Performance assessment on high strength steel endplate connections in fire

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Abstract

Purpose – This paper aims to investigate and assess a perspective of combining high-strength-steel endplate with mild-steel beam and column in endplate connections.

Design/methodology/approach – First, experimental tests on high strength steel endplate connections were conducted at fire temperature 550°C and at an ambient temperature for reference.

Findings – The moment-rotation characteristic, rotation capacity and failure mode of high-strength-steel endplate connections in fire and at an ambient temperature were obtained through tests and compared with those of mild-steel endplate connections. Further, the provisions of Eurocode 3 were validated with test results. Moreover, the numerical study was carried out via ABAQUS and verified against the experimental results.

Originality/value – It is found that a thinner high-strength-steel endplate can enhance the connection's rotation capacity both at an ambient temperature and in fire (which guarantees the safety of an entire structure) and simultaneously achieve almost the same moment resistance with a mild steel endplate connection.

Keywords High strength steel, Endplate connections, Beam-to-column connections, Structural fire performance, Fire condition

Paper type Research paper

1. Introduction

Fires in buildings often have enormous consequences on safety and economy. Structural fire safety is therefore a key consideration in the design of buildings and is attracting worldwide attention. Beam-to-column connections are important components of steel-framed structures, as they are supposed to resist resultant forces at the end of the beam and transfer them into the columns and surrounding structural components. The fracture of a connection can cause the collapse of the connected beam, which may lead to a progressive collapse of the entire building structure. Therefore, the behaviour of connections in a building is of extreme significance, not only at an ambient temperature but also in fire.

In Europe, endplate connections are typical beam-to-column connections for steel structures produced by welding at workshops and erected by bolting *in situ*. The simplicity and economy associated with its fabrication make this type of connection popular in steel structures. Rules for prediction of strength, stiffness and deformation capacity of endplate connections at an ambient temperature have been included in

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current leading design standards, such as Eurocode 3 Part1-8 (CEN, 2005). According to Eurocode 3, for structural steels up to S460, plastic design of connections may be used. However, for steel grades higher than S460 and up to S700, only elastic design of connections can be used (CEN, 2004), which is very uneconomical for steel structures. This is because of the lack of experimental and theoretical evidence that these high-strength-steel connections have sufficient deformation capacities. Coelho and Bijlaard (2007) have found that the high-strength-steel S690 endplate connections satisfy the design provisions for resistance and achieve reasonable rotation demands at ambient temperature. However, research results on fire performance of high-strength-steel endplate connections are not available in literature.

In this paper, a perspective of combining high-strength-steel endplate with mild-steel beam and column in beam-to-column endplate connections is proposed, investigated and assessed. The aim of this research is to reveal more information and understanding on behaviour of high-strength-steel flush endplate connections in fire.

First, seven full-scale tests on beam-to-column high strength steel endplate connections were conducted at an elevated temperature of 550°C under steady state fire condition and at an ambient temperature as reference. The high-strength-steel endplates were made of S690 and S960 in test connections. The parameters investigated herein are the endplate thickness and the endplate material. All the specimens are designed to confine failure to the connections rather than the beam or column. The moment-rotation characteristic, rotation capacity and failure mode of high strength steel endplate connections in fire and at an ambient temperature were obtained through tests and compared with those of mild-steel endplate connections. Further, the provisions of Eurocode 3 were validated with test results of high strength steel endplate connections. Moreover, the numerical study on high-strength-steel endplate connections under fire conditions was carried out via the commercial package ABAQUS. The accuracy of this numerical modelling was validated against the experimental results on moment-rotation relationship, failure mode and yield line pattern of endplate connections.

This research opens a perspective of using high strength steels to replace mild steels in structural optimizing design. The experimental and numerical study on high-strength-steel endplate connections in fire is expected to be used by structural engineers or researchers as a basis for an effective application of high strength structural steels in civil engineering and enhancing the fire safety of steel structures.

2. Experimental study

2.1 Test specimen

In the endplate connections, the endplates are made of high-strength steels (S690 and S960), whereas the beam and column are made of Q345 (mild structural steel, the nominal yield stress of which is 345 MPa, similar to S355). The beam sections used in this study are HW300 × 300 (comparable to European Section HE320A), whereas the column sections are HW400 × 400 (comparable to European Section HE300M). For comparison, the connections with endplates made of mild steels Q235 (mild structural steel, the nominal yield stress of which is 235 MPa, similar to S235) and Q345 are also included herein. In this experimental study, there are two series of endplate connections, see Table I. In each of them, the load-bearing capacities of the connections are designed to be similar, whereas the endplate materials and thicknesses vary. To compare the behaviour of endplate connections under fire conditions with that at an ambient

Table I.
Test specimens and fire test conditions

Connection ID	Endplate material	Endplate thickness (mm)	Weld type	Weld Size (mm)	Temperature (°C) of specimens
1-1 A	Q235	20	Overmatched	8	20
1-2 A	S690	12	Matched	10	20
1-3 A	S960	10	Under matched	10	20
2-1 A	Q235	25	Overmatched	8	20
2-2 A	Q345	20	Overmatched	8	20
2-3 A	S690	15	Matched	10	20
2-4 A	S960	12	Under matched	10	20
1-1 E	Q235	20	Overmatched	8	550
1-2 E	S690	12	Matched	10	550
1-3 E	S960	10	Under matched	10	550
2-1 E	Q235	25	Overmatched	8	550
2-2 E	Q345	20	Overmatched	8	550
2-3 E	S690	15	Matched	10	550
2-4 E	S960	12	Under matched	10	550

temperature, the tests at an ambient temperature on each concerned endplate connection were conducted as well. The overall dimension of the endplate connection test specimen is shown in Figure 1, whereas the endplate materials and thicknesses of the specimens are shown in Table I.

2.2 Test set-up

All fire tests were conducted in a gas furnace (4.5 × 3.0 × 1.7 m). Because applying a tensile load under fire conditions is more stable than applying a compressive load, the

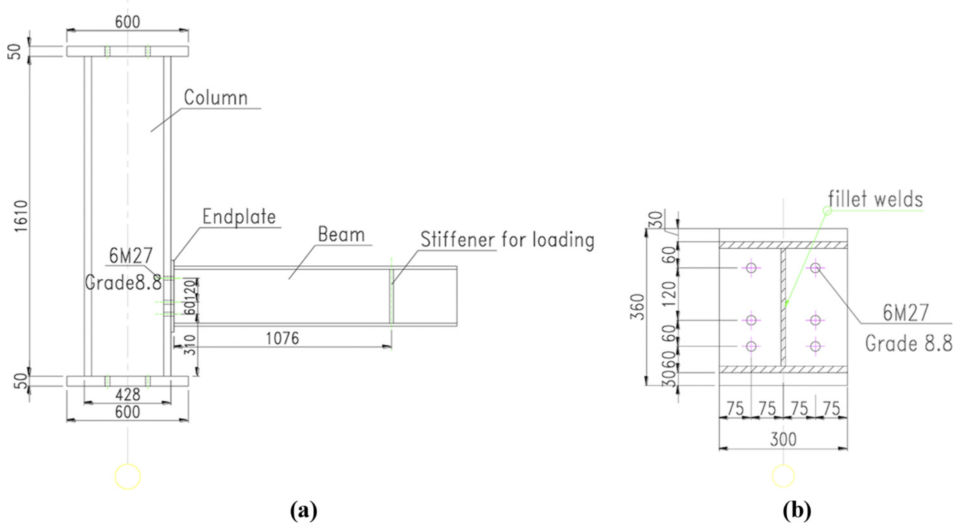


Figure 1.
Dimension of endplate connection specimen (unit: mm)

Notes: (a) Endplate connection; (b) Endplate connection specimens were designed to be located upside down to easily apply the tensile load from the outside of the furnace, as shown in Figure 2. The members below the furnace cover are in fire during fire tests, whereas those above the furnace cover are out of the fire field at an ambient temperature, see Figure 2.

2.3 Displacement measurement

In the fire tests, three vertical displacement sensors (DT1-DT3) were used to obtain the vertical displacement of the beam, as shown in Figure 2. According to the vertical displacements of the beam, the rotation of the beam can be calculated. To record the displacement of column, two vertical displacement sensors (DT5 and DT10) were arranged. According to the displacement of column, the rotation of the column can be calculated. To measure the displacement of endplate, one vertical displacement sensor (DT4) and four horizontal displacement sensors (DT6-DT9) were placed, as shown in Figure 2. According to the displacement of endplate, the rotation of endplate can be calculated. Based on the displacements of the aforementioned components, the rotation of endplate connection in tests can be obtained.

2.4 Test procedure

The full-scale fire tests on endplate connections were conducted under steady state fire condition. The specimens were first heated to a pre-selected elevated temperature (550°C) at a constant heating rate of 10°C/min, which corresponds to a natural fire to buildings. When the temperature of the concerned components reached the pre-selected elevated temperature, the mechanical load (moment for the connection) was applied to the specimen at this constant elevated temperature (550°C) until failure occurred. During loading, displacement control was used by controlling the displacement of piston of the hydraulic actuator at a constant rate 10 mm/min.

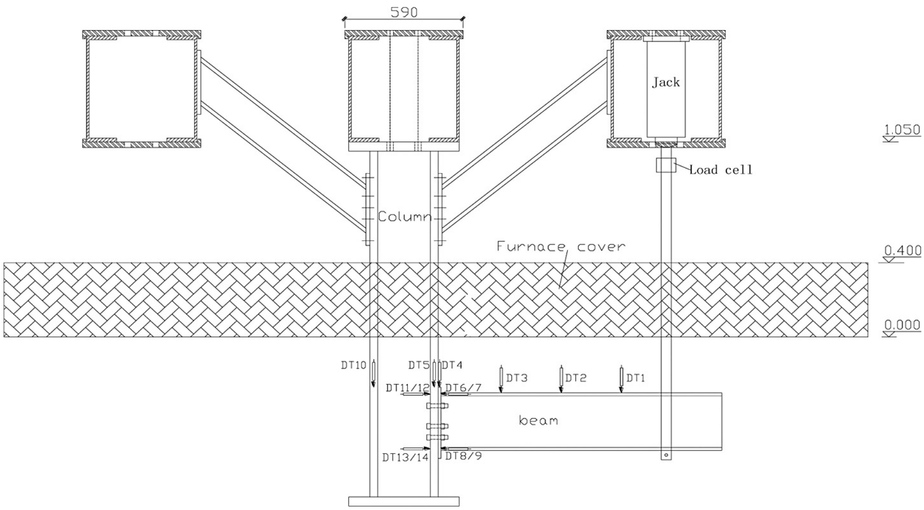


Figure 2.
Fire test set-up (unit: mm)

2.5 Test results

2.5.1 Deformation at the end of tests. An overall description on components of all connections at the end of the fire tests is provided in Table II.

2.5.2 Moment-rotation relationship of endplate connections. The characteristics of moment-rotation relationship for all endplate connections at an elevated temperature of 550°C obtained from tests are presented in Table III.

3. Numerical study

The finite element software package ABAQUS 6.8 was used to numerically simulate the behaviour of high-strength-steel endplate connections in fire and at an ambient temperature as well.

3.1 Finite element model

The geometric details of all connections' components modelled in finite element model (FEM) are the same as those of the test specimens. Because the geometric details, load, temperature distribution and boundary conditions of the beam-to-column endplate connection are symmetrical, half of the endplate connection was modelled to reduce computer costs. There were seven surface-to-surface contact interactions and seven tie interactions in this FEM, and the materials were endowed with non-linear properties. The whole connection was modelled using C3D8I elements.

3.2 Contact interaction and analysis process

The contact pairs in the endplate connection comprised the bolts-to-column flange, column flange-to-endplate, endplate-to-nuts and bolt shanks-to-bolt holes. The nuts

Table II. Description of components at the end of fire tests

Test ID	Endplate material	Endplate thickness (mm)	Endplate yielding	Fracture of bolts in top tensile row	Nuts in top tensile row stripped off	Weld failure in heat affected zone
1-1 E	Q235	20	Yes	Yes	No	No
1-2 E	S690	12	Yes	Yes	No	No
1-3 E	S960	10	Yes	Yes	No	No
2-1 E	Q235	25	Yes	Yes	No	No
2-2 E	Q345	20	Yes	Yes	No	No
2-3 E	S690	15	Yes	Yes	No	No
2-4 E	S960	12	Yes	Yes	No	No

Table III. Characteristics of connections at an elevated temperature of 550°C

Series	Connection ID	Endplate		Peak load		Connection rotation
		Material	Thickness (mm)	Moment (kN · m)	Force (kN)	ϕ_C (mrad)
	1-1 E	Q235	20	83.91	77.98	314
1	1-2 E	S690	12	105.92	98.44	304
	1-3 E	S960	10	100.05	92.98	313
	2-1 E	Q235	25	120.40	111.90	191
2	2-2 E	Q345	20	111.16	103.31	313
	2-3 E	S690	15	120.78	112.25	330
	2-4 E	S960	12	113.18	105.19	320

were tied to the corresponding bolt shanks. Surface-to-surface contact, with a small sliding option, was used for all contact surfaces to fully transfer the load. The penalty friction with friction coefficient 0.44 was used in the contact interaction property. To handle the contact interaction problem, the whole analysis process comprised five steps. In the first step, the bolts and endplate were restrained of all degrees of freedom temporarily, and then a very small pretension was applied to every bolt for temporarily restraining the bolt assembly. The temperature field for all components was 20°C. In the second step, the bolts and the endplate were freed from any temporary restraint. In the third step, the length of every bolt was fixed. In the fourth step, the temperature field for all components was modified to 550°C. (For the numerical analysis at an ambient temperature, the temperature field was kept constant.) In the fifth step, an equivalent vertical surface traction converted from the vertical load was applied to the beam flange at the stiffener for loading. The first three steps helped contact interactions to be established smoothly, which is effective to decrease calculation time and eliminate errors.

3.3 Material properties

In this study, the material properties of mild steels (including Q235 and Q345) at an ambient temperature were obtained according to tensile tests on the mild steel materials used in full-scale tests; their material properties at elevated temperatures were obtained according to the recommended reduction factors of structural steels in fire from Eurocode 3 part 1-2 (CEN, 2005b). The material properties of Grade 8.8 bolts at ambient and elevated temperatures used herein were those reported by the University of Sheffield (Hu, 2009; Theodorou, 2003). The material properties of HSS S690 and S960 at ambient and elevated temperatures input herein were obtained from material tests presented in reference (Qiang *et al.*, 2012; Qiang, 2013). The input mechanical properties of various materials in this FE modelling are true plastic strain and true stress. The actual strain and actual stress are calculated according to equations (3 and 4) based on the engineering strain and engineering stress obtained from the material tests [via equations (1 and 2)]:

$$\varepsilon_{eng} = \frac{\Delta l}{l_0} \tag{1}$$

$$\sigma_{eng} = \frac{F}{A_0} \tag{2}$$

$$\varepsilon_{true} = \int_{l_0}^{l} \frac{dl}{l} = \ln\left(\frac{l}{l_0}\right) = \ln(1 + \varepsilon_{eng}) \tag{3}$$

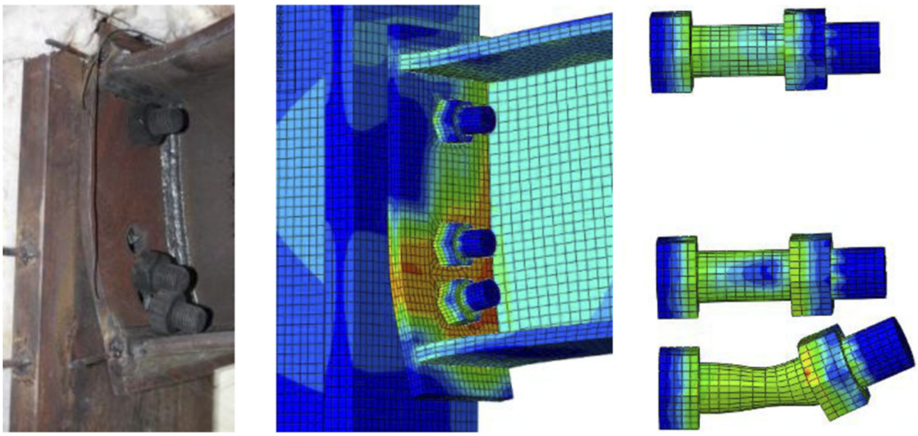
$$\sigma_{true} = \frac{F}{A} = \frac{F}{A_0 \frac{l_0}{l}} = \sigma_{eng}(1 + \varepsilon_{eng}) \tag{4}$$

4. Discussions

4.1 Validation of numerical modelling against experimental results

4.1.1 Deformation at the end of test. The comparisons on final deformation states of all beam-to-column endplate connections at the end of the tests between numerical simulations and experimental results were conducted at an elevated temperature of 550°C and at an ambient temperature. For instance, Figure 3 shows the comparisons on experimental final deformation state of connection 2-3E (S690 15 mm) after failure at an elevated temperature of 550°C with corresponding contour plots of Mises stress obtained from numerical modelling. It can be found that good agreements exist on the final deformation state of connection 2-3 E (S690 15 mm) at an elevated temperature of 550°C. Although the current numerical model cannot simulate the fracture of the bolts, it is able to reveal the location where the fracture initiates and evolves, as shown in Figure 3 (c). The current FEM stops when the first failure of components occurs, i.e. the bolts in the top tensile row for this connection under fire condition. In the experimental study, after the failure of the bolts in the top tensile row, the bolts in the second tensile row experienced significant bending deformation until failure occurred. But the present numerical model is not able to simulate the failure of bolts in the second tensile row and the corresponding deformations of other components after the failure of bolts in the top tensile row. Similar conclusions can be drawn for all seven connection specimens at an elevated temperature of 550°C and at an ambient temperature.

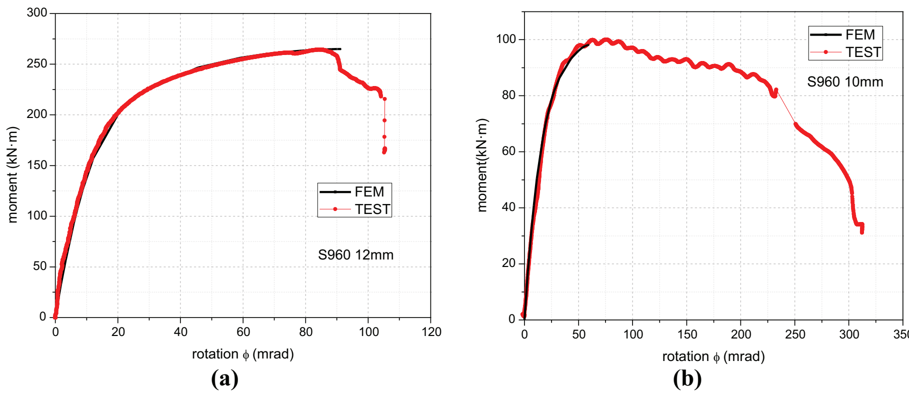
4.1.2 Moment-rotation characteristic. The comparisons of numerical modelling and experimental study on the moment-rotation relationship of various endplate connections (both high strength steel endplate connections and mild steel endplate connections) at an elevated temperature of 550°C and at an ambient temperature were carried out, where good agreements exist in general on initial stiffness, load-bearing capacity and the connection rotation at the maximum load level $\phi_{M\,\max}$. For example, Figure 4 illustrates the moment-rotation comparison of two connections 2-4 A and 1-3 E.



(a) (b) (c)

Notes: (a) Connection in test; (b) connection in FEM; (c) bolts in FEM

Figure 3.
Comparison on final deformation state of connection 2-3 E (S690 15 mm) at an elevated temperature of 550°C



Notes: (a) 2-4A(S96012mm) at ambient temperature; (b) 1-3A(S96012mm) at elevated temperature 550˚C

Figure 4. Moment-rotation comparison of endplate connections

4.2 Verification of Eurocode 3

4.2.1 Failure modes. According to Eurocode 3 Part:1-8 (CEN, 2005), there are three failure modes for endplate connections. Mode 1 is complete yielding of endplate or column flange, Mode 2 is bolt failure with yielding of endplate or column flange, whereas Mode 3 is bolt failure. Mode 3 is considered to be brittle and should be avoided in practical design. The failure modes of all endplate connections obtained via theoretical analysis based on the rules of Eurocode 3 Part: 1-8 (CEN, 2005) were validated against those from tests, as shown in Table IV. It can be observed that the predictions of Eurocode 3 agree very well with the test results.

4.2.2 Plastic flexural resistance. The plastic flexural resistances of all endplate connections at an elevated temperature of 550°C were compared with the theoretical predictions of Eurocode 3 (CEN, 2005), as listed in Table V. It can be seen that reasonable agreements exist between the theoretical predictions and the experimental results. By comparing Ratio_3, it can be found that $M_{j,Rd,test,1}$ obtained based on Zanon and Zandonini's definition (Zanon and Zandonini, 1988) is generally smaller than $M_{j,Rd,test,2}$, which is defined according to Weynand's proposal (Weynand, 1997) and the simplified method recommended by Eurocode 3 (CEN, 2005). By comparing $M_{j,Rd,test,1}$ with the predicted plastic flexural resistance by Eurocode 3, see

Connection ID	Material	Endplate Thickness (mm)	Failure mode EC3	Test
1-1 E	Q235	20	Mode 2	Mode 2
1-2 E	S690	12	Mode 2	Mode 2
1-3 E	S960	10	Mode 2	Mode 2
2-1 E	Q235	25	Mode 2	Mode 2
2-2 E	Q345	20	Mode 2	Mode 2
2-3 E	S690	15	Mode 2	Mode 2
2-4 E	S960	12	Mode 2	Mode 2

Table IV. Failure modes of connections at an elevated temperature of 550°C

Table V. Evaluation of plastic flexural resistance of connections at an elevated temperature of 550°C

Test ID	Connections (mm)	$M_{j,Rd,EC3}$ (kN · m)	$M_{j,Rd,test,1}$ (kN · m)	$M_{j,Rd,test,2}$ (kN · m)	$\text{Ratio}_1 = M_{j,Rd,EC3} / M_{j,Rd,test,1}$	$\text{Ratio}_2 = M_{j,Rd,EC3} / M_{j,Rd,test,2}$	$\text{Ratio}_3 = M_{j,Rd,test,1} / M_{j,Rd,test,2}$
1-1 E	Q235 20	76.77	68.13	72.94	1.127	1.053	0.934
1-2 E	S690 12	89.90	89.99	105.38	0.999	0.853	0.854
1-3 E	S960 10	95.26	84.68	93.74	1.125	1.016	0.903
2-1 E	Q235 25	109.29	106.50	108.79	1.026	1.005	0.979
2-2 E	Q345 20	107.37	104.68	105.86	1.026	1.014	0.989
2-3 E	S690 15	105.94	101.25	120.02	1.046	0.883	0.844
2-4 E	S960 12	105.41	104.83	111.90	1.006	0.942	0.937

Notes: $M_{j,Rd,EC3}$ is the predicted plastic flexural resistance according to Eurocode 3 (1); $M_{j,Rd,test,1}$ is the test obtained plastic flexural resistance according to Zanon and Zandonini's method (10); $M_{j,Rd,test,2}$ is the test obtained plastic flexural resistance according to Weynand's evaluation method (11)

Ratio$_1$, it can be seen that the predictions of Eurocode 3 are generally non-conservative when the test result is obtained based on Zanon and Zandonini's definition. However, the comparison of $M_{j,Rd,test,2}$ with the predicted plastic flexural resistance by Eurocode 3 shows that the predictions of Eurocode 3 are generally on the conservative side when the definition of the test result is based on Weynand's proposal and the simplified method recommended by Eurocode 3.

5. Conclusions

The following conclusions can be drawn from this experimental and numerical study:

- The load-bearing capacity and rotation capacity of endplate connections are dependent on the combination of endplate material and endplate thickness.
- The accuracy of Eurocode 3 for plastic flexural resistance of endplate connections both at an ambient temperature and in fire is acceptable, regardless of whether the endplate is made of mild steels or high-strength structural steels.
- The plastic flexural resistance of connections based on the definition of Zanon and Zandonini is generally smaller than that according to Weynand's proposal and the simplified method recommend by Eurocode 3. This conclusion is valid for all endplate connections in this study (both mild steel endplate connections and high strength steel endplate connections).
- In endplate connections, a proper design using a relatively thin high strength steel endplate can achieve the same failure mode, similar load-bearing capacity and comparable or even higher rotation capacity, both at an ambient temperature and in fire condition, in comparison to a connection with relatively thick mild-steel endplate.
- The challenge of numerical modelling contact interactions considering material and geometric non-linear effects has been solved successfully.
- This finite element analysis gives reasonable accuracy compared with the experimental results, providing an efficient, economical and accurate tool to study the fire performance of high-strength steel endplate connections.
- This study opens a perspective of using high-strength steels to take place of mild steels in structural optimizing design.

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