The performance in fire of restrained steel columns in multi-storey construction

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ABSTRACT: The Universities of Ulster and Sheffield are collaborating in an investigation of the load-carrying properties of steel columns in multi-storey buildings under fire conditions. At Ulster an experimental programme is investigating the effect of axial restraint on column behaviour. A range of columns is involved, the three major parameters considered being loading level, slenderness ratio and degree of axial restraint. Modelling of the tests, which are of elastically restrained isolated columns, has been done at Sheffield. This has been followed by simulations of the effects of fire on columns within much more realistic three-dimensional building frames, in fires which are localised by the natural vertical compartmentation of the building. The behaviour of columns in fire is clearly affected to a very high extent by the nature and amount of their restraint, particularly against axial movement.

1. INTRODUCTION

1.1 Tests at Ulster

As part of a joint research project involving the Universities of Ulster and Sheffield, a series of steel columns is being furnace-tested under fixed axial applied compressive loads. The series is to include columns which are free to expand, as well as some which are subject to axial spring restraint. The tests are taking place at Ulster, with numerical modelling being handled mainly at Sheffield. The initial series of tests (Ali *et al.* 1997) is free from axial restraint, and is being used partly to develop the furnace. The second of these tests took place on 17 September, 1996, and this report describes a sensitivity study comparing the test results with various numerical simulations.

The test specimen was a 1.8m long 178x102x19 Universal Beam section (minor axis slenderness=75), instrumented with one axial displacement transducer at the top and two lateral displacement transducers at mid-height. Four groups of thermocouples were used, two on the top half of the column and two on the bottom half as shown in Fig. 1. Each group comprised 7 thermocouples equally spaced around the column cross-section. Heat was provided by two gas burners situated at the bottom of the furnace, and the load level of 0.2 times the design load capacity was applied via two hydraulic rams at the top of the column. The column had no axial restraint stiffness and was seated on two half-round bearings to provide pinned support allowing only minor-axis rotation.

The test was conducted in two stages. Firstly the column was loaded in four steps each applying one quarter of the final 92.8 kN load, with displacement readings being taken at each stage. When the entire load had been applied, the gas burners were ignited, and subsequent readings taken at 20-second intervals. For the purpose of this investigation into the effects of fire, only the heating stage of the test will be considered.

1.2 Modelling at Sheffield

The heated column has been modelled in the version of INSTAF developed at Sheffield for 3-dimensional analysis of framed structures in fire (Najjar & Burgess 1996), using spring elements to provide the required rotational and axial restraint. A rotational spring element was placed at each end to allow study of the effects of support friction at the ends of a pin-ended column. In addition, a purely elastic axial spring was placed at the same end of the column as the applied load. The elastic stiffness of this axial spring was kept very low, to simulate the negligible axial restraint provided by the test rig. This is

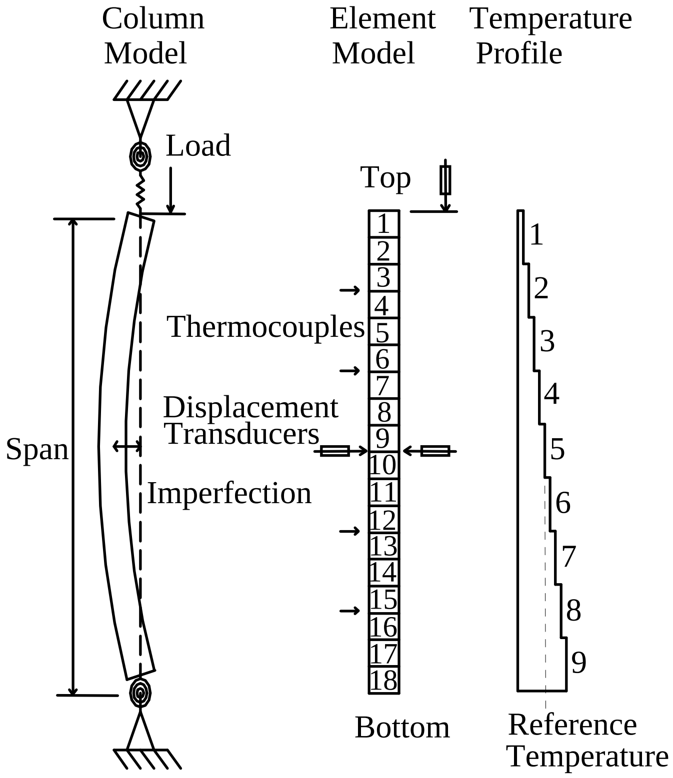


Fig. 1. Column test and modelling.

shown in Fig. 1 The column was modelled using 18 equally-sized elements. A temperature profile of nine steps was defined to represent the temperature gradient along the length of the column. Temperature steps 2 and 8 were matched with the thermocouples in the test, with the other temperature steps calculated to give a constant temperature gradient along the column. Temperature step 5 is taken as the reference temperature also shown in Fig. 1

1.3 Motivation and objectives

Fire is an accidental event, and as such the important aspect of the structural response is that fire fighting should not be rendered impractical by structural collapse and that the natural fire compartment boundaries should be maintained. Thus, the fact that a local structural element ceases to carry load is not all-important provided that the load paths within the structure are diverted so that the applied loads are carried in alternative ways. It is most usually felt by designers that columns must be fire-protected because the failure of a column leaves upper storeys without support, but in many situations the capability exists for such a diversion of load paths into the columns above and surrounding the fire compartment. The restraint to expansion of a column provided by the cumulative stiffness and strength of upper storeys can also provide the means by which the load paths can be diverted when it begins to experience an effective shortening due to buckling or material degradation at high temperatures. The prime objective of the present study is therefore to examine the effects of upper-storey restraint on column behaviour at elevated temperatures, using both discrete spring models and typical multi-storey frame fire scenarios.

2. PARAMETRIC STUDIES

2.1 Material properties

In order to model the test, a number of assumptions have to be made about the material properties of the test column. At the time of writing the steel had not yet been tested to determine its strength or modulus, so various nominal values based on BS5950, 1990 and the draft Eurocode 3, 1993 have been tried. The column was first assumed to have an initial imperfection of 1.8mm (=*Span/1000*) and an analysis was performed. The out-of-straightness (which is not the only component of the equivalent imperfection) was later measured physically and found to be much lower, at 0.21mm, so a further analysis was performed. The physical dimensions of the section were also measured and found to differ from those given in standard section tables.

The effects of these various material properties on the behaviour are shown on Fig. 2. Each case plotted is a variation on the standard analysis of a column with 0.21mm imperfection using measured section sizes, yield strength of 275kN/mm^2 and Young’s modulus of 210kN/mm^2. In no case does the analysis show deflections as large as those eventually shown by the test data. This is because the column has lost nearly all of its stiffness at this stage and deflects very rapidly. The program treats this sudden loss of stiffness as failure and terminates, whereas the test transducers continue to record the large deflections until the data logging equipment is switched off. For this reason only the corresponding part of the test data has been plotted on Fig. 2 for comparison with the analysis. Since two lateral displacement transducers were used during the test, two sets of lateral test results are shown. There seems to be a significant discrepancy between these two results.

From the actual forms of the two curves it seems that there may be a constant zero-shift between the two sets of readings, which is producing an almost constant offset of the order of 0.5 mm. This is not

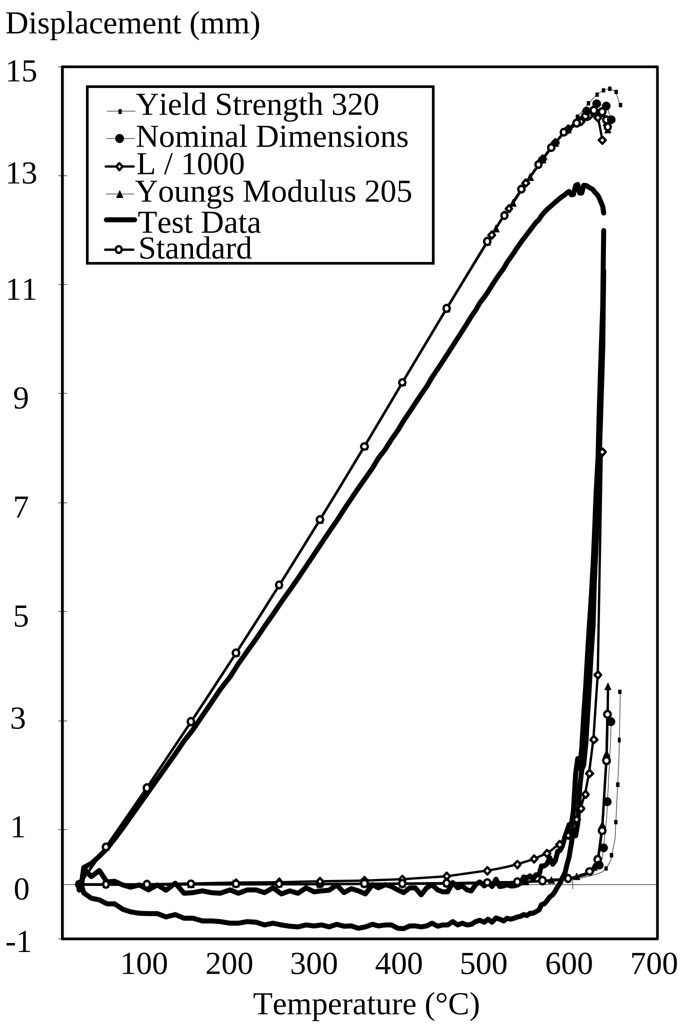


Fig. 2. Comparison of the effects of varying material properties of isolated column on modelling.

totally unexpected; these transducers are extended by quartz rods which protrude through the furnace walls and are cemented to the column web, and the bond between the rod which is induced to move into the furnace by column deflection and the web is likely to be imperfect at high temperatures. It seems reasonable to eliminate this transducer's curve completely, rather than taking an average. As a result, only one set of lateral deflection results (from the transducer which is pushed outwards by the deflection) is plotted on further graphs.

As can be seen from Fig. 2 the model is fairly accurate in reproducing the data seen in the test. Changing the Young's modulus from 210kN/mm^2 to 205kN/mm^2 has a negligible effect on the results, as does using the nominal section dimensions defined in standard tables as opposed to the measured values, even though the difference in these dimensions is quite noticeable. The magnitude of the initially assumed geometric imperfection has a slightly larger effect on the results for minor axis deflection, but axial displacements are similar to the standard case.

Changing the yield strength of the steel results in a noticeable, but still very small, deviation from the standard case. The column has a higher deflection at failure in this case, which occurs at a higher temperature than previously seen. The yield strength of the steel used in the test is not known at this time, and so a value of 275kN/mm^2 is used in further analyses. All the other parameters referred to appear to have little effect on the results, so the standard set of parameters is used.

2.2 Rotational Restraint

Because of the way in which the test rig supports the column, it was considered important to investigate the effect of rotational end-restraint on the column's behaviour. This restraint is introduced due to friction in the bearings, and since the previous analysis assumes that no friction is present this could cause inaccuracy in the model. The effect, even of fairly minor frictional moments at the ends, is to reduce a column's effective length in buckling, and could thus have a significant strengthening effect.

Rather than simply analysing the effects of a constant value of rotational restraint stiffness, a bilinear model was used. This more accurately represents frictional effects, since friction resists rotation until it is overcome, after which the resistance is effectively constant. These models are shown in Fig. 3. The effects produced by these levels of rotational restraint are shown in Fig. 4, from which it is very clear that friction does not

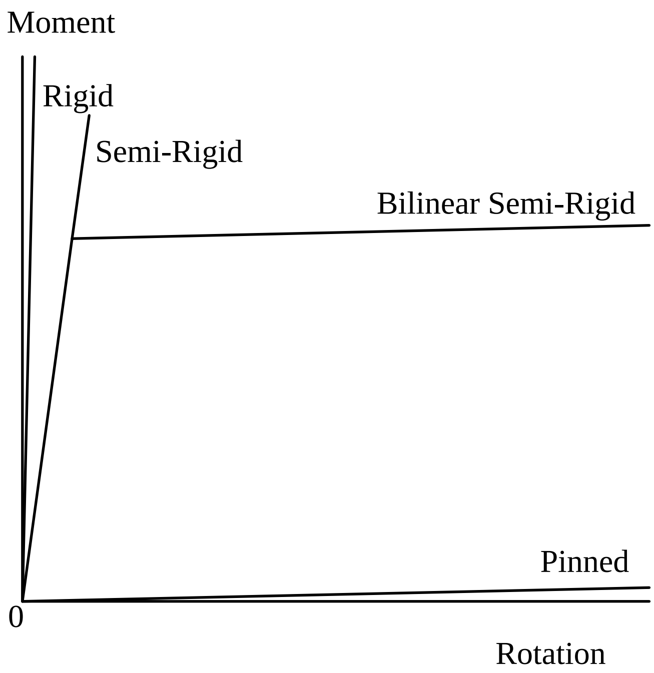


Fig. 3. Support end-rotation models.

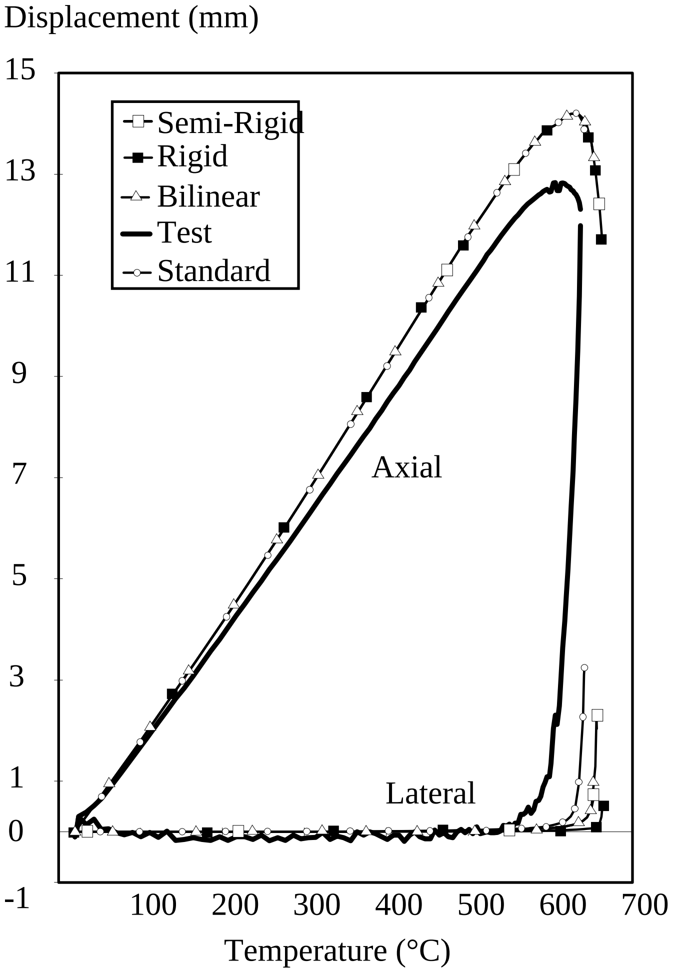


Fig. 4 Comparison of effects of rotational spring models on column behaviour.

have a major effect on the collapse behaviour, and in terms of axial response is hardly perceptible.

2.3 Thermal Expansion

The major discrepancy between experimental results and analysis in Fig. 2 is in the axial displacement in the early stages of the test. This points towards an inaccurate assumption of thermal expansion coefficient. The program uses a quadratic function which is defined in Eurocode 3 Part 1.2, 1993 to model how the thermal expansion changes with temperature. For the purpose of this study, various constant values of the expansion coefficient were used in the analysis, as well as scalings of the quadratic function. The results of these analyses are shown in Fig. 5.

Of the constant expansion coefficients, a value of 1.3×10^{-5}/°C gives results closest to those of the test, although it does not give a very good simulation of the overall behaviour of the test column. In the lower temperature range, the analysis shows deflections larger than those recorded in the test. However, when the temperatures approach the failure region, the deflections are lower than those recorded in the test.

The case where the thermal strain represented by the quadratic function has been scaled by 95% gives the best overall match with the test data. It consistently shows deflections only slightly greater than those of the test data and so is fairly close to the test deflections at failure. These consistently larger deflections indicate that the test column expands in a similar way to that which the quadratic function indicates, but that the actual value of the expansion coefficient implied by the function should be scaled by slightly less than 95%.

2.4 Discussion

It can be seen from this investigation that there are many factors which may be of importance when modelling the tests. The analyst has very little influence over the material properties of the test specimens, and these have been shown in this particular case to have had little effect on the accuracy of the results. Even the friction of the bearings in the test has been insignificant. More

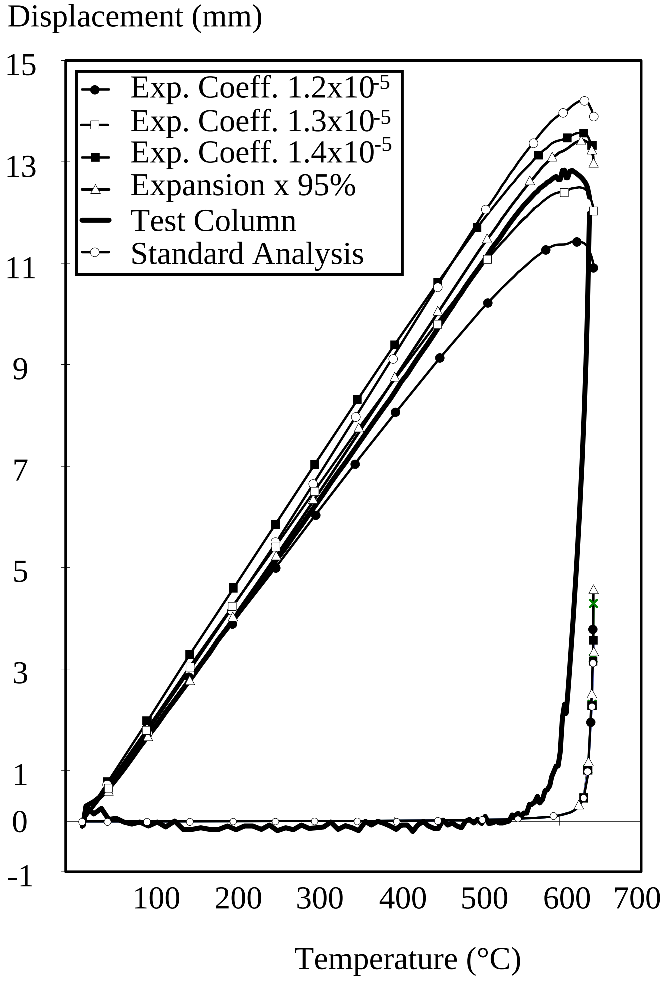


Fig. 5 Effect of thermal expansion characteristics on column behaviour.

accurate data on the thermal expansion of steel is needed, since the EC3 recommendation seems to misrepresent the test.

It may be implied from the lack of sensitivity to geometric imperfection and to rotational end-restraint that the column is "stocky", with a stability limit which is dictated mainly by the degradation of material strength. While this is probably the case, it is rather surprising to observe such behaviour in a column of minor-axis slenderness ratio of 75.

3. AXIAL RESTRAINT

3.1 Spring model

In order to investigate the effects of axial restraint, a heated column has been modelled, using an axial spring element to represent the restraint stiffness of the structure of higher storeys of the frame. For this preliminary 2-dimensional study, a 203x203x52 UC Grade 43 steel column of length 5.16 m and slenderness ratio 100 was used in a similar arrangement to Fig. 1. The strut was given a sinusoidal initial geometrical imperfection, and a load ratio of 0.6 according to EC3. In addition, the elastic stiffness of the axial spring was varied to give the required restraint factor (defined as the elastic stiffness of upper storeys at the column head as a proportion of its own axial elastic stiffness). The results are shown in Figs. 6 and 7.

In cases in which high axial restraint is provided by a very stiff axial spring a high axial force is initially induced in the column as expansion is resisted while the elastic modulus has degraded very little. Further heating causes the column increased thermal strain and consequent increase of axial force, until buckling takes place and the axial force drops very abruptly. However, a further stable equilibrium state exists at this same temperature for which, after initial buckling failure and a nett shortening of the column, the load is largely supported by the spring. It should be noted that the analysis was unable to find stable solutions past initial failure for the least restrained cases although it may be assumed that these do exist.

It is ultimately of no consequence how strong the column is, since this idealised perfectly elastic spring can support any level of load. The force plot of Fig. 7 shows that the force in the column suddenly snaps back to a very low value and tails off towards zero as the temperature increases above this failure region. This idea is supported by the axial displacement plot of Fig. 6, in which the displacement suddenly snaps from the failure point to a stable position at the same temperature at which the top of the column has only displaced slightly further. This extra displacement is due to the axial

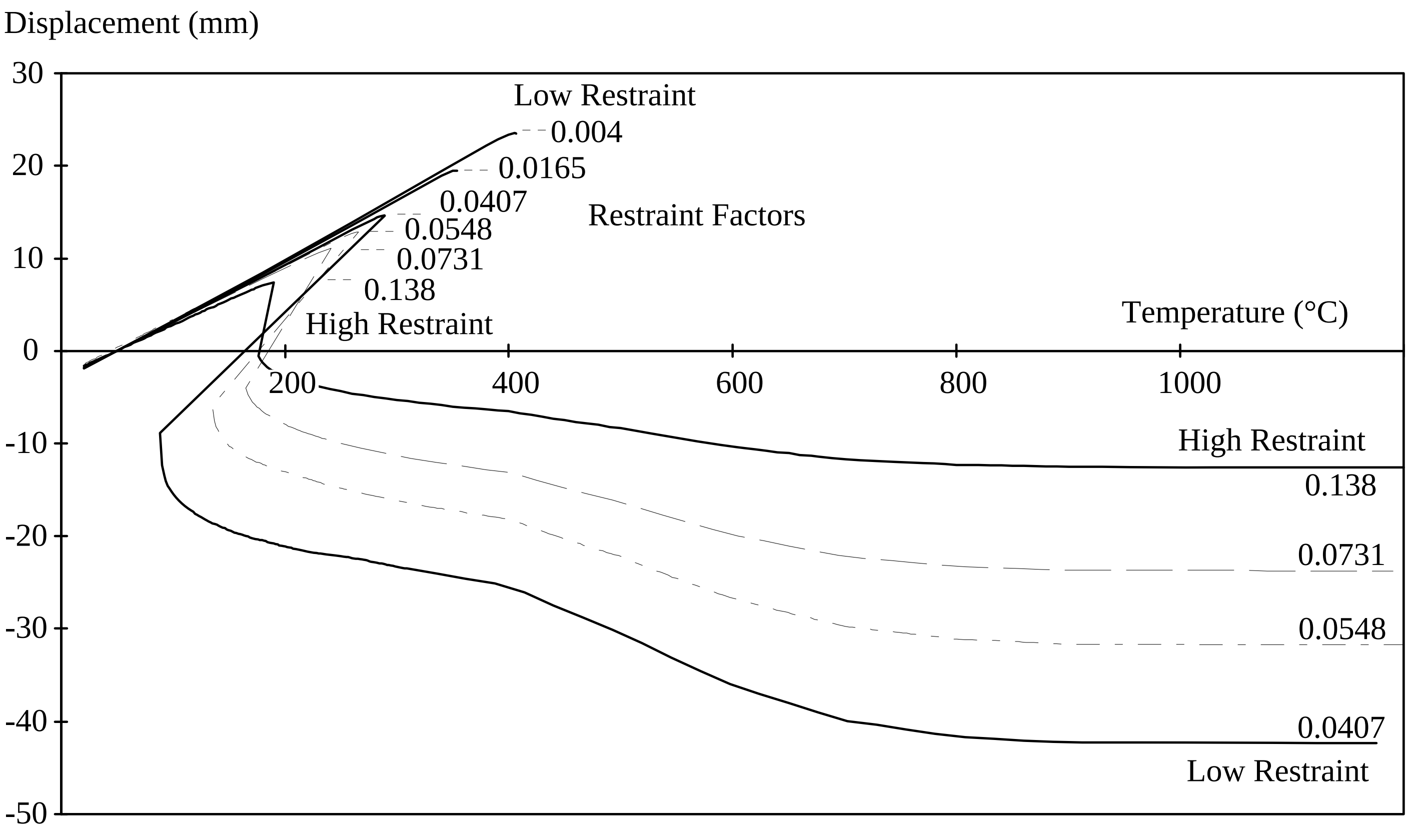


Fig. 6. Variation of axial displacement of top of isolated column with elastic restraint.

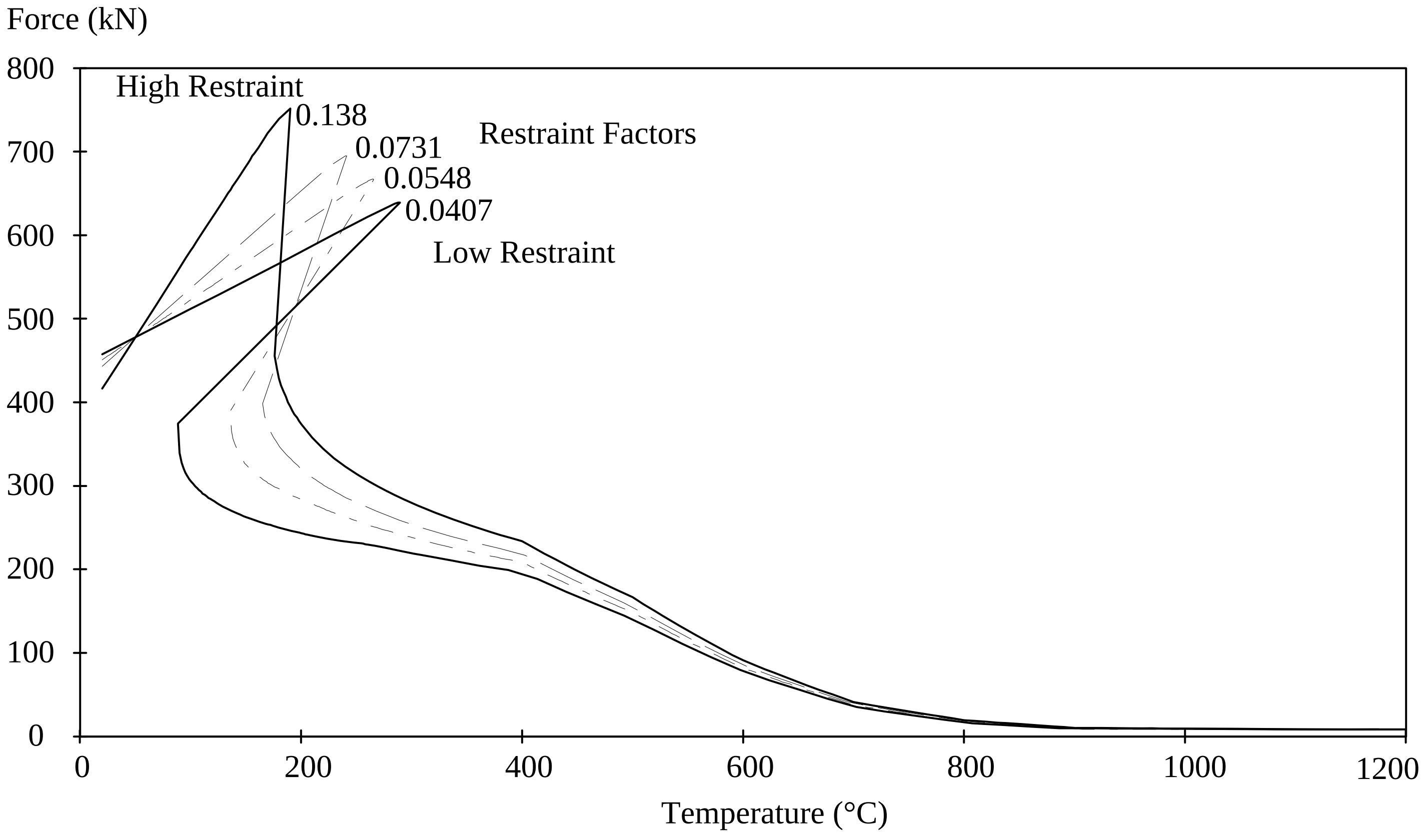


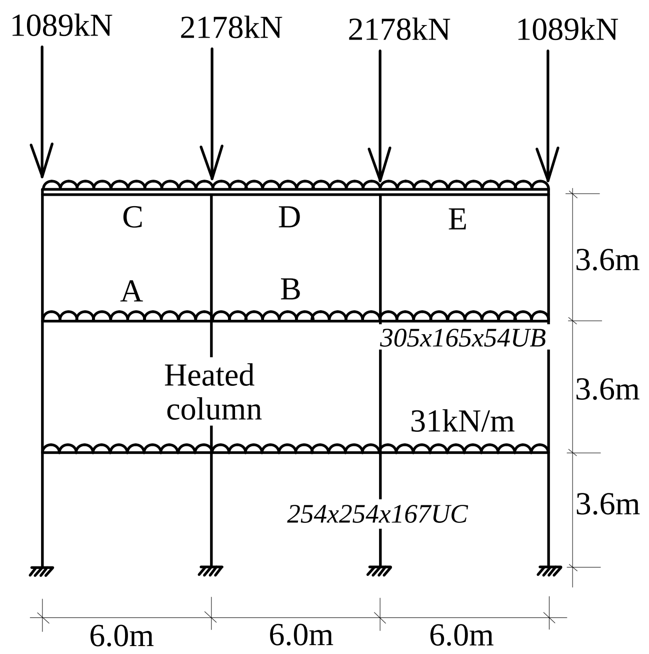
Fig. 7 Axial force variation with restraint factor for isolated column with elastic restraint.

spring extending under the extra force applied to it, creating the reduction in force in the column. Cases which provide less axial restraint by having axial springs of lower stiffness deflect more than the stiffer springs as the temperature rises above the failure region.

3.2 Frame behaviour

To investigate the axial restraint applied to a column by its surrounding frame, the 3-storey, 3-bay steel rigid-jointed frame shown in Fig. 8, which was previously used in a study made by the Steel Construction Institute (Bailey & Newman 1996) was modelled in two dimensions using INSTAF. An inner column on the middle floor was heated and different levels of axial restraint were provided by changing the section size of the continuous beam along the top of the frame which may be taken to represent the cumulative stiffness of even higher storeys. Each column was given an initial geometric imperfection of L/1000. Uniformly distributed loads were applied along every beam, together with additional superimposed loads at the top of each column, to give 0.6 times the load capacity according to BS5950. Thirteen different axial restraint conditions were studied, using Universal Beam sections for the top beam, which produce a reasonable range of elastic restraint factors and also give a progressive yielding beyond the elastic limit at the ends of the beam.

The vertical displacement of the top of the heated column is plotted on Fig. 9 and the axial force in the heated column is plotted on Fig. 10. As can be seen from these graphs, a case with little axial restraint expands as the temperature rises but little change of axial force is induced into the column.



Fig, 8 Two-dimensional 3-storey test frame.

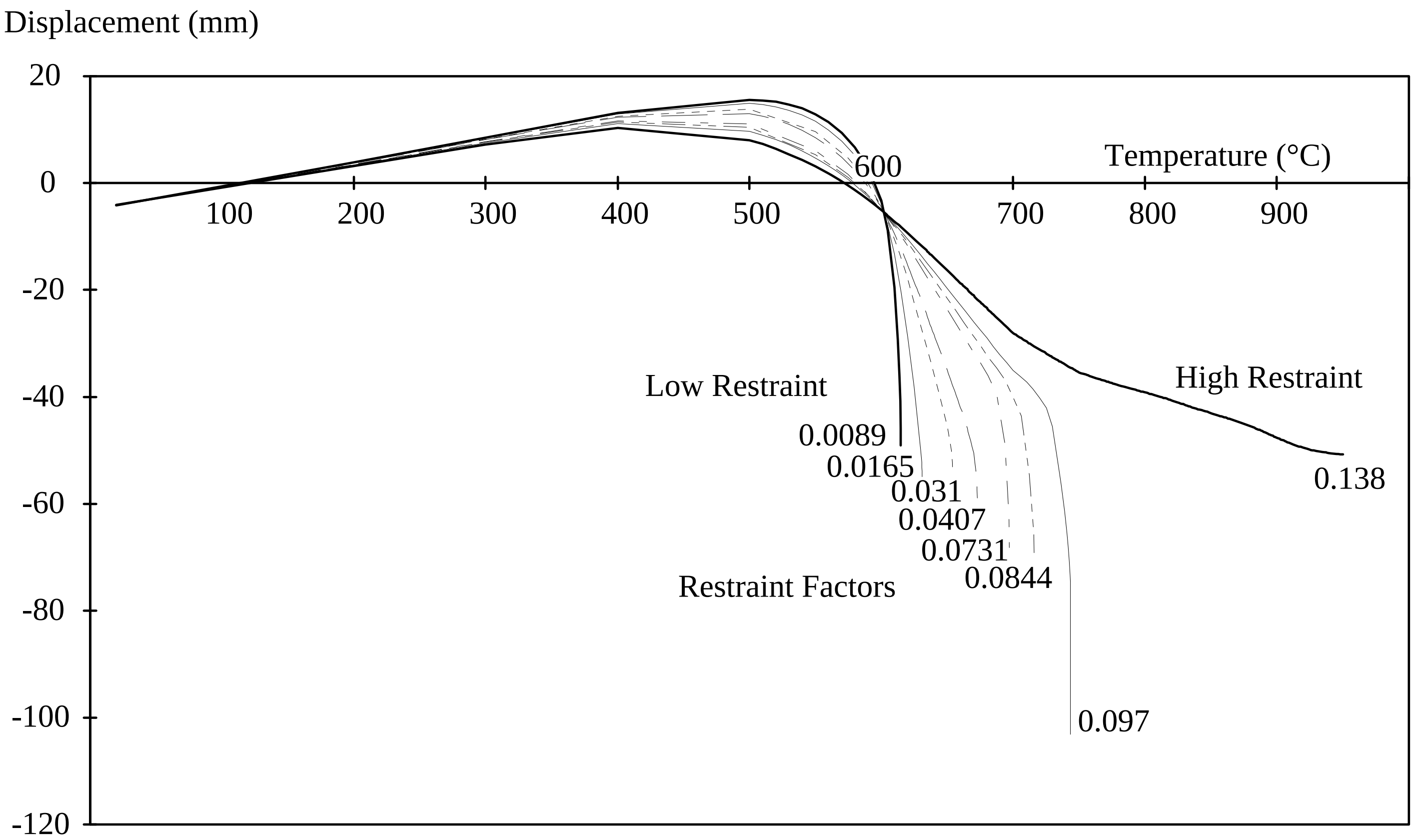


Fig. 9 Vertical deflection of top of heated column in 3-storey frame.

At around 500°C the column has softened sufficiently for its rate of compressive mechanical straining to overtake its tensile thermal straining, and by 600°C it has returned to its original length. Once shorter than its original length, more and more load is being supported by the beams above the column as it shortens. Eventually, these beams have sufficient relative deflection between their ends for all of them, including the top beam, to yield and the column is allowed to collapse.

Cases with more axial restraint allow the column to expand less as the temperature rises, inducing greater change of axial force in the heated column. Once again, by 600°C the column has softened sufficiently to return to its original length, and once shorter than this, the load is supported by the top beam. To provide high values of axial restraint, large section sizes are used for the top beam. These large sections support a much higher column force before yielding, resulting in higher failure temperatures. In fact, the largest top beam selected, which gives a relative restraint factor of 0.138, does not yield at all; at 950°C hardly any axial force remains in the heated column, since most of it is supported by the top beam which redistributes it to the adjacent columns.

4. CONCLUSIONS

As can be seen from the figures, there is a marked difference in behaviour between the two axial restraint models. The actual values of failure temperature are unimportant, since the two models contain sections of very different sizes, effective lengths and rotational restraint levels. However, the general trend of columns with large restraint factors having higher failure temperatures applies only to columns within frames. This is due to the different ways of providing restraint to the column. In the frame model, beams initially provide restraint and later provide support for the heated column. These beams can yield, and so the ultimate failure of the column is governed by the progressive development of plasticity in the beams. The idealised spring model is purely elastic and has infinite strength, so the column is never seen to fail.

It must be noted that this spring model does not accurately represent the axial restraint used in the Ulster tests. The test rig can impose axial restraint to an expanding column, but is not capable of supporting the column in tension once it becomes shorter than its original length. It would therefore be expected to behave in a similar fashion to Figs. 6 and 7 only whilst the column remains longer than its original length. Once the column is shorter than this, it acts as totally unrestrained, and the behaviour

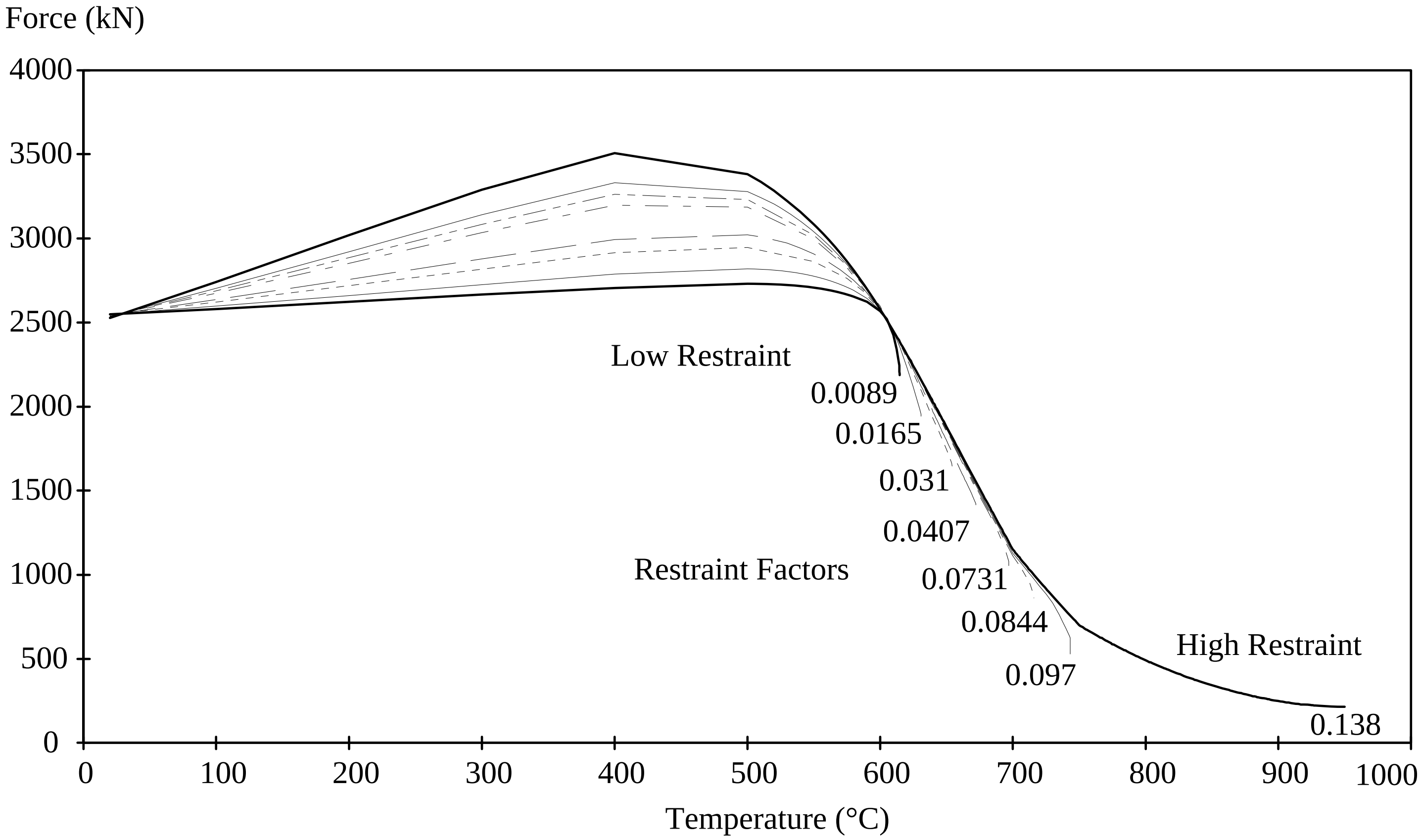


Fig.10. Axial force in heated column in 3-storey frame.

patterns are no longer comparable. The re-stabilising branch will not be seen in the restrained test behaviour in the present test set-up.

From this investigation it can be seen that there is a need for more column tests to be performed at various levels of axial restraint. This will give a more in-depth understanding of the way columns behave in fire. Extensive modelling of columns in frames, with a proper representation of the restraint provided by multi-storey frames of different extents will also facilitate understanding of the effects of bridging action in which loads are redistributed to cool columns surrounding the heated compartment. It will then be possible to begin the process of producing design guidance to engineers on how these potentially beneficial bridging actions may be taken into account when designing a building. This offers the prospect of adopting fire engineering design strategies which combine compartmentation and appropriate active and passive protection with mechanisms for diverting load paths. It may then be possible to dispense with much of the added passive fire protection, except possibly on perimeter columns, which could make a significant contribution to improving the economics of steel building construction without compromising safety.

5. REFERENCES

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