Earthquakes and Structures, *Vol. 12, No. 4 (2017) 449-455*
DOI: https://doi.org/10.12989/eas.2017.12.4.449

Study on the effects of various mid-connections of x-brace on frame behavior

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(Received November 5, 2016, Revised March 29, 2017, Accepted April 9, 2017)

Abstract. Using X-braced frames in steel structures is a current procedure to achieve good strength against lateral loads. Study on mid-connections of X-braces and their effects on frame behavior is a subject whose importance has been more or less disregarded by researchers. Experimentally inspecting models involves considerable expense and time; however, computer models can be more suitable substitutes. In this research, a numerical model of X-braced frame has been analyzed using finite element software. The results of pushover analysis of this frame are compared with those of the experimental test. With the help of computer model, the effects of different mid-connection details on ductility and lateral strength of the frame are inspected. Also performances of bolted and welded connections are compared. Taking into account ductility and strength, this study suggests details of a decent pattern for the mid-connection.

Keywords: steel structures; X-brace; mid-connection; ductility; lateral strength

1. Introduction

Steel structures have good strength and ductility which result in potentially favorable behavior against seismic loads. Yet, something that is important in steel structures is that how an engineer can improve the behavior of the building against earthquake loads. Using bracing systems is one of the best and well-known procedures to access this target. X-braces are widely used in steel structures. The mid-connection of such braces is an effective parameter that can affect ductility and lateral strength of X-braced frames. Although this subject is of high importance, few researchers have considered it. In such braces, usually one of the diagonals is intersected in the middle to let the other pass continuously and then a plate can be used to connect the two joining ends of the intersected brace members. This plate also connects to the continuous diagonal brace.

The corner gusset plate behavior of X-braced frames is studied more than central plates (mid-connection) and most researchers have tended to work in the former area. Studying the behavior of corner gusset plates can be useful to figure out the probable behavior of central plates. Whitmore (1952) studied the connection of truss plates, which was one of the leading works in this area. Thornton (1984) experimented on a plate with addressing all possible details. He found out that the ultimate buckling load of the plate is equal to the buckling capacity of the equivalent column under compression. Cheng *et al*. (1993) studied on the inelastic behavior of plates under buckling load. Every plate in their experiments was considered either completely fixed or free. In other words, when the brace was allowed to buckle out of plane, the condition is said to be free and fixed condition refers to the plate when the brace cannot show this kind of buckling. Furthermore, they indicated that brace angle, loading conditions and frame details are effective parameters on joint behavior. Also buckling and nonlinear behavior of gusset plates studied by some researchers such as Rajasekaran and Wilson (2013), Hassan *et al*. (2014) and Deliktas and Mizamkhan (2014). Fang *et al*. (2015) used experimental, numerical, and analytical investigations to evaluate compressive strength of gusset plate connections with single-sided splice members. Hadianfard *et al*. (2015) studied non-linear behavior of bracing gusset plates considering the presence or absence of longitudinal and transverse stiffener on the bracing splice plates as well as the arrangement of edge stiffener on gusset plates. Hadianfard and Khakzad (2016) used non-linear static analysis to investigate the buckling and post-buckling behavior of bracing gusset plates. Effects of parameters such as: dimension and thickness of the gusset plate and the influence of position of the bracing member examined.

As seen in the above researches, most studies on bracing connection plates have disregarded effects of existence of the frame and the plates are either modeled analytically or studied experimentally, separately from the whole frame. Experimental and numerical modeling of the whole frame structure by taken into consideration of its all components and their interaction require extensive works and details which eventually lead to make too much simplifications and assumptions on modeling process. What should be taken into consideration is that when a plate is numerically or experimentally modeled with its frame, the frame and plate can affect each other and this interaction between them can lead to a somewhat different behavior from the case in which no frame is supposed to be effective in the responses.

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http://www.techno-press.com/journals/eas&subpage=7
ISSN: 2092-7614 (Print), 2092-7622 (Online)

Tremblay *et al*. (2003) studied the seismic response of braces. Their models contained diagonal and X-braces. The braces of their models were of HSS sections. The loads were quasi static and results for the X-braces indicated that the effective length of a brace was a good parameter to determine the compressional strength of the brace. Mahmoudi and Zaree (2011) used nonlinear static pushover analysis to evaluate the over-strength of concentrically braced frames considering post-buckling strength. Caruso-Juliano *et al*. (2014) used nonlinear dynamic analyses to investigate the seismic performance of existing single-storey concentrically braced frame. Experimental and analytical investigations on seismic behavior of braced frames carried out by researchers such as Zahrai1a and Jalali (2014), Guneyisi and Ameen (2014) and Unal and Kaltakci (2016). Moni *et al*. (2016) used nonlinear static pushover and dynamic time history analyses to assess ductility and seismic performance of buckling restrained braced frames. Salawdeh and Goggins (2016) designed single storey steel concentrically braced frames, based on direct displacement for seismic loads.

Working on X-braced frames and their mid-connections does not date back to a long time ago. One of the first studies on X-braced frames with regard to its mid-connection was done by Davaran and Hoveida (2009). A numerical study of an X-braced frame and its mid-connection was done in that work based on the finite element method. They suggested a connection detail in which instead of interrupting two sections of a diagonal brace in the middle of X-braces, one of the sections of each diagonal would be intersected. Using this connection type along with cover plates can improve frame strength. Davaran *et al*. (2012) worked on experimental evaluating the seismic performance of X-braces. Some parameters such as dimensions of the brace, plate thickness, etc. were studied. The tests showed that instability of the connections was a common behavior for all the studied cases.

In a study by Yamashita (2012), seismic performance of X-braces involving equal-leg steel angles was studied. He used equal-leg angles as brace sections and exerted monotonic and cyclic loads. The concentration of this research was on X-brace performance and not on the mid-connection of this brace. Since the model of this work was very accurate, it could be a very suitable option for verification of the numerical models. Then, in this study, one of the Yamashita's tests is modeled in Abaqus software for verification.

In this paper, at first experimental Yamashita's model (Yamashita 2012) is explained. The explanations include models parts and dimensions, property definitions and the condition and parameter of loading. Next, a computer model is employed with regard to the experimental model. Assumptions of the computer model and verifications are then discussed. Afterwards, effects of different parameters on ductility and lateral strength of the X-braced frame are put forward. In other words, effects of different mid-connections with and without cover plates as well as bolted and welded connections on non-linear behavior and strength of the frame are studied.

In general, the two diagonals of an X-brace can be under compression or tension according to loading direction. In the current paper, discontinuous braces are always supposed to be under compression. Because buckling is the major cause of failure in compression, bracing members under compression may be more critical compared to the state of presence of tensile loads.

2. Experimental model

In this section, one of the Yamashita's models (Yamashita 2012) is introduced and its required parameters, values, and loadings are explained. Yamashita's model was a braced rectangular frame with its height and width equal to 3.7 meters. The selected model has a double angle of L75×6 mm for the brace members. Columns and beam are steel H sections and the X-braces are installed to the diagonals and connected to the frame using high-strength bolt and gusset plates. The thickness of gusset plate is 12 mm and five high strength bolts are used per one joint. A web-connection is used to connect the column and beam in the frame, and the frame is fixed at the bottom to the thick concrete floor slab. Details of the experimental model are shown in Fig. 1. Details of the mid-plate, gusset plate and joints are shown in Figs. 2 and 3. Also, geometrical and material properties are presented in Table 1. The members and plates material is SS400 steel.

The frame is subjected to pushover analysis by applying incremental displacements at the top of the model. The pushover diagram is defined where the X-axis is γ and Y-axis is Q/Q_{y0}, both non-dimensional parameters. γ signifies frame drifts angles and is obtained from Eq. (1). Q stands for lateral frame strength and Q_{y0} is the lateral yield strength of the frame obtained from Eq. (2)

$$\gamma = \frac{\delta}{l_0 \sin\theta} \tag{1}$$

$$Q_{y0} = \sigma_y A \cos\theta \tag{2}$$

in which frame displacements are shown by δ and the angle and length of the brace between two end plates are shown by θ and l_0, respectively. For the selected model, θ and l_0 are equal to 45 degrees and 5232.6 millimeters, respectively. For the second equation, σ_y and A are yield strength and section area of brace, respectively.

Table 1 Properties and section specifications

Properties	2L75x6	Units
Elastic Modulus	205	GPa
Yield strength	305	N/mm^2
Ultimate strength	424	N/mm^2
Angle flange length	75	mm
Thickness	6	mm
Area	17.454	mm^2
Gusset Thickness	12	mm
High strength bolts	5M20	

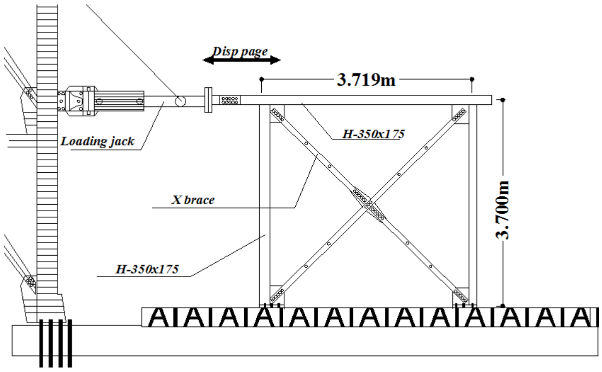

Fig. 1 Yamashita’s experimental model (Yamashita 2012)

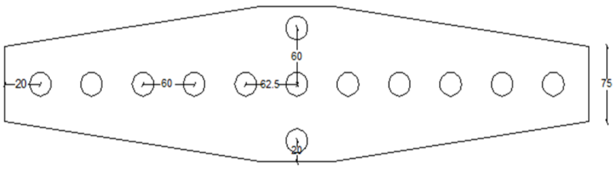

Fig. 2 Mid-plate details (Yamashita 2012), dimensions in mm

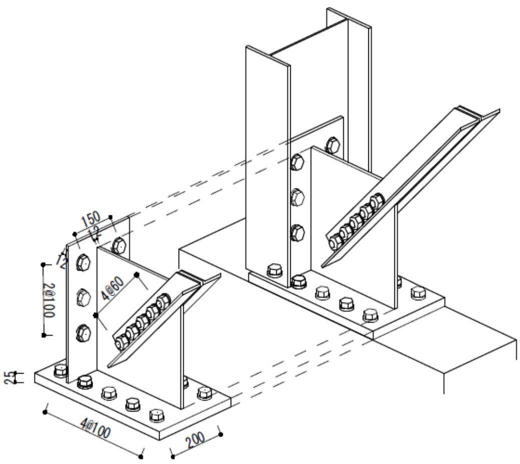

Fig. 3 Frame joint and gusset plate details (Yamashita 2012), dimensions in mm

3. Computer model and verification

The explained experimental model (Yamashita 2012) was modeled in the finite element software program Abaqus. All properties of the computer model were similar to those of the experimental one except for two as listed below:

- The average of displacements of the two ends of the beam in the experimental model is assumed to be the displacement of the numerical model roof.
- In computer modeling such as in Abaqus, in order to inspect buckling, a primary imperfection is first to be introduced to the intended member (Hibbitt 2010). This Imperfection shall be defined by the user and its value is usually equal to a percentage of the plate thickness or section width. Finding the correct value for imperfection needs a lot of try and errors. The best value of this parameter with which computer and experimental models have a good accordance was 40% of plate thickness.

The material characteristics are same as Yamashita’s models (Yamashita 2012). The members and plates material is SS400 steel that is defined in Table 1. The nonlinear stress-strain curve of steel is assumed to be bi-linear with yield stress equal to 305 MPa and ultimate stress equal to 424 MPa.

The computer model is shown in Fig. 4. The model is meshed with rectangular S4R elements and the connections are defined by the Tie Interaction property. Static Riks is the name of the analysis used for the computer model. Comparisons regarding buckling locations, buckled braces and pushover diagrams for both models are respectively presented in Figs. 5-7.

The maximum value of Q/Q_{y0} is equal to 1.41 for the experimental model and 1.48 for the computer one. It is better to compare the two diagrams above at different points, so the error values of the computer model are calculated at different points. The error is shown in Fig. 8 and it can be seen that it does not exceed eight percent for the worst condition.

Analysis of the frame under cyclic loading can lead to more accurate results than monotonic loading. Nonlinear analysis of the frame with considering all components and details under cyclic loading requires extensive time and work. However, push over analysis of the frame under monotonic loading is simple and relatively accurate and saves a lot of time and cost. Therefore, in researches to investigate the effects of some parameters on lateral behavior of the structure that require many structural analysis, push over analysis under monotonic loading can substitute the analysis under cyclic loading. In Fig. 9, the

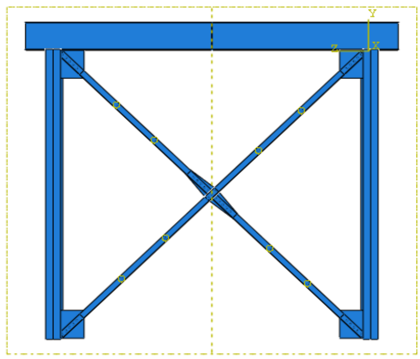

Fig. 4 Computer model

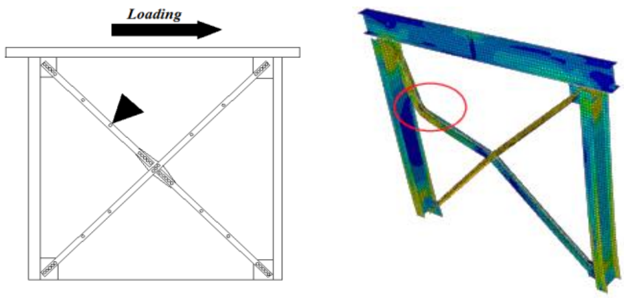

Fig. 5 Comparison of buckling location in the models

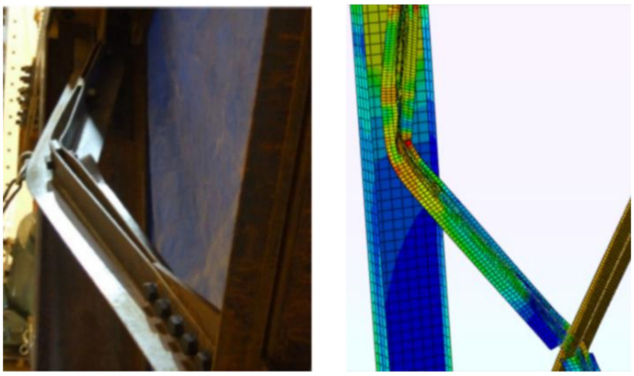

Fig. 6 Comparison of buckled braces in the models

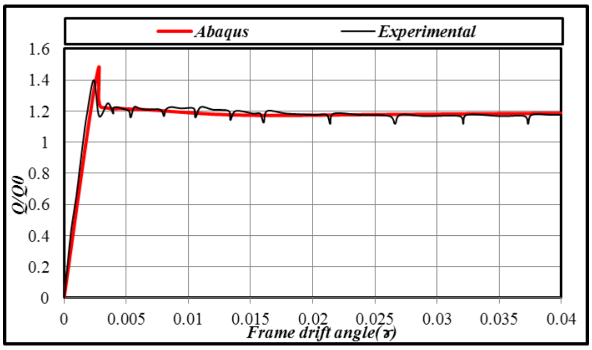

Fig. 7 Pushover diagrams of the models

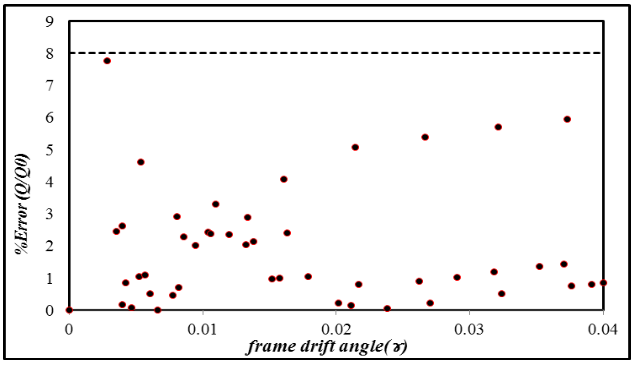

Fig. 8 Verification error

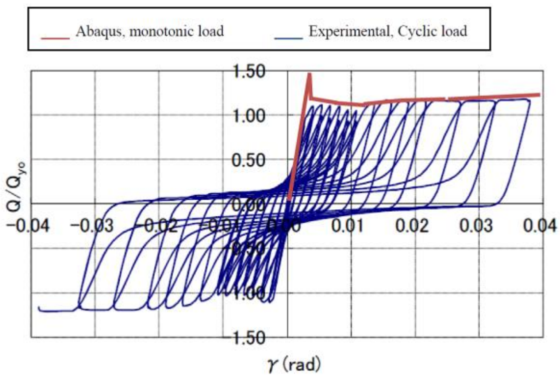

Fig. 9 Comparison of results of monotonic and cyclic loads

results of push over analysis under monotonic loading is compared with the experimental results of tested frame under cyclic loading (Yamashita 2012). This comparison shows that accuracy of the push over analysis to predict lateral behavior, ductility and lateral strength of the frame is very good. Thus, in this study, only push over analysis is used.

4. Concepts of buckling and ductility

For the sake of better comprehension of the next sections, it is necessary to define ductility and buckling strength. In tensional pieces, fracture is assumed to occur when one or more points reach the plastic behavior. In compression pieces of high slenderness, however, it is primarily buckling that controls fracture. Strength against buckling is hence an important concept which in accordance with Fig. 10 corresponds to the maximum point of the pushover diagram (H_u).

Ductility is ability of a structure to sustain large deformations after yielding without any significant reduction in ultimate strength. Park and Priestley (1987) defined ductility for some experimental models according to which ductility ratio is obtained by Eq. (3)

$$\mu = \frac{\Delta_{\max}}{\Delta_y} \tag{3}$$

Where, $\Delta_{\max}$ is value of displacement when the pushover diagram reaches its maximum strength. In other words, the corresponding displacement of H_u is equal to $\Delta_{\max}$ in Fig. 10. The value of displacement when the structure is reaching the yield point is equal to Δ_y. Since finding the yield point is not simple, Park proposed four procedures to calculate Δ_y one of which is used in this paper as illustrated in Fig. 11. According to this figure, the first point where the diagram starts getting non-linear is the first yielding and its corresponding displacement is Δ_y.

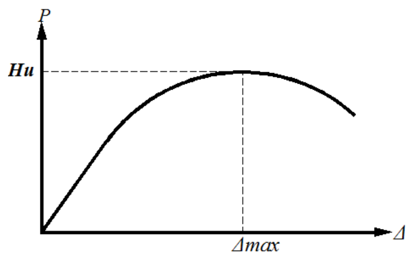

Fig. 10 Pushover diagram and lateral strength (buckling strength)

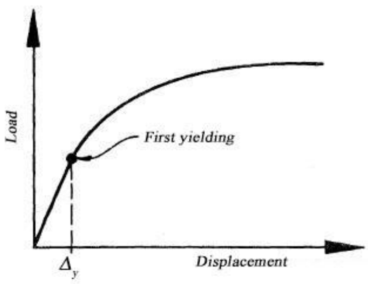

Fig. 11 Yield displacement (Δ_y) according to Park's (1987) procedure

5. Effects of mid-connection types on frame behavior

5.1 Types of mid-connections

In case of using double sections (for example, double angle or channel) for bracing members, one of the diagonal braces should be interrupted in the middle to let the other one pass. This non-continuous brace usually connects over via a central plate (mid-connection). In some cases, two single sections of one diagonal brace are intersected while for the other diagonal the sections are continuous. In this type of connection, the central plate is rectangular since the discontinuous diagonal brace needs more length to connect to the plate. This connection is named Connection Type I and is shown in Fig. 12 schematically. In some bracings with double sections, one section of each diagonal is continuous while the other is discontinuous. The central plate of this kind of connection is square. This connection is named Connection Type II and is shown in Fig. 13 schematically. Figs. 14 and 15 show comparisons of ductility and lateral strength of the frame for these two kinds of connections.

For Connection Type I, from the diagrams drawn for different thicknesses of the central plate, it is clear that by increasing the thickness of the plate from 6 to 8 mm, ductility and lateral strength of the frame increase significantly. However, by increasing the thickness of the plate from 8 mm, the changes in ductility and lateral strength of the frame are insignificant. Since for the plate with 6 mm thickness, buckling occurs in the plate while in the thicker plates it is in the bracing member. In Connection Type II, for all central plates thicknesses, buckling occur in the bracing member. Then, with increasing the thickness of the plate, ductility and lateral strength of the frame will not change significantly. Consequently, to increase ductility and lateral strength of the frame, buckling of bracing members should occur before the central plate.

Also two Figs 14 and 15 show that for different thicknesses of central plates, the Connection Type I has a better performance with regard to ductility and strength. An exception, on the other hand, exists for the plate with a thickness equal to 6 millimeters. The reason of this exception is the location of buckling. When plate thickness equals 6 millimeters, in Connection Type I buckling occur in the plate while in Type II it is in the bracing member. With accordance to the discussions above, the first option to perform the mid-connection details is Connection Type I if and only if the mid-plate could not buckle; else, Type II is preferable.

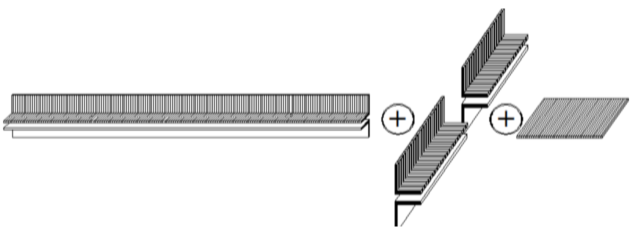

Fig. 12 Details of the Connection Type I

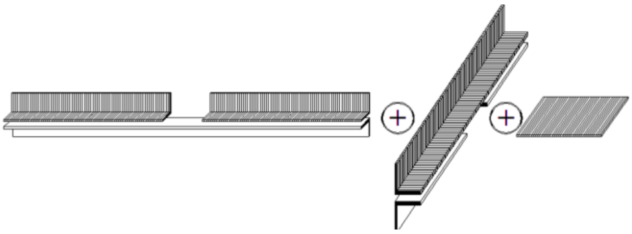

Fig. 13 Details of the Connection Type II

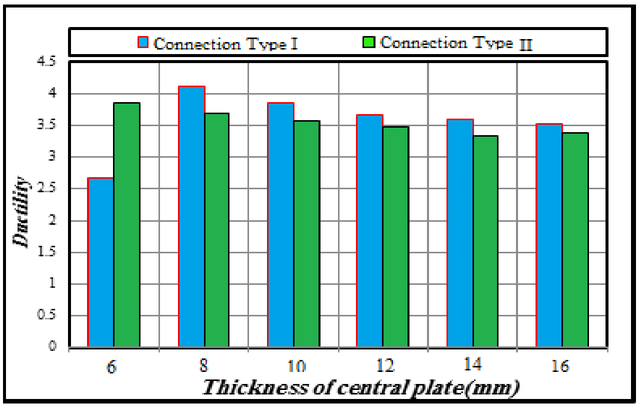

Fig. 14 Ductility comparison of two details with different central plates

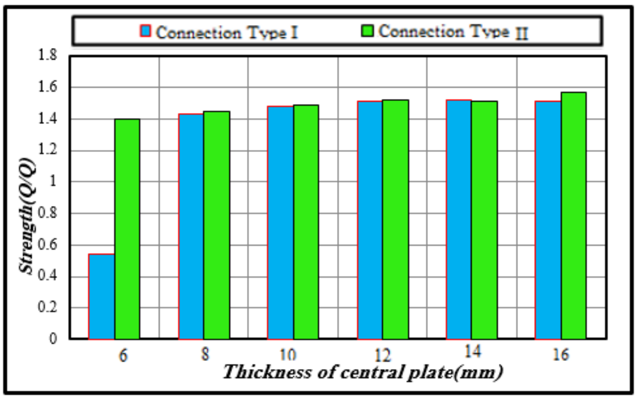

Fig. 15 Strength comparison of two details with different central plates

5.2 Using cover plates

Sometimes, in the mid-connection, two cover plates connect the two single sections of each side of the diagonal brace to have a better performance. Fig. 16 shows these two cover plates schematically.

The effects of three conditions are studied in this section, the first of which is a mid-connection without using any cover plates, this connection was previously named as Connection Type I and is shown in Fig. 12. The second condition is a mid-connection using a cover plate at each side (see Fig. 16) whose thickness is equal to half of the mid-plate thickness; this connection is named Connection Type III. The cover plate thickness of the third condition is equal to the mid-plate thickness. Then only difference between the last condition and the second is in the cover plate thickness while other aspects are quite similar. The third condition is called as Connection Type IV. Figs. 17 and 18 illustrate comparisons of these three conditions with regard to ductility and lateral strength, respectively.

According to the figures, using cover plates with thicknesses equal to half of mid-plate thickness leads to better performance than when no cover plate is used. Using cover plates with thicknesses equal to mid-plate connection gives similar results. This is while the comparison between Connection III and Connection IV shows no considerable difference though Connection IV is only slightly better than Connection III. Nevertheless, in Connection IV two cover plates with a thickness two times higher than that of the cover plate of Connection III has been used just for slightly better performance. This means that Connection III is the most preferable and using a cover plate with a thickness equal to half of that of the mid-plate results in the best performance with regard to economy, ductility and lateral strength of the frame.

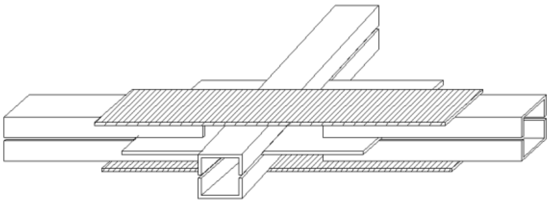

Fig. 16 Details of the mid-connection with cover plates (Connection Type III and IV)

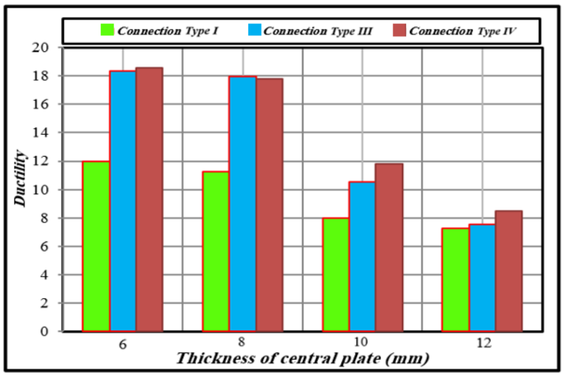

Fig. 17 Ductility comparisons for three different conditions of using cover plates

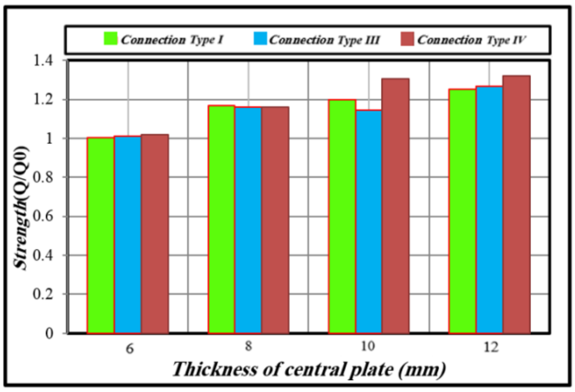

Fig. 18 Strength comparisons for three different conditions of using cover plates

5.3. Bolted and welded connections

To connect diagonal bracing members in the mid-connection of a X-braced frame, bolt or weld may be used. Discussion about which connection method may have better performance is an important subject. In this section, two frames are considered, all details of which are quite similar except for their connection method. The first model has welded connections while the second has bolted ones. Analyses are repeated for central plates with different thicknesses. Figs. 19 and 20 illustrate the comparison of the models with regard to their strength and ductility, respectively.

According to the Figs. 19 and 20, frame strengths are almost equal for both connections whereas bolted connections are of better ductility. Because, when the bolts are used to form the connection, a little sliding can occur between them and the plates. This sliding, which depends on such factors as mid-plate thickness, stiffness, type of bolts and loading, may be the best explanation for the manifested higher ductility.

6. Conclusions

X-braced frames have good strength and ductility against lateral loads. The mid-connection of such frames can affect the frame behavior. Hence, some types of mid-connection details have been studied in this research. The results obtained from the numerical analysis of the models

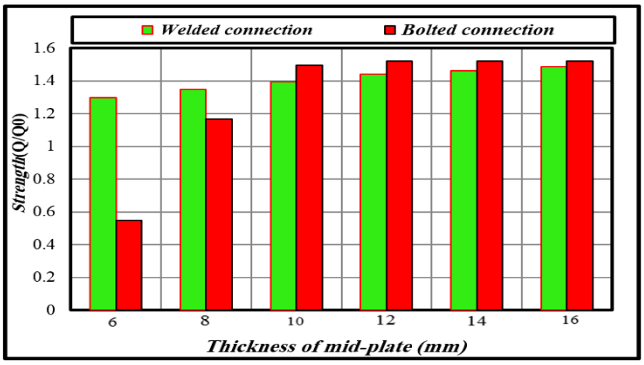

Fig. 19 Strength comparisons of bolted and welded connections

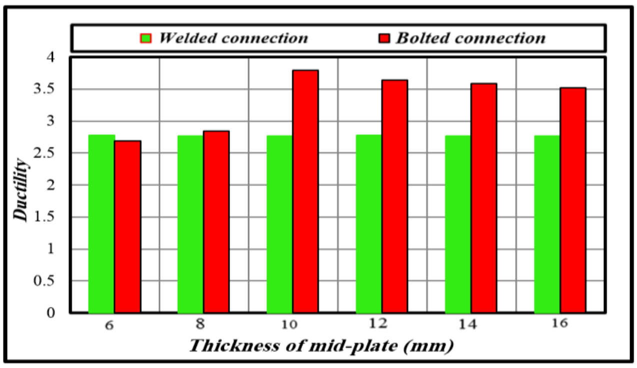

Fig. 20 Ductility comparisons of bolted and welded connections

are as follows:

- To increase ductility and lateral strength of the frame, buckling of bracing members should occur before the central plate connection.
- If the plate of mid-connection could not buckle before bracings; with increasing the thickness of the plate, ductility and lateral strength of the frame will not change significantly.
- It is better to perform the mid-connection details according to the Connection Type I if and only if the mid-plate could not buckle; otherwise the Connection Type II is more preferable.
- When the thickness of the mid-plate is small, it can easily buckle and hence Connection Type II can improve the lateral strength.
- Using cover plates leads to better performance. A cover plate with a thickness equal to half of the mid-plate thickness (Connection Type III) results in the best performance with regard to ductility, lateral strength of the frame and expense.
- Comparison between bolted and welded connections shows that strengths are almost equal for both connection methods but ductility of the case of bolted connections is more. The reason is that when bolts are used in the connection, some sliding may occur which may be the best reason of higher ductility.

Acknowledgments

The authors wish to thank Mr. Behtash JavidSharifi from Shiraz University of Technology for reviewing the manuscript and his precious comments.

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