Behaviour of Continuous Beam to Column Connections in Post Earthquake Fire

M. Yahyai & B. Hasanpour Ghamsari
Civil Engineering Department, K.N. Toosi University of Technology

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SUMMARY:
Earthquake events are often followed by fire which may cause more damage than the earthquake itself. Unprotected steel is practically vulnerable to fire hazard and the mechanical strength of steel reduces drastically at elevated temperatures. In this paper, the behaviour of a specific kind of continuous beam to column connection at elevated temperatures is studied. This is a proposed connection for earthquake-resistant steel structures. In this connection, two beams pass next to the column faces without interruption and are connected to the column flanges by vertical plates. The coupled temperature displacement finite element analysis was conducted. The moment-temperature-rotation curves were derived for these connections. The result shows that, as the temperature increases strength and moment resistance of connection decreases and moment capacity of connection have decreased significantly over 400˚C. In addition the influence of different parameters such as thickness of connection plates and the length of the beams was investigated.

Keywords: Post Earthquake Fire, Elevated Temperatures, Connection, Finite Element Modelling.

1. INTRODUCTION

Fire safety is a major concern with steel structures. Since the mechanical properties of steel significantly deteriorate at high temperatures, the load capacity of steel structures under condition of a structural fire will decrease intensively. A structure is constructed with separate members, which are jointed together by connections. The study of the behavior of connections in steel structures at elevated temperature is of great importance.
Considering the ability of finite element method (FEM) in prediction of steel connection behavior, several studies have been conducted. Some of these researchers are presented below:
Liu (1994, 1999) was the first to attempt to use FEM in modeling connection behavior at elevated temperatures. A 3-D FEM was developed by El-Houssieny et al. (1998) to simulate the response of extended end plates at both ambient and elevated temperatures. Silva and Coelho (2001) presented an equivalent elastic model to evaluate the response of steel joints under bending and axial force.
ANSYS was used by Spyrou et al. (2002) to model T-stub specimens at elevated temperatures.. Rahman et al. (2004) studied the response of fin plate joints in fire using ANSYS. Sarraj et al. (2006) also developed 3-D ABAQUS models of fin plate connections, which include the important contact interaction between the bolts and the fin plate and beam web. The models were validated against lap joint data at ambient temperature and a fire test conducted by Wald et al. (2006) at the Czech Technical University. A finite element model was developed by Al-Jabri et al. (2006) to study the behavior of flush end plate bare steel joints at elevated temperatures using the general purpose finite element software ABAQUS.Lou and Li (2006) used ANSYS to model the behavior of cruciform tests with extended end plates in fire.
Saedi Daryan et al. (2009(b)) carried out four experimental tests on Khorjini connections as semi rigid connections at elevated temperature. The connections were modeled using ABAQUS finite element program. Comparison between the result of numerical models and experimental test results showed good agreement in elastic and plastic ranges.

From the presented overview, it is clear that FE methods provide a reliable technique, which can be efficiently used in predicting the elevated-temperature behavior of joints to an acceptable degree of accuracy and enable a wider range of parameters to be considered than would be the case with a laboratory-based investigation.

The main purpose of this paper is to study the behavior of Continuous beam to column connections in fire. Continuous beam to column connections are classified as semi-rigid connections that are widely used in some countries including Iran. Despite the frequent use of these connections, no extensive research is carried out about these connections. Thus, in this paper finite element model of these connections are developed and the results of the models are compared to that of experimental tests in standard fire condition to verify the finite element models. Then, the behavior of these connections under fire is studied and moment-rotation-temperature as well as stiffness-temperature curve are calculated. These curves are good representatives for connection behavior in fire and are needed for fire-resistant design of structures.

In the following, the effect of some parameters on fire behavior of these connections is studied.

2. CONNECTION MODELS

The connection models selected for this study and for verifying its numerical modeling are taken from experiments of Saedi Daryan et al (2009(b)). In these series of tests, some experimental tests have been conducted to study the fire-resistant capacity of Continuous beam to column connections at elevated temperature. More details about the experiment on this specific connection are presented in the references Saedi Daryan et al (2009(b)). Results are presented in the form of temperature-rotation diagram. In addition, the influence of different parameters such as the value of the applied moment, and other geometrical and mechanical characteristics of the connections were studied.

3. CONTINUOUS BEAM TO COLUMN CONNECTION WITH ANGLES

3.1. Geometries of Connection Models

Semi-rigid connection in steel structures has garnered considerable attention in recent years due to its simplicity and the possibility of tuning the connection's stiffness, which can optimize the distribution of moment between connected elements. In Continuous beam to column connections, a pair of continuous beams cross several columns and connect to the sides of the columns by means of angle sections. This type of construction saves not only on erection time and labor cost, but also on the limitations on availability and the cost of deep-rolled sections in the country. The use of two parallel beams instead of one deeper beam is the only alternative in most cases.

In this study, four experimental tests were carried out on Continuous beam to column connections. In all of the tests, the connections connect an 800mm height column of profile IPE300 to two 3600mm beams of profile IPE120. Details of the specimens are shown in

Fig. **1**. The only difference with these tests is the amount of bending moment applied to the connections. Applied moment on each connection is given in Table 1 by the connection's rotation capacity.

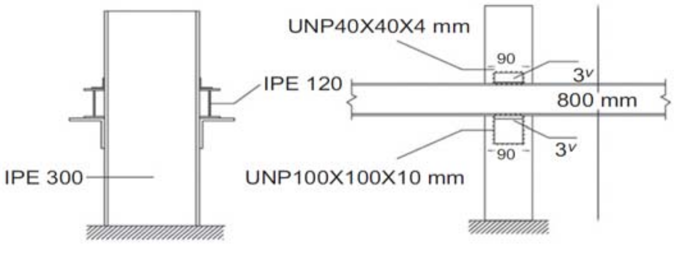

Fig. 1. Details of tested connection

Table 1. Level of loading for connection tests

Specimen number	Moment level(Mcc)	Applied M(KN.m)
1	0.2	3
2	0.4	6.5
3	0.65	10.5
4	0.85	13.5
Mcc = moment capacity of the connection		

3.2. Material Property

At elevated temperatures, connections undergo large plastic deformation; therefore, elastic-plastic material model with strain hardening was adopted.
Analytical models are simplified models so it is sufficient to incorporate the main parameters like stiffness and strength. These parameters represent the degradation of material properties with temperature. To achieve this goal, the properties of main material used in the specimens (stiffness and strength of material) are reduced according to the deterioration equations for elevated temperature in EC3: Part 1-2 and are presented in Table 2.
The steel properties of the specimens are obtained from references (Saedi Daryan 2009(a)). It should be noted that the results of Mill test is presented in Table 3.
In the FE analysis, the Von Mises yield criterion was used for connection materials. A thermal expansion coefficient of $12\times10^{-6}/^{\circ}c$ was used for steel to take into account the temperature variation.

Table 2. Reduction factors for stress–strain curves of steel at elevated temperatures

θ_s	$k_{y,\theta} = f_{y,\theta}/f_y$	$K_{E,\theta}=E_{s,\theta}/E_s$
20	1	1
100	1	1
200	1	0.9
300	1	0.8
400	1	0.7
500	0.78	0.6
600	0.47	0.31
700	0.23	0.13
800	0.11	0.09
900	0.06	0.0675
1000	0.04	0.045
1100	0.02	0.0225

Table 3. Material properties of the specimens

Material	Yield stress (N/mm^2)	Ultimate stress (N/mm^2)	Modulus of elasticity (N/mm^2)
Beam & column & angle	235	420	2.06×10^5

3.3. Boundary Conditions and Applied Loads

The structure was initially subjected to a predefined concentrated force at a specific distance from the face of the column flange, which generates the required moment about the connection. A uniform temperature in the neighborhood of the connections was then gradually increased to a desired level to study the effect of temperature on the structural behavior of the beam-column configuration.
The column is assumed to be fixed at the bottom and free at the top, in order to reflect the experimental set-up as shown in Fig. 2. The beam was allowed to deflect downward only, while horizontal movement was restrained to prevent any possibility of premature failure of the beam by lateral torsional buckling. The beam was also allowed to expand freely along the longitudinal axis, thus ensuring that no thermal stresses are generated. The rotational degrees of freedom are not active for solid elements, so vertical deflections can be calculated by equation (3.1).

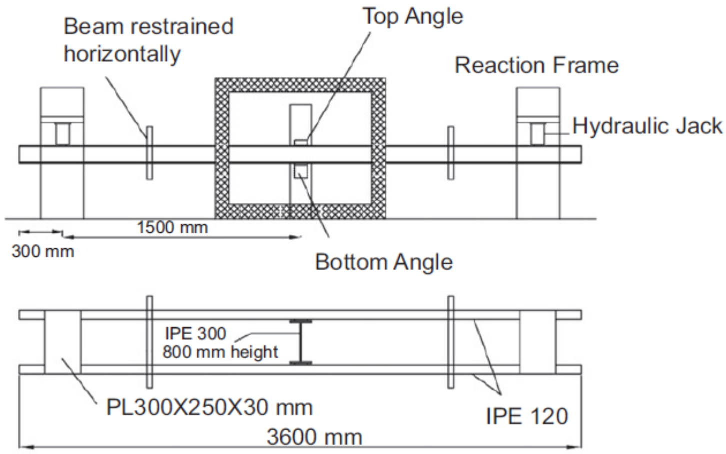

Fig. 2. Test set-up

$$\varphi = \tan^{-1}(u/L) \qquad (3.1)$$

The boundary condition and loading process is similar to the experimental tests. The loading process consists of two steps. First, the specimens were loaded to reach a predetermined load level. Then the fire was started in the furnace while a constant load was applied to the specimens. In the tests conducted on these series of connections at elevated temperatures, the temperature of furnace is increased according to the curves provided by ASTME119 (2003) and ISO834 (2002). In the present study, these values are used as input temperatures for the software. Fig. 3 shows the average temperature of each specimen.

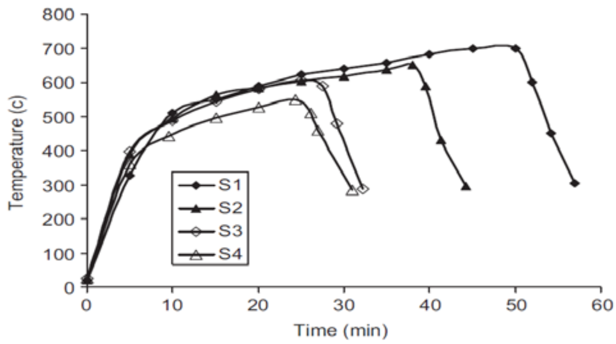

Fig. 3. Average temperatures in the tested specimens

3.4. Finite-Element Model

Finite element software was used to simulate the behavior of Continuous beam to column connections at elevated temperatures.

Fig. 4 shows a three-dimensional (3D) finite element model of the configuration. The FE model was used to estimate lateral deflections of the beam subjected to an initial constant concentrated force applied downward at the free end of the beam section. For accurate results, a fine mesh was used in the vicinity of the connection, where high stress and strain gradients are expected to take place, whereas a coarser mesh was used in areas far from the connection zone, where low stress levels are expected. This modeling leads to accurate results near the connection, which is the main interest. The structure is assumed to behave nonlinearly at high temperatures; elements are typically defined by the basic shape and chosen to fulfill these requirements. Due to their reliable performance, eight-nodded reduced integration brick elements are used. To obtain acceptable results, at least three elements should be used through the plate width. Friction between the contact surfaces at the connection is modeled using the classical Coulomb model, where the friction coefficient was set 0.1.

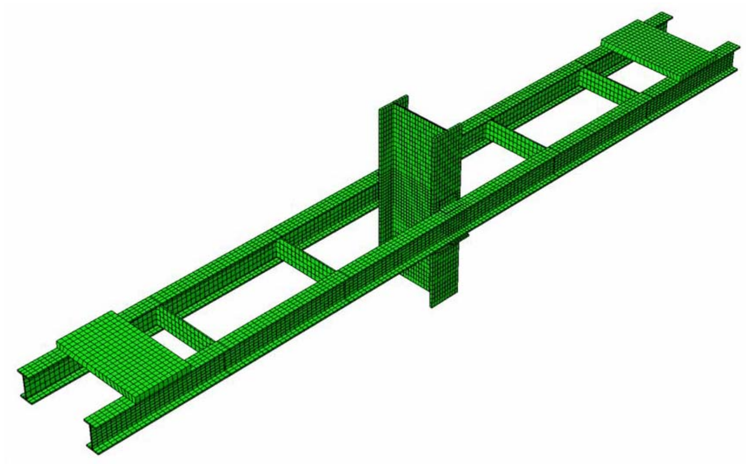

Fig. 4. Finite-element model of the connection.

3.5. Verifying the Models

To validate the results of the FE analysis, four elevated temperature tests were modeled. A comparison of the temperature-rotation response of the connections at different moments is shown in
Fig. 5. The temperature-rotation response curves of the connections agree well with tests at the elastic and plastic stages. Differences between the numerical simulations and the test results may have several causes, including numerical modeling simplification, test specimen defects, residual stress, contact surface interactions, frictional forces, or nonlinear constitutive models of materials at elevated temperatures.

As it was mentioned at the beginning of this paper, for fire-resistant design of a structure, the behavior of every single member of the structure as well as the behavior of whole structure against fire should be determined. Considering the importance of connections in structure design, the change of main constitutive characteristics of a specific connection (including moment-rotation and stiffness) by temperature increase should be known to make the design reliable. Having verified the finite element simulation in predicting the behavior of continuous beam to column connections, the procedure of changes of moment-rotation of these connections by temperature increase is determined.

Considering the importance of knowledge about the connection stiffness at different temperatures, the change of connection stiffness by temperature increase as well as the effect of some other parameters that influence the stiffness of these connections is studied.

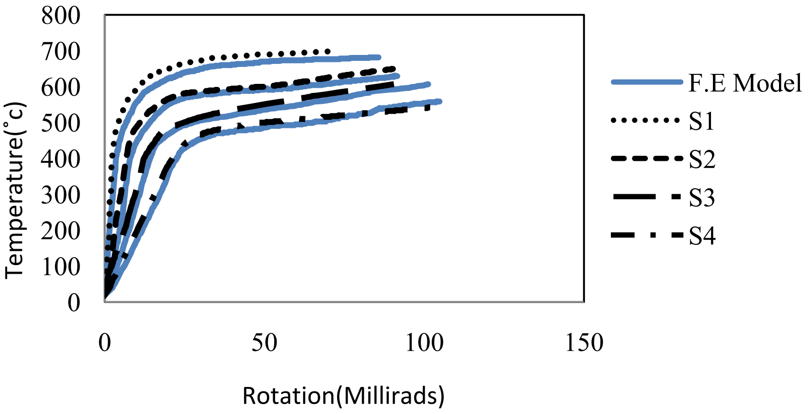

Fig. 5. Comparison of FE and experimental results for four different tests

4. CONTINUOUS BEAM TO COLUMN CONNECTION WITH CONNECTION PLATES

4.1. Geometries of Connection Models

In this structural system, the beam shear force and bending moment are transferred to the column simultaneously by the connection plates. These plates are located along the column flanges and their sides are welded to the column flanges and their beveled edges are welded to the beam flanges. In order to avoid beam web crippling and buckling, continuity plates are placed between beam flanges on both sides of the beam web along the axis of connection plates. The panel-zone in this connection is a part of beam web between two continuity plates which might be reinforced by doubler plates. At each side of the connections, for the purpose of integrity, the flanges of two continuous beams are connected to each other by two horizontal constraints.
A pair of continuous IPE beams (European Section) has been passed next to column faces without interruption and is connected to the column flanges by vertical plates. A box is chosen as the cross section of the column for reasons specified in reference Mirghaderi (2008).
The dimensional values and characteristics are introduced in Table 4 and Table 5. The column section and integrated connection plate are shown in Fig. 6 and Fig. 7. Moreover, the mechanical properties of steel materials are given in Table 3.

Table 4. The dimensional values and characteristics of the specimen

Beam	
section	IPE 140
length (m)	4.6
Connection plate	
Thickness (m)	0.012
L1 (m)	0.08
L2 (m)	0.33
L3 (m)	0.14
L4 (m)	0.3
L5 (m)	0.22
L6 (m)	0.06

Table 5. The dimensional values of column section of the specimen

Column	
section	Box
length (m)	4
dc (m)	0.3
hc (m)	0.3
tc (m)	0.02
s (m)	0.02

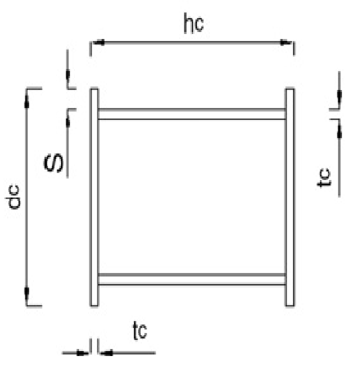

Fig. 7. Column section used in specimens

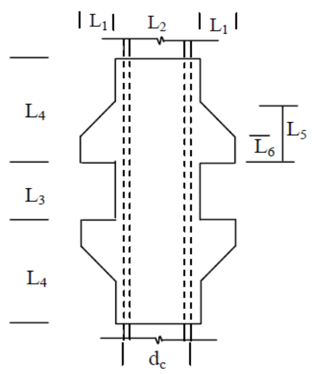

Fig. 6. Integrated connection plate, used in specimens

4.2. Results and Discussion

4.2.1. Moment-Rotation curves
One of the most important and applicable curves in connection design is the moment-rotation curve.

Fig. 8 shows that the moment-resistance of the connection is severely decreased. In general, these types of continuous connections that have been made by usual constructional steel have no moment resistance at temperatures higher than700°C.
In the following, the influence of some parameters that affect the stiffness of Continuous beam to column connection is studied.

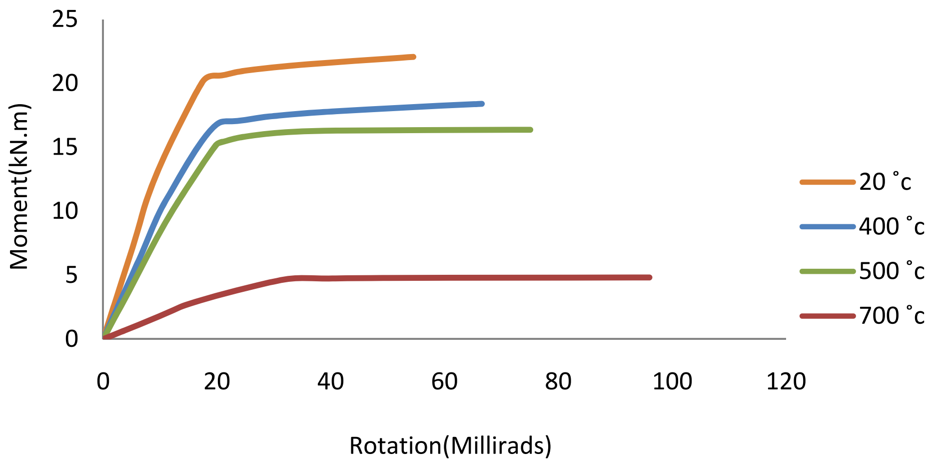

Fig. 8. Moment-rotation-temperature curves

Before presenting the results of the next parts of the study, It should be noted that connection design is generally carried out as shear or flexural and thus, determination of the values of connection shear and moment is essential for connection design. Consequently, two parameters i.e., V_b the applied shear on beam and M_b the applied moment on beam are defined. These parameters are related to each other by equation (4.1) :

$$M_b = V_b \times d \tag{4.1}$$

Where d is distance between the location of shear force application and the connection. Considering the importance of these parameters on design of a connection, the effect of these parameters at elevated temperatures is studied in the following.

4.2.2. Effect of the applied moment on beam
In this section, the value of shear force V_b is constant and the distance (d) is variable to change the value of the applied moment on beam (Table 6). The effect of applied bending moment on connection stiffness at different temperatures is shown in Fig. 9. The effect of applied bending moment is significant. The connection stiffness is increased by decreasing the applied moment value.

Table 6. Magnitude of bending moment

d (m)	1.8	1.3	0.6
Moment(kN.m)	8.3	5.7	2.8

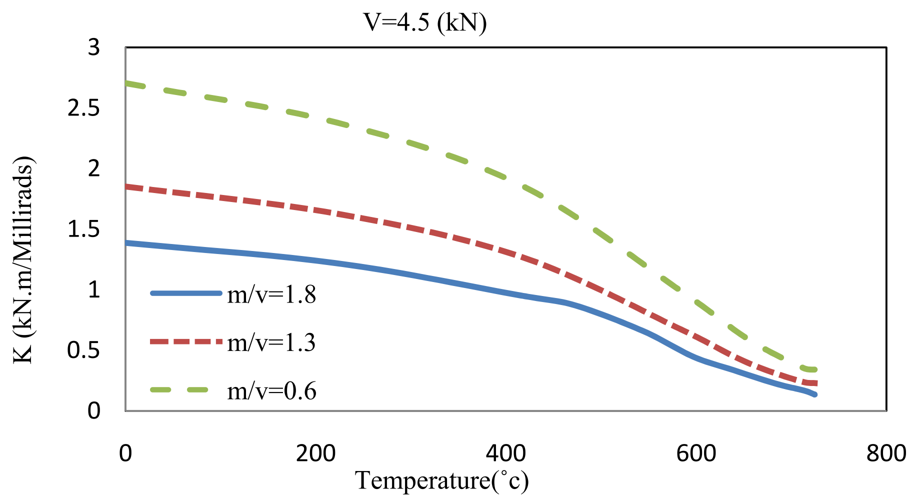

Fig. 9. Effect of applied moments on connection stiffness

4.2.3. Effects of thickness of connection plates on flexural stiffness and moment capacity

Three specimens with different thickness of connection plates have been chosen to analyze the effects of thickness on flexural stiffness and moment capacity. As the thickness of the connection plates changes, so does the stiffness. The difference is noticeable only in ambient temperatures; at elevated temperatures of around 400 degrees Celsius, where the steel enters its inelastic zone, the change in thickness does not have significant effects on flexural stiffness or moment capacity (Fig. 10).

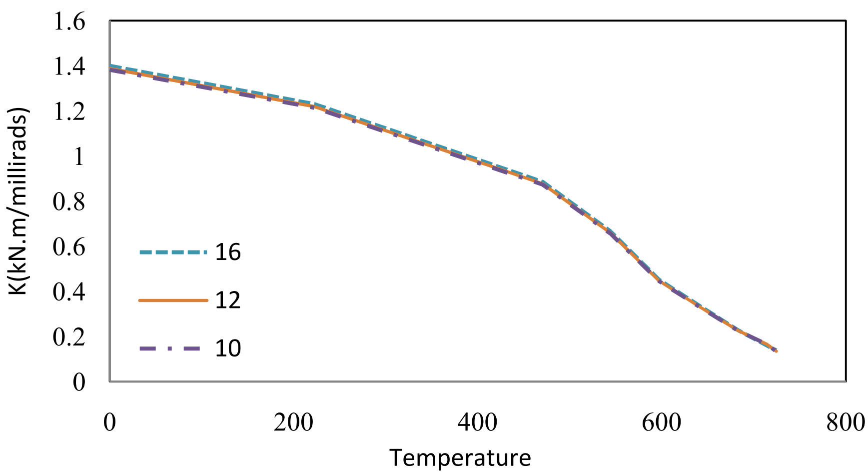

Fig. 10. Effects of thickness of connection plates on connection stiffness

Moment- rotation curves in Fig. 11 show that there is no substantial difference between the moment capacities of connections with different thicknesses and that there is also more rotation capacity in the connection with the thinner plate due to less flexural stiffness and more ductility

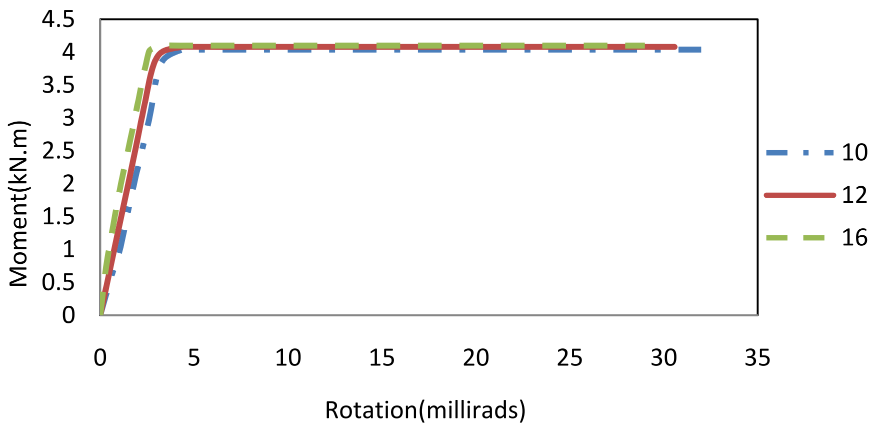

Fig. 11. Moment-rotation curves of connection with different thickness

6- Conclusion

This study applied the general purpose finite element method to investigate the fire response of continuous beam to column connections. Results of the analyses were then presented as rotation-temperature curves. Good agreement was achieved between the model and experiment, confirming that the finite element method is capable of predicting the behavior of these connections at elevated temperatures.

Moment-rotation-temperature curves were derived for this type of connections as a result. The study of the curves shows that as temperature rises the flexural strength of these connections decreases, becoming negligible when temperature exceeds 700°C.

Effects of different parameters on connection stiffness were also studied. The results show that for constant shear force, change of the moment applied at connection significantly affects the connection stiffness; the higher the applied moment, the lower the connection stiffness. Change in thickness of connection plates is noticeable only in ambient temperatures; at elevated temperatures of around 400 degrees Celsius, where the steel enters its inelastic zone, the change in thickness does not have significant effects on flexural stiffness or moment capacity.

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