A Component Approach to Modelling Steelwork Connections in Fire: Behaviour of Column Webs in Compression

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Abstract

This paper outlines some of the main results in 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 concurrently with axial compression due to superstructure loading. The ultimate objective is to be able to construct component-based models of end-plate connections within global numerical modelling of steel and composite building structures in fire conditions. This is the only feasible analytical approach to connection modelling under the simultaneous effects of loading, thermal degradation of materials and forces due to restraint to thermal expansion. A simplified semi-empirical model has been validated against ANSYS modelling and isothermal high-temperature experiments.

Introduction

In the past 20 years considerable progress has been made in the parallel research fields of the behaviour of semi-rigid steelwork connections and the structural fire engineering of steel-framed buildings. Bringing these themes together it should be possible to develop safe and economic design methods for the fire-resistance of steel frames, using the semi-rigid nature of their connections in fire. Because of the large number of possible variables in the detailed design of a semi-rigid beam-to-column connection a versatile approach for calculating the rotational stiffness and load capacity of connections was developed in the European research project Cost Action C1, and its results have been introduced into the draft Eurocode EC3 Part 1.8 (CEN, 2000a). The originality of this "Component Method" is to consider any joint as a set of individual basic components. In the particular case of Figure 1, which illustrates an external beam-to-column joint using an extended end-plate connection subject to bending, the joint is divided into the three major zones (tension, shear and compression), and then each zone is divided into the relevant components.

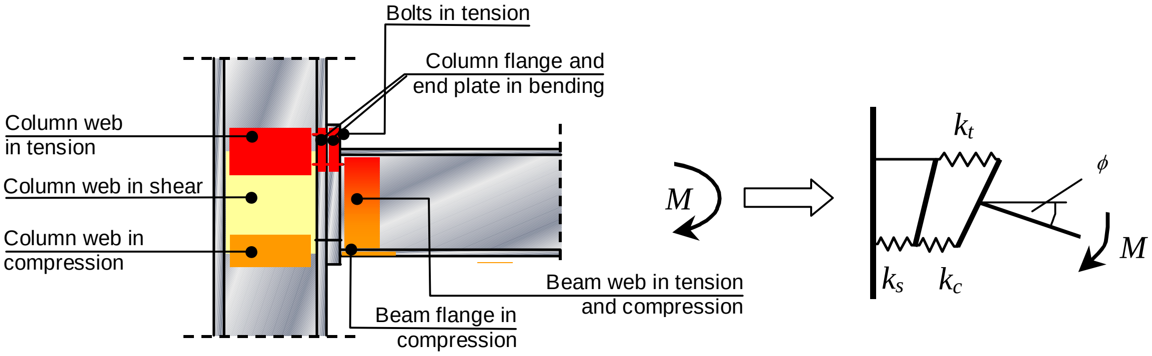

Figure 1. Components of a beam-to-column joint and a simple spring model.

For each component the stiffness and maximum load is computed and assembled to form a spring model, which gives the rotational behaviour of the whole connection. Recent research (Kuhlmann *et al.*, 2000) has shown that the 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 more critical because of the stronger tension zone given by continuing slab reinforcement.

In a building fire the compression zone becomes even more critical because of the thermal expansion of the steel beams, which causes large compressive forces in the column web. Full-scale fire tests and accidental fires have clearly shown that joints have a considerable effect on the survival time of the structure because they may occur at interfaces at which forces from a hot part of the structure react against cooler zones. Considering this, realistic modelling of joints in global analysis could be of great importance in scenario-based design calculations, which can either be used to give confidence about safety margins or to help to reduce the cost of fire protection strategies.

For more than 12 years the University of Sheffield has developed the software *Vulcan*. This is a three-dimensional frame analysis program, which has been developed mainly to model the behaviour of skeletal steel and composite frames, including the floor slabs, under fire conditions. Geometrical and material non-linearity, as well as cooling and large-deflection behaviour, are considered. Connections are usually modelled as pinned or fully rigid, although their behaviour is clearly much more complex. Especially in fire conditions, considerable moments and thrusts are developed, even in simple connections, due to the large deformations of the heated beams. *Vulcan* currently offers the possibility of defining temperature-dependent moment-rotation curves for joints. Because there is clearly interaction between moment, thrust and shear it is intended to introduce component modelling of connections, so that connection behaviour at elevated temperatures can be modelled without the need for moment-rotation-temperature relationships of the complete joints.

Design approaches for the compression zone at ambient temperature

As the compression zone in the column web is a key component in fire, this paper concentrates on that part of a joint. To find its resistance at elevated temperatures, the logical way is to use a proven approach for ambient temperature and to apply the well-established strength reduction factors adopted in EC3 Part 1.2 (CEN 2000b) to it. To find the most accurate equation for the ultimate load at ambient temperature, different design approaches have been compared with the results of 64 compression tests on continental European and British rolled sections conducted by Aribert *et al.* (1990), Bailey (1999) and Spyrou (2001). Most of the design approaches are conservative and give erratic correlation with the ultimate loads found in the experiments. All the tests used just two opposed transverse loads introduced through the column flanges, and the co-existent axial force present in a real column has been neglected. A statistical comparison of the approaches is shown in Table 1.

Table 1. Statistical comparison of ambient-temperature design approaches for ultimate load of the column web compression zone.

F_U / F_R	EC 3: Part 1.1 - 2nd Draft	EC 3: Part 1.8 - 2nd Draft	BS 5950 Part 1-2000	Lagerqvist *et al.*
Average	1.411	1.554	1.477	1.323
Standard deviation	0.1225	0.1389	0.1700	0.1170
Coefficient of variation	0.0869	0.0894	0.1151	0.0884
Upper 5% fractile	1.612	1.783	1.757	1.515
Lower 5% fractile	1.209	1.326	1.197	1.131

From the table above it is clear that the method developed by Lagerqvist *et al.* (1996) is the most accurate and has shown the best consistency over the range of parameters. This equation has therefore been used as the base for a high temperature approach. To include these temperatures the reduction factors $k_{y,\theta}$ for the yield stress and $k_{E,\theta}$ for the Young's modulus from EC3 Part 1.2 are used. The equations for the ultimate load at elevated temperatures, $F_{R,\theta}$, can be written as:

$$F_{R,\theta} = k_{y,\theta} f_{yw} L_{eff} t_w \tag{1}$$

$$L_{eff} = \chi_F l_y \quad \text{in which} \quad \chi_F = \frac{0.5}{\lambda_F} \leq 1.0 \tag{2, 3}$$

$$\lambda_F = \sqrt{\frac{l_y t_w k_{y,\theta} f_{yw}}{F_{cr}}} \tag{4}$$

$$F_{cr} = k_F \frac{\pi^2 k_{E,\theta} E}{12(1-\upsilon^2)} \frac{t_w^3}{d_w} \quad \text{with} \quad k_F = 3.5 \tag{5}$$

and $$l_y = s_s + 2t_f\left(1+\sqrt{m_1 + m_2}\right) \tag{6}$$

with $$m_1 = \frac{f_{yf} b_f}{f_{yw} t_w} \tag{7}$$

$$m_2 = 0.02\left(\frac{d_w}{t_f}\right)^2 \quad \text{if } \lambda_F > 0.5, \text{ if not } m_2 = 0 \tag{8}$$

In this approach, an effective length L_{eff} is calculated, over which the web is assumed to reach yield. This is found by equating internal and external energies in the mechanical model shown in Figure 2, minimizing the load with respect to the distance between the outer plastic hinges. The effective length is reduced if the plate slenderness factor λ_F exceeds the value 0.5, but in this case parts of the web are included in calculating the plastic moments of the outer plastic hinges in the flanges. The load width s_s is calculated by using a dispersion angle of 45° through the end-plate, and d_w is the depth of the web between the root radii. Using this effective length, the web thickness t_w and the yield stress f_{yw}, the ultimate capacity of the component can be calculated.

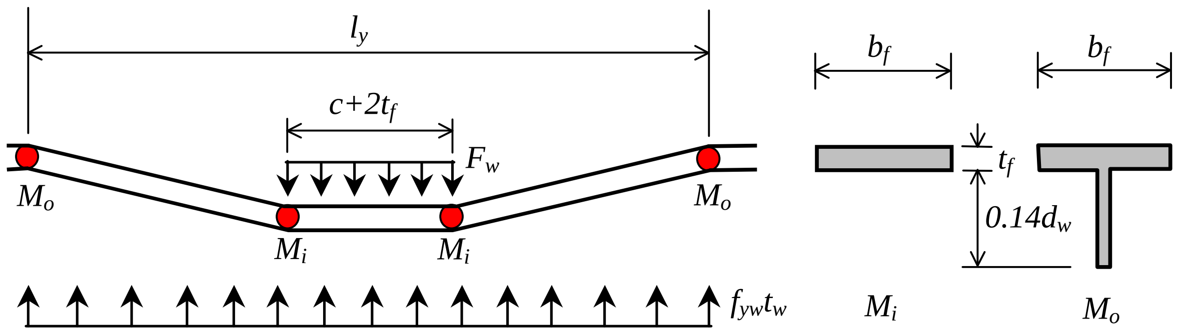

Figure 2. Assumed plastic mechanism in the compression zone

The approach of Lagerqvist *et al.* (1996) does not consider axial forces in the column but it has been shown by Kuhlmann *et al.* (2000) that these longitudinal forces may have a significant influence on the ultimate transverse load. To acknowledge this phenomenon the reduction factor for axial load used by Kuhlmann *et al.* (2000) has been converted for elevated-temperature conditions. This reduction factor $k_{N,w}$ is given below. Here $\sigma_{N,w}$ is the axial stress in the column web and f_{yw} the yield stress of the web.

$$k_{N,w} = \sqrt{1 - \left(\frac{\sigma_{N,w}}{k_{y,\theta} f_{yw}} \right)^2} \tag{9}$$

The ultimate resistance of the column web under transverse load while subjected to elevated temperature and axial load is then calculated from:

$$F_{R,\theta} = k_{y,\theta} f_{yw} L_{eff} t_w k_{N,w} \tag{10}$$

If this approach is to be used in global frame analysis at elevated temperatures more complete force-deflection curves are needed over the relevant range of temperatures. In order to find these characteristics, and to validate the equation above at elevated temperatures, a series of isothermal furnace tests of the column-web compression zone were conducted at temperatures up to 765°C by Spyrou (2001) at the University of Sheffield. Parallel to the experimental work a numerical investigation using the commercial finite element package ANSYS was carried out by the first author.

Finite Element Modelling

Initially 2D numerical analyses of the four experimentally tested column sections were conducted as a basis for investigating the importance of out-of-plane plastic buckling deformation in describing the force-deflection relationship of the compressed column web, and whether the strength-reduction factors of EC3 Part 1.2 could be used to predict the observed behaviour of the component.

Subsequently a parametric study on a 3D model of the compression zone was conducted using a 203x203x46 Universal Column section in order to find the key factors affecting the ultimate load and the corresponding deformation. The geometrical and material properties were varied, together with the load width and the axial load level.

2D Modelling. For the 2D-analysis the elements used to create and analyse the model were the ANSYS PLANE type. With these elements it is possible to apply the non-linear material properties of steel at ambient and elevated temperatures. To include the high temperature material properties the approximate stress-strain relationship given by EC3 Part 1.2 were used. In order to compare the numerical modelling with the experimental results, the curves were based on tensile-coupon tests from each specimen at ambient temperature. Because of the low material thickness of the webs a uniform distribution of temperature over the cross-section is applicable without being too conservative. To avoid shear forces, which would occur if unequal moments were applied by the beams on either side of the column, only symmetric and directly opposed loads were considered in the study. It was therefore only necessary to model one half of the column, assuming an axis of symmetry along the middle of the web. In order to consider the different thicknesses of the flange and web the option "*plane stress with thickness*" was used, and the measured geometrical properties of the specimens were applied to the models. The root radius was divided into four areas of constant thickness. The load was introduced as a set of concentrated nodal forces over a length of 12 mm. A typical mesh is shown in Figure 3(a) below.

A comparison of the force-displacement curves of the numerical models with the experimental results at different elevated temperatures shows good correlation for all tested sections and temperatures. A typical set of these curves can be seen in Figure 3(b) below; the dots represent test results while numerical modelling results are shown as continuous lines.

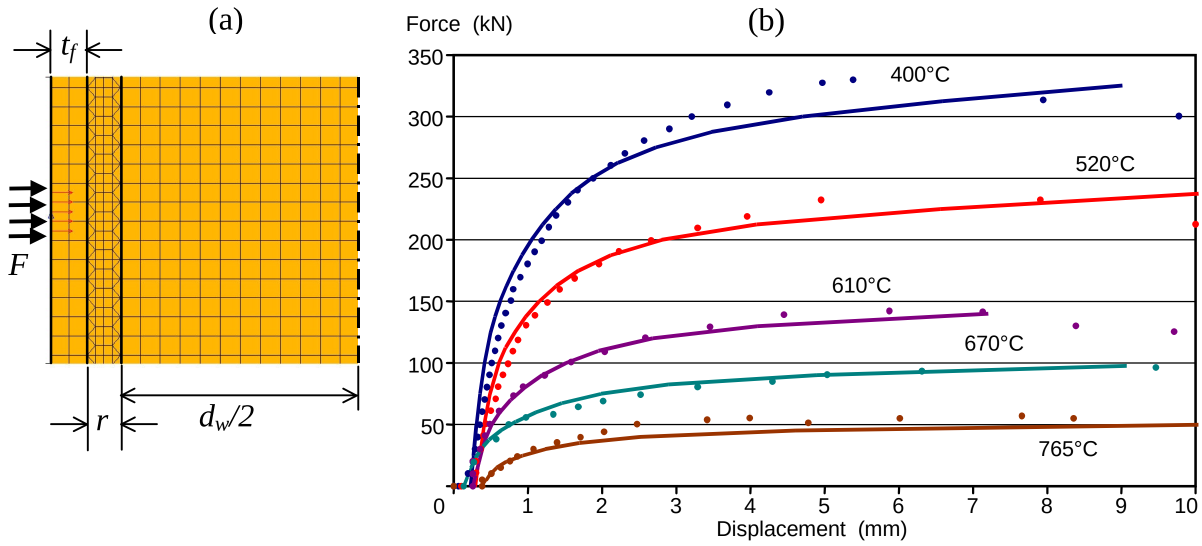

Figure 3. (a) Typical mesh of the FE model; (b) comparison with test results.

The good correlation of the model with test results shows that by using the strength reduction factors of EC3 for elevated temperatures the high-temperature behaviour of the observed component can be modelled accurately. It has also been shown that 2D models describe adequately the force-deflection behaviour of the component, but that to find the ultimate load out-of-plane effects need to be considered. Example stress distributions in the transverse and longitudinal directions in the column, calculated by the ANSYS model are shown in Figure 4.

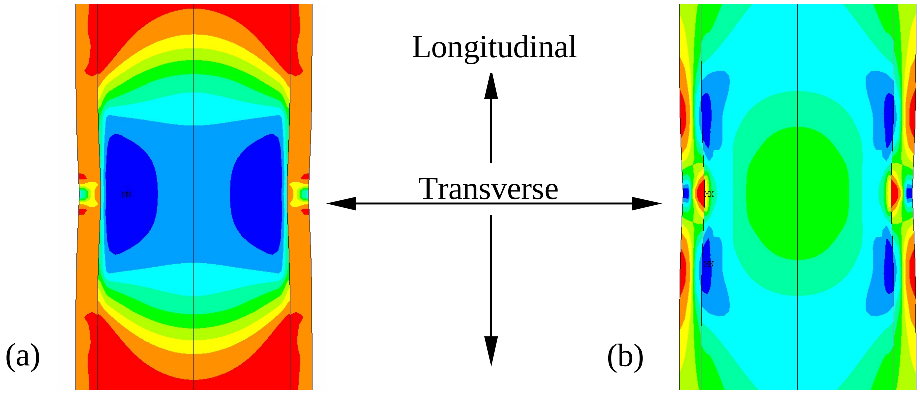

Figure 4. Stresses in (a) transverse and (b) longitudinal directions at 670°C.

Figure 4(b) shows the plastic-hinge mechanism in the column flanges. It compares well with the mechanical model shown in Figure 2, on which the approach of Lagerqvist *et al.* (1996) is based. The assumption that a part of the web should be considered in calculating the plastic moment of the outer plastic hinges also appears to be reasonable, and therefore it is used at high temperatures for non-slender webs such as those in all rolled sections.

In order to predict the ultimate load and the corresponding displacement of the component at elevated temperatures it is necessary to include out-of-plane rotation and buckling in the modelling. This can only be done with a 3D shell model considering geometrical non-linearity and initial imperfections.

3D Modelling. A 203x203x46 Universal Column section was modelled using ANSYS SHELL181 elements. Good correlation with the experiments was found, and the effects of varying the steel grade over a range from S235 to S460, the web thickness from 4 to 10.7mm, the web depth from 95 to 270mm, the flange thickness from 4 to 15mm and the length over which the transverse load is applied from 12 to 96 mm, were investigated.

The parameter with the greatest influence on the ultimate load was found to be the web thickness. It was apparent that the plastic region in the web adjacent to the load has a nearly constant shape, which is independent of web depth, being approximately a semicircle with a radius equal to half of the distance between the outer plastic hinges in the flange. The flange thickness was found to be another important parameter. It controls the spread of load over the web, and therefore the change of force-displacement behaviour from a ductile plastic failure to a failure similar to elastic buckling. In a rolled section the flange thickness is large enough to prevent elastic buckling, so this problem will only appear in fabricated sections with thin flanges. Increasing the load-patch width produces similar behaviour. The force-displacement curves for different load widths are shown in Figure 5.

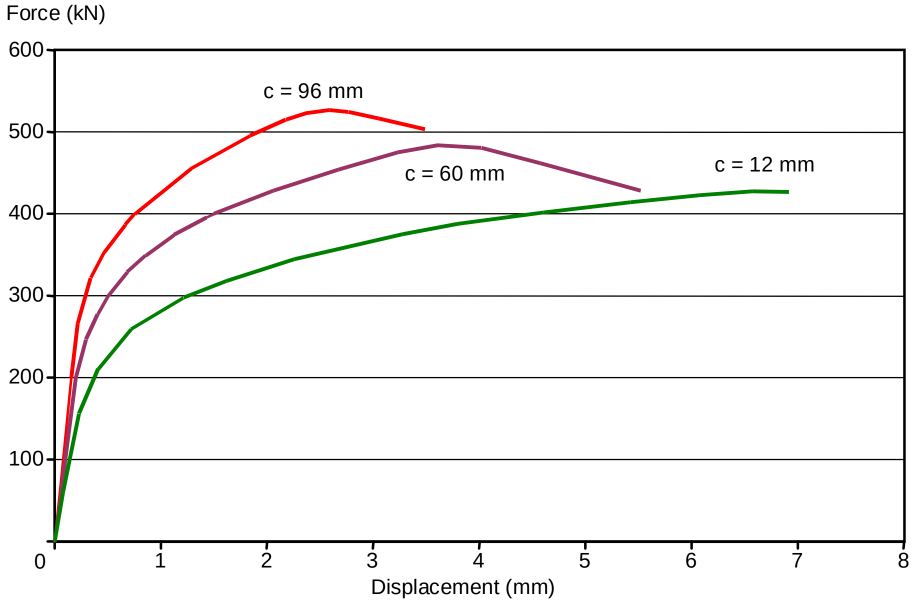

Figure 5. Effect of increase of the load-patch width

As can be seen from Figure 5, the ultimate load increases for a higher load introduction length, but the displacement at which this load occurs is significantly lower and the ductility reduces considerably. This needs to be considered if rotation capacity is used to design a steel frame plastically. The load widths investigated in this study can easily be reached in an end-plate connection, and restrained thermal expansion of the beam in a fire can cause a load width greater than 100 mm to occur. From the results of the parametric study it was possible to postulate an approach to predict the deflection under which the compression zone reaches its ultimate resisting force.

Analytical approach

The force-deflection behaviour of the compression zone can be divided into three parts:

1. A linear-elastic range,
2. A stable plastic range, from first yield to the ultimate load,
3. The post-buckled region, beyond the ultimate load.

The elastic part of the compression zone can be taken from the spring stiffness given in EC3 Part 1.8 for this particular component. This spring stiffness considers only load on one column flange, so for the current assumptions two springs must be considered in calculating the overall spring stiffness as shown below:

$$\frac{1}{k_c^*} = \frac{1}{k_{c,1}} + \frac{1}{k_{c,2}} \quad \text{with} \quad k_{c,1} = k_{c,2} = \frac{0.7 b_{eff} t_w}{d_w} \quad \text{follows} \quad k_c^* = \frac{0.35 b_{eff} t_w}{d_w} \tag{11}$$

Substituting L_{eff} for b_{eff} and applying the ultimate load $F_{R,\theta}$ the elastic part of the displacement under maximum load can be computed from:

$$\delta_{u,el} = \frac{F_{R,\theta}}{k_{E,\theta} E k_c^*} = \frac{F_{R,\theta} d_w}{0.35 k_{E,\theta} E L_{eff} t_w} = \frac{k_{y,\theta} f_{y,w} d_w k_{N,w}}{0.35 k_{E,\theta} E} \tag{12}$$

The plastic part of the displacement is given by the empirical formula (13) derived from the parametric study described. The deflection $\delta_{u,pl}$ is the aggregate for both column flanges in the case of double punching. To calculate the deflection at only one flange $\delta_u/2$ can be used.

$$\delta_{u,pl} = 0.5 k_{N,w} \frac{l_y t_w^2}{b_f t_f} \sqrt{\frac{t_w}{t_f} \frac{d_w}{c}} \tag{13}$$

The total displacement is the sum of the elastic and the plastic parts:

$$\delta_u = \delta_{u,el} + \delta_{u,pl} \tag{14}$$

To describe the force-displacement curve from the end of the elastic range up to the ultimate load a modification of the Ramberg-Osgood (1943) approach is used as shown below:

$$\delta_i = \frac{F_i d_w}{0.35 k_{E,\theta} E l_y t_w} + \delta_{u,pl} \left(\frac{F_i}{F_{R,\theta}} \right)^5 \tag{15}$$

A comparison of the new approach described above for the force-deflection behaviour of the compression zone of the column web at elevated temperatures against results from the isothermal furnace tests on a 203x203x46 UC at different temperatures is shown below in Figure 6.

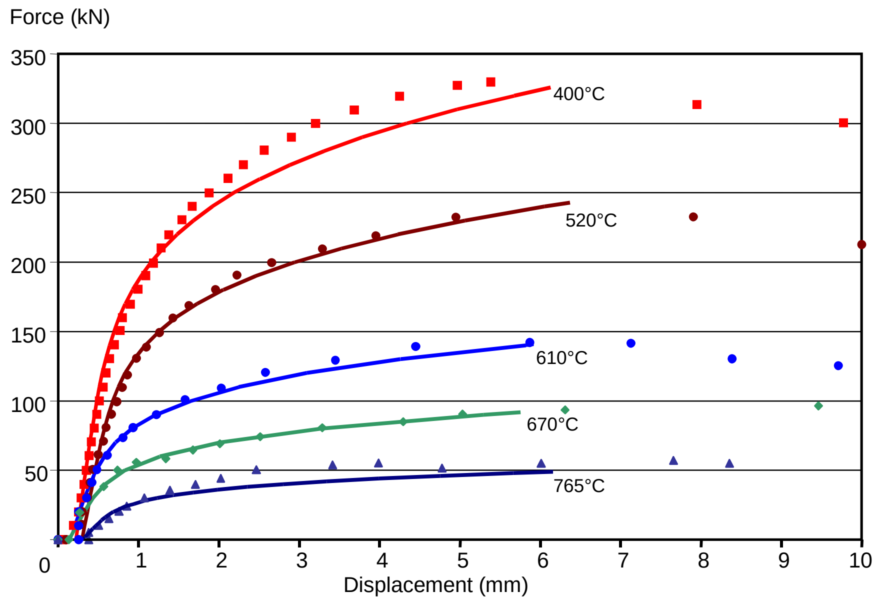

Figure 6. F-δ curves of a UC 203x203x46 from tests and the new approach

Figure 6 shows that the new approach predicts the test results very accurately. Only the displacement at ultimate load is predicted conservatively at very high temperatures.

Conclusions

From a comparison at ambient temperature the approach of Lagerqvist *et al.* (1996) was found to be the most accurate and economic of those surveyed, and therefore forms the base for the elevated-temperature approach. To acknowledge the effect of axial force in the column a modification of the reduction factor used by Kuhlmann *et al.* (2000) has been used.

From experiments and numerical modelling at elevated temperature it has been shown that the use of the EC3 strength reduction factors for elevated temperature in the approach gives accurate results for the ultimate load.

To describe the force-displacement curve of the column web compression zone at elevated temperatures a semi-empirical model has been developed on the basis of a parametric study. This model uses the elastic stiffness definition from EC3 Part 1.8 and an empirical formula for the deflection at ultimate load. To combine these to give a full curve, a modification of the Ramberg-Osgood approach has been used. It has been shown that the new model compares well with high-temperature experiments.

As a secondary outcome of the parametric study, it has been seen that the ductility of the compression zone is significantly reduced by an increase of the width of the line-load, which needs to be considered if the rotational capacity of a connection is vital.

It is necessary still to develop an analytical equation for the deflection at ultimate load. However the equations developed for the column-web compression component represent a key step in assembling a semi-rigid connection element for global structural modelling in fire.

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