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Tensile Stiffness of MERO-Type Connector Regarding Bolt Tightness

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Abstract: In order to take into account the connector effects in structural analysis, their behavior under applied load should be predicted. In double layer grids that are an important family of space structures, the main internal forces are axial forces and bending effect is secondary. In the present research, to determine force-displacement relationship of MERO jointing system, some tensile tests were carried out on a connector of this type with different degrees of bolt tightness. The obtained force-displacement relationship was used in the analysis of a double layer grid which its experimental response was available. The experimental results show that the degree of bolt tightness has significant effect on the connector behavior. Also, results obtained from analysis with connector consideration, give better approximation of actual response of the grid in comparison with the analysis regardless of connector effect consideration.

Key words: Force-displacement relationship, MERO-type connector, bolt tightness, nonlinear analysis, connector effects, double layer grid

INTRODUCTION

One of the most popular types of connectors that is widely used in the construction of double layer grids is the MERO-type system. Experimental results show that the actual behavior of double layer grids that are constructed using the MERO-type system is rather different from that suggested by conventional linear analysis (Davoodi *et al*., 2007; Androic, 1992). The discrepancy between the actual and theoretical responses of these structures is due to the fact that the behavior of connectors affects the response of the structures. In order to obtain a better approximation of the response of these structures, the actual stiffness of the connectors should be considered in the analysis. Since, the main internal forces in double layer grids are axial forces and non-axial effects (such as bending) are normally secondary, in order to consider the effects of connector in the analysis, their force-displacement relationship should be determined.

The state of stress and strain in a MERO-type connector is so complicated. This jointing system consists of a number of pieces including bolts. These pieces are from different materials involving high tensile steel and different grades of mild steel. In this system, discontinuities will be inevitable between the connecting parts due to the presence of bolts. The mechanism of load transfer at these discontinuities is complex and the presence of gaps and prestressing will give rise to more complexity. The degrees of tightness of bolts affect the width of gaps and prestressing. Furthermore, effects of the tightening of one bolt on the degree of tightness of other bolts will result in different degrees of tightness for different bolts in a structure. The experimental studies show that the degree of bolt tightness has significant effect on the static and dynamic behavior of the connector which, in turn, affects the behavior of the whole structure (Izumi *et al*., 2009; Davoodi *et al*., 2007; Pashaei *et al*., 2006; Chenaghlou, 1997; Shibata *et al*., 1993).

In the present study, in order to achieve a good understanding about the influence of bolt tightness on the tensile stiffness of a MERO-type connector, some tensile tests were carried out. The force-displacement relationships of the connector were obtained with different levels of bolt tightness.

MERO-TYPE SYSTEM

The MERO-type system is a multidirectional system allowing up to fourteen tubular members to be connected together at various angles. The system consists of tubular elements that are connected together by means of a MERO jointing system, as shown in Fig. 1.

The details of the connector are shown in Fig. 2a and b. The constituent parts of the system are:

- A forged steel ball
- Two forged steel conical end piece
- Two high tensile bolt
- Two sleeve with a window
- Two dowel pin

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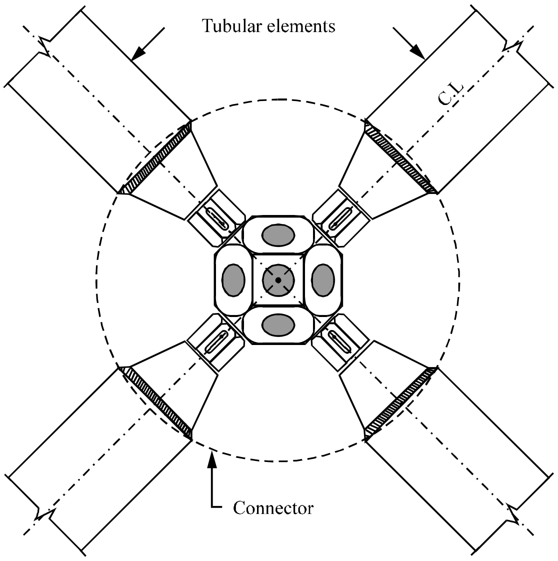

Fig. 1: General view of four connected elements

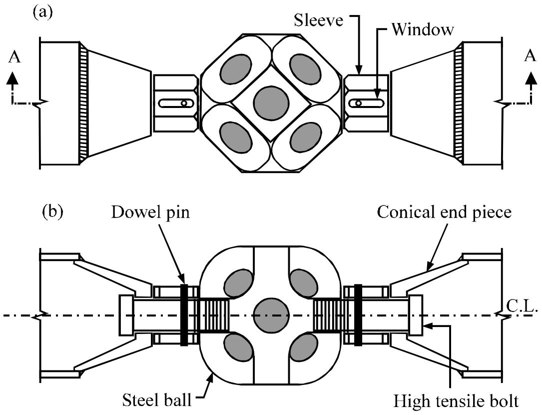

Fig. 2: Details of MERO jointing system. (a) outside view and (b) section A-A

The ball is located at the intersection of the longitudinal axes of tubular elements. The conical end pieces are welded to the end of the tube element. A high tensile bolt passes through the conical end piece and is screwed into the ball by means of a sleeve. A dowel pin is used to constrain the bolt to the sleeve in order to allow the turning of the bolt. There is a window on the sleeve that allows the movement of the dowel pin and indicates the penetration of the bolt in the ball.

The longitudinal axis of a tubular element and all the constituent parts of its end connectors are along together. This axis is referred to as axis of the member.

CONNECTOR STIFFNESS

A MERO connector in a double layer grid can be subjected to tensile and compressive forces. When tensile loads are applied to tubular elements, then the tension is transmitted through the ball, bolts and conical end pieces and the sleeves are inactive. In this case the stiffness constant of the connector in the elastic range is equivalent to the stiffnesses of the two conical end pieces, two bolts and a ball in series. It can be expressed as:

$$\frac{1}{K_{conn}}=\frac{1}{K_{ball}}+\frac{2}{K_{coni}}+\frac{2}{K_{bolt}} \tag{1}$$

Where:

K_{conn} = Stiffness of a connector
K_{ball} = Stiffness of a ball
K_{coni} = Stiffness of a conical end piece and
K_{bolt} = Stiffness of a bolt

The above mentioned tensile load transfer mechanism is idealized form. In practice, each bolt in a connector is tightened to a specific degree of tightness. Tightening the bolt causes the tension in the bolt that is called the pre-tension or bolt preload. It exists in the connector after the bolt has been tightened no matter whether the external tensile load is exerted or not. Since, due to tightening of the bolt different parts of the connector are being clamped together, the clamping force which produces tension in the bolt induces a compression in the other parts (conical end piece, ball and sleeve) of the connector. This prestressing that its amount depends on the degree of bolt tightness (Budynas and Nisbett, 2006), affects the stiffnesses of different parts of the connector. In this case the internal load of the bolt is:

$$F_{bolt}=\frac{K_{bolt}}{K_{bolt}+K_{slee}}+T+F_i \tag{2}$$

Where:

T = External tensile load
F_i = Bolt preload
K_{slee} = Stiffness of a sleeve

In order to determine K_{bolt} in Eq. 1, F_{bolt} from Eq. 2, should be considered as internal load of the bolt. This equation is valid only as long as some clamping load remains in the sleeves. After that, the internal load of the bolt is equal to external load of T.

TEST SPECIMENS

In order to obtain force-displacement relationship of the connector with respect to degree of bolt tightness,twelve specimens were constructed. A specimen consists of two tubular elements connected together by means of a connector (the tubular elements in a specimen were used to apply tensile load to the

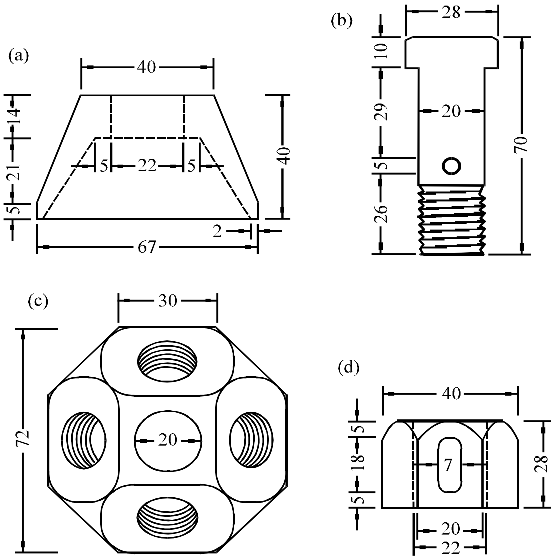

Fig. 3: Dimensions of test connector. (a) conical end piece (b) bolt (c) steel ball and (d) sleeve

connector). The dimensions of the components that are used in the connectors are shown in Fig. 3a-d. All dimensions in Fig. 3 are in millimeter.

The specimens were tested with four different levels of tightness of bolts.

- The bolts of three connectors were tightened using an adjustable torque wrench to 60 Nm. A connector with this degree of bolt tightness is referred to as T60
- The bolts of three other connectors were tightened to 120 Nm. A connector with this degree of bolt tightness is referred to as T120
- The bolts of three connectors were tightened 180 Nm. A connector with this degree of bolt tightness is referred to as T180
- The bolts of three connectors were tightened to 240 Nm. A connector with this degree of bolt tightness is referred to as T240

TEST PROCEDURE

To conduct the experimental investigations, the test set-up shown in Fig. 4 was used for experimental work. The connectors were tested with monotonically increasing tensile load to the tubular elements using a universal testing machine.

Due to lack of fitness of components during the manufacturing in the factory and human error during the welding of tubular elements to the conical end pieces, the connectors are deformed a bit. Due to eccentricity of the applied load as a result of this deformation the connectors are under combination of tensile load and bending moment. In order to eliminate the bending moment effect as well as increasing test results accuracy, four displacement transducers were used for displacement measurement of the connector. These four displacement transducers were divided into two pairs, that is DT1-DT3 and DT2-DT4 as shown in Fig. 5. The pairs of displacement transducers were connected diametrically opposite each other so that, in addition to the axial displacements, any bending moment`s deformation might be recorded. Since, amounts of shortening and elongation of each pair of transducers due to pure bending moment are the same, the average of the displacements of a pair transducers represents the axial displacement of the connector.

Fig. 4: The test set-up

TEST RESULTS

Figure 6 shows the experimental force-displacement relationships of the T60 connector. In order to achieve more accurate results, the average value of the measurements of two pairs transducers was considered as the displacement related to a load. The force-displacement relationships shown by dashed lines are related to the first, second and third test connectors, respectively and force-displacement relationship shown by black line is their average. This average relationship of the measurements for three different tests was considered as the force-displacement relationship of the connector with a specific degree of bolt tightness. As can be seen in Fig. 6, the T60 connector showed semi-rigid behavior in uniaxial tensile loading. In addition, a considerable nonlinearity observed in force-displacement relationship of connector, especially at final stages of loading. As shown in Fig. 7-9, the T120, T180 and T240 connectors had similar behavior. Representing force-displacement relationships of all the connectors, Fig. 10 shows that degree of bolt tightness affects the behavior of the connector.

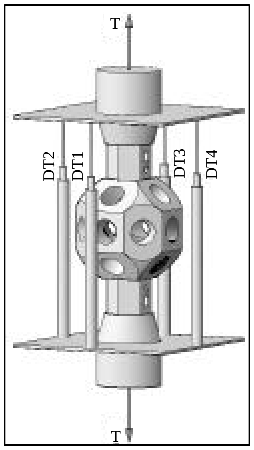

Fig. 5: Transducer arrangement

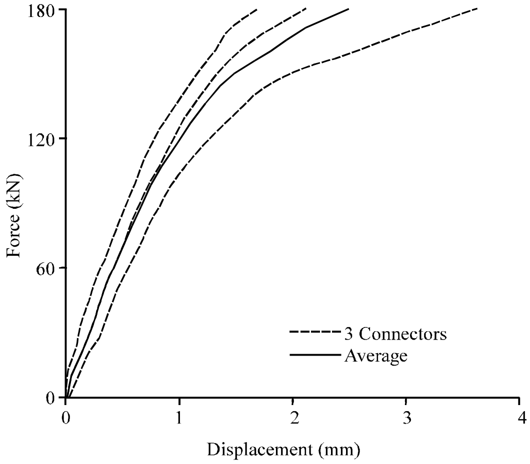

Fig. 6: Force-displacement relationships of three T60 connectors and their average

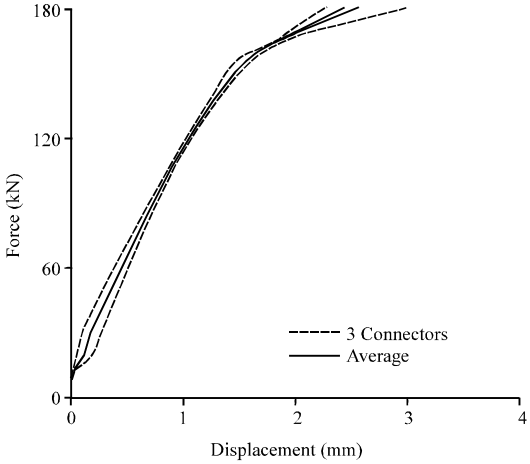

Fig. 7: Force-displacement relationships of three T120 connectors and their average

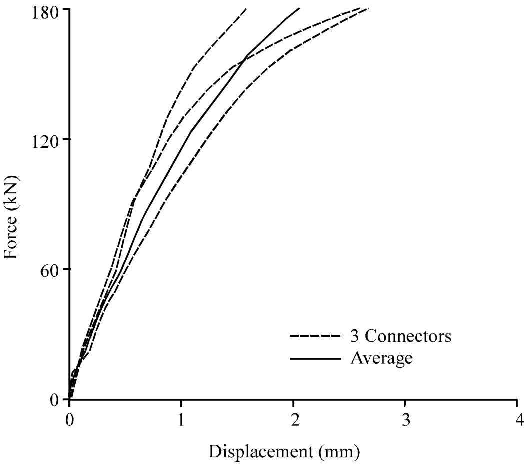

Fig. 8: Force-displacement relationships of three T180 connectors and their average

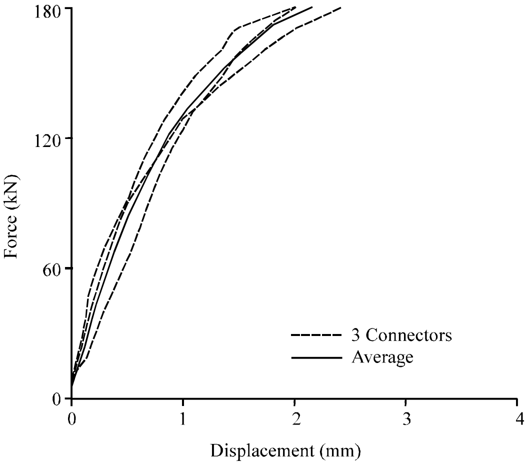

Fig. 9: Force-displacement relationships of three T240 connectors and their average

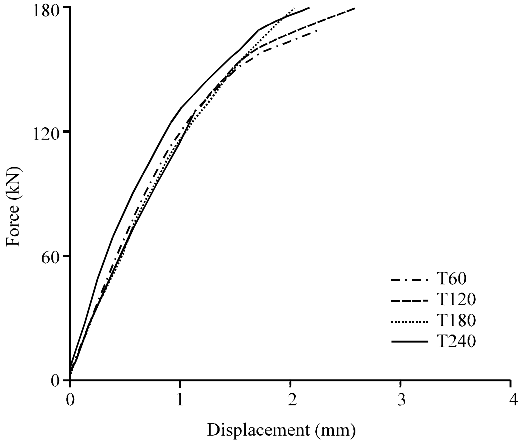

Fig. 10: Average force-displacement relationships of all connectors

ANALYSIS OF A DOUBLE LAYER GRID WITH CONSIDERATION OF THE EFFECTS OF THE CONNECTORS

A double layer grid has been studied experimentally and analytically by Davoodi *et al.* (2007). The plan of this double layer grid is shown in Fig. 11. In Fig. 11, the top layer elements are shown by continuous lines, the bottom layer elements and the web elements are shown by dashed and dotted lines, respectively.

The centre-to-centre distance between the top and bottom layers is 1000 mm. All the components of the grid are identical and all the connectors are the same as the connector that its stiffness is obtained experimentally in the present work. The dimensions of a typical component are shown in Fig. 12a.

Two-directional roller supports were used for all the supports of the grid. An incremental concentrated vertical load was applied to the central node of top layer of the grid as indicated by a small circle in Fig. 11. The deflections of the bottom layer nodes 1 to 12 (shown by little solid circles in Fig. 11) versus applied load has been obtained experimentally. Due to symmetry of the grid as well as the loading and the support conditions, deflections of nodes 1, 2 and 3 were considered as responses of the grid. Figure 13-15 show the load-deflection responses for nodes 1, 2 and 3 of the grid with 120 Nm degree of bolt tightness and twelve supports at the positions indicated by small squares in Fig. 11. The load-deflection responses of nodes 1, 2 and 3 of the grid with 120 Nm degree of bolt tightness and four supports at four corners are shown in Fig. 16-18. The dotted lines in Fig. 16-18 show the test results and the numerical results obtained through linear elastic analysis of grid for the relevant nodes are shown as a straight dashed line in Fig. 16-18 (Davoodi *et al.*, 2007).

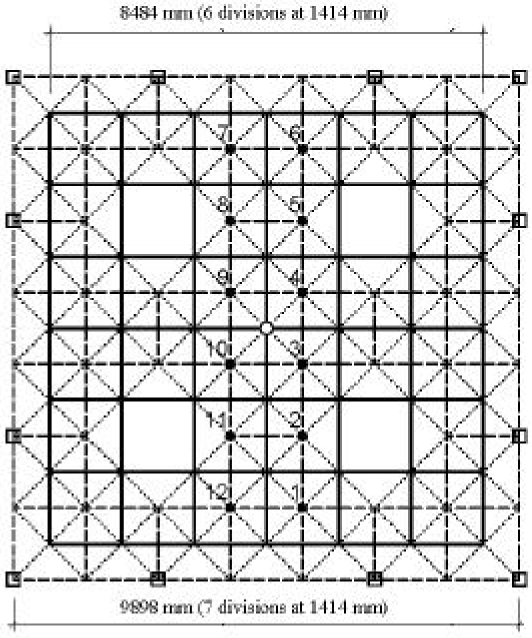

Fig. 11: The plan of the studied grid

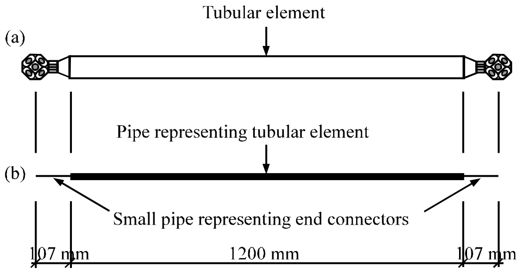

Fig. 12: (a) A typical component and (b) An analytical model

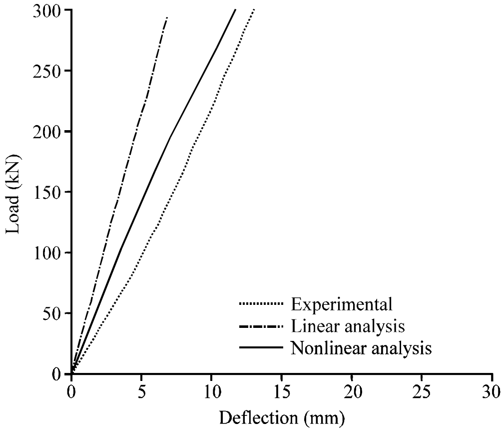

Fig. 13: Load-deflection response for node 1 of the grid with twelve supports

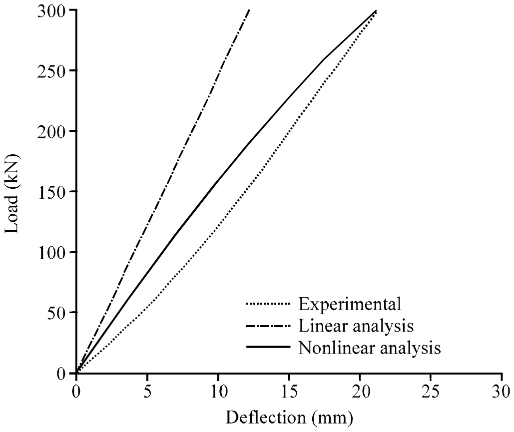

Fig. 14: Load-deflection response for node 2 of the grid with twelve supports

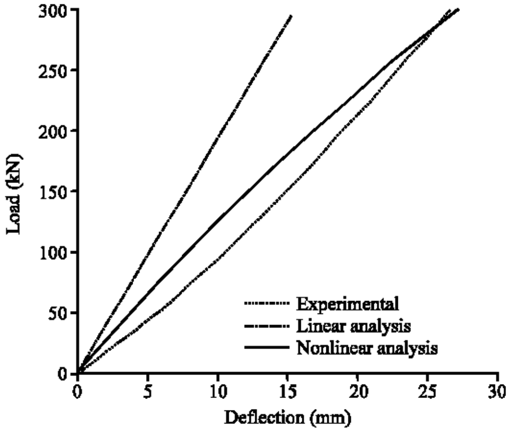

Fig. 15: Load-deflection response for node 3 of the grid with twelve supports

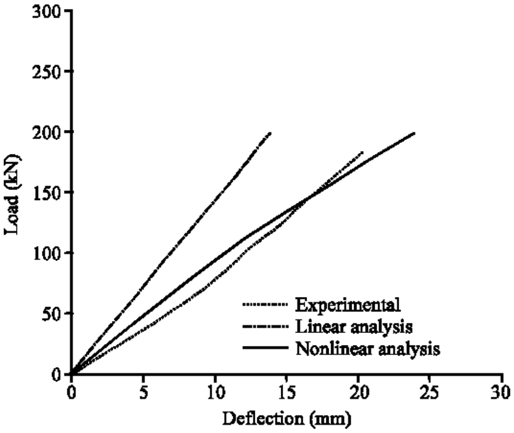

Fig. 16: Load-deflection response for node 1 of the grid with four supports

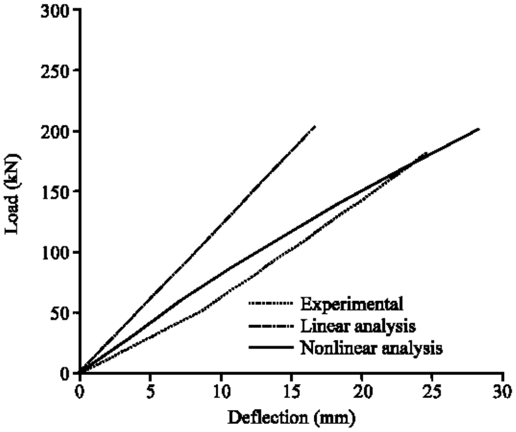

Fig. 17: Load-deflection response for node 2 of the grid with four supports

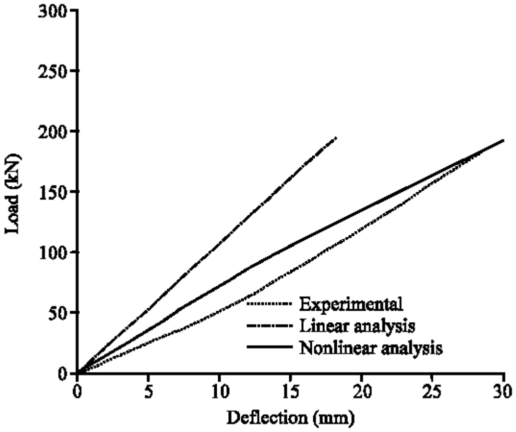

Fig. 18: Load-deflection response for node 3 of the grid with four supports

As can be seen in Fig. 13-18, there are considerable disagreements between the actual deflections of the nodes of the grid and analytical results obtained from linear elastic analysis. The main reason for the disagreement is due to the relative softness of the connectors that was not taken into account in the analysis. In order to obtain a better approximation of the response of the grid, in the present study the actual stiffness of the connectors was considered in the analysis.

As shown in Fig. 12a, a typical component of the MERO system consists of a steel tubular element together with the end connectors. To model space frame members which include the effects of joint characteristics, the joint at the ends of the member could ideally be simulated by typical structural components. Figure 12b shows a possible simulation of the typical component that was used in analysis of the grid.

The ANSYS software suite was used for analysis of the grid. The PIPE20 is a plastic straight pipe element, which has 6 degree of freedom at each end. This library element is used to model the tubular elements as well as the end connectors.

The tubular element is modeled using a pipe with outer diameter of 76.4 mm, thickness of 3.5 mm and the length of 1200 mm that is the length of tubular element. The material of the pipe modeled with a Bilinear isotropic hardening material model in ANSYS, with yield stress, Young's modulus, tangent modulus and Poisson's ratio of 240, 205000, 20500 and 0.3 N mm^{-2}, respectively.

The end connector is modeled using a pipe with the same cross section and the length of 107 mm that is the length of the end connector (Fig. 12). The experimental force-displacement relationship of the connector with 120 Nm degree of bolt tightness was used to obtain the equivalent stress-strain relationship of the connectors. The stress values were obtained using average force values in Fig. 7 divided by the cross section area of the pipe. The strain values were obtained from half of the average displacements values in this figure divided by the length of an end connector that is 107 mm, since each end connector in analytical model corresponds to half of the experimental connector shown in Fig. 4. Material type of the end connector was considered as multilinear isotropic and its stress-strain relationship was defined by 10 straight lines at least.

The numerical results obtained through nonlinear analysis of the grid with 120 Nm degree of bolt tightness and two different support conditions are shown as full lines in Fig. 13-18. These demonstrate that by considering actual behavior of connection in analysis, much more coincidence between numerical and experimental results is obtained.

DISCUSSION

A general observation of the force-displacement relationships of the connector with different degrees of bolt tightness leads to the following findings:

- The experimental results indicate that the force-displacement relations of the connector, in particular in the initial and the final stages of loading are nonlinear
- The force-displacement relationships of the connector show that the degree of bolt tightness has a considerable effect on the behavior of the connector. Similar results had been obtained by earlier studies (Izumi *et al*., 2009; Davoodi *et al*., 2007; Pashaei *et al*., 2006; Chenaghlou, 1997; Shibata *et al*., 1993)
- The nonlinear analysis of a double layer grid with consideration of the effects of the connectors shows that the actual nonlinear response of double layer grid is due to behavior of the connectors
- Earlier studies (Davoodi *et al*., 2007; Androic, 1992) mentioned that the actual behavior of double layer grids that are constructed using the MERO-type system is rather different from that suggested by conventional linear analysis. In agreement to this, present study indicated that in order to obtain a better approximation of the response of a double layer grid built in MERO jointing system, the actual force-displacement relationship of its connectors should be taken into account in the analysis

CONCLUSION

In the present study, twelve MERO-type connectors in four different groups were experimentally investigated in uniaxial tension. Each group includes three connectors with the same specific degree of bolt tightness. Average force-displacement relationships of different groups were obtained and compared. All the force-displacement relationships showed that the behavior of connector was nonlinear and was affected by the degree of bolt tightness. Furthermore, in order to study the effects of connector behavior on the global behavior of structures, a previously tested double layer grid were modeled using available codes, having the ability to consider the connection behavior. Comparing to the results of standard linear analysis without consideration of connector effects, analytically obtained nonlinear force-displacement relationships of the double layer grid considering the effects of connectors showed much better agreement with the test results.

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