Behaviour of Pretensioned Bolted Steel Column – Beam Connections Subjected to Monotonic Loading

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Abstract

This study presents that different types of steel column-beam connections with end-plates, in which all of the bolts are pretensioned, are numerically modelled. Numerical models have been carried out by ANSYS which is a finite element simulation software. The main purpose of this work is to simulate two column-beam connections with end-plates which were performed by experimental work and simulation in the literature and to compare the results in the literature with the results obtained in this study. The finite element models are compared with test results and observed good harmony. The second purpose is to derive a new specimen from these two specimens. These three specimens are also regarded with different material property which has tri-linear stress-strain relationship, and then the effects of changing material properties are investigated. After all, the regarded specimens are compared with the specimens which are taken in the literature in point of moment-rotation relationship and distribution of stresses.

Keywords: *Column-beam connections, finite element model, pretensioned bolt.*

1 Introduction

In steel structures, bolted column-beam connections, especially end-plate types, have increased in popularity. They have the advantages of requiring less supervision and shorter assembly times than welding joints (Bahaari and Sherbourne, 2000). There are two main types of end-plate connections; flush and extended. Conventional analysis methods idealise the connections as rigid or pinned. Actual behaviour of connections usually fall between these two extreme situations and the connections are therefore semi-rigid. Semi-rigid connections distribute the internal forces and also allow deformation of connections.

Many researchers have observed the behaviour of end-plate connections experimentally, theoretically and numerically under monotonic, cyclic and seismic loads (Sherbourne and Bahaari, 1994, Bahaari and Sherbourne, 1996, Bahaari and Sherbourne, 1996, Bursi and Jaspart, 1998, Beg et al., 1999, Bahaari and Sherbourne, 2000, Maggi et al., 2005, Shi et al., 2008, Mashaly et al., 2011, Mashaly et al., 2011, Diaz et al., 2011, Eldemerdash et al., 2012, Baei et al., 2012, Kaushik et al., 2013, Wang et al., 2013, Saber et al., 2014, Shaker and Abd Elrahman, 2014). All these studies deal column-beam connections as numerical model by commercially available finite element softwares. Finite element models can be used to determine the mechanical behaviour of joints. Finite element analysis allows that overcoming the lack of experimental study, understanding important local effects which is difficult to measure by experimental study.

This study presents that different types of steel column-beam connections with end-plate are numerically modelled by ANSYS (ANSYS Inc., 2011) finite element analysis software. The main purpose of this study is to simulate two column-beam connections with end-plate which were performed by experimentally and numerically in the literature and to compare the results in the literature with the results which obtained in this study. Therefore, two column-beam connections are referred from one of previous studies (Shi et al., 2008). The previous study presents the simulation and analysis of eight column-beam with end-plate connections and pretensioned bolts by using ANSYS. These eight connections have also been tested physically in order to validate the finite element models and the results. The end-plate type of one of the eight specimens have been taken as flush and the others have been extended. In this study, two of the eight specimens are referred as flush and extended end-plate type. The second purpose of this study is modelling another specimen which are derived from these two specimens but is not included in the eight specimens of the referred study. In specimens, two kinds of material properties have been used. That is, one of them is considered for steel profile such as beam and column, and the other one is regarded

for bolts. They are going to be called as “first group of material properties”. These three specimens are analyzed twice because of second group of material properties. First group of material properties is used as the same with the referred study. Second group of material properties is referred from another study (Mashaly et al., 2011). Thus, the effects of changing material properties are observed.

2 Development of Specimens

In this study, three column-beam with end-plate connection specimens and pretensioned bolts, two of which are referred from the referred study (Shi et al., 2008). These specimens are modelled with same (first) group of material properties and forces. Each specimens is also analyzed with different (second) group of material properties.

2.1 Geometric details of connections

In this study, three different geometric specimens are prepared. Column and beam profiles, end-plate thickness, bolt diameter, column height and beam length are same for all specimens and taken from the referred study (Shi et al., 2008). Beam and column dimensions are given in Table 1. End plate type of specimen 1 and specimen 2 are flush and extended, respectively. Specimen 3 is derived from these specimens. End-plate type of this specimen is extended only in tension side, it is extended above the beam and is flush below the beam. For all connections, column flange is cut within the length range of 100 mm above and below the extension of the end-plate and this gap are filled by column plate. End-plate and column plate thicknesses and bolt diameter are taken as 20 mm for all specimens. The details of connections are shown in Figure 1.

Table 1. Column and beam dimensions (mm) (Shi et al., 2008).

Section	Section depth	Web thickness	Flange width	Flange thickness
Beam	300	8	200	12
Column	300	8	250	12

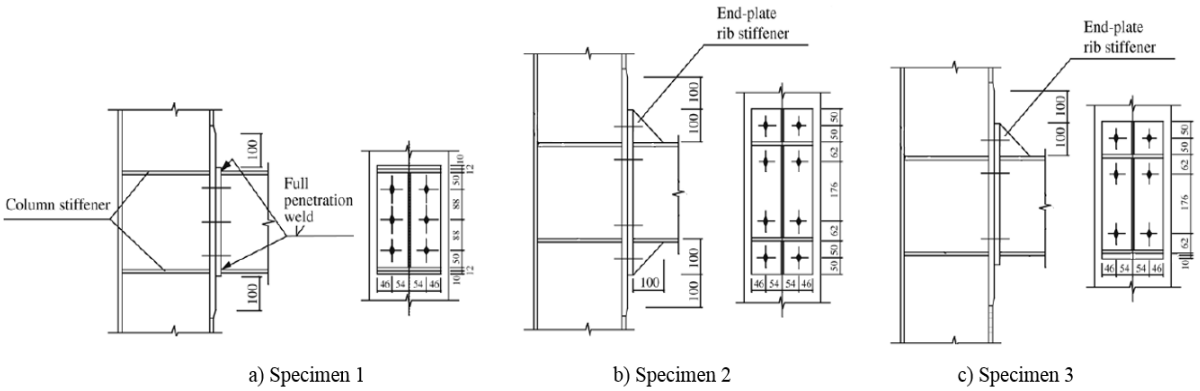


Figure 1. Details of connections (mm) (Specimen 1 and 2 are taken from the referred study (Shi et al., 2008)).

2.2 Finite Element Models

The models are investigated by finite element software ANSYS (ANSYS Inc., 2011). Three-dimensional solid elements are used for finite element modelling. After completing geometrical model, due to geometrical symmetry about the axis which is parallel to beam and column webs, one half of each specimen is taken into account for finite element analysis in order to reduce computation time. For example, complete and reduced model for Specimen 2 is shown in Figure 2.

The specimens in the referred study were meshed by tetrahedral solid elements. However, all components in the specimens are meshed by hexahedral solid elements in this study. Tetrahedral elements are more rigid when compared with hexahedral elements, so tetrahedral elements restrict deformations of components. Components may also be meshed with less elements by hexahedral elements. Meshes of the referred study and this study for Specimen 2 and its bolt are shown in Figure 3. Meshes of end-plate and column plate in this study are shown in Figure 4. The numbers of element and node for the finite element models are given in Table 2 for the specimens.

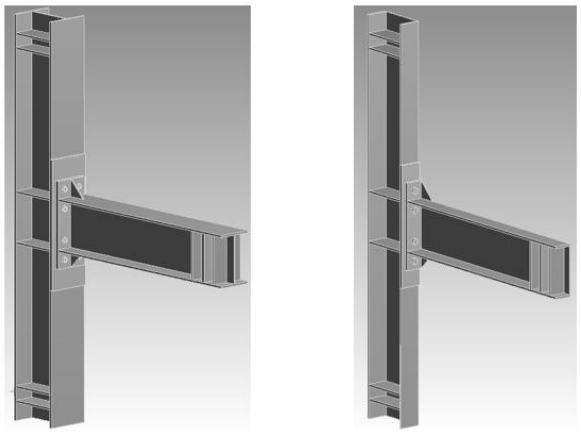


Figure 2. Complete and reduced model for specimen 2.

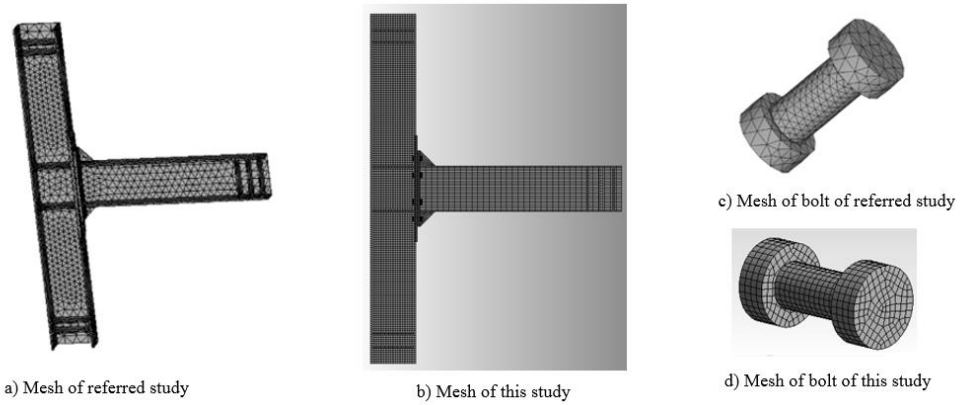


Figure 3. Meshes of the referred study (Shi et al., 2008) and this study.

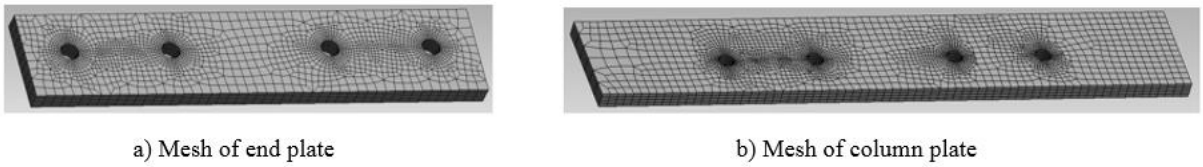


Figure 4. Meshes of end-plate and column plate.

Table 2. Numbers of element and node for each specimen.

	Specimen 1	**Specimen 2**	**Specimen 3**
Element number	27057	37498	30713
Node number	145342	196472	159997

2.3 Contact Properties

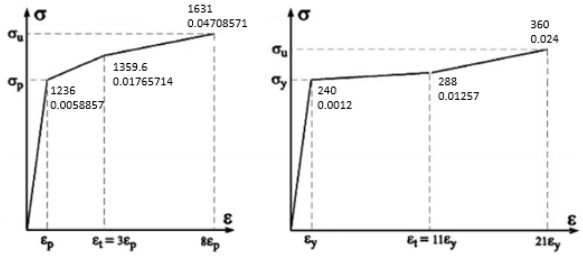
Bolted column-beam connections consist of many components such as bolt, nut, column, beam and plates. There is interaction between each pair of components which contacts each other. Contact type between column plate and end-plate is taken as non-linear and friction coefficient is taken as 0.44. Other contact types between components are taken as linear.

2.4 Material Properties

Each specimen is analyzed twice because of second group of material properties. First group of material properties is taken from the referred study (Shi et al., 2008). The stress-strain relationship for the high strength bolts is given in Table 3. For the other steel components, it is taken as elastically-perfect plastic. The yield strength and modulus of elasticity of steel plates thicker than 16 mm are taken as 363 MPa and 204227 MPa, respectively; for other steel plates 391 MPa and 190707 MPa, respectively. Trilinear stress strain curves are used to define second group of material properties for all components. These curves are taken from another study (Mashaly et al., 2011) and shown in Figure 5. For all groups of material properties, the poisson's ratio is taken as 0.3. As seen in Figure 5 for second group of material properties yield and ultimate stresses of bolts are more, however yield and ultimate stresses of other components are less when compared with first group of material properties.

Table 3. First material properties for high strength bolts (Shi et al., 2008).

Stress (MPa)	0	990	1160	1160
Strain (%)	0	0.483	13.6	15



a) For bolts and nuts b) For other components.

Figure 5. Second groups of material properties for high strength bolts and other components (Mashaly et al., 2011).

2.5 Loading

The analysis of each specimen consists of two load steps. Firstly, only 155 kN pretension forces are applied to the bolts. Secondly, after solving first load step, downward displacement load is applied at the loading point. The distance from the loading point on the beam to the column flange is taken as 1200 mm. Each load step is divided into at least 25 substeps. So, pretension force and displacement load subjected step by step instead of at a time because of steady-state non-linear analysis. Therefore, geometric non-linearity is taken into account for all specimens.

3. Results and Discussion

The first purpose of this study is to obtain same results with the referred study (Shi et al., 2008). Table 4 shows that the comparison of loading capacities between this study and the referred study. Figure 6 and 7 show the comparisons between this study and the referred study which is performed by experimentally and numerically in point of moment-rotation and moment-shearing rotation curves, respectively. The method of obtaining moment and rotation values were taken from another study (Shi et al., 2007). The joint rotation (ϕ) of the connection includes two parts: shearing rotation (ϕ_s) and gap rotation (ϕ_{ep}). Shearing and gap rotations are calculated by Δ/h_t and δ/h_t, respectively. Where, Δ is displacement difference between column plate at the centre lines of the top and bottom beam flanges, δ is gap between column plate and end-plate at the centre lines of the top beam flange and h_t is the distance between the centre lines of the top and bottom beam flanges. The joint moment is obtained by load and distance from the loading point to the column plate. As seen from Figure 6 and 7, for specimen 2 both in linear and non-linear ranges between results of this study and finite element analysis of the referred study seem as extremely close. For specimen 1 in non-linear range the results are almost same for two curves, but in linear range the agreement has small discrepancies. The discrepancies are more in comparison by moment-shear rotation.

Table 4. Comparison of loading capacities (kN).

	Experimental test by Shi et. al, 2008 (A)	**FEA by Shi et. al, 2008 (B)**	**FEA in this study (C)**	**(C)/(A)**	**(C)/(B)**
Specimen 1	155.3	156.2	150.63	0.97	0.96
Specimen 2	286.4	276.8	273.12	0.95	0.99

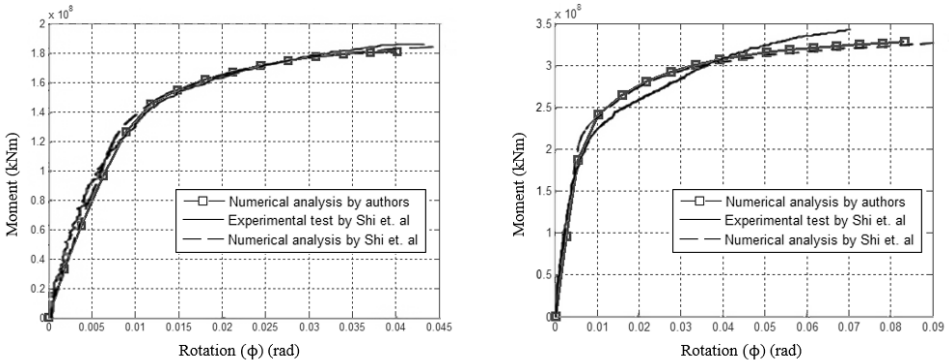


Figure 6. Comparison between moment-rotation curves of this study and referred study (Shi et al., 2008).

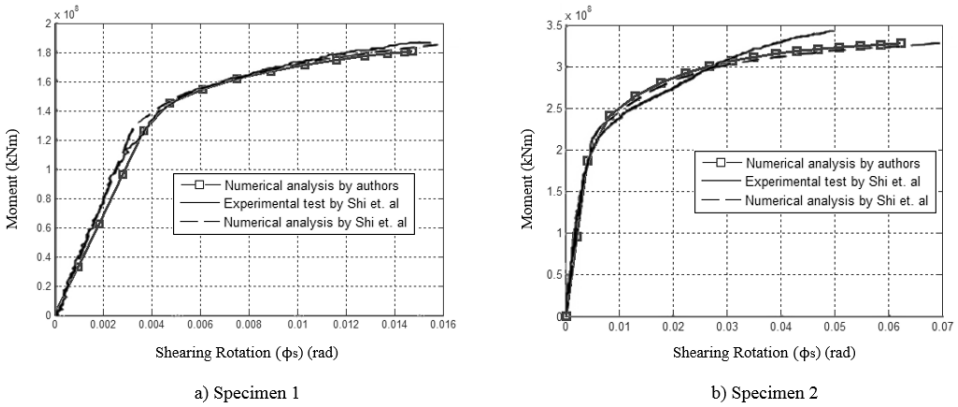


Figure 7. Comparison between moment-shearing rotation curves of this study and referred study (Shi et al., 2008).

Figure 8 shows comparison of ultimate failure mode of Specimen 1 with experimental one. Comparison of distribution of pressure of specimen 2 between the end-plate and column plate caused by pretension force is shown in Figure 9.

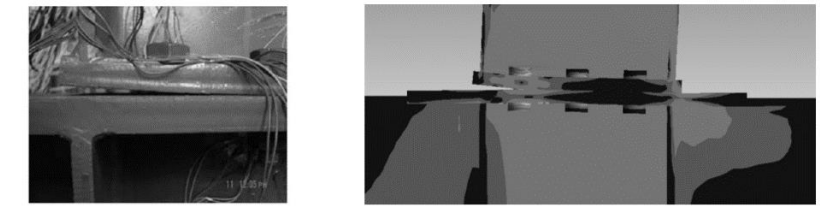


Figure 8. Comparison of ultimate failure mode of Specimen 1.

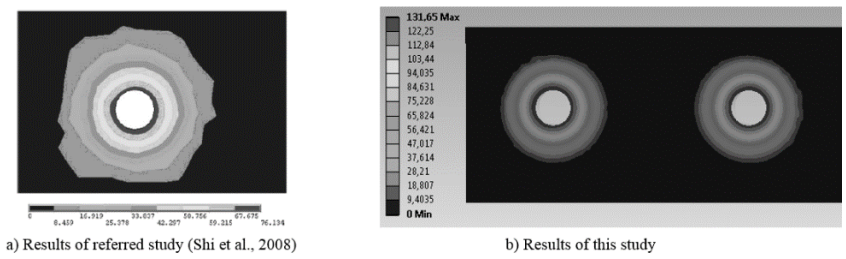
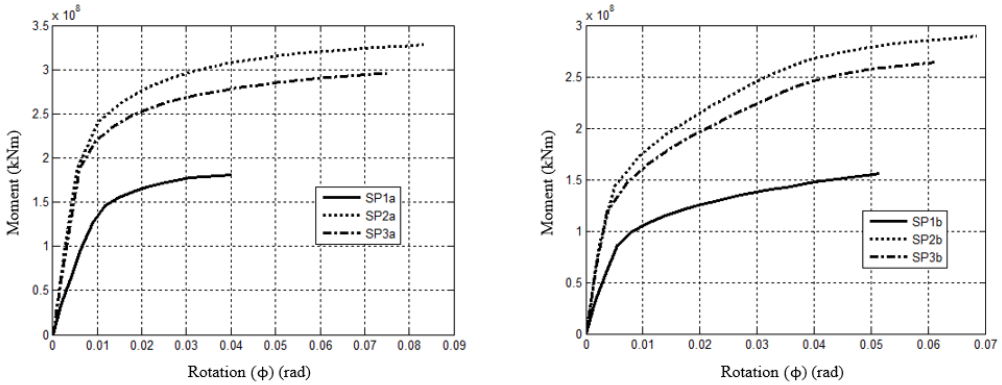


Figure 9. Comparison of distribution of pressure between the end-plate and column plate by bolt pretension force for Specimen 2.

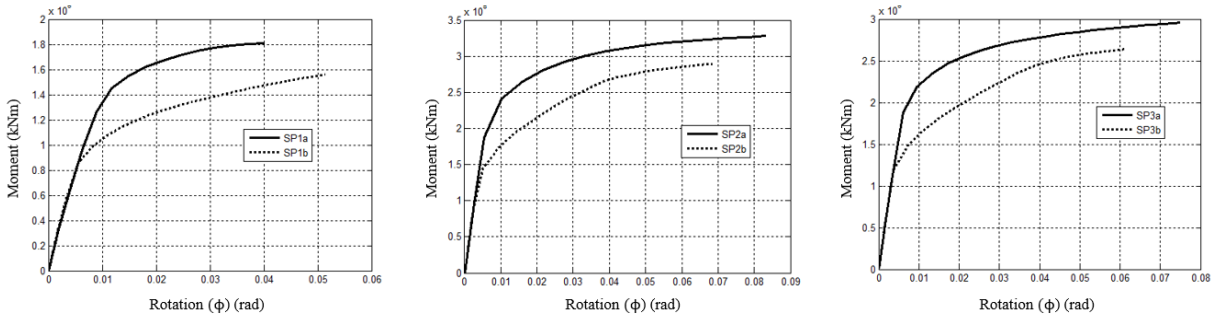
It is observed that the comparisons of moment-rotation curves, moment-shearing rotation curves, load capacities and failure modes in good agreement with each other. Comparison of distribution of pressure between the end-plate and column plate by pretension force is not coherent. The discrepancies may be several reason such as mesh density, the number of contact element, element types.

The second purpose of this study is to derive a new specimen from these two specimens. These three specimens are also analyzed with the second group of material properties which has tri-linear stress-strain relationship, so the effects of changing material properties are investigated. The comparison of moment-rotation curves of three specimens for both groups of material properties are shown in Figure 10. In these diagrams "Specimen" abbreviated as "SP". First and second groups of material properties are indicated as "a" and "b", respectively. Moment capacity of Specimen 3 is close to Specimen 2 and slopes of curves in linear range are same. Second group of material properties cause decreasing moment capacity of specimens because of decreasing yield and ultimate stresses of structural steel. For each specimen the effect of changing group of material properties are also shown separately in Figure 11. As shown in Figure 11, for Specimen 2 and 3 both moment capacity decreases approximately 12 percent and rotation capability decreases approximately 13 percent. However, for Specimen 1 moment capacity decreases approximately 11 percent, whilst rotation capability increases approximately 25 percent. Consequently, it is worth to say that increase of stiffness in connection as in Specimen 2 and 3 give proportional effect between moment and rotation capacity. However, decrease of stiffness in connection as in Specimen 1 give inversely proportional effect between them.



a) Material properties (a) b) Material properties (b)

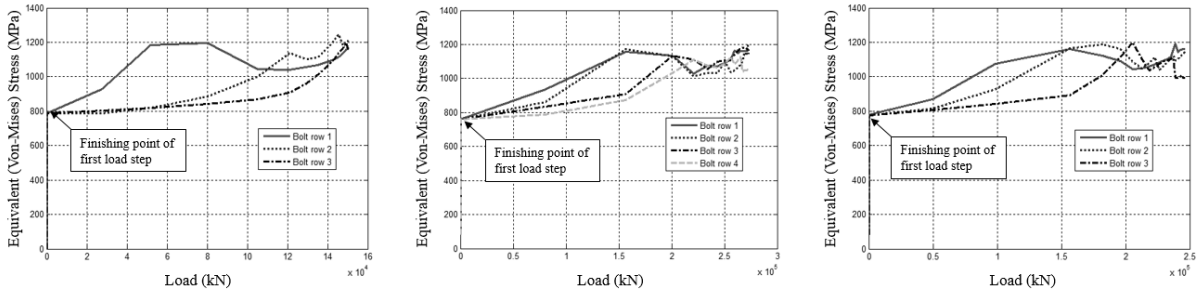
Figure 10. The comparison of moment-rotation curves of three specimens.



a) Specimen 1 b) Specimen 2 c) Specimen 3

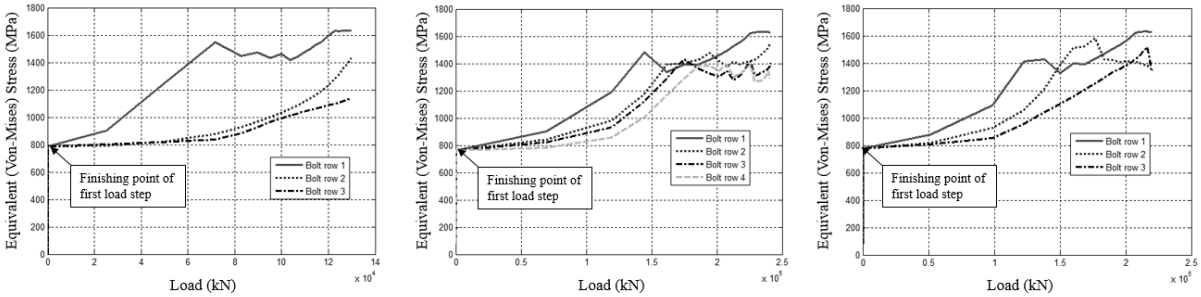
Figure 11. The effect of changing material properties for each specimen.

For each group of material properties, load which subjects to loading point at the beam and maximum equivalent (Von-Mises) stress on the bolt curves are shown in Figure 12 and 13, respectively. Bolt rows are entitled from upper bolt row to bottom bolt row. At first load step, there is not load at the loading point, there is only pretension force. After first load step, the upper bolt row subjected to more stress until yielding. As shown in Figure 12 and 13 usage of different groups of material properties effects relationship of stress level of bolts under carried load. Stress level of bolts are affected from stiffness of connections and contact level under loading process.



a) Specimen 1 b) Specimen 2 c) Specimen 3

Figure 12. With first group of material properties, curves of maximum equivalent stress on bolts versus load at loading point for the specimens.



a) Specimen 1 b) Specimen 2 c) Specimen 3

Figure 13. With second group of material properties, curves of maximum equivalent stress on bolts versus load at loading point for the specimens.

4. Conclusion

Bolted column-beam connections are investigated in this study. Three different specimens are prepared and each specimen is analyzed with two group of material properties to investigate effects of changing material properties. Two of these specimens are taken from the referred study (Shi et. al, 2008). From this study, the following can be concluded:

- Comparisons of moment-rotation curves, moment-shearing rotation curves, load capacities and failure modes between referred study (Shi et al., 2008) and this study in good agreement with each other. Comparison of distribution of pressure between the end-plate and column plate by pretension force is not coherent. The discrepancies may be several reason such as mesh density, the number of contact element, element types.
- Moment capacity of Specimen 3 is close to Specimen 2 and slopes of curves in linear range are same.
- Second group of material properties cause decreasing moment capacity of specimens because of decreasing yield and ultimate stresses of structural steel. Increase of stiffness in connection as in Specimen 2 and 3 give proportional effect between moment and rotation capacity. However, decrease of stiffness in connection as in Specimen 1 give inversely proportional effect between them.
- Usage of different groups of material properties effects relationship of stress level of bolts under carried load. Stress level of bolts are affected from stiffness of connections and contact level under loading process.

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