SiF 2020– The 11th International Conference on Structures in Fire
The University of Queensland, Brisbane, Australia, June 24-26, 2020

INVESTIGATION OF THE PERFORMANCE OF A NOVEL DUCTILE CONNECTION WITHIN BARE-STEEL AND COMPOSITE FRAMES IN FIRE

Yu Liu[1], Shan-Shan Huang[2], Ian Burgess[3]

ABSTRACT

In order to improve the performance of connections and enhance the robustness of structures in fire, a novel, axially ductile connection has been proposed. The component-based models of bare-steel ductile connection and composite ductile connection have been proposed, and incorporated into the software Vulcan to facilitate global frame analysis. These component-based models are validated against detailed Abaqus FE models. A series of 2-D bare-steel frame models and composite frame models with ductile connections, rigid connections, and pinned connections, have been created using Vulcan to compare the fire performance of ductile connection with other connection types in bare-steel and composite structures.

Keywords: Fire; component-based model; ductility; steel connection; composite connection

1 INTRODUCTION

The Cardington full-scale fire tests [1] in 1995-96 indicated that standard connections were potentially the weakest parts of a steel-framed or composite structure. Connection failures subsequently occurred in the collapse of the World Trade Centre buildings [2] in 2001. Failure of connections in a fire accident may lead to the detachment of connected beams, causing collapse of floor panel and the spread of fire into adjacent compartments, buckling of columns, and even the progressive collapse of the entire building. Connections play a crucial role in maintaining structural integrity, by tying structural members together. However, current commonly-used connection types lack the push-pull ductility required to accommodate either the compressive effects due to the constraint of thermal expansion of connected beams in the early stages of a fire, or the tensile effects caused by the catenary action of the connected beams when most of the steel strength has been lost at high temperatures. In order to improve the performance of connections and enhance the robustness of structures in fire, a novel ductile connection has been proposed by the authors [2-6]. Additional axial ductility is provided to a connection which is essentially a web-cleat by the inclusion of a semi-cylindrical zone in the connection leg which is attached to the beam web.

Traditional research on connection behaviour is largely limited to moment-rotation characteristics, which has been shown to be almost irrelevant to full structures in fire conditions. Connections undergo different combinations of loading at different stages of a fire. Numerical modelling is a most accessible way of reproducing these complex loading combinations, because experiments need to cover a large range of combinations of axial force and rotations over a range of temperatures, and are expensive to conduct. However, due to the time-consuming nature of model building and computational runtimes, detailed finite element approaches using solid elements are not suitable to be used, particularly where global frame

---

[1] Mr. Yu Liu, University of Sheffield
e-mail: yliu230@sheffield.ac.uk, ORCID: https://orcid.org/0000-0001-7468-1089
[2] Dr. Shan-Shan Huang, University of Sheffield
e-mail: s.huang@sheffield.ac.uk, ORCID: https://orcid.org/0000-0003-2816-7104
[3] Prof. Ian Burgess, University of Sheffield
e-mail: ian.burgess@sheffield.ac.uk, ORCID: https://orcid.org/0000-0001-9348-2915

analysis needs to be conducted. An alternative, and more economical, strategy for conducting large structural frame analyses in fire conditions is the use of a high-temperature component-based method to simulate the connection behaviour within a structural finite element program. Component-based modelling strategies, and component models of traditional steelwork connections, have been proposed as a result of studies [7-16] over many years by researchers at the University of Sheffield. Leston-Jones [7] developed a component-based model, including components representing the column flange in bending, bolts in tension, endplate in bending and column web in compression to simulate the high-temperature rotational behaviour of flush end-plate connection. Block [9] used an analytical model of a T-stub developed by Spyrou [8] to represent the tension bolt rows, and a simplified analytical model of the column web in compression to represent the compression zone of the connection in his component-based model for end-plate connections. Sarraj [10, 11] conducted a series of finite element simulations, and proposed equations to describe the bearing and shearing behaviour of fin-plate connections. Yu [12] proposed and validated a yield-line based model for end-plate connections. Yu [13] also developed a component-based model for web-cleat connections including a mechanical model based on simple plastic theory to predict the behaviour of web cleats subjected to tying forces. Continuing Block and Yu's work, Dong [14] further developed a used-defined connection model, a flush end-plate connection model and a reverse-channel connection model, all for elevated temperatures. In addition, Hu [15] developed a flexible end-plate connection model, and Taib [16] developed a model for fin-plate connections based on the equations previously proposed by Sarraj [10]. The component-based model of the novel ductile connection has been developed by the authors [4-6] in the context of steel-framed buildings, as the most recent stage of this progression. It has been incorporated into the software Vulcan, which is used to carry out 3D modelling and robustness assessment of structures in fire.

The structural behaviour of composite connections is quite different from that of bare-steel connections, due to the continuity of the composite slab and its reinforcing mesh across the connection. At elevated temperatures, the composite slab acts as insulation to the reinforcement, reducing its temperature to very low levels compared with the steel-to-steel part, and thus enhancing its performance. Apart from this, the composite slab restrains the thermal expansion of steel beam in the initial stage of the fire, leading to thermal bowing, which also affects the deformation of connection. Up to now, only limited researches can be found on the structural performance of composite connections in fire. Leston-Jones [7, 17] carried out tests on composite flush end-plate connections to obtain their moment-rotation characteristics. Continuing his work on rotational behaviour, AI-Jabri [18] conducted high-temperature tests on composite flexible end-plate connections and developed component-based models of these connections. Li et al. carried out tests [19] to investigate the fire-resistance of flush end-plate composite joints, and developed a simplified component-based model [20] to calculate the initial stiffness and ultimate moment capacity of flush end-plate composite joints at elevated temperatures.

In this paper, the design of the novel ductile connection, and the component-based models of bare-steel and composite ductile connection are introduced. Sub-frame models of 2-D bare-steel and composite versions of the new ductile connection have been used to verify whether the component-based models of the bare-steel and composite connection have been correctly incorporated into Vulcan, by comparing the results with those from detailed finite element modelling using Abaqus. Finally, the structural performance of the ductile connection in steel-framed and composite structures is compared with that when conventional rigid or pinned connections are specified.

2 DESIGN AND COMPONENT-BASED MODELS OF THE DUCTILE CONNECTION

2.1 Detail of the ductile connection

The proposed novel connection consists of two identical parts, each of which may be characterised as a fin-plate which is bolted to the beam web, a face-plate which is bolted to either the column flange or web, and a semi-cylindrical section between these, as shown in Figure 1. The basic part of this ductile connection can be manufactured by simply bending a steel plate. The function of the semi-cylindrical section is to provide additional push-pull ductility by allowing the fin-plate to move towards and away from the face-plate. The radius of this section should not be too small, otherwise, the ductility of connection will be reduced and the axial force generated in the adjacent structural components will be increased. Therefore, the semi-cylindrical section radius should be determined according to the ductility demand of the connected beam during a fire event, which can be calculated by equations proposed in the previous papers [2, 6].

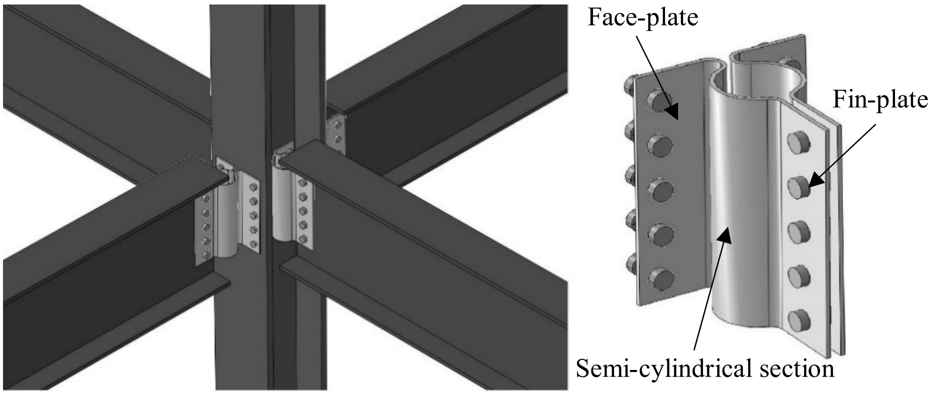


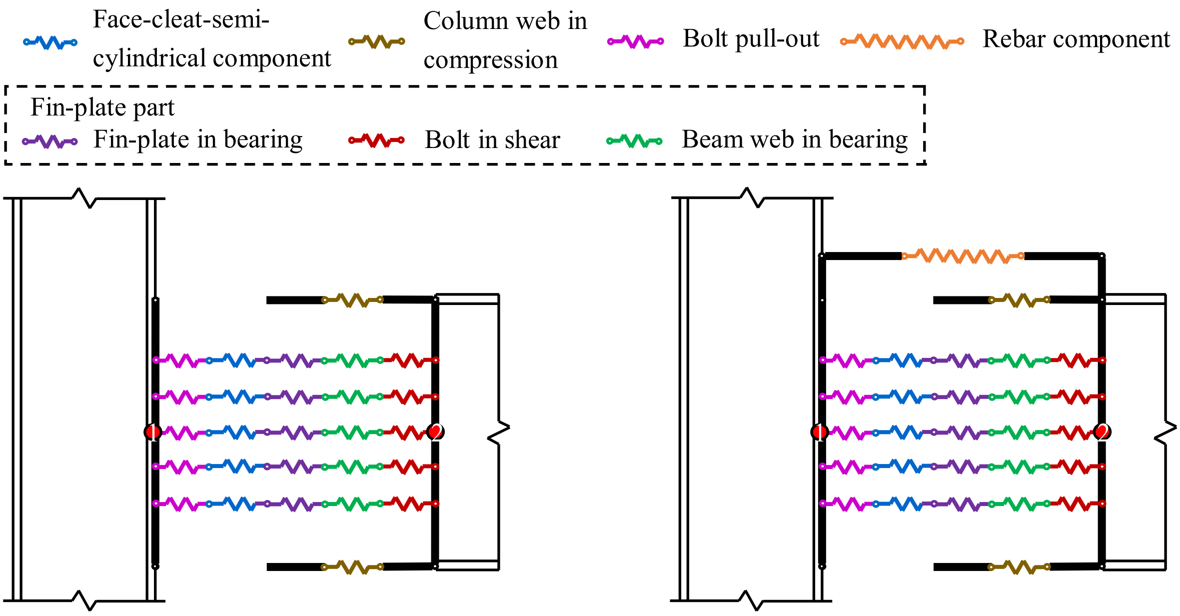
Figure 1. The proposed novel connection

2.2 Component-based models of the ductile connection

The component-based model of the bare-steel ductile connection has been proposed by the authors [4], as shown in Figure 2 (a). The basic structural actions of the component-based model include bolt pull-out, column web in compression, fin-plate in bearing, beam web in bearing, bolt in shear, and face-plate-semi-cylindrical component. The gap between the column web in compression and the vertical “rigid bar” represents the maximum axial compressive displacement before the beam bottom flange contacts the column flange. The two end nodes of the component-based model locate at the intersection points between the reference axes of the beam and column. The component-based model is assumed to be rigid in the vertical direction. Therefore, the vertical shear behaviour, which represents the slip between the beam end and the column flange, has not been taken into consideration. Design of this aspect of the connection uses the standard process for simple connections. The force-displacement curves of the fin-plate in bearing, beam web in bearing and bolt in shear are generated using the curve-fit equations proposed by Sarraj [10] based on a series of finite element parametric studies. The limiting strength of the bolt pull-out component is calculated using the simplified ‘plastic cone’ model developed by Dong [14]. Block [9] derived some equations for calculating the force-displacement curves of column web in compression, which have been directly applied to the current component-based model. As for the face-plate-semi-cylindrical component, the analytical models, based on simple plastic theory, developed by the authors [4] can be used to generate its characteristics.

The complete force-displacement relationship of a spring row under a complete axial load cycle in the component-based model of a bare-steel ductile connection is shown in Figure 3. The blue loop starts in pulling, and then the spring row is unloaded and pushed-back to its original state. The red loop starts in pushing, and the spring row is then unloaded and pulled back to its original shape. It is assumed that the stiffness of the unloading curve is the same as that of the initial elastic loading curve, for both tensile and compressive unloading. It can be seen from Figure 3 that the stiffness of tension and compression unloading is very large, resulting in a sudden change of spring row force when unloading occurs.

The component-based model of the composite ductile connection has been established by adding a reinforcement component to the bare-steel connection model [6], as shown in Figure 2 (b). The reinforcement component, which considers the pull-out of reinforcing bars and the influence of the anchorage and fracture of weld points in the mesh, is developed on the basis of the simple rebar slip model created by Sezen and Setzler [21]. It is further assumed that a discrete concrete crack occurs at the outer surface of the column flange, according with the experimental results obtained by Al-Jabri [18]. On one side of the crack, the development length is limited by the first three weld points, while on the other side of the crack, the development length is limited by the first weld point and the centre line of the column section. Therefore, the slip of reinforcing bars on both sides of the concrete crack should be calculated separately, and the sum of the slips on both sides is the total displacement of reinforcement component.



(a) Component-based model of bare-steel connection (b) Component-based model of composite connection

Figure 2. Component-based models of the ductile connection

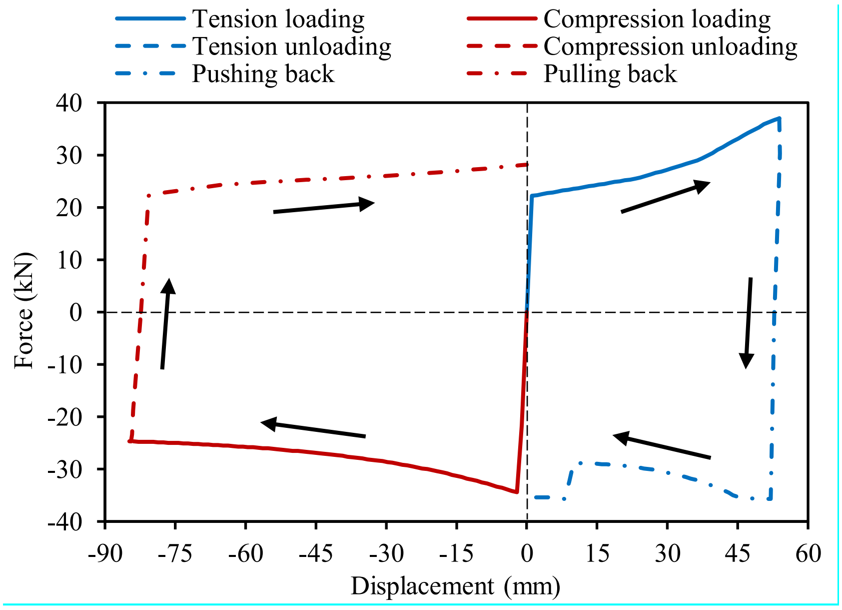
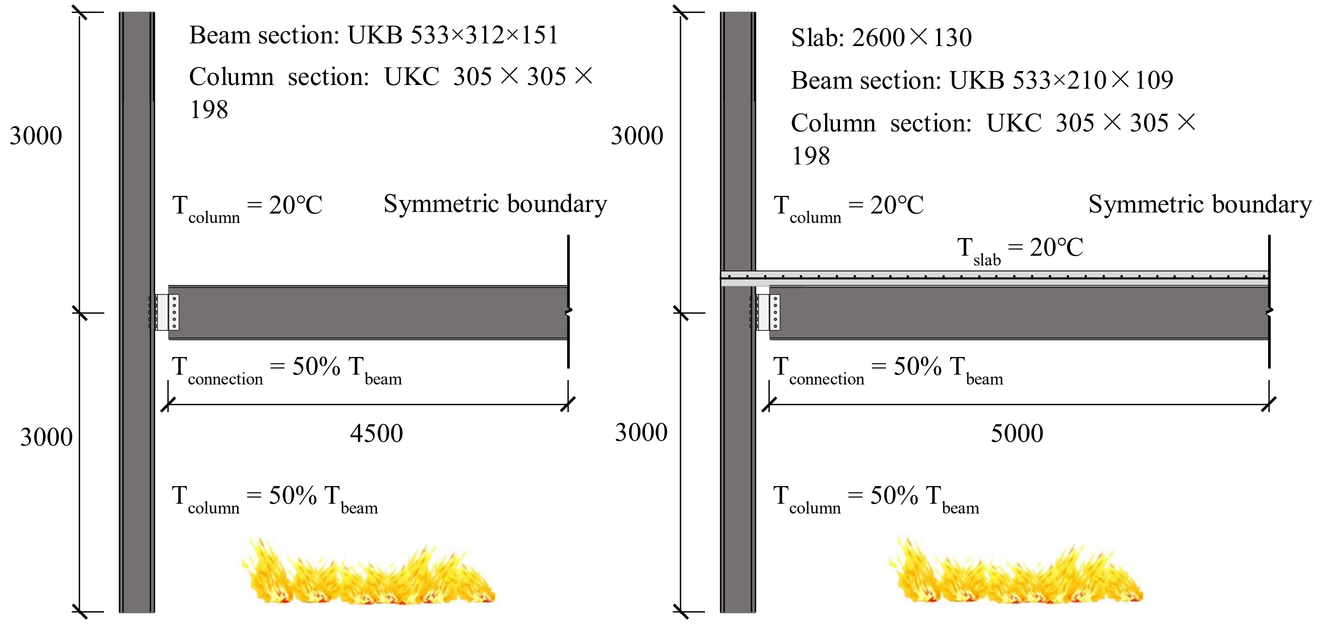


Figure 3. Loading and unloading process for a spring row

3 VALIDATION AGAINST DETAILED ABAQUS FE MODELS

3.1 Validation of the bare-steel connection model

According to the principles of the finite element method, the component-based model of the bare-steel ductile connection has been converted into a two-noded connection element located between the beam-end and the column, which has been incorporated into the software Vulcan [5]. In this section, a 2-D bare-steel sub-frame model, shown in Figure 4 (a), is created using both Vulcan and Abaqus to check whether the connection element has been correctly incorporated into Vulcan. In order to save computational cost, only half of the model is built, and symmetric boundary conditions are applied at the mid-span of the beam. It is further assumed that fire only occurs on the lower floor, and the temperatures of the connection and the lower column are set to be half of the beam temperature. The detailed dimensions of the ductile connection used in the sub-frame model are listed in Table 1. The results from the Vulcan and Abaqus models are compared and shown in Figure 5 (a) and (b). It can be seen from these figures that Vulcan results are in good agreement with Abaqus results. The temperature-force and temperature-displacement curves of each spring row in the Vulcan model are shown in Figure 5 (c) and (d). At the start of heating, all the spring rows undergo compressive displacements, due to the thermal expansion of the connected beam. When the beam temperature reaches around 600°C, the compressive displacement of each spring row decreases gradually, and eventually changes into tensile displacement, as the connected beam enters its catenary action stage. It can be seen from Figure 5 (d) that, compared with other spring rows, Spring row 1 (the top spring row) experiences the largest tensile displacement, and is the first row to fail due to the pull-out of the bolt at that level. After the failure of Spring row 1, other spring rows fail row-by-row in the same manner. Once all the spring rows have failed, the connection element is considered as having failed, and will be removed from the model, leading to detachment of beam from the column face.



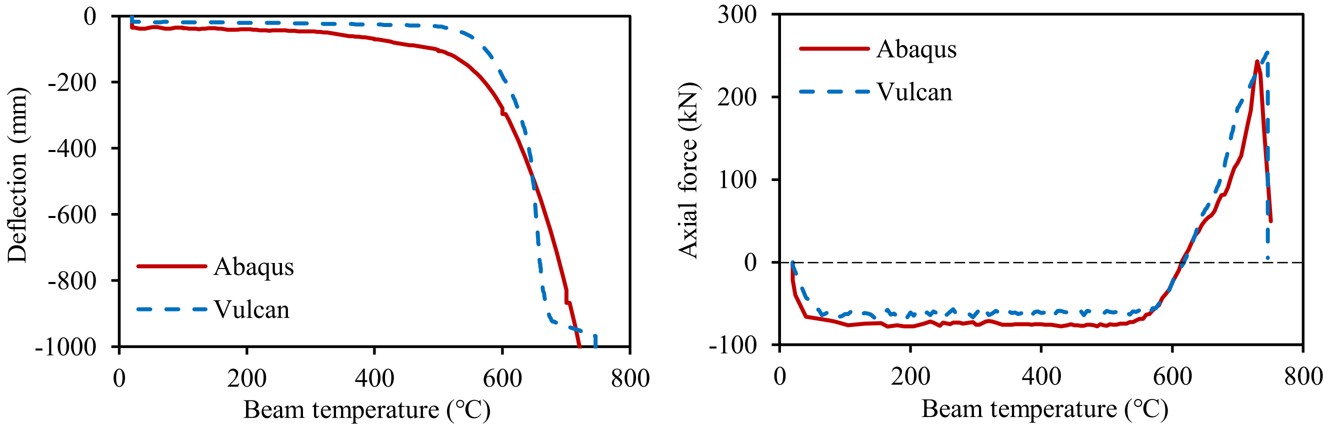
(a) 2-D bare-steel sub-frame model

(b) 2-D composite sub-frame model

Figure 4. 2-D sub-frame model (units in mm)

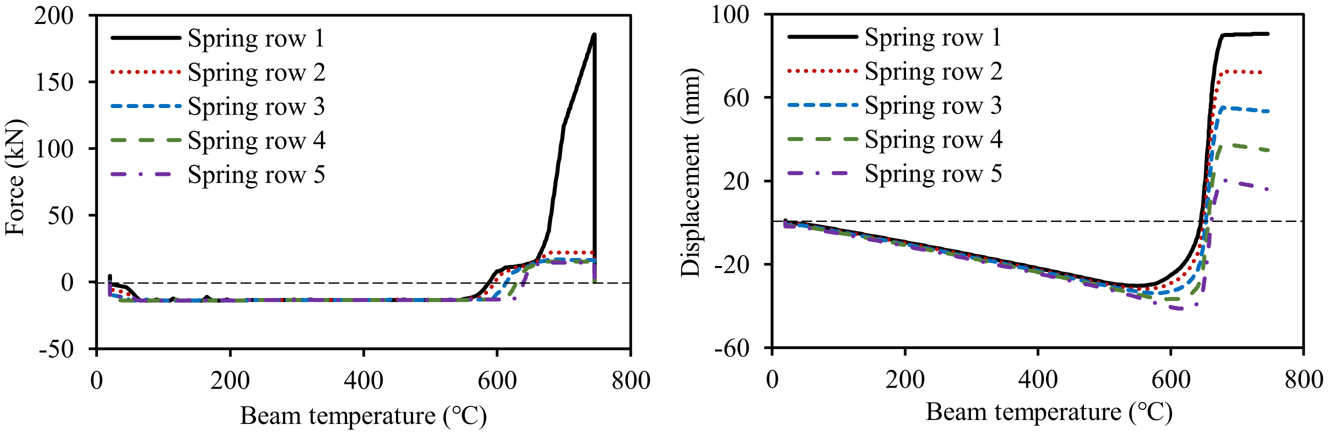
Table 1. Connection size

Inner radius of semi-cylindrical section (mm)	50
Plate thickness (mm)	6
Fin-plate width (mm) × depth (mm)	100×360
Face-plate width (mm) × depth (mm)	100×360
Number of bolt rows	5



(a) Mid-span beam deflection

(b) Beam axial force at mid-span



(c) Temperature-force curves

(d) Temperature-displacement curves

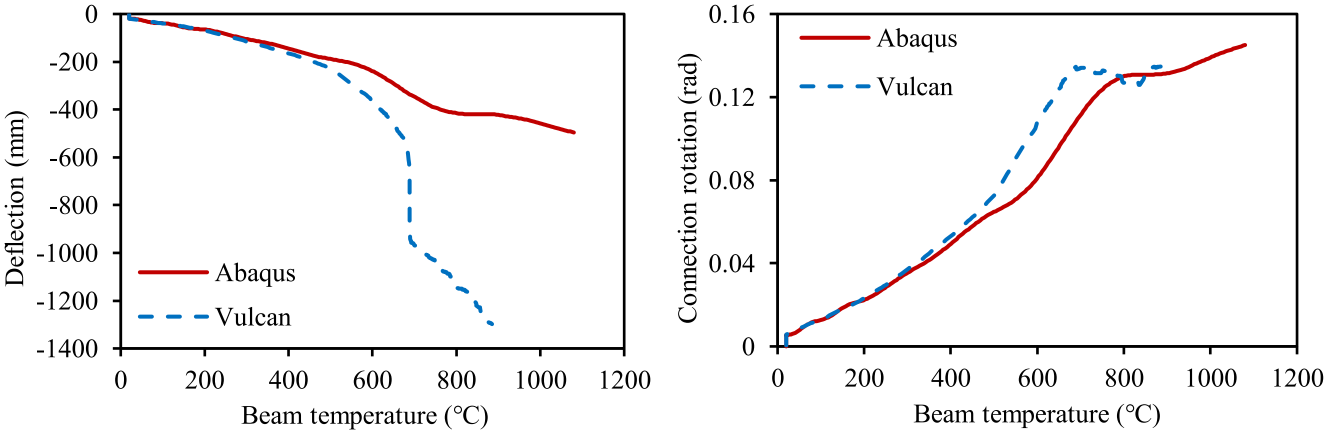
Figure 5. Results of the 2-D bare-steel sub-frame model

3.2 Validation of the composite connection model

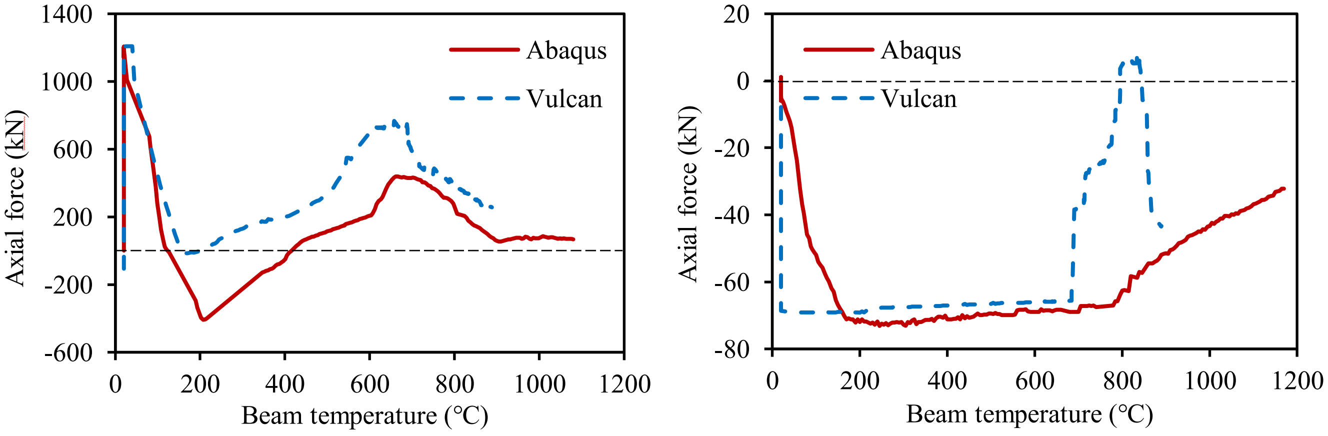
The component-based model of the composite ductile connection has been converted into a connection element and incorporated into Vulcan [6]. The 2-D composite sub-frame shown in Figure 4 (b) has been modelled using Vulcan and Abaqus to test the performance of the composite connection element. The dimensions of the ductile connection used in the composite frame model are the same as those used in the bare-steel frame model, as listed in Table 1. The ductile connection is modelled in detail using solid elements in the Abaqus model, while the developed composite ductile connection element is used in the Vulcan model. The models adopt different methods to simulate the ductile connection. The are two key differences between the models are:

1. Concrete cracking and the pull-out of reinforcing bars are not considered in Abaqus model.
2. In the developed composite connection element, if the displacement of a spring row changes its direction, then unloading occurs. The force of the spring row changes its sense rapidly (Figure 3). This elastic unloading property is not considered in the detailed Abaqus model.

Figure 6 shows a comparison of the results of Vulcan model with those of Abaqus model. Above 200°C, the mid-span deflection and connection rotation of Abaqus model are smaller than those of Vulcan model, indicating that Abaqus model appears to be stiffer than Vulcan model. This is due to the fact that the Abaqus model does not take into account the concrete cracking and the pull-out of reinforcing bars, which makes the composite slab of Abaqus model stronger than that of Vulcan model. At about 686 °C, the mid-span deflection of Vulcan model increases rapidly, which is due to the change of spring row displacement direction. This will be further explained below. The mid-span beam axial forces of the Vulcan model and Abaqus model are compared in Figure 6 (c). As can be seen from the figure, with the increase of temperature, the initial tensile mid-span beam axial force decreases gradually due to the restraint of beam thermal expansion. The decrease of the tensile mid-span beam axial force of the Abaqus model is larger than that of the Vulcan model (the mid-span beam axial force of the Abaqus model can reach -407kN around 211℃), which is because the composite slab of Abaqus model has stronger constraint on the beam thermal expansion than that of Vulcan model. Under the influence of thermal bowing, the mid-span beam axial force increases again at about 200℃. When the steel beam finally enters the catenary action stage, the mid-span beam axial force decreases again around 700℃. The comparison of the connection axial forces obtained from the Vulcan and Abaqus models is shown Figure 6 (d). The changes of the connection axial force are affected by the combined effects of beam thermal expansion and material degradation. It can be seen from the figure that the compressive axial force of the connection in the Vulcan model decreases rapidly at around 686℃, and changes temporarily into tension at about 800 ℃. Above this temperature, the connection axial force becomes compressive again. It must be remembered that the Vulcan connection component assembly has the ability to reverse the direction in which each spring row moves; when this happens the row component unloads elastically and then changes the sense of its force. The Abaqus model does not have this capability. This explains the very marked divergence between the Vulcan and Abaqus curves shown in Figure 6 (a) and (d). It can be seen from Figure 7 that the displacement direction of all the five spring rows changes around 686 ℃, resulting in a sudden decrease in the compressive force of all the spring rows. This is manifested in the sudden increase of beam mid-span deflection, as shown in Figure 6 (a), and the sudden decrease of connection compressive axial force as shown in Figure 6 (d). When the beam temperature reaches about 838 ℃, the displacement direction of all the five spring rows changes again, leading to reversal of the connection axial force to compression. In general, the performance of the Vulcan connection element is in good agreement with the detailed Abaqus model, until the connection components' axial displacements change direction; beyond this stage the Vulcan model is more representative of the real behaviour, although this is not directly validated by Abaqus at this time. The current indication is that the Vulcan composite connection element can be used to investigate the effect of applying the ductile connection within a composite structure in fire conditions.

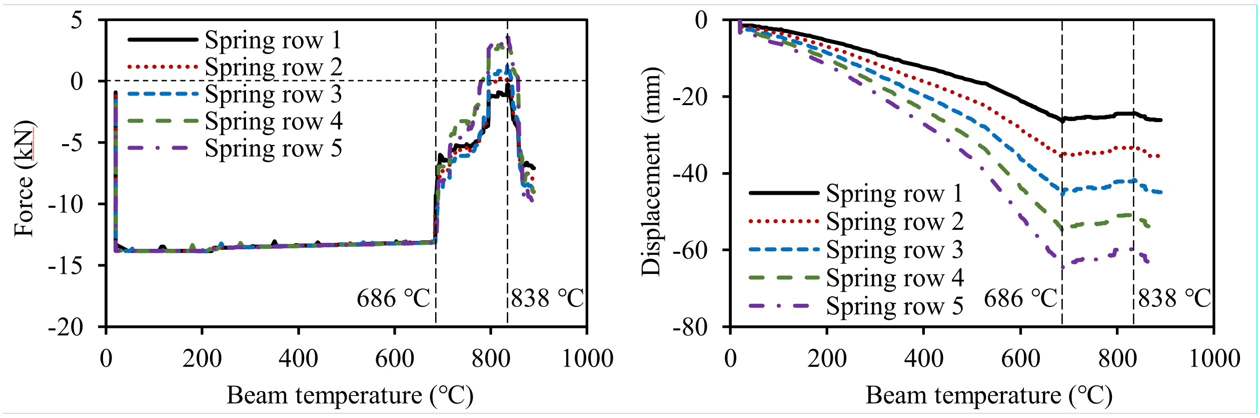


(a) Mid-span beam deflection (b) Connection rotation



(c) Mid-span beam axial force (d) Connection axial force

Figure 6. Results of the 2-D composite sub-frame model



(a) Temperature-force curve of each spring row

(b) Temperature-displacement curve of each spring row

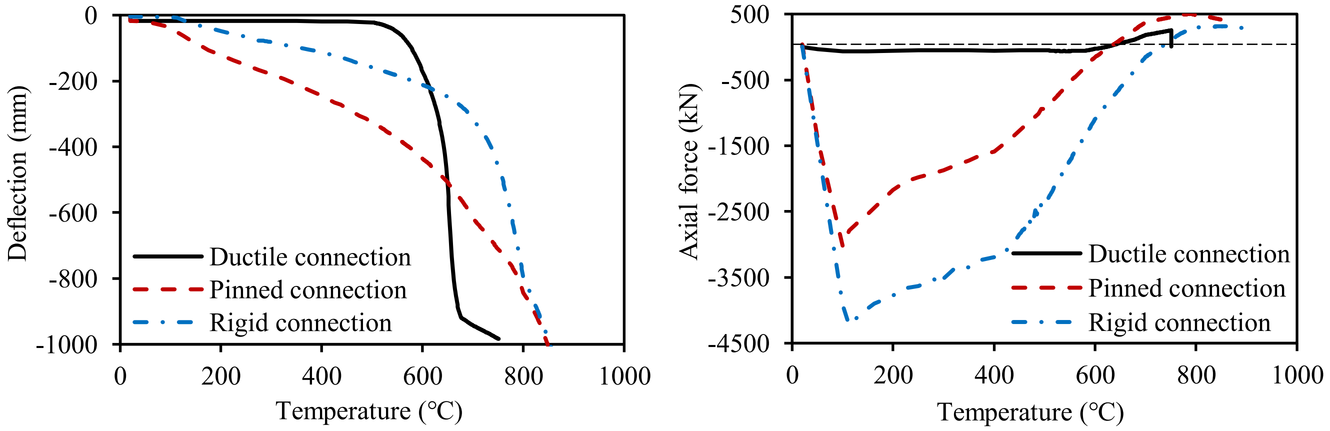
Figure 7. Temperature-force and temperature-displacement curves of each spring row

4 COMPARISON OF THE DUCTILE CONNECTION WITH OTHER CONNECTION TYPES

4.1 Performance comparison within bare-steel frame

In this section, the 2-D bare-steel sub-frame models shown in Figure 4 (a) are used to compare the performance of ductile connection with that of idealised pinned and rigid connection types. The comparison results are shown in Figure 8. As can be seen from Figure 8 (a) the mid-span deflection of the beam with the ductile connection is lower than those of the beams with the idealised connections up to around 600 °C. After that temperature, the deflection of the beam with ductile connection increases rapidly, and finally exceeds those of beams with idealised connections. The mid-span axial force generated in the heated beam with the ductile connection is significantly reduced compared with the beams with pinned and rigid connections, as shown in Figure 8 (b).

This phenomenon indicates that the ductile connection can provide additional ductility to accommodate the axial deformation of connected beam generated in fire conditions. The ductility of the ductile connection can also contribute to the reduction of axial forces to which the surround structural elements are subjected.



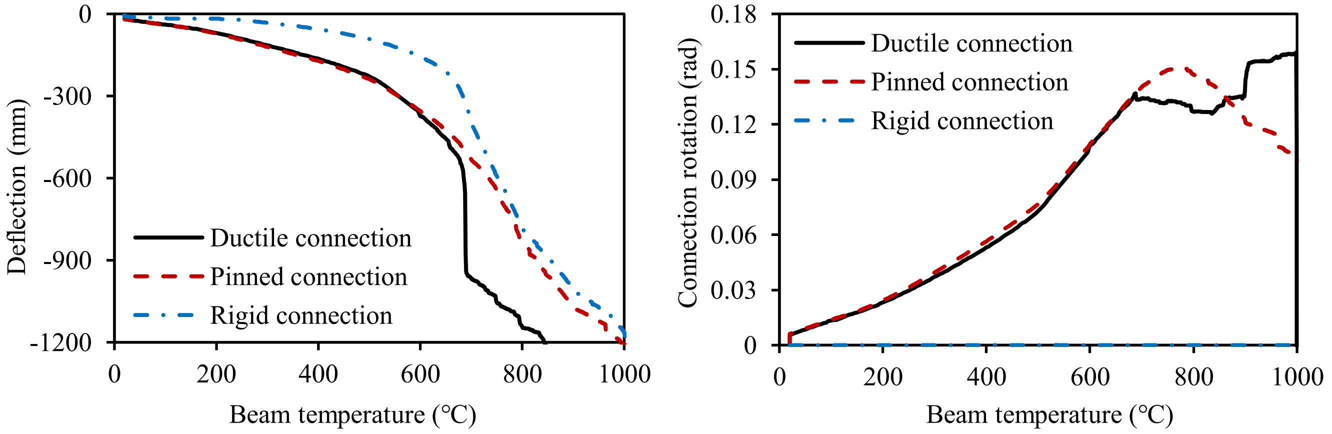
(a) Mid-span beam deflection

(b) Mid-span beam axial force

Figure 8. Performance comparison within bare-steel frame

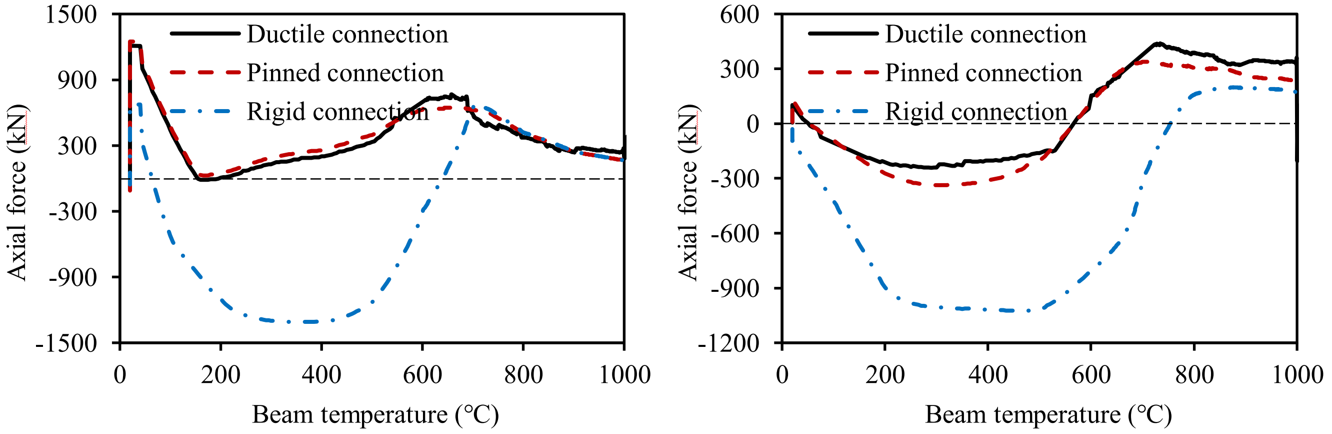
4.2 Performance comparison within composite frame

The structural behaviour of connections within composite structures is quite different from that of connections within bare-steel frames, due to the existence and continuity of the composite slab. Two-dimensional composite sub-frame models with different connection types, including the ductile connection, the pinned and rigid connection, as shown in Figure 4 (b), are created using Vulcan in this section to compare the performance of the ductile connection with other connection types in composite structures. The comparison results are shown in Figure 9. As can be seen from Figure 9 (a) the mid-span deflection of the beam with ductile connections is basically the same as that of the beam with the idealized pinned connection up to about 680 °C. Within this temperature range, the rotation of the ductile connection is also almost equal to that of the pinned connection, as depicted in Figure 9 (b). After that, the rotation of the ductile connection continues to increase, while the rotation of the pinned connection begins to decrease. This is manifested in the rapid increase of the mid-span deflection of the beam with ductile connections above 680 °C (Figure 9 (a)). The mid-span and end axial forces of the beams with different connection types are compared in Figure 9 (c) and (d). The axial force generated in the beam with ductile connections is almost the same as that in the beam with pinned connections. However, rigid connections restrain the thermal expansion of the beam to a great extent, resulting in a very large compressive axial force in the beam. Once again, the ductile connection exhibits its good axial deformation capacity to accommodate the deformation of connected beam, thus reducing the compressive axial force generated.



(a) Mid-span beam deflection

(b) Connection rotation



(c) Beam axial force at mid-span

(d) Beam axial force at end

Figure 9. Performance comparison within composite frame

5 CONCLUSIONS

Connections are potentially the weakest part of a structure. In order to improve the ductility of connections and enhance the robustness of structures in fire, a ductile connection has been proposed by the authors. In this paper, the design and the component-based models of the bare-steel and composite ductile connections have been introduced.

A 2-D bare-steel sub-frame with ductile connections was modelled using Vulcan and Abaqus. Vulcan results are in good agreement with Abaqus results, indicating that the component-based model of the bare-steel ductile connection has been correctly incorporated into Vulcan. Through the analysis of Vulcan model results, it is found that Spring row 1 (the top spring row) experiences the largest tensile displacement and is the first to fail due to bolt pull-out. After this, other spring rows fail row by row in the same manner. A 2-D composite subframe was used to check the performance of the component-based model of the composite ductile connection by comparing the results of Vulcan and Abaqus models. Comparison of the results shows that the Vulcan model is in good agreement with the detailed Abaqus model, up to the point where the connection components' axial displacements change direction. In the proposed connection element, the direction change of the spring row displacement leads to a rapid change of spring row force. This characteristic is not taken into consideration in the Abaqus model. The current indication is that the Vulcan composite connection element can be used to facilitate global frame analysis to investigate the effect of adopting the ductile connection in composite structures under fire conditions.

Performance of the ductile connection within bare-steel and composite frames has been compared with that of conventional connection types including idealized pinned and rigid connections. Results show that the compressive axial force generated in the heated bare-steel beam can be significantly reduced when the ductile connection is used. The axial force of the composite beam with ductile connection is basically the same as that when an ideal pinned connection is used. However, compared with the composite beam with rigid connections, the axial force in the composite beam with ductile connections is still greatly reduced. These comparison results demonstrate the axial deformation capacity of the proposed ductile connection.

REFERENCES

1. Lennon T, Moore D. The natural fire safety concept—full-scale tests at Cardington. Fire Safety Journal. 2003;38:623-43.
2. Liu Y, Huang S-S, Burgess I. Investigation of a steel connection to accommodate ductility demand of beams in fire. Journal of Constructional Steel Research. 2019;157:182-97.
3. Liu Y, Huang S-S, Burgess I. Ductile connections to improve structural robustness in fire. Proceedings of the 6th Applications of Structural Fire Engineering Conference (ASFE'19): Sheffield; 2019.
4. Liu Y, Huang S-S, Burgess I. Component-based modelling of a novel ductile steel connection. Engineering Structures. 2020;208:110320.
5. Liu Y, Huang S-S, Burgess I. Performance of a novel ductile connection in steel-framed structures under fire conditions. Journal of Constructional Steel Research. 2020;169:106034.
6. Yu Liu S-SH, Ian Burgess. Fire performance of axially ductile connections in composite construction. Fire Safety Journal. 2020.
7. Leston-Jones LC. The influence of semi-rigid connections on the performance of steel framed structures in fire: University of Sheffield; 1997.
8. Spyrou S. Development of a component based model of steel beam-to-column joints at elevated temperatures: University of Sheffield; 2002.
9. Block FM. Development of a component-based finite element for steel beam-to-column connections at elevated temperatures: University of Sheffield Sheffield, UK; 2006.
10. Sarraj M. The behaviour of steel fin plate connections in fire: University of Sheffield; 2007.
11. Sarraj M, Burgess I, Davison J, Plank R. Finite element modelling of steel fin plate connections in fire. Fire Safety Journal. 2007;42:408-15.
12. Yu H, Burgess I, Davison J, Plank R. Development of a yield-line model for endplate connections in fire. Journal of Constructional Steel Research. 2009;65:1279-89.
13. Yu H, Burgess I, Davison J, Plank R. Tying capacity of web cleat connections in fire, Part 2: Development of component-based model. Engineering structures. 2009;31:697-708.

14. Dong G. Development of a General-Purpose Component-based Connection Element for Structural Fire Analysis: University of Sheffield; 2016.
15. Hu Y, Davison B, Burgess I, Plank R. Component modelling of flexible end-plate connections in fire. International Journal of Steel Structures. 2009;9:1-15.
16. Taib M, Burgess I. A component-based model for fin-plate connections in fire. Journal of Structural Fire Engineering. 2013;4:113-22.
17. Leston Jones L, Burgess I, Lennon T, Plank R, Elevated-temperature moment-rotation tests on steelwork connections. Proceedings of the Institution of Civil Engineers-Structures and Buildings. 1997;122:410-9.
18. Al-Jabri KS. The behaviour of steel and composite beam-to-column connections in fire: University of Sheffield; 1999.
19. Li J-T, Li G-Q, Lou G-B, Chen L-Z. Experimental investigation on flush end-plate bolted composite connection in fire. Journal of Constructional Steel Research. 2012;76:121-32.
20. Li G-Q, Chen L-Z, Li J-T, Lou G-B. Modeling of end-plate bolted composite connection in fire considering axial force effects. Journal of Constructional Steel Research. 2012;76:133-43.
21. Sezen H, Setzler EJ. Reinforcement slip in reinforced concrete columns. ACI Structural Journal. 2008;105:280.