HIGH-TEMPERATURE EXPERIMENTS ON JOINT COMPONENT BEHAVIOUR

F. M. Block[1], I. W. Burgess[1], J. B. Davison[1] and R. J. Plank[2]

[1] Department of Structural and Civil Engineering, University of Sheffield,
Sheffield, S1 3JD, UK
[2] School of Architectural Studies, University of Sheffield,
Sheffield S10 2TN, UK

ABSTRACT

This paper describes the comparison of a series of high-temperature experiments on column webs under transverse compression at different axial load ratios and temperatures with a simplified design approach. The study forms a part of an ongoing project aimed at developing high-temperature models for the behaviour of the main components of steel end-plate beam-to-column connections in fire. In this particular phase of the work the emphasis is on the compression zone in the column web, when transverse compression acts simultaneously with axial compression due to superstructure loading. The ultimate objective is to be able to construct component-based models of end-plate joints in global numerical modelling of steel and composite building structures in fire conditions. This is the only feasible analytical approach to joint modelling under the simultaneous effects of loading, thermal degradation of materials and forces due to restraint to thermal expansion.

KEYWORDS

Structural fire engineering, high temperature experiments, steel joints, component method, compression zone, initial stiffness.

INTRODUCTION

Partially fire-protected steel and composite frames, which have been built extensively in the UK in recent years, need to withstand forces and deformations in a fire which are different from those caused by the design limit states at ambient temperature. One major difference is the development of axial forces in the beams. Initially these are compressive, due to restrained thermal expansion, but they later become tensile as catenary action is developed when the beams lose their bending resistance and behave like cables hanging between the supports, as shown by Liu *et al.* (2002). During the cooling stage of the fire the plastically deformed beams contract significantly and experience further tension forces as described by Bailey *et al*. (1996).

To ensure that the frame survives the fire, the beam-to-column joints must be robust enough to transfer these forces into the columns and any surrounding cold structure. Furthermore, recent research by Yin *et al.* (2004) has shown that the magnitude of the axial forces developed depends strongly on the stiffnesses of the joints and the surrounding structure. All this shows clearly the need to include realistic joint stiffness and resistance in global analysis of steel and composite frames in fire.

Because of the nonlinear interaction of joint loads and the large number of possible variables in the detailed design of a beam-to-column joint, a versatile approach for calculating the rotational and axial stiffness and also the capacity of joints at elevated temperature is required. With the Component Method, which was initially developed by Tschemmernegg *et al.* (1987) and later introduced into the draft Eurocode EC3 Part 1.8 (2003), such an approach is given. The original feature of this method is to consider any joint as a set of individual basic spring-like components. In the particular case illustrated in Fig. 1, which shows an external beam-to-column joint using an extended end-plate connection which is subject to moment and axial force, the joint is divided into the three major zones (tension, shear and compression), and then each zone is divided into the relevant components.

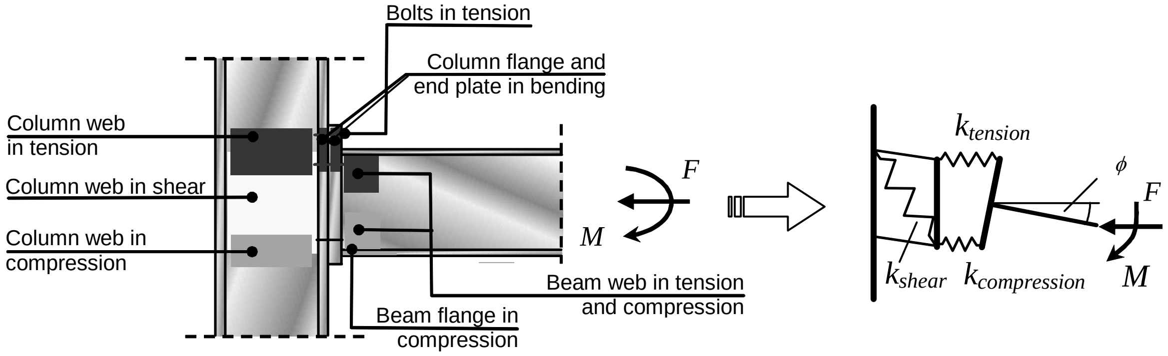

Fig. 1: Components of a beam-to-column joint and the appropriate simple spring model

For each component the nonlinear stiffness and maximum force is computed and assembled to form a spring model, which represents the behaviour of the whole joint. In structural fire analysis each component will have its own temperature-dependent force-displacement curve and the whole joint will therefore interact realistically with the surrounding structure.

Cruciform connection tests at elevated temperatures conducted by Leston-Jones (1997) have shown that an unstiffened compression zone in the column web can be the critical component from the three zones in the connection if rotational capacity is needed, because of its limited ductility. In composite connections this zone becomes even more critical because of the stronger tension zone and greatly increased lever arm produced by continuing slab reinforcement. In a building fire the compression zone becomes even more critical because of restraint to the thermal expansion of the steel beams, which causes enhanced compressive forces in the column web.

After an extensive high-temperature experimental programme and finite element modelling, semi-empirical simplified models for the force-displacement behaviour of the compression zone have been developed by Spyrou *et al.* (2004) and Block *et al.* (2004a). In these studies the axial load in the column has been neglected, although at ambient temperature research by Kühnemund (2003) has shown that the axial load has an influence on the maximum load and displacement of this component. In order to investigate this influence at elevated temperatures a finite element study was conducted. From this study it was found that the influence of axial force increases further at elevated temperatures, and reduction factors for the maximum transverse load and the corresponding displacement have been developed by Block *et al.* (2004b). This paper summarises results from an experimental study at elevated temperatures including axial loading in the compression zone and compares the results with the simplified force-displacement model for this component.

HIGH TEMPERATURE EXPERIMENTS

Small British column sections (UC152x152x37) were tested horizontally in a purpose-built electric furnace, loaded both axially and transversely. The test arrangement can be seen in Fig. 2 below.

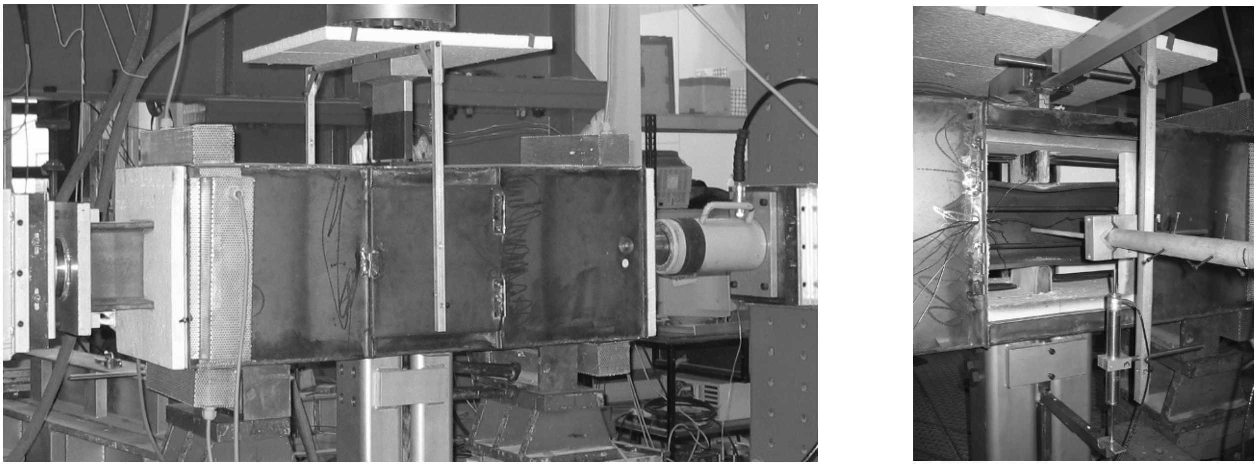

Fig. 2: Overview of the test setup

The axial load, simulating the superstructure load in the column, was introduced by a hydraulic jack attached to a reaction frame and powered by a pressure-controlled pump, which kept the axial load constant as the specimen expanded due to increasing temperature. A displacement-controlled actuator applied transverse compression to the section, introduced by opposed 20mm thick steel plates. This loading arrangement simulates the lower beam flanges in an internal joint. An electrically-heated furnace box was fitted around the column section. Thermocouples were used to measure the steel temperatures at five points across the section near the transverse load-introduction area. Transverse displacements were measured by two LVDTs outside the furnace, allowing the use of standard transducers. The out-of-plane movement of the column web was measured with a ceramic rod attached to a transducer located outside the furnace.

The testing procedure comprises three steps: firstly, the specimen is loaded axially; it is then heated to the test temperature, maintaining its axial load; finally, it is loaded transversely with a loading rate of 0.75mm/min until failure occurs in the column web. This testing procedure results in a steady-state experiment. The experiments showed the expected reduction in ultimate load with increase in temperature due to the loss of strength and stiffness of the steel. No significant reduction due to axial load was observed at lower temperatures, and only a slight reduction in resistance was found at high temperatures, which can be explained by the increased relative axial load ratio.

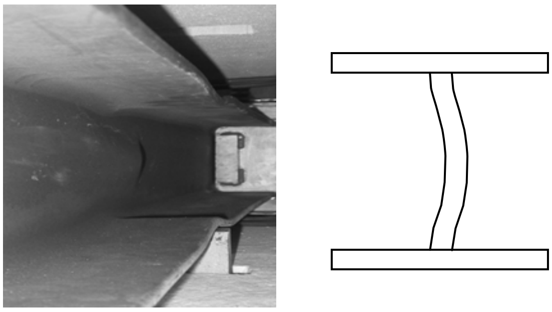

Fig. 3: Failure mode 1

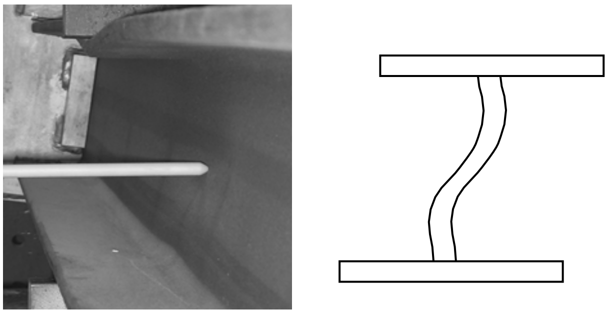

Fig. 4: Failure mode 2

Two different failure modes occurred in the experiments. In the first, the column web failed in a symmetric buckle (see Fig. 3). In the second failure mode, the web deformed into an S-shape, with simultaneous relative lateral displacement of the flanges (see Fig. 4). A more detailed description of the experiments has been published by Block *et al.* (2005).

FINITE ELEMENT MODELLING

In the previous finite element study by Block *et al.* (2004b) imperfect finite element models, created using ANSYS layered shell elements, were used to study the influence of axial load on the compression zone behaviour at elevated temperatures. At the time of this study only the first failure had been considered, but after the second failure mode was experienced in some tests the study was extended to both modes, which are shown in Fig. 5 and Fig. 6 below.

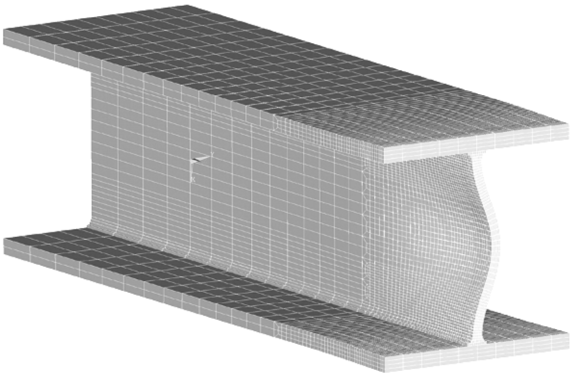

Fig. 5: Typical mesh and scaled imperfection for Mode 1

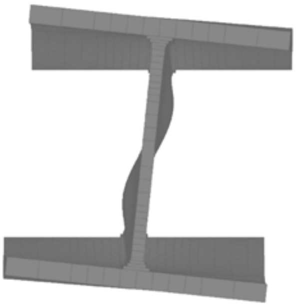

Fig. 6: Deformed shape for Mode 2

In order to investigate the usability of the results of tests which failed in Mode 2, for the validation of the simplified model, both failure modes have been simulated. The analyses showed similar ultimate loads and force-displacement behaviours for both modes, which indicates that the behaviour of the compression zone in relatively stocky column webs is controlled by plastic deformation rather than by stability. Both failure modes can therefore be used for the validation of the simplified model.

SIMPLIFIED MODEL OF THE COMPRESSION ZONE

The simplified model for predicting the force-displacement behaviour of the compression zone at elevated temperatures consists of three parts, of which the firstly is an approach for the ultimate resistance, based on a proposal by Lagerqvist and Johansson (1996). This assumes a series of plastic hinges forming in the column flange in combination with yielding of the web. This plastic resistance load is reduced if a certain web slenderness is exceeded, to account for stability effects. The second part is an empirical equation predicting the displacement at the ultimate load. This equation has been fitted to a large number of finite element models, varying geometrical and material parameters. Finally a curve-fitting approach using the initial stiffness approach given in the EC3 Part 1.8 (2003) and a Ramberg-Osgood type of equation are combined to predict the force-displacement behaviour. The simplified model for the compression zone can be extended to elevated temperatures by using the temperature reduction factors for steel given in Eurocode Part 1.2 (2003).

COMPARISON OF THE TEST RESULTS WITH THE SIMPLIFIED MODEL

As stated above, a model of the force-displacement behaviour of the column web is essential to developing the component method for elevated temperatures. It represents the stiffness and the resistance of the compression spring needed to determine joint responses in fire. In Fig. 7 and Fig. 8 the simplified model is compared with selected test results, which are summarised in more detail in Table 1. For each test the model has been calculated twice in order to provide a solution envelope using the reduced yield stress f_y and an assumed high-temperature ultimate stress f_u based on the transient material tests by Kirby and Preston (1988).

From Fig. 7 and Fig. 8 a significant reduction in the resistance of the compression zone with increasing temperatures can be seen. The displacement to reach this load seems fairly similar in all tests. The F-δ curves predicted by the model compare accurately with the experiments when the ultimate stress is used. This can be explained by the deformations at ultimate load, which involve high strain levels. The work of Kirby and Preston showed that no strain-hardening occurs in transient material tests, which are generally assumed to represent the real building fire situation realistically. Therefore using the yield stress forms a lower bound to the results and could be used for fire design calculations.

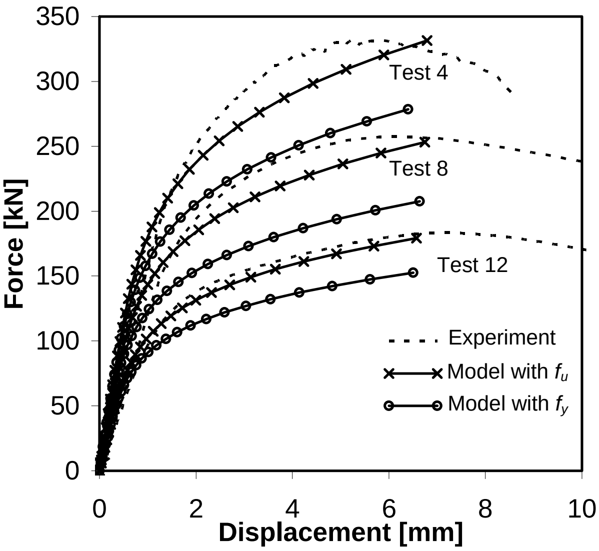

Fig. 7: F-δ curves of test no. 4, 8 and 12

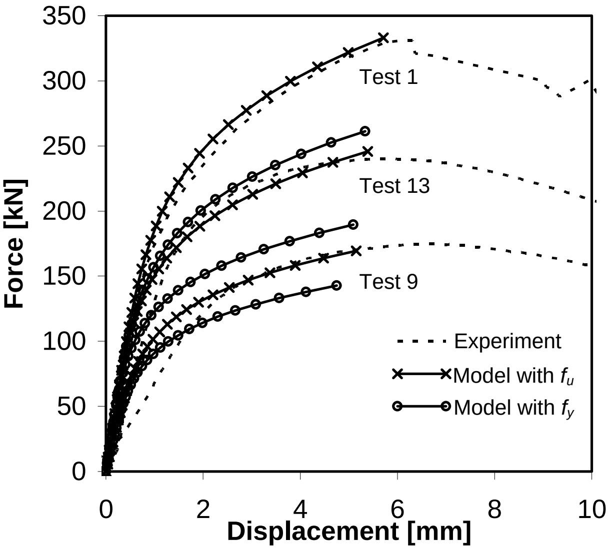

Fig. 8: F-δ curves of test no. 1, 9 and 13

All the tests conducted are summarised in Table 1 and are compared with the simplified model. In the tests at ambient temperature the solution envelope between the models using the yield stress and the one using the ultimate stress is quite large, which shows that the displacements, and therefore the strains in the compression zone, are not large enough to utilise the full steel strength. The envelope becomes smaller with increasing temperature, representing the loss of strain-hardening even in steady-state experiments above 600°C, as can be seen from the work of Kirby and Preston.

Table 1
Summary of tests and comparison with simplified model

Test #	Web temp.	Flange temp.	Axial load	Mode	Test $F_{u,exp}$	Test $\delta_{u,exp}$	Initial stiffness	Model $F_{u,fy}$	$F_{u,fy}$ / $F_{u,exp}$	Model $\delta_{u,fy}$	Model $F_{u,fu}$	$F_{u,fu}$ / $F_{u,exp}$	Model $\delta_{u,fu}$
	[°C]	[°C]	[kN]	[-]	[kN]	[mm]	[kN/mm]	[kN]	[-]	[mm]	[kN]	[-]	[mm]
11	20	20	3	2	418.3	6.5	270	312.3	0.75	6.3	475.3	1.14	6.3
10	20	20	265	2	421.7	6.9	283	305.8	0.73	5.6	471.9	1.12	5.9
3	20	20	394	2	413.7	6.4	270	297.6	0.72	6.0	467.7	1.13	5.7
6	20	20	398	2	423.4	7.5	280	297.3	0.70	5.2	467.6	1.10	5.7
4	450	424	3	2	331.7	5.7	157	278.6	0.84	6.4	331.5	1.00	6.8
1	453	440	266	2	331.0	6.0	216	268.3	0.81	5.6	342.5	1.03	6.4
7	458	429	403	1	331.4	5.9	128	254.9	0.77	5.2	328.9	0.99	5.7
8	549	513	2	2	257.4	6.2	120	207.7	0.81	6.6	253.2	0.98	6.7
13	547	520	266	1	240.2	6.0	134	197.3	0.82	5.4	253.2	1.05	5.6
2	515	482	390	1	280	5.2	122	220.8	0.79	5.1	293.6	1.05	5.6
12	597	582	5	1	183.3	7.2	105	152.5	0.83	6.5	179.1	0.98	6.6
9	591	562	266	1	175.1	6.8	67	150.3	0.86	5.2	176.8	1.01	5.5

Since no clear trend for the influence of the axial load could be found it has been decided to continue the experiments with smaller column sections, allowing for higher load ratios and also repetition of some of the tests to increase confidence in the results.

CONCLUSION

This paper presents preliminary results from a test series on the force-displacement behaviour of the joint component consisting of the compression zone in the column web at elevated temperatures. A simplified model predicting the force-displacement behaviour of the compression zone has been compared with the experiments and sufficient agreement has been found. Further high-temperature experiments are planned to test the simplified model fully. The compression zone in the column web is one of the major components needed to describe the full moment-rotation-thrust-temperature characteristics of steel and composite joints in fire, which is needed for a more accurate analysis of steel-framed structures in fire which may increase the safety and economy of structural design.

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