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Performance of Steel Angle Connections at Elevated Temperatures

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Abstract
The performance of connections is crucial for maintaining stability of structural system during fire conditions. In current practice, no special consideration is given to account for various high temperature effects, including fire induced forces, on the behavior of connections. To overcome some of the drawbacks in current design provisions and to characterize the realistic behavior of double angle connections, a numerical study has been undertaken. As part of this study, a finite element model of beam to column double angle connection has been developed and validated against experimental results. The finite element model accounts for material nonlinearity, geometric nonlinearity and degradation of constitutive properties with increasing temperature along with non-linear contact interactions. The validated finite element model was applied to study the effect of bolt-hole size and beam web thickness on the performance of double angle connections. Results from the analysis indicate that higher bolt-hole size enhances flexibility of the connection. Also, the results show that higher web thickness leads to larger stiffness and load carrying capacity in the double angle connections.

1. Introduction
In a steel framed structural system, connections play an important role in transferring loads from one member (beams, columns) to another. Double angle connections are widely used in buildings due to the higher tying resistance and rotational capacity. However, steel connections lose strength and stiffness at a faster rate due to increasing temperatures. Once the connection capacity drops below the forces resulting from external loading, a part of the structure or the entire structure may not sustain the load and this might leads to catastrophic failure. Generally, double angle connections are designed to resist shear forces, however these connections experience additional fire induced forces (tensile, compressive) due to axial elongation/shortening and large deflections that result in structural members under fire conditions. Also, the nature of the forces change from compression to tension with the progression of fire from heating phase of fire (compressive forces) to cooling phase of fire (tensile forces). Such transformations in forces are to be properly accounted for in the design of connections. Thus, the behavior and performance of double angle connections is vital in determining the overall response of the structural system under fire conditions.

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Furthermore, major structural collapses in the past have shown that the failure almost always originated at the connections. As structural fire engineering is an emerging area, the behavior of double angle connections under fire conditions has not been fully understood. In conventional design, connections are often assumed to exhibit complete rigidity (fixed) or flexibility (pinned). However, the actual behavior of connections lies somewhere in between these two limiting cases i.e., the behavior of connections that are assumed to be fixed at ambient temperature may possess some flexibility at higher temperatures, while those assumed to be pinned at room temperature may exhibit significant levels of strength and stiffness at elevated temperature. Additionally, most of the current information on fire performance of connections is based on the experimental investigations that are tested in isolation and are not considered to be a part of the structural frame assembly. Structural continuity will affect the connection behavior since the heated member expands or contracts, but the adjacent (cold) structural members restrain this motion; therefore, additional axial forces and moments develop on the connections. The additionally developed forces can be very high and these might lead to the failure of connections. This type of phenomenon is not clearly captured when connections are tested in isolation, and connections are to be tested as a part of structural frame assembly to capture this behavior.

To characterize the realistic performance of double angle shear connections under fire conditions, a numerical study has been undertaken. As part of this study, a beam-to-column double angle connection has been modeled using commercial finite element software ANSYS. The FE model was validated by comparing predicted response parameters with measured test data. The validated numerical model was applied to study the effect of bolt-hole size and beam web thickness on the fire performance of double angle connections.

2. State-of-the-Art review

This section provides information on the experimental and numerical studies conducted to evaluate the behavior of different type of connections under fire conditions.

2.1 Experimental studies

A review of literature indicates that there is very limited number of experimental studies on the fire behavior of connections. This is mainly due to high cost and practical complexities such as specialized test furnaces and large number of response parameters to be monitored. Most of the previous experimental studies were designed to generate the moment-rotation characteristics on isolated connections (or joints) and did not consider the overall behavior of connections in a structural frame network.

Lawson (Lawson, 1990) conducted tests on beam-to-column joints at elevated temperatures to quantify the effect of the structural continuity. A total of eight tests were conducted which included five on non-composite beams, two on composite beams and one on a shelf angle floor beam. Three types of joints such as extended end plate, flush end plate and a double-sided web cleat were also studied. Results from these tests indicated that the steel joints possess significant strength even at elevated temperatures and were able to sustain large moments (up to two-thirds of ambient temperature moment capacity) in fire.

Leston-Jones (Leston-Jones et al. 1997) conducted eleven tests on flush-end plate connections at elevated temperatures in order to develop moment-rotation relationships for connections. The results showed that the stiffness and moment capacity of the connections decreased with temperature with significant reduction in the temperatures range of 500-600°C. Al-Jabri (Al-Jabri et al. 1998) conducted experimental studies to investigate the degradation of steel and composite connection characteristics at elevated temperature. As part of the experimental study, test were conducted on five groups of connections namely two full end-plate, one flexible end-plate bare steel connections and two flexible end-plate composite connections. Using the results obtained from the elevated temperature tests conducted at constant load level, the authors interpolated moment-rotation-temperature curves for different connection types (Al-Jabri et al. 2005).

Wald (Wald et al.2006) carried out fire resistance tests to study the global structural behavior of a compartment on the 8-storey steel-concrete composite frame building at BRE's Cardington test facility. The test program was aimed at examining the temperature distribution within structural elements, distribution of internal forces, behavior of slab, beam, columns and connections. Data from these tests indicated that even under severe fire scenarios composite floor system can sustain large forces provided the integrity of connections is maintained.

Wang (Wang et al. 2007) undertook an experimental study to investigate the fire-resistance capacity of the extended end-plate joints, using four full-scale steel specimens. The authors obtained the failure characteristics and failure modes of the extended end-plate joint specimens from the experiments. A comparison of the capacity of the joints with and without rib stiffeners was done to characterize the influence of rib stiffeners and depth of end-plates on fire-resistance capacity of the joints. The authors developed a spring-component model and established its validity by comparing the results obtained from the model with the experimental results. Based on the test results, it was concluded that the extended end-plate joint has great rotation ability at elevated temperatures.

Yu (Yu et al. 2009) carried out experimental studies to characterize the behavior of fin plate connections in fire. The authors investigated the behavior of four types of connections namely flush endplates, flexible end plate, fin plates (shear tab) and web cleats (angle). Results from these tests indicated that the resistances of fin plate connections are significantly affected by temperature and bolt shear fracture tends to govern the failure of the fin plate connections at elevated temperatures. For the web cleat connections, the authors observed that these connections have excellent rotational ductility, and the resistance of these connections reduces rapidly with increasing temperature.

2.2 Numerical studies

Studies related to modeling the connection behavior at elevated temperatures were initially carried out by Liu (Liu, 1996). Liu developed a three dimensional model to simulate the response of steel framed structures in fire. The model is based on tangential stiffness approach and takes into consideration of material plasticity, non-uniform thermal expansion, large deformation and degradation of the material properties at elevated temperatures. Using the numerical model, Liu analyzed beam members and beam-to-column connections, with different loading and structural continuity and compared the results to those obtained from experimental studies. Based on the results, the author concluded that the fire resistance of the beams can be substantially enhanced by continuity and also the top tension bolts in connections were less affected and thus they help in improving the connection's fire resistance.

El-Houssieny (El-Houssieny et al. 1998) carried out an analytical evaluation of the moment rotation stiffness, bolt forces and stresses for semi-rigid extended end-plate connections, both at normal and elevated temperature. The authors developed a three-dimensional finite element model to simulate the connection behavior and validated the model by comparing the numerical results with those obtained from experiments. The validated model was used to carry out a parametric study to study the influence of varying connection configurations.

Al-Jabri (Al-Jabri et al., 2006) studied the behavior of flush end-plate bare-steel connections at elevated temperatures using the finite element software ABAQUS. The numerical model accounted for material nonlinearity, degradation of steel properties with increasing temperatures and contact interactions between various connection components. The FE model was used to establish the moment-rotation characteristics of the connections under the combined loading of a concentrated force and elevated temperature. Daryan et al. (Daryan et al. 2009b) used finite element software ANSYS to study the behavior of bolted angle connections at ambient and elevated temperatures. The FE model considered the material nonlinearity of the steel members and connection components, friction between connection components, entire stress-strain-temperature curves as well as the degradation of the material properties with temperature according to Eurocode 3 (Eurocode 3, 1995). The results obtained from the FE model were compared to the test data on bolted angle connections carried out by Azizinamini (Azizinamini 1982), Saedi (Daryan A.S., 2006), Saedi and Yahyai (Daryan A.S, Yahyai. M, 2009a) and showed a good agreement. The authors used the validated FE model to study the failure mechanism of top-seat angle connections.

Garlock and Selamet (Garlock and Selamet, 2010; Selamet and Garlock, 2010) developed three dimensional FE model of single plate shear connection in a subassembly to simulate Cardington building test. The FE model was validated against the experiment data from the Cardington tests and the behavior of the subassembly was also tested under different fire scenarios and also with different connection parameters. Based on the FE results, the authors concluded that the behavior of single plate connections can be improved by adding a doubler plate to the beam web, using a larger distance from the bolt-hole centerline to the beam end and increasing the gap distance between the end of the beam to the connection member. Also, the authors found that larger bolt holes can improve the fire performance through less axial restraint which implies that the beam has more freedom to move under fire-imposed thermal loads.

The above review illustrates that there have been limited experimental and numerical studies on the fire performance of connections. Majority of the tests were conducted under standard fire exposure without any consideration to natural fire with a cooling phase, realistic loading and restraint conditions. Almost all of the studies were aimed at developing the moment-rotation characteristics of end plate connections. Despite the fact that the double angle connections have good tying resistance and rotational capacity, most of the previous studies focused on the performance of shear tab, flush end-plate or flexible end-plate connections. There has been only handful of studies on the fire performance of double angle connections. Thus, to have a complete understanding about the high temperature behavior of the double angle connections, and the effects of increasing bolt hole size and beam web thickness, a numerical study in the form of finite element modeling has been undertaken. Details about this study are presented in the following sections.

3. Finite element modeling

3.1 The finite element model

To study the fire performance of double angle connections, a three-dimensional (3-D) FE solid model of a double angle shear connection was developed. For the analysis, the connections system tested by Yu et.al. (Yu et. al., 2009) was selected. The particular test that is chosen for analysis is the one in which the test specimen was heated to 550°C and then the loading applied at an angle of 35° to the beam centerline . The geometry of the double angle connection along with the connection details are shown in Fig.1. The column section used in the study was UC 254x89 , while the beam was of UB 305x165x40. The flanges of the column were connected to web of the beam through L90x8 with equal legs.

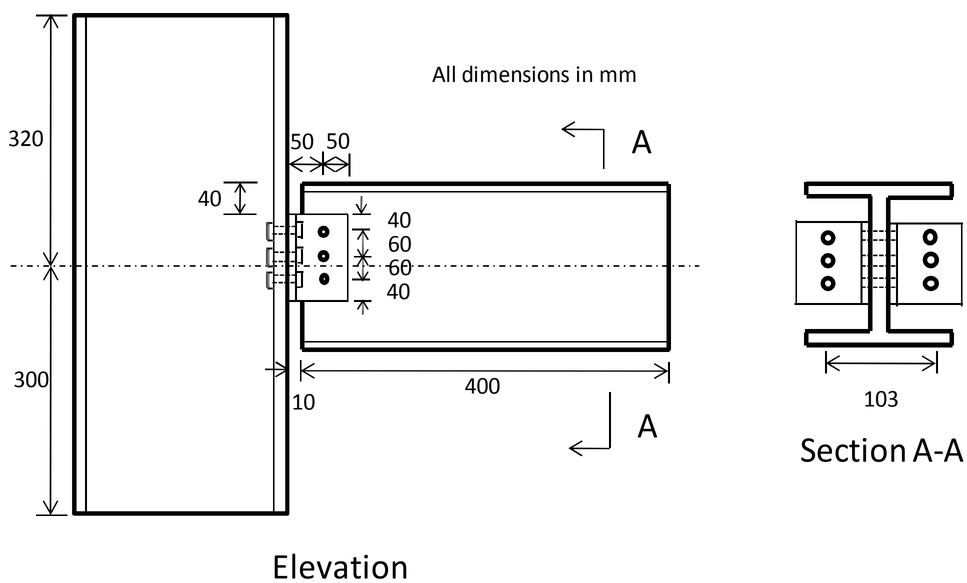


Figure 1: Details of the test specimen used in the finite element model

As the geometry of the tested connection is symmetrical, only half of the column, beam, double angle are modeled, as shown in Fig. 2. In the test specimen designed by Yu et. al. (Yu et. al., 2009), the column was designed to be very stiff and it was supposed to be fully restrained against any movement or rotation. During the test, Yu et. al. (Yu et. al., 2009) observed very small degree of rotation (upto 0.5°) of the column and the connection rotation was almost equal to that of beam rotation throughout the test. Therefore the deformation of column is ignored in the current finite element model. As the column was designed to be stiff and very small rotation was observed during the test, only the column flange connected to the angle is created in the finite element model. A small strip in the middle of the column flange is fully restrained to simulate the restraining boundary condition from the column web.

The geometry of the test specimen is modeled using ANSYS APDL script language and is discretized using SOLID185 (ANSYS, 2009) elements. These elements have the capability of representing large deformation, geometric and material non-linearity (ANSYS, 2009). However, to accurately capture the behavior of stress concentrations around the bolts, bolt holes and angle where failure might be initiated, a relatively finer mesh was used within the vicinity of these regions. As details concerning the size of bolt holes were not provided by Yu et. al. (Yu et. al., 2009), the bolt holes were assumed to be of the same diameter as that of the bolt shanks (i.e., normal-size bolt holes). Bolt shanks and bolt holes were assumed to be of same size in order to avoid the use of any artificial boundary condition to eliminate the rigid body motion and to stabilize the bolt shanks in larger bolt holes. The heads of the bolt and the nut were modeled as hexagonal volumes.

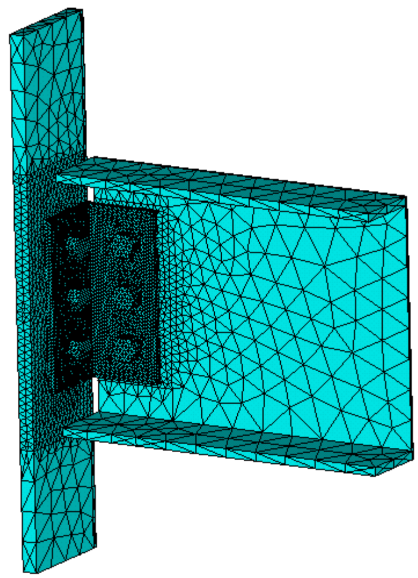


Figure 2: Finite element model geometry of the test specimen

The contact phenomenon between different parts (eg: bolt shank and bolt hole, angle and beam, angle and column etc) is modeled using contact elements CONTA174 and TARGE170 (ANSYS, 2009). Implementation of contact interactions is a big challenge because of the large number of interacting contacting surfaces. The contact behavior between the contacting surfaces is defined as surface-to-surface contact with no separation but sliding permitted option. The amount of sliding depends upon the frictional force (or coefficient of friction) and the friction (between bolts, bolt holes, angles etc) is defined according to Coulumb's frictional law. Bolts were not assumed to be pre-tensioned and a constant co-efficient of friction of $\mu = 0.3$ was adopted for all the contact surfaces throughout the analysis.

In preliminary runs using ANSYS, it was observed that a proper selection of contact element parameters (such as the contact stiffness) and the contact behavior (such as no separation with sliding permitted) plays a crucial role and are often the governing factors in achieving solution convergence. Improper definition of contact model and parameters leads to solution convergence issues and results in incorrect results (deformed shape, stresses). In the current FE model a contact stiffness (FKN) of 0.01 was used and the stiffness of contact elements was updated at each iteration (based on the current mean stress of the elements) to enhance the behavior of contact surfaces and to achieve/improve solution convergence.

3.2 High-temperature material properties

To accurately simulate the behavior of connections using FE models, appropriate material properties of the test specimens should to be used. The material properties used in the current FE model are those reported by Yu et. al. (Yu et. al., 2009). Based on the ambient temperature standard tensile tests conducted on test specimens, Yu et. al. (Yu et. al., 2009) reported that the steel used for the beam had a yield stress (f_y) of 356 N/mm^2, an ultimate tensile stress (f_u) of 502 N/mm^2 with a modulus of elasticity (E) equal to 176.35 kN/mm^2. For the double angle, the steel yield stress (f_y) was 350 N/mm^2, ultimate tensile stress (f_u) was 455 N/mm^2 with a modulus of elasticity (E) of 134.62 kN/mm^2.

In the experimental study, the authors heated the test specimen to the desired temperature and then end of the beam was loaded till the test specimen failed. Since the experimental study was a steady-state temperature testing, the transient high-temperature material model presented in Eurocode 3 (Eurocode 3, 1995) cannot be used directly. As recommended by Yu et. al. (Yu et. al., 2009), the steady-state high temperature material model proposed by Renner (Renner, 2005) was used. The high-temperature stress-strain relationships developed based on Renner's test data are shown in Fig. 3. Since the FE model cannot account for the material softening; only the portion of stress-strain curves till the ultimate tensile stress are used.

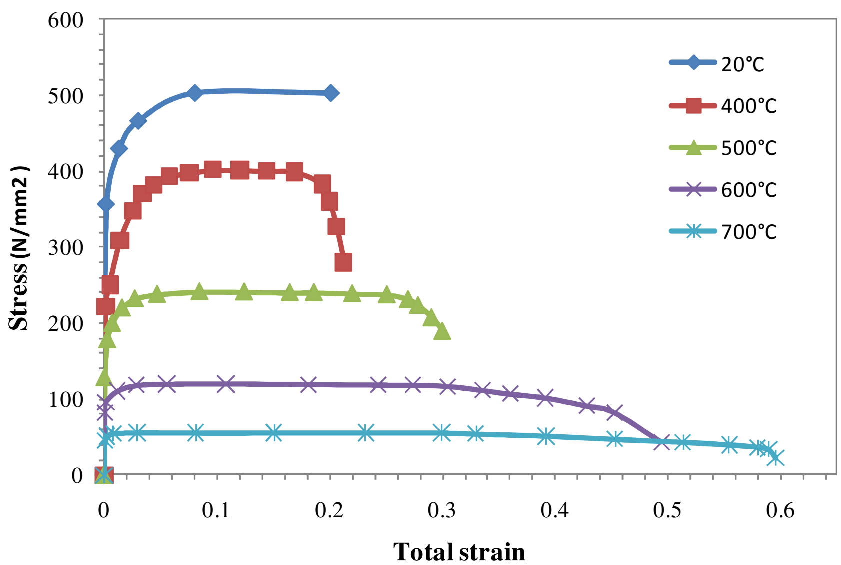


Figure 3: High-temperature stress-strain curves used in the FE model

3.3 Validation of the finite element model

The above model was validated by comparing predicted response parameters from ANSYS with measured test data. In the experimental study, Yu et. al. (Yu et. al., 2009) heated the test specimen to 550°C. The load was applied at the beam end away from the connection and the loading was continued until the test specimen failed by fracture of the angle. The maximum force applied on the test specimen during the test was 61.21 kN. The test specimen failed with the development of crack in the angle at the intersection of two legs.

The FE analysis of the double angle connection was carried out in two stages as uncoupled thermo-mechanical analysis. In the first stage (thermal analysis), a uniform temperature of 550°C was applied as a body force to all the components and the analysis was carried out. In the second stage, horizontal and vertical components of the external load (as obtained from experimental study) were applied at the beam end away from the connection an implicit static analysis was carried out. The force-rotation relationship obtained from the FE model and that obtained from experiment are compared in Fig.4. It can be seen from the figure, FE results show similar behavior and the FE model gives a very good prediction of the test response from the beginning till the maximum applied force. The discrepancy in the initial stages between the FE model and test results could be attributed to the fact that in the test setup the bolt holes were of larger diameter than that of the bolt shanks itself and thus the bolt shanks were able to slide freely inside the bolt hole to perfectly interlock. However, in the current FE model due to unavailability of bolt ole size data, the bolt holes were modeled as having the same diameter as that of bolt shanks. Due to the initial sliding of bolt shanks, the test specimens experienced more rotation per load and the FE response shows somewhat stiff behavior in the initial stages. Also, in the FE model a constant value of coefficient of friction was assumed throughout the analysis but in the test setup the frictional coefficient might be varying based on the applied contact stresses.

In the tests, cracks started to develop within the angle and the resistance of the angle started to fall rapidly (Yu et. al., 2009) towards the end of the test. The current FE model is unable to consider fracture of the material, and thus the descending branch of the force-rotation curve cannot be obtained. The final deformed shape obtained from the FE model and that from the experiment is compared in Fig. 5, and it can be seen that there is good agreement between the two. Thus, based on the assumptions considered in modeling the connections and the response obtained from the FE model it can be concluded that the FE model developed in the current study is able to accurately predict the behavior of connections at elevated temperature.

4. Parametric studies

The validated FE model of double angle connection was used to investigate the effect of bolt-hole diameter and web thickness (beam) on the overall performance of the connection. Details about these modification and the results obtained are presented in the following sections.

4.1 Increasing bolt-hole diameter

The effect of increasing the bolt-hole diameter in the beam web and the double angle is investigated. The basis for studying the effect of increasing bolt-hole diameters is to reduce the contact forces acting on the bolt shank, bolt hole region and also the bolt shank has more flexibility to move freely in the bolt-holes. The normal size bolt-holes in the original FE model were modified as over size bolt-holes which are 2 mm larger in diameter compared to the bolt shank diameter.

The force-rotation relationships, for normal-size bolt holes and over-size bolt holes, obtained from the FE model are shown in Fig.6. The final deformed shape of connection with normal-size and over-size bolt holes is shown in Fig. 7. It can be seen from the Fig. 6 that by increasing the bolt-hole diameter the nominal load carrying capacity of the connection remains almost the same but the connection experiences higher rotation (from initial stages till failure). The higher rotation (flexibility) of the connection in the initial stages (for rotations up to 4-5°) compared to normal-size holes can be attributed to the fact that the bolt shanks are free to rotate inside the over-size bolt holes without experiencing high contact stresses. In other words, for the same amount of external loading, connections with over-sized bolt holes exhibit higher flexibility in comparison to normal-sized bolt holes. The higher rotations experienced by the connection towards the end (as can be seen from Fig.7 (b)) is due to the fact that bolt holes on the beam web underwent significant amount of elongation, which indirectly was aided by the presence of larger hole diameter. Based on the force-rotation relationships, it can be concluded that increasing the bolt hole size does not change the load carrying capacity of the connection but the connection exhibits higher flexibility in comparison to normal-size bolt holes.

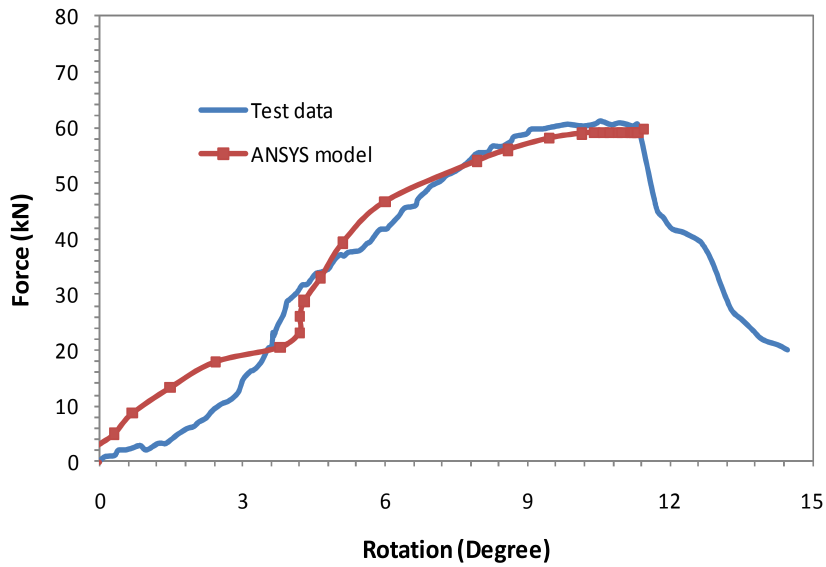
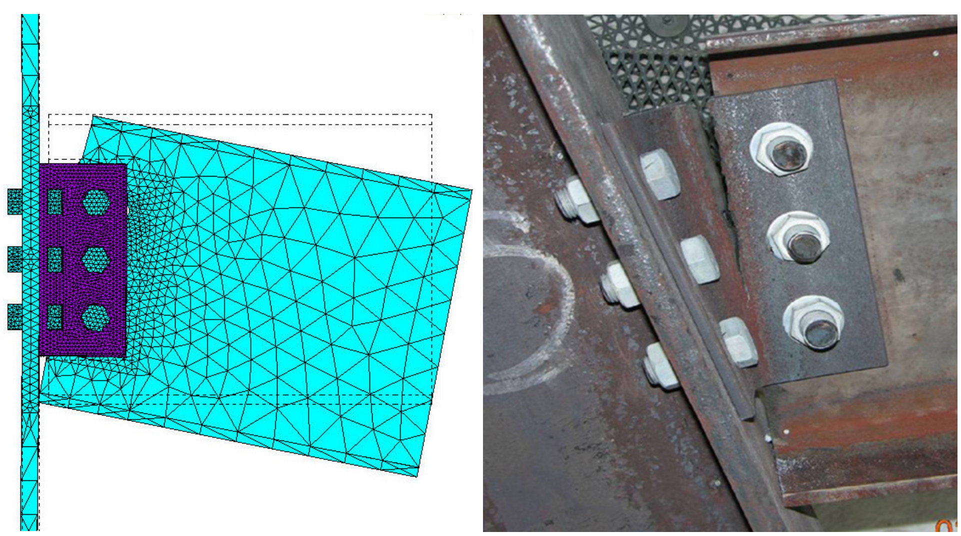


Figure 4: Comparison of force-rotation relationship obtained from test and FE model



(a) FE model (b) Experiment

Figure 5: Comparison of final deformed obtained from FE model and experiment

4.2 Increasing beam web thickness

To investigate the effect of increasing web thickness of the beam on the fire performance of double angle connection, the thickness of the web was increased from 6 mm to 8 mm to match the angle thickness. Fig.8 shows the force-rotation relationships of the connection for different web thickness. It can be seen from the figure that by increasing the web thickness, the load carrying capacity increased marginally and the connection was able to carry the entire applied loading. But the amount of rotation that the connection underwent is significantly lower in comparison to the connection with 6 mm thick web. This indicates that by increasing the beam web thickness the stiffness of the connection increases. These observations are on the expected lines because by increasing the web thickness, the overall strength and stiffness of the connection has been increased.

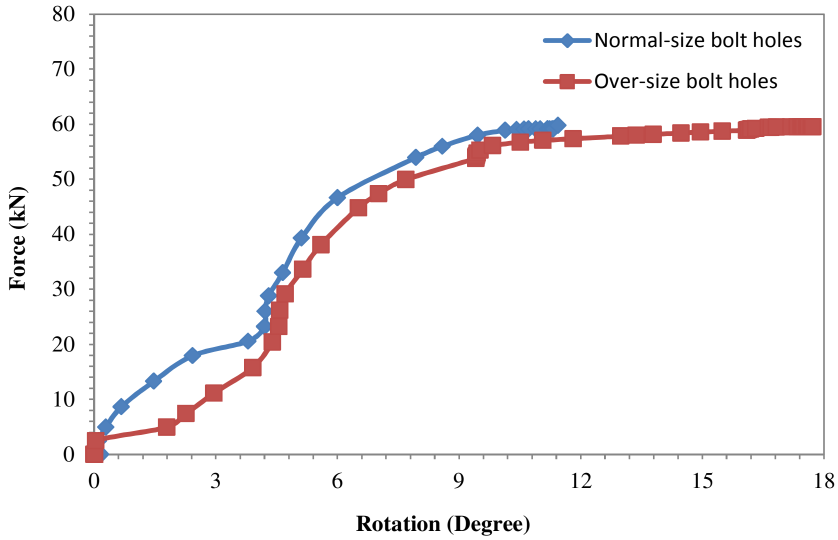
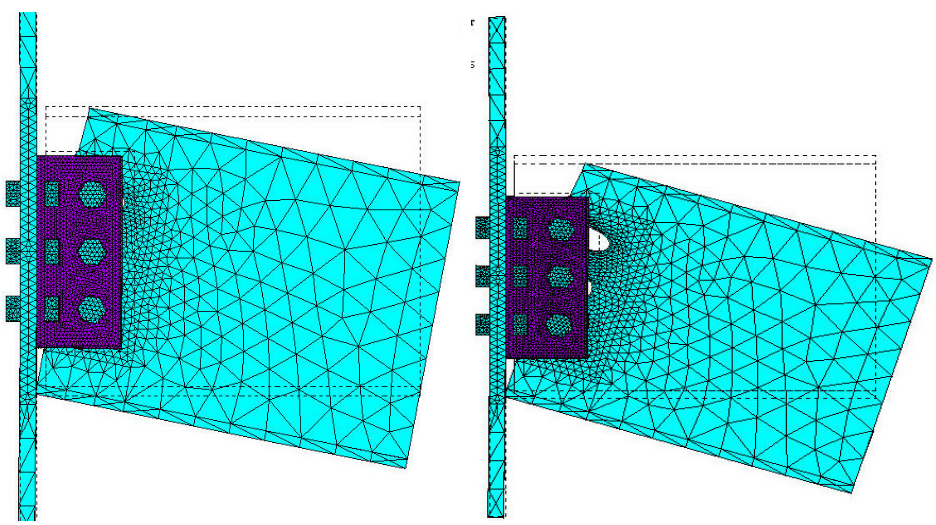


Figure 6: Comparison of force-rotation relationships obtained from FE model for normal-size and over-size bolt holes



(a) Normal-size (b) Over-size

Figure 7: Comparison of final deformed obtained for (a) normal-size and (b) over-size bolt holes

Based on the force-rotation relationships and the deformed shape, it can be concluded that increasing the beam web thickness improves the performance of the connection by increasing the load carrying capacity of the connection and the connection exhibits higher stiffness. This can be a minor yet subtle modification to the connection detail by which the vertical deflection of the beam can be reduced/limited and subsequently the second-order effects and the magnitude of forces in the connection components (beams and columns) can be reduced.

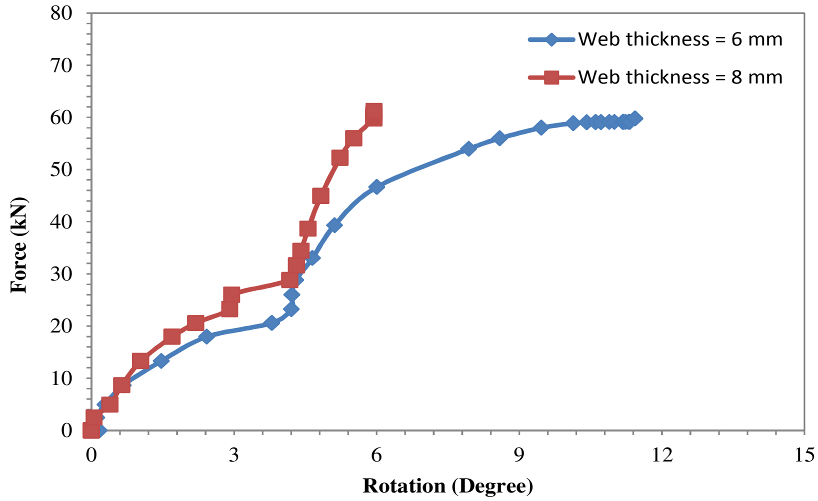


Figure 8: Comparison of force-rotation relationships obtained from FE model for varying web thickness

5. Conclusions

This paper presented the development of a three dimensional (3-D) FE model, by using ANSYS APDL code, for simulating the behavior of shear angle connections at elevated temperatures. The model accounts for material nonlinearity, geometric nonlinearity and degradation of constitutive properties with increasing temperature. Implementation of contact interactions is a big challenge in itself because of the complexity associated in defining/ choosing appropriate contact parameters and contact surface behavior. This complex phenomenon is successfully incorporated into the model using contact elements through surface-to-surface contact surface behavior. Frictional force between beams, columns and bolts are taken into account and are modeled according to Coulumb's frictional law. The FE model has been validated with the results obtained from the experiments. The effect of increasing the bolt hole size and the beam web thickness on the overall performance of the connection has been investigated. The main conclusions that can be drawn based on the results presented in this paper are:

- In general, double angle connections have good tying resistance and rotational capacity in comparison to shear tab, flush end-plate or flexible end-plate connections.
- There is limited data from fire experiments and numerical studies on the fire behavior of double angle connections.
- A three-dimensional FE model, similar to the one presented in this paper, can be used to simulate the behavior of shear angle connections at elevated temperature.
- Careful consideration should be given in modeling the contact interaction between different contact surfaces. An improper selection of contact surface behavior or contact parameters can create solution convergence issues.
- Increasing the bolt hole size does not change the load carrying capacity of the connection, but the connection exhibits higher flexibility in comparison to normal-size bolt holes.
- Increasing the beam web thickness improves the performance of the connection by increasing the stiffness and load carrying capacity of the connection. By increasing the stiffness of the connection, the overall deflection of the beam can be limited within

allowable range. Such reduction in beam deflections lead to lower fire induced forces in connections and this in turn delays failure time of connections.

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