AN INVESTIGATION OF OVERTURNING MOMENTS OF PORTAL FRAMES AT ELEVATED TEMPERATURES

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1 INTRODUCTION

In the UK, single-storey steel buildings account for over half of the constructional steelwork due to its ease of fabrication and cost-efficiency. The most common of these are portal frames. One of the major disadvantages of constructional steel is its sensitivity to fire, as steel looses strength and stiffness rapidly. For this reason, fire protection is often required, which can add to the expense of structure.

In fire, the rafter often loses stability through a snap-through-buckling mechanism (see Fig. 1.). This, however, can be capable of restabilising at high deflections, when the roof has inverted. In static analysis methods, only the initial loss of stability can be determined. In fire conditions it is imperative that boundary walls stay close to vertical, so that fire is not allowed to spread to adjacent property. The current UK fire design guide (Ref.1) provided by Steel Construction Institute (SCI) provides a method for the determination of the overturning moment at the column base that must be resisted in order to prevent stability of walls. However, the method makes a number of arbitrary assumptions and does not attempt to model the true behaviour of the frame during fire, leading to very uneconomical design details. An elaborate study of the collapse mechanism using the finite element program VULCAN has been described by Song *et al* (Ref. 2, 3). Wong (Ref.4) studied the responses of industrial pitched portal frame structures in fire both experimentally and numerically. He developed a method for calculation of the critical temperature of a steel portal frame. His method is limited to determining the temperature at which the snap-through buckling of portal frame occurs, without any consideration of post-snap through behaviour. Song *et al* (Ref.2,3) continued the work of Wong and conducted a study of the behaviour of portal frames using dynamic analysis. Song investigated the failure mechanism of a single-storey haunched portal frame in fire subject to different support conditions at their column base. They pointed out that the rafter is capable of restabilising after it collapsed through snap-through-buckling mechanism. Vassart *et al* (Ref.5) presented a comparative study on a double span portal frame in fire designed by Franssen *et al* (Ref. 6). Yin *et al* (Ref.7) performed a numerical study of large deflection behaviour of restrained steel beams at elevated temperatures.

It was established that the large deflection behaviour of steel beams could significantly affect their survival temperature in fire, and they particularly emphasized the behaviour of axially restrained steel beams in catenary action. In the present paper, a non-linear elasto-plastic dynamic finite element analysis is presented that can be used to simulate the collapse of a

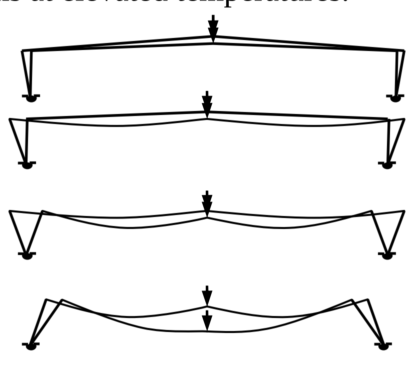


Fig. 1. Snap-through mechanism

portal frame in standard ISO834 fire (Ref. 8). The results of the dynamic model are validated through comparison against results found in the literature, and also through results obtained using the same model but solved using implicit static, implicit dynamic and explicit dynamic analyses.

It is demonstrated that an explicit dynamic analysis is a viable alternative to an implicit dynamic analysis, and has the advantage of being computationally more efficient to solve when the problem is quasi-static in nature. The implicit dynamic model is used to investigate the current UK fire design guide (Ref. 1) published by SCI.

2 MATERIAL PROPERTIES AT ELEVATED TEMPERATURE

Fig.2 shows the reduction of ultimate strength of steel at different temperatures to that at ambient temperature. As can be seen, there is no loss in ultimate strength at temperatures up to 400^{o}C. Fig.3 shows stress-strain curves of steel at 20^{o}C, 400 ^{o}C, 600 ^{o}C, 800 ^{o}C and 1000 ^{o}C in accordance to Eurocode 3 (Ref.8). It should be noted that there is no strain-hardening in the Eurocode curves and it is assumed in SCI method that only 6.5% of steel strength at ambient temperature is retained at while the steel is subjected to a temperature of 890^{o}C. The coefficient of thermal expansion is assumed according to the same code. A value of 0.3 is used as Poisson's ratio for the whole analysis, and steel is considered as an isotropic material with a density of 7850.0 kg/m^3.

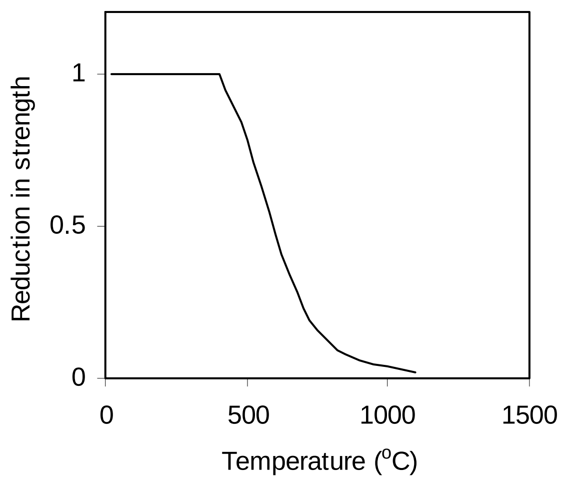


Fig.2. Variation of reduction in ultimate strength of steel against temperature

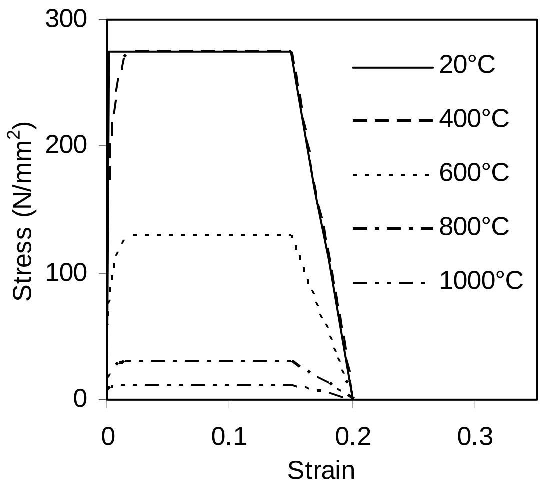


Fig. 3. Stress-strain curves for steel grade S275

3 FIRE MODEL

Fig.4 shows the standard fire rating curve (ISO834). Eurocode 3 provides a simple calculation method for calculation of section temperature while the section is unprotected or protected. The calculated temperature for an unprotected steel section IPE450 is presented in the same graph for comparison. It should be noted that ISO834 curve shows a rapid heating as compared to the section temperature based on the simple calculation method of EC3. This is because the surrounding gas temperature is assumed equal to the standard temperature while the temperature is rising inside the steel section by heat conduction and radiation.

4 BENCHMARK MODELS

The dynamic finite element model used in Section 5 of this paper needs first to be validated against the results of two benchmark models: a single span frame after Song *et al* (Ref.2) and a double span frame after Vassat *et al* (Ref.5). For both cases, non-linear elasto plastic implicit dynamic analyses were used. In the case of the analysis by Song *et al*, the finite element program VULCAN was used for the analysis. In the case of the analysis by Vassat *et al*, the general purpose finite element program ABAQUS was used.

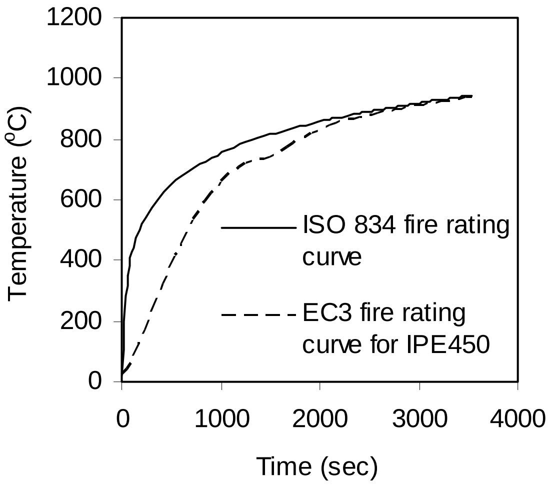


Fig. 4. Time-temperature curves

4.1 Single span portal frame

Fig.5 shows details of the single span portal frame. As can be seen, the columns of frame are pinned and the frame is loaded through a uniformly distributed load of 5.76 kN/m. The frame is modelled in ABAQUS using beam elements B21. Sixteen elements are used for each column and thirty-two elements for each side rafter.

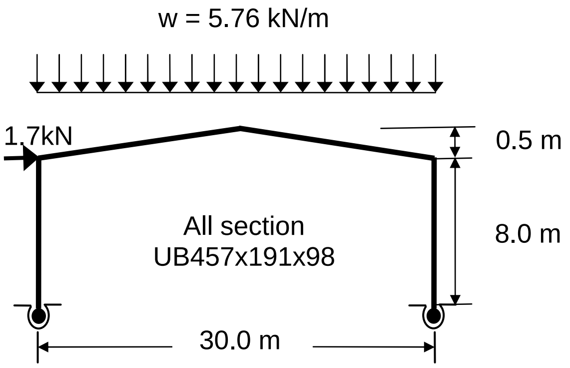


Fig. 5. Details of single span frame after Song *et* al (Ref.2)

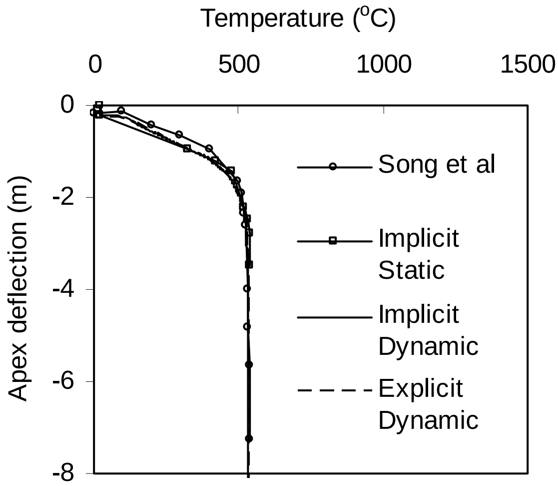


Fig. 6. Variation of apex deflection against temperature for single span frame

Fig.6 shows details of the variation of apex deflection against temperature. It can be seen that the implicit static analysis fails to converge at an apex deflection of 2.2 m when the structure starts to become geometrically unstable. The problem of geometrical instability can be overcome by using either implicit dynamic or explicit dynamic analysis. As can be seen from the same figure, the results of the implicit dynamic and explicit dynamic are similar to the results obtained by Song *et al* using VULCAN. The frame experiences snap-through-buckling at a temperature around 560^{o}C.

4.2 Double span portal frame

Fig.7 shows details of the double span portal frame. As can be seen, temperature is increased in the left hand side rafter and column only. The right hand side column and rafter, including the middle column, are kept at ambient temperature. It can be seen from Fig.8 that only the left hand side of the portal frame will experience snap-through-buckling. Fig. 9 shows details of the variation of left hand side apex deflection against temperature. It can be seen that the implicit dynamic and explicit dynamic results are similar to results obtained by Vassart *et al*.

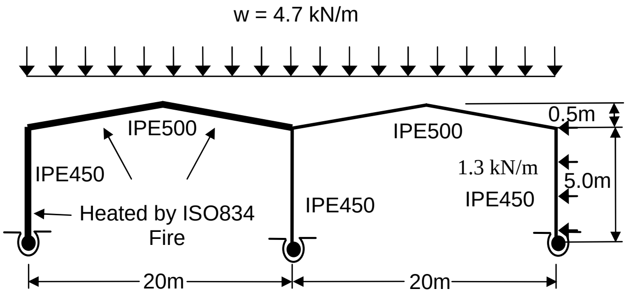


Fig.7. Details of double span frame after Vassart et al (Ref.5)

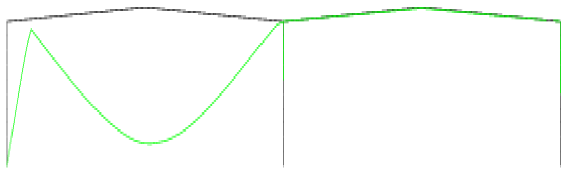


Fig. 8 Deformed shape at 1100°C (Deflections magnified by a factor of 50)

4.3 Discussion of results

For both benchmark models, it has been demonstrated that the implicit dynamic and explicit dynamic results are similar. For the purposes of the study in the following section, an implicit dynamic analysis will be adopted.

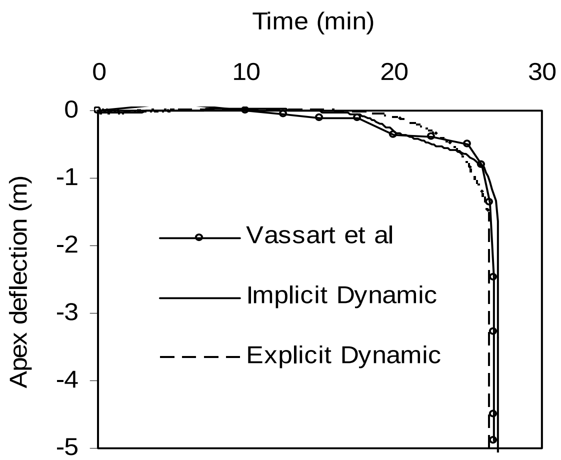
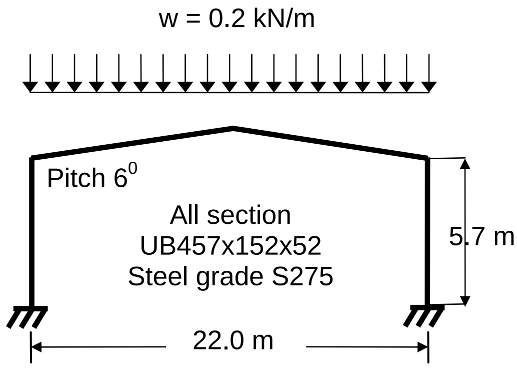


Fig. 9. Apex deflection of left rafter against time

5 COMPARISON AGAINST EXISTING DESIGN RECOMMENDATIONS

The SCI have published guidelines for the design of portal frames at fire boundary conditions (Ref. 1). This method is based on calculating an overturning moment (OTM) that needs to be resisted in order to maintain stability of the column and allow the collapse of the rafter. If this method is used, fire protection needs only be applied to the columns and the rafters can remain unprotected. Fig 10 shows the details of the portal frame analysed for comparison. Fig. 11 shows the variation of overturning moment against temperature for two frames. In the first frame, the column is unprotected, while in the second frame the column is protected. In both models the frames do not collapse at a temperature of 1100°C, with an apex deflection of less than 0.1 m. Using the SCI method, the overturning moment is calculated to be 61.3 kNm. This value of overturning moment is indicated in the same figure. As can be seen, the overturning moment obtained by the finite element model for both cases is higher than the overturning moment calculated using the SCI method. The dotted lines at 301 kN represents the plastic moment capacity of the steel section detailed in the figure.



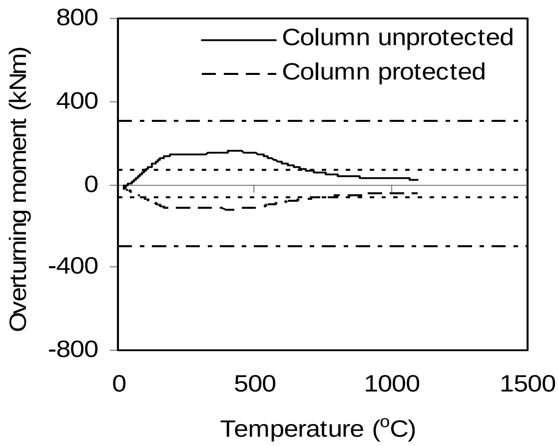


Fig.10. Details of explemplar single span portal frame after SCI (Ref. 1)

Fig. 11. Overturning moment

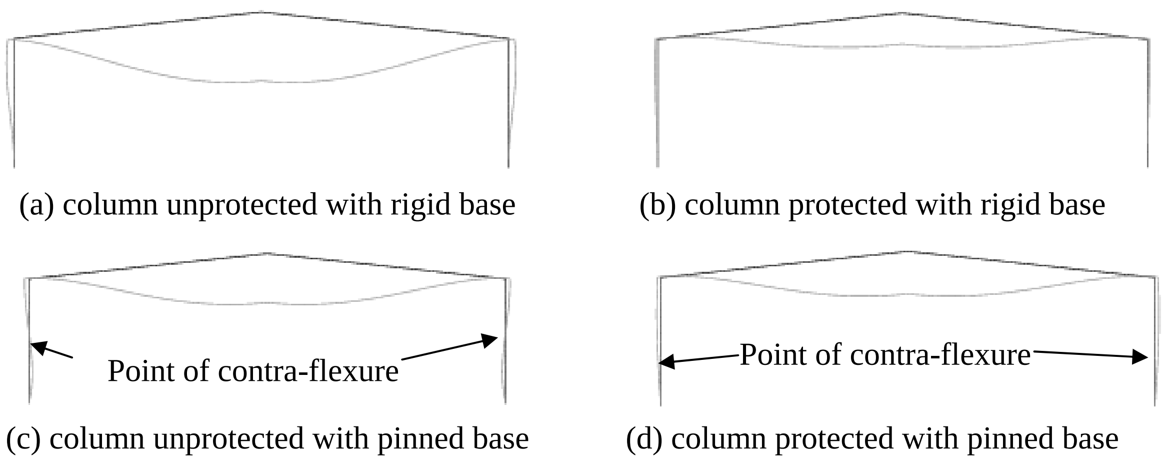


Fig. 12 Deformed shape (Deflection magnified by a factor of 25)

It is interesting to note that the reactant moment for the case of column unprotected and column protected are opposite in direction. Two further models were analysed in which the column base was pinned. The deformed shapes for all four models at 1100°C are shown in Fig.12. From deformed shape of the frames having pinned bases, it can be seen why the overturning moments act in opposite directions. One can notice the point of contraflexure in the middle of columns.

6 LOADS FOR SNAP-THROUGH BUCKLING

The frame described in the Section 5 did not undergo snap-through-buckling. In this section, the same geometry of frame has been analysed but varying the vertical uniformly distributed load from 0.5 kN/m to 5.0 kN/m. The results have been compared against the SCI model as shown in Fig 13. As can be seen, SCI method is conservative for the lower collapse load but for higher collapse load, this method overestimates the overturning moment and leads to uneconomic design of steel section. Fig 14 shows the variation of apex deflection at different temperatures with various types of loads on rafter. As can be seen from this figure, snap-through-buckling occurs for a load of around 3.5kN/m.

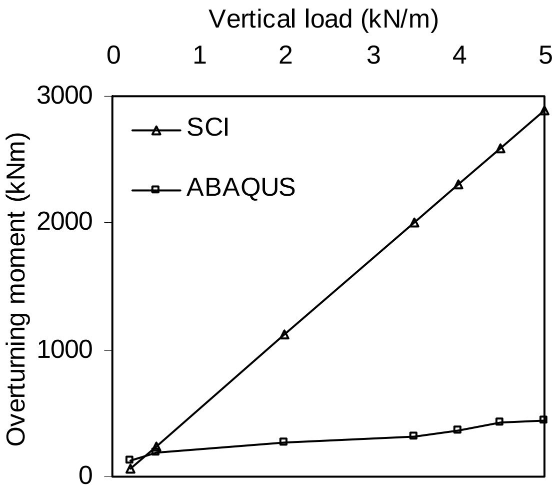


Fig. 13. Comparison of overturning moment

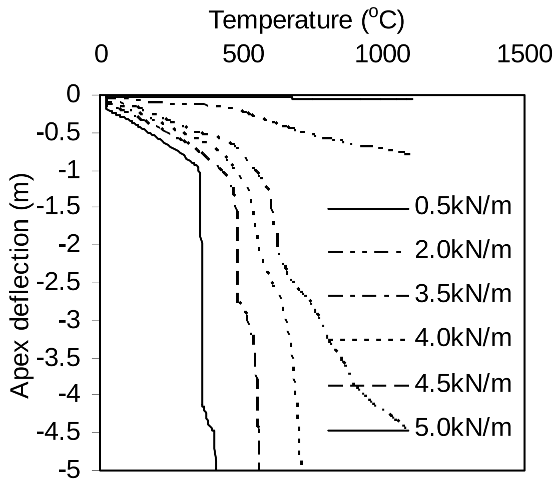


Fig. 14. Effect of different vertical loads

7 CONCLUDING REMARKS AND FURTHER WORK

Based on the present study, the following conclusion can be drawn:

- Both implicit dynamic and explicit dynamic analysis present the similar results.
- The present model is capable of predicting the post-snap-through-buckling behaviour.
- The reactant moment for the case of column unprotected and column protected are opposite in sign as point of contra-flexure is formed in the middle of column.
- The SCI OTM method can be over conservative.

In further work, the effect of axial and rotational restraints will be studied in order to determine whether they have any impact on the snap-through mechanism of the portal frame. In addition, a 3D analysis will be carried-out with a complete portal frame building.

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