Scientific Research

The Simple Model for Bolted Connections in Fire

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Abstract

Recent structural collapses caused by fire have focused attention on research concerning fire safety in building design. Steel connections are an important component of any structural steel building as they provide links between the principal structural members. Considering the importance of this matter this paper describes a spring-stiffness model developed to predict the behavior of bolted angle connections bare-steel joints at elevated temperature. The joint components are considered as springs with predefined mechanical properties *i.e.* stiffness and strength. The elevated temperature joint's response can be predicted by assembling the stiffness of the components which are assumed to degrade with increasing temperature based on the recommendations presented in the design parameters code. Comparison of the results from the model with existing experimental data showed good agreement. The proposed model can be easily modified to describe the elevated temperature behavior of other types of joint as well as joints under large rotations.

1. Introduction

The properties of steel structures such as load-carrying capacity degrade rapidly in fire due to the reduction in both stiffness and strength of the material. Steel-framed buildings may be subjected to a fire and therefore must be constructed to ensure life safety and property protection. In the past 20 years, there has been much interest in understanding the behavior of different structural elements in fire and experiments have been conducted on steel members and joints either in isolation or as part of a sub-frame assembly or even a full-scale structure. All structural members exposed to fire heat up, but the rate of temperature rise in each member is different. Joints in a steel-framed building tend to heat up slower than the material within the span of the beam because of the presence of additional materials (bolts, plates, angles, etc.) and due to their shielded location *i.e.* usually beneath a composite floor. In conventional analysis and design of steel and composite frames, beam-to-column connections are assumed to behave either as 'pinned' or as fully 'rigid' joints [1,2]. Although the pinned or rigid assumption significantly simplifies analysis and design procedures, in practice, the actual joint behavior exhibits characteristics from a wide spectrum between these two extremes. The difference between the two simplified joint types is that pin joints have rotational stiffness while rigid joints display flexibility. Designers may choose a more accurate representation of joint behavior for analysis and design, but many adopt simplified economical methods. Although these simplified approaches are sufficient for designs at ambient temperatures, when steel-framed structures are subjected to fire the behavior of the joints within a frame exerts an even greater influence on overall response. If the behavior of these connections is not considered properly, the analysis may misrepresent the performance of a structure. In general, experimental tests provide reliable results that can describe the behavior of the beam-to-column connections. However, in many cases experiments are either not feasible or too expensive to conduct. Although of high importance, they are always limited in terms of the number of geometrical and mechanical parameters studied, which obviously would not provide comprehensive understanding of connection performance. Therefore Various forms of analysis and modeling methods have been suggested including simple curve-fitting techniques, simplified analytical methods and sophisticated finite element models for both bare-steel and composite joints. The European code for the design of steel structures (EC3:

Part 1.8) [3] has adopted a simplified analytical procedure for the design of joints at ambient temperature. This method is based on dividing the joint into its basic components of known mechanical properties. By assembling the contributions of individual components which represent the joint as a set of rigid and deformable elements, the entire behavior of the joint may be determined. This method is known as the spring-stiffness or component method. However, there is a few of elevated temperature component models due to the lack of experimental data that describes the joint's behavior. This paper describes a spring-stiffness model developed in an attempt to use the component method to predict the behavior of bolted angle bare-steel joints at elevated temperature using the mechanical characteristics of the components that are available in the literature. In the model the joint's components are treated a springs with predefined characteristics such as stiffness and strength. By assembling the characteristics of individual components, the joint's response can be predicted with increasing temperatures. Only those parameters representing the stiffness and strength of the joint are degraded with increasing temperatures. Comparison of the results from the model with existing test data generated good results.

2. Spring-Stiffness Modeling

The originality of this 'Component Method' is to consider any steel beam-to-column joint as a set of individual components. A beam-to-column joint using the bolted angle connection can be divided into four major zones *i.e.* flexure, tension, and shear and compression zones. Each zone of the joint can be further divided into a number of components, each of which is simply a nonlinear spring, possessing its own strength and stiffness in flexure, tension, compression or shear, and will be reduced with elevation of temperature.

For each component, the initial stiffness and ultimate capacity is determined and assembled to form a spring model, which is adopted to simulate the rotational behavior of the whole joint. An idealized representation of the bolted angle connections bare-steel joint is shown in **Figure 1**. Connection components are named in **Figure 2**.

For simplicity, the flexure zone in the flange of column is represented by a separate spring K_{cfb} and the flexure zone of the top angle and web angle are represented by springs K_{ta} and K_{wa}. In addition the tension zone of the column web is represented by spring K_{cwt}. Similarly the deformation of the components, Δ_T, can be represented by the sum of the deformations of column flange, Δ_{cfb}, top angle, Δ_{ta}, web angle, Δ_{wa}, tension in bolts, Δ_{bt}, pressure in bolts, Δ_{bp}, and tension zone of the
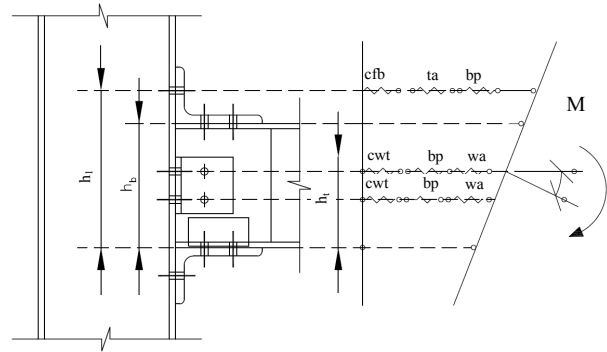
Figure 1. General representation of the proposed model.
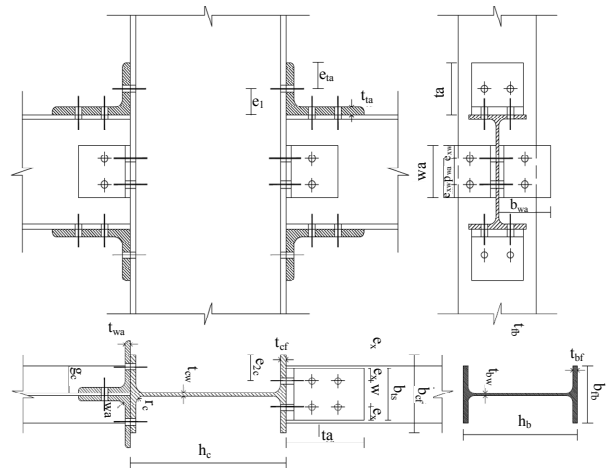
Figure 2. Specimen details.

web column, Δ_{cwt}, (Equation 1).

At initial elastic stage, small deformation assumption is adopted. The following equations can be obtained:

$$\Delta_T = \Delta_{cfb} + \Delta_{ta} + \Delta_{bp} + \Delta_{cwt} + \Delta_{wa}$$

$$= \frac{\sum F_{Rd,i}}{K_{cfb}} + \frac{\sum F_{Rd,i}}{K_{ta}} + \frac{\sum F_{Rd,i}}{K_{bp}} \quad (1)$$

$$+ \frac{\sum F_{Rd,i}}{K_{cwt}} + \frac{\sum F_{Rd,i}}{K_{wa}}$$

Considering that $\theta_T = \dfrac{\Delta_T}{h_t}$, $M_T = F_T \cdot h_t$, and The global rotational stiffness of the joint $K_\varphi = k_t \cdot h_t^2$ can be determined for any moment at any given temperature based on the assembled stiffness of all components as:

$$k_t = \frac{\sum_{i=1}^{n} k_i h_i}{h_t} \quad (2)$$

$$h_t = \frac{\sum_{i=1}^{n} k_i h_i^2}{\sum_{i=1}^{n} k_i h_i} \quad (3)$$

where:

$$k_i = \frac{1}{\dfrac{1}{k_{cfb}} + \dfrac{1}{k_{ta}} + \dfrac{1}{k_{bp}} + \dfrac{1}{k_{cwt}} + \dfrac{1}{k_{wa}} + \dfrac{1}{k_{bt}}} \quad (4)$$

With the spring model, the ultimate moment of the joint can be estimated using the following expression:

$$M_{pT} = \sum_{i=1}^{n} F_{Rd,i}.h_i \quad (5)$$

$$F_{Rd,i} = \min \left\{ \begin{array}{l} F_{V,ta,Rd}, F_{V,wa,Rd}, F_{bfb,Rd}, F_{cfb,Rd}, F_{cwt,Rd}, F_{ta,Rd}, F_{tat,Rd}, \\ F_{wa,Rd}, F_{bwb,Rd}, F_{wat,Rd} \end{array} \right\} \quad (6)$$

After obtaining the stiffness and ultimate load of each component, the moment–rotation relation may be obtained from the following Equation [4]:

$$M_T = M_{pT} \left\{ 1 - \exp\left[\frac{-(K_\varphi - K_{pt} - C\theta_T)\theta_T}{M_{pT}} \right] \right\} + K_{pT}\theta_T \quad (7)$$

where, K_{pT} can be expressed as $0.02K_\varphi$, and a zero value has been recommended for C [4]. Components forces are shown in **Figure 3**.

3. Degradation of the Joint's Characteristics at Elevated Temperature

When a steel bolted angle connection is subjected to fire, the temperature of the joint will be increased to a high level. At elevated temperature, the elastic modulus and strength of steel will be reduced. The reduction of stiffness and strength of the components was based on the reduction of structural steel at elevated according to EC3: Part 1.2 as shown in **Table 1**.
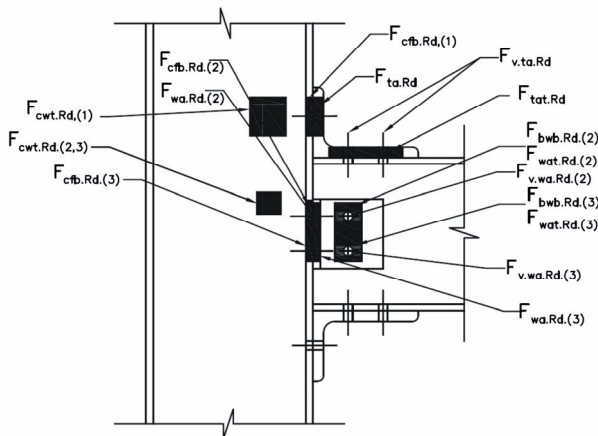

Figure 3. Forces in connection components.

Table 1. Properties of structural steel at elevated temperature (θ_s : steel temperature, f_y : yield stress, E_s : Young's modulus).

θ_s (°C)	Reduction factors	
	$k_{y,\theta} = f_{y,\theta}/f_y$	$k_{E,\theta} = E_{s,\theta}/E_s$
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
1200	0	0

However, the reduction of bolt stiffness and capacity is based on recommendations presented by Kirby [5] using Equation (8) to Equation (10).

If

$$\theta_b \leq 300°C \text{ then SFR} = 1.0 \quad (8)$$

If

$$\theta_b < 300°C \leq 680°C \text{ then}$$
$$\text{SFR} = 1.0 - (\theta_b - 300) \times 2.128 \times 10^{-3} \quad (9)$$

If

$$\theta_b < 680°C \leq 1000°C \text{ then}$$
$$\text{SFR} = 0.17 - (\theta b - 680) \times 5.13 \times 10^{-4} \quad (10)$$

where θ_b is temperature of the bolt and SFR is strength retention factor of the bolt. These reduction factors are suggested by Saedi Daryan *et al.* via experimental test. [6]

4. Initial Stiffness of Components at Elevated Temperature

In this part, the stiffness of each connection components that is necessary for calculation of Equation (4) is presented [7-10].

4.1. Calculates the Stiffness of Column Flange and Column Web

$$k_{cfb} = \psi E \frac{0.5 b_{eff,cfb} t_{cf}^2}{m_{cf}^3} \quad (11)$$

where:

$$b_{eff,cfb} = \min\{b_{eff,cfb,1}, b_{eff,cfb,2}\} \quad (12)$$

$$b_{eff,cfb,1} = d_{bh} + 2m_{cf} \quad (13)$$

$$c\, b_{eff,cfb,2} = \frac{b_{cf}}{2} + \frac{t_{cw}}{2} - e_{2c} - 0.8r_c \quad (14)$$

$$\psi = 0.57\left[\frac{t_{cf}}{d_b\sqrt{\frac{m_{cf}}{d_b}}}\right]^{-1.28} \geq 1 \quad (15)$$

$$k_{cwt} = E\frac{b_{eff,cfb}t_{cw}}{d_{cw}} \quad (16)$$

4.2. Calculates the Stiffness of Top Angle

$$k_{ta} = \left(\psi E\frac{0.5b_{eff,ta}t_{ta}^3}{m_{ta}^3} \times \frac{4}{7}\right) \times \left(\frac{h_b}{h_1}\right) \quad (17)$$

where:

$$\psi = 0.57\left[\frac{t_{ta}}{d_b\sqrt{\frac{m_{ta}}{d_b}}}\right]^{-1.28} \geq 1 \quad (18)$$

$$b_{eff,ta} = \min\{b_{eff,ta,1}, b_{eff,ta,2}, b_{eff,ta,3}\} \quad (19)$$

$$b_{eff,ta,1} = d_{bh} + 2m_{ta} \quad (20)$$

$$b_{eff,ta,2} = \frac{d_{bh}}{2} + m_{ta} + \frac{w}{2} \quad (21)$$

$$b_{eff,ta,3} = \frac{b_{ta}}{2} \quad (22)$$

$$m_{ta} = L_{ta} - 0.5t_{ta} - e_{ta} \quad (23)$$

4.3. Calculates the Stiffness of Bolt Row

$$k_{bp} = 1.6\frac{EA_b}{L_b}\left(5.1 + 3.25\frac{t_p}{d_b}\right);\ t_p = \frac{t_{cf} + t_{bw}}{2} \quad (24)$$

4.4. Calculates the Web Angle Stiffness

$$k_{wa} = \varphi E\frac{0.5b_{eff,wa}t_{wa}^3}{m_{wa}^3}\left(\frac{4}{7}\right) \quad (25)$$

where:

$$\varphi = 0.57\left[\frac{t_{wa}}{d_b\sqrt{\frac{m_{wa}}{d_b}}}\right]^{-1.28} \geq 1 \quad (26)$$

$$b_{eff,wa} = \min\{b_{eff,wa,1}, b_{eff,wa,2}, b_{eff,wa,3}, b_{eff,wa,4}\} \quad (27)$$

$$b_{eff,wa,1} = d_{bh} + 2m_{wa} \quad (28)$$

$$b_{eff,wa,2} = \frac{d_{bh}}{2} + m_{wa} + \frac{\rho_{wa}}{2} \quad (29)$$

$$b_{eff,wa,3} = \frac{d_{bh}}{2} + m_{wa} + e_{xw} \quad (30)$$

$$b_{eff,wa,4} = e_{xw} + \frac{\rho_{wa}}{2} \quad (31)$$

5. The Load Capacities of Connection Components

In this part, the Load-caring capacity of each connection components that is necessary for calculation of equation 6 is presented. [11-13]

5.1. Calculate the Shear Force of Bolts in Top Angle and Bolt Force in Beam Flange

$$F_{v,ta,Rd} = n_b n_s f_V A_b,\ f_V = 0.6f_{ub} \quad (32)$$

$$F_{bfb,Rd} = 2.5n_b f_u d_b t_{bf}\alpha \quad (33)$$

$$\alpha = \min\left\{\frac{e_1}{3d_\circ}, \frac{\rho_1}{3d_\circ} - 0.25, \frac{f_{ub}}{f_u}, 1\right\} \quad (34)$$

5.2. Calculate the Bolt Force in Column Flange

$$F_{cfb,Rd} = \min\{F_{cfb,Rd,1}, F_{cfb,Rd,2}, F_{cfb,Rd,3}\} \quad (35)$$

$$F_{cfb,Rd,1} = \begin{cases} \dfrac{4M_{cf,Rd}}{m_{cfi}} & \text{For top angle bolt row} \\ \dfrac{4M_{pl,Rd}}{m_{cfi}} & \text{For top angle bolt row} \end{cases} \quad (36)$$

$$M_{cf,Rd} = \frac{b_{eff,cfb,i}t_{cf}^2 f_y}{4} \quad (37)$$

$$M_{pL,Rd} = \frac{b_{eff,cfb,i}t_{cw}^2 f_y}{4} \quad (38)$$

$$b_{eff,cfb,i} = \{b_{eff,cfb,1}, b_{eff,cfb,2}\} \quad (39)$$

$$b_{eff,cfb,1} = 2\pi m_{cfi} \tag{40}$$

$$b_{eff,cfb,2} = 4m_{cfi} + 1.25e$$

$$\rightarrow \begin{cases} e = e_{2c} \text{ For top angle bolt row} \\ e = \dfrac{b_{cf}}{2} - \dfrac{t_{cw}}{2} - m_{cfi} - 0.8r_c \text{ In web angle bolt row} \end{cases} \tag{41}$$

$$m_{cfi} = \begin{cases} \dfrac{b_{cf}}{2} - \dfrac{t_{cw}}{2} - e_{2c} - 0.8r_c \text{ For top angle bolt row} \\ g_c + \dfrac{t_{bw}}{2} - \dfrac{t_{cw}}{2} - 0.8r_c \text{ For top angle bolt row} \end{cases} \tag{42}$$

$$F_{cfb,Rd,2} = \begin{cases} \dfrac{2M_{cf,Rd} + 2B_{Rd}n}{m_{cfi} + n} \text{ top angle bolt row} \\ \dfrac{2M_{PL,Rd} + 2B_{Rd}n}{m_{cfi} + n} \text{ web angle bolt row} \end{cases} \tag{43}$$

$$n = \begin{cases} e_{2c} - \left(\dfrac{b_{cf} - b_{ta}}{2} \right) \text{ top angle bolt row} \\ L_{wa} - g_c \text{ web angle bolt row} \end{cases} \tag{44}$$

$$B_{Rd} = 0.9A_b f_{ub} \tag{45}$$

$$F_{cfb,Rd,3} = 2B_{Rd} \tag{46}$$

5.3. Calculate the Tensile Force in Column Web

$$F_{cwt,Rd} = b_{eff,cwt} t_{cw} f_y \tag{47}$$

$$b_{eff,cwt} = t_{bf} + 5(t_{cf} + r_c) \text{ For top angle bolt row} \tag{48}$$

$$b_{eff,cwt} = b_{eff,cfb} \text{ For web angle bolt row} \tag{49}$$

5.4. Calculate the Force of Top Angle

$$F_{ta,Rd} = \min\{F_{ta,Rd,1}, F_{ta,Rd,2}, F_{ta,Rd,3}\} \tag{50}$$

$$F_{ta,Rd,1} = \frac{4M_{PL,Rd}}{m_{ta}} \tag{51}$$

$$M_{PL,Rd} = \frac{b_{ta}t_{ta}^2}{4} f_y \tag{52}$$

$$m_{ta} = L_{ta} - 0.5t_{ta} - e_{ta} \tag{53}$$

$$F_{ta,Rd,2} = \frac{2M_{PL,Rd} + e_{ta}\sum_{i=1}^{n} B_{Rdi}}{m_{ta} + e_{ta}} \tag{54}$$

$$F_{ta,Rd,3} = \sum_{i=1}^{n} B_{Rdi} \tag{55}$$

$$B_{Rd} = 0.9A_b f_{ub} \tag{56}$$

5.5. Calculate the Tensile Force in Top Angle and Web Angle Force

$$F_{tat,Rd} = \min\{Af_y, 0.9A_{net}f_u\} \tag{57}$$

$$F_{wa,Rd} = \frac{b_{eff,wa}t_{wa}^2 f_y}{m_i'} \tag{58}$$

$$b_{eff,wa} = \frac{b_{wa}}{2} \tag{59}$$

$$m_i = \frac{3}{2} \frac{t_{wa}}{\left[\left(\alpha \dfrac{y_i}{L_{wa}} \right)^2 + 3 \right]^{1/2} - \alpha \dfrac{y_i}{L_{wa}}} \tag{60}$$

$$\alpha = \frac{m_{max}}{t_{wa}} \tag{61}$$

$$m_{max} = \frac{m_{wa}^*}{\rho_{wa} + d_{wa}} L_{wa} \tag{62}$$

$$m_{wa}^* = m_{wa} - \varphi_1 \left(\frac{d_{bh}}{2} + \frac{t_{wa}}{2} + 0.2r_{wa} \right) \tag{63}$$

$$\varphi_1 = 1.89 - 3.22 \left(\frac{t_{ta}}{d_b \sqrt{\dfrac{m_{ta}}{d_b}}} \right) \leq 1 \tag{64}$$

$$d_{bh} = 1.6d_b, m_{wa} = g_c - t_{wa} - 0.8r_{wa} \tag{65}$$

5.6. Calculate the Shear Force of Bolts in Web Angle and Beam Web Bending Force and Tensile Force in Web Angle

$$F_{v,wa,Rd} = n_b n_s f_V A_b \tag{66}$$

$$F_{bwb,Rd} = 2.5\alpha n_b f_u d_b t_{bw} \tag{67}$$

$$F_{wat,Rd} = \min\{n_s b_{eff,wa} t_{bw} f_y, 0.9n_s A_{net}f_u\} \tag{68}$$

$$b_{eff,wa} = \frac{b_{wa}}{2} \tag{69}$$

6. Accuracy Calibration of the Proposed Model

In order to confirm and evaluate the accuracy of the spring-stiffness model under the fire conditions, four samples of the angle connection with bolts are used by experimental report, presented by Saedi Daryan *et al.* [6-14]

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6.1. Details of Specimens Tested by Saedi Daryan *et al*.

The specimens were configured in a symmetrical cruciform arrangement that consists of a single 80 cm high column of IPE300 section connected to two 250 cm long cantilever beams of IPE 220 section. The load was applied on a point 2 meters from the end of the beam. All of the bolts in the specimens were tightened to 150 N.m by a torque wrench to ensure consistency. The experimental tests were conducted on two different connection details:

Connection group 1: (SPECIMEN WITHOUT WEB ANGLE) (SOW)

Connection group 2: (SPECIMEN WITH WEB ANGLE) (SWW)

Connection group 1 (SOW) consisted of two angles, one connected to the top flange of the beam and the other connected to the bottom flange. The total system was bolted to the flange of the column. Each angle was bolted to the flange of the beam by six M16 bolts and to the flange of column by two M16 bolts. A detail of this group of connections is shown in **Figure 4(a)**.

The connection group 2 (SWW) had two additional angles compared with connection group 1. These angles were bolted to the web of the beam on one side and to the flange of the column on the other side. Web angles were connected to the web of the beam by two M16 bolts and to the flange of the column by two M16 bolts. Details of this group of connections are shown in **Figure 4(b)**. Details of all specimens are provided in **Table 2**.

6.1.1. Specimen Loading

The values of applied moment to each specimen in the tests are presented in **Table 3**. As it can be seen, first the rotation capacity of connection is theoretically calculated and then the applied moment is selected as a coefficient of connection rotation capacity and is applied to the specimens during the test.

The steel material properties of the specimens are presented in **Table 4**.

The effectiveness of the spring-stiffness model for

Table 2. Details of specimens tested by Saedi Daryan *et al*. [6].

Specimen NO	Group NO	Angle Size (mm)	Grade of Bolt
3	1	100*100*10	8.8
5	2	150*100*15	8.8
9	1	150*100*15	8.8
13	2	100*100*10	8.8

(a)

(b)
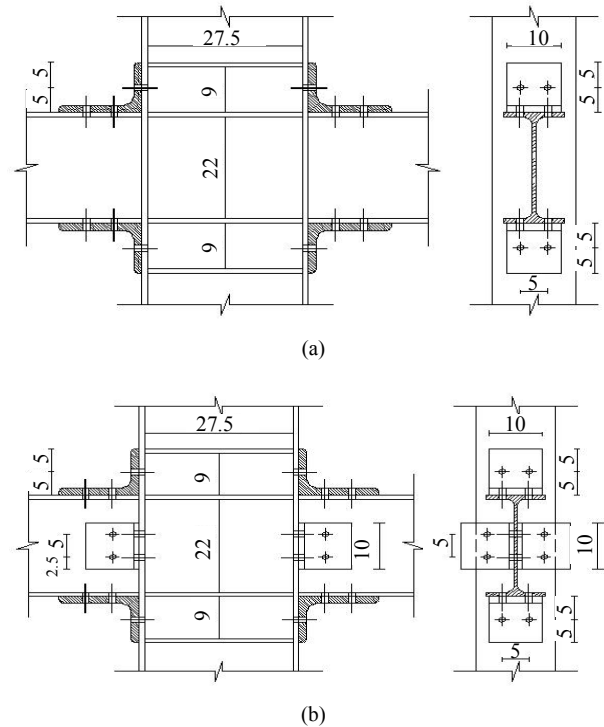
Figure 4. Details of the test conducted by Saedi Daryan *et al*. (a) Connection group 1 (SOW), (b) Connection group 2 (SWW).

Table 3. The value of applied moment for each specimen in the tests carried out by Saedi Daryan *et al*.

Specimen NO	Group NO	Moment (M) Level	Applied M (kNm)
3	1	Mcc	8.5
5	2	0.4 Mcc	8.5
9	1	0.6 Mcc	8.5
13	2	0.8 Mcc	8.5

Table 4. Material properties of specimens tested by Saedi Daryan *et al*.[6].

Material	Yield stress (N/mm^2)	Ultimate stress (N/mm^2)	Modulus of elasticity (N/mm^2)
Beam & Column & Angle	235	420	$2.06*10^5$
Bolts 8.8	740	866	$2.06*10^5$

simulating the behavior of the bolted angle joints subjected to fire may be validated with the experiments. In **Figure 5** temperature—rotation carves obtained by experimental tests are compared with the result of spring-stiffness model. In **Figure 6**, moment—rotation

carves presented by Saedi Daryan *et al*. are compared with the result of spring-stiffness model [15]. It can be seen that the predicted and the measured results of specimens agree with each other quite well. In the case of few specimens, some differences between the results are observed that, these may be due to the different rate of temperature increase. The rate of temperature increase has some influence on the creep strain of steel. So variation of the fire rate may impact on the response of connections. Further study of the influence of creep stain on the behavior of bolted angle joints will be done in the next stage of research. The good agreement of modeling with the test results demonstrates that the spring-stiffness model is a good representation of bolted angle joints. The spring-stiffness model can be used to predict the response of connections as well as of structures with bolted angle joints at elevated temperatures.

7. Conclusions

This research was carried out to simulate the behavior of

bolted angle connections in fire with spring-stiffness model. The model is developed according to the specifications of the details and behavior of the connection in elevated temperature. Comparisons of the springstiffness method with experimental results confirm predicted and measured responses both in elastic and plastic zones. This method is capable of predicting the results of the bolted angle connection in elevated temperature with desirable accuracy. However the proposed model requires further development to support following topics which could have an important effect on the connection behavior in high temperature:

- The applicability of the model to predict the joint behavior at higher levels of moment than those presented;
- The model was developed based on isolated joint tests, the effect of axial restrained on the joint behavior needs to be addressed in the model since this can have significant influence on the behavior of the structure in fire as observed from Cardington frame fire tests. Also, the joint behavior during the cooling
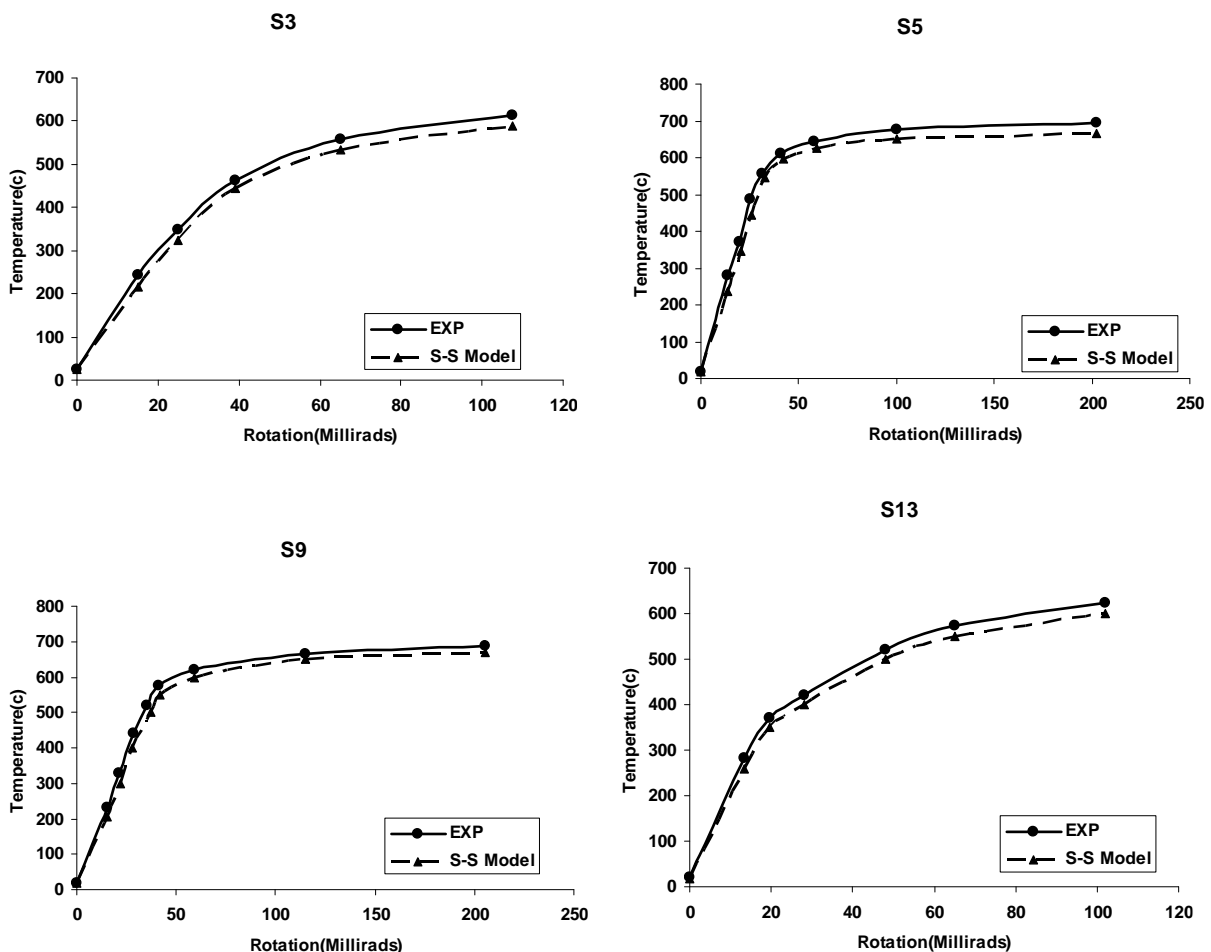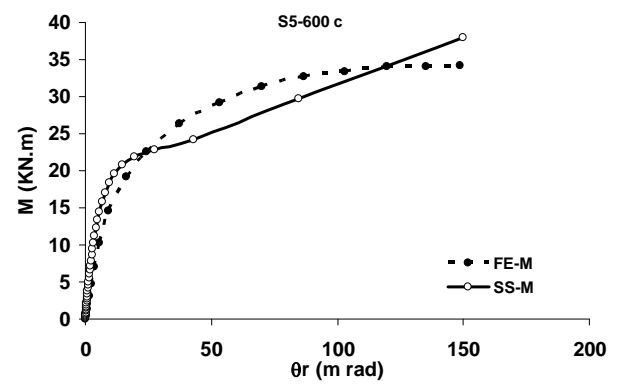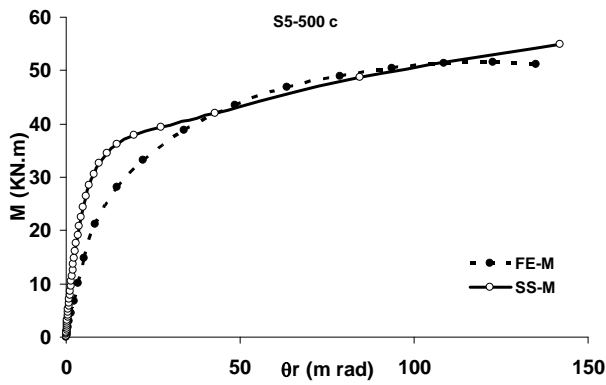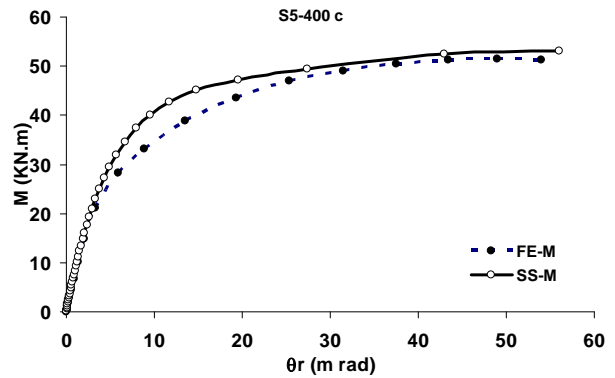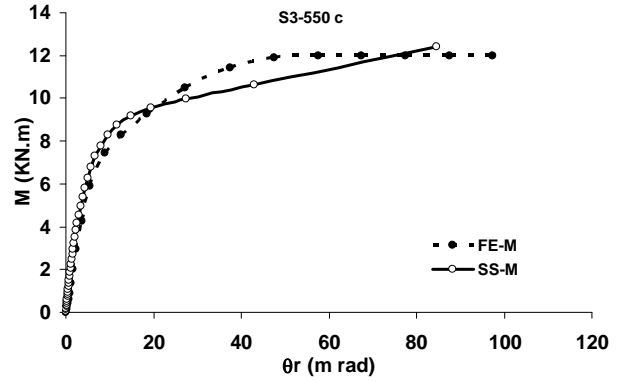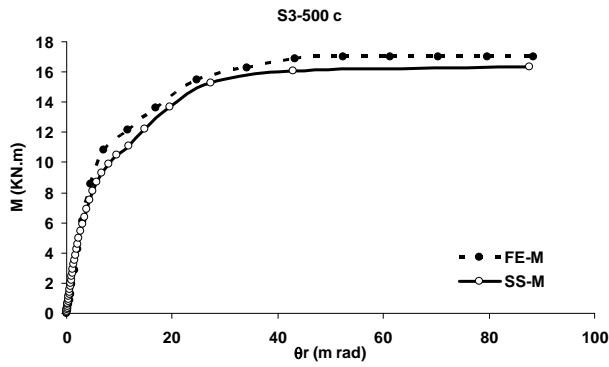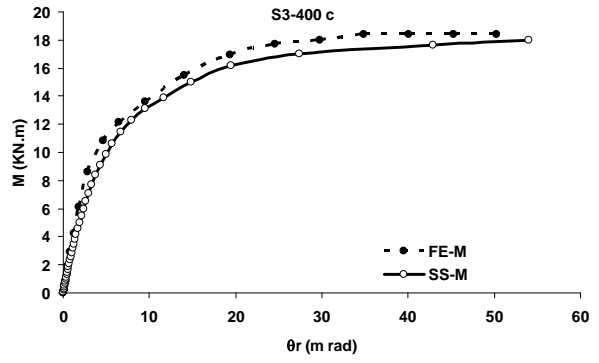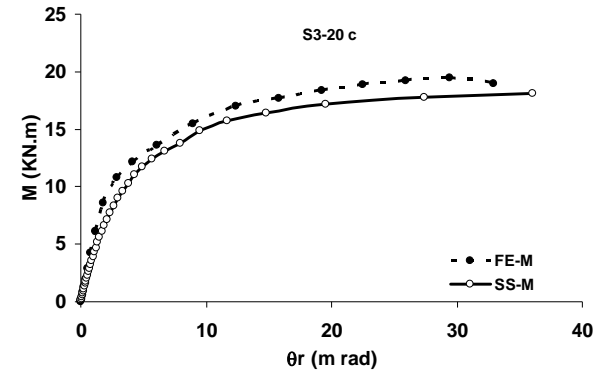

Figure 5. Comparison of temperature—rotation for spring-stiffness model and experimental tests [15].
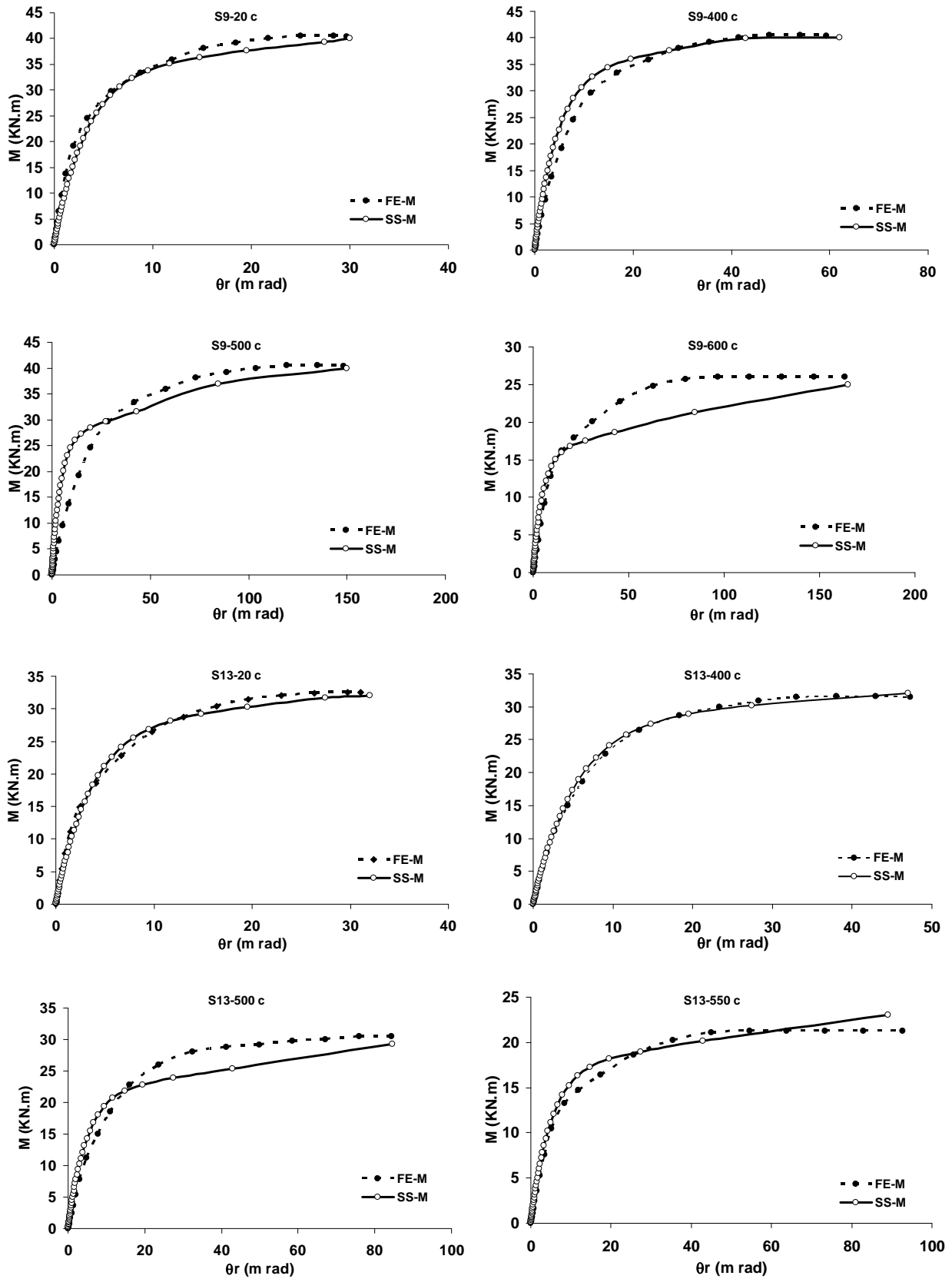
M. YAHYAI   *ET   AL*.
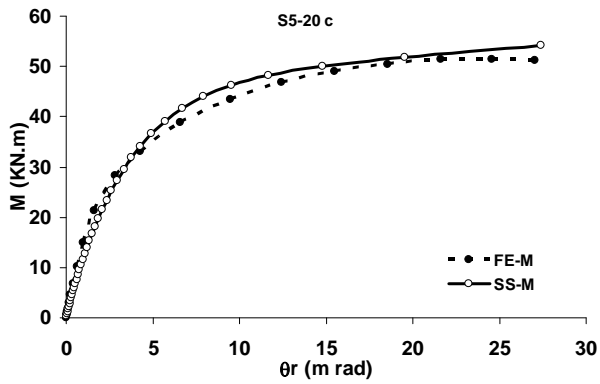
Figure 6. Comparison of moment—rotation for spring-stiffness model and reference [15].

phase needs to be investigated.

8. References

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Nomenclature:

θ_T	Rotation of connection at the different temperature.
h_t	Distance between center of rotation and top of the seat angle
k_i	Stiffness of the I th bolts row
k_t	Stiffness of the total bolts row
k_φ	Rotation stiffness of the connection
M_{PT}	Plastic moment of the connection
M_T	Moment of the connection at different temperature
k_{PT}	Plastic stiffness of the connection
$F_{wa,Rd}$	Web angle force
$F_{wat,Rd}$	Tensile force in web angle
$F_{bwb,Rd}$	Beam web bending force
k_{wa}	Web angle stiffness
$F_{v,ta,Rd}$	Shear force of bolts in top angle
$F_{v,wa,Rd}$	Shear force of bolts in web angle
f_v	Shear stress of bolt
$F_{cfb,Rd}$	Bolt force in column flange
$F_{cwt,Rd}$	Tensile force in column web
$F_{ta,Rd}$	Force of top angle
$F_{bfb,Rd}$	Bolt force in beam flange
$F_{tat,Rd}$	Tensile force in top angle
K_{cfb}	Stiffness of column flange
k_{cwt}	Stiffness of column web
K_{ta}	Stiffness of top angle
k_{bp}	Stiffness of bolt row
w	Distance between bolts at top angle
L_b	Thickness of the washers and half thickness of the nut and the bolt head
y_i	Distance of the bolt row to top of the web angle edge
b_{wa}	Width of web angle
h_l	Height of the first bolt row to center of rotation
g_c	Distance of the bolt connecting the column flange to the beam web
t_{bw}	Thickness of beam web
t_{wa}	Thickness of web angle
r_{wa}	Root radius of web angle

P_{wa}	Distance of web angle bolts
d_{wa}	vertical distance of web angle to the first bolt in web angle
L_{wa}	Length of web angle
n_b	Number of bolts bearing shear
n_s	Number of bolts bearing shear for each bolt
e_{xw}	Distance of web angle edge to the bolt connecting web angle to the beam
t_{ta}	Thickness of top angle
h_b	Height of beam
L_{ta}	Length of top angle
e_{ta}	Distance of the first bolt row to top angle edge
t_{cf}	Thickness of column flange
r_c	Root radius of column
t_{cw}	Thickness of column web
ρ	Distance between top angle bolt row and the first bolt row in web angle
d_{bh}	Bolt head diameter($1.6d_b$)
f_y	Yield stress in component of connection
f_u	Ultimate stress in component of connection
d_b	Diameter of bolt
e_{2c}	Distance between bolt connecting web angle to column flange edge
E	Steel module of elasticity for component of connection
υ	Poisson ratio
d_{cw}	Height of column web
b_{cf}	Width of column flange
f_{yb}	Yield stress of bolt
f_{ub}	Ultimate stress of bolt
e_1	Distance between top angle connected to beam flange and the first bolt row in top angle
d_o	Hole diameter of bolt
P_1	Distance between first bolt row and second bolt row
$b_{ta} = W$	Width of top angle
t_{bf}	Thickness of beam flange
A_{net}	Net area of angle
A	Area of angle
A_b	Area of bolt

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