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Numerical study on force transfer mechanism in through gusset plates of SCBFs with HSS columns & beams

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Abstract. In Special Concentrically Braced Frames (SCBFs), vertical and horizontal components of the brace force must be resisted by column and beam, respectively but normal force component existing at the gusset plate-to-column and beam interfaces, creates out-of-plane action making distortion in column and beam faces adjacent to the gusset plate. It is a main concern in Hollow Structural Section (HSS) columns and beams where their webs and gusset plate are not in the same plane. In this paper, a new gusset plate passing through the HSS columns and beams, named as through gusset plate, is proposed to study the force transfer mechanism in such gusset plates of SCBFs compared to the case with conventional gusset plates. For this purpose, twelve SCBFs with diagonal brace and HSS columns and twelve SCBFs with chevron brace and HSS columns and beams are considered. For each frame, two cases are considered, one with through gusset plates and the other with conventional ones. Based on numerical results, using through gusset plates prevents distortion and out-of-plane deformation at HSS column and beam faces adjacent to the gusset plate helping the entire column and beam cross-sections to resist respectively vertical and horizontal components of the brace force. Moreover, its application increases energy dissipation, lateral stiffness and strength around 28%, 40% and 32%, respectively, improving connection behavior and raising the resistance of the normal force components at the gusset plate-to-HSS column and beam interfaces to approximately 4 and 3.5 times, respectively. Finally, using such through gusset plates leads to better structural performance particularly for HSS columns and beams with larger width-to-thickness ratio elements.

Keywords: through gusset plate; force transfer mechanism; special concentrically braced frame; HSS column and beams

1. Introduction

Many studies on CBF have focused on adding ductile elements in bracing system to prevent buckling of the braces and thus limiting energy dissipation in those ductile segments (e.g., Zahrai and Jalali 2014, Zahrai 2015). However in SCBFs, braces dissipate earthquake energy with plastic deformations due to their inelastic buckling and tensile yielding. Since unsatisfactory performance of Special Moment Resisting Frames (SMRFs) was reported during the 1994 Northridge and 1995 Kobe earthquakes, SCBFs have been reliably used by structural engineers in the past few decades (FEMA 2000).

HSS cross-sections have large moment of inertia and radius of gyration, high torsional strength and stiffness in addition to proper axial strength and stiffness. Hence these cross-sections are mostly used against axial loads. Due to aforementioned advantages for HSS cross-sections, their use as columns and braces is very common. However, the connection of gusset plate to HSS column and beam has always been a challenge because their webs and gusset plate are not in the same plane.

Some studies were carried out on square and rectangular HSS braces by Tremblay (2002) and Shaback and Brown (2003). Test results showed that effective slenderness ratio and width-to-thickness ratio are the most important factors in hysteretic behavior of braces.

Fell (2008) and Fell and Kanvinde (2010) carried out some tests on nineteen full-scale braces. Cross-section in their tests included square HSS, standard circular HSS and wide flange. They studied the width-to-thickness ratio, brace slenderness ratio, bracing cross-section shape, loading history, loading rates and connection details. It was indicated that circular HSS and wide flange cross-sections show more deformation to failure due to more gradually having local buckling in comparison with square HSS. Square HSS creates large strains at the corners of cross-section and makes cross-section more susceptible to failure. It was concluded that loading rates have negligible effect on buckling and brace failure responses.

Limited experimental investigations have been carried out on gusset plates compared to conducted experiments on braces. Failure of gusset plate connections may lead to significant decreases in strength and stiffness of braced

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frames against lateral loading and such a decrease may cause soft story mechanism in the structure. The most significant investigation on gusset plates was done by Whitmore (1952) who supposed that the stresses are uniformly distributed over an effective area at the end of the brace. He indicated that the effective area of gusset plate through the last line of connectors is established by drawing 30-degree lines from the first connector.

Thornton (1984) presented a lower bound method for determination of compressive strength of gusset plates. From investigation of Williams and Richard (1986) it can be concluded that the connection of braced spans will change to rigid state according to codes due to existing gusset plates, even if the simple connections are used.

Uriz and Mahin (2004) investigated a full-scale one-bay two-story SCBF with chevron brace subjected to quasi static cyclic loading. Main plastic responses were observed in the first story with brace buckling in compression and yielding in tension and as a result the soft story mechanism occurred at the lower story. Plastic hinges formed in the brace member (one at mid-length of the brace and the other two at $2t_{Gp}$ distance in the gusset plates). This experiment proved concerns to soft story mechanism formation in multi-story SCBFs. Lai and Mahin (2013) tested three full-scale one-bay two-story braced frames subjected to quasi static cyclic loading in the University of California, Berkeley. They showed that the braced frame with circular HSS braces has more lateral deformation capacity than those with square HSS and wide flange braces before the beginning of significant strength losses. They also indicated that braces with circular HSS demonstrate more strength than other cross-sections against local buckling appearing later.

Hadianfard and Khakzad (2016) investigated the buckling and post-buckling behavior of gusset plates through finite element non-linear static analysis. They concluded that the position of the bracing splice plate regarding the free bending line and the size and thickness of the gusset plates affect their capacity, buckling and post-buckling behavior. Izadi and Aghakouchak (2018) studied seismic provisions of built-up SCBFs using non-linear finite element analysis of single diagonal and X-braced frames. They indicated that the 0.4 ratio related to slenderness ratio of individual elements between stitch connectors is conservative and can be increased based on the brace type.

In many experimental and numerical studies carried out in the recent two decades, gusset plates are mostly connected to H-shaped columns. Although obvious difference exists between gusset plate-to-HSS and H-shaped column connections, limited studies have been conducted on the gusset plate-to-HSS column connections. Various studies have been carried out on I-shaped beam to HSS column connections in SMRFs. These studies have proposed using external T- and angle stiffeners (Lee *et al*. 1993, Shin *et al*. 2004), external triangular plates (Ting *et al*. 1991), inclined rib-plated collar-plated configuration with web plates (Goswami and Murty 2009), top flange stiffener with side stiffener (Kiamanesh *et al*. 2010), vertical plate passing through the square HSS column (Mirghaderi *et al*. 2010, Torabian *et al*. 2012), bolted end-plate welded to a short stub beam (Erfani *et al*. 2016), double-angle bolted (Song *et al*. 2016), two external diaphragm collar plates welded to perimeter of the circular HSS column (Sabbagh *et al*. 2013) and end-plate to HSS (EP-HSS) using a wide flange beam and HSS column (Nuñez *et al*. 2017).

Gusset plate connection to HSS column was investigated only by Kosteski and Packer (2003) and Alipour (2009). Kosteski and Packer (2003) provided a set of numerical and experimental studies on gusset plate to rectangular HSS column connections. They applied a through plate for increasing gusset plate connection strength at both flanges of rectangular hollow section. They checked two series of gusset plate connections to rectangular HSS columns, one with and the other without the through plate. Due to existing two yield lines in the connection model with the through plate (in the two flanges of rectangular HSS), they concluded that connection model with the through plate can lead to have a connection strength two times more than the connection model without the through plate. Alipour (2009) presented a gusset plate connection to the HSS columns using a through plate in CBFs. Her model caused to improve force transmission from the brace member to the column web.

Generally, gusset plate connections to HSS column and beam are designed similar to gusset plate connections to H-shaped column and I-shaped beam. Moreover, the forces at gusset plate interfaces are calculated using various methods such as Uniform Force Method (UFM) (AISC 2016b), method by Ebrahimi *et al*. (2019). However, these methods proposed for H-shaped column and I-shaped beam cannot be generalized for HSS column and beam. For gusset plate to HSS column and beam connections, since the gusset plate and webs of HSS column and beam are not necessarily in the same plane, the gusset plate does not have sufficient stiff support. Accordingly, large distortion and out-of-plane deformation occur in HSS column and beam faces at the vicinity of the gusset plate. This problem may result in the fracture of end gusset plate connection and stiffness degradation of the brace preventing complete transfer of the brace force and finally decreasing lateral strength and stiffness of the whole braced frame. This study proposes a new connection named "through gusset plate" approximating its behavior to that of H-shaped column and I-shaped beam gusset plate connection. It is expected that through gusset plate creates a sufficient support transmitting forces directly and eliminating large distortion and out-of-plane deformation in HSS column and beam faces at the vicinity of the gusset plate. Hence in such cases, using the Uniform Force Method (UFM) (AISC 2016b) and the method by Ebrahimi *et al*. (2019) can be acceptable.

In this study, to innovatively evaluate through gusset plate performance improvement in their connections to the HSS columns and beams, twelve one-bay two-story SCBFs with diagonal brace and square & circular HSS columns and twelve one-bay two-story SCBFs with chevron brace and square & circular HSS columns and square HSS beams are studied. These frames for two cases with conventional and through gusset plates are considered. These frames have same properties except for shape and thickness of columns and thickness of square HSS beams. In this investigation, the strength and stiffness of frames with through gusset plates are compared to those of the frames with conventional gusset plates. The effect of through gusset plate in preventing distortion and out-of-plane deformation of HSS column and beam faces that are adjacent to gusset plate is investigated too. Also, in this study the role of through gusset plate in increasing the resistance of the normal force components at the gusset plate-to-HSS column and beam interfaces is assessed.

2. Proposed connection and force transfer mechanism

Brace member and its two gusset plates at the ends behave similar to three springs in series for braced frames with the same force (Fig. 1).

The stiffness of set of brace and end gusset plates is given as follow

$$\frac{1}{K}=\frac{1}{K_{GP1}}+\frac{1}{K_{brace}}+\frac{1}{K_{GP2}} \tag{1}$$

It can be concluded from the Eq. (1) that the stiffness of the set is less than the stiffness of every spring. If gusset plate loses its stiffness and strength due to out-of-plane action of column and beam faces at the connection, the stiffness of the gusset plate will reduce and as a result, the general stiffness reduces leading to a decrease in entire lateral stiffness of the braced frame.

In this research, a new connection is proposed (Figs. 2 and 3) that consists of a one-piece gusset plate (gusset plate is assembled with partial beam web that its length is equal to length of gusset plate-to-beam interface) passing through HSS column at the joint area and is named through gusset plate in this study.

As shown in Figs. 2(a) and 3(a), in connection area, HSS column is divided into two parts and aligned slots are placed on HSS column and through gusset plate passes through these slots and gets connected to them. In I-shaped beam connection to through gusset plate, to simulate the flanges of beam continuing to the column face, the finger stiffeners are connected to both sides of one-piece through gusset plate and then I-shaped beam is connected to through gusset plate by two web connection plates on both sides of through gusset plate. In square HSS beam, slots are placed on beam flanges and longitudinal connections of the flanges to both sides of through gusset plate, provide square HSS beam connection to through gusset plate. Through gusset plate can be used in orthogonal braced frames by a cruciform through gusset plate to assemble the beams in the vertical directions more easily.

Beside the shear force (V_{uc}) which is essential action at

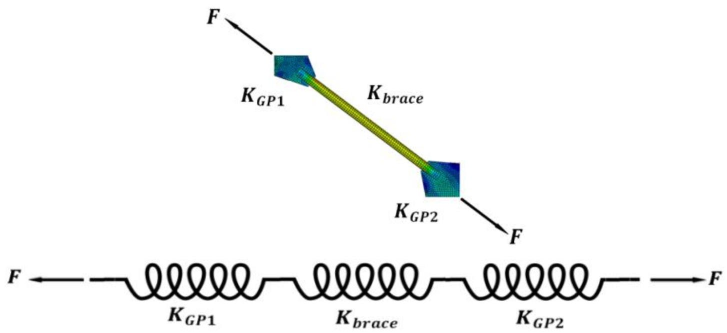
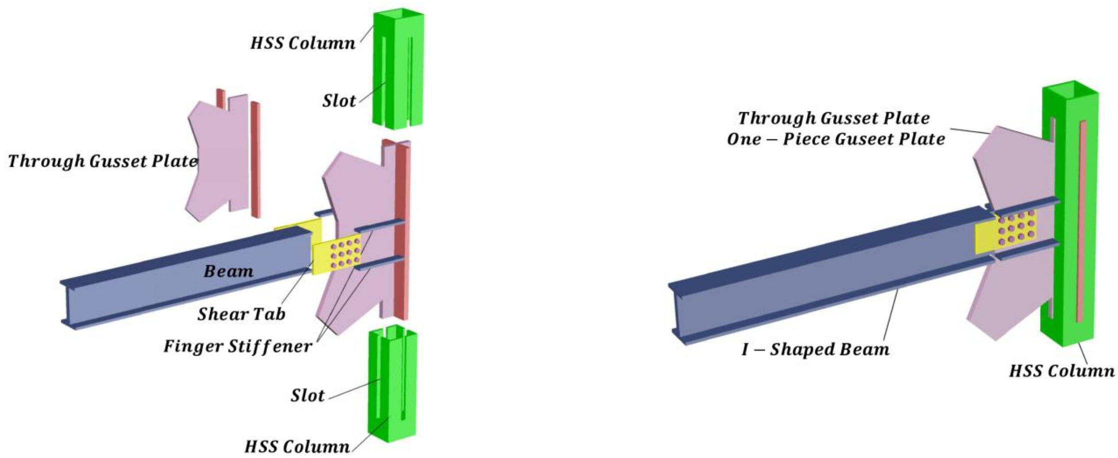


Fig. 1 Sequence of gusset plates and brace



(a) (b)

Fig. 2 Frame with I-shaped beam (a) Through gusset plate assembly; (b) Through gusset plate configuration

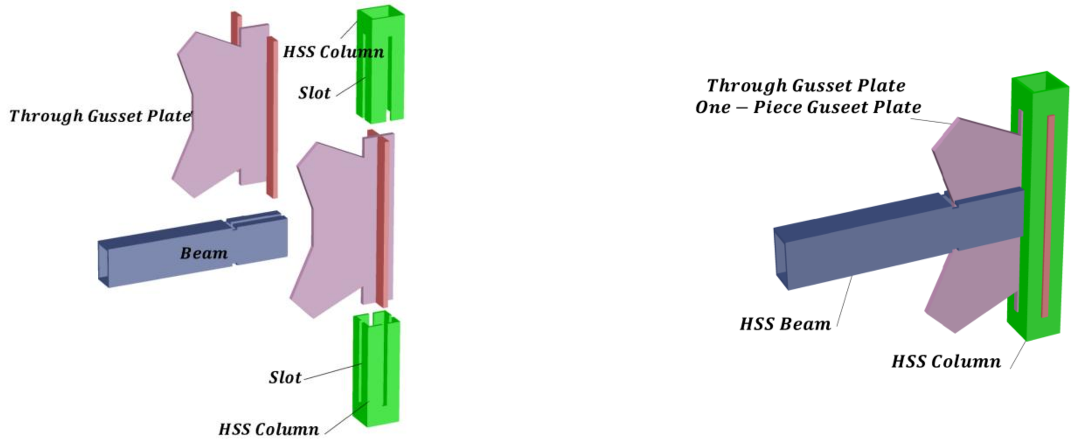


Fig. 3 Frame with HSS beam (a) Through gusset plate assembly; (b) Through gusset plate configuration

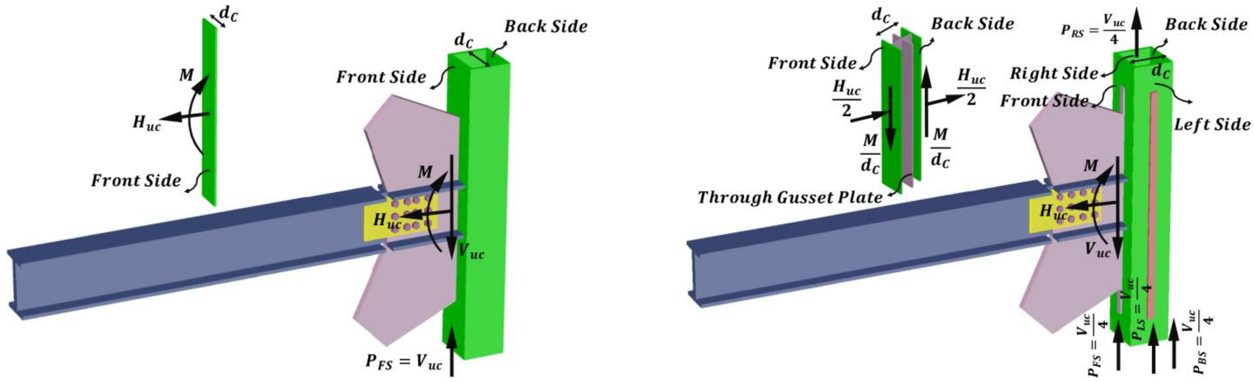


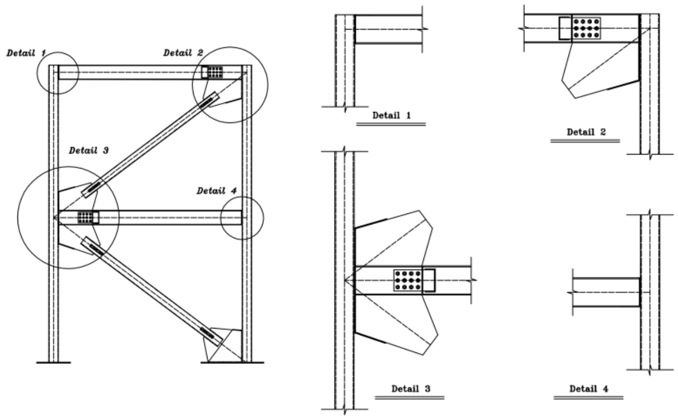
Fig. 4 Force transfer mechanism (a) Conventional gusset plate; (b) Through gusset plate

the gusset plate-to-column interface, there are other actions including normal force (H_{uc}) and bending moment (M). However, it should be noted that the normal force, H_{uc}, and the bending moment, M, own small values compared to shear force, V_{uc} (Ebrahimi *et al*. 2019). In connection area of conventional gusset plate, these three actions are imposed to the front side of HSS column at the connection. In other words, the entire HSS column cross-section does not participate in sustaining the forces transmitted from the gusset plate. As shown in Fig. 4(a), the normal force, H_{uc}, and the bending moment, M, are tolerated by out-of-plane action of the front side of HSS column. Therefore, these load components can impose large distortion and out-of-plane deformation which may result in connection fracture.

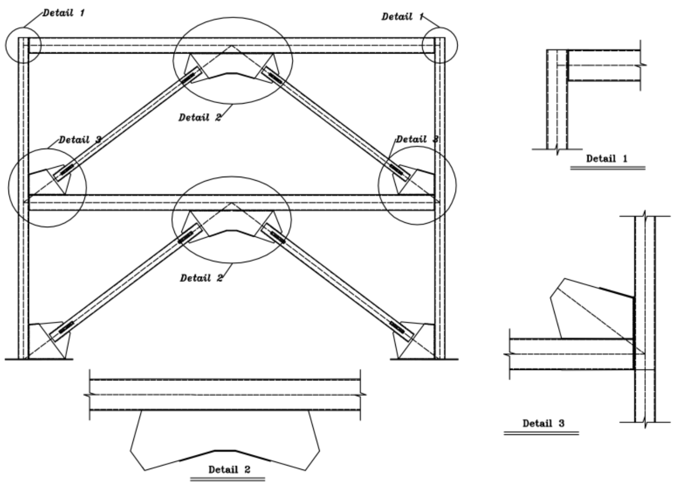
However in case of through gusset plate, just a part of the shear force, V_{uc}, is imposed to the front side of HSS column at the connection and the rest is transferred to other sides (back, right and left) by through gusset plate. Based on equilibrium equations, it can be concluded that $P_{FS} = P_{BS}$ and $P_{RS} = P_{LS}$ in which P_{FS}, P_{BS}, P_{RS} and P_{LS} are transferred forces to front, back, right and left sides of HSS column, respectively. It should be noted that through gusset plate inside HSS column has four parts behaving similar to four springs in parallel; consequently the relationship between mentioned forces follows this expression: $P_{FS} = P_{BS} = P_{RS} = P_{LS} = \frac{V_{uC}}{4}$. In other words, the presence of through gusset plate leads to participating the whole HSS column cross-section in sustaining the shear force, V_{uc}, transmitted from gusset plate. As shown in Fig. 4(b), the normal force, H_{uc}, is sustained by out-of-plane action of the front and back sides of HSS column and thus this force has more appropriate support than that in conventional gusset plate connections. Moreover, the induced bending moment, M, at the gusset plate-to-column interface can be replaced by a couple of shear forces $(\frac{M}{d_C})$ on two opposite sides of through gusset plate. So, these shear forces are transmitted to front and back sides of HSS column by connections and as a result, the bending moment, M, is sustained by in-plane action of HSS column.

3. Numerical models

In this study, twelve one-bay two-story SCBFs with diagonal brace within each story and twelve one-bay two-story SCBFs with chevron brace are used. Figs. 5 and 6 show the frames with conventional and through gusset plates, respectively.



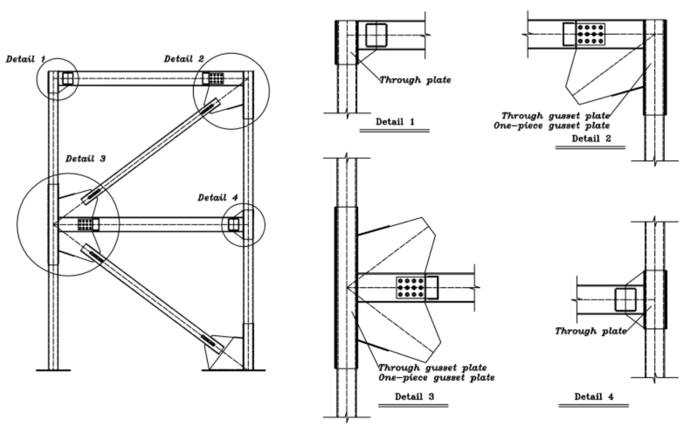
(a)



(b)

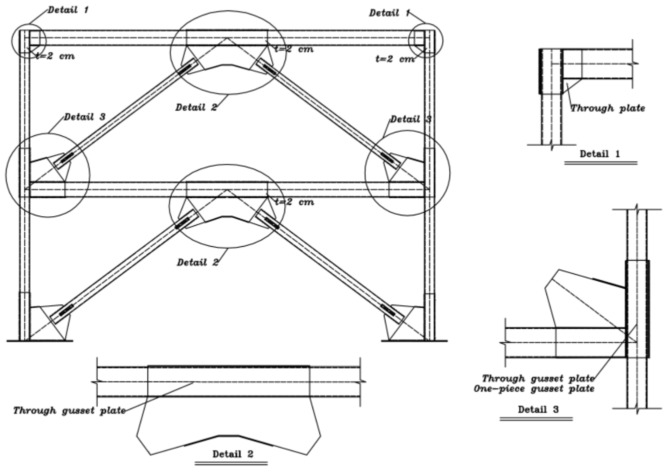
Fig. 5 Configuration of the frames with conventional gusset plates (a) SCBFs with diagonal brace; (b) SCBFs with chevron bracing

There are three reasons for selecting Figs. 5(a) and 6(a): (1) both tension and compression braces are presented in each cycle of loading; (2) two braces are connected to a node and the maximum vertical force occurs in the column; (3) one brace is connected to a node where the normal force at its gusset plate-to-column interface is larger than that at the gusset plate-to-column interface of the node with two braces. In SCBF specimens, the story height and the length



(a)

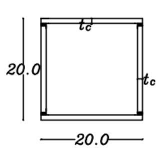
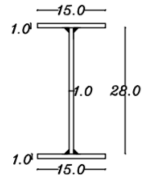
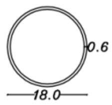
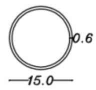
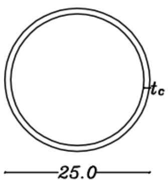
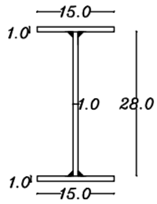
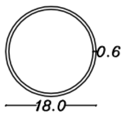
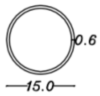
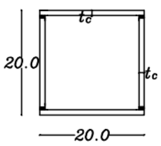
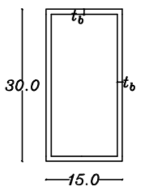
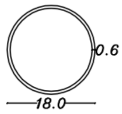
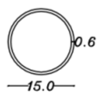
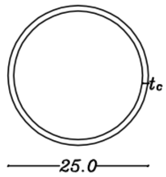
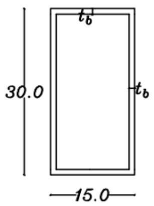
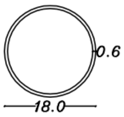
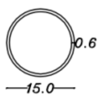
Fig. 6 Configuration of the frames with through gusset plates (a) SCBFs with diagonal brace; (b) SCBFs with chevron bracing



(b)

Fig. 6 Continued

Table 1 Applied cross-sections at the considered models

	Column	Beam	1st story brace	2nd story brace
SCBF with diagonal brace (1)				
SCBF with diagonal brace (2)				
SCBF with chevron brace (1)				
SCBF with chevron brace (2)				

of the span were considered 3 m and 4 m, respectively. In chevron braced frame models, the story height and the length of the span were considered 3 m and 8 m, respectively. The frames were designed in such a way that out-of-plane buckling occurs in all of the braces.

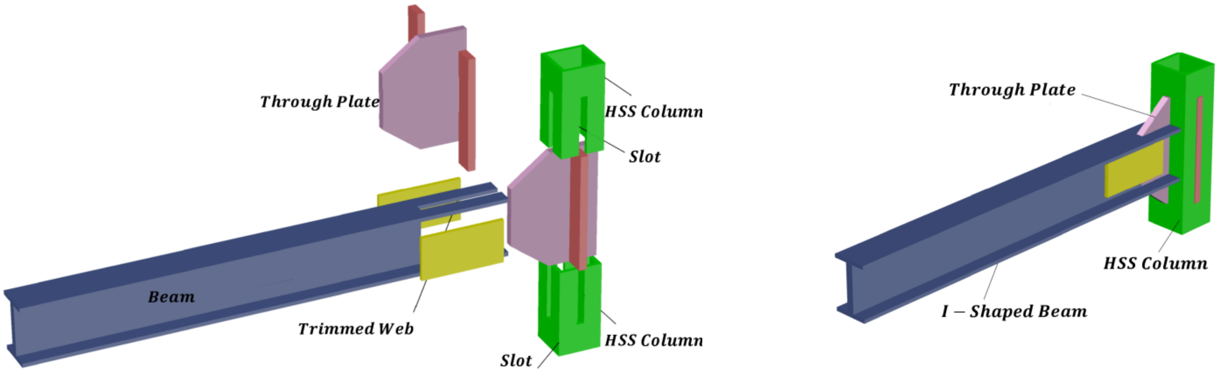
The considered SCBFs with diagonal and chevron brace are designed according to AISC Seismic Provisions (AISC 2016a) for base shear forces equal to 390 kN and 780 kN, respectively. Applied cross-sections at beams, columns and the braces are as Table 1.

In this study, the thicknesses of the column (t_c) and square HSS beam (t_b) were considered 8, 10 and 12 mm. It should be noted that the columns of case (1) and case (2) have almost the same area and thickness as presented in Table 2.

Also in this study, tapered gusset plates were used and

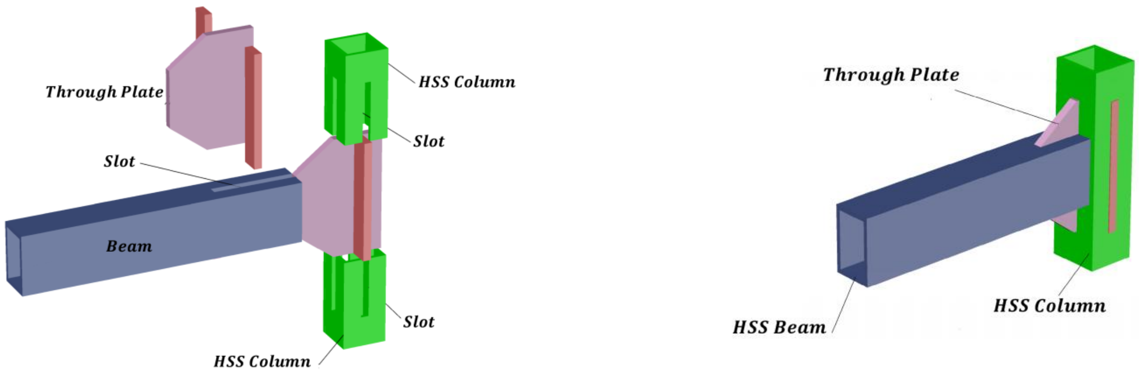
Table 2 Thickness and area of cross-sections of columns with different dimensions

Column thickness (t_c) (mm)	Column area of square HSS (mm^2)	Column area of circular HSS (mm^2)	Width-to-thickness ratio of square HSS	Diameter-to-thickness ratio of circular HSS
8	6144	6082	25	31.25
10	7600	7540	20	25
12	9021	8972	16.67	20.83



(a) (b)

Fig. 7 Through gusset plate with I-shaped beam: (a) components; (b) assembled configuration



(a) (b)

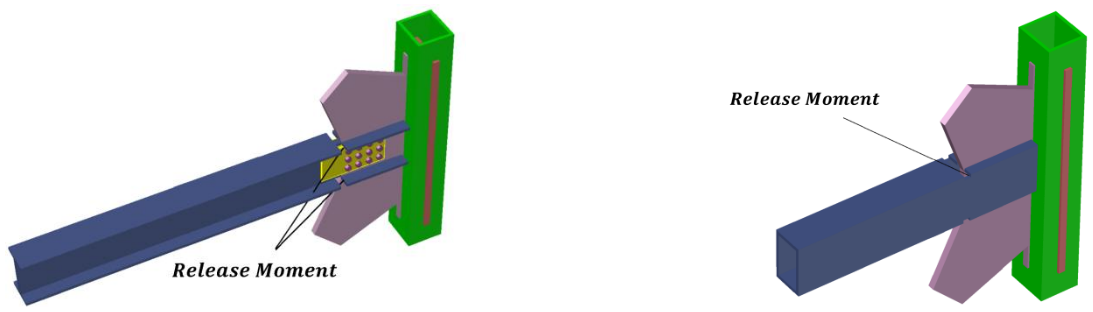
Fig. 8 Through gusset plate with HSS beam: (a) components; (b) assembled configuration

designed according to the Uniform Force Method (UFM) proposed in AISC Seismic Provisions (AISC 2016b). These tapered gusset plates have better out-of-plane rotation capability than rectangular gusset plates. Due to governing out-of-plane buckling in braces, a distance of $2t_{Gp}$ is considered to allow plastic hinges formation in gusset plates. Here, plates with 20 mm thickness are used for gusset plates and also for orthogonal through plates as shown in Fig. 2. Also, one-piece-gusset plate was used in intersecting braces at a joint for the following reasons:

(1) Omitting two through gusset plates at the brace node of the first story of SCBF models (otherwise, two through gusset plates are needed because of existing 2 gusset plates at the level of the first story).
(2) Otherwise, there will not be a through gusset plate at the Work-Point of column-beam-brace. As a result, the forces would not get interacted properly.

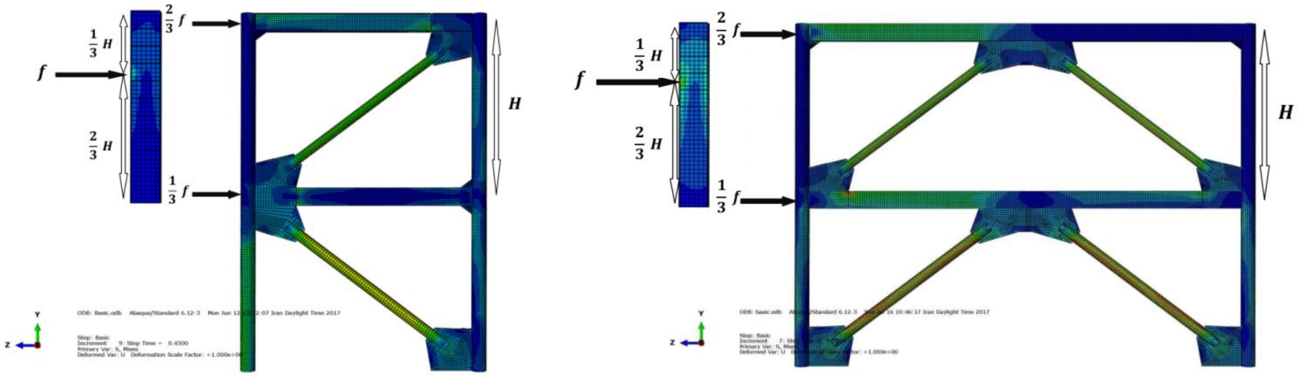
In this study, for the connection of beam to column, moment connection are used in braced frames with conventional gusset plates while through plate (Figs. 7 and 8) are considered in braced frames with through gusset plates to maintain the load capacity of frames after brace failure (Liu and Astaneh-Asl 2000).

Through plate connection consists of a vertical plate passing through HSS column. As shown in Figs. 7(a) and 8(a), in connection area, HSS column is divided into two parts and aligned slots are placed on HSS column and through plate passes through these slots and then is connected to them. After trimming the web of I-shaped beam and placing slots on flanges of square HSS beam in this region, the beam is connected to through plate by



(a) (b)

Fig. 9 Releasing moment at the gusset plate-to-beam interfaces in frame (a) with I-shaped beam (b) with HSS beam



(a) (b)

Fig. 10 Load distribution at stories with the ratio of 1 to 2: (a) model with diagonal brace (b) model with chevron brace

longitudinal connection of the flanges to both sides of the through plate and in I-shaped beam, two web connection plates are placed on both sides of the through plate. The through plate can be used in orthogonal braced frames by a cruciform through plate to assemble the beams in the vertical direction.

4. Beam to gusset plate connection at beam to column joint

In general, effect of frame distortion is not considered in designing brace connections. Frame distortion cannot be neglected during enormous earthquakes with 2%or 2.5% story drifts. Williams and Richard (1986) studies indicated that the gusset plates at braced bays may change connections to a rigid state. The beams make distortions due to moments made from lateral loading which would apply compression force to the gusset plate due to such deformation. The compression forces may cause buckling and related pinching in gusset plates, even if the braces are subjected to tension forces. The pinching of gusset plate was observed in Lopez *et al*. (2004) experiments. The gusset plates make reactions against compression forces and impose forces to the beam and finally local buckling and beam failure occur. This behavior was observed in Lai and Mahin (2013) studies too. To remove or decrease pinching at braced frames, Thornton and Muir (2008) proposed the use of more compact and smaller gusset plates or releasing the moment at the edge of gusset plate-to-beam interfaces (Fig. 9). In this study, release of moment at the edge of gusset plate-to-beam interfaces is used in order to decrease pinching.

5. Loading history

If multi-story braced frames are loaded only at the roof level, real condition cannot be presented. In this study, quasi-static cyclic loading protocol was used with the inverted triangular distribution (induced force at the top story is two times of the induced force at the lower story). A vertical loading simply supported beam is used to provide required load distribution to the first and second level stories with the ratio of 1 to 2. To consider the displacement-control loading protocol, displacement was applied at the distance of $\frac{1}{3}$ of vertical loading beam length from top of the beam (this point is called the reference point). The connection between the braced frame and vertical loading beam was considered as simple. As a result, induced force at the top story is two times of the induced force at the lower story (Fig. 10). ATC-24 loading protocol was selected in this investigation as shown in Fig. 11 (ATC 1992).

For imposing displacement, θ was multiplied by the height (ATC-24 loading protocol values) and then was induced to the frame as a reciprocating way. Sabelli and

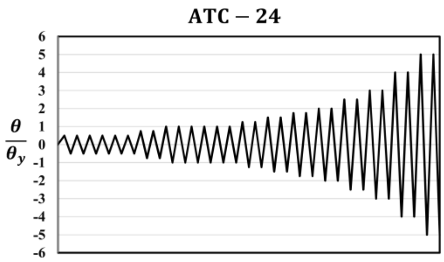


Fig. 11 ATC-24 loading protocol (ATC 1992)

Table 3 Yield drifts for the braced frames

	Column thickness (t_c) mm	Beam thickness (t_b) mm	θ_y of reference point
SCBF with diagonal brace	8	10	0.0024
	10	10	0.0025
	12	10	0.0027
SCBF with chevron brace	8	8	0.0024
	10	10	0.0025
	12	12	0.0027

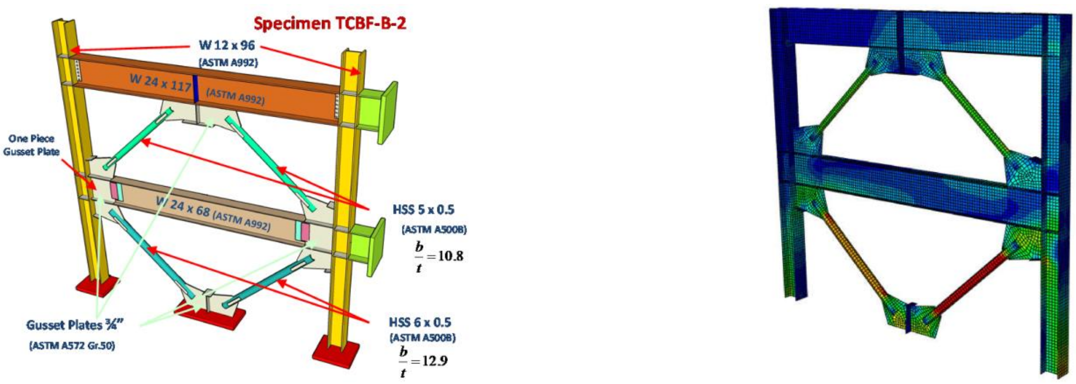
Hohbach (1999) indicated that the maximum average value of story drift in a SCBF subjected to a danger level with occurrence possibility of 10% in 50 years can be 3.9%. They also estimated the average value of plastic drift proportion (stable deformation) of 2.5%. The maximum value of drift proportion was considered nearly 4% in this study.

It is necessary to define θ_y (corresponding to frame yield drift) in ATC-24 loading protocol. Fell (2008), Fell and Kanvinde (2010) expressed that brace buckling occurs in braced frames at 0.2-0.4% story drift leading to a plastic hinge formation at the middle of the brace and braced frames experience maximum drift of 4% under the most severe seismic force. Lai and Mahin (2013) found that yield drift is equal to 0.0019 that is approximately in agreement with 0.2% value in Fell (2008), Fell and Kanvinde (2010) studies. To determine frame yield drift, an incremental displacement is imposed to the reference point of the considered frames in this investigation and then displacement of the reference point-base shear curve is illustrated and the frame yield drift is calculated (Table 3).

It can be concluded from Table 3 that the frame yield drift is approximately 0.2% that is in agreement with the values obtained by Fell (2008), Fell and Kanvinde (2010) and Lai and Mahin (2013).

6. Finite element models

Numerical modelling of examples is developed in ABAQUS. ABAQUS considers both geometric and



(a) (b)

Fig. 12 (a) Experimental specimen of Lai and Mahin (2013) (b) model developed in ABAQUS

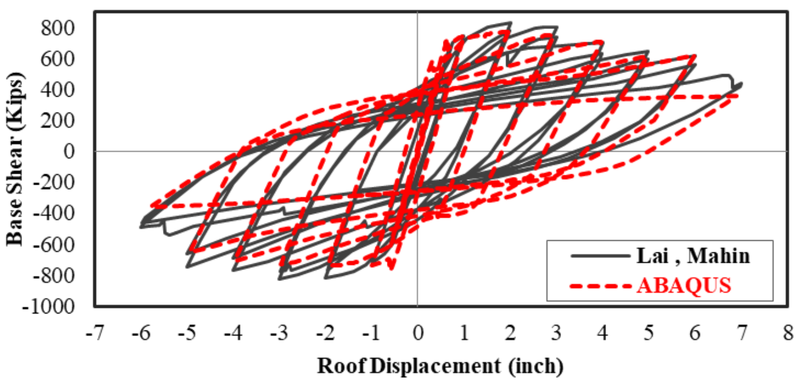


Fig. 13 Comparing numerical results by ABAQUS to the experimental results by Lai and Mahin (2013)

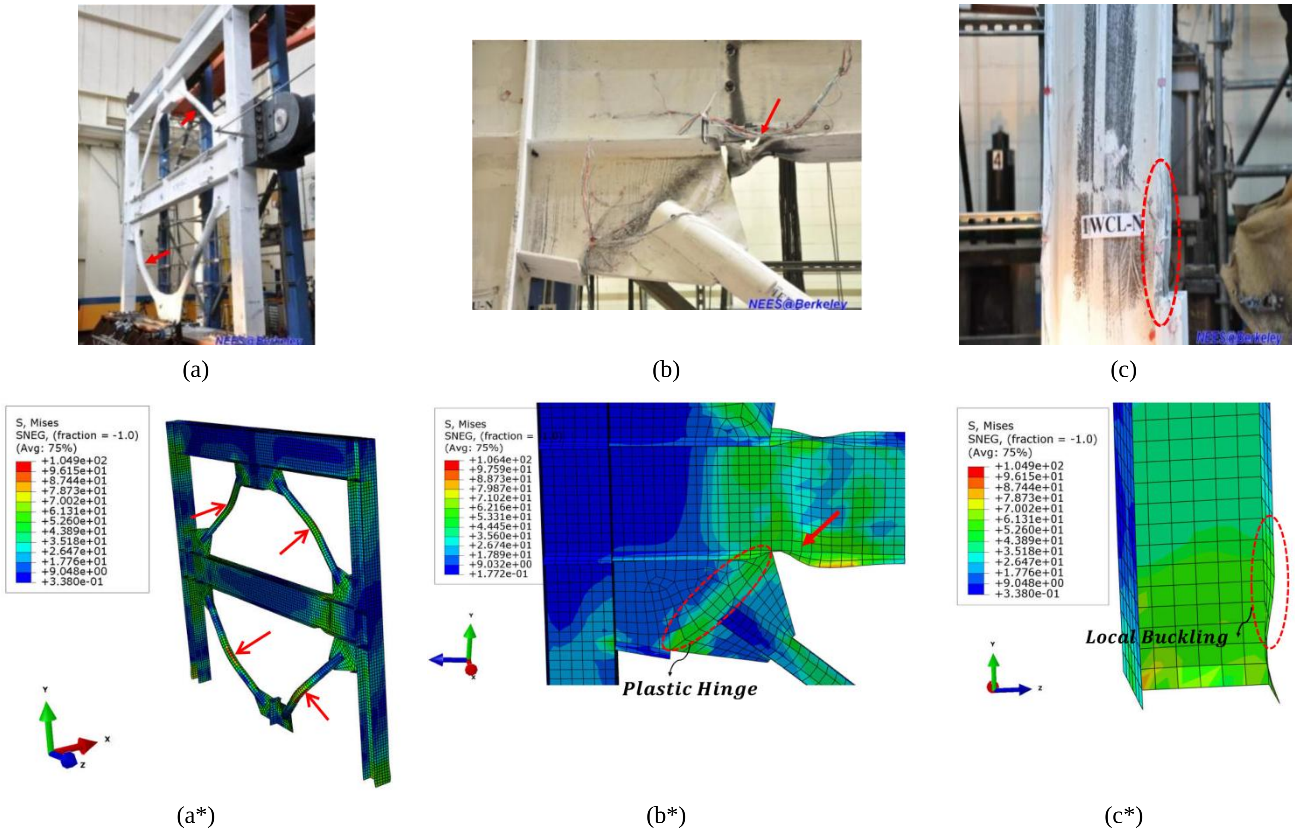


Fig. 14 The similarities between the tested specimen (Lai and Mahin 2013): (a) deformed shape of chevron bracing; (b) plastic hinge at gusset plate; (c) local buckling and corresponding numerical results: (a*), (b*) and (c*)

material nonlinearities that the nonlinear geometry option is used for computations of effects of large displacement. In this modelling, a 4-node doubly curved shell element with reduced integration S4R from the ABAQUS element library is selected for steel elements. For complex plastic buckling behaviour, S4R element with six degrees of freedom per node is used preparing accurate solutions for most relevant applications. Nonlinear kinematic hardening plasticity material model and a bilinear stress-strain curve are used for the steel. St37 steel is used for material of force-control members including beams, columns, gusset plates, through plates and stiffeners as well as displacement-control members or braces with the elasticity modulus (E) and Poisson's ratio (υ_s) of 2×10^5 MPa and 0.3, respectively. The nominal yield stress (F_y) and the ultimate stress(F_u) values are specified as 240 MPa and 370 MPa, respectively. For hinged connections between the vertical loading beam and the first and second level stories, Reference Point (RP) is selected at center of hinged connections. Kinematic coupling interactions with constrained degrees of freedom U_1, U_2 and U_3 are defined to provide a constraint between a Reference Point (RP) and the nodes on surfaces of vertical loading beam and the first and second level stories at the location of hinged connections.

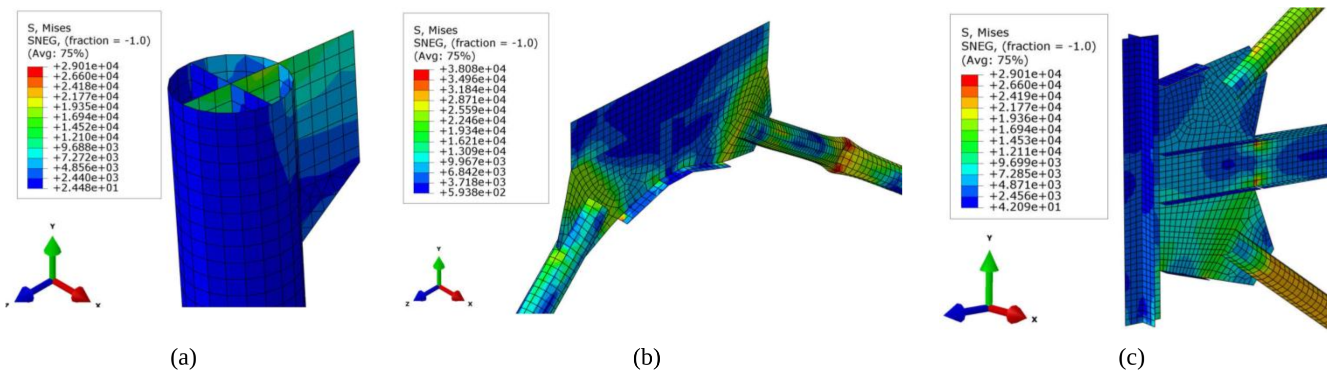


Fig. 15 Through gusset plate models (a) at the beam connection to HSS column; (b) at the chevron bracing connection to middle of HSS beam; (c) at the brace connection to HSS column with two braces

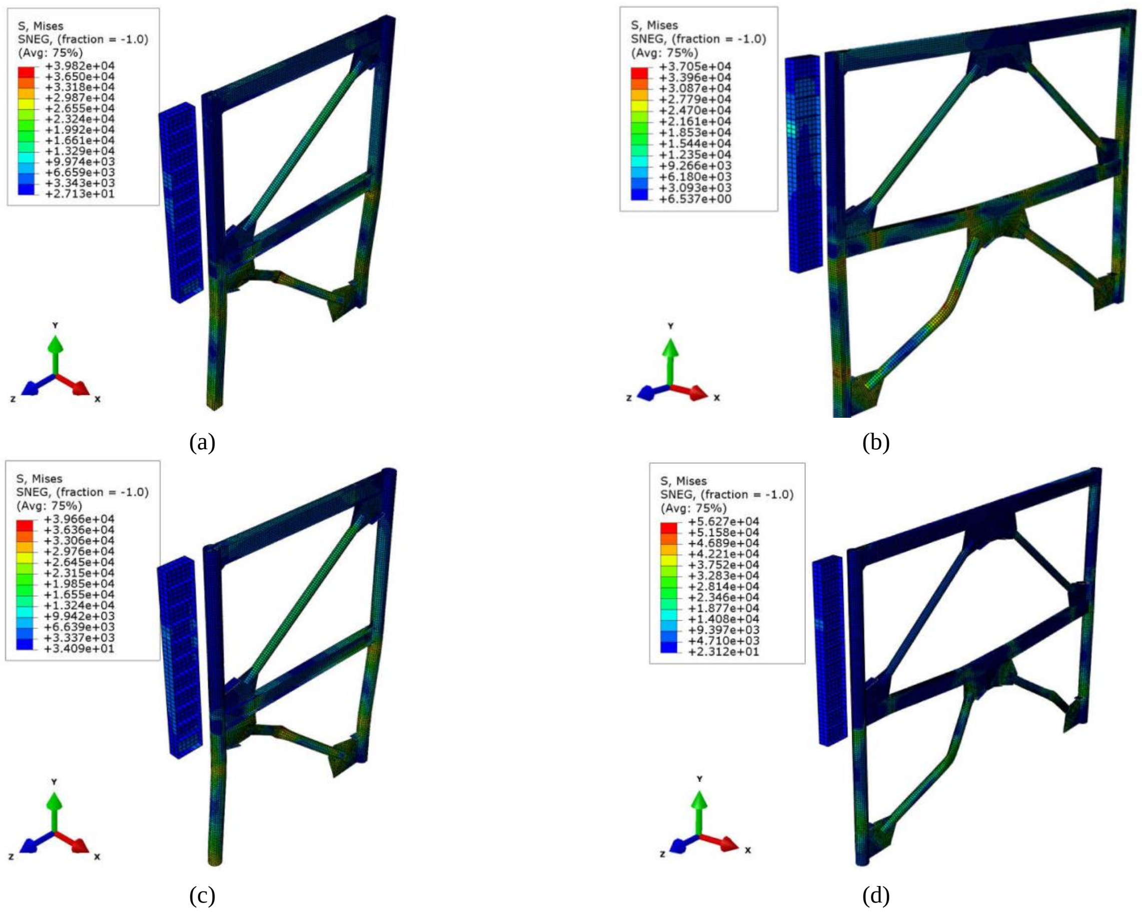


Fig. 16 Numerical models of SCBF developed in ABAQUS with (a) diagonal brace (1); (b) chevron brace (1); (c) diagonal brace (2); (d) chevron brace (2)

7. Verification of Numerical Result

For validating the numerical studies conducted here, the experimental results of Lai and Mahin study (2013) were utilized. In their investigation, one-bay two-story SCBF with the story height of 9 ft and bay width of 20 ft were considered (Fig. 12(a)). In their studies, the actuator of first story was force-control and the other actuator at the second story was displacement-control. They used inverted triangular loading distribution at the stories. During the experiments, displacement protocol was imposed to the second story. The existing force of actuator was specified at the second story at every moment while half of the force belonged to the first story by another actuator. Their test protocol was made using the basis of the Appendix T of the AISC Seismic Provisions (AISC 2016b). Six supplemental cycles corresponding to one half of the elastic design drift (0.5 Dbe) and two cycles at the elastic design drift (Dbe)were added to the commencement of the test protocol (Lai and Mahin 2013). To examine the validity of numerical results, a similar model (Lai and Mahin 2013) was constructed in ABAQUS (Fig. 12(b)) and its hysteresis curve was compared to that of the study by Lai and Mahin (Fig. 13).

Fig. 14 shows other similarities between the tested specimen of Lai and Mahin (2013) and the developed model in ABAQUS.

Figs. 13 and 14 indicate that the models constructed in ABAQUS enjoy reasonable validity.

8. Investigating the numerical results

In this investigation, two models were constructed in ABAQUS, one with conventional gusset plate and the other one with through gusset plate. In through gusset plate models, for connection of beam to column, brace to beam and finally beam and brace to column, through plates and through gusset plates were used (Fig. 15).

In this study, to investigate performance of through gusset plate, twelve SCBFs with diagonal brace and twelve SCBFs with chevron brace were constructed in ABAQUS (Fig. 16) and then ATC-24 loading protocol was applied at reference point of the frames. In SCBF specimens with diagonal brace, the thickness of columns was considered 8, 10 and 12 mm and in SCBF specimens with chevron brace, the thickness of columns and beams were considered 8, 10 and 12 mm.

8.1 Plastic hinges

Plastic hinge formation and out-of-plane buckling in braces are shown in Fig. 16 indicating that plastic hinges are mainly formed at middle of brace and at its end gusset plates.

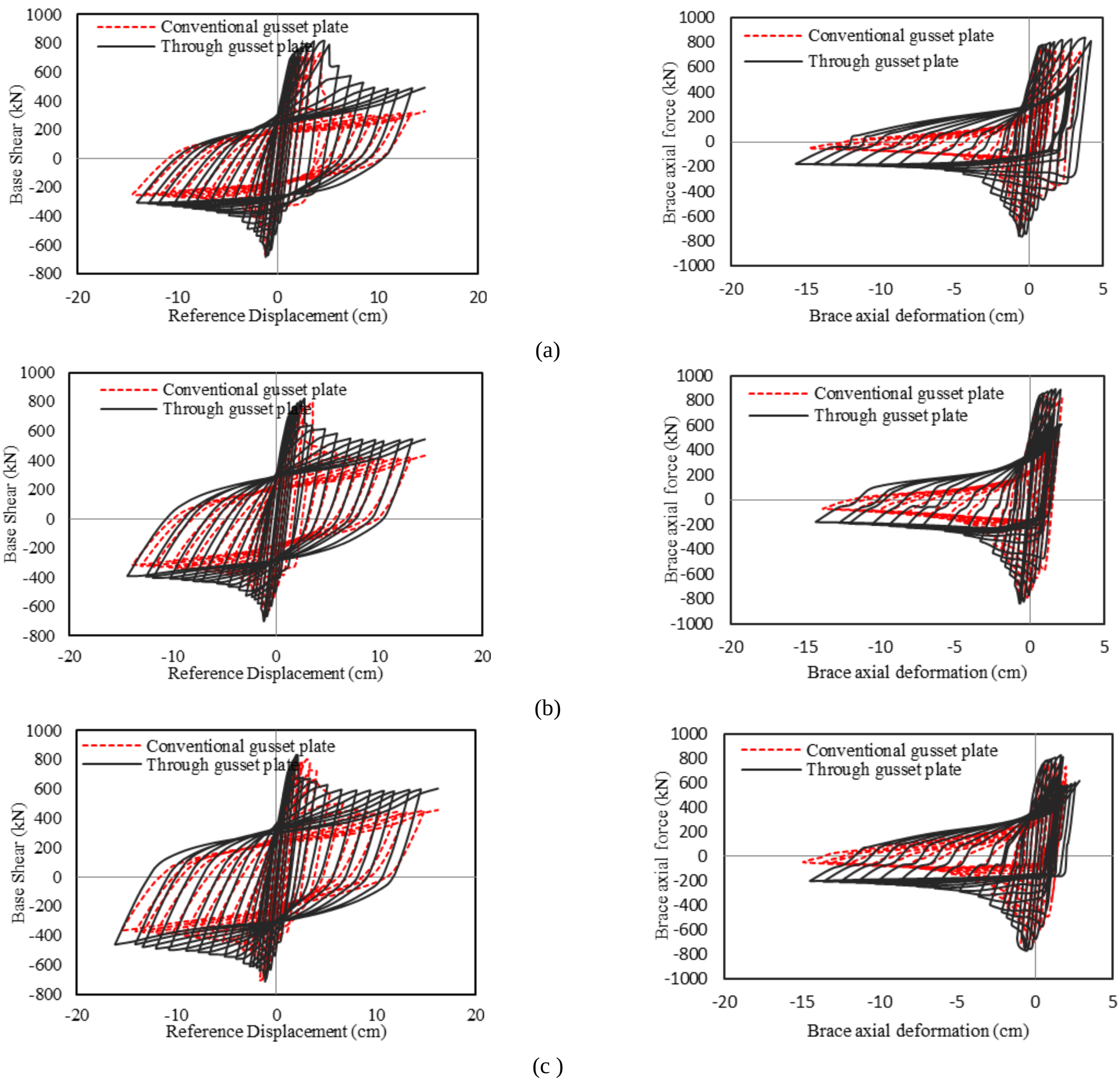


Fig. 17 Comparing hysteresis curves for SCBFs with diagonal brace and conventional and through gusset plates (braces of story 1) and column thickness of: (a) 8 mm; (b) 10 mm; (c) 12 mm

8.2 Hysteresis curves

In this section, base shear versus reference point displacement hysteresis loops and brace hysteresis loops for both models with conventional and through gusset plate are compared in Figs. 17 and 18. Results of numerical analysis in ABAQUS showed that hysteresis loops for SCBFs with diagonal brace (1) and SCBFs with diagonal brace (2) and also SCBFs with chevron brace (1) and SCBFs with chevron brace (2) are similar because cases (1) and (2) are similar to each other in every respect except for shape of columns. It should be noted that square and circular HSS columns have equal thickness and area.

It can be concluded from Figs. 17 and 18 that models with through gusset plate have approximately 40% more stiffness, approximately 32% more post-yielding strength and post-buckling strength and approximately 28% more energy dissipate capacity than the models with conventional gusset plates because through gusset plate prevents distortion and out-of-plane deformation in HSS column and beam faces that are adjacent to gusset plate. This behavior increases gusset plate stiffness and finally increases frame stiffness and strength.

8.3 Gusset plate buckling and soft story mechanism

In this investigation in order to decrease buckling and pinching in gusset plates, release of moment was used at the edge of gusset plate-to-beam interfaces. Fig. 19 shows that using this method prevents from pinching in gusset plates and deteriorating of beam flanges adjacent to gusset plate.
From Fig. 19, it can be concluded that method of Thornton and Muir proposed for I-shaped beams is applicable for square HSS beams. Numerical analysis results show that the soft story mechanism occur at both story of SCBFs with diagonal and chevron brace (Fig. 20). Also, this behavior was observed in investigation by Uriz and Mahin (2004).

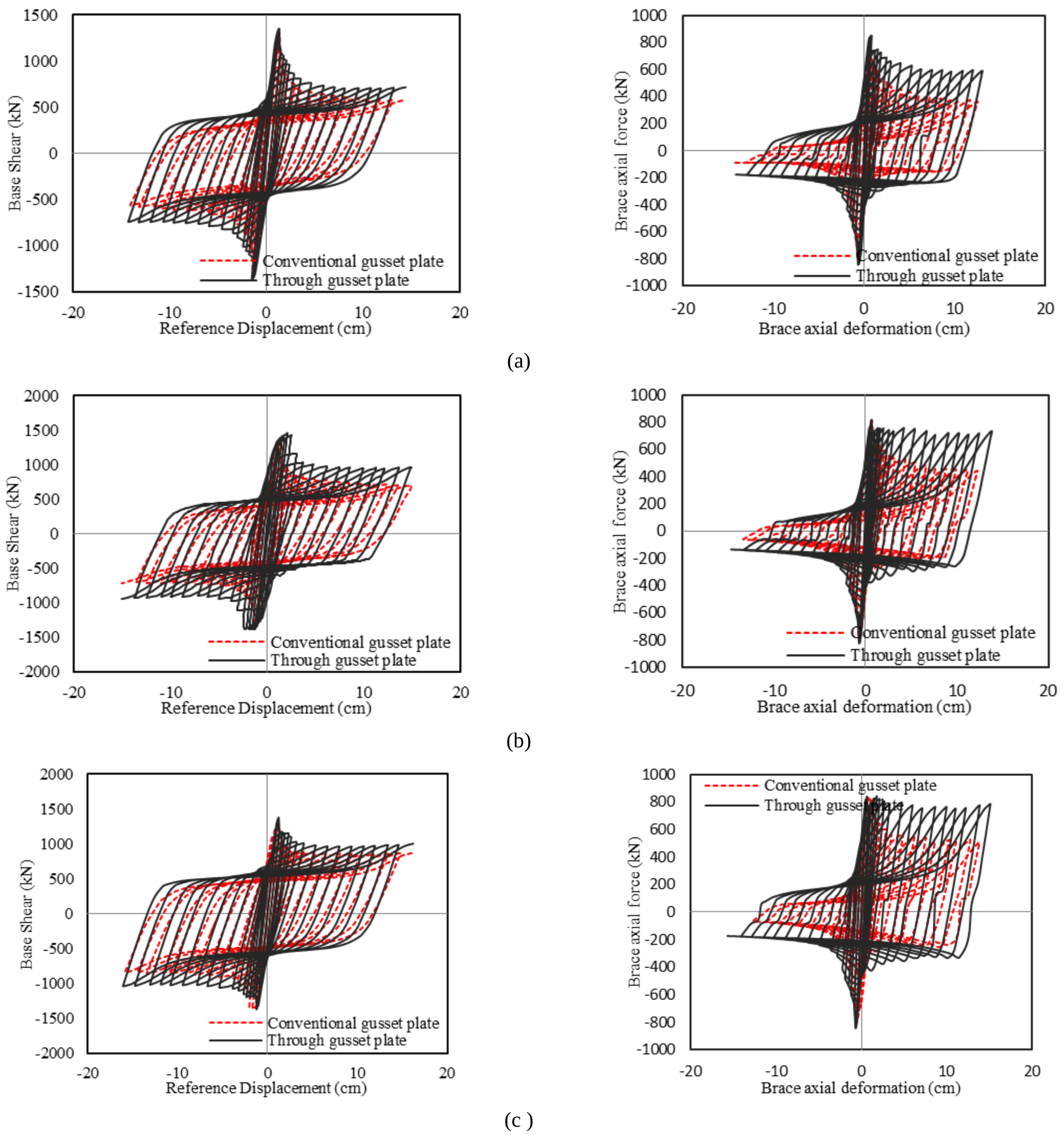
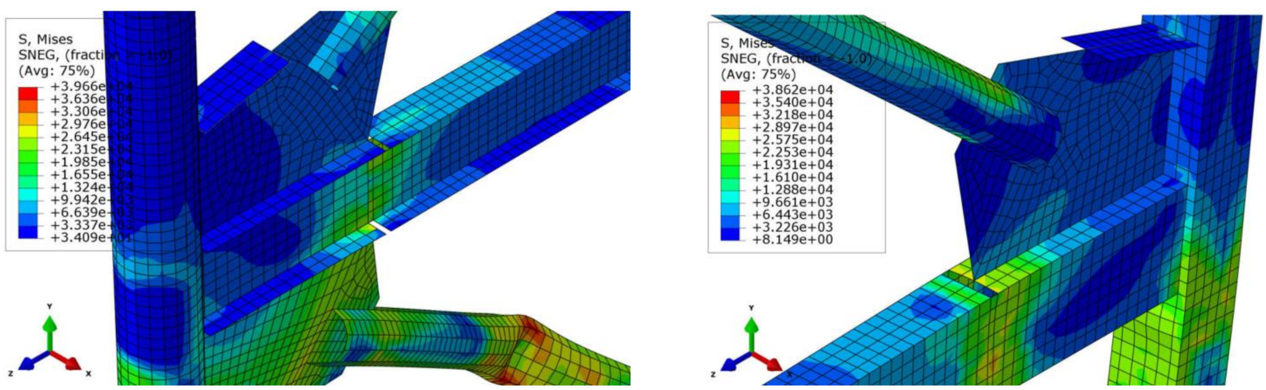
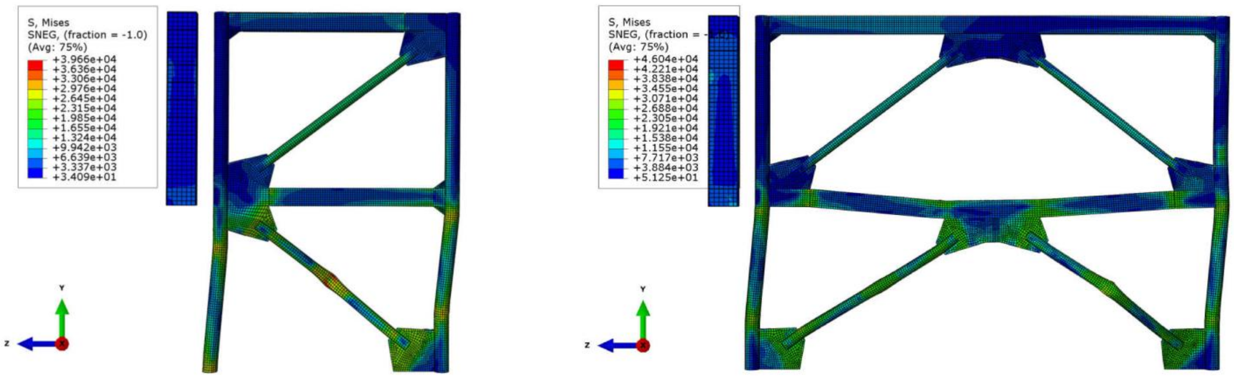


Fig. 18 Comparing hysteresis curves for SCBFs with chevron brace and conventional and through gusset plates (braces of story 1) and column and beam thickness of (a) 8 mm; (b) 10 mm; (c) 12 mm



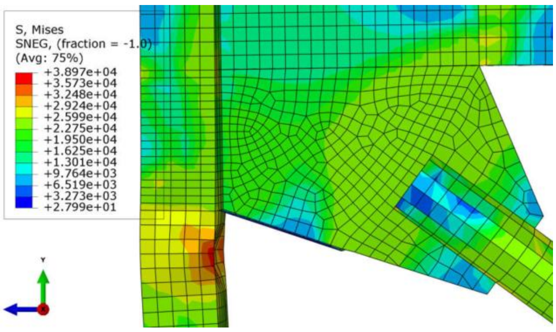
(a) (b)

Fig. 19 Releasing moment to prevent pinching in gusset plates: (a) I-shaped beam (b) HSS beam

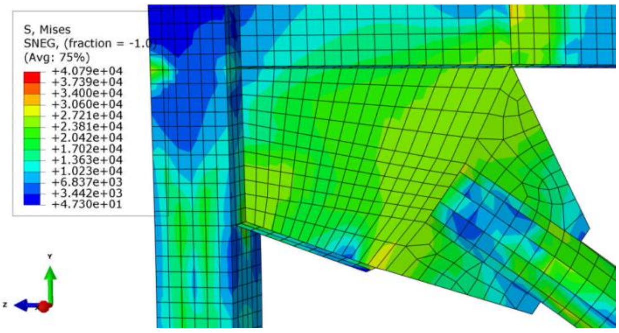


(a) (b)

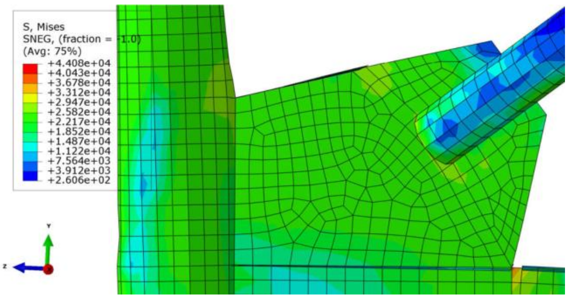
Fig. 20 Formation of the soft story mechanism at both story (a) SCBFs with diagonal brace (b) SCBFs with chevron brace



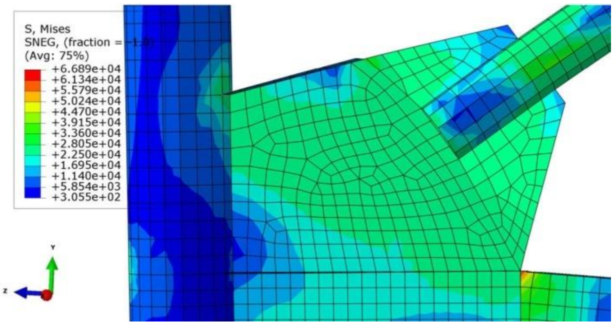
(a) SCBF with diagonal brace (1) and conventional gusset plate



(b) SCBF with diagonal brace (1) and through gusset plate



(c) SCBF with diagonal brace (2) and conventional gusset plate



(d) SCBF with diagonal brace (2) and through gusset plate

Fig. 21 Effect of through gusset plate in preventing distortion and out-of-plane deformation in SCBFs with diagonal brace

8.4 Distortion and out-of-plane deformation

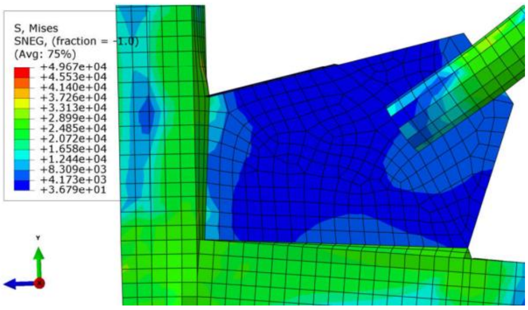
In braced frames, normal force component existing at the gusset plate-to-HSS column and beam interfaces, creates distortion and out-of-plane deformation in column and beam faces adjacent to gusset plate. In this section, effect of through gusset plate is investigated in order to prevent from such deformation. Numerical analysis results with conventional and through gusset plates showed that through gusset plate can prevent from excessive distortion and out-of-plane deformation in HSS column and beam faces (Figs. 21 and 22).

8.5 Normal force component

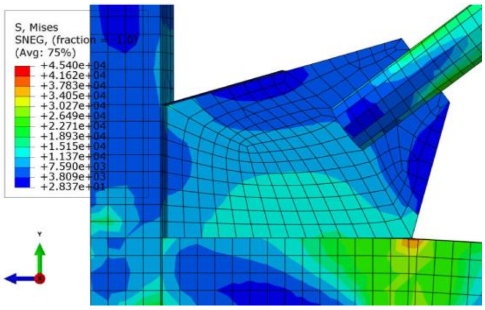
According to Uniform Force Method (UFM), at the gusset plate-to-column and beam interfaces a normal force (H_{uc} in column and V_{ub} in beam) is formed which should be transmitted by the connections. Since the web of HSS columns and beams and gusset plate are not at the same plane, such forces cannot be transmitted directly and in an in-plane action state by connections. Behavior of through gusset plate in HSS columns and beams was investigated in this study. Figs. 23 and 24 demonstrate that through gusset plate leads to make a sustainable normal force component increasing at gusset plate-to-HSS columns and beams interfaces to approximately 4 and 3.5 times, respectively.

9. Conclusions

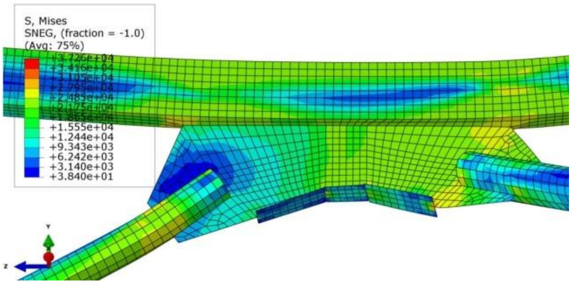
Both normal and shear force components are induced at gusset plate-to-column and beam interfaces. Since HSS column and beam webs and gusset plate are not in the same



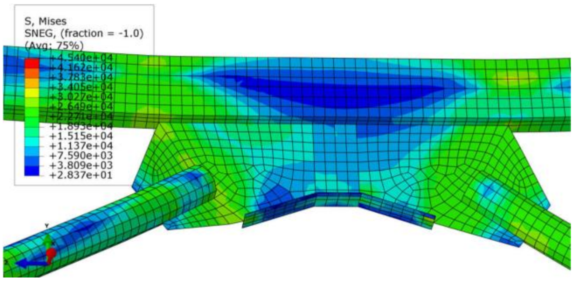
(a) Column of SCBF with chevron brace (1) and conventional gusset plate



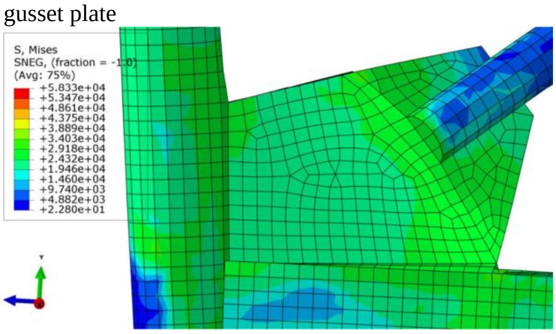
(b) Column of SCBF with chevron brace (1) and through gusset plate



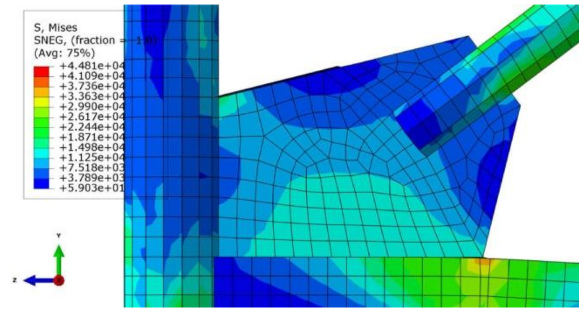
(c) Beam of SCBF with chevron brace (1) and conventional gusset plate



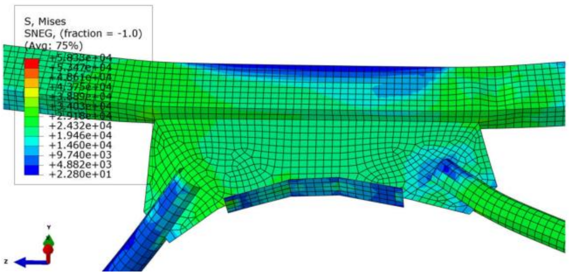
(d) Beam of SCBF with chevron brace (1) and through gusset plate



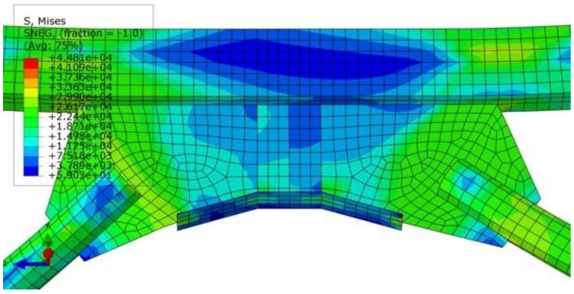
(e) Column of SCBF with chevron brace (2) and conventional gusset plate



(f) Column of SCBF with chevron brace (2) and through gusset plate



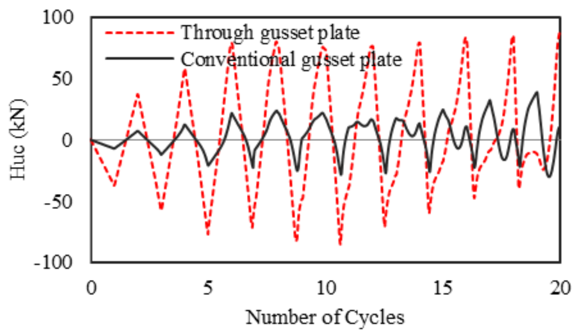
(g) Beam of SCBF with chevron brace (2) and conventional gusset plate



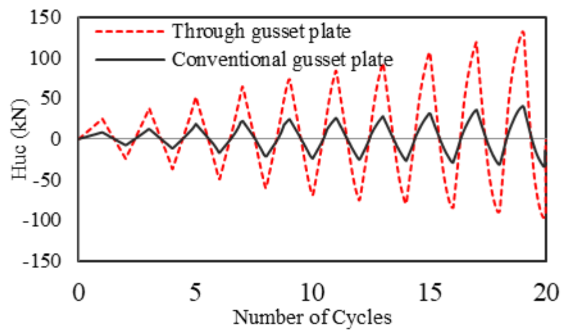
(h) Beam of SCBF with chevron brace (2) and through gusset plate

Fig. 22 Effect of through gusset plate in preventing distortion and out-of-plane deformation in chevron braced frame specimens.

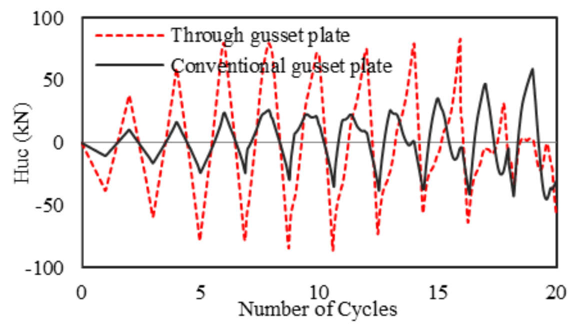
plane, the normal force component creates considerable distortion and out-of-plane deformation in the regions adjacent to the gusset plate. In these connections, the normal force component does not have sufficient support and is sustained via out-of-plane action of the front side of HSS column and beam and it might lead to connection fracture. Also, this problem decreases the brace stiffness such that the brace force cannot be completely transmitted finally reducing the whole lateral strength and stiffness of the braced frame. In HSS columns and beams, using methods like UFM and Ebrahimi *et al*. (2019) to calculate forces at the gusset plate interfaces are not appropriate; because these methods were proposed for H-shaped column and I-shaped beam. This study proposes a new connection named "through gusset plate" approximating its behavior to that of H-shaped column and I-shaped beam gusset plate connection such that using UFM and the method by Ebrahimi *et al*. can be acceptable. It is expected that



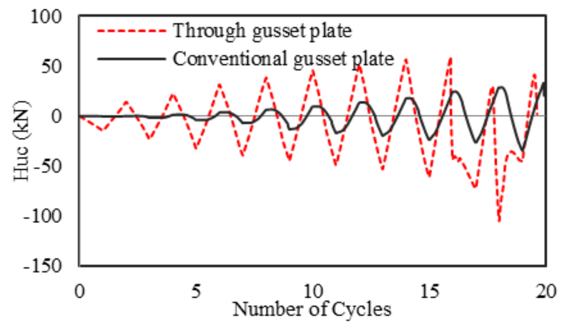
(a) Gusset plate of story 1 of SCBF with diagonal brace (1) and 8 mm column thickness



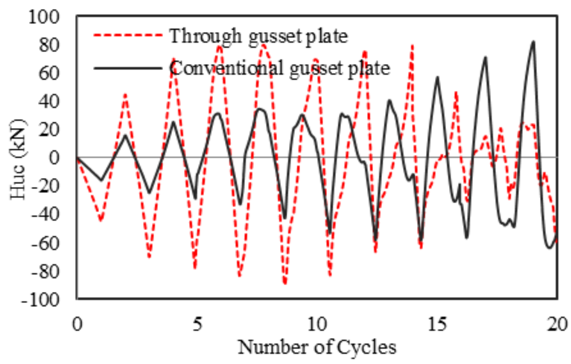
(b) Gusset plate of story 2 of SCBF with diagonal brace (2) and 8 mm column thickness



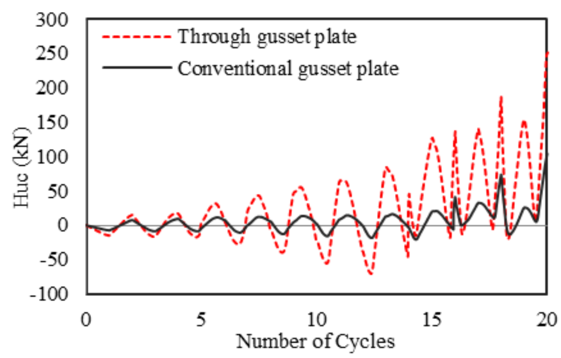
(c) Gusset plate of story 1 of SCBF with diagonal brace (1) and 10 mm column thickness



(d) Gusset plate of story 2 of SCBF with diagonal brace (2) and 10 mm column thickness



(e) Gusset plate of story 1 of SCBF with diagonal brace (1) and 12 mm column thickness



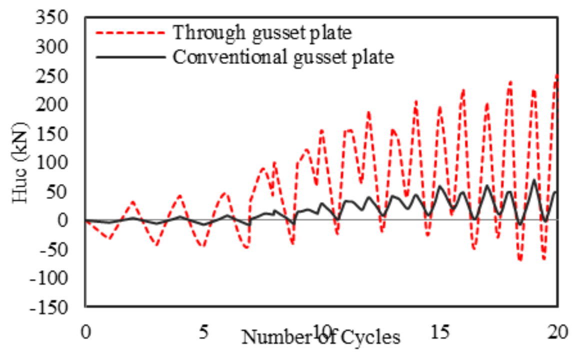
(f) Gusset plate of story 2 of SCBF with diagonal brace (2) and 12 mm column thickness

Fig. 23 Comparing normal force component at gusset plate-to-HSS column in SCBFs with diagonal brace

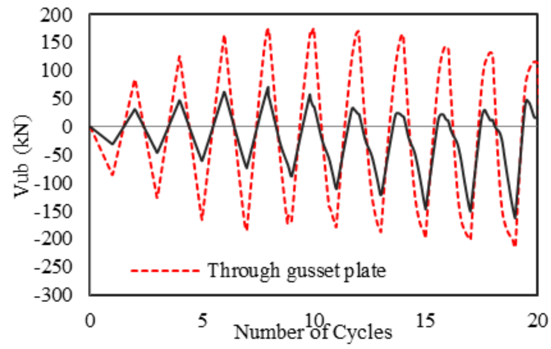
through gusset plate creates a sufficient support transmitting forces directly and eliminating large distortion and out-of-plane deformation in HSS column and beam faces at the vicinity of the gusset plate.

In this paper, twelve one-bay, two-story SCBFs with diagonal brace and square and circular HSS columns and twelve one-bay, two-story SCBFs with chevron brace, square and circular HSS columns and square HSS beams were studied. These frames in two cases with conventional and through gusset plates were considered. The results obtained from this limited study are as follows:

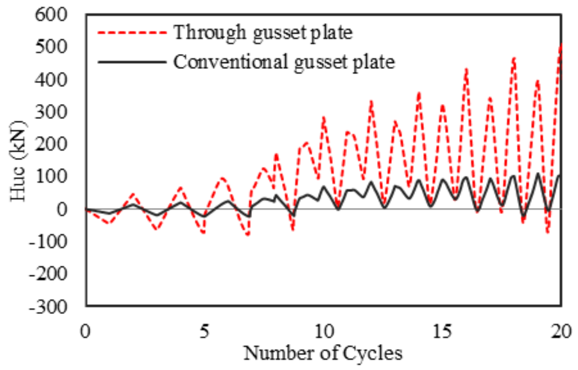
- Excessive distortion and out-of-plane deformation occur in HSS columns and beams with conventional gusset plate. This behavior decreases gusset plate stiffness and finally decreased frame stiffness and subsequently decreases frame strength.
- Presence of through gusset plate at brace connection with HSS columns and beams prevents from large distortion and out-of-plane deformation leading to more strength and stiffness.
- Comparing hysteresis loops for connections with conventional and through gusset plates, it was shown that those with through gusset plate increase stiffness, post-yielding strength of tension brace, post-buckling strength of compression brace and energy dissipation capacity around 40%, 32%, 32% and 28%, respectively.
- It can be concluded that the use of releasing the moment at the edge of gusset plate-to-beam interface is applicable for square HSS beam.
- The results obtained from numerical analysis with conventional gusset plate showed that HSS columns and beams cannot resist normal force components



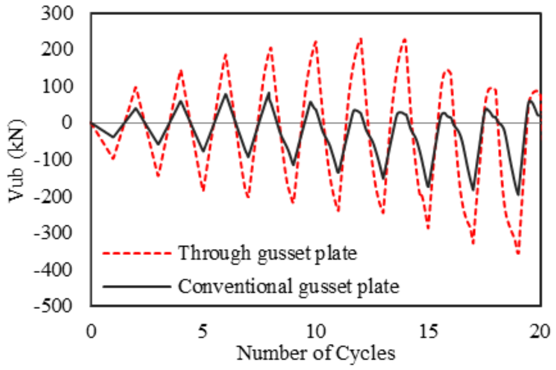
(a) Corner gusset plate of SCBF with chevron brace (1) and 8 mm column and beam thickness



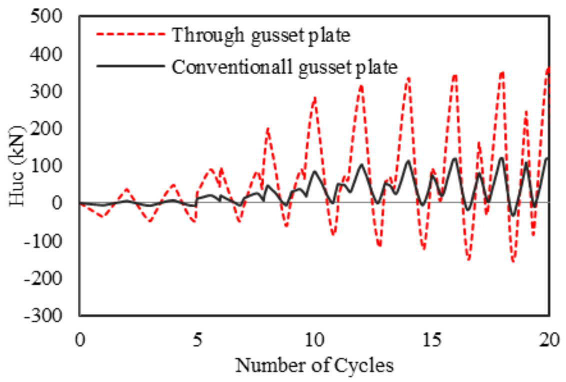
(b) Corner gusset plate of SCBF with chevron brace (2) and 8 mm column and beam thickness



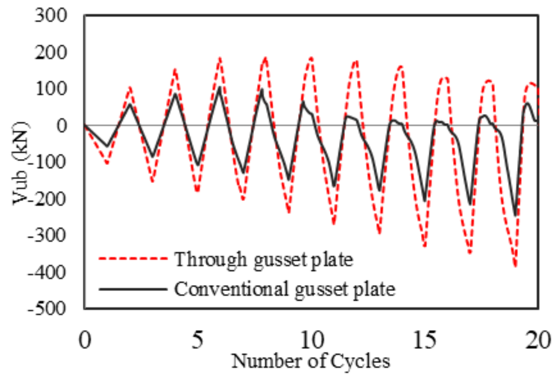
(c) Corner gusset plate of SCBF with chevron brace (1) and 10 mm column and beam thickness



(d) Corner gusset plate of SCBF with chevron brace (2) and 10 mm column and beam thickness



(e) Corner gusset plate of SCBF with chevron brace (1) and 12 mm column and beam thickness



(f) Corner gusset plate of SCBF with chevron brace (2) and 12 mm column and beam thickness

Fig. 24 Comparing normal force component at gusset plate-to-HSS column and beam in SCBFs with chevron brace

existing at their connections. By using through gusset plate, sustainable normal force component at gusset plate-to-HSS columns and beams approximately increases 4 times and 3.5 times, respectively.

- The soft story mechanism might occur at either story of SCBFs with diagonal and chevron braces similar to previous studies.

Acknowledgments

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