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A numerical study on the structural performance of a ductile connection under fire conditions

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Abstract

The component-based model of a novel ductile connection has been incorporated into the software *Vulcan* in order to facilitate global frame analysis within a performance-based structural fire engineering design process. This paper reports on the validation and verification of the model, as well as the applications of the model in order to investigate the effects of the ductile connections on the structural responses of long-span frames at high temperature. Firstly, three single-beam models with the novel connections at both ends, connected to rigid supports, are used to verify that the component-based connection model has been correctly incorporated into Vulcan, via comparisons against detailed finite element modelling with *Abaqus*. The structural performance in fire of long-span frames with the novel ductile connections has been compared with the performance of the same frames with idealized rigid, idealized pinned and conventional end-plate connections, initially using a limited sub-frame model. Results show that, compared with the above mentioned three connection types, the ductile connection provides much higher axial and rotational ductilities to accommodate the deformations generated by the connected beams as their temperatures rise. As part of this process, these connections are instrumental in greatly reducing the axial forces to which the surrounding structure is subjected. Finally, parametric studies varying several key parameters have been carried out, in order to optimize the design of the ductile connection to enhance its performance subject to catenary action at very high temperature to prevent potential connection fracture and progressive collapse.

Keywords

Component-Based Model, Ductility, Parametric Study, Steel Connection

1 Introduction

Connections are potentially the weakest part of a structure in a fire event. Connection failures could lead to the detachment of connected beams, collapse of floor, spread of fire into adjacent compartments, buckling of column, and eventually the progressive collapse of the entire structure. Due to the complex combination of internal forces experienced by connections in fire, the structural behaviour of connections is quite different from that at ambient temperature. At the initial stage of heating, the connections experience compressive forces due to the restraint to the thermal expansion of the connected beams. This compressive force eventually turns into tension, induced by the catenary action of the connected beam at very high temperatures. During cooling, the thermal contraction of the beam superposes the tensile force in the connections. Such complicated load conditions are very difficult to reproduce in experiments, except for full-scale testing, which are extremely costly. Numerical simulation is an efficient alternative to investigate the performance of connections in fire.

In general, there are three different numerical approaches to model connections, so called curve-fit model, finite element simulation and the component-based model, as summarised by Block [1]. The curve-fit method uses mathematical expressions to describe the moment-rotation characteristics of connections based on experimental data, which was first used by El-Rimawi [2] to represent the behaviour of connections in fire using the Ramberg-Osgood expression. This method can be easily implemented into frame analysis as rotational spring elements at beam ends. However, its limitations are quite obvious: curve-fit models can only be applied to connections which have been previously investigated experimentally, and the influence of axial forces on the behaviour of connections in fire cannot be included into the models. The finite element method, in which connections can be modelled using solid or shell elements, have been widely used by researchers around the world. This method can explicitly consider many aspects in detail, such as applied external loads, boundary conditions, change of temperature, and contacts between different parts. This method was first adopted by Liu [3, 4] to model connections using his finite element program FEAST, in which shell elements were used to represent beam flanges and beam webs, and beam elements were used to represent bolts. Compared with the curve-fit method, the finite element method is a more reliable technique, which enables to simulate the connection behaviour in a very detailed and complex manner.

This method also enables to investigate a variety of connections of different types and dimensions under different load and heating conditions. However, due to the huge computational costs, the finite element method is not suitable for practical engineering design, especially when global frame analysis is required. The concept of the component-based method, in which a connection is divided into several components with known stiffnesses and strengths, was first proposed in 1980s [5], and then adopted in the design guidance [6]. Jaspart [7] summarized three principal steps of the component-based method, which are (i) the identification of active components (such as endplate in bending, column web in compression, column flange in bending, bolts in tension); (ii) the characterisation of the active components, and (iii) the assembly of the active components into a connection model. This method enables the considerations of geometric and material nonlinearities, influence of axial forces, reduction of material properties with the increase of temperature. It delivers an optimum balance between accuracy and computational efficiency, compared with the other two methods, and therefore becomes more and more popular in recent years.

The existing commonly-used connection types lack the ductility to accommodate the axial deformation of connected beams in fire, which could trigger the brittle facture failure of connections. In order to improve the ductility of connections and enhance the robustness of structures in fire, a novel ductile connection has been proposed by the authors [8, 9]. Two component-based models of the novel connection have been developed and compared [10]. In this paper, the component-based model of the novel connection has been incorporated into the finite element software Vulcan. Three single beam models, in which the novel connections are applied to beams of different spans, have been used to verify that the component-based model has been correctly incorporated into Vulcan, by comparing the results with those from detailed finite element modelling using Abaqus. The structural performance in fire of long-span frames with the novel connections has been compared with those with idealized rigid, idealized pinned and conventional end-plate connections, using a limited sub-frame model. Finally, parametric studies varying several key dimensions of the novel connection have been carried out, in order to optimize its performance under the tensile axial forces generated by the eventual catenary action of heated, unprotected beams at high temperatures.

2 Design and component-based model of the novel connection

2.1 Design of the novel connection

The novel ductile connection proposed by the authors [8, 9] consists of two identical parts which can be manufactured by deforming a steel plate, and each part includes a fin-plate bolted to the beam web, a web-cleat bolted to the column flange, and a semi-cylindrical section between the fin-plate and web-cleat, as shown in Figure 1. The semi-cylindrical section is the key component in providing additional ductility by allowing the fin-plate to move towards and away from the web-cleat. Therefore, the radius of the semi-cylindrical section should be determined according to the axial ductility demands of the connected beam, which can be evaluated as detailed in [8, 9]. The fin-plate and web-cleat of the novel connection can be designed according to EC3 [6].

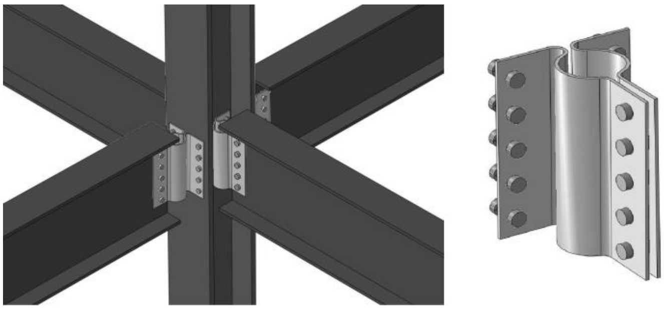
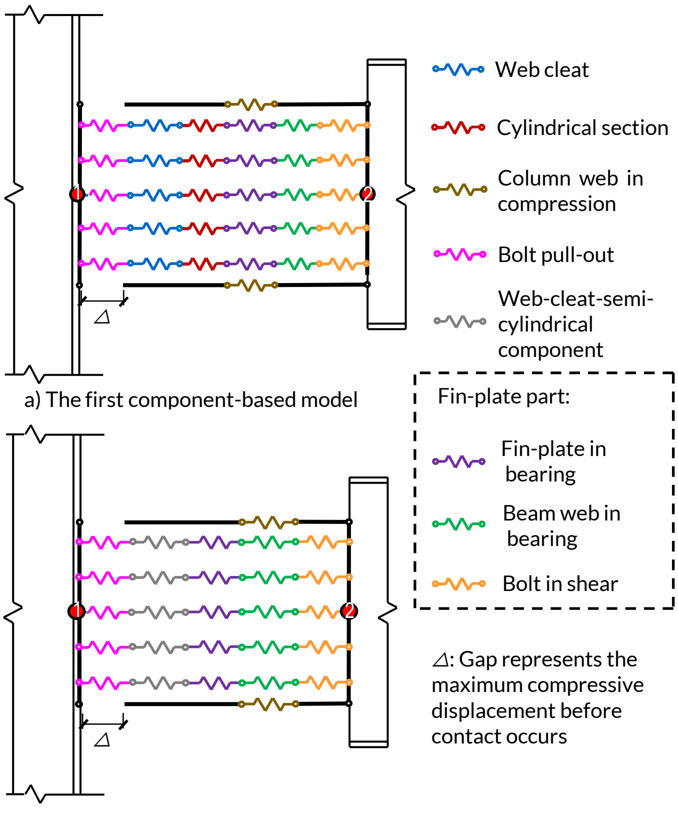


Figure 1 The proposed novel connection

2.2 Component-based model of the novel connection

The two component-based models of the novel connection proposed by the authors [10] are shown in Figure 2. Basic components of the first scheme of the component-based model include web-cleat, cylindrical section, bolt pull-out, column web in compression, fin-plate in bearing, beam web in bearing and bolt in shear, whereas the web-cleat and cylindrical section are replaced by the web-cleat-semi-cylindrical component (WCSC) for the second scheme of component-based model. The gap between the column web in compression and the rigid bar is designed to represent the maximum axial compressive displacement before contact occurs.



a) The first component-based model

b) The second component-based model

Figure 2 Two component-based models

The analytical models of the cylindrical section and web-cleat component based on simple plastic theory have been developed by the authors in [8] and [10], respectively. The curve-fit equations proposed by Sarraj [11], based on their finite element parametric studies, are used here to generate the force-displacement curves of the fin-plate in bearing, beam web in bearing and bolt in shear. The simplified 'plastic cone' model developed by Dong [12] is used to calculate the limitation strength for the bolt pull-out component. As for

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the column web in compression, the force-displacement curves derived by Block [1] are adopted. The purpose of the so-called web-cleat-semi-cylindrical component (WCSC) is to combine the two components into a single component by considering the interaction between the semi-cylindrical section and the web-cleat during the actual deformation process. The analytical models of the WCSC component for different cases have already been developed by the authors [10]. By comparing the two component-based models [10], it was concluded that the second scheme is in better accordance with experimental results and Abaqus simulations. Therefore, the second component-based model is selected here to be incorporated into Vulcan.

3 Incorporation of the component-based model into Vulcan

The component-based model of the novel connection has been incorporated into Vulcan following the principles of the finite element method. The tangent stiffness matrix derived by Block [1], as represented by Equations (1) and (2), is used here to convert the component-based model into a connection element. The out-of-plane and torsional degrees of freedom are assumed to be fully restrained, considering their little importance in steel structures. In order to check if the component-based model has been correctly incorporated into Vulcan, three single beams with the ductile connections at their ends have been modelled in Vulcan. A UDL of 42.64 kN/m is applied on the beam and the load ratio of 0.4 is adopted for the three models. It is assumed that the temperature of the connection is half of that of the connected beam. The beam span, beam section size and connection dimensions are listed in Table 1.

$$k=\begin{pmatrix}
K_{11} & 0 & 0 & 0 & K_{15} & 0 & -K_{11} & 0 & 0 & 0 & -K_{15} & 0\\
0 & \infty & 0 & 0 & 0 & 0 & 0 & -\infty & 0 & 0 & 0 & 0\\
0 & 0 & K_{33} & 0 & 0 & 0 & 0 & 0 & -K_{33} & 0 & 0 & 0\\
0 & 0 & 0 & \infty & 0 & 0 & 0 & 0 & 0 & -\infty & 0 & 0\\
K_{51} & 0 & 0 & 0 & K_{55} & 0 & -K_{51} & 0 & 0 & 0 & -K_{55} & 0\\
0 & 0 & 0 & 0 & 0 & \infty & 0 & 0 & 0 & 0 & 0 & -\infty\\
-K_{11} & 0 & 0 & 0 & -K_{15} & 0 & K_{11} & 0 & 0 & 0 & K_{15} & 0\\
0 & -\infty & 0 & 0 & 0 & 0 & 0 & \infty & 0 & 0 & 0 & 0\\
0 & 0 & -K_{33} & 0 & 0 & 0 & 0 & 0 & K_{33} & 0 & 0 & 0\\
0 & 0 & 0 & -\infty & 0 & 0 & 0 & 0 & 0 & \infty & 0 & 0\\
-K_{51} & 0 & 0 & 0 & -K_{55} & 0 & K_{51} & 0 & 0 & 0 & K_{55} & 0\\
0 & 0 & 0 & 0 & 0 & -\infty & 0 & 0 & 0 & 0 & 0 & \infty
\end{pmatrix} \tag{1}$$

In which

$$K_{11}=\sum_{i=1}^{n}k_{T,i}+\sum_{i=1}^{2}k_{C,i}\ ,\ K_{15}=K_{51}=\sum_{i=1}^{n}k_{T,i}\cdot l_{T,i}+\sum_{i=1}^{2}k_{C,i}\cdot l_{C,i}\ ,\ K_{33}=k_s\ ,$$

$$K_{55}=\sum_{i=1}^{n}k_{T,i}\cdot l_{T,i}^2+\sum_{i=1}^{2}k_{C,i}\cdot l_{C,i}^2 \tag{2}$$

In which the subscripts T, C and S represent the components working in tension, compression and shear, respectively. n is the number of bolt rows.

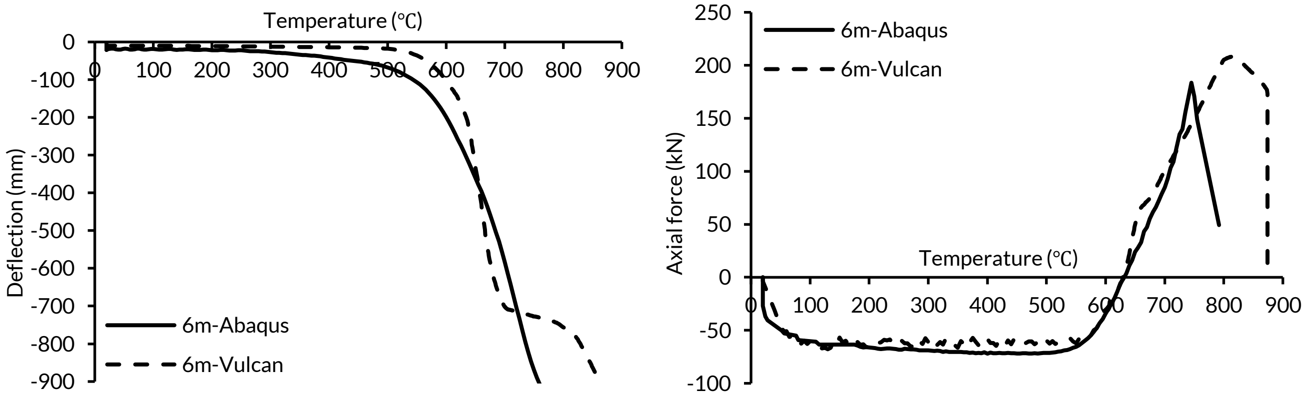
Figures 3-5 show that the Vulcan and Abaqus results are in good agreement, which indicates that the component-based model has been correctly incorporated into Vulcan. The temperature-force curves and temperature-displacement curves of each spring row in the 7.5 m beam model are shown in Figure 6. As shown in this figure, at the beginning of the heating, the displacements of all spring rows are compressive due to the thermal expansion of the beam. As temperature increases, these compressive displacements increase until about 300 °CThen, as the beam gradually enters the catenary action phase, the compressive displacement of each spring row gradually decreases and finally becomes tensile displacement. Compare to other spring rows, Spring row 1 has experienced the largest tensile displacement and is the first to fail (i.e. due to bolt pull-out). Soon after, the other spring rows will fail row by row in the same manner. When all spring rows fail, the connection is considered as failed in the model.

4 Comparison of the novel connection with conventional connection types

In this section, simple one-bay two-storey sub-frame models (shown as Figure 7) with different types of connections are modelled using Vulcan to compare the performance of the ductile connection with that of commonly-used connection types. It is assumed that only the first floor is subject to fire, and the temperatures of first floor columns and connections are half of that of the beams. Four different connection types are adopted, including the ductile connection, as well as end-plate, idealized rigid and idealized pinned connections. The end-plate connection element has already been incorporated into Vulcan by Block [1] and can be directly used here.

Table 1 Dimensions of the beams and connections

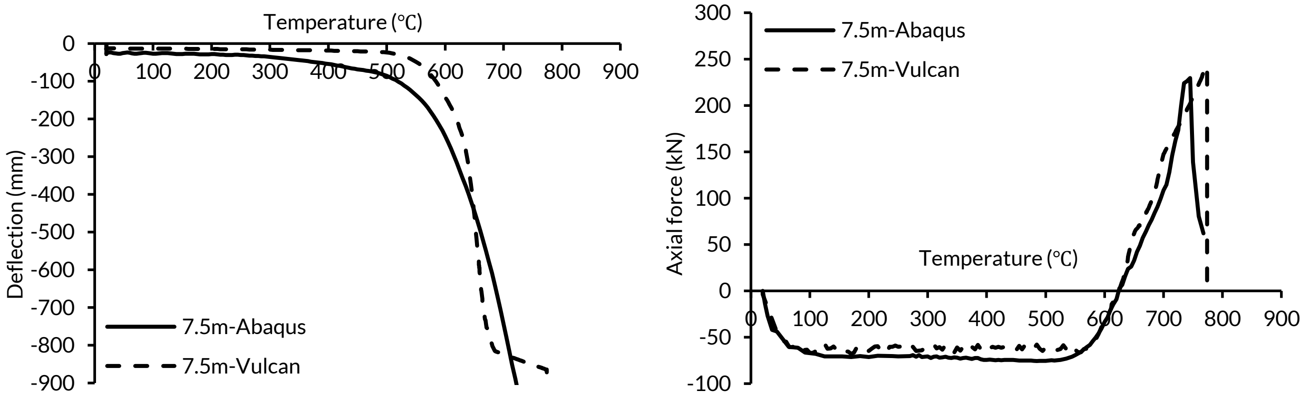
Beam span	Beam section	Inner radius of semi-cylindrical section (mm)	Plate thickness (mm)	Fin-plate width (mm)×depth (mm)	End-plate width (mm)×depth (mm)	Number of bolt rows
6 m	UKB 457×152×82	50	6	100×360	100×360	5
7.5 m	UKB 533×210×109	50	6	100×360	100×360	5
9 m	UKB 533×312×151	50	6	100×360	100×360	5



a) Mid-span deflection

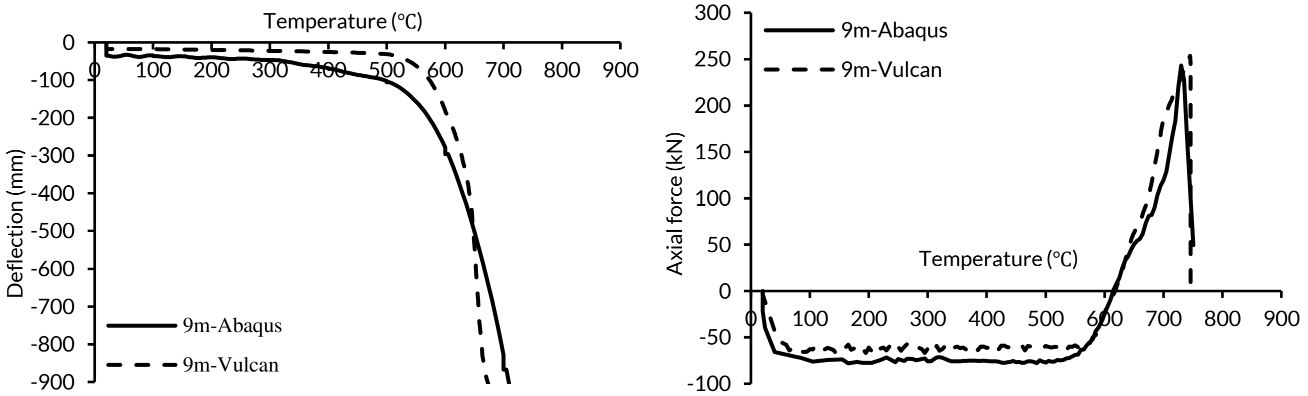
b) Axial force

Figure 3 Comparison results of Model 1 with beam length of 6 m



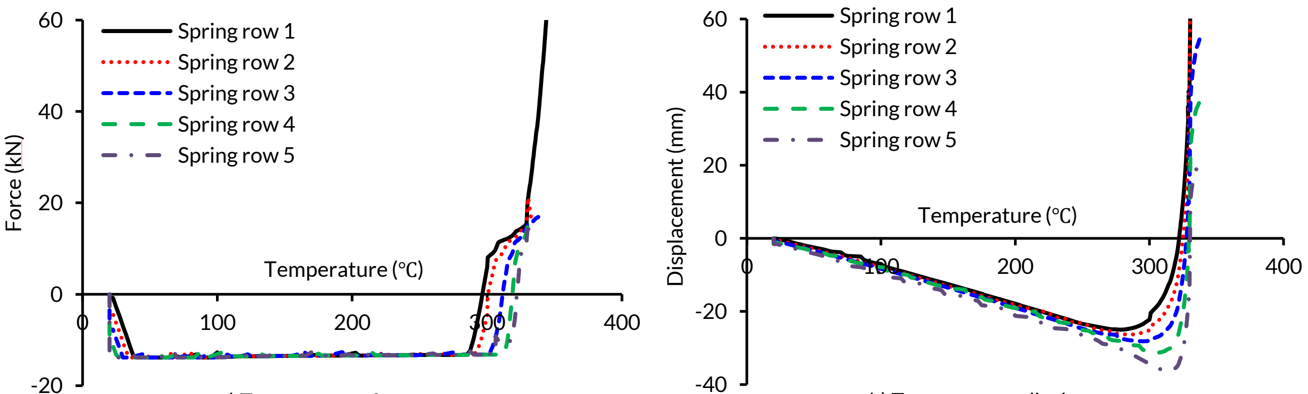
a) Mid-span deflection b) Axial force

Figure 4 Comparison results of Model 2 with beam length of 7.5 m



a) Mid-span deflection b) Axial force

Figure 5 Comparison results of Model 3 with beam length of 9 m



a) Temperature-force curves b) Temperature-displacement curves

Figure 6 Temperature-force and temperature-displacement curves of each spring row in the model with beam span of 7.5m

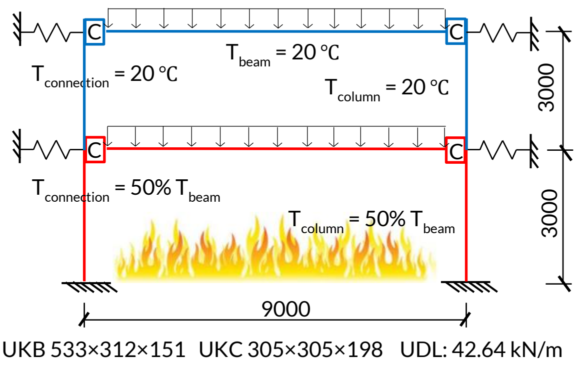
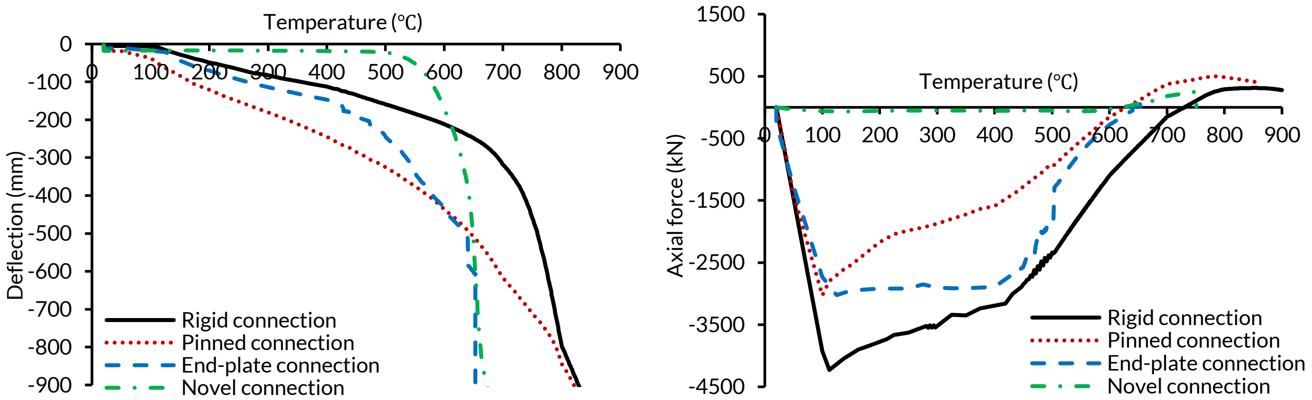


Figure 7 The one-bay two-storey sub-frame model

As shown in Figure 8 a), the mid-span deflection of the heated beam with the ductile connections is smaller than those of the beams with other connection types until about 600 ℃. After that, the deflection of the beam with novel connections increases rapidly, and gradually exceeds those of other beams. The axial force generated in the heated beam with novel connections is significantly reduced compared to those of beams with other connection types, as shown in Figure 8 b). This phenomenon indicates that the novel connection can provide much higher ductility, needed to accommodate the axial deformations generated by the connected beam throughout a fire. Besides, the novel connections are also instrumental in reducing the axial forces to which the surround structural elements are subjected. The failure (due to catenary tension) temperature of the novel connection is much higher than that of the end-plate connection. The parametric studies presented in the next section aims to optimising the design of the ductile connection to raise further their failure temperature.



a) Mid-span deflection

b) Axial force

Figure 8 Comparison between the novel connection and other connection types

5 Parametric studies

In order to further improve the performance of the novel connection at the final catenary tension phase, parametric studies on several key parameters, i.e. the inner radius of the semi-cylindrical section, plate thickness, connection temperature and connection material, have been carried out to optimize the design of the ductile connection. The ductile connection detailed in Section 4 is selected as the control case (inner radius of cylindrical section = 50mm, plate thickness = 6mm, T_C = 50%T_B, connection material: S275 mild steel). The sub-frame model, as shown in Figure 7, is used to conduct the parametric studies.

As mentioned previously, the semi-cylindrical section is the key component of the connection to provide the required additional ductility. Therefore, two different inner radii, 60mm and 70mm, are adopted to examine the effects of the radius on the connection performance. Figure 9 and Table 2 indicate that the inner radius makes a negligible influence on the failure temperature. This is because that the failure mode of each spring row is bolt pull-out, which occurs when the bolt row force reaches the bolt pull-out limit force. To raise the bolt pull-out limit force, it might be useful to increase the plate thickness, reduce the connection temperature, and/or use a higher grade of steel. As shown in Figure 10 and Table 2, the increase of plate thickness can effectively increase the ultimate failure temperature. For instance, the failure temperature of the connection of 10mm thickness is 17.2% higher than that of the control case (plate thickness = 6mm). However, the increase in plate thickness can also reduce the ductility of connection, resulting in the increase of the axial force generated in the connected beam. Therefore, the plate thickness cannot be increased excessively, otherwise the ductility of connection will decrease, which is contrary to the design intention of the novel connection. It is generally assumed that the connection temperature is half of the beam temperature in the single beam models in Section 3 and in the sub-frame models in Section 4. In reality, connections tend to experience much lower temperature than the surrounding structural elements due to their smaller exposed surface areas and fire protection measures. Based on the results shown in Figure 11 and Table 2, it can be concluded that reducing the connection temperature does have some effect on increasing the ultimate failure temperature. The last parameter studied is the steel grade. In general, the steel grade of the connections is the same as for the beams. However, Figure 12 and Table 2 indicate that the use of a higher grade of steel for connections is effective in raising the failure temperature.

In general, the parametric studies presented in this section reveals several feasible and useful ways to optimize the design of the ductile connection, incl. increasing plate thickness, reducing connection temperature and increasing steel grade.

Table 2 Beam failure temperatures with different connection parameters

Different parameters	Failure temperature of beam	Difference from the control case
Control case	751 ℃	0.0%
Inner radius: 60mm	752 ℃	0.1%
Inner radius: 70mm	754 ℃	0.4%
Plate thickness: 10mm	880 ℃	17.2%
Plate thickness: 14mm	897 ℃	19.4%
T_C = 30%T_B	780 ℃	3.9%
T_C = 20℃	787 ℃	4.8%
S355	772 ℃	2.8%
S420	800 ℃	6.5%

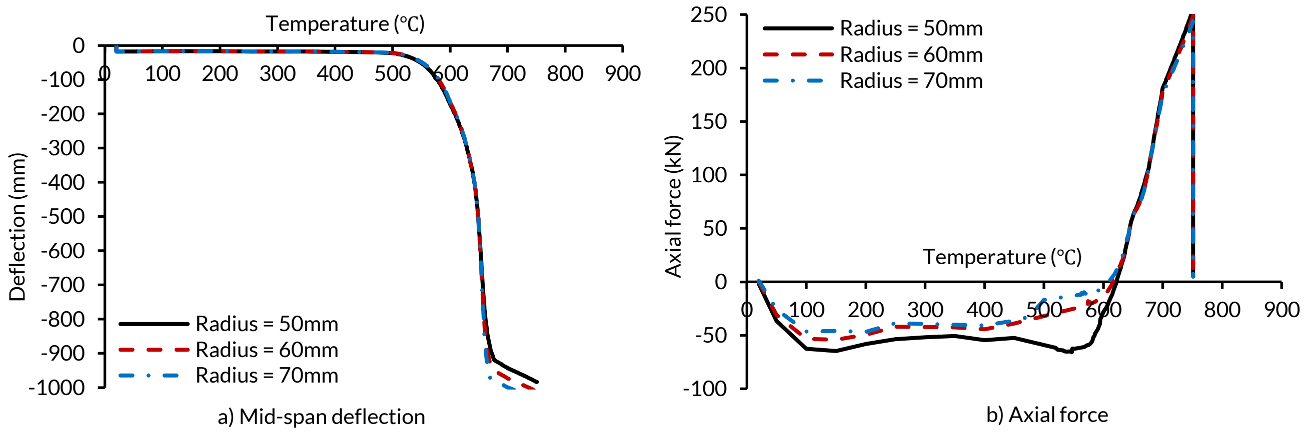
6 Conclusion

Connections are vital to the survival of structures in fire. In order to improve the ductility of connections and the robustness of structures, a novel ductile connection has been proposed by the authors. This paper summarised the design of the novel connection and the component-based models developed to model this new connection type.

The component-based connection model was converted into a connection element, and incorporated into the high-temperature frame analysis programme Vulcan. The integration of this new connection element into Vulcan is validated against detailed FEA modelling.

The performance of the novel connection was compared with that of conventional connection types, based on a sub-frame model. Results show that the axial force generated in the beam with novel connections is significantly reduced compared with the cases with other connection types. This confirms that the novel connection can provide satisfactory additional ductility to accommodate the deformations of connected beams in fire.

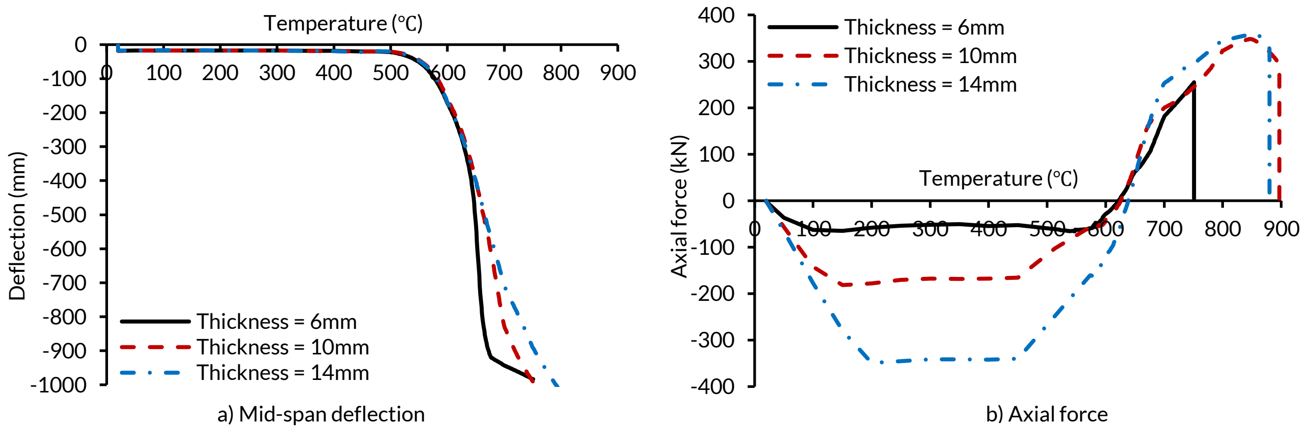
Finally, parametric studies were carried out to optimize the design of the novel connection. Increasing the plate thickness, reducing the connection temperature and increasing the steel grade are found effective in raising the ultimate failure temperature.



a) Mid-span deflection

b) Axial force

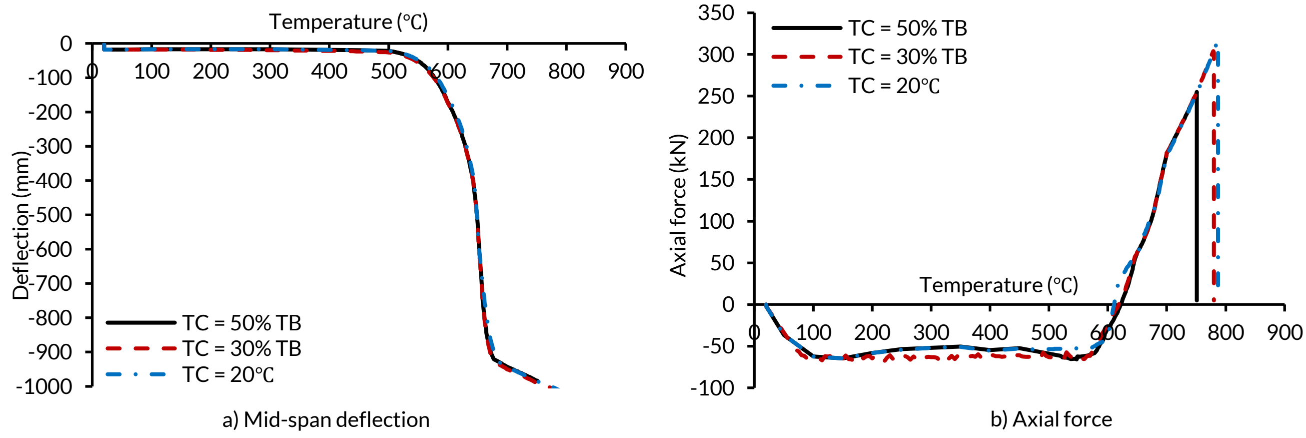
Figure 9 Different inner radius of semi-cylindrical section



a) Mid-span deflection

b) Axial force

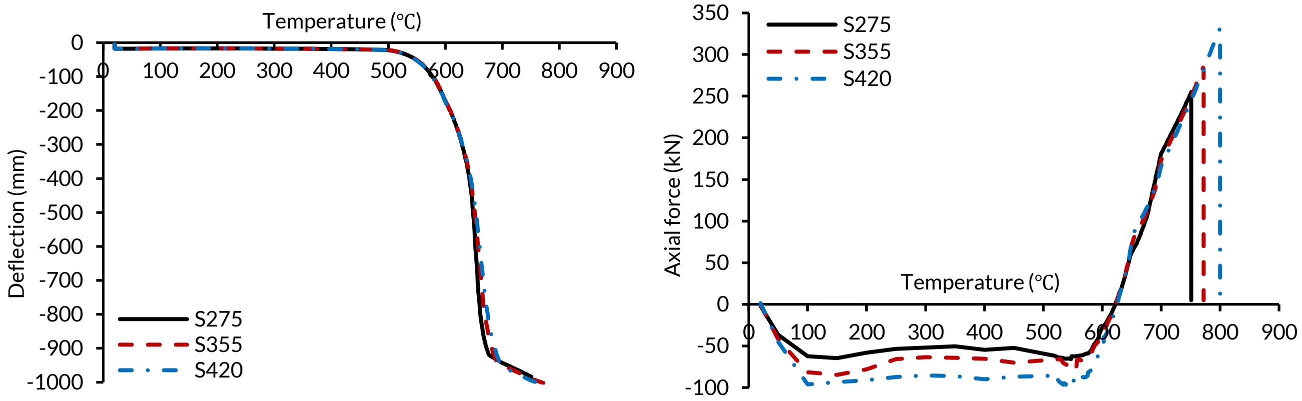
Figure 10 Different plate thickness



a) Mid-span deflection

b) Axial force

Figure 11 Different temperature assumptions



a) Mid-span deflection

b) Axial force

Figure 12 Different connection materials

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