THE EFFECT OF PUSH-OUT OF PERIMETER BUILDING COLUMNS ON THEIR SURVIVAL IN FIRE

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Abstract: There has been some concern that column distortion due to the expansion of beams exposed to fire may reduce the axial load capacity to such an extent that failure occurs in the column, even if it is protected from the fire. In this paper the structural analysis software VULCAN, which has been developed to perform non-linear analysis of three-dimensional frames and sub-frames subjected to fire, has been used to predict the behaviour of a range of column sub-frames in fire scenarios. The effect of thermal expansion of unprotected beams on the critical temperatures of edge columns has been studied for different levels of axial load. These preliminary results indicate that the reduction in column capacity is not critical, particularly when a composite frame is used.

1. INTRODUCTION

In current structural fire engineering design practice it is usual to use some method of fire-protection for steel columns because they play a key role in carrying loads back to foundations. Failure of columns, as distinct from beams, may cause widespread rather than localised collapse of the structure. However, some concern has been expressed [1], partly based on observation of the recent fire tests on a full-scale composite building at Cardington, that increased bending moments may be induced into the perimeter columns because of the pushing-out of unprotected beams due to thermal expansion. Internal columns, although often subject to higher loads, are generally unaffected by this because the effects of thermal expansion either side of the column are approximately balanced. No column failures were seen as a result of this push-out, but the phenomenon clearly merits investigation.

The concerns expressed have questioned whether existing specifications for fire-protection of columns are sufficient to ensure their stability, since this column distortion will lead to additional secondary bending stresses and cause a reduction in load capacity. The benefits of continuity due to cool upper and lower columns are already allowed for in EC3 Part 1.2 by the use of effective length factors of 0.5, thus removing one inherent safety factor which might otherwise have compensated for this reduction. In this paper, a parametric study, using both computer prediction and classical calculation, has been carried out to investigate the potential effects of thermal expansion of unprotected beams on the critical temperatures of edge columns.

2 PARAMETRIC STUDIES

A simple sub-frame, shown in Fig.1, was used to simulate the corner frame of a building, representing the worst case of column push-out. A constant axial load (P) is imposed at the top of the column, and the lower column and both beams are uniformly heated, with the upper column being kept cool. All the properties and dimensions of the column and beams are shown in Fig. 1. The effect of thermal expansion is represented as a horizontal force (F) acting at floor level (point A) as shown in Fig. 2. A classical solution for this can be obtained based on small deflection theory. Both local and lateral buckling in the out-of-plane direction are ignored.

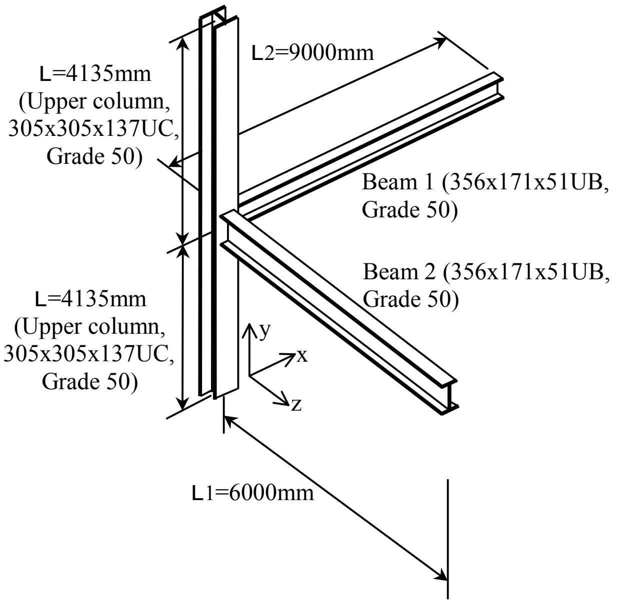

Fig.1 Corner sub-frame used for studies

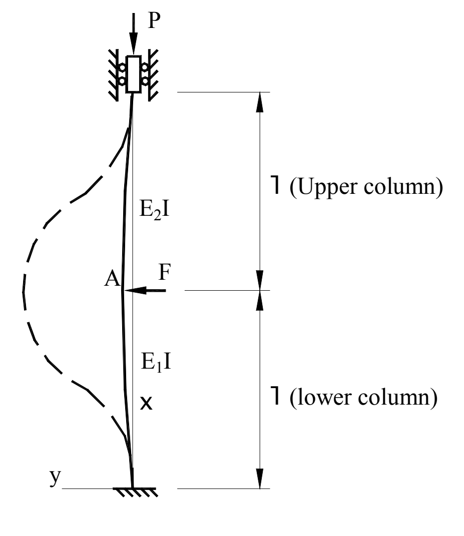

Fig. 2 Two-dimensional model for calculation

The differential equation for stability of long columns can be expressed as

$$\frac{d^4y}{dx^4} + K^2\frac{d^2y}{dx^2} = 0 \tag{1}$$

where $K^2 = P / EI$.

The general solution of Eqn. (1) is $y = C_1 \sin Kx + C_2 \cos Kx + C_3 x + C_4$ (2)

If we assume that initial out of straightness of the column is $y_0 = a_0 \sin(0.5\pi x / l)$ and apply the boundary conditions, the particular solution can be obtained from Eqn. (2).

The factors affecting deflection are: Young's modulus (E), column length (L), its second moment of area (I), axial load (P) and the thermal expansion force (F). There is a linear relationship between the deflection and the thermal expansion force. It is clear that the only parameter which varies with temperature is Young's modulus for the lower column (E_1). If the column is bending about its minor axis, with an axial load (P) of 3000kN (a load ratio of 0.59) and a thermal expansion force (F) of 100kN, and the reduction factor [2] for E_1 at elevated temperature is taken into account, the results of the classical analysis are as shown in Figs. 3 and 4.

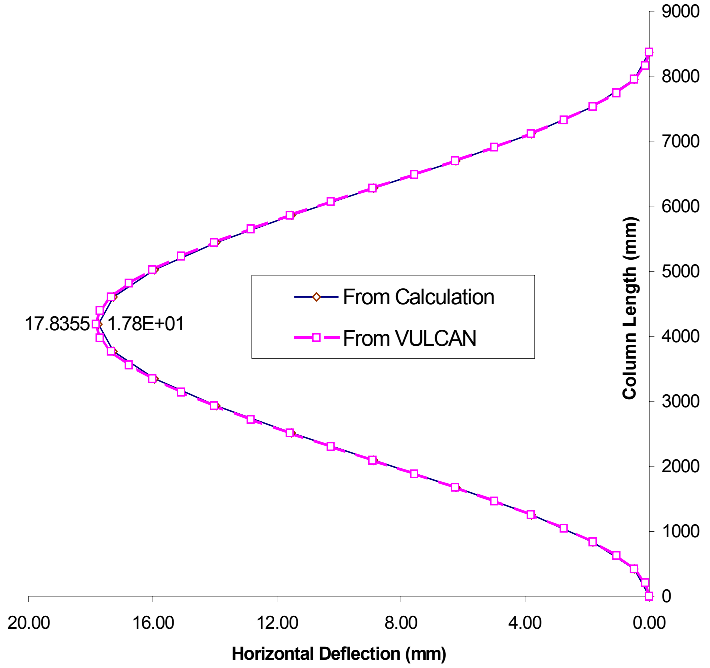

Fig. 3 Column horizontal deflection at room temperature (P = 3000kN, F = 100kN)

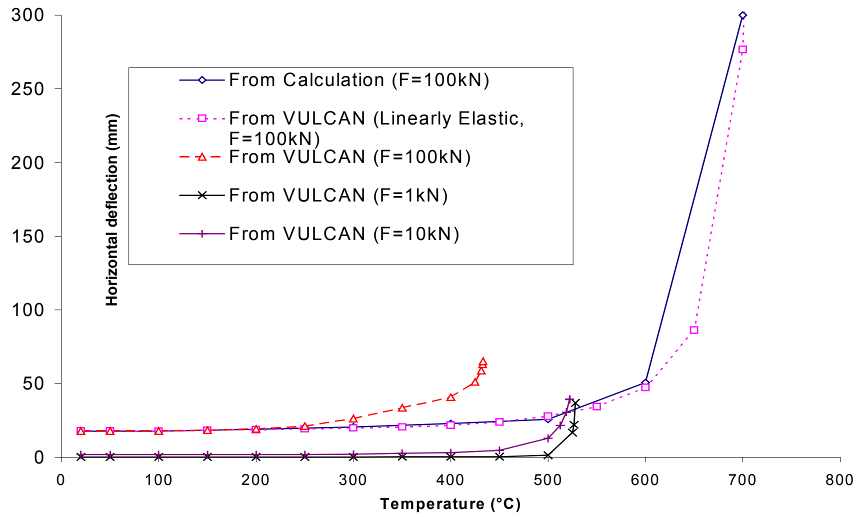

Fig. 4 Deflection-temperature plot for point A. (Axial load P = 3000kN)

Also shown are results from the software VULCAN, which has been developed at University of Sheffield to perform non-linear analysis of three-dimensional frames in fire. It is of interest to note that when VULCAN uses linear-elastic material properties it is in close agreement with the classical analysis. However when more realistic properties are used the two diverge significantly beyond 250°C because of the material yielding which is important for columns of medium or low slenderness [3].

The effects of thermal force, axial load and imperfection have been studied and the results are summarised in Figs. 5, 6 and 7. It may be seen from Fig. 6 that keeping the lower column temperature below 500°C is beneficial since there is only a relatively small change in behaviour at lower temperatures. Fig. 5 indicates that the deflection is proportional to the thermal force when axial load is constant. Fig. 7 indicates that at a low load ratio the magnitude of imperfections has negligible effect.

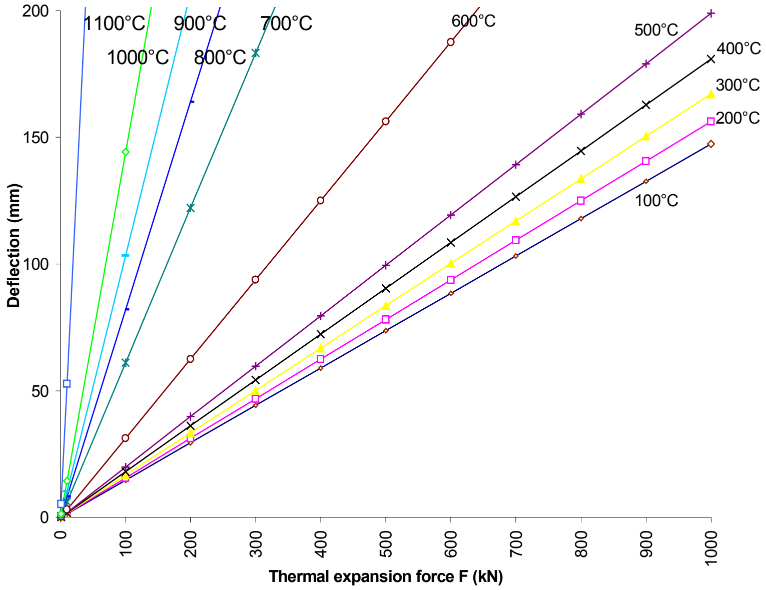

Fig. 5 Deflection-Thermal Force plot (Axial load P = 1000kN)

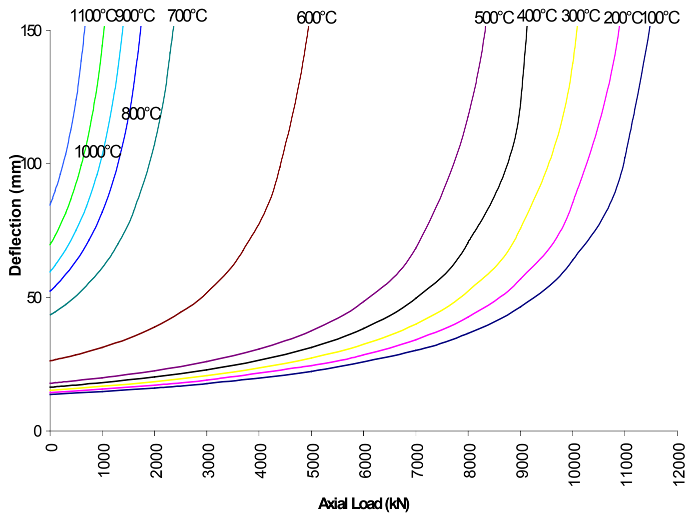

Fig. 6 Deflection-Axial load plot (Thermal expansion force (F) =100kN)

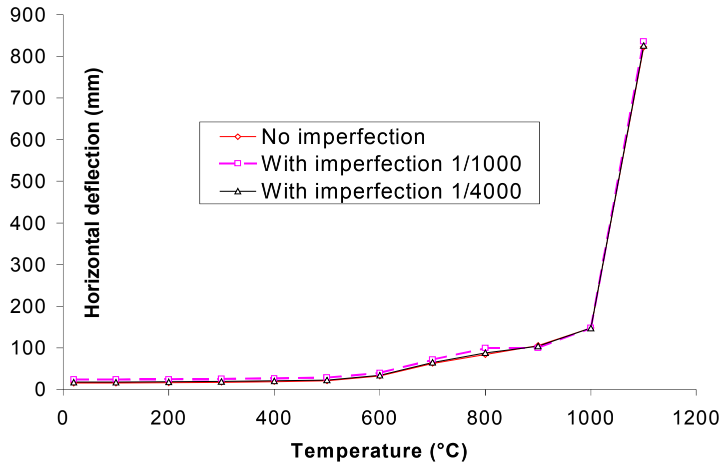

Fig. 7 Effect of imperfection on column with axial load 1000kN, thermal expansion force 100kN

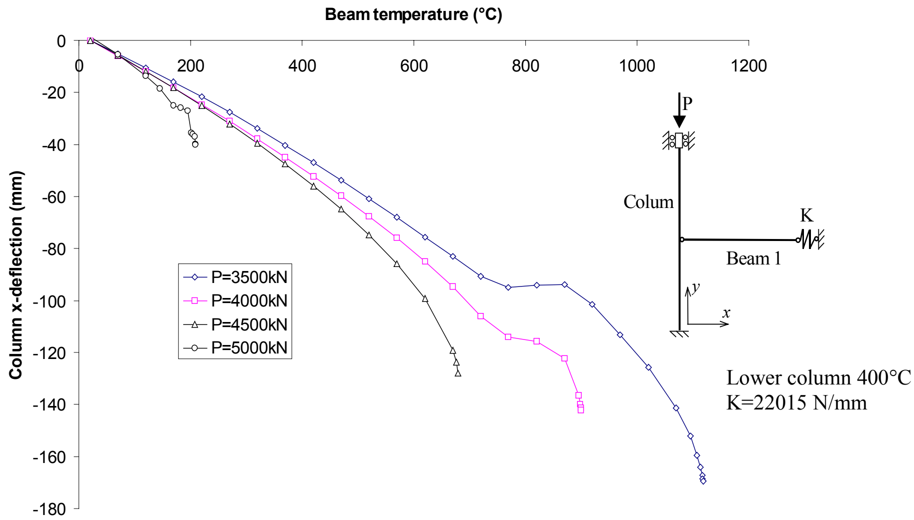

Fig. 8 *x*-deflections at 17/20 of lower column for *x*-*y* plane sub-frame case.

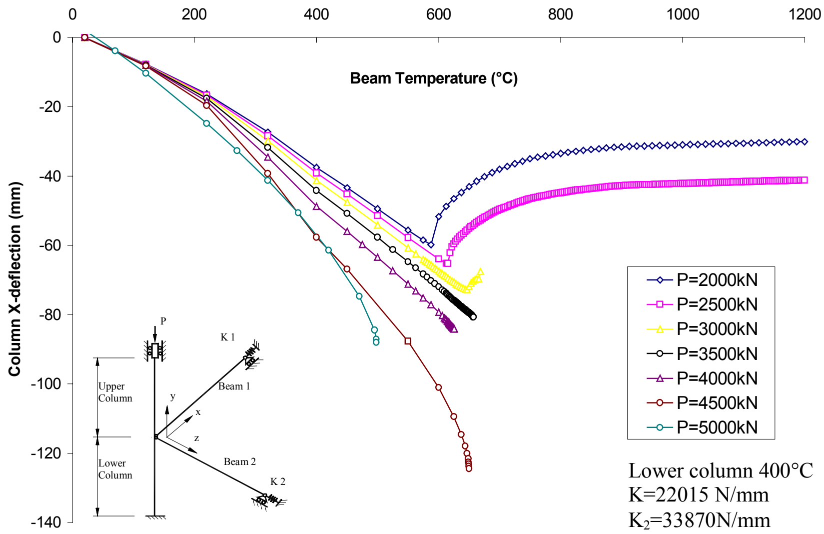

Fig. 9 *x*-deflections at 17/20 of lower column for 3D sub-frame case.

This study has been extended to consider the structure shown in Fig 1. Three models were considered; a 2D plane frame, a 3D skeletal frame, and a 3D frame including floor slabs. The beams are connected by pins to the columns and have springs at their remote ends. The lower-storey column is assumed to be at 400°C, while the beams are heated until column instability occurs. The results are summarised in Figs. 8 to 10. It is clear that the 2D frame does not present much difference in critical temperature from the 3D frame, whilst the inclusion of the slab has a significant influence in reducing the effect of beam expansion. In Figs. 9 and 10, because of beam buckling some curves reverse their directions.

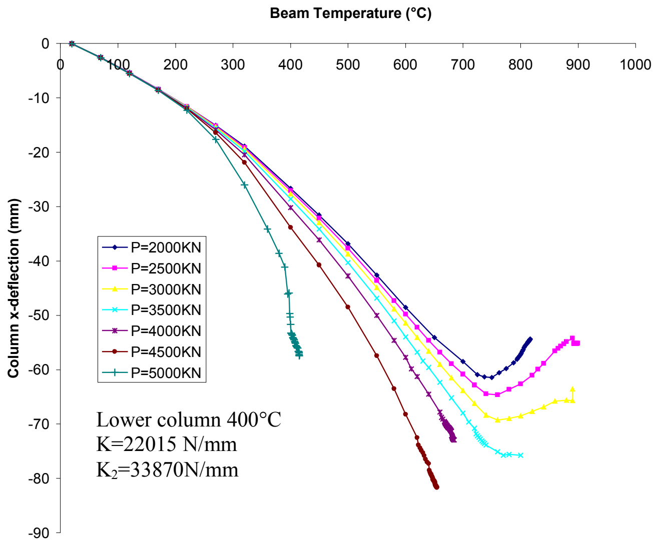

Fig. 10 *x*-deflections at 17/20 of lower column for 3D composite sub-frame case.

3 CONCLUSION

In this study, a classical buckling calculation has been implemented for a column with the assumption that thermal expansion of a floor beam can be expressed as a horizontal force acting at floor level. The results indicate that the effects of thermal expansion of unprotected beams reduce the survival temperature of column proportionally, and that $P-\Delta$ causes a significant reduction of this temperature in the case with high axial load. Both the effects of thermal expansion and axial load should be taken into account and it is suggested that designers use simplified calculation in two dimensions to model the structural instability approximately.

REFERENCES

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