PERFORMANCE-BASED SIMPLIFIED MODEL FOR A STEEL BEAM AT LARGE DEFLECTION IN FIRE.

A.M. Allam[1], I.W. Burgess[2], R.J. Plank[3]

[1] Arup Fire, Ove Arup & Partners, LS9 8EE, UK
[2] Department of Civil and Structural Engineering, University of Sheffield, S1 3JD, UK
[3] School of Architectural Studies, University of Sheffield, S10 2TN, UK

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ABSTRACT

This paper presents a simple model for a heated steel beam at large deflection taking into consideration the effect of the catenary action against the surrounding cold structure. This model can be used to predict the mid-span deflection and the tensile axial force of the heated steel beam at large deflection induced by the catenary action. This tensile axial force at large deflection can lead to integrity failure, and consequent fire spread, if sufficient strength and ductility are not designed into key elements such as beams and connections. However, provided that this can be done in particular cases, then it may be possible to achieve much greater real fire resistance than is estimated by the simple calculation methods currently used. The study highlights the effect of the axial horizontal restraints. However, for a heated steel beam within steel construction, catenary action, which may help the beam to hang to the surrounding cold structure, can prevent the run-away deflection when the tensile axial force of the beam has been overcome. The nature of this phenomenon has been investigated in a joint project between the University of Sheffield where the numerical analysis has been curried out, and the University of Manchester where the furnace tests were conducted. The prime objective of this study was to study computationally and analytically how different levels of restraint from surrounding structure, via catenary action in beams, affect the survival of steel framed structures in fire.

INTRODUCTION

In recent years steel-framed construction has become very popular for commercial buildings, largely because of faster construction times than are possible for other systems. Pre-cast reinforced concrete slabs have proved a definite success where structures are erected from pre-fabricated units in combination with steel frames. The fact that no shear connection exists between the pre-cast concrete slab and the steel beam gives the steel beam the flexibility to act independently of the slab. Methods of calculating limiting temperatures and design temperatures are proposed in the British Standard for the fire-resistant design of steel structures, BS5950 Part 8 [1]. Whether design is carried out to a limiting temperature based on the load level, or by calculating the moment capacity of a member at elevated temperature, both methods consider the material strength as the only factor governing the calculation. However, the horizontal stiffness provided by adjacent cold structure has a considerable influence on the behaviour of the heated steel beams. In addition, catenary action increasingly influences the behaviour of steel beams by changing their end conditions. This factor is not included in the usual calculation methods for steel members in fire. In this study illustrations are given that catenary action can play a significant part in enhancing the survival time for a steel beam in fire. This suggests that design methods should be extended to include its effect where practicable.

To prevent premature failure of a structure in fire, the UK Building Regulations require the load-bearing elements of the structure to have a minimum standard of fire resistance. The fire resistance of a load-bearing member measured as its survival time in standardised heating conditions before reaching a prescribed limiting deflection. Assessment of the resistance of members of steel-framed structures in fire continues to be based upon the performance of such isolated elements in standard furnace tests. This is despite the widespread acceptance amongst structural engineers that such an approach is over-conservative and, even more importantly, unscientific. Current codes such as BS5950 part 8 [1] treat fire-related loading as one of the design Limit States. Because of the restrictive cost of carrying out real fire tests on full-scale structures, and the complexity of advanced computational methods, suitably verified simplified analytical methods are now accepted as alternatives for determining the behaviour of structures in fire. These analytical methods should provide as accurate a prediction as possible, by taking into consideration all the significant factors governing the behaviour of the steel element in fire.

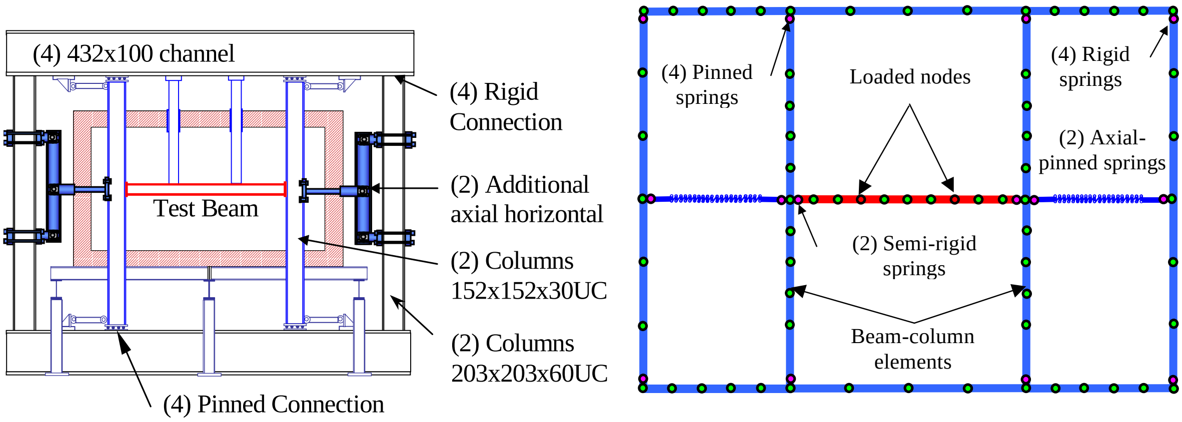
This paper discusses a performance-based simplified model for fire engineering design of a heated steel beam within a connected frame. The results are compared with those from experimental tests and the finite element model VULCAN [2], which has been used to investigate various aspects of restrained steel beam behaviour under fire conditions. The effects of restraint from protected columns and adjacent cool beams to the thermal movement of the ends of unprotected beams have been investigated

TEST SETUP AND COMPUTER MODELLING

In the test programme the beam was mainly unprotected, although the amounts of insulation were varied, including the case in which the web and the lower flange were exposed and the upper flange was fully protected. The columns were generally fire-protected and were re-used for a series of tests. The beam and column profiles in the region of the connection were normally protected. The top flange of the beam was protected by insulation. The beam size was 178x102x19UB and the column 152x152x30UC, both in S275 steel. The columns were secured in position at their top and bottom using roller bearings to give a pinned condition at their supports. The surrounding reaction frame consisted of two 203x203x60UC sections at the sides connected to pairs of 432x100 channels at the top and bottom.

Fig. 1 shows the element layout of the numerical model used to simulate the test set-up. The complete assembly and its details have been discussed in a former paper [3]. The finite element program VULCAN used in the analysis is based on a line element which is geometrically highly non-linear, and allows material non-linearity. Because of the inherently non-linear nature of the problem the solution procedures are highly iterative. The details of the formulation of these elements and the different material constitutive modelling at elevated temperatures have been explained in many references [4-6].

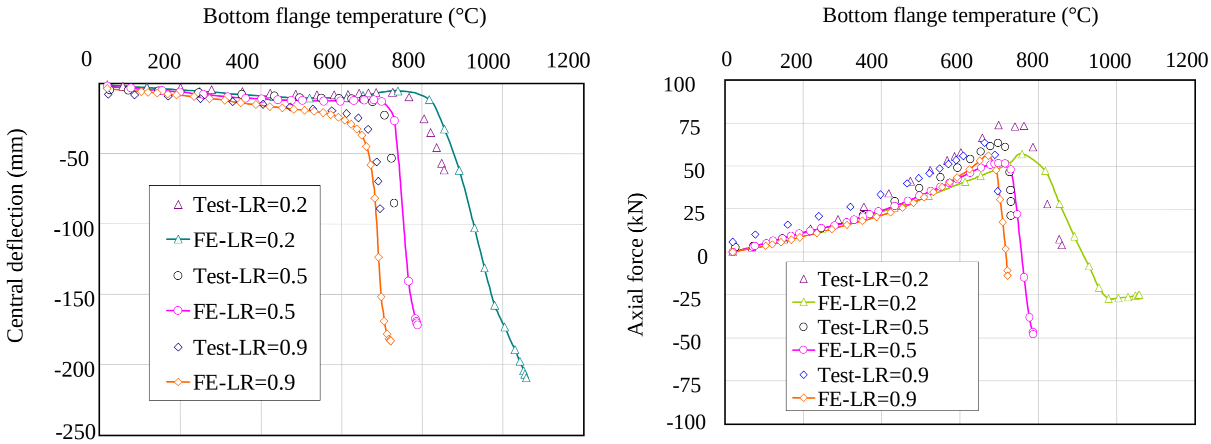
The beam-columns are represented by arrays of 2-noded line elements which are used to simulate the two internal columns, the reaction frame and the heated beam. The effect of the additional axial stiffness at both ends of the heated beam was represented by using pinned spring elements with the specified value of the axial stiffness provided during the test. To model the characteristics of steelwork connections two-noded spring elements of zero length were used, with the same nodal degrees of freedom as the beam-column elements. The moment-rotation characteristics of these elements were obtained from test results at ambient temperature, degrading according to the EC3 elevated-temperature strength reduction factors.



(a) General view of test arrangement. (b) Computer modelling

Fig. 1 General principles of test and modelling.

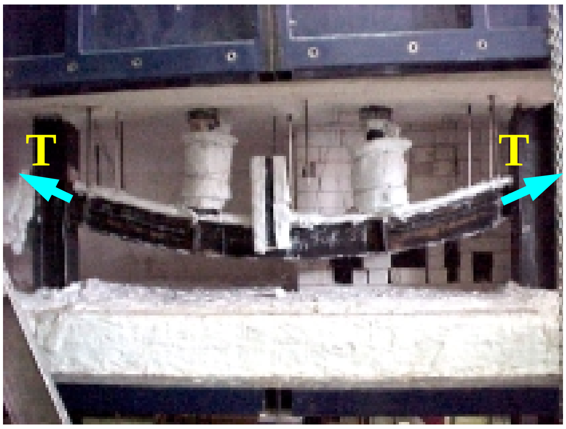
Little previous test data existed on the effect of degree of restraint on the performance of heated beams. It was therefore important to check that the software could model this satisfactorily, before embarking on a more comprehensive analytical parametric study. Typical comparisons for mid-span deflection and axial force of the heated beam, which were used in validating VULCAN against test results, are shown in Fig. 2. More details of the test results are discussed in the previous paper [7].



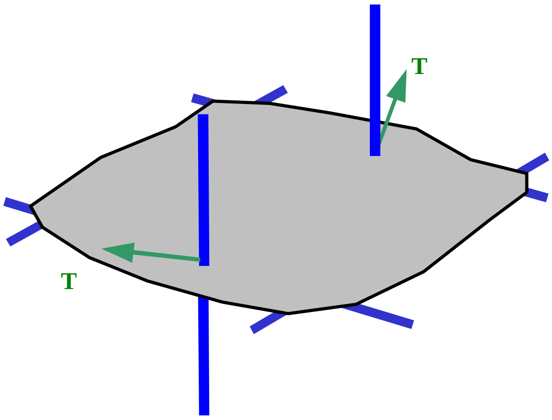
(a) Central deflection. (b) Axial force

Fig. 2 Comparisons between test and predicted central deflection and axial force (end-plate connection, axial stiffness K=8kN/mm) for different load ratios.

Large deflections seen in real structures are often misinterpreted as impending run-away failure. The results from this study suggest that deflections for restrained beams may become much larger than the *span/20* or *span/30* specified in codes of practice for structural fire testing, and that such levels have nothing to do with run-away. These deflections are largely caused by restrained thermal expansion, and are not a sign of loss of load capacity in the beam. At a later stage catenary action increasingly prevents run-away deflection at high temperatures under the effect of the applied load, as axial tension starts to develop, and the beam then acts as a cable hanging from the adjacent cold structure, as shown in Fig. 3.



(a) Fire test

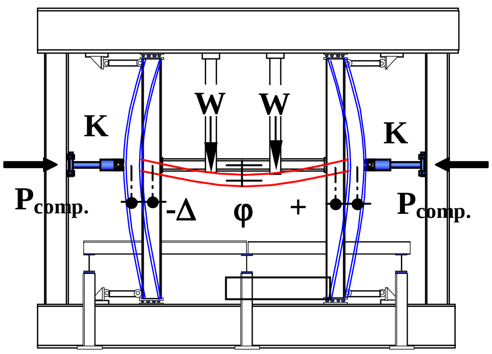


(b) Structure

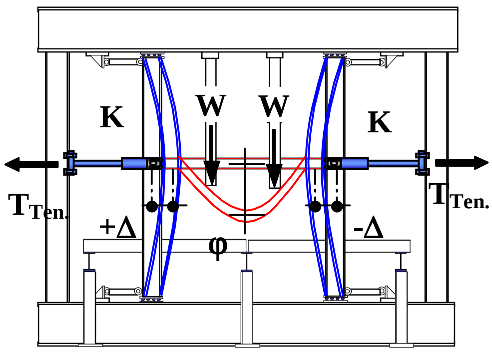
Fig. 3 Effect of catenary action on heated steel beam at large deflection.

INFLUENCE OF CATENARY ACTION

In this section an assessment is made of the influence of catenary action on survival of beams, taking account of the influence of external restraint. Variation of the horizontal restraint level can have a major effect on the behaviour of steel beam at high temperature and large displacement. An increase of horizontal stiffness helps the catenary action to prevent run-away at lower deflection, although in some cases it has a very limited influence on the fire resistance.



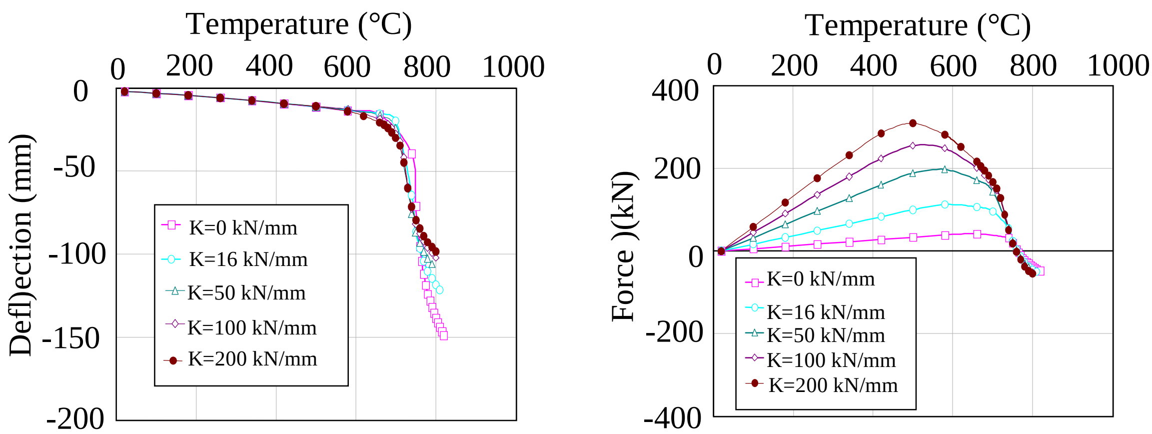
(a) Push-out (Thermal expansion)



(b) Pull-in (Catenary action)

Fig. 4 Behaviour of a connected steel beam in fire.

In the initial stages of heating the restraint from the surrounding structure tends to resist the expansion of a beam. The initial deflection is increased by this restrained expansion together with the thermal bowing caused by the temperature variation across the beam's cross-section. Since the steel's rate of loss of tangent stiffness increases rapidly for temperatures above 350°C the beam eventually experiences large run-away deflections, which depend on the applied load level. However, the run-away deflection may be attenuated when the beam starts to behave as a heated cable hanging from the surrounding structure, provided that this is also capable of redistributing and supporting the heated beam at the applied load level during the fire, as shown in Figs. 4. However, the state of stress associated with a member under a combination of catenary action and thermal bowing is not unique for a given deflection. This depends on the temperature distribution in the member, its material properties and restraint conditions.



(a) Central deflection (b) Axial force in the tested beam

Fig. 5 The effect of horizontal restraint stiffness.

Fig. 5 illustrates the main influence of the catenary action which is apparent in the deflection-temperature curves when the beams survive up to large deflection. The fact that the axial compression force in the beam changes to tension force tends to stop the run-away caused by the applied load and material degradation. Depending on the temperature history during the fire scenario, the remaining material strength helps the heated beam to act in catenary to support the load, and tends to prevent run-away. The analysis was carried out using end-plate connections and a 50% load ratio.

SIMPLIFIED MODEL

The model is based on the assumption that the heated steel beam hangs as a suspension cable from the surrounding cold structure, but because of the high temperature its Young's Modulus and strength are greatly reduced. The mathematical model is intended to be used to calculate the relationship between mid-span deflection and the associated axial tensile force at high temperature.

Considered as an isolated element, the catenary is the simplest structural form after the straight tie. Complexity arises only when catenary action is combined with other structural actions. The structural system can be investigated on the assumption that the cable is completely flexible and able to resist tensile forces only. Consequently, the cable curve coincides with the funicular curve of the load applied to it, as shown in Fig. 6.

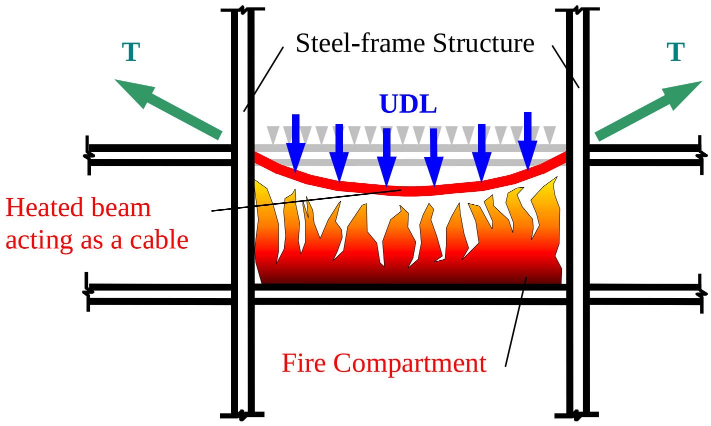


Fig. 6 Heated beam acting as a cable in catenary at large deflection

The horizontal restraint stiffnesses provided by the surrounding structure at each end are usually unequal because of the difference in the numbers of bays which provide the restraint. However, there is only a single stiffness $K = \left(\frac{1}{K_L} + \frac{1}{K_R} \right)^{-1}$ which links reaction force to the beam's net extension or contraction. The beam's shape may be considered as a simple symmetric parabola, as shown in Fig. 7.

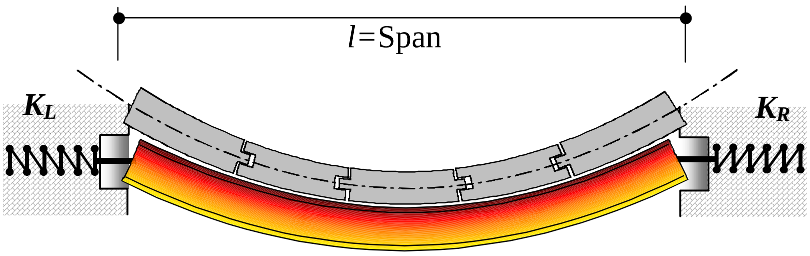


Fig. 7 Restrained beam supporting a pre-cast concrete slab

The purpose of the mathematical model is to provide the designer with a prediction of the co-existing deflection and axial force in the heated beam when it eventually hangs in catenary. The effect of a pre-cast concrete slab supported on the upper flange on the deflection and induced axial force at high temperature is not included at this stage..

Thermal effect

$\delta_\theta = \alpha \theta l$ is the elongation due to the thermal expansion … (1)

in which:

α is the thermal expansion coefficient of the heated material
θ is the average temperature across the heated length
l is the span of the heated beam or the length of the heated part of the beam

Mechanical effect

$\delta_m = \frac{T\,l}{EA}$ is the elongation due to a tensile axial force in the beam … (2)

in which:

T	is the axial force in the heated beam or the average force along the beam
l	is the span of the heated beam
A	is the cross-sectional area of the beam
E	is the elastic modulus of the beam material at temperature θ

Continuity effect

$\delta_s = \dfrac{T}{K}$ is the relative movement of the supports … (3)

in which:

T	is the tensile axial force in the heated beam
K	is the resultant horizontal stiffness provided by the surrounding structure

Total strain of the beam

The total relative movement of the beam ends is the sum of the individual components above. This equates to the relative movement due to deflecting the straight beam into a curve which may be approximated to a parabola. This relative movement is given by

$$\delta_\theta + \delta_m + \delta_s = \delta_c = \frac{8}{3}\left(\frac{y_o^2}{l}\right) \quad \text{… (4)}$$

Using equations 1, 2, 3 and 4, this can be written as:

$$\alpha\theta l + \frac{T l}{E A} + \frac{T}{K} = \frac{8}{3}\left(\frac{y_o^2}{l}\right) \quad \text{… (5)}$$

Fig. 8 shows the structural system used to obtain the simplified model.

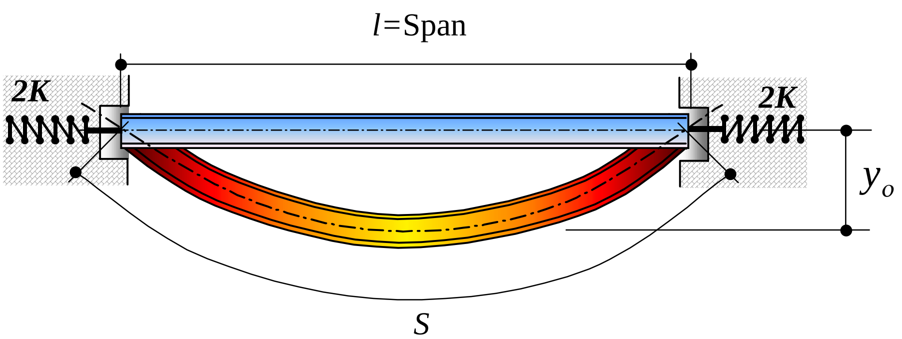


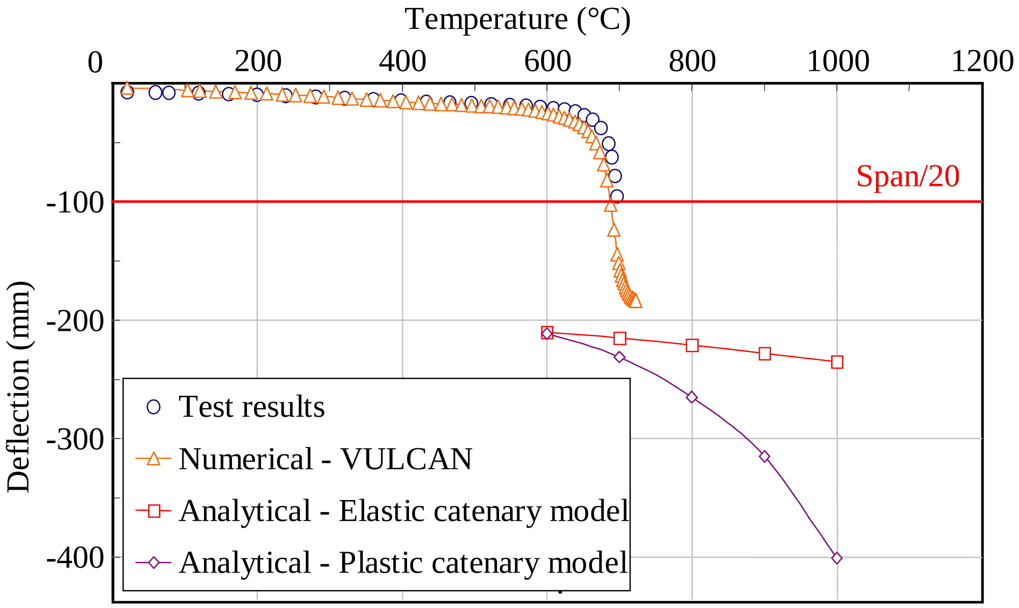
Fig. 8 Mathematical model set-up

The tension in a parabolic cable carrying a uniformly distributed load w is $T = \dfrac{wl^2}{8y_o}$, so equation 5 becomes

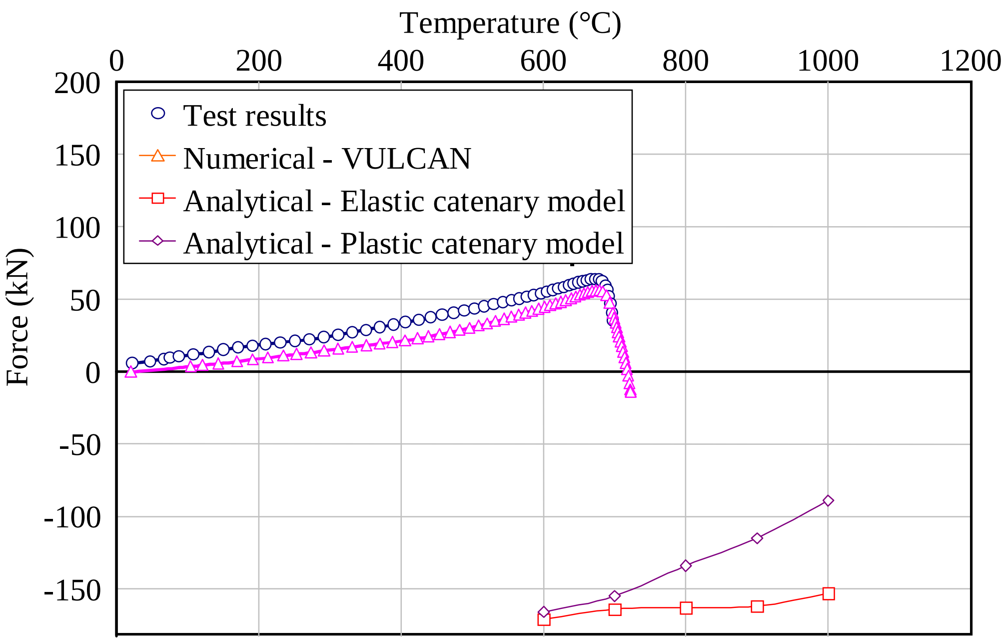
$$y_o^{\,3} - \frac{3}{8}\alpha\theta l^2 y_o + \frac{3wl^3}{64}\left(\frac{l}{EA} + \frac{1}{K}\right) = 0.0 \quad \text{… (6)}$$

Once the mid-span deflection is known, the tensile axial force can be calculated. The elastic modulus value in this equation degrades with temperature according to the EC3 modulus reduction factors.

Fig. 9 shows the predicted deflections and tensile axial forces in pure catenary action using equations 6 and 7, plotted together with the test results and the finite element analysis. For the tested beam with a span of 2000 mm and uniform applied load of 0.072 kN/mm, the predicted mid-span deflection, using the simplified model, is y_0 = 215 mm with a resultant horizontal axial stiffness of 4kN/mm between the ends of the tested beam and the associated tensile axial force can be obtained at different elevated temperatures, as shown in Table 1. Also shown are the values of the mid-span deflections and the tensile axial forces plotted against the bottom-flange temperature of the tested beam. For comparison, the deflection limit of Span/20 is shown in Fig. 9(a) giving an indication for the amount of inherent fire resistance in the steel beam as part of a complete frame in comparison to an individual element.



(a) Steel beam deflection



(b) Axial force comparison

Fig. 9 Prediction of heated steel beam behaviour at large deflection

Elastic [*E*]					
Temperature °C	600	700	800	900	1000
Deflection y_o *mm*	210	215	221	228	235
Axial force T_o *kN*	171	164	163	162	153
Plastic [*E,A*]					
Temperature °C	600	700	800	900	1000
Deflection y_o *mm*	211	231	265	315	401
Axial force T_o *kN*	166	155	134	115	89

Table 1 Predicted mid-span deflections and tensile axial forces

The role that of catenary action is now considered in terms of the survival time of a steel beam in fire, examining the effects of change of span/depth ratio, temperature increase above the critical temperature, axial horizontal restraint level and load ratio.

Fig. 10 demonstrates the effect of the different factors in the simplified model on the mid-span deflection of the tested beam. Fig. 10© suggests that the high levels of restraint stiffness only marginally increase the early deflection. An apparent run-away due to loss of bending stiffness is then re-stabilised more quickly as high restraint stiffness increasingly resists pull-in of the beam's ends. The remaining steel strength helps the heated beam to act in catenary to support the load and prevent run-away.

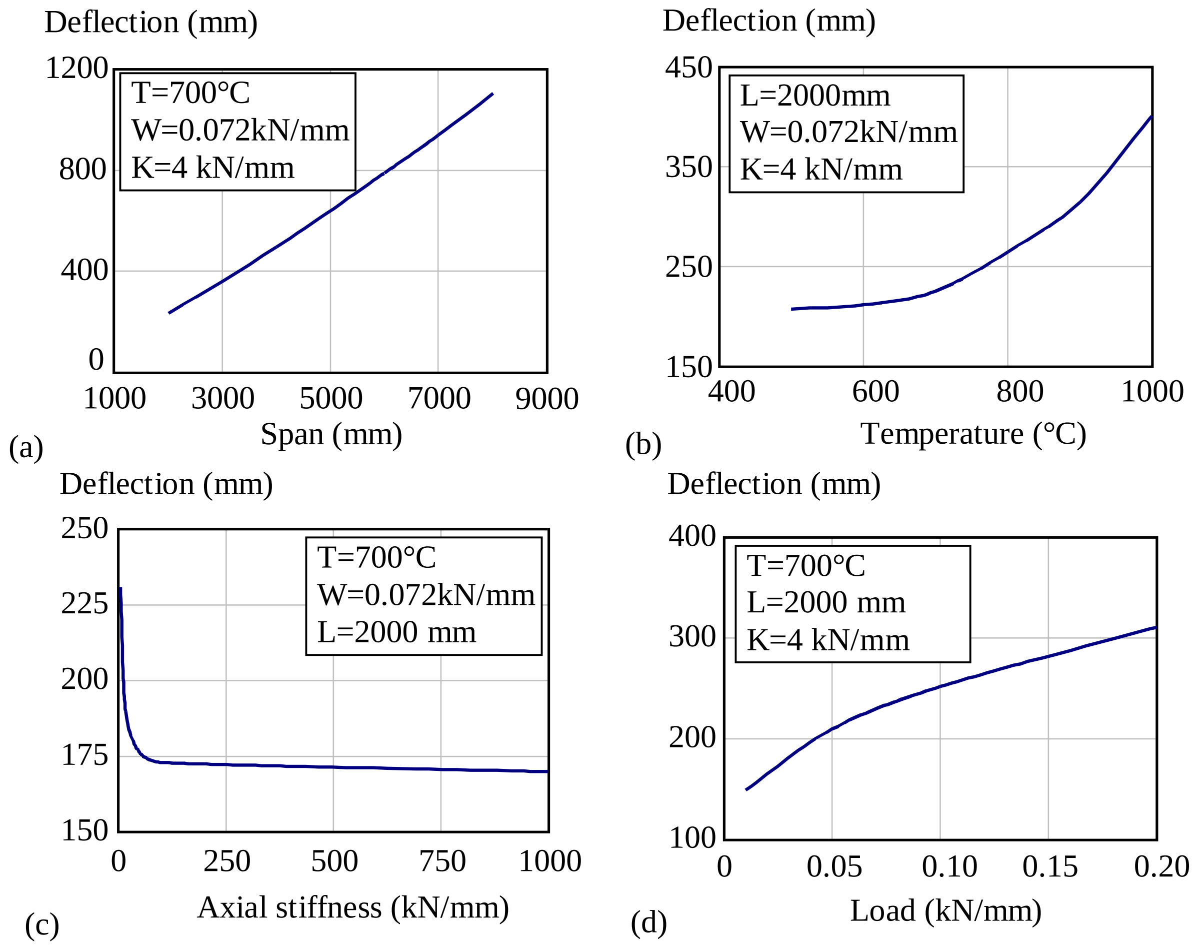


Fig. 10 Factors affecting the mid-span deflection of heated beam

In Fig. 11, a series of curves representing the simplified model, relating the thermal strain to the change in deflection/span ratio, according to different values of the "Structure Factor".

The thermal strain of a heated beam is $$\in_{thermal} = \frac{8}{3}\cdot(\Delta)^2 - F\cdot\frac{1}{\Delta}$$

in which $\in_{thermal} = \alpha\theta$ is the thermal strain,

$\Delta = \frac{y_o}{l}$ is the deflection-span ratio of the heated beam,

$F = \frac{w}{8}\cdot\left(\frac{l}{EA} + \frac{1}{K}\right)$ is a "Structure Factor".

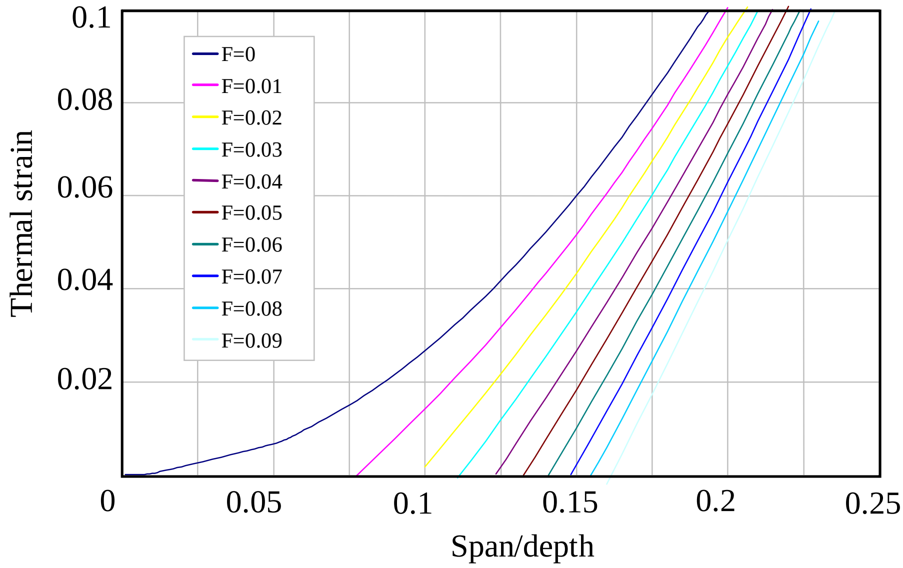


Fig. 11 Effect of the deflection/span ratio on the thermal strain

DISCUSSION AND CONCLUSIONS

Methods of calculating limiting temperature and design temperature are given in the British standard for the fire-resistant design of steel structures. Either by calculating a limiting temperature or by calculating the load capacity of a heated beam, the calculations consider the material strength as the only controlling factor. However, the axial restraint provided by adjacent cold structure can have a great influence on the behaviour of the steel beam. This is largely the result of catenary action in the beam. This aspect of restraint is not included specifically in any existing calculation method for the fire-resistant design of steel beams. In this study, the case has been made that catenary action can enhance survival times for steel beams in fire, suggesting that such methods should be extended to include its effect where support conditions are appropriate.

Complex structural systems can now be analysed by finite element programs for three-dimensional analysis of structures under fire conditions, without any deep understanding by the user of structural behaviour in fire. This, combined with the fact that the computer will not on its own suggest favourable modifications to a less efficient structural system, may lead to the acceptance of less-than-optimal systems. In the design process the most important decisions are generally made in the early phase when synthesis dominates over analysis.

However, in this phase synthesis needs to be supplemented by simple analytical methods to give some quantitative assessment of the different structural forms. The simple analytical methods required in the preliminary design phase are not the approximate methods which were applied to detailed design before the use of computers, but much simpler and less accurate methods.

Catenary action certainly occurs, and has been seen to affect a heated beam's behaviour by preventing run-away deflection at high temperature plus applied load. The tensile axial force grows progressively as the deflection grows provided that some horizontal reaction stiffness exists. A change of the horizontal restraint stiffness can have a large effect on the behaviour of the beam at high deflection, and the loading on the beam can be carried very effectively as catenary tension replaces bending.

It can be seen, particularly from Fig. 9(a), that catenary action does not necessarily dominate the mechanics of a beam's load-path until a late stage, at which the bending stiffness has deteriorated greatly and deflections are large. Unfortunately this stage was beyond the range of the physical test results because of the safety implications of testing to very high deflections in a practical furnace. It is however apparent that the finite element results are validated by the test, and that they are distinctly tending towards the catenary action lines at the point at which the analysis ends. The horizontal restraint stiffness used in this example was on the low side compared with what might be expected in continuous building frames, and more practical values would reduce the deflections for catenary action, making the transition from bending to tension much more rapid. The method presented in this paper, which considers only the stage where bending strength is no longer part of the load-bearing mechanism, gives a view of what can be achieved by beams at high temperatures. In order to make use of such a method the remaining imperative is to devise appropriate acceptability limits, not necessarily based simply on ultimate strength, but possibly also the need to limit deflections to protect the integrity of compartmentation or for the safety of fire fighters.

REFERENCES

[1]. *"BS 5950: Structural Use of Steelwork in Building: Part 8: Code of Practice for Fire Resistance Design "*, British Standards Institution, London, 1990.

[2]. Huang, Z., Burgess, I.W. and Plank, R.J., "Non-linear analysis of reinforced concrete slabs subjected to fire", *ACI Structural Journal*, 96(1), (1999) pp127-135.

[3]. Allam, A.M., Fahad, M.K., Liu, T.C.H., Burgess, I.W., Plank R.J. and Davies, J.M., "Effects of restraint on the behaviour of steel frames in fire", 2nd European Conference on Steel Structures, Praha, Czech Republic, 1(77), (1999) pp 279-282.

[4]. Najjar, S.R. and Burgess, I.W., "A non-linear analysis for three-dimensional steel frames in fire conditions", *Engineering Structures*, 18(1), (1996) pp77-89.

[5]. Bailey, C.G., Burgess, I.W. and Plank R.J., "Computer simulation of a full-scale structural fire test", *The Structural Engineer*, 74(6), (1996) pp93-100.

[6]. Fahad, M.K., Liu, T.C.H, Davies, J.M., "The behaviour of steel beams in fire and the effect of restrain columns", Steel Structures of 2000s Conference, Istanbul, Turkey, (2000).