DUCTILE CONNECTIONS TO IMPROVE STRUCTURAL ROBUSTNESS IN FIRE

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Abstract

The ductility of connections is a key property in preventing the brittle failure and subsequent progressive collapse of steel-framed structures in fire conditions. Conventional connection types have insufficient ductility to accommodate the deformations generated by the connected beams as their temperatures rise, or to withstand the forces to which they are subjected. This paper aims to investigate the mechanical performance of a new type of connection proposed to meet the ductility demand created by long-span steel beams in fire conditions. This novel connection consists of two identical parts, each of which includes a fin-plate, an endplate and a semi-cylindrical section. Analytical component models have been developed and validated, based on which a component-based model is proposed. A simple Abaqus frame model with these novel connections has been created to assess the structural performance of the novel connection under realistic conditions.

Keywords: Ductile Connection, Component-Based Model, Robustness, Fire

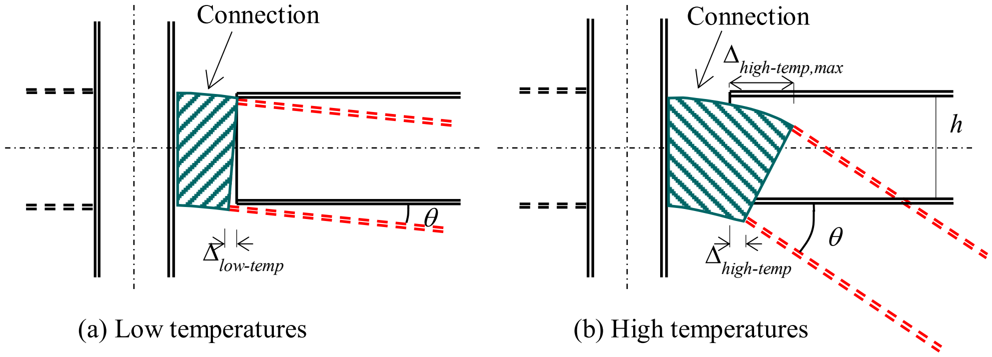
1 INTRODUCTION

Connection failures observed in the collapse of the World Trade Centre (McAllister and Corley, 2002) and some of the Cardington full-scale fire tests (Newman et al., 2000) have indicated that connections are more vulnerable in fire conditions than conventional assumptions in prescriptive codes indicate. Connections are subject to different combinations of loads at different stages of a fire incident, and their failures may trigger detachment of connected beams, leading to buckling of columns, and eventually to disproportionate collapse of an entire building (Gann et al., 2008). Connection failures can also cause breaching of floor slabs and spread of fire into adjacent compartments. To maintain structural integrity and prevent progressive collapse, connections are particularly important as the key components tying structural members together. However, current commonly-used connection types lack the axial ductility required to accommodate compressive deformation due to thermal expansion of long-span beams in the early stages of a fire, leading to large compressive forces being applied to surrounding structural members. They are also incapable of allowing tensile deformation of beam-ends at high temperatures, in order to reduce the catenary forces in beams to levels that can be resisted.

In order to improve the performance of connections, and therefore to enhance the robustness of entire structures against fire, a novel ductile connection is proposed in this paper, and preliminary investigations have been carried out on its mechanical behaviour. Simple analytical models of this ductile connection, based on plastic theory, have been developed and tested against Abaqus simulations. A component-based model of the novel connection, which will be implemented into the fire engineering software Vulcan, has also been proposed.

2 DESIGN OF THE NOVEL DUCTILE CONNECTION

Connections are restrained by adjacent structural members. In the early stages of a fire (usually when the beam temperature is below about 600°C), the bottom of connection should be able to accommodate movement $\Delta_{low-temp}$, caused by the thermal expansion of connected beam, which is illustrated in Figure 1(a), in order to reduce the axial compressive force and prevent the beam from buckling. At a later fire stage, when the beam is acting essentially in catenary action in the high-temperature range, the top and bottom of the connection should respectively be able to withstand the movements $\Delta_{high-temp,\max}$ and $\Delta_{high-temp}$, which are also shown in Figure 1(b), to prevent both abrupt tensile fracture and hard contact between the beam-end and the column flange. These critical movements, which can be considered as the beam's ductility demand in fire, can be simply calculated according to Equations (1)-(3), assuming that the deflected shape of the beam can be represented as approximately parabolic.



(a) Low temperatures (b) High temperatures

Fig. 1 Critical connection deformations due to beam-end movements.

$$\Delta_{low-temp} = \frac{1}{2}(\alpha l T + h\theta) - \frac{4}{3}\delta^2 / l \tag{1}$$

$$\Delta_{high-temp} = \frac{4}{3}\delta_{\max}{}^2 / l - \frac{1}{2}(\alpha l T_{\max} + h\theta) \tag{2}$$

$$\Delta_{high-temp,\max} = \frac{4}{3}\delta_{\max}{}^2 / l - \frac{1}{2}(\alpha l T_{\max} - h\theta) \tag{3}$$

In these equations α is the beam's coefficient of thermal expansion, l is its length, T is its temperature corresponding to a midspan deflection δ (of which $T_{\max}$ and $\delta_{\max}$ are the maximum values). It should also be remembered that, under the parabolic shape assumption, $\theta \approx 4\delta / l$.

The novel ductile connection shown in Figure 2 is proposed to attempt to meet the beam ductility demand mentioned above. This novel connection consists of two identical parts, each of which can be manufactured by deforming a steel plate, and takes the form of a fin-plate which is bolted to the beam web, an end-plate which is bolted to either the column web or flange, with a semi-cylindrical section between the fin-plate and end-plate. The complex geometry of the connection could lead to stress concentration in zones between the semi-cylindrical section and the fin-plate, but this would not affect the performance of the connection, since its purpose is to mobilise the steel's ductility. An alternative fabrication method might be to weld two plates to a tube, which would be costlier and more labour intensive. The function of the semi-cylindrical section is the key to providing the additional axial push-pull ductility which is necessary in fire, by allowing the fin-plate to move towards and away from the end-plate. Therefore, the diameter of the semi-cylindrical section, which has a great impact on the ductility of whole connection, should be selected according to the maximum values of $\Delta_{low-temp}$, $\Delta_{high-temp,\max}$ and $\Delta_{high-temp}$. In this way, the ability of the entire connection to resist large tensile and compressive deformation can be ensured, and the probability of brittle failure modes and progressive collapse is minimized.

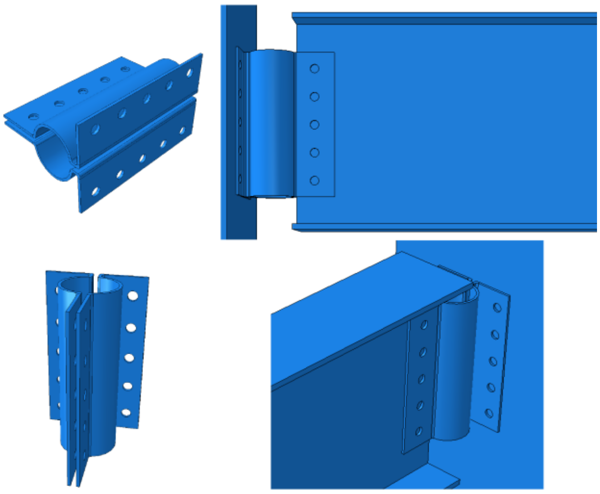


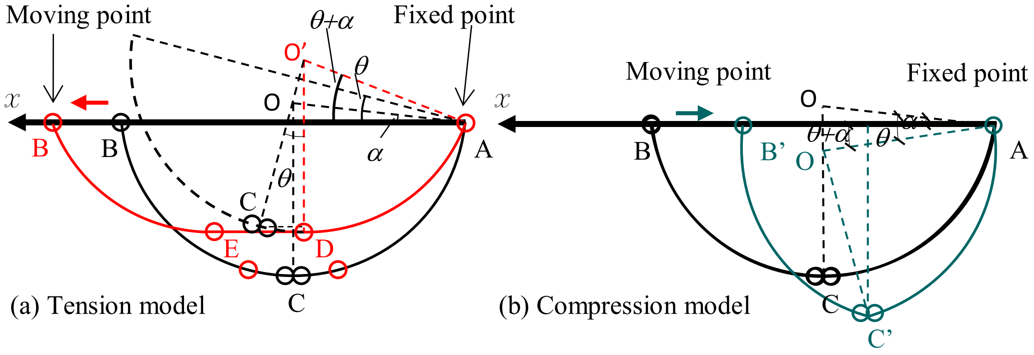
Fig. 2 Design of the novel ductile connection.

3 DEVELOPMENT AND VALIDATION OF ANALYTICAL MODELS

3.1 Development of Analytical Models

A horizontal strip at any vertical level in the connection is mainly subject to tensile or compressive deformation, which is achieved by bending of the semi-cylindrical section. Plastic hinges will form in such strips at the positions where the internal bending moments are greatest. The Virtual Work principle can be adopted to develop analytical models of the plastic mechanisms at each strip. If the plastic mechanisms in tension and compression of a strip are considered in the same way, four plastic hinges, located at the two ends and the inner edges of the circular arcs, are formed during the deformation of each connection strip. These occur naturally at the positions of maximum bending moment.

Several assumptions are made about the tension model. The two end plastic hinges remain unchanged in position throughout the deformation process, whereas the two hinges at the inner edge of the circular arcs will move towards their nearest ends as the connection is stretched; they eventually meet the end hinges when the cylindrical section has been stretched flat, as shown in Figure 3(a).



(a) Tension model (b) Compression model

Fig. 3 Push-pull analytical models of a horizontal strip through the connection.

The difference between the tension model and the compression model is that the positions of the two inner plastic hinges remain unchanged during the compressive deformation, as shown in Figure 3(b). In order to create a model of the whole connection, it is divided into a vertical array of connection strips, each of which is either pushed or pulled when the connection deforms in some combination of rotation and push-pull. An illustration of such an array, for a connection which is constrained only to rotate about its centre point, as shown in Figure 4. The moment generated by the whole connection can be calculated as the sum of the moments of each connection strip about the centre of rotation:

$$M = \sum_{i=1}^{N/2} (T_i + C_i) Z_i \tag{4}$$

Because of the difference between the compressive and tensile strip mechanisms, the fixed centre of rotation is also, in general, subject to a net axial force:

$$F = \sum_{i=1}^{N/2} (T_i + C_i) \tag{5}$$

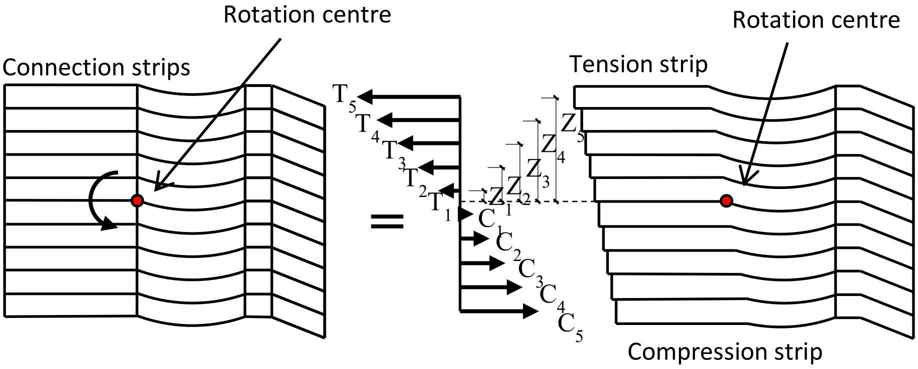


Fig. 4 Component-based model using strips.

3.2 Validation of Analytical Models

In order to check the validity of the component-based model, an identical connection was simulated using Abaqus finite element modelling. The shell element S4R was adopted to save computational effort. As boundary conditions for the push-pull Abaqus model, the end-plate was fixed and the out-of-plane displacement of the fin-plate was constrained, since it is bolted to the beam web. To assess the impact of the simplification of deformation compatibility at the top and bottom of any two adjacent connection strips, which is only piecewise in the analytical model, two Abaqus connection models were created; a whole-connection model and a model containing disconnected strips. When only push-pull deformation is applied it can be seen from Figure 5 that the analytical model and Abaqus simulation correlate well; the discrepancy between the curves can be attributed to the finite lengths and thicknesses of plastic hinges in the FE model, as compared to the discrete positions assumed in traditional plastic-theory modelling.

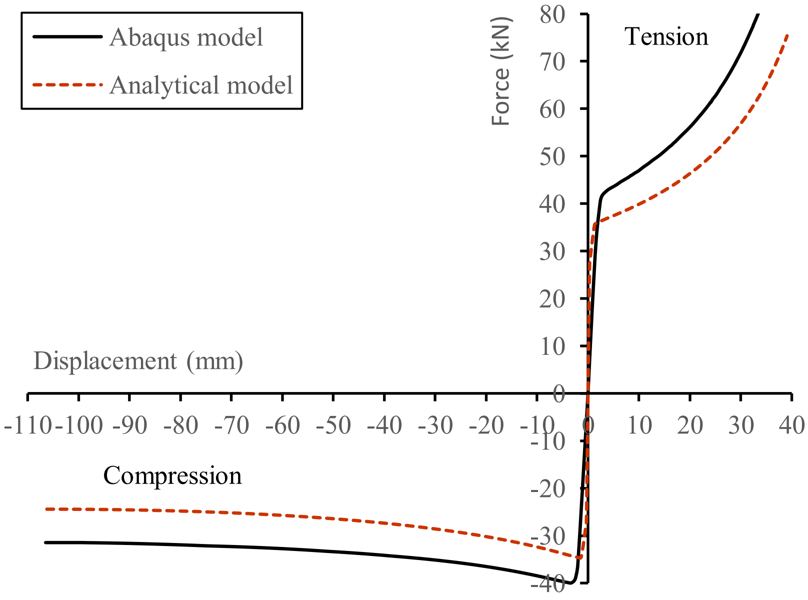


Fig. 5 Comparison of analytical model against Abaqus model for push-pull.

Comparing the analytical and Abaqus models for pure rotation about the centre of the connection, shown in Figure 6, a much larger discrepancy can be seen, even between the Abaqus strip model and the analytical model, as is shown in Figure 6; this appears to be caused mainly by the fact that out-of-plane bending and torsion of individual connection strips is ignored in the analytical model. And as mentioned above, with a centre of rotation which is constrained in the axial direction, external axial reaction forces are required to balance the model of the connection during the rotation process. The net axial forces at ambient temperature, obtained by the analytical and Abaqus models, are shown in Figure 7. It must, however, be noted that the absolute values of moment generated are extremely small compared with the moment capacity of a practical beam which might use this connection, which suggests that the connection is acting essentially as a simple hinge at the end of the supported beam.

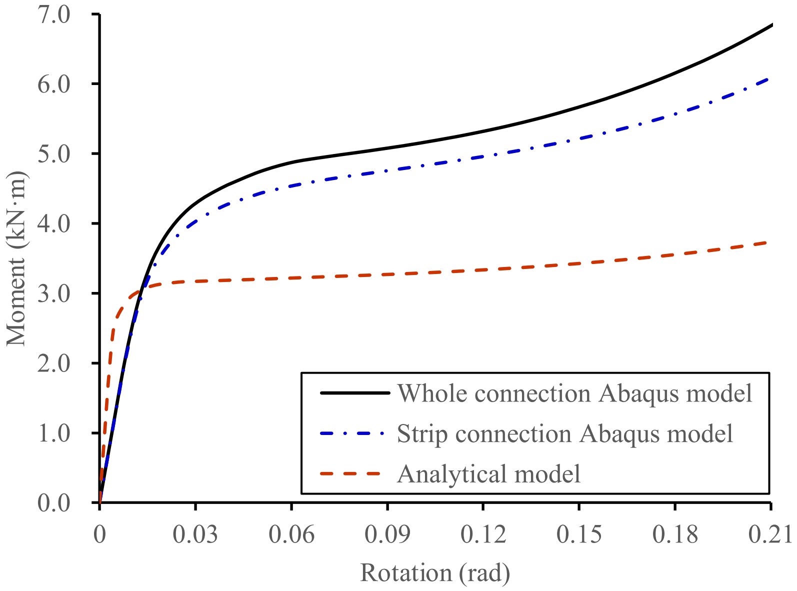


Fig. 6 Comparison of analytical and *Abaqus* models for pure rotation about connection centre.

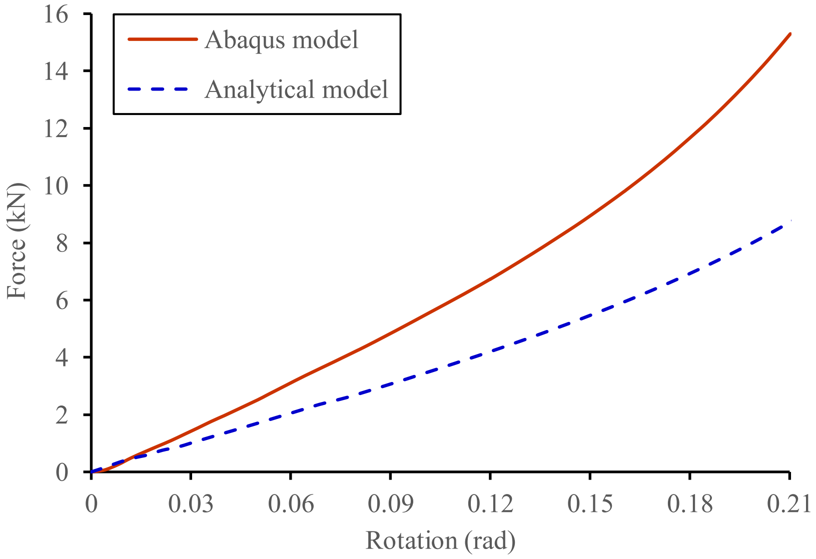


Fig. 7 Resultant axial force of the connection during rotation.

4 PERFORMANCE OF THE NOVEL CONNECTION WITHIN A SIMPLE FRAME

To assess the performance of the new connection in practical circumstances, a simple two-storey three-bay plane steel frame, depicted in Figure 8, is used. The UKB 533*210*109 is selected as the beam section and UKC 305*305*198 is selected for all column sections. It is further assumed that a fire occurs only in the ground floor of the central bay, and the two adjacent cold bays on both sides can therefore be simplified as elastic horizontal springs with known axial stiffness. The stiffness of each of the two horizontal elastic springs can be calculated according to Equation (6), where K_{column} and $K_{connection}$ represent the lateral sway stiffness of a perimeter column and the axial push-pull stiffnesses of the connections in the outer bays, respectively.

$$K = \frac{1}{2/K_{connection} + 1/K_{column}} \tag{6}$$

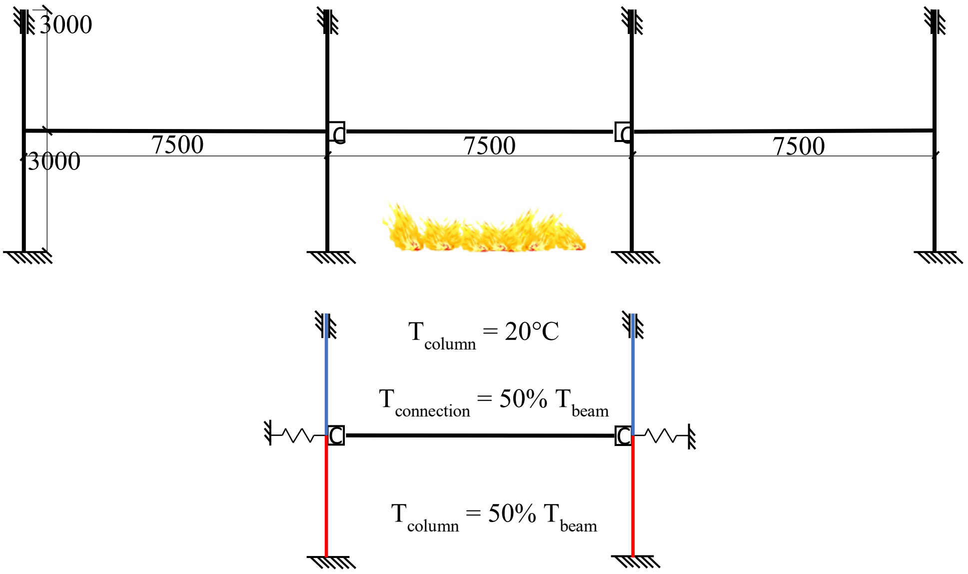


Fig. 8 Plane steel frame model and its equivalent subframe.

Due to the symmetry of the structure, only half of the central bay is used in the Abaqus model, which is shown as Figure 9, to save computational effort. A uniform line load is applied to the top flange of beam, generating a load ratio of 0.5 with respect to the capacity of a simply supported beam.

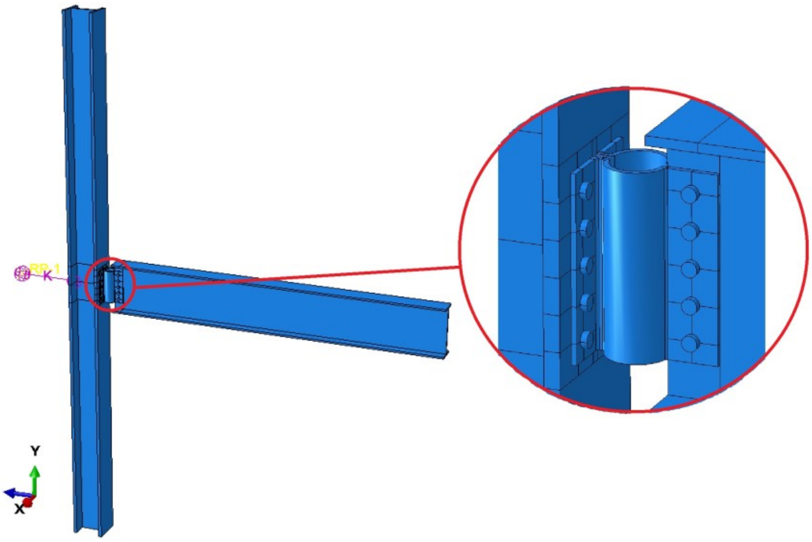


Fig. 9 Abaqus frame model.

The complex contacts involved in this model could lead to numerical singularities if a static solver is used, and so the dynamic solver is used to analyse the model. To solve a quasi-static problem using a dynamic solver, the loading speed is of greatest concern in ensuring that the response of the system can be treated as approximately static. A step time of 0.1s was selected for the current model, and a frame model with web-cleat connections, which has previously been found to be one of the most ductile in push-pull and rotation among conventional connection types, was also created as a logical comparator.

Comparative results between the frame with the new ductile connections and the same frame with appropriate web-cleat connections are shown in Figure 10 and Figure 11.

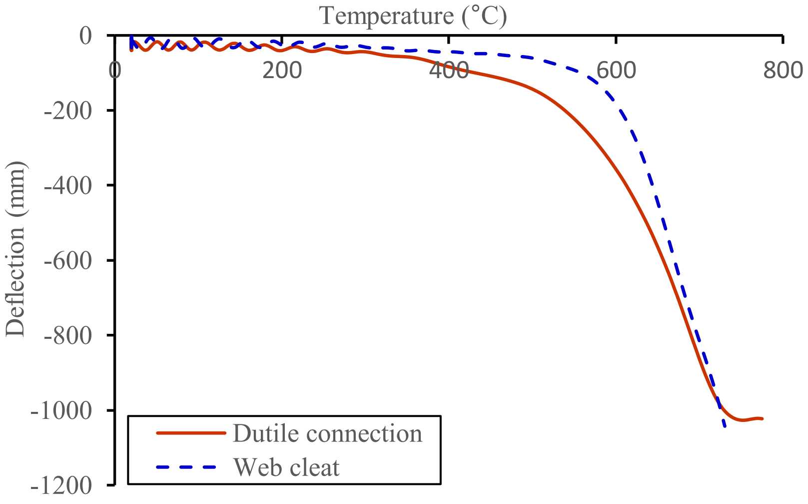


Fig. 10 Results comparing the new connection with web-cleat connections. Deflection at beam mid-span.

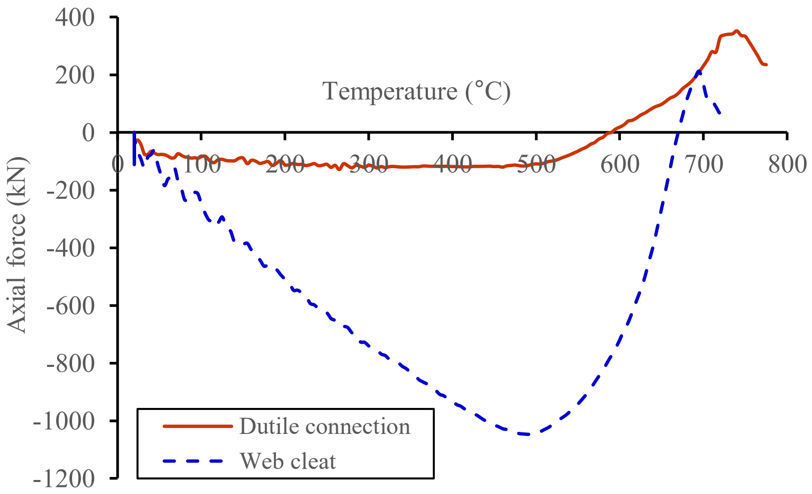


Fig. 11 Results comparing the new connection with web-cleat connections. Axial force of beam.

It can be seen from Figure 10 that the solid curve representing mid-span deflection of the beam with the new connections is very close to that of the beam with web-cleat connections, represented by the dashed line. The comparison of axial forces (shown in Figure 11) shows that the axial force generated in the beam with the new connections was significantly reduced due to the high axial ductility created. This shows well the axial ductility of the novel connection, which accommodates the deformation of the connected beam in fire conditions, reducing the axial forces compared with the conventional connection type. A parametric study was carried out to investigate the influence of the plate thickness of the novel connection on its structural performance. Four different plate thickness values (6mm, 10mm, 18mm and 22mm) were selected for the same beam conditions; the two larger thicknesses were chosen for illustrative purposes rather than as likely practical solutions. The results are shown in Figure 12 and Figure 13.

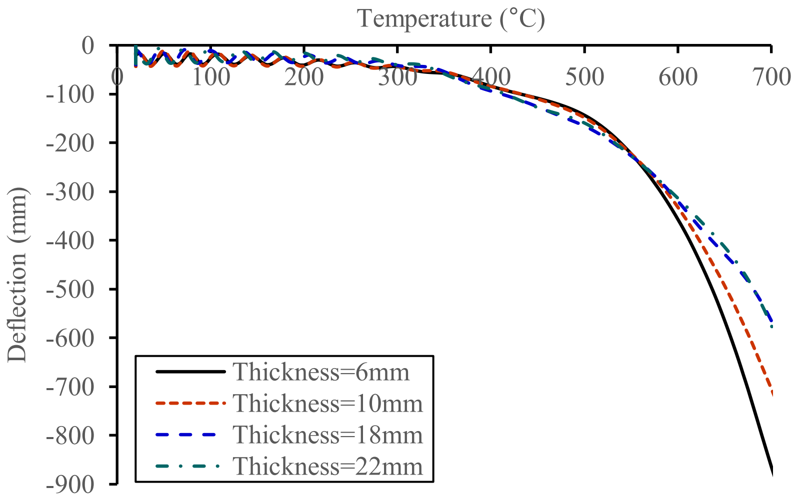


Fig. 12 Parametric study on the effect of connection plate thickness. Deflection of beam centre.

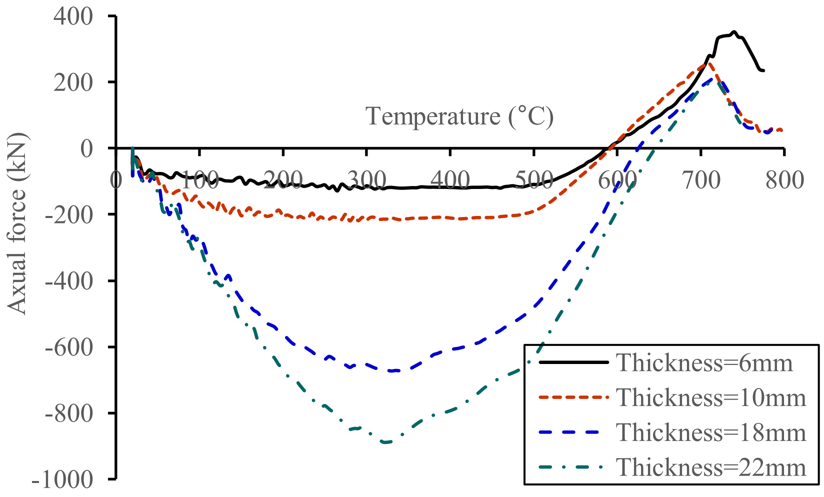


Fig. 13 Parametric study on the effect of connection plate thickness. Axial force of beam.

It can be concluded from the results of the parametric study that deflection of beam decreases with the increase of connection thickness, whilst larger axial forces are generated; these observations are completely logical. Further studies could establish optimisation criteria for effective connection thickness, but the greatest load capacities in the high-temperature catenary tension phase are shown for the thinner (or "normal") plate thicknesses. Other critical parameters, including load ratio, beam span, local passive fire protection, also need to be studied in order to postulate design principles for the novel connection, in order to take full advantage of its ductility in fire, as well as making it an efficient simple connector in normal service.

5 COMPONENT-BASED MODEL OF THE NOVEL CONNECTION

In order to save computational effort, only half of the central bay was created in the Abaqus simple frame model presented in Section 4; even with this simplification, each model took more than one day to complete a case. Such detailed FE simulations are not really suitable for use in practical fire engineering design, particularly where global frame analysis needs to be conducted. In like-against-like terms the component-based method involves the use of considerably fewer degrees of freedom, and therefore uses a much smaller computational model; it is a much more computationally efficient way to take into account all the problems involved in the investigation of connections in fire, such as large deformation, interactions between connections and connected structural members, and continuously changing material properties. The software Vulcan, developed by the Structural Fire Engineering Research Group at the University of Sheffield, is able to simulate connection behaviour in fire using the component-based method. Vulcan can be used to carry out 3D modelling in order to assess the performance, including eventual collapse, of steel-framed and composite structures in fire. A combination of static and dynamic solvers, which can make full use of the advantages of both types of solution process, developed by Sun (2012) has been implemented in Vulcan in order to model the whole behaviour of a structure from ambient temperature, through local failure to final complete collapse. To enable analysis of the effects of the novel ductile connection within global frame behaviour in fire scenarios, the component-based model of the novel connection will be implemented into Vulcan in the next phase of the work. The component-based model of the novel connection, in which each identical component row integrates six different types of component, has been developed and is shown in Figure 14.

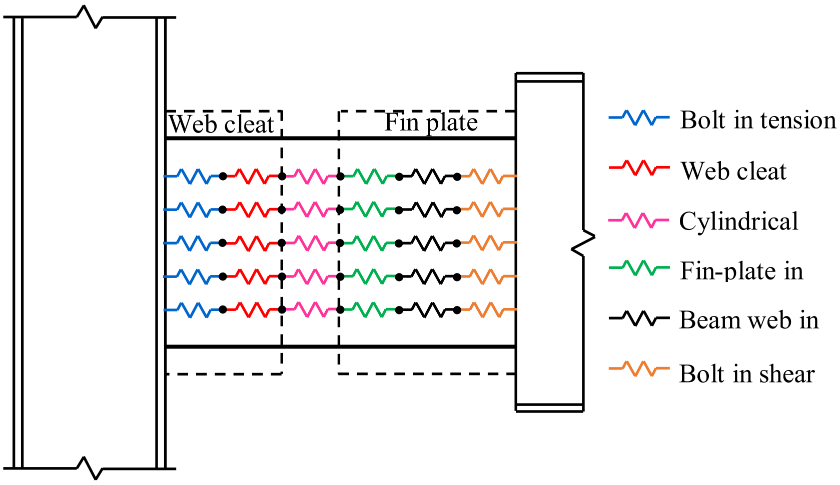


Fig. 14 Component-based model

Since there are five bolt rows in the design of the novel connection shown in Figure 2, the component-based model proposed here consists of five parallel component rows, each of which includes six springs in series. The properties of the "bolt in tension" spring are simply derived from the experimental stress-strain curves (Theodorou, 2001) of the bolt material at both ambient and elevated temperatures. The analytical model of the web-cleat connection developed by Yu (2009) is adopted here to describe the tensile behaviour of the "web-cleat" spring. These two types of springs act in series as the web-cleat part of the novel connection. The analytical model of semi-cylindrical section, presented in Section 3, is used to generate the force-displacement curves of the cylindrical section spring in both tension and compression; this represents most of the ductility for which the connection is designed. Three types of spring are employed to simulate the mechanical behaviour of the "fin-plate" part of the novel connection, including "fin plate in bearing", "beam web in bearing" and "bolt in shear". The properties of these three types of spring are those defined by Taib (2013) in her fin-plate model. As can be seen in Figure 15, there is a significant discrepancy between moment-rotation characteristics of the component model and the detailed Abaqus model.

Although the discrepancy in moment prediction is high compared to the absolute moment capacity of the connection, the range of moment generated is rather low compared with the beam's rotational moment capacity. This component-based model will be implemented into Vulcan to carry out global model studies of bare-steel and composite frames using the novel ductile connections in fire.

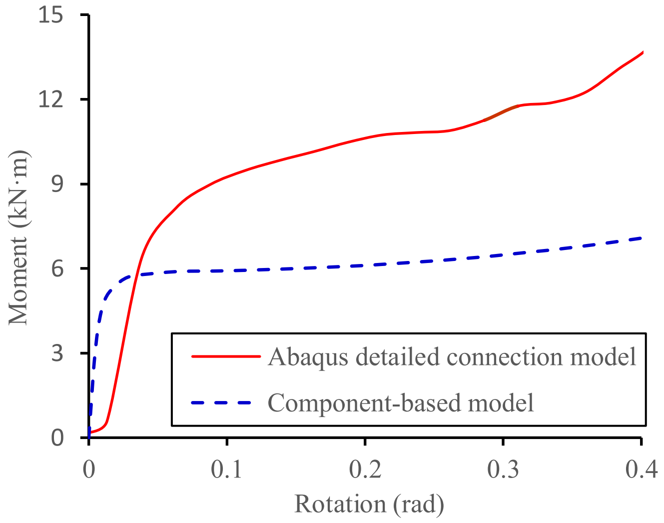


Fig. 15 Comparison of moment-rotation behaviour at ambient temperature of component-based and detailed FE models.

6 CONCLUSIONS

Ductility of connections is a key property in preventing abrupt failure and subsequent progressive collapse of framed structures in fire. Therefore, to provide the level of ductility needed to ensure the robustness of structures in fire, a new type of steel connection has been proposed, and component-based analytical models have been developed and tested. A preliminary investigation of the performance of the novel connection within a simple frame has been carried out using Abaqus, and a parametric study on the influence of connection thickness on the beam behaviour has been conducted. In comparison with the behaviour when web-cleat connections are used, it has been shown that the novel connection can provide sufficient ductility to reduce the axial forces generated in the connected beams. A simple component-based model has been developed; this will be implemented into Vulcan to enable global analysis of structures using these connections.

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