HIGH-TEMPERATURE EXPERIMENTS ON JOINT COMPONENTS
The Behaviour of the Compression Zone in the Column Web

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ABSTRACT
This paper describes a series of high-temperature experiments on column webs under transverse compression at different axial load ratios and temperatures. These form 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. The test arrangement is described and preliminary results are given.

1 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 load cases 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 [1]. During the cooling stage of the fire the plastically deformed beams contract significantly and experience tension forces [2]. 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 the surrounding cold structure. Furthermore, recent research [3] 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 stiffnesses and also the capacity of joints at elevated temperature is required. With the Component Method, which was developed by Tschemmermegg et al. [4] and later introduced into the draft Eurocode EC3 Part 1.8 [5], 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.
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.

Recent research [6] has shown that an unstiffened compression zone in the column web is the critical component from the three zones in the connection if rotational capacity is needed, due to 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 [7, 8]. In these studies the axial load in the column has been neglected, although at ambient temperature research has shown that the axial load has a significant influence on the maximum load and displacement of this component [6]. In a finite element study it was found that this influence increases further at elevated temperatures, and reduction factors for the maximum transverse load and the corresponding displacement have been developed [8]. This paper describes preliminary results from an experimental study to validate the numerical findings in [8], which are summarised below.

2 Finite-Element Modelling

In reference [8] imperfect finite element models using ANSYS layered shell elements were used to study the influence of axial load on the compression zone behaviour at elevated temperatures. A typical model is shown in Fig. 2 below.
To analyse the behaviour in fire conditions the material model and the temperature reduction factors given in the Eurocode 3 Part 1.2 [9] have been used. Temperatures up to 650°C and axial load ratios up to a maximum of 80% of the plastic capacity, based on the reduced effective yield stress at 2% strain, have been considered. The reduction factors for the ultimate load \( k_{\text{axial, } F_u} \) and for the peak displacement \( k_{\text{axial, } \delta} \), which have been developed on the basis of this study, are given below in Eqns. (1) and (2) respectively.

\[
k_{\text{axial, } F_u} = \sqrt{1 - \left( \frac{\sigma_{\text{axial}}}{f_{y, \theta}} \right)^{1.55}} \quad (1)
\]

\[
k_{\text{axial, } \delta} = -0.70 \frac{\sigma_{\text{axial}}}{f_{y, \theta}} + 1 \quad (2)
\]

Where \( \sigma_{\text{axial}} \) is the longitudinal stress in the column web and \( f_{y, \theta} \) the effective yield stress at the temperature considered. To validate these reduction factors an experimental test programme at elevated temperatures was in progress at the time this paper was written.

3 TEST ARRANGEMENT

3.1 General description

The high-temperature tests have been conducted in the Heavy Structures Laboratory at the University of Sheffield. Small British Universal Column sections (UC 152x152x37) were chosen because of their relatively low axial capacity, which reduces the size of the loading and reaction gear. The specimens were tested in a horizontal alignment in a purpose-built electric furnace, loaded both axially and in the transverse direction. The test arrangement can be seen in Fig. 3 below.

![Fig. 3: Overview of the test setup](image)

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 the transverse compression to the section, which was introduced by opposed 20mm thick steel plates with rounded edges, resulting in a load-introduction width of about 14mm. This loading arrangement simulates the beam flanges in an internal joint. The load-introduction plates could be moved out of the furnace to prevent them from becoming overheated. To allow for vertical rigid-body movement of the specimen, which occurs when the transverse load is applied, roller-blocks were mounted at the ends of the specimen. These allowed nearly frictionless movement, even under an axial load of 400kN. An electrically-heated furnace box was constructed around the column section, which protruded through shaped holes in removable panels at both ends. The furnace
was insulated with 50mm fibre-board and used commercial electric heating elements, closely arranged around the specimen. The elements had a total power rating of 8kW. Each of the four elements was controlled independently to achieve uniform heating of the section.

K-type thermocouples were used to measure the steel temperatures at five points across the section near the transverse load-introduction area and at two points left and right of the loaded area, some distance away, to measure the longitudinal temperature distribution in the specimen. The displacements in transverse directions were measured by two LVDTs outside the furnace, which made it possible to use 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.

Four standard tensile coupon tests, two taken from the web and two from the flanges, were conducted by an independent testing laboratory. Averaging revealed the following material characteristics: yield strengths 289.5 N/mm$^2$ for the web and 288 N/mm$^2$ for the flange, ultimate tensile strengths 486 N/mm$^2$ for the web and 495 N/mm$^2$ for the flange. The Young’s moduli of the web and flanges were 170,010 N/mm$^2$ and 166,785 N/mm$^2$ respectively, which are significantly lower values than the usual assumed value of 210000 N/mm$^2$. Furthermore, none of the test diagrams showed an upper yield stress. These results appear unusual for certified S275 steel, but no explanation has so far been found. The geometric properties were measured, and after averaging resulted in the following dimensions: depth of the section $d_w = 161.4$ mm, flange width $b_f = 154.2$ mm, web thickness $t_w = 7.6$ mm and flange thickness $t_f = 11.0$ mm. Based on these values the cross-sectional area of the specimens was calculated as $A = 4510$ mm$^2$. The axial load ratios have been calculated on the basis of these values.

### 3.2 Test procedure

The experimental 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 speed of 0.75 mm/min until failure occurs in the column web. Tests were planned at 20°C, 450°C, 550°C and 600°C with axial load ratios of 0.0, 0.2 and 0.3, but due to the heat lost during the final loading phase the steel temperatures fell below those planned, especially in the flanges. A maximum axial load ratio of 0.3 may appear low, but considering a buckling length of 3.0 m the tested column would utilize only 60% of its squash load at ULS and, considering the partial safety factors at the Fire Limit State (FLS), the design load would be reduced by about 50%, resulting in an axial load of about 30% of the plastic capacity of the column.
4 TEST RESULTS

At the time of writing not all the planned tests had been conducted, so only preliminary results and conclusions can be presented here.

4.1 Visual observations

Two different failure modes occurred in the experiments. In the first, the column web failed in a single buckle, according with the prediction of the numerical analysis (see Fig. 6). In the second failure mode, the web deformed into an S-shape, with simultaneous lateral displacement of the upper flange (see Fig. 7). The second failure mode can be explained by the vertical actuator’s relatively low lateral stiffness, which is not sufficient to restrain the column flanges laterally for the specimens at the lower test temperatures. Attempts to increase this stiffness had been unsuccessful at the time of writing, but further improvements are planned. This problem had occurred in the earlier work [6] in which two tests at the same temperature failed under similar loads in the two different shapes, which indicates that there is no large difference in the plastic buckling resistance in the two modes.

4.2 Temperature distribution

The purpose-built furnace heated the specimen reasonably uniformly, at a similar heating rate to a F60 protected steel column in a Standard Fire, reaching 550°C in 60 min. A typical time-temperature curve of the specimen is shown in Fig. 8 below.

From Fig. 8 the typical test procedure can be seen: from 0–74 min heating at full power; from 74–83 min stabilising the test temperature until the temperature distribution in the cross-section is uniform; from 83–100 min loading of the compression zone. The drop in the
temperature of the upper (1) and lower (5) flanges in the final phase is caused by contact with the cooler load-introduction blades.

4.3 Summary of the tests conducted

A summary of all the tests conducted so far is shown in Table 1 below. The axial load ratio is calculated using the reduced yield stress at 2% strain, based on the Eurocode 3 Part 1.2 [9] temperature reduction factors. The results of the finite element modelling are also shown. These use the EC3 Part 1.2 material model for elevated temperatures and a new set of material curves based on high-temperature steady-state tensile tests [10].

<table>
<thead>
<tr>
<th>Test #</th>
<th>Web temp. [°C]</th>
<th>Flange temp. [°C]</th>
<th>Axial load N [kN]</th>
<th>Axial load ratio [-]</th>
<th>Failure shape</th>
<th>Test F_u,exp [kN]</th>
<th>Test δ_u,exp [mm]</th>
<th>FEM F_u,FEM,EC3 [kN]</th>
<th>FEM F_u,FEM,SS [kN]</th>
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<tr>
<td>6</td>
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<td>424</td>
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<td>0.00</td>
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</table>

From Table 1 a significant reduction of the ultimate transverse load due to increasing temperatures can be seen, but the displacement to reach this load seems to be fairly similar in all tests. However, the axial load seems to have no influence on the resistance at temperatures of 20°C and 450°C, whereas for the higher temperatures more tests at similar temperatures have to been conducted before a comparison can be made. In contrast, the numerical analyses show a reduction due to axial load. Comparing the two types of finite element models at elevated temperatures it becomes clear that the results from the EC3 model give significantly lower values than the models using steady-state material curves. The reason for this is that the EC3 approach is based on transient tensile tests, which include some thermal creep. This results in a larger reduction of the material strength and stiffness than can be observed in steady-state material tests [10]. The most significant difference between the two sets of material models is that in steady-state curves strain-hardening can be seen up to temperatures of about 600°C, which becomes very important for the behaviour of the compression zone in which local strain in the vicinity of the load can reach up to 15%. Therefore, the two sets of numerical results form an upper (Steady-State) and a lower (Transient) bound for the experiments, which have a slower loading speed than standard steady-state tests and therefore allow some creep effects to happen. Furthermore, uncertainties exist about the amount of friction, which can be generated in the roller blocks at the ends of the specimens. Modelling has shown that the frictionless case is about 5% weaker is than the fixed case. These different factors may be influencing the lack of strength reduction due to the relatively low axial load.

4.4 Force-displacement behaviour

As stated above, a model of the force-displacement behaviour of the column web is essential to developing the component method at elevated temperature. It represents the stiffness and the resistance of the compression spring needed to determine joint response in fire. In Fig. 9
the recorded force-displacement curves at 20°C and 450°C are shown. The curves represent the average of the two vertical transducers outside the furnace. The displacements have been corrected to account for thermal expansion of the load-introduction blades.

From Fig. 9 the reduction of strength and stiffness due to the increase of temperature can be seen. However, no significant reduction due to axial load could be found, which may be due to the relatively low axial load.

Further reductions of stiffness and capacity can be seen in Fig. 10 under a relatively small increase of temperature, because of the rapid degeneration of the mechanical properties of steel around this temperature, and also to the disappearance of strain-hardening.

5 SUMMARY

This paper presents preliminary results from a test series on the force-displacement behaviour of the joint component formed by the compression zone in the column web, at elevated temperatures and under the influence of axial column load. 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 necessary for more accurate modelling of steel-framed structures in fire, and for the development of performance-based design using full-structure modelling. These experiments are being used to validate finite element models and reduction factors for the effect of axial load. Because
the tests are done at a constant temperature, but with a loading speed rather slower than in most steady-state experiments, the finite element models using the EC3 Part 1.2 high-temperature material properties, which are based on transient tests which allowing for thermal creep, under-predict the test results. By using material curves derived from high-temperature steady-state experiments a solution envelope can be generated to which the experiments fit. However, the tests so far do not show the expected reduction due to axial load, and the axial load will be increased in a further series of experiments.

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REFERENCES


KEYWORDS

Structural fire engineering, high temperature experiments, steel joints, component method, compression zone, axial load.