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The study of welded semi-rigid connections in fire

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SUMMARY

Considering the deterioration of steel properties by temperature increase and the importance of the influence of connection behavior on the behavior of steel structures, we find that the exact understanding of the behavior of a specific steel connection in fire as well as the information about the effect of fire on the principal constitutive characteristics of the connection is necessary for safe design against fire. Thus, in this paper, the behavior of welded angle connections is studied at elevated temperatures using the ABAQUS finite element software. Steel members and connection components are considered to behave nonlinearly; the degradation of steel properties with increasing temperature is considered according to EC3, BS5950 recommendations. The results of finite element and experimental tests conducted on welded angle connections are compared, and the obtained failure modes and moment–rotation–temperature characteristics are in good agreement with those associated with the experimental tests. In the following, since the knowledge about moment–temperature–rotation behavior of a specific connection is needed for a fire-resistant design, these properties are accurately determined, and finally, the effect of some parameters such as the moment applied on beam, change of column axial force and change of beam shear force on the stiffness of these connections at elevated temperatures is determined.

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KEY WORDS: welded angle connections; finite element modeling; fire modeling; elevated temperature; ABAQUS software; moment–rotation–temperature

1. INTRODUCTION

The temperature sensitivity of steel is a weakness in 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. Thus, researchers have special interest in the study of fire effect on steel structures and their components. Considering the importance of connections in steel structures as a joint for distribution of forces and the evidence from the collapse of the WTC building (National Institute of Standards and Technology, 2005) and full-scale fire tests at Cardington (Newman *et al*., 2004), we can conclude that connections may often be the weakest link in a fire. Consequently, the study of the behavior of connections in steel structures at elevated temperature is of great importance.

However, the behavior of steel beam–column connections at elevated temperatures is very complicated and has not been fully studied. Different methods, including finite element analysis, are used to study the behavior of steel beam–column connections at elevated temperatures. The finite element method (FEM) provides an attractive means to investigate the beam–column joints in more detail than experimental tests would usually allow.

Considering the ability of FEM in the prediction of steel connection behavior, researchers have conducted several studies. Some of these researchers are mentioned below.

Liu (1999) and Liu and Morris (1994) were the first to attempt to use FEM in modeling connection behavior at elevated temperatures. Liu developed a finite element model (FEAST) to predict the behavior of different types of joints at elevated temperatures. The beam, column, end plate and stiffeners were modeled using eight-nodded shell elements and considered the nonlinear behavior of the material

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with nonuniform thermal expansion across a section as well as large deformations in fire. The stress–strain–temperature characteristics were adopted based on the recommended values from the experimental tests. Close agreement was observed with the experimental data for different types of joints. A 3-D FEM was developed by El-Houssieny *et al.* (1998) to simulate the response of the extended end plates at both ambient and elevated temperatures. Results from the developed model compared well with the experimental results, and subsequent parametric studies were conducted to investigate the influence of connections on the behavior of the subframe elements in fire. da 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. Good comparison was found between the experimental results and 3-D analyses. Rahman *et al.* (2004) studied the response of the fin plate joints in fire using ANSYS. Two types of 3-D solid elements, pretensioning elements and contact elements were used in the modeling of beams, columns, fin plate and bolts, respectively. Transient time–temperature fire loading was applied. Despite realistic results predicted by the model, no experimental data were used to investigate its accuracy. 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 the lap joint data at ambient temperature, and a fire test was conducted by Wald *et al.* (2006) at the Czech Technical University. Sarraj has used the finite element (FE) modeling to develop a component spring model assembly.

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. The finite element model was used to establish the moment–rotation characteristics of the flush end-plate bare steel joints with a concentrated force at elevated temperatures. The joint components were modeled using 3-D brick elements, whereas contact between the various components was modeled using Coulomb friction. Material nonlinearity was considered to model steel members and the joint components. Degradation of steel properties with increasing temperatures was taken in accordance with design code recommendations. The obtained FE-simulated failure modes and moment–rotation–temperature characteristics of the joints compared well with the experimental data in both the elastic and plastic regions.

Lou and Li (2006) used ANSYS to model the behavior of cruciform tests with extended end plates in fire. A sequential analysis was used: a transient thermal analysis was conducted first followed by a static structural analysis. Nonuniform thermal expansion, geometric nonlinearity, temperature-dependent nonlinear material behavior, bolt pretension and surface-to-surface contact were all included in the analyses. Excellent correlation between the analyses and experimental results from two fire tests was achieved.

In the case of other connection details, Saedi Daryan (2006) and Saedi Daryan and Yahyai (2009a, 2009b) modeled the bolted angle connections with and without web angles considering the effect of elevated temperatures and concentrated forces applied to the connections using ANSYS finite element software. In this research, stiffness and strength deterioration of steel and bolts as well as nonlinear behavior of materials were considered. The results were presented in the form of rotation–temperature curves, and connection failure mechanisms are compared with those of the experimental tests, and good agreement is achieved, which shows the ability of the finite element modeling to predict the behavior of these specific connection details at elevated temperatures.

Saedi Daryan and Bahrampoor (2009c) 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. More discussion about Khorjini connections and their application and the fire effect on this connection type can be found in the study of Saedi Daryan and Yahyai (2009a).

From the presented overview, it is clear that FEMs 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.

As it can be seen from the above researches, several investigations have been carried out to study the behavior of the connection in fire. However, it should be noted that the connection behavior under fire condition is a very complicated phenomenon, and should a specific connection be used reliably in

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structure design, the fire behavior of the connection must be studied and the main constitutive characteristics of the connection that are used in design process (moment–rotation–temperature curve, stiffness–temperature curve and so on) should be accurately calculated.

Since different types of connections are used worldwide depending on economical and available construction facilities, some of these connections are not extensively studied from thermal point of view. Consequently, to assure the reliability of structure design against fire loading, the behavior of the connection used in the structure should be well understood in fire condition. Considering the high cost of fire tests and the limitation of parameters that can be studied in a test as well as the accuracy and ability of FEM in predicting the connection behavior, we find that FEM is applicable for study and determination of the behavior of different connections in fire. This method is especially applicable for the connections whose behavior is not well understood.

The main purpose of this paper is to study the behavior of welded angle connections (with and without a web angle) in fire, considering the above-mentioned subjects. Welded angle connections are classified as semi-rigid connections that are widely used in some countries including Iran (Building and Housing Research Center, 2007) (especially in semi-rigid frames with braces). Despite the frequent use of these connections, no extensive research is carried out about these connections. Thus, in this paper, the finite element models of these connections are developed and the results of the models are compared with that of the experimental tests in standard fire condition to verify the finite element models. Then, the behavior of these connections under fire is studied, and the 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. INVESTIGATION THEORY

As it was mentioned before, the main purpose of this study is to determine the constitutive characteristics of welded angle connections at elevated temperatures. One of the most important characteristics of a connection that is needed in connection design is the connection rotation and stiffness. The recognition of these values and their change during temperature increase is needed for a reliable design. These two parameters are calculated from the equations below (Mao *et al*., 2009):

$$K = M_\mathrm{b}/\Delta\theta_\mathrm{r} \tag{1}$$

where M_b is the moment of the interface of the beam and column and $\Delta\theta_\mathrm{r}$ is the rotation of the steel connection.

$$\Delta\theta_\mathrm{r} = \theta_\mathrm{r}^b - \theta_\mathrm{r}^c = \tan^{-1}\left(\frac{\Delta_\mathrm{bf}^t - \Delta_\mathrm{bf}^b}{h_\mathrm{bf}}\right) - \tan^{-1}\left(\frac{\Delta_\mathrm{cw}^t - \Delta_\mathrm{cw}^b}{h_\mathrm{bf}}\right) \tag{2}$$

where θ_r^b is the rotation of the steel beam, θ_r^C is the rotation of the steel column, Δ_bf^t is the horizontal displacement of an intersection point of the middle surfaces of the top flange and web of the beam and the interface of the beam and column, Δ_bf^b is the horizontal displacement of an intersection point of the middle surfaces of the bottom flange and web of the beam and the interface of the beam and column, Δ_cw^t is the horizontal displacement of an intersection point of the middle surfaces of the top flange of the beam and the centerline of the column, Δ_cw^b is the horizontal displacement of an intersection point of the middle surfaces of the bottom flange of the beam and the centerline of the column and h_bf is the distance of the middle surfaces of the top and bottom flange of the beam. Figure 1 shows the definition of these variables.

3. CONNECTION MODELS

The connection models selected for this study and for verifying its numerical modeling are taken from the experiments of Saedi Daryan and Yahyai (2009d) and Saedi Daryan (2011).

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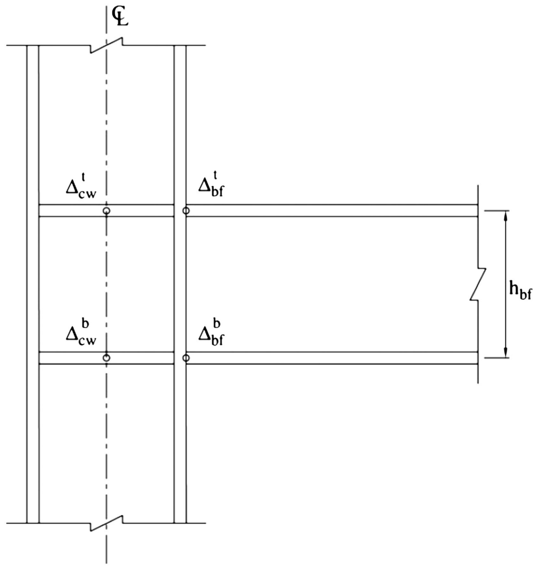

Figure 1. Definition of joint deformation components.

In these series of tests, some experimental tests have been conducted to study the fire-resistant capacity of welded angle connections at elevated temperature on two different types of beam–column welded angle connection (welded angle connection with and without a web angle).

Failure characteristics and fracture modes of the specimens were studied, and results are presented in the form of temperature–rotation curves. In addition, the influence of different parameters such as thickness of the angles, the value of the applied moment and other geometric and mechanical characteristics of the connections were investigated.

3.1. Geometries of connection models

Two groups of welded angle connections have been tested:

Connection group 1: Specimen without a web angle (SOW).
Connection group 2: Specimen with a web angle (SWW).

Connection group 1 (SOW) consisted of two angles. One of the angles was welded to the top flange of the beam and the other was welded to the bottom flange. This assembly was welded to the flange of the column, as shown in Figure 2.

For connection group 2 (SWW), in addition to the two SOW angles, two more angles were welded to the web of the beam and to the flange of the column. The web angles used in all specimens were 100 * 100 * 10 mm and are shown in Figure 3.

In this paper, four specimens tested in the study of Saedi Daryan (2006) were selected. The specimen properties are tabulated in Table 1. Two of these four specimens were selected from the first group (without a web angle), and two other ones were selected from the second group (with a web angle).

4. FINITE ELEMENT METHOD

4.1. Modeling and analysis

The finite element code ABAQUS is used to simulate the behavior of welded angle connections at elevated temperatures.

It is tried to develop the connection model with full details to obtain more accurate results from numerical analysis. One of the details considered especially in connection modeling is welding. The

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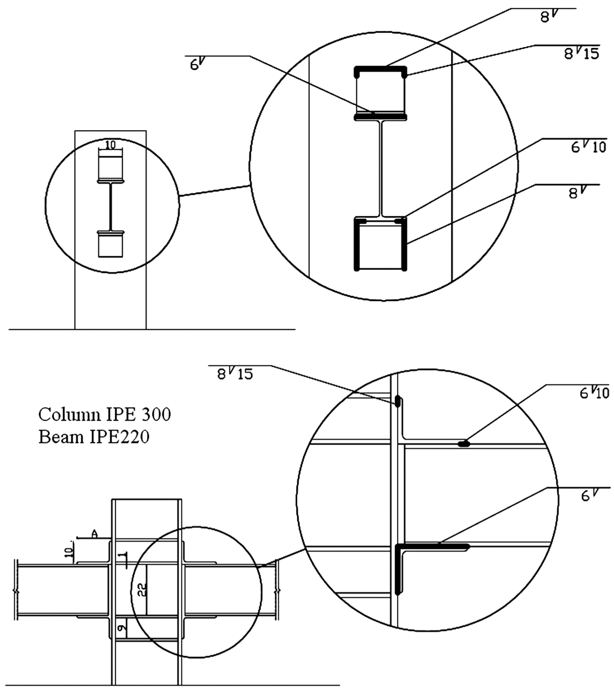

Figure 2. Specimen details for the SOW connection group.

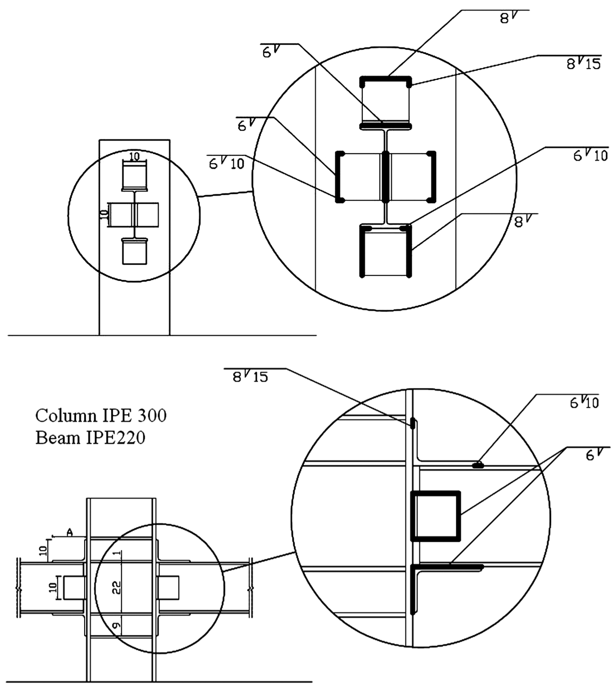

Figure 3. Specimen details for the SWW connection group.

weld is one of the important components of a welded connection that connects the different components of connection. Accurate modeling and simulation of weld behavior significantly affect the accuracy of the obtained results from numerical analysis. Considering that the results of the experimental tests showed that the ultimate failure mode of these specimens was at the weld location (Saedi Daryan, 2011, Saedi

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Table 1. Connection geometric details.

Test NO	Connection group	Size of angle (mm)
S2	1	150 * 100 * 15
S3	2	150 * 100 * 15
S8	1	100 * 100 * 10
S9	2	100 * 100 * 10

Daryan and Yahyai, 2009d), the modeling of welds is of great importance. Consequently, all connection welds (fillet welds) are separately modeled, including the following:

1- Weld line connecting the horizontal leg of the top angle to the beam flange.
2- Weld line connecting the vertical leg of the top angle to the column flange.
3- Weld line connecting the horizontal leg of the bottom angle to the beam flange.
4- Weld line connecting the vertical leg of the bottom angle to the column flange.

All of these parts are shown in Figure 4. Separate modeling of welds in connection finite element makes it possible to assign the accurate properties of weld metal to the related elements (the four parts mentioned above). In this way, the modeled welds accurately simulate the weld in experimental specimens. Thus, it is possible to simulate the connection failure from the weld location in the models. This subject significantly increases the ability of finite element models in predicting the behavior of this type of connection. Typical subparts of the 3-D finite element model are shown in Figure 4.

To obtain accurate results, we used a fine mesh in the vicinity of the connections where high stress and strain gradients were expected to take place, whereas a coarse mesh was used in areas far from the connection zone where low stress levels were expected. This modeling leads to accurate results around the connection, which is the region of prime interest. The structure is assumed to behave nonlinearly under high temperatures; elements are typically defined by the basic shape and chosen in such a way that they fulfill these requirements. In this analysis, eight-nodded reduced-integration brick elements were deemed to be the most reliable and therefore the element of choice.

Contact simulation in ABAQUS software can be carried out using surface-to-surface contact, 3-D elements. The sliding of the surfaces on each other can be considered using these elements, and no

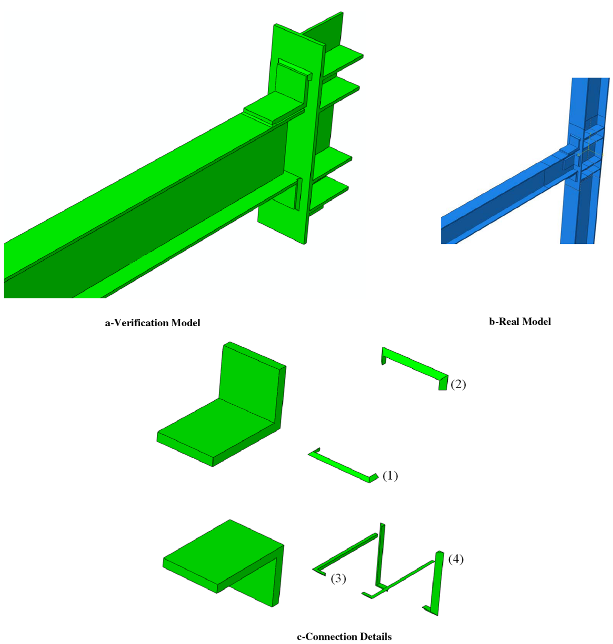

Figure 4. Finite element model of the connection. (a) Verification model. (B) Real model. (C) Connection details.

penetration occurs during the loading process. The surface-to-surface contact elements of the ABAQUS software can be seen in Figure 5.

Friction between the contact surfaces at the connection was modeled using the classical Coulomb model where the friction coefficient is taken as 0.1.

Since the behavior of the assembly of beam, column and connection is studied under static and thermal loading, coupled temperature-displacement analysis is used to increase the accuracy of the analyses. Thermal loading of finite element models is applied as boundary condition according to the time–temperature curve obtained experimentally in each part of the specimen under thermal loading.

4.2. Boundary conditions and applied loads

It should be noted first that the connection geometry is also the same for all the models (Table 1); the boundary condition and loading type are applied in two different forms. In the first part, the verification according to experimental test results is conducted, and the load application process and boundary condition are similar to the experimental tests. In the second part, the main characteristics of these connections are studied, and the boundary conditions and loading process are different. It is tried in the second part that the boundary conditions and applied loads are a good representative of the real condition of an unprotected beam-to-column connection in a real structure.

4.2.1. First part (similar to the tests for verification)

As it was mentioned before, the boundary condition and loading process are 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. For the analysis of the models, the specified concentrated force is first applied at a distance 200 cm from the column flange, in order to create the necessary moment in the connection. Since the column and beam in the furnace were wrapped with a 2.5-cm-thick ceramic fiber blanket in the tests and only the connection zone, including the angles, the flange and the web of the columns in the vicinity of the angles were exposed to the fire, in the finite element models, the area around the connection is subjected to the full temperature regime, whereas the sections away from the connection are subjected to ambient temperature in order to simulate the experimental tests. Since the experimental test arrangement is cruciform, axial symmetry exists around the vertical axis, and thus, to decrease the calculations, only half of the test arrangement is modeled (Figure 4(a)). The column is assumed to be fixed at the bottom, since no displacements were expected to take place at nodes far away from the connections, and was free to move at the top, in order to reflect the experimental test set-up. The beam was allowed to deflect downward only, whereas 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 no thermal stresses were generated.

The boundary condition of the specimens in the first part of the study (similar to the experimental test to verify the finite element models) is shown in Figure 6.

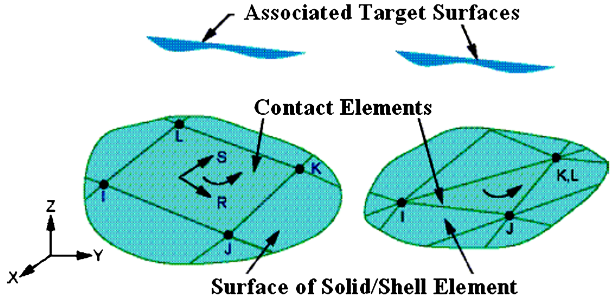

Figure 5. Surface-to-surface contact element.

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In the tests conducted on these series of connections at elevated temperatures, the temperature of furnace is increased according to the curves provided by ASTM E 119 (2003) and ISO 834 (2002). As a result of increase in the temperature of the furnace, the temperature of the specimens is also increased and is recorded by thermocouples connected to each specimen. The average values of the recorded thermocouple temperatures for each specimen are presented in Saedi Daryan and Yahyai (2009d) and Saedi Daryan (2011). In the present study, these values are used as input temperatures for the software. Figure 7 shows the average temperature of each specimen.

The values of the applied moment to each specimen in the tests are presented in Table 2.

4.2.2. Second part (similar to real condition of an unprotected beam-to-column connection)

In contrast to the experimental condition mentioned in the previous part, the boundary condition in the second part is tried to be a representative of the real beam to the column arrangement in a common structure. Since in a real structure, cruciform arrangement does not necessarily exist in many cases (such as corner columns of a structure) and in the cases where cruciform arrangement exists, symmetry does not necessarily exist and the moment values at the sides of column are not equal; the arrangement of a corner column of a structure is considered to make the column rotation possible. (Figure 4(b)) The boundary condition is shown in Figure 8.

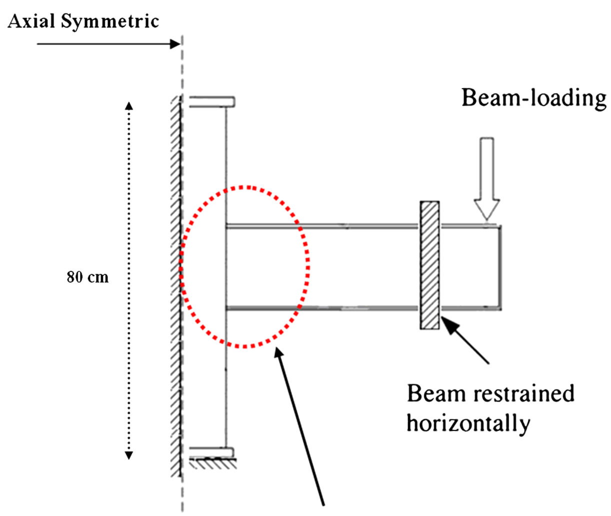

Figure 6. Boundary conditions and applied loads in the first part.

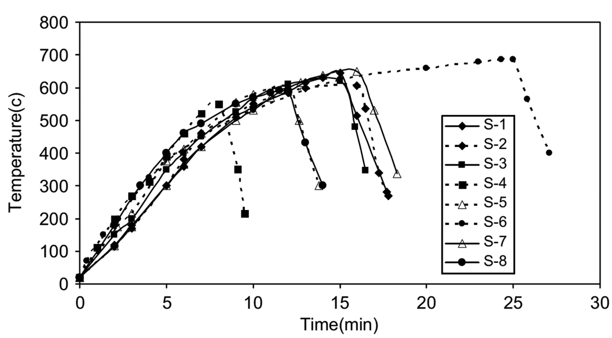

Figure 7. Average temperatures of each specimen.

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Table 2. Values of applied moment for each specimen in the tests conducted by Saedi Daryan *et al*.

Specimen number	Group number	Moment (*M*) level	Applied *M* (kN m)	Average recorded *M* (kN m)
S2	1	0.6*Mcc	8.5	8.55
S3	2	0.4*Mcc	8.5	8.47
S8	1	0.5*Mcc	4.25	4.26
S9	2	0.5*Mcc	6.5	6.53

As it can be seen from Figure 8, it is assumed that the assembly of beam, column and connection is exposed to standard fire condition, and fire is not limited to the connection area. The temperature distribution pattern in different areas of the specimen is determined by the experimental tests on beam-to-column connection (Mao *et al*., 2009). Since different areas of each specimen (beam, column and connection) had different temperature during the test time, temperature–time curves are applied as boundary condition for each area. The temperature of different areas of the specimen is shown in Figure 9. Except the above-mentioned points, the other details are similar to that of the first part.

4.3. *Material property*

At elevated temperatures, the connection undergoes large plastic deformation; therefore, elastic–plastic material model with strain hardening was adopted.

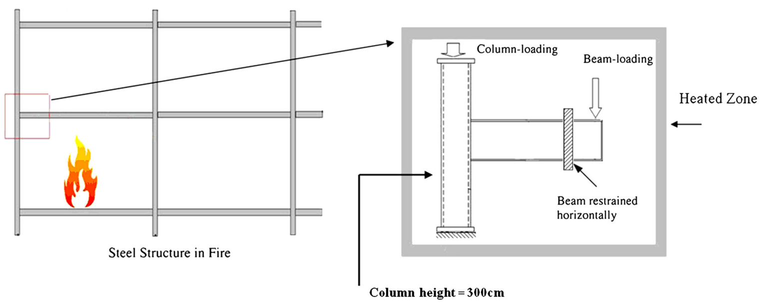

Figure 8. Boundary conditions and applied loads in the second part.

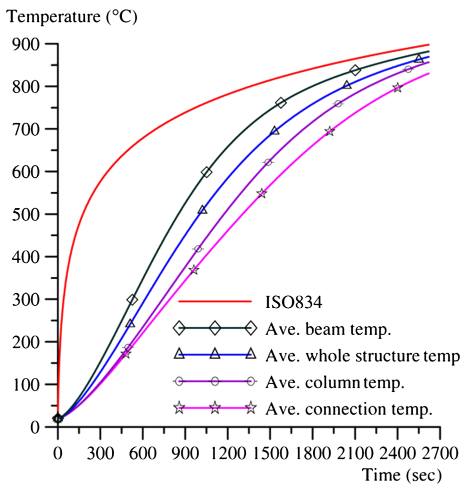

Figure 9. Temperature profiles of each region of connection (Mao *et al*., 2009).

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Analytical models are considered as simplified models; however, it is sufficient to incorporate the main parameters (i.e. stiffness and strength) representing the degradation of material properties with temperature.

To achieve this goal, the properties of the main material used in the specimens (stiffness and strength of the material) are reduced according to the deterioration equations for elevated temperature in BS5950, part 8 and EC3: parts 1–2. It should be noted that in fact, two materials are used to manufacture these specimens. The first material is the steel used in the beam, column and angles. The second material is the weld electrode that is used for welding and connection of angles to the beam and column. As it was mentioned in part 4–1, since the weld line connecting different components is modeled in this research, it is possible to assign the exact weld metal properties to the welds in a finite element model. Since the properties of weld metal and steel are different, the reduction factor at elevated temperatures is different for these two materials. Considering this subject as well as the criteria of constructional codes, two different series of reduction factors are used for simulation of material behavior at different temperatures. The first series are reduction for steel, and the second series are used for weld metal. The reduction equations proposed by codes of BS5950, part 8 and EC3: parts 1–2 are presented in Figure 10.

The steel properties and weld metal properties of the specimens are obtained from the studies of Saedi Daryan (2006) and Saedi Daryan and Yahyai (2009a). It should be noted that the results of the Coupon test for each specimen is presented in the study of Saedi Daryan (2006), and the results of Mill test is presented in Table 3.

The properties of the electrode used for manufacturing the experimental specimens are presented in Table 4.

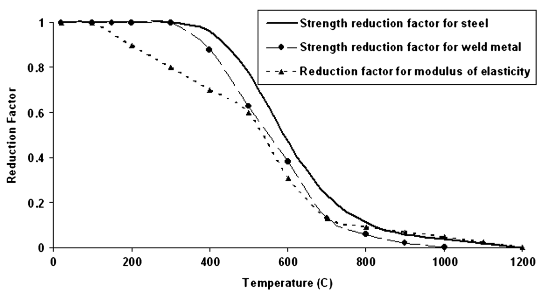

Figure 10. Reduction factor at elevated temperature.

Table 3. Material properties.

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

Table 4. Weld metal properties.

	Yield strength (N/mm^2)	Ultimate strength (N/mm^2)	Modulus of elasticity (N/mm^2)	CVN (J)
Weld metal (E7018)	485.8	555.2	2.06×10^5	185

charpy V-notch (welding)

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5. VERIFYING THE MODELS

The FE results are compared with the experimental data generated by Saedi Daryan *et al*. in terms of temperature–rotation characteristics and failure modes of the connections. Figures 11 and 12 show the comparison between the predicted and measured deformation for connection S2. Figure 13 shows the deformation modes of the same connection components compared with the real connection components' deformation after the test.

Figure 11 shows a local deformation at the top and bottom angles, particularly at the top angle, where it is subjected to the highest tensile stresses. Because of the high strength of columns used in the test, the columns are not deformed compared with the angles.

The weld line that connects the vertical leg of the top angle is under the highest value of tensile stress and failed, but the other welds did not fail. As can be seen in Figure 12, this behavior is well predicted by the finite element model.

Figure 13 shows the deformed shapes of each component of the connection assembly compared with the same component after the test, where damage in terms of permanent deformation takes place in the top and bottom angles. This matter is clearly visible, and the same thing can be seen in the real components of the connection. The column and beam have no significant deformation.

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 Figure 14. The temperature–rotation response curves of the connections agree well with tests at the

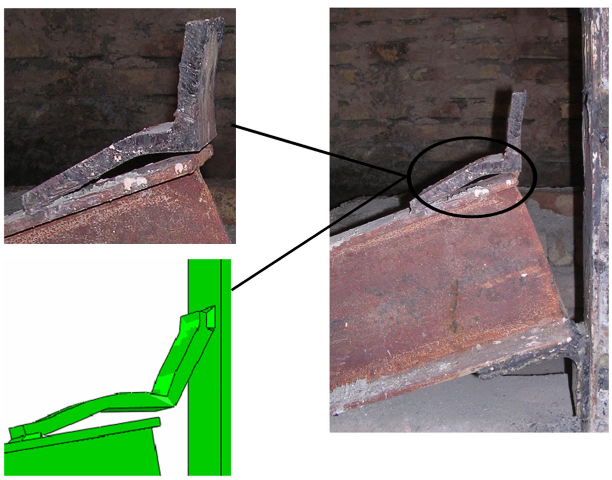

Figure 11. Deformation of the beam-to-column configuration. Connection S2.

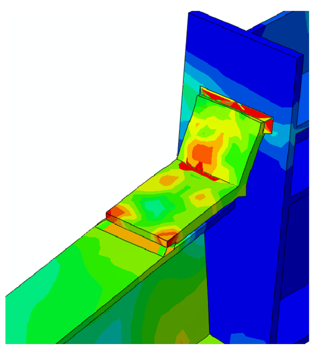

Figure 12. Predicted deformation of the beam-to-column configuration. Connection S2.

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Figure 13. Detail of deformation of the connection S2 components.

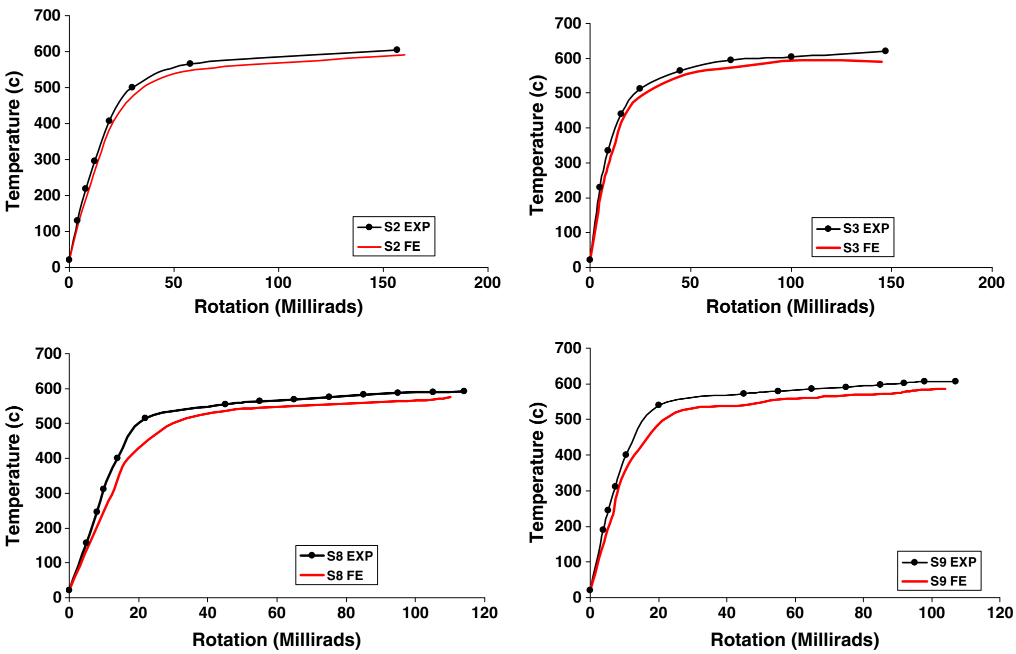

Figure 14. Comparison of FE and experimental results for four different tests.

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 the whole structure against fire should be determined. Considering the importance of connections in structure design, we believe that the change of the 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 welded angle connections (with and without a web angle), the procedure of changes of the moment–rotation of these connections by temperature

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

6. RESULTS AND DISCUSSION

One of the most important and applicable curves in connection design is the moment–rotation curve. This curve is shown in Figure 15 for four types of connections at different temperatures using FEMs. For all tests, deterioration of connection characteristics resulting from temperature increases is predicted well by the models.

Figure 15 shows that the moment resistance of the connection is severely decreased. In general, these types of angle connections that have been made by the usual constructional steel have no moment resistance at temperatures higher than 800°C.

In the following, the influence of some parameters that affect the stiffness of welded angle connection is studied.

6.1. Effect of thermal expansion

The effect of thermal expansion on connection stiffness is first investigated. As it can be seen from Figure 16, if the thermal expansion is neglected, the connection stiffness is constant when the connection is elastic, then it is decreasing gradually when the connection is plastic. However, if the thermal expansion is considered, the connection stiffness keeps rising when the steel temperature is below 250°C, and then the connection stiffness is decreasing when the steel temperature is over 250°C. This phenomenon is owing to the effect of thermal expansion, and the nonuniform temperature distribution of connection induces the rotation increment of the column faster than that of the beam, and the rotation of connection is decreased; thus, the connection stiffness is increased until the steel temperature reaches 250°C.

When the average connection temperature is over 500°C, the effect of this parameter becomes negligible and the stiffness curve of the connection in both cases (with and without considering the thermal expansion) becomes coinciding.

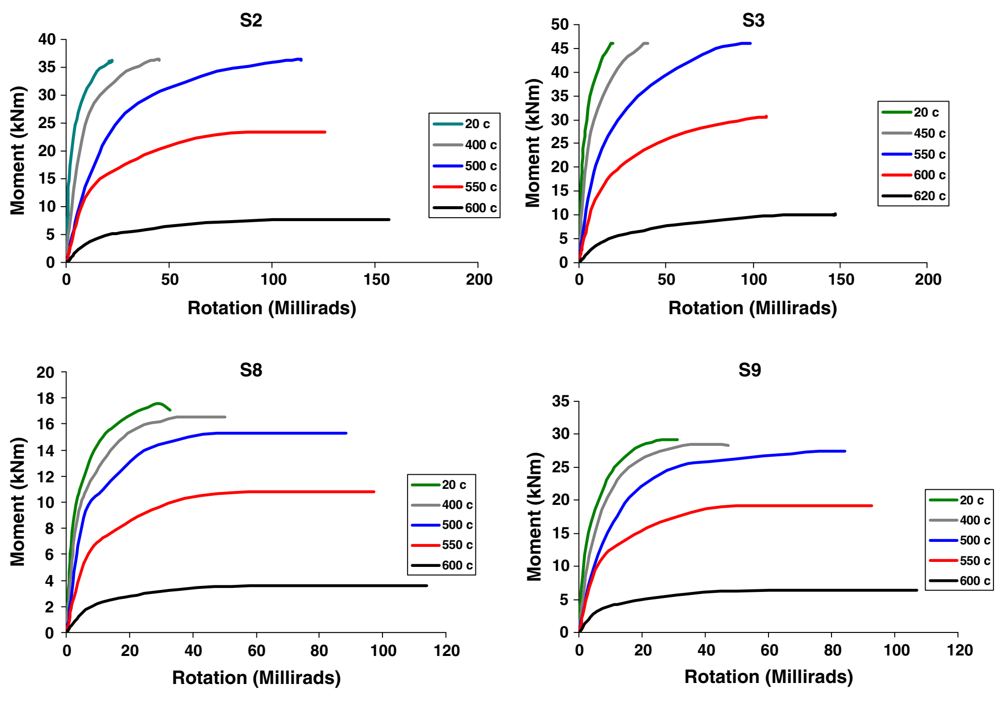

Figure 15. Moment–rotation–temperature curves.

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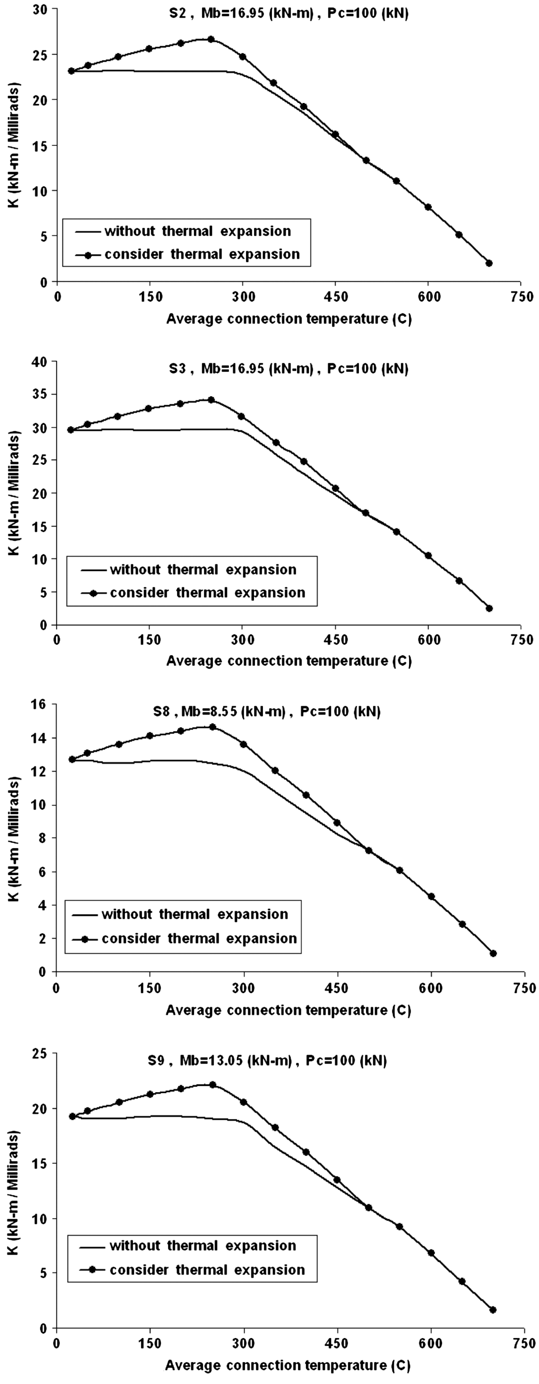

Figure 16. Effect of thermal expansion on connection stiffness.

6.2. Effect of axial load of column

Various axial loads of column are applied to study its effect on connection stiffness. The parameter P_c in the curves is the column axial force. It can be seen in Figure 17 that the column axial load does not significantly affect the connection stiffness.

The result of this study is significant since in tall buildings, every two or three successive storeys are designed similarly and the beams, columns and connections are the same in these successive storeys. However, the axial load of the columns in these similarly designed storeys is different. The results of this

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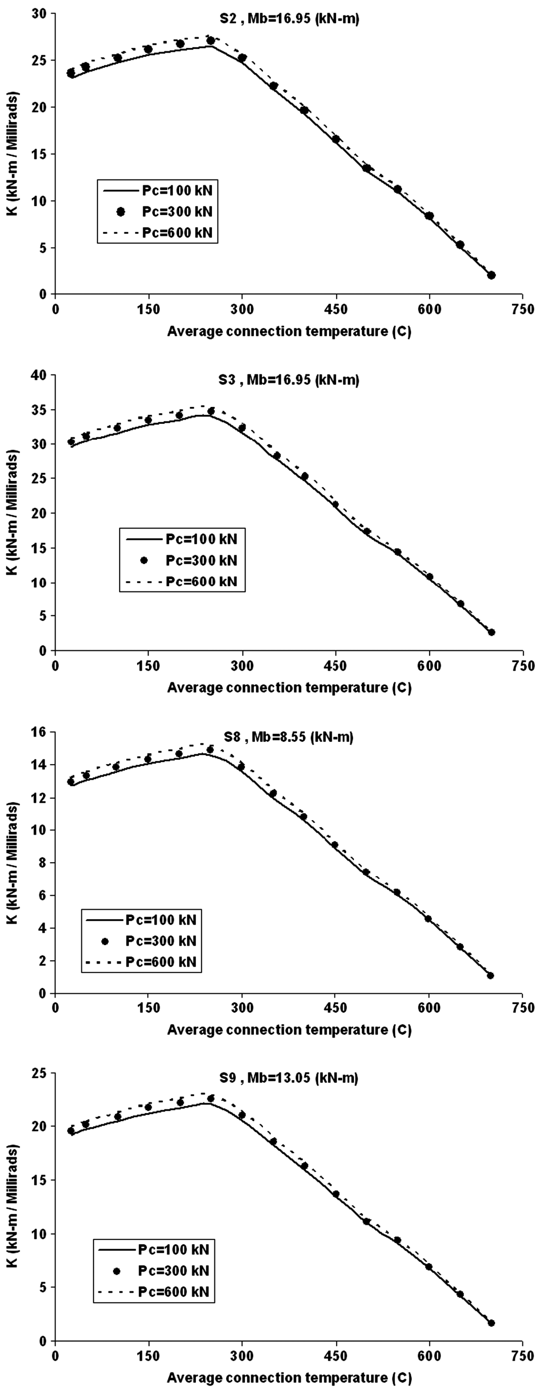

Figure 17. Effect of axial load of column on connection stiffness.

study assure the designers that the difference in axial load of columns in similar storeys of a tall building does not affect the connection stiffness of the storey in fire condition.

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 the connection shear and moment is essential for connection design. Consequently, two parameters, i.e., V_b, the applied shear on the beam, and M_b, the applied moment on the beam are defined. These parameters are related to each other by the following equation:

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$$M_b = V_b * d \tag{3}$$

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

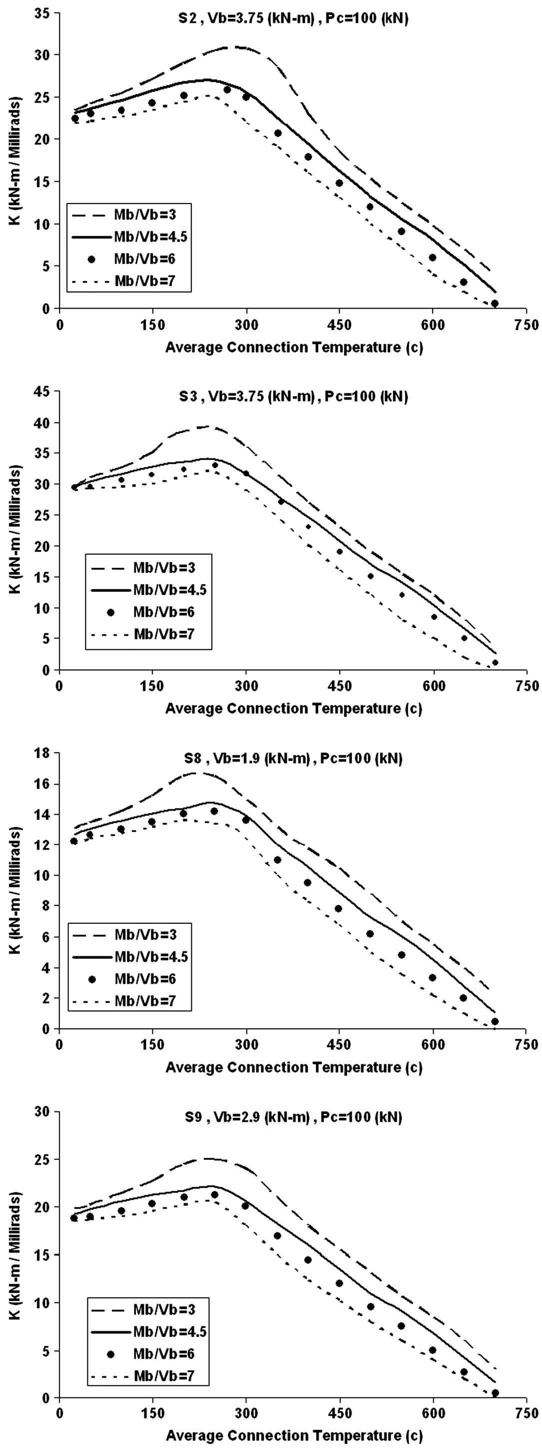

Figure 18. Effect of applied moments on connection stiffness.

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6.3. *Effect of the applied moment on beam (constant* V_b and variable M_b)

In this section, the value of shear force V_b is constant and the distance d is variable to change the value of the applying moment on the beam. The effect of applied bending moment on connection stiffness at different temperatures is shown in Figure 18. The effect of applied bending moment is significant. The connection stiffness is increased by decreasing the applied moment value.

6.4. *Effect of beam shear force (constant* M_b and variable V_b)

In this section, the beam shear force and the distant of shear force from the connection location are changed in a way that the applying moment remains constant. Figure 19 shows the effect of the beam

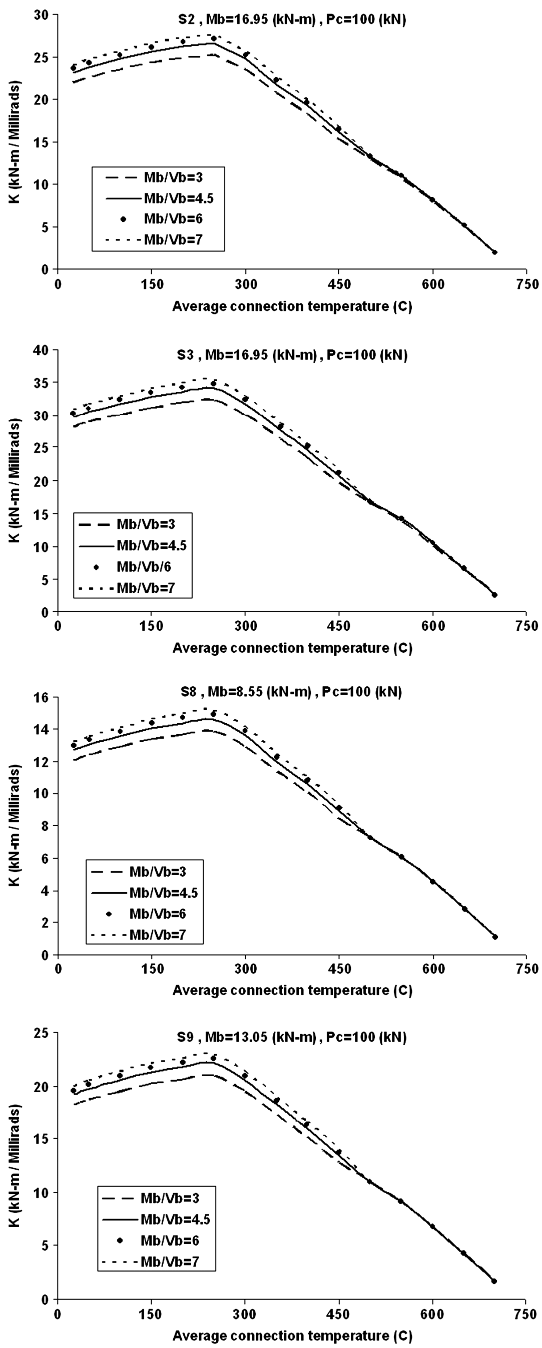

Figure 19. Effect of shear forces of beam on connection stiffness.

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shear force on the connection stiffness. It is found that its effect is not significant and the connection stiffness is slightly increasing with respect to the decrease of beam shear force. As it can be seen, this effect is higher in the elastic range of the connection stiffness. These effects decreases when temperature increases and connection behavior becomes plastic. This effect disappears when the average connection temperature exceeds 500°C.

Comparing the results of parts 6–3 and 6–4, we can see that the applied moment on the connection is also calculated by multiplying the shear force value to the distance between the force application point and the connection location, but the shear, in contrast to the moment, does not directly affect the stiffness of the connection at elevated temperatures. Shear force only affects the connection stiffness when its decrease or increase changes the applied moment. In a general sentence, it can be said that the change of applied moment directly affects the connection stiffness at elevated temperatures, whereas shear force changes only affect the connection stiffness at elevated temperature when it changes the applied moment.

7. CONCLUSION

Considering the complex behavior of steel connections in fire, the change of the main characteristics of a connection at elevated temperatures is needed to be known for a safe fire-resistant design. Taking the importance of this subject into account, this study applied the general purpose finite element software ABAQUS to investigate the fire response of welded angle connections with and without a web angle and built an effective numerical model to investigate the fire response of the steel connections. Results of the analyses were then presented as rotation–temperature curves and deformed shapes, and the results were compared with those of the experimental tests. The comparison confirms the ability of the FEM in simulating the behavior of welded angle connections.

Having verified the results of finite element models using the experimental results, the change of the main characteristics of this type of connection at elevated temperature is studied. Since moment–rotation behavior as well as connection stiffness is needed for the design, change of these properties is investigated at elevated temperature. First, temperature–rotation–moment curve is derived for this type of connections. The study of the curves shows that the flexural strength of these connections is negligible when temperature exceeds 800°C.

The results show that the stiffness of steel moment connections increases with increasing temperature before approximately 250°C, and then a downturn occurs from the peak. The reason is nonuniform distribution of temperature at the beam, column and connection as well as the existence of thermal expansion. In the following, the effect of different parameters on connection stiffness is studied. The results show that a change of the moment applied at a connection significantly affects the connection stiffness. The higher the applied moment, the lower the connection stiffness. In contrast to the applied moment that directly affects the connection stiffness, shear force has no effect on connection stiffness provided that the shear change does not change the applying moment. Finally, it is shown that the axial force in the column does not significantly affect the connection stiffness when the temperature is increasing.

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