EXPERIMENTAL AND ANALYTICAL STUDIES OF STEEL JOINT COMPONENTS AT ELEVATED TEMPERATURES

Spyros SPYROU[1], Buick DAVISON[1] Ian BURGESS[1] Roger PLANK[2]

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

ABSTRACT

This paper reports on experimental furnace testing and development of simple analytical models intended to initiate the development of a Component Method for modelling of steel beam-to-column connections in fire conditions. The basic theme of the Component Method is to consider any joint as an assembly of individual simple components. Each of these components is simply a non-linear spring, possessing its own level of strength and stiffness in tension, compression or shear, and these will degrade as its temperature rises.

The main objective of this study was to investigate experimentally and analytically the behaviour of tension and compression zones of end-plate connections at elevated temperatures. A series of experiments has been carried out, and these are described in the paper. Simplified analytical models of the component behaviour have been developed, and these have been validated against the tests and against detailed finite element simulations. The simplified models have been shown to be very reliable for this very common type of joint, although similar equations will need to be developed for other configurations. The component models developed have been shown to produce moment-rotation curves which correlate well with the results of previous furnace tests on complete connection behaviour in fire. The principles of the Component Method can be used directly in either simplified or finite element modelling, without attempting to predict of the overall joint behaviour in fire. This will enable semi-rigid behaviour to be taken into account in the analytical fire engineering design of steel-framed buildings, for which it is inadequate simply to consider the degradation of the ambient-temperature moment-rotation characteristics of a joint without taking account of the high axial forces which also occur.

Keywords: *fire engineering, joints, component method, steel structures, furnace testing, simplified modelling, FE modelling.*

INTRODUCTION

Structural steel frames usually consist of universal beams and columns assembled together by means of connections. In conventional analysis and design of steel and composite frames, beam-to-column joints are assumed to behave either as “pinned” or as fully “rigid”. Although the pinned or fixed assumption significantly simplifies analysis and design procedures for the engineer, real joint behaviour exhibits characteristics over a wide spectrum between these two extremes.

To date, data on the real response of joints at elevated temperatures has been gathered from full-scale furnace tests [1-3] on cruciform arrangements, which have concentrated exclusively on moment-rotation behaviour in the absence of axial thrusts. However, when steel-framed structures are subjected to fire, the behaviour of the joints within the overall frame response is greatly affected by the high axial forces, which are created by restraint to the thermal expansion of unprotected beams. If moment-rotation-thrust surfaces were to be generated at different temperatures this process would require prohibitive numbers of complex and expensive furnace tests for each joint configuration. The alternative, and more practical, method is to extend the principles of the “Component Method” of joint analysis and design to the elevated-temperature situation.

The basis of the Component Method is to consider any joint as an assembly of individual simple components as shown in Fig. 1. A steel joint under the action of a member end-moment is divided into the three principal zones shown: the tension, compression and shear zones.

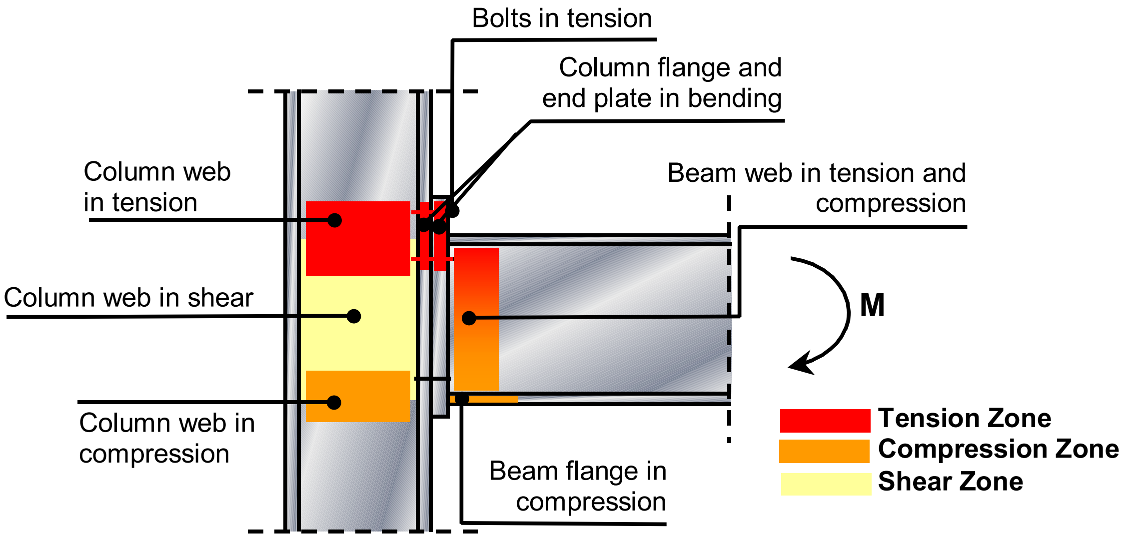

FIGURE 1: The three zones and their components within an end-plate steel joint.

Each of these components is simply a non-linear spring, possessing its own level of strength and stiffness in tension, compression or shear, and these will degrade as its temperature rises. The main objective of the study reported here was to investigate experimentally and analytically the behaviour of tension and compression zones of end-plate connections at elevated temperatures. A series of experiments has been carried out, and these are described in the paper. A simplified analytical model has been developed, and this has been validated against the tests and against detailed finite element simulations. The simplified model is shown to be very reliable for this very common type of joint, although similar methods will need to be developed for other configurations. The principles of the Component Method can be used directly in either simplified or finite element modelling, without attempting to predict the overall joint behaviour in fire, to enable semi-rigid behaviour to be taken into account in the analytical fire engineering design of steel-framed and composite buildings.

APPARATUS FOR ELEVATED TEMPERATURE TESTING

Testing at high temperatures poses a major problem, mainly because the conventional types of displacement-measurement devices could not be applied. The usual method of using silica rods as extensions to transducers mounted outside the furnace is highly unreliable; the rods are very fragile, undergo some extension over their heated lengths, and often lose contact with the specimen. Inclinometers are usually used to measure rotations in the furnace, but need to be continuously cooled throughout a test and their wiring is very vulnerable to being burnt-through. An efficient and robust form of measurement of deflections was required for the large number of high-temperature component tests. For this reason a novel image acquisition and processing technique [4,5] was developed to measure deflections during high-temperature tests.

Video cameras were mounted outside a 1m^3 capacity electric furnace capable of reaching 1100^{0}C and equipped with viewports at the top and on the side perpendicular to the loading direction. In total three video cameras were used to view the critical zone of the component under test. The testing procedure was to take the specimen up to a pre-determined temperature and then apply a sequence of load steps using a 500kN horizontal actuator (Fig. 2). Images were captured at different load steps in constant-temperature tests, and these were processed using image processing software, producing a load-displacement plot.

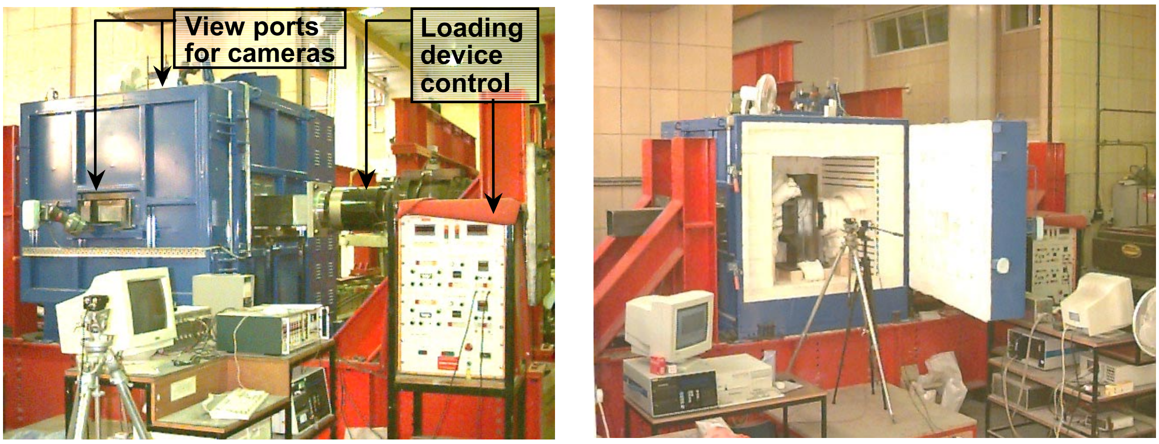

FIGURE 2: The experimental set-up: electric furnace and loading gear.

TENSION ZONE TESTS

The first elevated temperature tests were performed on components of the tension zone of a steel beam-to-column end-plate joint. The tension zone plays a fundamental role in the behaviour of a joint at ambient and elevated temperatures. The three major components within the tension zone are:

- The end-plate in bending,
- The column flange in bending,
- Bolts in tension.

All these components are modelled using an equivalent T-stub, which consists of two T-elements connected as shown in Fig. 3 through the flanges by means of one or more bolt rows.

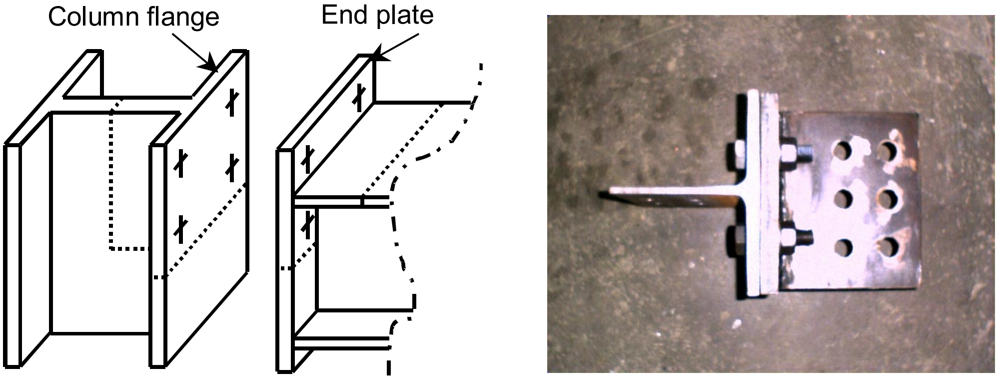

FIGURE 3: T-stub identification and orientation for extended end-plate joint.

The deformation of each equivalent T-stub assembly is a combination of the elastic and plastic flexure of the column flange and end plate, and the elastic and plastic elongations of the bolts. It is well known that these T-stub assemblies can fail according to the three possible failure modes shown in Fig. 4.

1. Yielding in the T-stub flange, followed by yielding and fracture of the bolts,
2. A complete yield mechanism in the T-stub flange,
3. The T-stub flange remains elastic until fracture of the bolts.

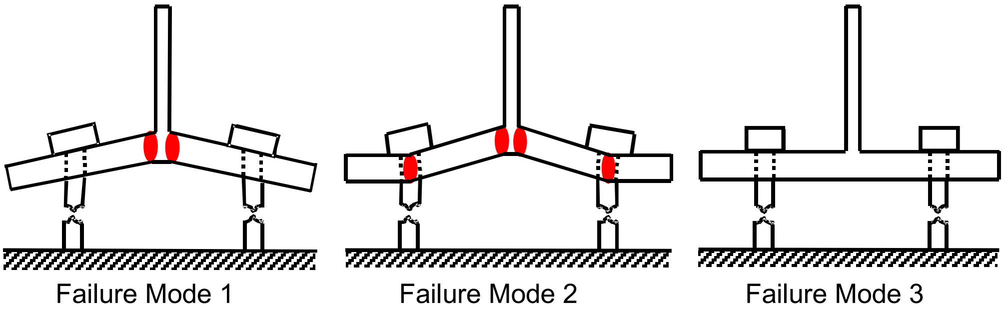
Failure Mode 1 Failure Mode 2 Failure Mode 3

FIGURE 4: Failure modes for the T-stub flange.

A simplified model was developed using plastic theory and classical elastic structural mechanics [6,7]. The model was then extended to predict the three failure modes of the T-stub specimens from their geometrical and mechanical properties at ambient and elevated temperatures. Tests were performed at elevated temperatures on specimens with different geometrical properties to investigate these three failure modes. In total 45 specimens were tested at temperatures ranging from 20°C to 800°C, these temperatures being measured using thermocouples at different positions on the flange and bolts. The last 25 T-stub specimens were connected as shown in Fig. 5, representing the real tension zone of an extended-end-plate joint. The use of Grade 8.8 bolts and nuts resulted in a nut-stripping failure, so instead High Strength Friction Grip nuts were used for subsequent tests. From the first tests at elevated temperatures it was obvious that bolt flexibility was a key parameter in the behaviour of the T-stub tension zone specimens.

The load-deformation comparisons between the simplified model and the actual elevated-temperature test results were in good agreement for all the failure modes, as shown in Figs. 5-7, especially so considering the complexity of the problem of interacting flange and bolt forces and the stress-strain curves at elevated temperatures.

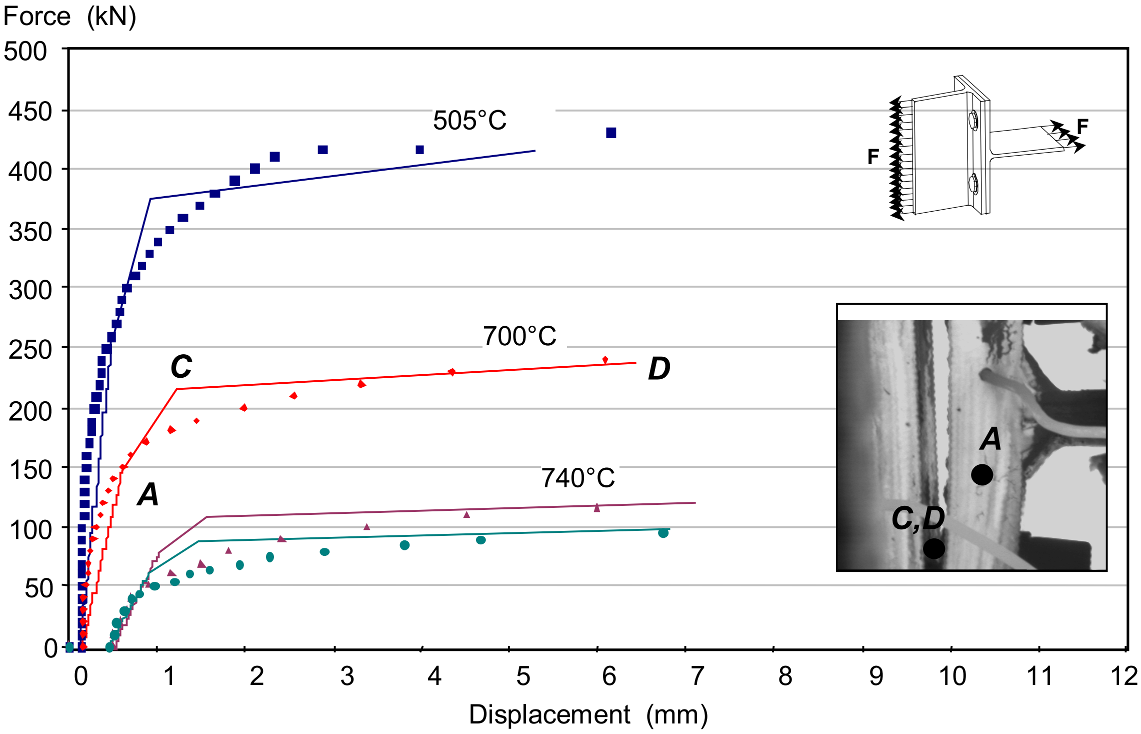

FIGURE 5: Typical force-deflection curves for end plate T-stub in Failure Mode 1.

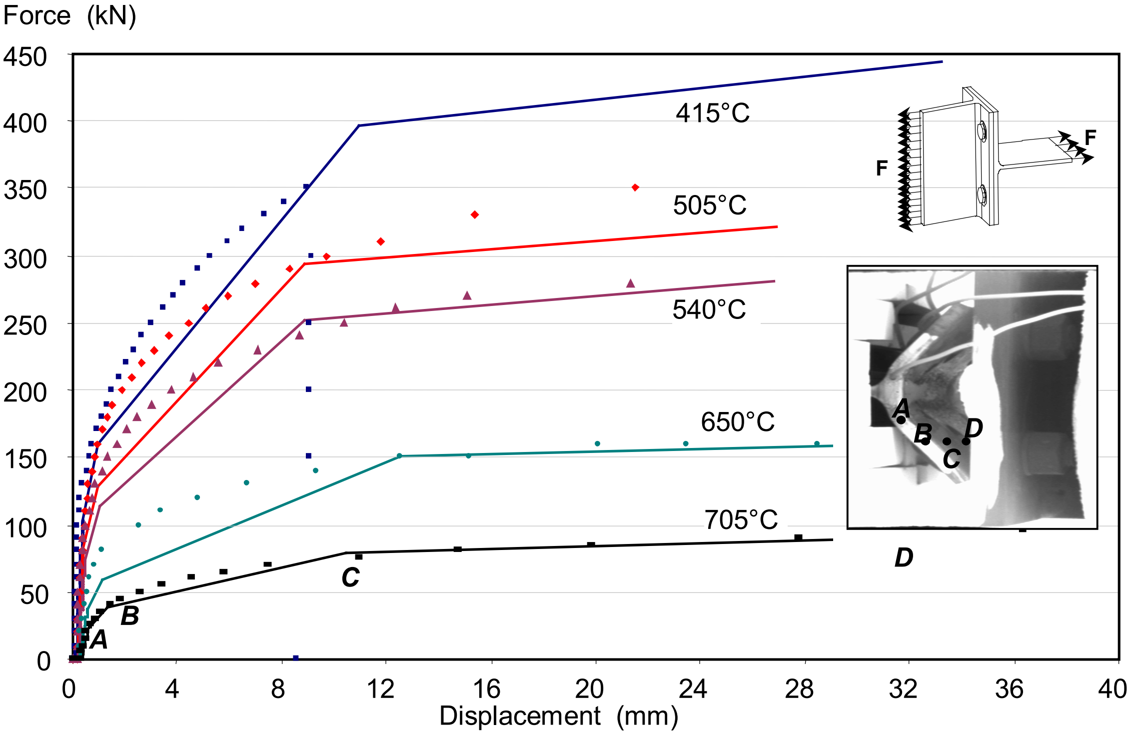

FIGURE 6: Typical force-deflection curves for end plate T-stub in Failure Mode 2.

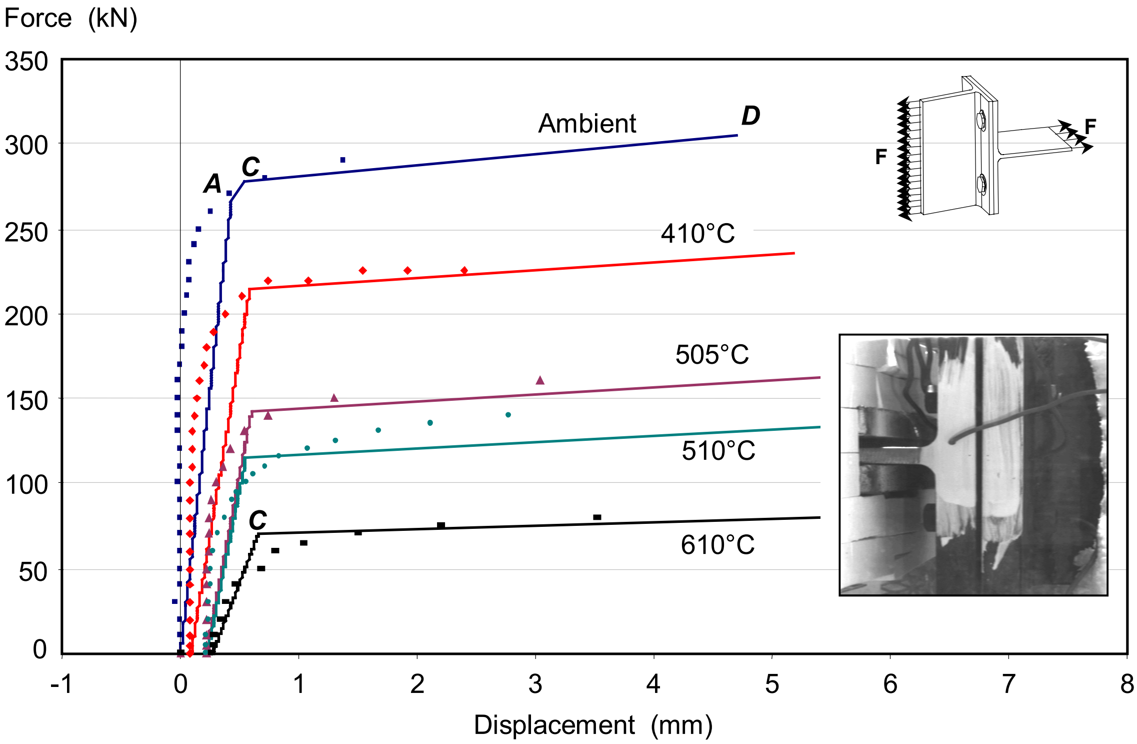

FIGURE 7: Typical force-deflection curves for end plate T-stub in Failure Mode 3.

In contrast 2-D finite element analysis using ANSYS did not generate particularly good comparisons with the test results. This concurs with the findings of the COST C1 Workgroup WG6, which performed studies using 2-D and 3-D modelling, and concluded [8] that 2-D modelling is not satisfactory. Factors affecting the accuracy of FE modelling include the meshing of the model (the optimum mesh size), simulation of bolts (to model the bolt as a flexural element is not an easy task), choice of elements, material behaviour, and most importantly the modelling of contact and gap elements.

COMPRESSION ZONE

At ambient temperatures researchers [9-11] have focused on producing simplified models in order to predict the ultimate capacity of a column web subjected to transverse compressive forces (Fig. 8) and thereby assist engineers to design steel joints efficiently. Another reason for producing these models was to eliminate the use of column web stiffeners, which are expensive to install and interfere with the minor-axis framing of beams into the column.

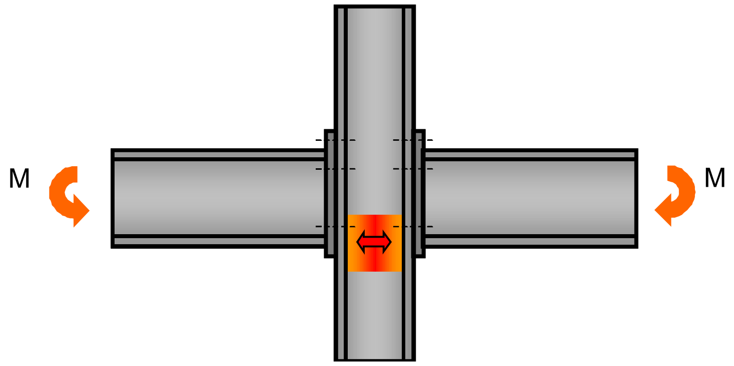

FIGURE 8: Extended end-plate joint showing the column web component (shaded).

Resistance to concentrated forces is a complex problem to which it is difficult to derive closed-form theoretical solutions. Therefore, studies aimed at predicting the ultimate resistance of column webs to concentrated forces tend towards empirical solutions. In this project, a parametric study was performed initially to verify the accuracy of the formulae described in BS5950 [12] and EC3:Annex J [13] at ambient temperatures. It was apparent from a wide range of sources [14] that both current design codes gave very conservative results for the ultimate capacity of column webs under transverse compressive force when compared with test results. The problem acquires a further degree of complexity when another variable, such as temperature, is introduced. A new empirical model was investigated, with the aim of providing not only the ultimate capacity of the column web at elevated temperatures but also its stiffness in the elastic and plastic regions. An experimental investigation was carried out first and then, based on the test observations and results, a simplified empirical model was developed.

The experimental set-up is illustrated in Fig. 9. Compressive forces were applied directly across the column section, and in order to prevent the column specimen from rotating freely in space finger-tight bolts were placed below the compression force contact point. In total 29 compression zone tests were performed, at ambient and elevated temperatures, covering a broad range of web slenderness (*depth between fillets/web thickness* between 12.7 and 22.3). From the early stages of this investigation it was realised that the ultimate load capacity of the column web was determined essentially by the strength characteristics of the specimen.

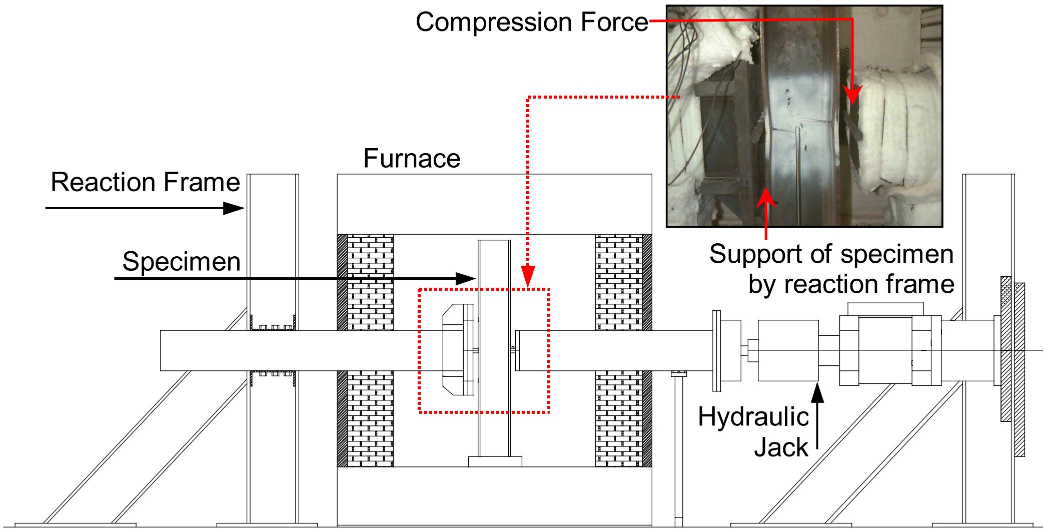

FIGURE 9: Arrangement for compression zone tests.

Literature searches for empirical formulas for calculating the ultimate load capacity of column webs at ambient temperature were unsuccessful, as these did not include the effects of the stiffness of the column flanges, but studies of plate girders subjected to patch loading [15] proved useful. One formula by Drdacky [16], for rather thick plate girder webs, had given good correlation with ambient-temperature tests [15].

$$P_u = 0.55 t_{wc}^2 \sqrt{E_{wc}\sigma_{wc}} \sqrt{\frac{t_{fb}}{t_{wc}}} \left[0.9 + \left(\frac{1.5c}{d_{wc}} \right) \right] \tag{1}$$

Where E_{wc} *and* σ_{wc} are the Young's Modulus and yield strength respectively of the column web, t_{wc} is the thickness of the web, t_{fb} is the flange thickness, d_{wc} is the depth between fillets, and c is the patch load length.

Markovic *et al* [15] suggest that the mean value for the ratio of predicted to experimental capacity should be 0.72. This means that, instead of using a coefficient of 0.55 in equation (1), a new value of 0.76 could be used. This formula, altered to take into account the degradation of material properties at elevated temperature, gave good correlation with the test results from the current study, but when compared with finite element studies performed to investigate the significance of the *c* value (the uniformly distributed patch length in Fig. 10) on the behaviour of the column web it was found to give unconservative values for the ultimate capacity of the column web. For this reason a new empirical formula was derived, based on the Drdacky formula:

$$P_u = t_{wc}^2 \sqrt{E_{wc}\sigma_{wc}} \sqrt{\frac{t_{fb}}{t_{wc}}} \left\{ 0.65 + \left[\left(\frac{1.6c}{d_{wc}} \right) \left(\frac{2\beta}{2\beta + c} \right) \right] \right\} \qquad (2)$$

where β is defined in Fig. 10.

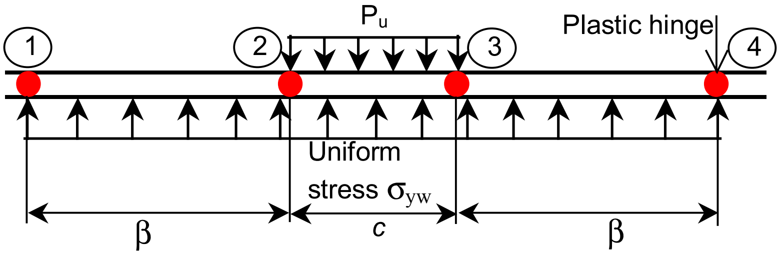

FIGURE 10: Assumed mechanism of web yielding.

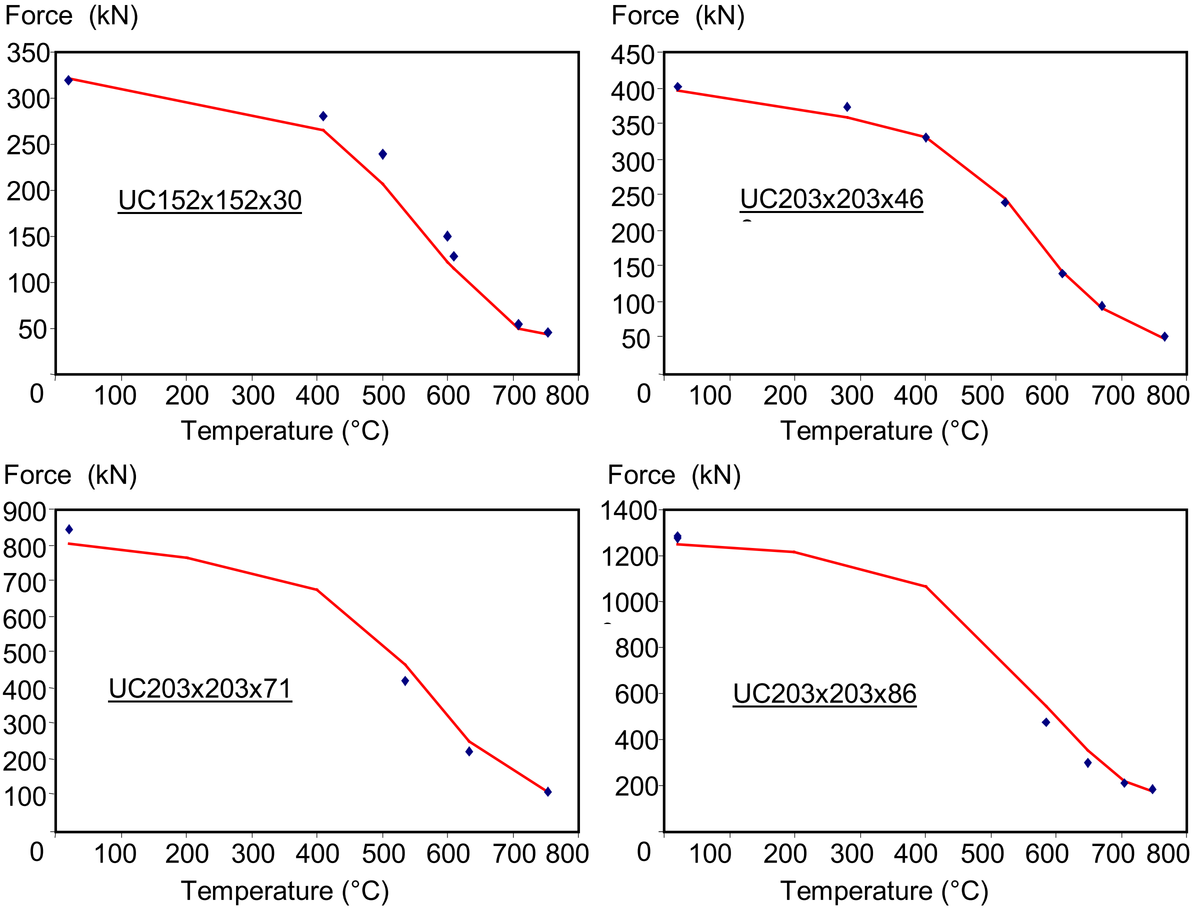

FIGURE 11: Test and Equation (2) results for strength of various column webs.

The comparison of column web strength with experimental results at elevated temperatures is shown in Fig. 11, in which the continuous lines plot the simplified equation (2) and the individual points show the experimental results.

For the stiffness parameters of a column web under transverse compressive loading, an empirical model has been derived based on experimental observations, together with 2-D and 3-D finite element analyses [17]. The results from these finite element analyses and the simplified model compared very well with the test results, and a typical case is shown in Fig. 12. It is only beyond the peak load, when there is some fall-off of load capacity, that 3-D finite element modelling (rather than 2-D web modeling only) is necessary to find the falling path. The clear logic of the comparison is that the load capacity is essentially controlled by the development of plasticity in the web-plate, and that buckling is essentially a secondary effect. This was repeated across the whole range of web slenderness tested, as well as for some more slender webs analysed using ANSYS [17].

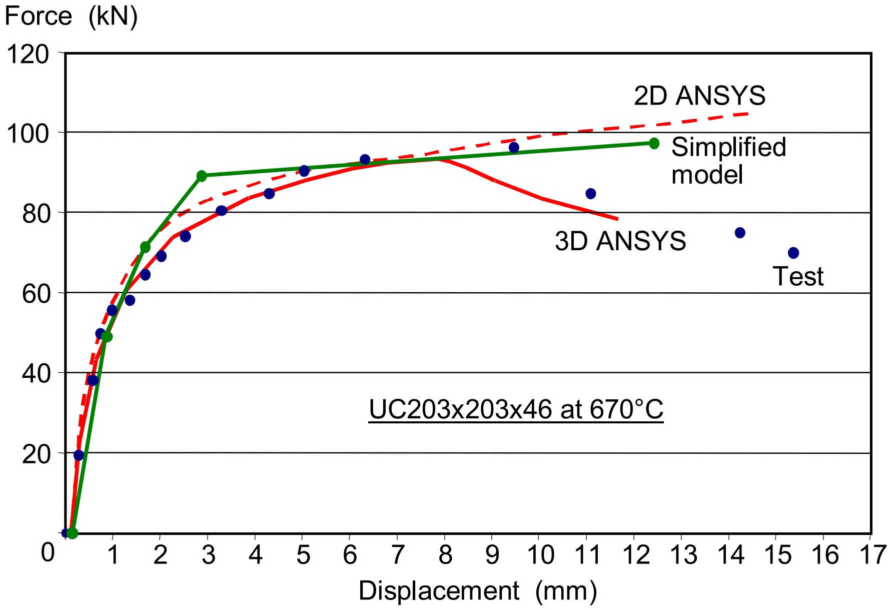

FIGURE 12: Comparison of test results, ANSYS 2-D, and 3-D modelling and the simplified model.

JOINT MODELLING AND FRAME RESPONSE

In early studies of steel frame response at ambient temperature the most appropriate means of including the effects of semi-rigid joint action relied on representations of moment-rotation test data. Whilst this is an effective way of representing the joint response, and in early studies that resulted in a better understanding of the role of the steel joints within a steel frame, there are several limitations associated with the use of experimentally derived joint characteristics. These are the expense associated with testing, the wide range of steel joint types commonly adopted and the effects of their detailed parameters, and the limited availability of carefully documented existing test data. At elevated temperatures there is the added complexity caused by high compressive and tensile axial thrusts on the joint which act simultaneously with the rotational effects.

As a result there was a real need to consider ways in which joint characteristics might be generated analytically. The form of expression used must represent the joint response in terms of the main parameters, such as initial stiffness and moment resistance, and should have the capability of representing the entire non-linear moment-rotation response. Having investigated experimentally and analytically the main components within the tension and compression zones, the principles of the component approach were developed to predict the moment-rotation behaviour of joints at ambient and elevated temperatures. The response of a joint as a whole may be obtained by modeling it as an assembly of individual components in the compression and tension zones, as shown in Fig. 13. This assumes that the interaction between connected components has a negligible effect on the response of individual components.

The moment-rotation results given by assembling joints from their individual component models have been compared against ten elevated-temperature cruciform tests on flush end-plate joints conducted by Leston-Jones [2] and Al-Jabri [3]. The correlations were excellent, as illustrated in Fig. 14, and show that the analytical component models may be combined very effectively to represent the overall rotational response of a joint.

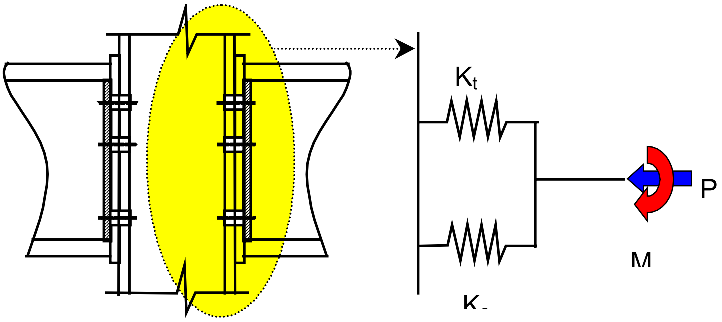

FIGURE 13: Component modelling of a joint under axial force and moment.

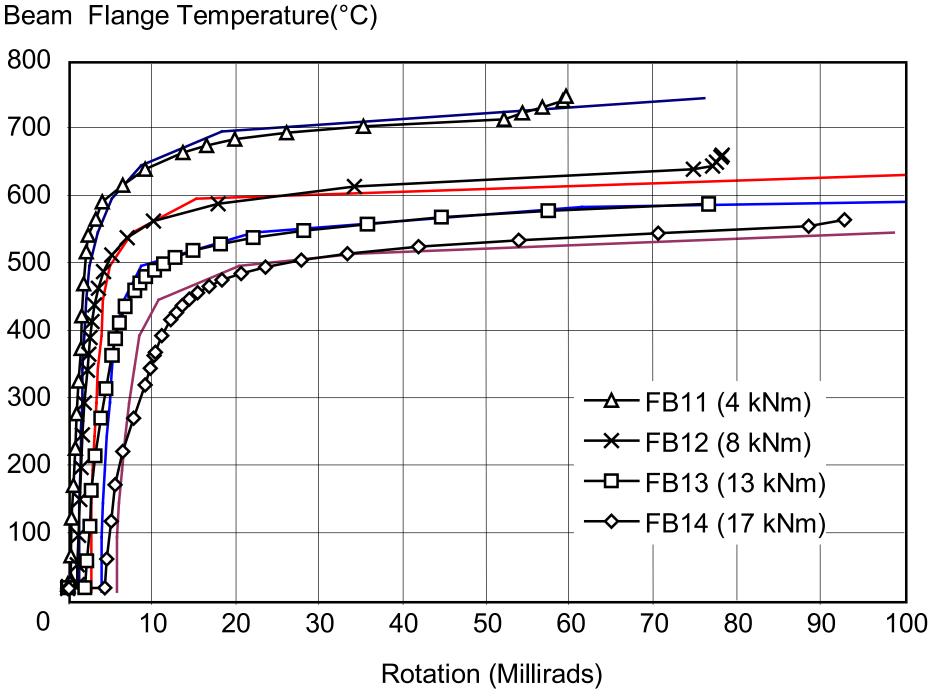

FIGURE 14: Comparison of Al-Jabri fire tests and component-based model on flush end-plate joints.

The main advantage of using the component approach to analyse a steel joint at elevated temperatures is that it becomes unnecessary to predict full high-temperature moment-rotation characteristics. Instead it is possible to incorporate the tension and compression components *directly* as springs into the frame analysis, and hence the moment-rotation-temperature response is generated within the analysis and does not need to be input as data. The advantage of this approach is clear when it becomes necessary to account for the effect of large axial forces generated in the beams during a fire. It is important to consider these tensile or compressive axial forces as they may completely change the rotational characteristics of the joints. High axial compressive forces can be developed in the initial stages of a fire, but in the later stages the net thrust is usually tensile. With the conventional approach to frame analysis, moment-rotation-temperature-thrust-displacement relationships would be required, making the problem three degrees more difficult than an ambient-temperature semi-rigid frame problem. Clearly these would be extremely cumbersome to predict and to input into frame analysis programs. Using the temperature-thrust-deflection relationships for the individual component zones (Fig. 15) directly in the analysis would remove this complication and allow different temperatures to be used for different zones or components.

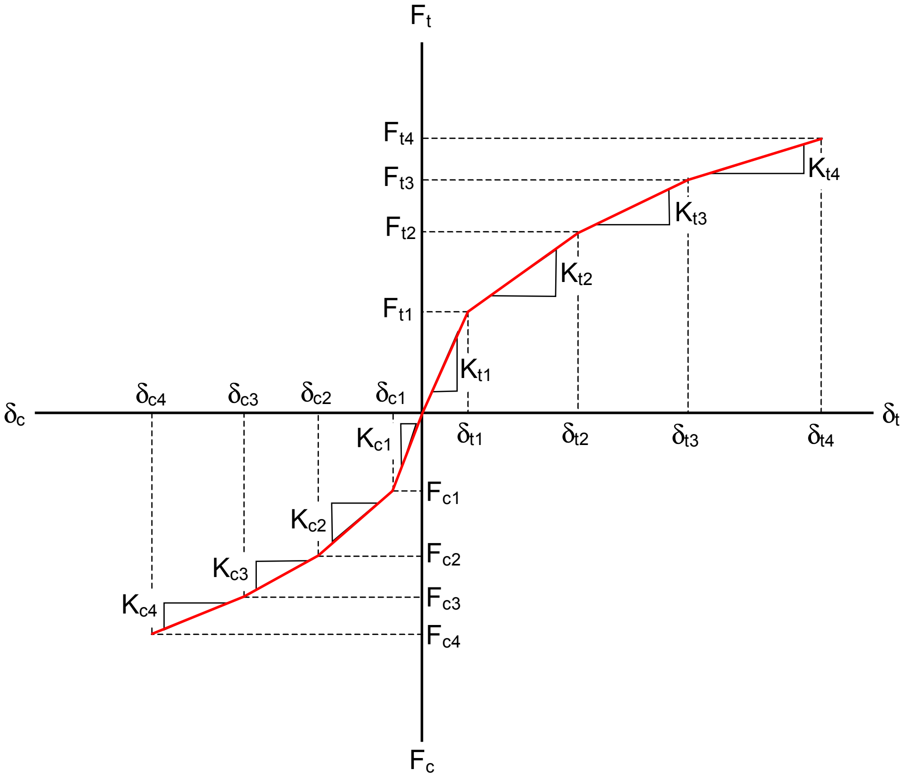

FIGURE 15: Load-deformation characteristics of the tension and compression zones.

The methodology would permit the effect of critical ductile components on overall frame behaviour to be studied, assisting designers to identify these critical locations and to assess how best to protect them in order to avoid premature failure of the steel joints at elevated temperatures.

CONCLUSIONS

This study has been a first step in demonstrating the potential for incorporating component-based models in the modeling of steel joint behaviour at elevated temperatures. Having the advantage of being able to predict the behaviour of any joint arrangement under fire conditions from geometrical and mechanical properties minimises the need to carry out costly, time consuming and complex tests at elevated temperatures.

The major components within a steel flush end-plate joint, in the tension and compression zones, have been furnace-tested and investigated analytically, and load-deformation characteristics for individual components at elevated temperatures have been collected for the first time. The influence of compressive axial force on joint response is very important, especially because this force can result in local inelastic buckling of the column web or beam bottom flange. This was observed in the Cardington fire tests in several cases. This local inelastic buckling of the lower flange of the beam needs to be further investigated experimentally and analytically, although the indication from the compression zone studies is that inelastic buckling only affects the post-peak loss of stiffness of the component

The research has been limited to a single, though very common, type of beam-to-column joint, so other types of component need to be investigated experimentally and acceptable analytical models developed in order to generalise the applicability of the method. However, the very good correlation between the component tests and modelling, and the subsequent use of the simple models to reproduce high-temperature moment-rotation characteristics, show that the component method is potentially the best way to include semi-rigid connection behaviour in full-frame analysis.

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