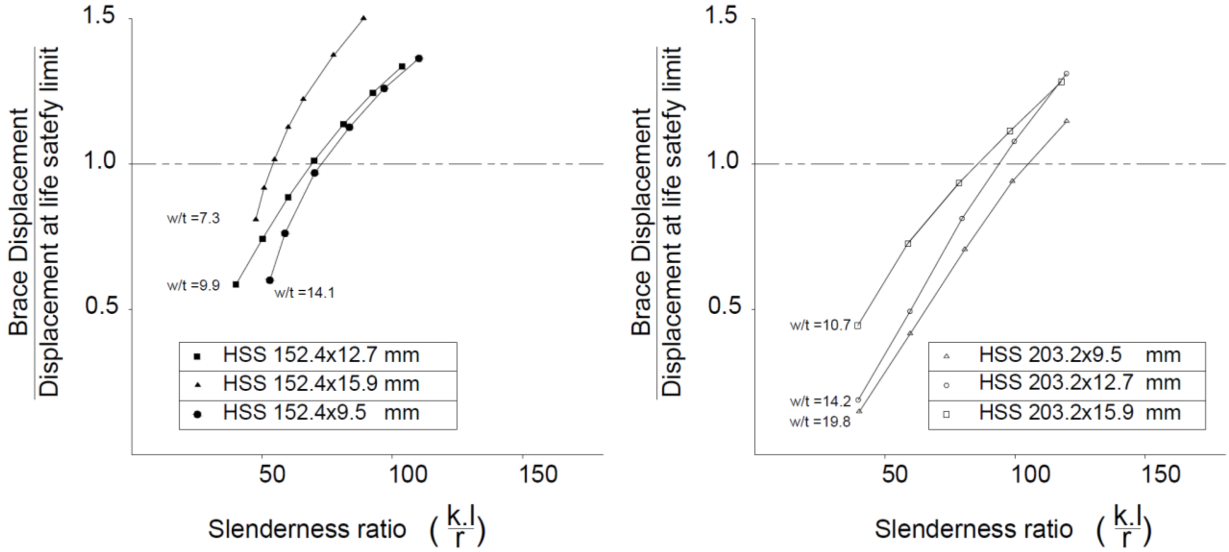


Fig. 11: Comparison the displacement to life safety displacement limit for HSS elements with different slenderness and compactness ratios

4 CONCLUSION

MDCBF is an efficient seismic force resisting system (SFRS) that is commonly used in Canada for area of high seismic activities. In this type of SFRS, HSS with slotted gusset plate is a common connection. To prevent the brace from net section failure, side cover plates are typically added to the HSS through welding. This increases the net section area of the HSS, which eliminate the brace from fracture. However, the added side plate increases the axial stiffness of the HSS, which lead to stress concentration to the HSS, which lead to local buckling of the brace under compression. To systematically examine the failure mode of the HSS with side plates and slotted gusset plate connection, a robust finite element model was developed. Detailed parameter study of the model with varying slenderness (kl/r) and compactness (w/t) ratio was conducted. The result shows as the slenderness ratio (kl/r) increases, the failure mode changes from local buckling to global buckling. Similarly, as the compactness (w/t) ratio decreases, the failure mode will also change from local buckling to global buckling. In addition to the above mentioned trend, the failure displacement of the HSS with side cover plates and slotted gusset plate connection was compared with the life safety displacement limit as specified in ASCE-41, the result shows as the compactness ratio (w/t) decreases or the slenderness (kl/r) ratio increases, the failure displacement increases. Hence, it is crucial to select HSS section with side plates and gusset plate connection with sufficient slenderness (kl/r) and compactness (w/t) ratios as presented in Equation 1.

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