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Analysis of the effect of stiffener on the buckling capacity and non-elastic behavior of bracing gusset plates

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Abstract. Bracings, due to their high rigidity and strength, are widely employed in seismic design of steel buildings. They play a fundamental role in the absorption and dissipation of earthquake forces. Failures of braced steel buildings are often due to the shortage of compressive strength and out-of-plane buckling of bracing connections. One of the factors which contributes to the buckling behavior of gusset plates is position and type of connection of bracing to the gusset plate. In this paper, the pre- and post-buckling behavior of gusset plates is studied considering the presence or absence of longitudinal and transverse stiffeners on the bracing splice plates as well as the arrangement of edge stiffeners on gusset plates. To this purpose, a nonlinear static analysis is performed, the results of which are compared to the results obtained from the laboratory model. Results of the research show that application of longitudinal stiffeners leads to an increase in the buckling and post-buckling behavior of gusset plate while transverse stiffeners only influence the post-buckling behavior of gusset plate. In addition, implementation of double stiffeners on a gusset plate somewhat adds to the buckling capacity of the gusset plate, but affects post-buckling behavior of gusset plate better.

1. Introduction

Connections or joints of steel buildings are of great importance. One of the weaknesses of bracing systems is possibility of buckling of gusset plates or reduction in their load bearing capacity [1]. An important problem associated with the design of bracing connections is the buckling and post-buckling behavior of gusset plate, which reflects its capacity and out-of-plane deformations [2]. Due to the high rigidity and strength of centric braced steel frames, they are widely employed for the seismic design of steel buildings. Since these frames play the main role in absorption and dissipation earthquake-induced energy, it is necessary to study their connections [3]. Bracing connections in steel structures are very important and due to their complicated behavior, in many cases, it has been observed that the collapse of structure is due to improper connection design and insufficient knowledge about operation of the bracing gusset plates [1,4].

The majority of previous researches, such as the ones by Whitmore [5] and Thornton [6], were focused on the buckling capacity of gusset plate. In the method introduced by Whitmore [5], the buckling capacity of gusset plate is determined by introducing an equivalent

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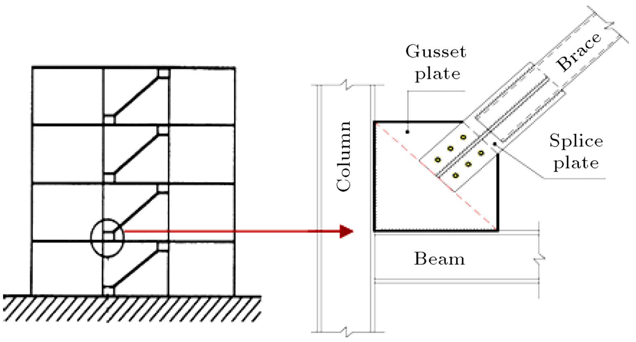

Figure 1. The schematic shape of corner gusset plate.

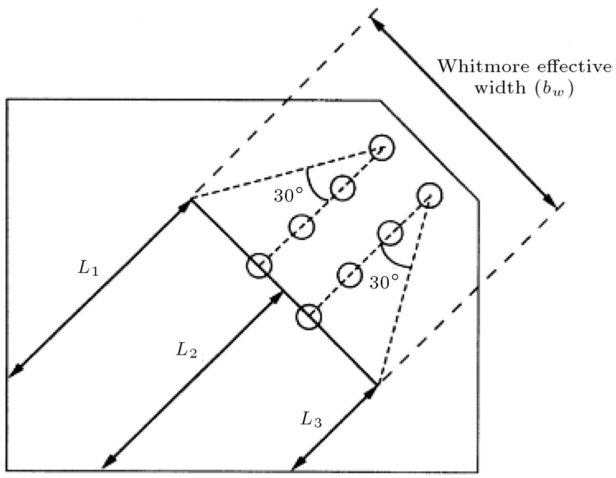

Figure 2. Whitmore's effective width and Thornton's method [5,6].

column to the gusset plate. The effective width of the column is the distance between the two lines that start from the beginning of the first row of bolts with an angle of 30 degree and end to the last row of bolts. Figure 1 shows the schematic shape of the gusset plate, and Figure 2 shows parameters related to the Whitmore and Thornton's methods. Thornton [6] used an effective length factor of 0.65 in order to reduce the length of the equivalent column proposed by Whitmore and obtained buckling load values that were more similar to the values obtained from tests. The length of the column strip, Lc, is equal to the maximum value of L_1, L_2, or L_3 (Figure 2). Thornton's method is used in AISC-LRFD [7] to estimate the critical load of a gusset plate under pressure Pcr. Gross also introduced a method that was similar to Thornton's method. However, his method was different from Thornton's method in that he used an effective length factor of $K = 0.50$ to provide adequate compressive strength [8]. In the studies of Astaneh-Asl [9], the use of conservative value of 1.2 for k in the column buckling equation when the end of the bracing moves toward the out-of-plane space, is recommended.

Yam and Cheng [10,11] proposed the modified Thornton method to calculate the effect of redistribution of load on a gusset plate under pressure. It shall be noted that the modified Thornton's method uses a 45-degree angle instead of a 30-degree angle to determine Whitmore's effective width. In their supplementary studies, they studied the effects of some factors, such as thickness and size of gusset plate, bracing angle, out-of-plane fixity condition of bracing, bending moments in frames and out-of-plane eccentricity of bracing load on the behavior and strength of gusset plates under compression loads.

Sheng et al. [12] assessed parameters, such as the length of free edge of gusset plates, type of joints, and effects of stiffener plates, in order to study the buckling resistance of gusset plates. Their studies revealed that the critical load on samples is decreased with increase in the length of free edge of gusset plates. In addition, it was found out that adding edge stiffeners can somewhat enhance the buckling capacity of gusset plates as well.

Rabinovitch and Cheng [13] also studied the effect of edge stiffeners and found out that edge stiffeners did not considerably contribute to the enhancement of the tensile behavior of gusset plate. Walbridge et al. studied the effect of preliminary imperfection on the buckling behavior of gusset plate and indicated that decrease in preliminary defects leads to improvement of behavior of gusset plate [14].

Furthermore, in the parametric studies by Chou et al., on twin bracing plates, the effects of central stiffener and positions of gusset plate were studied. It was found out that twin plates increase the buckling capacity of gusset plate by 10-35% [15]. In the researches by Hashemi-Hosseini et al. the effects of eccentricity were studied [16]. Lehman et al. and Roeder et al. also indicated that large and thick gusset plates lead to the concentration of deformation on the middle of gusset plate and decrease ductility of the gusset plate. They also studied the effect of failure modes on the reduction in the capacity and ductility of joints [17,18].

In the recent years, Naghipour et al. have investigated the inelastic compressive behavior and strength of gusset plates in braced frames, using analytical studying by finite element modeling [4].

As it is seen, all the previous researches were conducted on the buckling capacity and buckling behavior of bracing gusset plates and the effects of edge stiffeners. In addition, none of the previous studies focused on the effects of longitudinal and transverse stiffeners on splice plates and buckling and post buckling behavior of gusset plates. Also, no comprehensive study has been conducted on edge stiffeners.

As seen in Figure 3, in the majority of under construction projects, bracings are connected to gusset plates by using splice plates and without stiffeners. Hence, it is necessary to study the effect of stiffener

Figure 3. Typical connection of bracing splice plate to gusset plate.

on splice plate and its effect on the buckling capacity and behavior of gusset plate.

In this study, the pre- and post-buckling behavior of gusset plate is assessed by performing a nonlinear static analysis in Abaqus [19] software. In order to assess the accuracy of the created model, the results of numerical analyses were compared to the results obtained from the laboratory model introduced by Yam and Cheng [10]. In this research, the connections are modeled by using the dimensions and thickness values that are common in the majority of under construction buildings.

2. Structural modeling

A bracing corner gusset plate was chosen for the present analytic study. In the modeling practice, the gusset plate is connected to the beam and column by welding and is connected to the bracing using splice plate and bolts (Figures 1 and 3). The splice plate is also connected to the bracing by welding. Yield stress, ultimate stress, elasticity modulus of plates, and Poisson's ratio are 360 MPa, 470 MPa, 210000 MPa, and 0.3, respectively. The nonlinear stress-strain curve of steel is assumed to be bi-linear. All of the materials used in the models are isotropic. In order to perform the nonlinear static analysis, the finite element software (Abaqus-version 6.9) is used.

The primary design of structure is based on Iranian earthquake code. The braces sections are selected on the basis of conventional construction in Iran. Also the geometry of the connections and primary dimensions of gusset plate are almost the same as Yam and Cheng [10,11]. The sections of all bracings are 2UNP140 and the sections of all beams and columns are IPB340. In the nonlinear buckling analysis, three factors: initial imperfection, eccentricity of axial external loads and existence of lateral loads cause buckling. In the ideal condition and in the theoretical environment of software, without above factors, the buckling does not occur. But in practical cases, small values of these parameters always exist. Then, to calculate nonlinear buckling capacity of a plate, consideration of at least one of the above parameters in the analysis is necessary. Use of an initial imperfection is common in buckling analysis of plates. This initial imperfection is normally assumed to be similar to the buckled shape, and can be considered as small coefficient of buckling mode shapes. This small coefficient is assumed to be some percent of the plate thickness or plate width [14,20,21]. Therefore in a finite element software, at first of all, the linear buckling analysis, which is called Eigen values method, is done by defining the first five buckling mode. In this method, eigen values of buckling for different modes are calculated, and shows that the first, second and third modes are controller, then by exert imperfection in the plate, by the method of applying small coefficients in the combination of all deformations caused by linear buckling, the first geometrical model for non-linear buckling analysis is calculated. Finally, by defining RIKS analysis method in the software, the applied load is started from zero, and step by step it is increased till buckling is performed. This method is applicable for studying the buckling and post-buckling behavior of gusset plates. In the RIKS analysis, we need a method to specify when the step is completed. Since the loading magnitude is part of the solution, we can identify a maximum value of the load proportionality factor, or a maximum displacement value at a specified degree of freedom. The step finish when either value is crossed. If neither of these stopping conditions is specified, the analysis will continue for the number of increments specified in the step definition.

Also all members were modeled using the four-node shell elements, which has six degrees of freedom in each node. A relatively fine mesh (25 mm by 25 mm) was used near gusset plate connection according to recommendation of Lehman et al. [17,18]. A coarser mesh was used elsewhere, where only limited plastic deformations were expected. By changing the mesh size, the accuracy of modeling and mesh dependency is controlled. The final mesh size has enough accuracy and is according to Lehman [17,18] consideration.

3. Assessment of accuracy of modeling

In order to assess the accuracy of modeling, the laboratory results of Yam and Cheng were used [10].

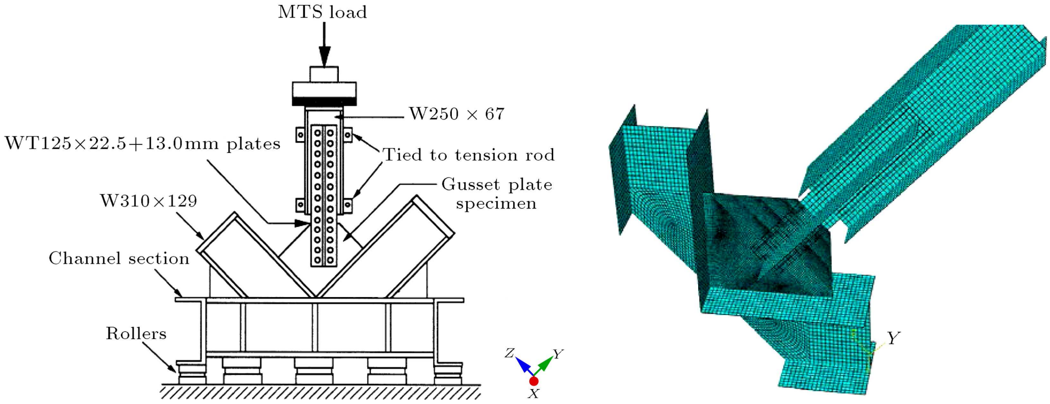

Figure 4. Laboratory and numerical models of a bracing gusset plate considered by Yam and Cheng's test [10].

The laboratory model is dedicated to calculation of the compressive strength of corner gusset plate under uniform compressive loads. Yam and Cheng studied the effects of the thickness and dimensions of gusset plate, bracing angle, and end moments of beams and columns on the buckling capacity of gusset plate. Results of their experiments revealed that increase in the thickness or decrease in the dimensions of gusset plate lead to the growth of buckling capacity. In addition, they found out that end moments of beams and columns and also bracing angle do not influence the buckling load of gusset plate. Figure 4 shows the laboratory model introduced by Yam and Cheng as well as the finite element model and meshing of the gusset plate. In Table 1, the results of two laboratories model GP2 and GP3 of Yam and Cheng are compared with results acquired from numerical analysis. The amount of error level of analytical method is less than 6% that shows adequate accuracy of the analytical modeling. Also pushover curve of non-linear analysis for GP2 and GP3 specimens are provided in Figure 5(a) and (b) that compares the buckling loads of analytical method and experimental method.

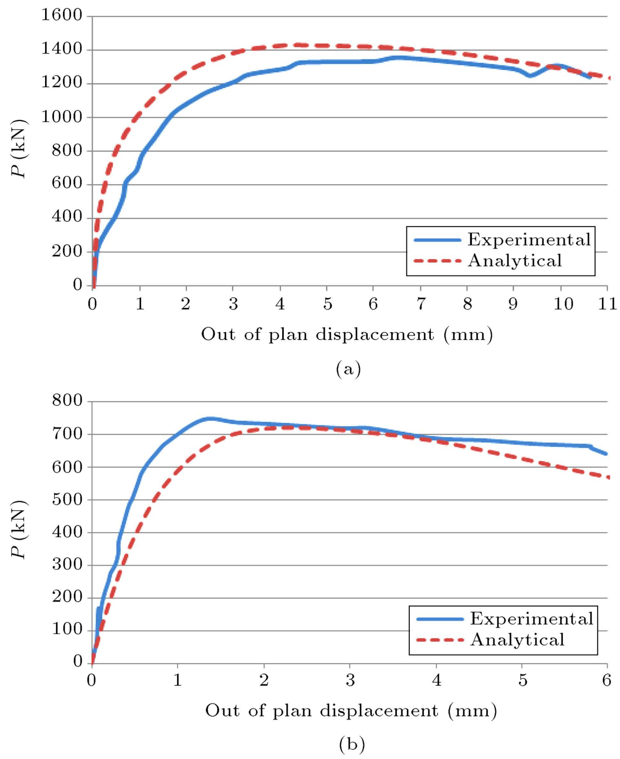

Figure 5. Push over curve associated with assessment of the accuracy of numerical modeling and laboratory results obtained by Yam and Cheng [10]: a) Specimen GP2; and b) specimen GP3.

4. Examination of the finite element analysis

4.1. Study of the effects of using longitudinal stiffener on bracing splice plate

One of the important parameters associated with connection design is the effect of longitudinal stiffeners on buckling behavior. Figure 6 shows the position of a longitudinal stiffener on a splice plate. The dimensions of the gusset plate are 45 × 45 × 0.8 cm and the dimensions of the splice plate are 55 × 20 × 1.5 cm. Moreover, the dimensions of the longitudinal stiffener of splice plate are 10 × 10 cm. In model *a* no longitudinal stiffener is used on the splice plate while in model *b* a longitudinal stiffener is used on the splice plate.

Table 1. Description of the experimental model.

Specimen	Col. & beam section	Brace section	Gusset plate section	Splice plate section	Ultimate load (experimental)	Ultimate load (analytical)
GP2	W310*129	W 250*67	PL50*40*0.98	2PL87*14.8*1.3	1356 kN	1435 kN
GP3	W310*129	W 250*67	PL50*40*0.65	2PL87*14.8*1.3	742 kN	719 kN

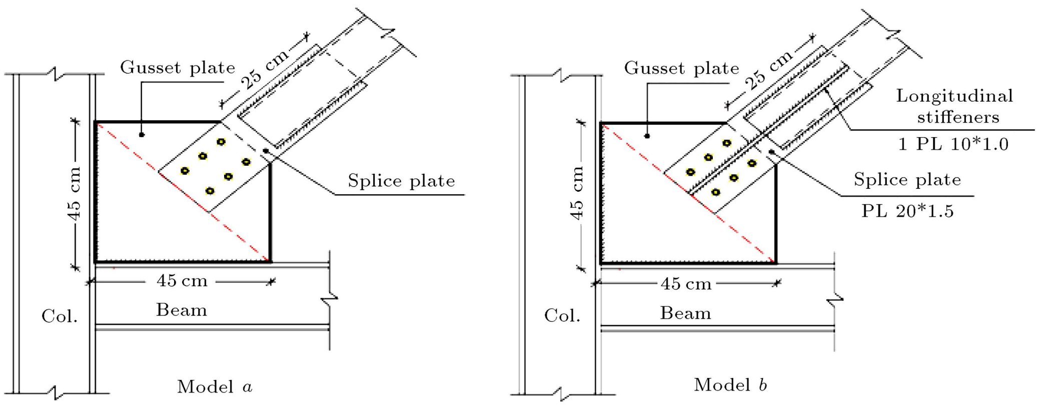

Figure 6. Presence/absence of longitudinal stiffener on the splice plate.

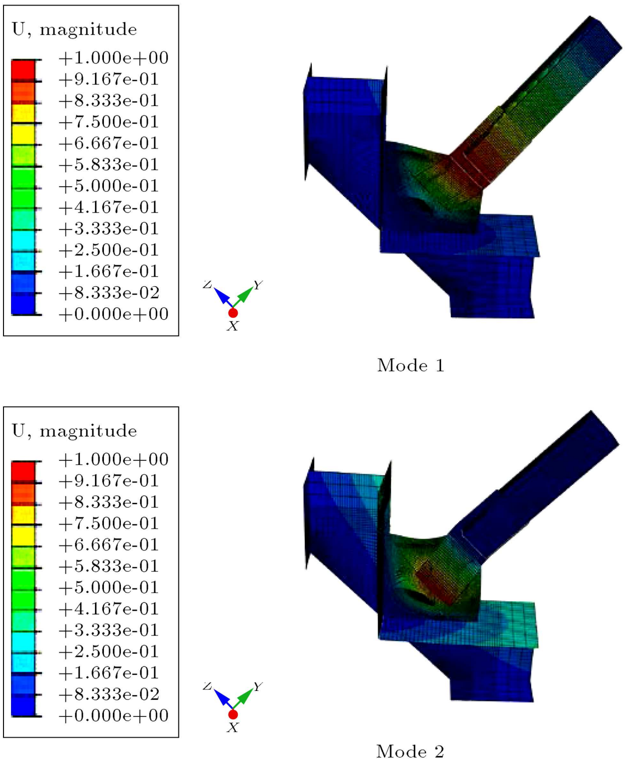

Figure 7. Buckling and deformations of gusset plate in the absence of stiffeners on the splice plate.

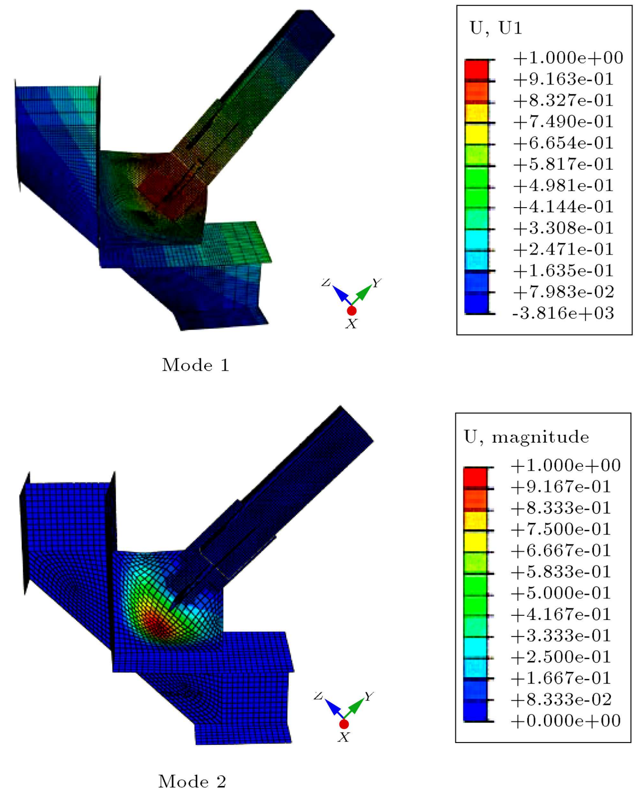

Figure 8. Buckling and deformations of gusset plate in the presence of stiffeners on the splice plate.

As seen in Figure 7, in the absence of longitudinal stiffener plate, buckling mode 1 occurs to the splice plate in the distance between the gusset plate and the bracing. In addition, in mode 2 of buckling, the splice plate in the gap moves outward and causes buckling at the end of the splice plate. However, in the presence of longitudinal stiffener plate (Figure 8), all of the buckling modes occur to the gusset plate instead of the splice plate. Therefore, as seen in these figures, in the absence of longitudinal stiffener plate on the splice plate, no buckling occurs in the gusset plate; modes 1 and 2 of buckling are related to splice plate. Thus, the gusset plate does not contribute in the formation of buckling modes. Consequently common construction details of bracing connections, by using splice plates in the absence of longitudinal stiffeners (Figure 3), are incorrect. Hence, to use the overall buckling capacity of gusset plates, the use of longitudinal stiffeners on splice plates is necessary.

According to Figure 9, it can be concluded that in the absence of longitudinal stiffeners on the bracing splice plate, the buckling capacity of the gusset plate is reduced significantly, and the gusset plate undergoes fewer deformations. Therefore, the buckling capacity of model *b* after 16 mm of deformation is equal to the buckling capacity of model *a* after 2 mm of deformation.

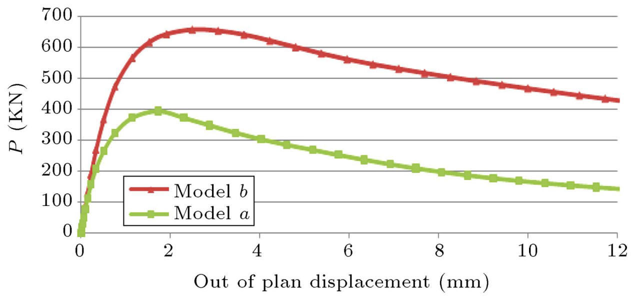

Figure 9. Push over curve of the buckling behavior of the gusset plate in different models in the presence/absence of longitudinal stiffener on splice plates.

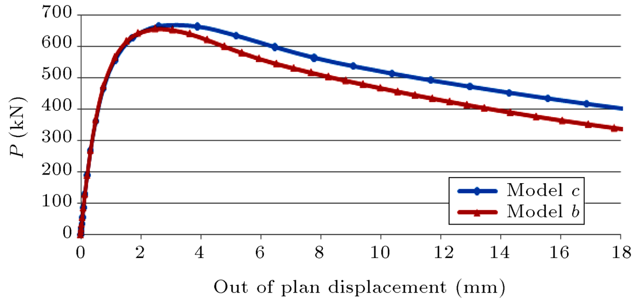

Figure 11. Push over curve of the buckling behavior of gusset plate for different models in the absence or presence of transverse stiffener plates.

4.2. Study of the effects of using transverse stiffener along with longitudinal stiffener on splice plates

Another study on the behavior of gusset plate is the effect of using transverse stiffeners on the splice plate. Figure 10 shows the presence and absence of transverse stiffener on the splice plate. The dimensions of the stiffener plates are 10×10 cm.

According to Figure 11, when both transverse and longitudinal stiffeners are used, the post-buckling behavior of the gusset plate is somewhat enhanced but the pre-buckling capacity and behavior of the gusset plate are not affected. It is clearly evident that absence or presence of transverse stiffener does not significantly affect the compressive strength and deformability of the gusset plate.

4.3. Study of the effects of using edge stiffener plate

In Figure 12, the position of edge stiffener on the gusset plate is shown. The dimensions of the stiffener are 15×1.0 cm. Model d shows a gusset plate with only edge stiffener while model e shows a gusset plate with edge stiffener that is restrained using compressive stiffeners on single side of the gusset plate. Model f shows a gusset plate with edge stiffener together with two-side compressive stiffeners.

Diagrams depicted in Figure 13 reflect the fact that using compressive stiffeners, perpendicular to edge stiffeners, does not significantly affect the buckling behavior of gusset plate but improves the post-buckling behavior of gusset plate. In addition, the diagrams imply that using compressive stiffeners on one side of the gusset plate instead of its both sides does not have any effect on the buckling and post-buckling behavior of gusset plate. Therefore, it is enough to use only one stiffener on one side of the gusset plate, and it can be concluded that model e is the most economic model.

Presence of edge stiffener leads to elimination of edge buckling in the model, and creation of buckling at the end of the bracing member. Considering energy dissipation to be shown by the surface below the force-displacement curve, it can be said that edge stiffener leads to increase of energy dissipation of the gusset plate and enhances its performance.

4.4. Analysis of the buckling capacity and behavior of bracing gusset plate for all models under study

Table 2 and diagrams in Figure 14 indicate that model f gives the highest buckling capacity and model a gives the lowest buckling capacity. That is to say, the buckling capacity of the gusset plate in the absence of

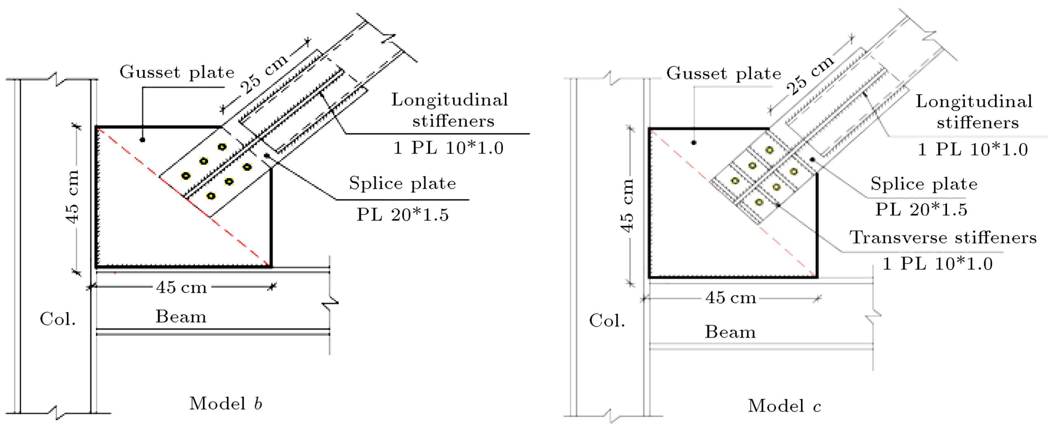

Figure 10. Position of the transverse and longitudinal stiffener plates on the splice plate.

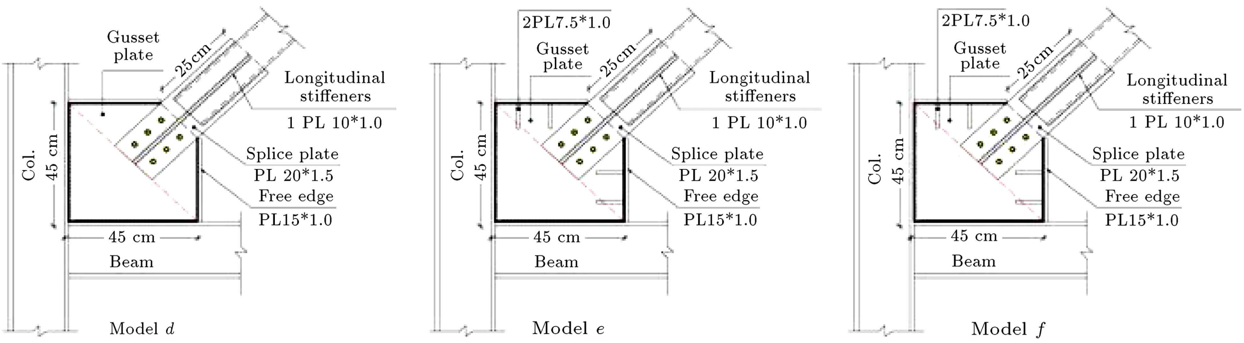

Figure 12. Position of edge stiffener plate on the bracing gusset plate.

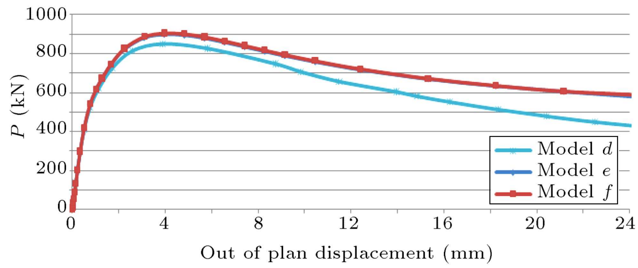

Figure 13. Push over curve of the buckling behavior of gusset plate in the presence of edge stiffeners.

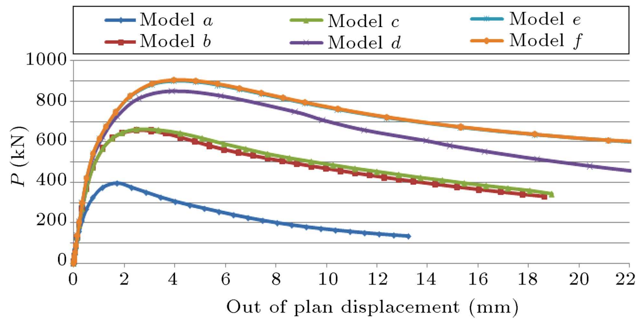

Figure 14. Push over curve of the buckling behavior of gusset plate in all models under study.

Table 2. Buckling capacity of models under study.

Model	Buckling capacity	Model	Buckling capacity
Model *a*	395 kN	Model *d*	851 kN
Model *b*	657 kN	Model *e*	899 kN
Model *c*	663 kN	Model *f*	906 kN

stiffener (395 kN) is increased to 906 kN in the presence of longitudinal, transverse and edge stiffeners.

5. Conclusion

Main results of numerical analyses of models under study are presented below:

1. When no longitudinal stiffener is used on the splice plate, buckling does not completely occur to the bracing gusset plate and part of it occurs to the splice plate.
2. When a longitudinal stiffener is used on the splice plate, the load bearing capacity of the connection is increased considerably.
3. Using transverse stiffener along with longitudinal stiffener on the splice plate does not affect the pre-buckling capacity and behavior of gusset plate, but somewhat enhances post-buckling behavior of gusset plate.
4. Edge stiffener somewhat adds to the buckling capacity of gusset plate.
5. Using compressive stiffeners, perpendicular to edge stiffeners, leads to an increase in the post-buckling capacity of the gusset plate.
6. Presence of compressive stiffeners on both sides of the gusset plate instead of one side does not considerably affect the buckling capacity of gusset plate. Therefore, it is economic to use single stiffener.
7. The model that gives the highest buckling capacity is the model that uses longitudinal stiffener on the splice plate and edge stiffener on the gusset plate simultaneously.

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