DEVELOPMENT OF A GENERAL COMPONENT-BASED CONNECTION ELEMENT FOR STRUCTURAL FIRE ENGINEERING ANALYSIS

Gang Dong[a], Ian Burgess[b] and Buick Davison[b], Ruirui Sun[a]

[a]MMI Engineering, Warrington, WA4 6NL
[b] Department of Civil and Structural Engineering, University of Sheffield, Sheffield S1 3JD,
e-mails: gdong@mmiengineering.com, ian.burgess@sheffield.ac.uk,
j.davison@shef.ac.uk,rsun@mmiengineering.com

Abstract

This paper reports on the development of general-purpose component-based connection finite element intended to model the performance of steel-to-steel joints in fire. The element is generally consistent with Eurocode principles. The development began with the creation of an assembled component-based finite element to represent the flush endplate connection type, in the main using temperature-dependent connection component characteristics which had previously been developed at the University of Sheffield for behaviour up to very high distortions and ultimate fracture, as well as for force reversal. In subsequent work, components for the reverse-channel have been characterized and validated against both numerical modelling and high-temperature testing. The element has been incorporated into the nonlinear global structural analysis program *Vulcan*, developed at the University of Sheffield.

Keywords: connections, composite columns, robustness

INTRODUCTION

The performance of a steel framed structure in fire is significantly influenced by the response of its beam-to-column connections under complex combinations of shear, bending and axial forces. Observations from the full-scale fire tests at Cardington, and the collapse of the buildings at the World Trade Centre in 2001, have raised concerns that joints are potentially the weakest parts of a structure (Burgess, 2007). To accurately predict the behaviour of steel frames in fire, it is essential to include the effects of connection behaviour; in particular the combined effect of axial load and co-existent large rotation, and the reduction of strength and stiffness with increased temperature. This has aroused interest in enabling engineers to predict the behaviour of connections in fire, track the progressive collapse sequence, and design robust structures on performance-based principles.

One approach is to conduct full-scale or isolated fire testing, which is so expensive that it cannot economically produce a sufficient database of results for direct practical design purposes. Alternatively, the creation of detailed FE models of sub-structures can be very accurate, provided that they include the connections and that the analysis is non-linear in terms of material and geometrical changes with temperature. However, the computational expense is often prohibitive for general design purposes.

Tschemmernegg (1987) and others proposed the well-known practical approach to representing connections for semi-rigid design, known as the Component Method, which now has been included in Eurocode 3 (2005). This is an intermediate method, requiring the minimum of computational effort while retaining the key characteristics of connection behaviour and offering accepTab. predictions of frame behaviour. This paper reports on the development of a general-purpose component-based connection finite element intended to model the large-deflection performance of steel-to-steel joints in fire. The element is generally

consistent with Eurocode principles. This development took place within the COMPFIRE project (RFCS, 2008), on the behaviour in fire of connections to composite (concrete-filled and partially-encased) columns. The reverse-channel connection, shown in Fig. 1(b), has proved to be capable of higher ductility than all conventional types under the large deflections and rotations which can occur in fire (Huang, 2011).
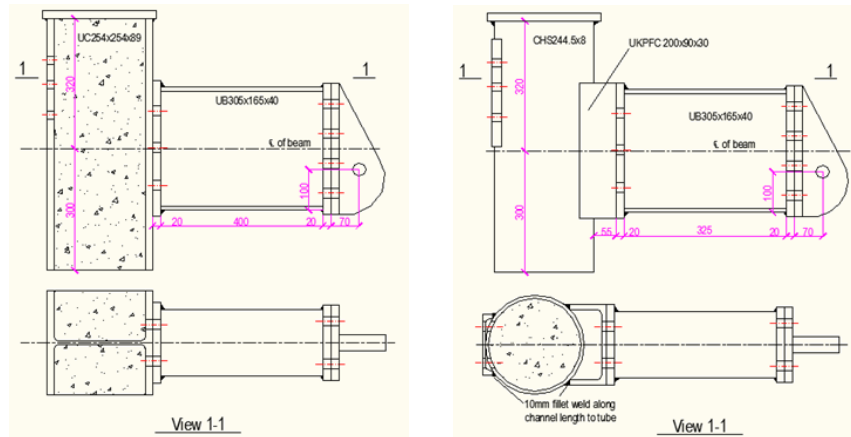

Fig. 1: (a) Endplate and (b) reverse-channel connections to composite columns (Huang, 2012).

1 DEVELOPMENT PROCEDURE

Following the principles of the component method, the connection is divided into several key components which contribute to its deformation and ultimately limit its capacity (Block, 2006). Each key component is characterized as a horizontal temperature-dependent non-linear spring which includes inelastic behaviour and a failure limit. These springs are assembled between rigid "bars" to model the connection behaviour. The connection element is then able to deal with very high distortions and ultimate fracture, as well as unloading.

2 GENERAL-PURPOSE COMPONENT ASSEMBLY

Fig. 2 presents a schematic illustration of the component assembly of a simple connection. The identified active components are assembled between rigid surfaces to represent the whole connection. In its implementation the connection assembly is designed to include a maximum of five tension spring (bolt) rows and two compression spring rows. Node 1 is located at the intersection between the beam and column reference axes. Node 2 is the end-node of the beam. Vertical shear behaviour has not so far been included in the assembly, and the connection is therefore assumed to be rigid in the vertical shear direction. The connection element is assumed to have no physical length since the modelled connection length (in the vicinity of the column face) is relatively small compared with the attached beams (Li, 1995).
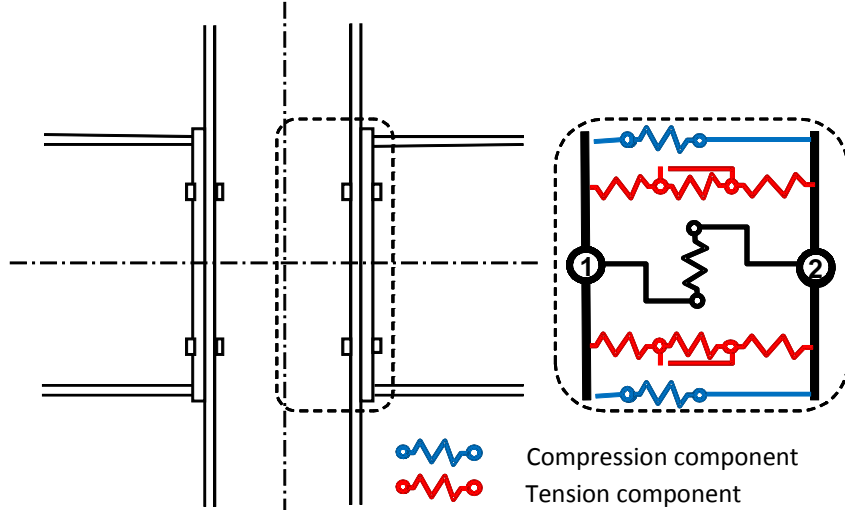
Fig. 2: Schematic component assembly (Block 2006).

3 COMPONENT MODELS

Connections in fire are generally subject to extremely large deformations, which take them considerably out of the elastic range, and therefore the adopted component characteristics must not only be able to deal with the initial stiffness and elastic limit for ambient-temperature design, but also to consider the plastic resistance and ductility over a range of elevated temperatures. This connection element largely uses component characteristics which have been developed in previous projects, by Spyrou (2002), Block (2006), and Yu (2009). In addition, component models for the less conventional reverse-channel connection have been characterized in the course of the COMPFIRE project (RFCS, 2012a).

4 INCORPORATION OF THE CONNECTION ELEMENT INTO *VULCAN*

Block (2006) first derived the tangent stiffness matrix ($K_c^{'}$) of the connection element, shown as Eqn. 1. The out-of-plane and torsional DOF are assumed to be connected rigidly, and without interaction, because these are currently under development and are in any case of relatively minor importance in steel or composite building structures.

$$K_C^{'} = \begin{bmatrix} K_{11}^{'} & 0 & 0 & 0 & K_{15}^{'} & 0 & -K_{11}^{'} & 0 & 0 & 0 & -K_{15}^{'} & 0 \\ 0 & \infty & 0 & 0 & 0 & 0 & 0 & -\infty & 0 & 0 & 0 & 0 \\ 0 & 0 & K_{33}^{'} & 0 & 0 & 0 & 0 & 0 & -K_{33}^{'} & 0 & 0 & 0 \\ 0 & 0 & 0 & \infty & 0 & 0 & 0 & 0 & 0 & -\infty & 0 & 0 \\ K_{51}^{'} & 0 & 0 & 0 & K_{55}^{'} & 0 & -K_{51}^{'} & 0 & 0 & 0 & -K_{55}^{'} & 0 \\ 0 & 0 & 0 & 0 & 0 & \infty & 0 & 0 & 0 & 0 & 0 & -\infty \\ -K_{11}^{'} & 0 & 0 & 0 & -K_{15}^{'} & 0 & K_{11}^{'} & 0 & 0 & 0 & K_{15}^{'} & 0 \\ 0 & -\infty & 0 & 0 & 0 & 0 & 0 & \infty & 0 & 0 & 0 & 0 \\ 0 & 0 & -K_{33}^{'} & 0 & 0 & 0 & 0 & 0 & K_{33}^{'} & 0 & 0 & 0 \\ 0 & 0 & 0 & -\infty & 0 & 0 & 0 & 0 & 0 & \infty & 0 & 0 \\ -K_{51}^{'} & 0 & 0 & 0 & -K_{55}^{'} & 0 & K_{51}^{'} & 0 & 0 & 0 & K_{55}^{'} & 0 \\ 0 & 0 & 0 & 0 & 0 & -\infty & 0 & 0 & 0 & 0 & 0 & \infty \end{bmatrix} \quad (1)$$

in which

$$K_{11}^{'} = \sum_{i=1}^{n} k_{T,i}^{'} + \sum_{i=1}^{2} k_{C,i}^{'} \quad (2)$$

$$K_{15}^{'} = K_{51}^{'} = \sum_{i=1}^{n} l_{T,i} k_{T,i}^{'} + \sum_{i=1}^{2} l_{C,i} k_{C,i}^{'} \qquad (3)$$

$$K_{33}^{'} = k_{s}^{'} \qquad (4)$$

$$K_{55}^{'} = \sum_{i=1}^{n} l_{T,i}^{2} k_{T,i}^{'} + \sum_{i=1}^{2} l_{C,i}^{2} k_{C,i}^{'}$$

$$(5)$$

In which the subscripts 'T' and 'C' represent components working in tension or compression, and n is the number of bolt rows. The subscript 's' denotes a shear component.

This tangent stiffness matrix has been incorporated successfully into a version of *Vulcan* which incorporates alternate static and dynamic analysis solvers, attempting to use both to best advantage (Sun, 2012). Fig. 3 shows the flow-chart for modelling of a connection failure sequence. Generally a quasi-static analysis solver is used, up to the point at which the first component fails. From this point the dynamic solver is activated to track the structural behaviour. If stability is not regained, this initiates a cascade of failures of the other components, leading to complete detachment of the members.
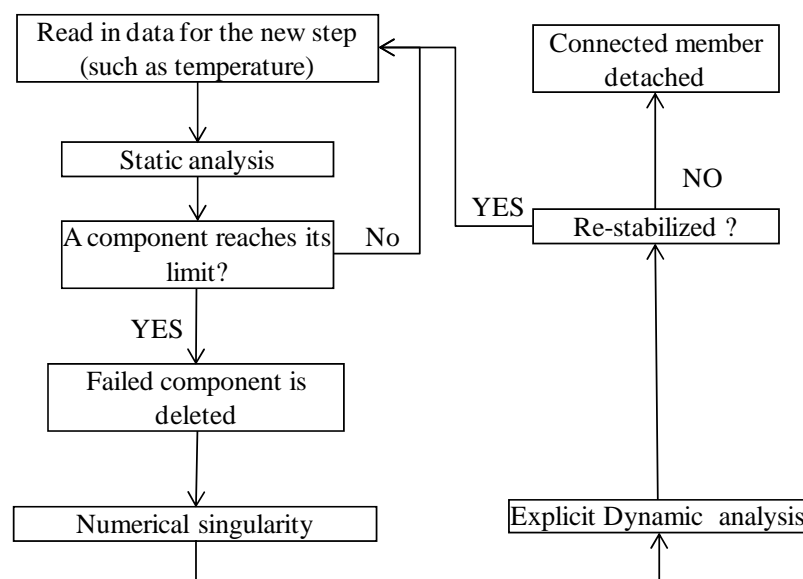

Fig. 3: procedure of connection failure modelling

5   APPLICATION OF THE CONNECTION ELEMENT

Within the COMPFIRE project the University of Manchester completed four sub-frame tests with reverse channel connections (RFCS, 2012b). A global finite element model was analysed in *Vulcan* to test the behaviour of the connection element within this subframe. Fig. 4 shows the schematic set-up of the model in *Vulcan* for test TD1. As the applied loads were actually released in an uncontrolled manner during the cooling phase of the test, this analysis does not consider cooling. The column section was CHS 244.5x8, the beam UB 178x102x19 and the connection used a reverse-channel cut from a UK SHS 180x180x42.7. The structure was heated after the applied load *(F)* had reached 40kN, and this applied load was maintained throughout the test.

Fig. 5 shows the curve of beam mid-span deflection against the average temperature in the beam's bottom flange. The analytical curve initially stays close to the test result, but beyond 682°C the deflection begins to rise sharply. At 745°C, the maximum deflection of 220mm is reached, and at this point both of the tension bolt rows are shown as failing due to the bolt heads pulling-out of their holes in the reverse channel. The failure identified in the test was actually bolt thread-stripping, which means that the model used to characterize bolt pull-out is probably on the conservative side.
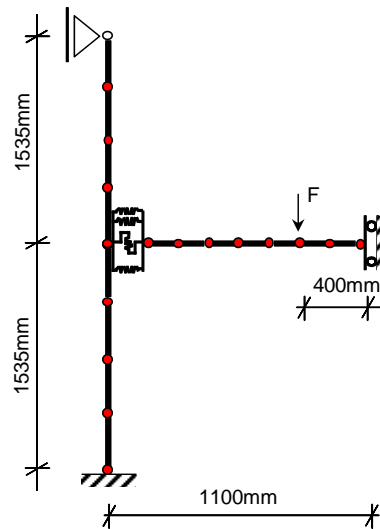
Fig. 4: Sub frame model of Manchester Test TD1 (RFCS, 2012b)
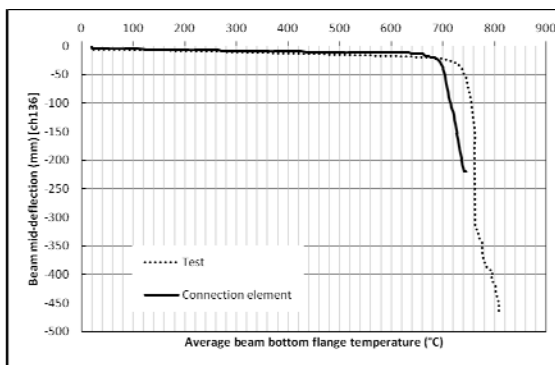

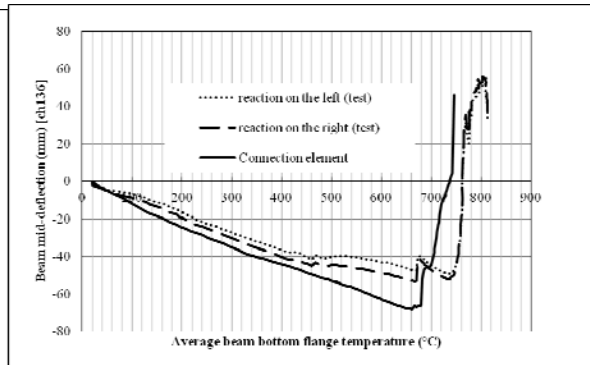Fig. 5: Mid-span deflection   Fig. 6: Axial force in the connection

Fig. 6 presents the connection axial force-temperature relationships; the temperature used for reference is the average test value in the beam bottom flange. The test axial force is the sum of the horizontal reaction forces recorded in the load cells. There is a small initial force, generated when the 40kN load was applied at ambient temperature. The beam's axial compressive force stays close to the test value in the initial heating phase. At around 660 °C the axial force reaches its maximum compressive value, beyond which it declines sharply. At around 745°C the axial force in the connection changes from compression to tension, and the beam enters the catenary-tension phase of its behaviour. Fig. 7 shows the movements of the spring rows in the connection. The movement of the top and bottom spring rows reached over 20mm in the catenary stage. This was possible because the reverse channel connection mobilized considerable ductility. Fig. 7 also shows that the component-based connection element is capable of tracking the behaviour of the reverse-channel connection.
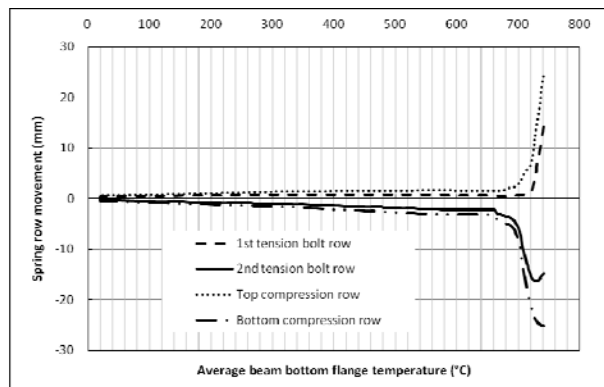
Fig. 7: Spring row movements in Test TD1.

6   CONCLUSION

The component-based connection element, implemented in the *Vulcan* software, has been checked against a sub-frame test conducted at the University of Manchester. In Fig.s 5 and 6 it has demonstrated very accepTab. representations of the global test behaviour, and could provide a practical way of modelling the influence of connections in global analysis. The connection element has been shown in this paper to predict the behaviour and ductility of components up to their first fracture within joints in structural fire scenarios. In other recent studies (Sun, 2012) the element has been tested with a dynamic solver to allow progressive failures of components to be tracked. This is intended to make it possible for progressive failure of buildings to be predicted in scenario-based analytical design against fire.

7   ACKNOWLEDGEMENT

REFERENCES

Block, F.M. (2006), 'Development of a component-based finite element for steel beam-to-column connections at elevated temperatures', PhD Thesis, University of Sheffield.

Burgess I.W. (2007), 'Connection modelling in fire', Proc. COST C26 Workshop "Urban Habitat Constructions under Catastrophic Events", Prague, (2007) pp 25-34.

CEN (2005), EC3: Design of steel structures, Part 1.8: Design of joints, European Committee for Standardization, Document BS EN1993-1-8: 2005.

Dong, G., Burgess, I.W. and Davison, J.B. (2011), 'Component-based element for endplate connections in fire', Proc. ASFE 2011, Prague, April 2011, pp 195-200.

Dong, G., Burgess, I.W. and Davison, J.B. (2012), 'Application of a general component-based connection element in structural fire analysis', Proc. 11th Int. Conference on Steel, Space and Composite Structures, Qingdao, China.

Heistermann, T., Iqbal, N., Veljkovic, M., Lopes, F., Santiago, F. and Simões da Silva, L. (2011) 'Finite element modelling of reverse-channel connections at elevated temperature', EUROSTEEL 2011, Budapest, Hungary. August 31 - September 2, 2011.

Huang, S.-S., Davison, J.B. and Burgess, I.W. (2011), 'Elevated-temperature tests on joints to composite columns', Proc. 6th European Conference on Steel Structures, Budapest, Hungary, pp1593-1598.

Huang, S.S., Burgess, I.W. and Davison, J.B. (2012), 'Robustness of joints to composite columns in fire', Proc. 11th Int. Conference on Steel, Space and Composite Structures, Qingdao, China,.

Li, T.Q., Choo, B.S. and Nethercot, D.A. (1995), 'Connection element method for the analysis of semi-rigid frames', Journal of Constructional Steel Research, 32, pp. 143-171.

RFCS (2008), Design of joints to composite columns for improved fire robustness, Research Fund for Coal and Steel, Grant agreement n° RFSR-CT-2009-00021, European Commission, Belgium.

RFCS (2012a), Deliverable 3 (D3) Report on simplified structural behaviour of components Research Fund for Coal and Steel, Grant agreement n° RFSR-CT-2009-00021, European Commission, Belgium.

RFCS (2012b), Deliverable 6 (D6) Recommendations on accurate and efficient FE modelling of composite structures under fire loading incorporating realistic joint behaviour. Research Fund for Coal and Steel, Grant agreement n° RFSR-CT-2009-00021, European Commission, Belgium.

Tschemmernegg, F., Tautschnig, A., Klein, H., Braun, Ch. and Humer, Ch. (1987), "Zur nachgiebigkeit von rahmenknoten – Teil 1" (Semi-rigid joints of frame structures Vol. 1– in German), Stahlbau 56, Heft 10, pp299-306.

Spyrou, S. (2002), 'Development of a component-based model of steel beam-to-column joints at elevated temperatures', PhD Thesis, University of Sheffield.

Sun, R.R., Burgess, I.W., Huang, Z.H. and Dong, G. (2012), 'Modelling of progressive failure of connections and ductility demand of connections in fire', 7th International Conference: Structures in Fire, Zurich

Yu HX, Burgess IW, Davison JB and Plank RJ (2009), 'Development of a yield-line model for endplate connections in fire', J. Construct. Steel Research, Vol. 65 (6), pp. 1279-1289.