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The Robustness of Steel Connections in Fire

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Abstract

Connections are key components in framed structures, tying floor beams either directly to supporting columns or to primary beams. Failure of a connection could cause collapse of the connected beam, which could lead to further buckling of the column as it loses its lateral support, or to progressive collapse of floor slabs. In performance-based fire design, beams are sometimes allowed both to develop very large deflections and to support the floor by developing large catenary tension forces. The tying capacity of connections to transfer these significant forces to adjacent structure when they are already subject to high rotations is essential to maintain structural stability.

Traditionally, connections have been studied in terms of their moment-rotation behaviour alone. Some research has been performed on the tying capacity of connections at ambient temperature, mainly conducted in terms of a pure normal tying force. Recently however, some work has been done to investigate the behaviour of commonly used steel connections subjected to an inclined tying force at elevated temperatures. The effect of co-existent shear force and rotation on the tying capacity has been studied in furnace tests at different temperatures.

This paper discusses the results of these tests on four different connection types, and their implications. A key objective is to facilitate the inclusion of the major aspects of joint behaviour into global structural analysis for performance-based structural fire engineering design of steel-framed and composite structures by means of a component approach. The test results have been used to validate models of the principal components of such connections.

Key Words: *Connections, joints, robustness, fire, steel, tying forces, rotations, performance-based design.*

1. Introduction

Structural steel connections have been extensively investigated over the past three decades to determine their moment-rotation characteristics. However, the importance of tying capacity had been realized even earlier, since the explosion at Ronan Point (Bignell *et al.* 1977) in 1968 caused progressive collapse of a large part of the building. The UK structural steelwork design code BS5950 (2001) now requires connections to have minimum tying capacities. The UK SCI/BCSA (2002) design guidance checks the tying capacity as an isolated action, whereas in reality a combination of tying force, shear force and moment usually exists. For individual bolts, resistance to tying force may be affected by co-existence with other forces. For a complete bolted connection combined actions can prevent a uniform distribution of the resultant tying force between the bolts, causing them to fail sequentially, significantly reducing the tying capacity.

In design for fire resistance, the increasing adoption of performance-based design principles means that structures are now treated integrally in structural fire safety design. Connections, as the key components which tie structural members together, are important in maintaining structural integrity and preventing progressive collapse. Evidence from the collapse of the WTC buildings (NIST 2005, 2008) and full-scale fire tests at Cardington (Newman *et al.* 2004) have shown that connections are vulnerable to fracture in fire. Only limited research has been done on the performance of connections at elevated temperatures, most of which has concentrated on endplate connections, and has mainly been confined to moment-rotation behaviour. A further complexity is that interactions between structural members during heating cause continuous changes in the forces and moments taken by the connections.

The Universities of Sheffield and Manchester have conducted a joint research programme with the aim of investigating the capacity and ductility of steel connections at elevated temperatures. A recent trend in the design of composite floor systems has been to fire-protect beams on the main column grid, while leaving other beams unprotected. The protected beams eventually deflect considerably under the combined effect of high steel temperatures and enhanced loading, shed from the unprotected members, and will impose high tying forces on their connections. In non-composite steel construction, the beams deflect at high temperatures and experience catenary tension, which is transferred to the supporting structure through the connections. Previous tests (Ding 2007) have shown that connections can be subjected to tying forces varying from 0.65 to 1.6 times their shear force at high temperatures. Hence, the current investigation adopted a test setup in which the connections were subjected to a combination of tension and shear forces. Moments and rotations were generated at the connections due to the lever arm of the applied force. In total, four types of connection were studied; flush endplates, flexible endplates, fin plates and web cleats.

2. Test Setup

A detailed description of the test setup and test measurements has been given previously (Yu *et al.* 2007), so only a brief overview will be given here. The tests were performed in an electrically heated oven of 1.0m^3 internal capacity, as shown in Figure 1. The specimens were heated slowly to the specified temperature, and then loaded to failure at constant temperature. A special loading system was designed to allow very large rotation of the tested connection. It includes three link bars, each connected to a central pin, with their other ends respectively connected to the jack, the specimen and a fixed hinge. When the head of the jack moves downward, it applies a tensile force to the end of the specimen through the action of the linkage. The loading jack was displacement-controlled. The applied load was measured from strain-gauges attached to the bars. The deformations of the connection were measured using a digital camera facing the connection through a glass window in the oven door.

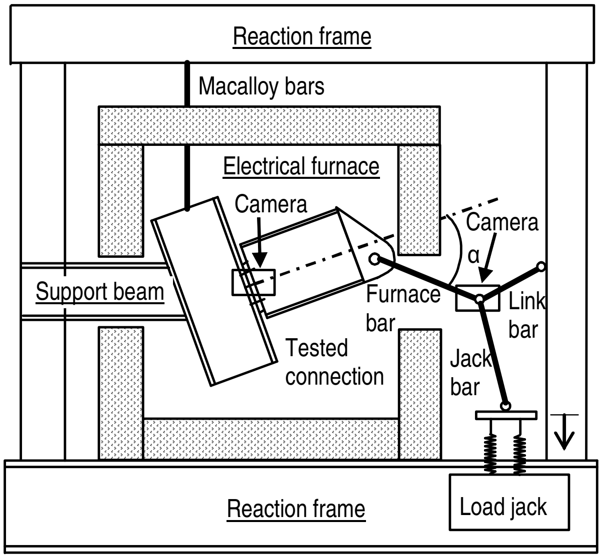

Figure 1. Test setup.

In all cases a UC254×89 section was used for the column, and the beam specimens were all UB305×165×40. A custom-made connector was bolted to the free end of the beam, and the load from the tie-bar was applied to this connector through a pin.

3. Semi-rigid connections - flush endplates

Flush endplate connections are widely used in the UK, and their moment-rotation characteristics have been investigated previously at ambient (Aggarwal 1994) and elevated (Al-Jabri *et al.* 2005) temperatures. Normal calculation of the tying capacity assumes that the connection is subjected to pure tension, and that each bolt row can contribute fully to the resistance of the connection. This is obviously impossible in practice. Co-existing actions may overload individual fasteners, which indicates that all the bolt rows cannot reach their maximum resistance at the same time if their behaviour is not ductile enough, and this may cause an “unzipping” failure.

Figure 2 shows the details of a typical connection. The arrangement of the bolts is typical of current UK design, with one exception. Although it is common practice to use an endplate 20mm thick, in order to serve the objective of developing a component-based model, it was desirable to generate various failure modes. Therefore, three endplate thicknesses, of 8, 10 and 15mm, were tested. Most tests used three bolt rows, as shown in Figure 2, but for two tests the middle bolt row was removed.

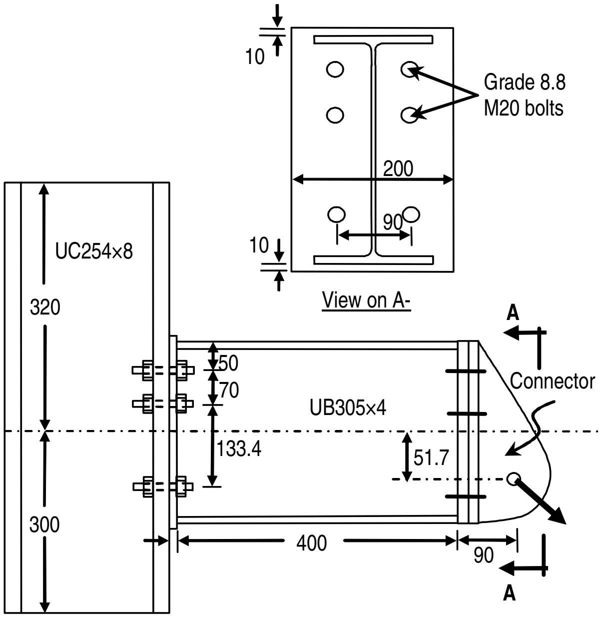

Figure 2. Typical endplate joint.

Connections were tested at three different combinations of shear and tying force, corresponding to different angles α in Figure 1. Three nominal initial angles α, of 55°, 45° and 35° were chosen between the axis of the steel beam and the furnace bar. Its value was monitored throughout the tests using two cameras. During each test the angle α changed progressively from its initial value, the degree of variation depending on the exact geometry of the loading system. In total, 17 tests were planned, but only 15 were successfully finished. In two cases the loading equipment failed and hence the maximum resistance was not achieved.

The force-rotation relationships for the tests using 10mm endplates are shown in Figure 3. At 550°C, the test at 45° was the first in this series. During this test the bolts failed by thread-stripping from the nuts. For this reason the force decreases progressively after 1.5° rotation. After this test two nuts were used on each bolt to prevent thread-stripping. The other tests were able to maintain a relatively stable resistance up to about 7°. The resistance of the connection reduced rapidly with increase of temperature. The load angle has some effect on the overall connection resistance, but not on the failure mode. Comparison of three 550°C tests with 8mm, 10mm and 15mm in Figure 4 shows the main effect of endplate thickness on the response of the connection; a thick endplate enhances resistance but significantly reduces ductility. The effect of removing one bolt row is shown in Figure 5, comparing 2 tests with 3 rows with 2 tests with 2 rows; removing the middle bolt row clearly reduces the resistance of the connection, but is seen from the results at 550°C also to reduce the ductility.

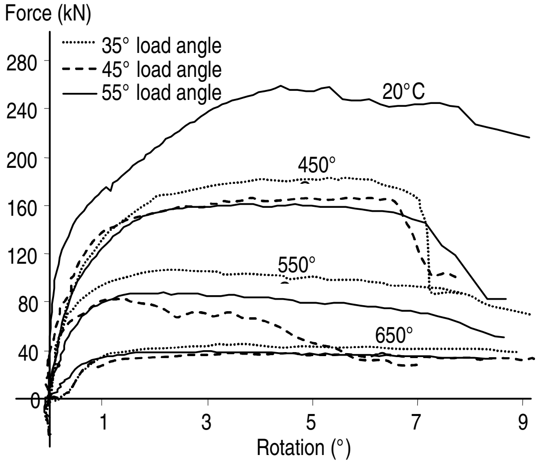

Figure 3. Force-rotation for 10mm endplate connections.

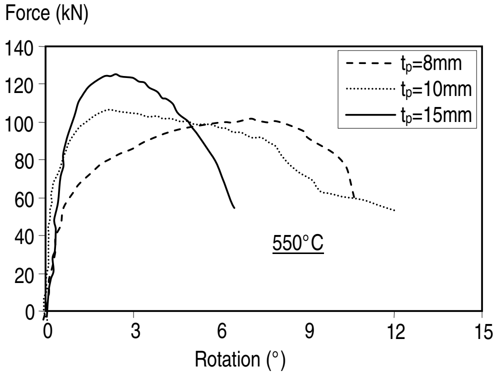

Figure 4. Effect of endplate thickness.

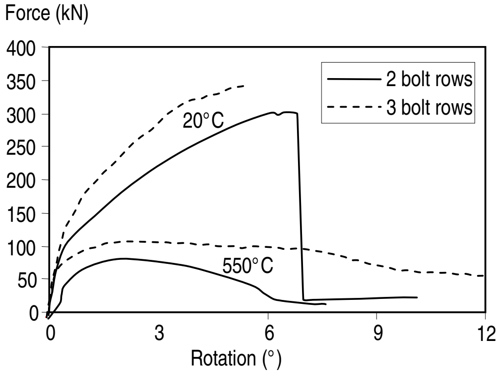

Figure 5. Effect of number of bolt rows.

For the tests with t_p=10mm and three bolt rows, two failure modes were observed. At 20°C and 450°C failure was controlled by endplate fracture; Figure 6 shows an example after a test at 450°C. This is a block-shear fracture of the endplate in the heat-affected zone of the welds, extending from the beam web to the free edge of the beam flange, producing a sudden drop of resistance at around 7° rotation. At 550°C and 650°C, failure was controlled by the very ductile bolt extension characteristics, as shown in Figure 7. Here the endplate is seen to have a moderate amount of bending deformation, and bolts were actually gradually pulled apart, with no obvious breaking point. When the top two bolts were completely fractured, at very large deformation, the middle two bolts had shown quite visible necking. Both rows of bolts had acquired significant bending deformations.

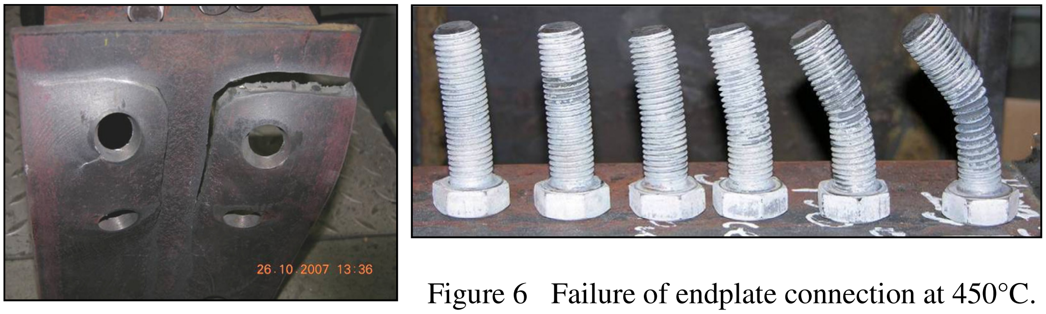

Figure 6 Failure of endplate connection at 450°C.

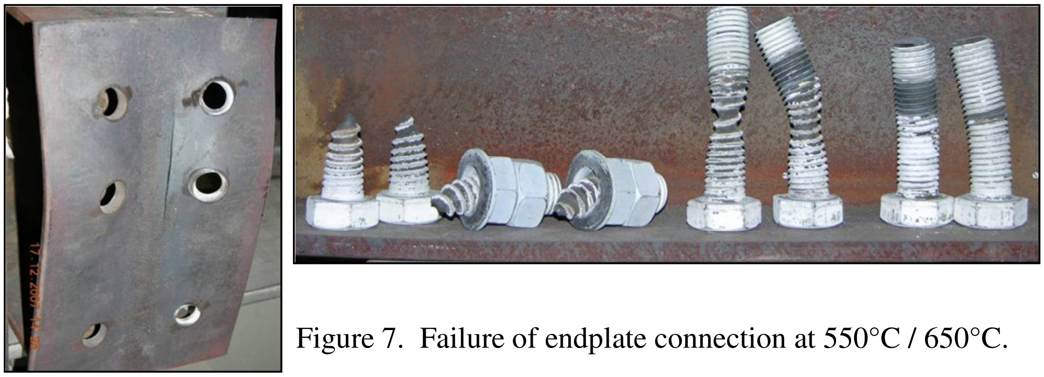

Figure 7. Failure of endplate connection at 550°C / 650°C.

For the 15mm thick endplate the failure was, unsurprisingly, controlled by the bolts. However, compared with the joints using thinner endplates, the bolts remained almost straight, and the endplate was almost undeformed after the test. In the tests using two rows of bolts, bolt fracture controlled the failure in both ambient- and high-temperature tests. At 20°C, the bolts caused significant bending deformation to the endplate before they underwent a brittle fracture. At 550°C, the endplate remained relatively straight.

4. Comparison with simple connections

Similar tests have been performed on commonly used simple connections, namely flexible endplate, fin plate and web cleat connections, designed according to "Green Book" (SCI & BCSA 2002) recommendations to connect columns and beams of these sizes. The responses of these simple connections are compared with the flush endplate connection in Figure 8. It can be seen that the major effect of the shear force is to generate a moment at the connection; the shear force itself at this level does not have a significant effect on the behaviour of the connection. Hence, the initial stiffnesses of the curves in Figure 8 are also their rotational stiffnesses. At all the temperatures tested, flush endplates clearly show rigidity compared to the other connection types. Their force-displacement curves are characterized by a rapid rise to peak resistance, and failure at low rotation angles.

All the flexible endplate connections tested failed by fracture of the endplate in the heat-affected zone adjacent to the welds to the beam web. This failure mode gives this connection type very low rotational capacity at high temperatures. At ambient temperature, the performance of flexible endplate connections is comparable to that of other simple connections, in terms both of resistance and rotation capacity.

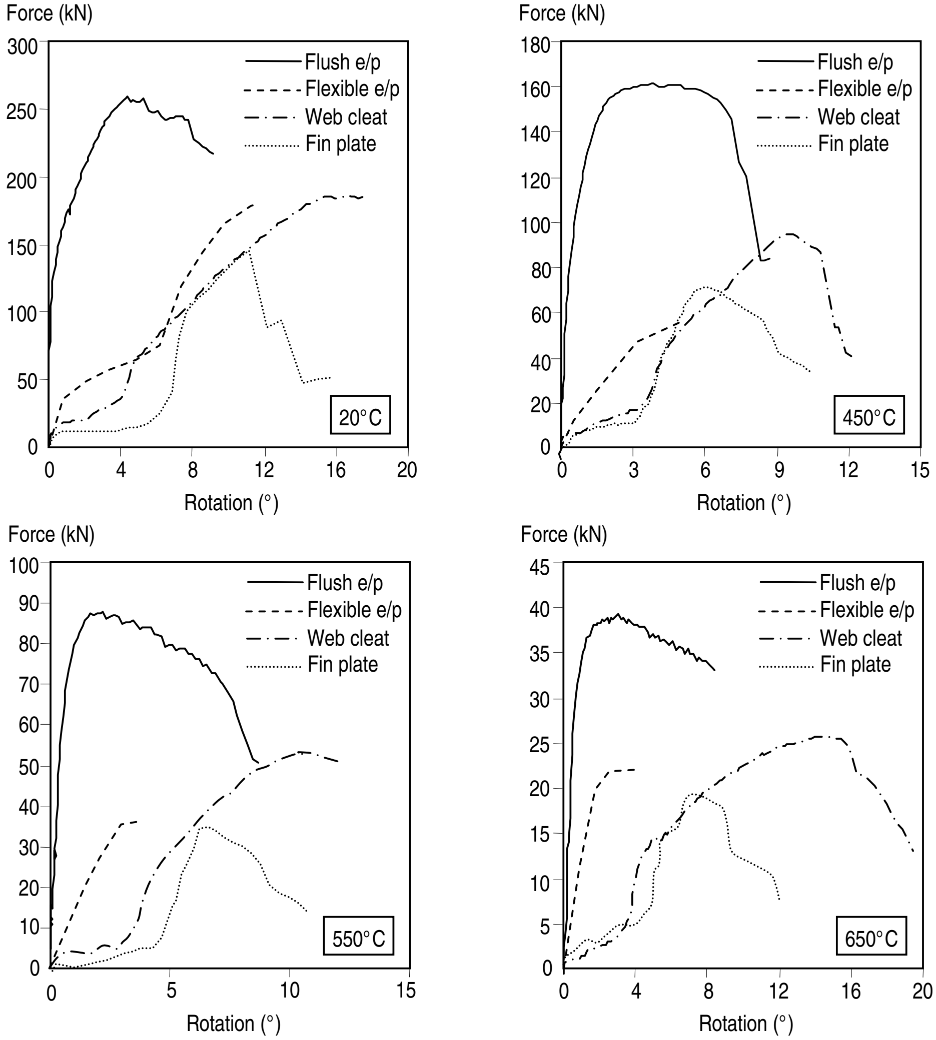

Figure 8. Comparison of the behaviour of different connection types.

All the fin plate connections tested failed by shear fracture of their bolts. Bolt clearance at holes allowed the connection a rotation of up to 4° before the bearing surfaces were in contact. This gave them a rotation capacity slightly better than that of flexible endplates. The "Green Book" states that bolt shear fracture can be avoided by limiting the thickness of the bearing plate to less than half of the bolt diameter. This proved to be inadequate at high temperatures, although at ambient temperature the bolts did cause bearing deformation of the bolt holes, and increased the rotation capacity by 2-3°. Other tests (Yu *et al.* 2009), using Grade 10.9 bolts, successfully changed the failure mode to block-shear fracture of the beam web, and increased the rotation capacity by about 3° at ambient temperature. However, this benefit is not seen at high temperatures, since the failure is again by shear fracture of the bolts.

The web cleat connections failed in a more complex fashion. At ambient temperature, the bolt head punched through the angle connected to the column flange. At 450°C and 550°C, the angle fractured close to its heel at a significantly smaller deformation than at ambient temperature. At 650°C, the ductility of the angle seemed to have improved again, and failure of the connection was by shear fracture of the bolts through the beam web. At all temperatures web cleat connections showed high rotation capacity, due to the "straightening" of the angle cleats. With the increase of rotation, the load capacity increased steadily, which gave the web cleat connections a significantly higher ultimate resistance than the other simple connections.

5. Design implications

Connections within a structural sub-frame, if heated together with the beams that they support, will initially be subjected to compressive forces due to the restrained thermal expansion of the beams. The magnitude of this force depends on the span of the beam and the axial restraint stiffness provided by the connections themselves and adjacent structure. Some connections, such as fin plates, can fail due to this force. Although this has been suggested as the cause of failure of WTC 7 (NIST 2008), it has never been observed in the UK, probably because the multi-storey composite-framed structures typical of UK practice provide less axial restraint to beams. Endplate connections cannot fail under compressive forces.

If the connections do not fail under compressive forces, then the compression will continue to increase until the beam reaches its limit capacity under the combined effect of the bending moment and compression. It then experiences a rapid increase of deflection, and attenuates the compression force to a limiting value as the thermal expansion is accommodated by the deflection. With further temperature increase the progressive reduction of steel strength decreases the compressive force, to the extent that the axial component eventually becomes tensile. This tension increasingly takes over from the bending resistance of the beam in carrying the loads by "catenary action". At this stage the upper bound to the tensile force is given by the lower of the reduced strengths, at the appropriate temperatures, of the beam or its connections. This has been demonstrated in small-scale structural frame tests by Ding (2007). In UK construction the beam-end connection is almost always weaker than the beam section which it connects, especially since the normal tying force tends to be greatest when the connection has already experienced a very high rotation.

The capacities in terms of moment, tying force and rotation are completely inter-dependent. The relationship between moment capacity and tying capacity of can be established with relative ease. Both are based on the tensile behaviour of each bolt row. Increase of the connection moment will decrease its tying capacity and vice versa. The rotation of a connection is the most important influence on its strength and on its ductility in terms of movement of the beam-end relative to the column face. Semi-rigid or rigid connections, which have higher moment resistances, generally have lower rotational capacity than simple connections, which may limit their application to develop catenary action.

It is not necessary to consider these three parameters directly in order to establish the limit state of a connection in fire. In most cases a component-based model can provide a sufficiently accurate and practical solution to the modeling of connections in fire. Previously component-based models have been developed mainly for endplate connections at ambient temperature, in order to generate rotational stiffnesses and moment capacities for semi-rigid frame design. The Sheffield group has now conducted several successive research projects on steel connection behaviour in fire, culminating in the test program and numerical modelling of this research project. The behaviour of most components of the four connection types tested has been represented in simplified high-temperature non-linear spring models. Because of the need to emphasise the issue of robustness in fire, it is necessary for these models to have two innovative characteristics:

1. The pre-peak part of the load-displacement curve for a component can be as important as the peak resistance, since uniform distribution of displacement to all the bolt rows is unlikely.
2. Formation of a yielding mechanism is not necessarily synonymous with fracture. The behaviour of each component up to large deflection or fracture is necessary.

Following these basic principles, component-based models have been developed for use in modeling the four types of connection studied in this project, and these have been shown to predict the connection behaviour with satisfactory accuracy.

A few general conclusions may be drawn about the behaviour of these connections:

1. The rotational capacity of a connection is mainly determined by the deformational ductility of its components, together with the lever arm between the top bolt row and the compressive fulcrum, which is usually the bottom flange of the beam. The ductility of these components can be affected by temperatures.
2. A general conclusion which applies to all bolted connections is that the strength of bolts is reduced more rapidly at high temperatures than that of hot-rolled steel. For some connections, whose ductility is maintained by avoiding bolt failure, this needs to be considered for robustness in fire, and the use of stronger boltsthan are needed for ambient-temperature design is recommended.
3. For fin plate connections, details which can increase include using stronger bolts and higher bolt hole clearances. Tests have shown that, if the failure mode can be changed from bolt shear fracture to plate block shear, the rotational capacity can be increased considerably.
4. For flush endplate connections, ductility is mainly due to bending deformation of the endplate. Hence, thin endplates should be used where ductility is required.

For all the connections, ductility is enhanced if the bolt rows are placed as close to the lower flange of the beam as possible. However, this also causes a significant sacrifice of moment capacity.

6. Concluding remarks

This paper has summarized some of the major outcomes from a research project on robustness of steel connections in fire. This has included a test programme on four types of commonly used steel connections, and development of component-based models. Flush endplate connections were the only semi-rigid type tested; the other three were typical of "simple" construction. The resistance of connections to fracture in framed construction depends most critically on three parameters: moment, tying force, and connection rotation. The complexity of their inter-relation makes it difficult to determine the failure of a connection simply. A practical solution is to represent the connection behaviour by component-based models, and to incorporate them directly in global structural modelling.

More detailed studies are needed on failure of bolts at high temperature, both in shear and in tension. The resistance of bolts was observed to reduce gradually with progressive deformation, after reaching a fairly early peak. Simple models have been proposed by Yu *et al.* (2009a, 2009b) to account for this behaviour. In general, there is a lack of reliable criteria for the final fracture of steels at elevated temperatures, and this information is crucial if the robustness of steel framed structures is to be investigated analytically using modeling. The co-existence of vertical shear affects the moment and tying capacities of some connection types, such as the fin plate and the web cleat. In some respects this effect is easy to consider, but it is not yet known how this can be implemented in component-based models.

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References

Aggarwal A.K. (1994), Comparative Tests on Endplate Beam-to-Column Connections, *J. Construct. Steel Research*, **30**, pp 151-175.

Al-Jabri K.S., Burgess I.W., Lennon T., Plank R.J. (2005), Moment-rotation-temperature curves for semi-rigid joints, *J. Construct. Steel Research*, **61**, pp 281-303.

Bignell, V., Peters, J., and Pym, C. (1977), *Catastrophic failures*, Open University Press, Milton Keynes.

BS5950 (2001), *Structural Use of Steelwork in Building- Part 1: Code of practice for design-Rolled and welded sections,* British Standards Institution, London.

Ding, J. (2007), *Behaviour of Restrained Concrete Filled Tubular Columns and Their Joints in Fire*, Ph.D Thesis, University of Manchester, UK.

Newman, G.,M., Robinson, J.,T., Bailey, C.,G. (2004), *Fire Safety Design: A New Approach to Multi-Storey Steel-Framed Buildings*, The Steel Construction Institute, Ascot.

NIST (2005), *Final Report on the Collapse of the World Trade Center Towers*, National Institute of Standards and Technology, USA.

NIST (2008), *Final Report on the Collapse of World Trade Center Building 7*, U.S. Department of Commerce and National Institute of Standards and Technology, USA.

SCI & BCSA (2002), *Joints in steel connection, Simple connections,* The Steel Construction Institute and British Constructional Steelwork Association, UK.

Yu H.X., Burgess I.W., Davison J.B., and Plank R.J., (2009a), Experimental Investigation of the Behaviour of Fin Plate Connections in Fire, *J. Construct Steel Research,* **65,** pp 723–736.

Yu, H.X., Burgess, I.W., Davison, J.B. and Plank, R.J. (2007a), Experimental Investigation of the Behaviour of Fin Plate Connections in Fire, Proc. ICSCS 2007, Manchester, pp 541-548.

Yu, H.X., Burgess, I.W., Davison, J.B. and Plank, R.J. (2007b), Experimental Investigation of the Robustness of Fin Plate Connections in Fire, Proc ICASS 2007, Singapore.

Yu H.X., Burgess I.W., Davison J.B., and Plank R.J., (2009b), Tying Capacity of Web Cleat Connections in Fire Part 1: Test and Finite Element Simulation, *Engineering Structures*, (in press).