DYNAMIC BEHAVIOUR OF PORTAL FRAME AT ELEVATED TEMPERATURE

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Abstract: In this paper, a non-linear elasto-plastic finite element analysis is presented using dynamic analysis method that can be used to simulate the collapse of a portal frame in fire. The results of the dynamic model are validated through comparison against results found in the literature, and also through results obtained by using the same model but solved by different methods. It is demonstrated that the snap-through-buckling temperature is susceptible to the load on rafter, level of fire protection used in column and rafter, and rotational stiffness of column base of portal frame. While the column base support is pinned, the snap-through-buckling temperature is independent of level of fire protection. While the column base support is fixed, the snap-through-buckling temperature is shifted to a higher value. Increase of loads on rafter decreases the snap-through-buckling temperature, and increase of rotational stiffness increases the snap-through-buckling temperature.

Keywords: Snap-through-buckling, collapse, instability, elevated temperature

1. Introduction

Single-storey steel buildings account for over half of the constructional steelwork in the UK for its ease of fabrication and cost-efficiency. The most common of these are portal frames. One of the major disadvantages of using constructional steel is its sensitivity to fire, as steel reduces strength and stiffness rapidly. Therefore, fire protection is often required, which increases the expense of the structure.

In fire, the rafter often loses stability through a snap-through-buckling mechanism (see Figure 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 residences. The current UK fire design guide (Simms and Newman, 2002) provided by Steel Construction Institute (SCI) provides a method to determine 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 is unable to model the behaviour of the frame during fire accurately, 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 (2007). Wong (2001) studied the responses of industrial pitched portal frame structures in fire both experimentally and numerically. He developed a method for prediction 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 (2007) 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 (2007) presented a comparative study on a double span portal frame in fire designed by Franssen et al (2004). Yin et al (2004) performed a numerical study of large deflection behaviour of restrained steel beams at elevated temperatures.

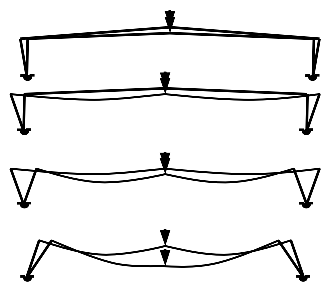

Figure 1. Snap-through-buckling mechanism.

It is established that the large deflection behaviour of steel beams could significantly affect their survival temperature in fire with particularly emphasizes on the behaviour of axially restrained steel beams in catenary action. In the present paper, a non-linear elasto-plastic finite element analysis using explicit dynamic method is presented to simulate the collapse of a portal frame in standard ISO834 fire (BS EN 1993-1-2: 2005). The results of the dynamic model are compared with results found in the literature, and also with results obtained using the same model but solved using static and implicit dynamic analyses.

It is demonstrated that an explicit dynamic analysis is a feasible 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.

2. Why explicit dynamic method of analysis

Explicit dynamic analysis is less often used in general structural analysis problems. However, for the present model, it is felt that explicit dynamic analysis is suitable for the following reasons.

First, the duration of the fire loading on the portal frame suggests that the model is quasi-static in nature (i.e. neither fully static nor fully dynamic), which suggests that the present model is a best candidate for explicit dynamic analysis; and secondly, materials with degradation and failure, as in the case of portal frame in fire, often lead to severe convergence difficulties in either static method or implicit dynamic method of analysis, but explicit dynamic analysis programs can easily model such material until the material stiffness degrades to zero.

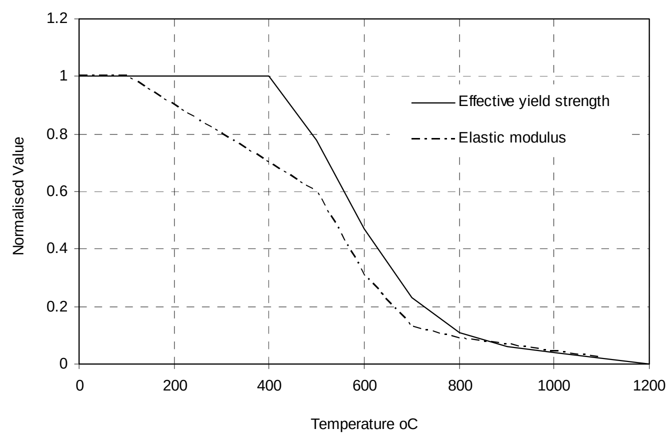

Figure 2. Variation of effective yield strength and elastic modulus of steel at different temperature.

3. Material properties at elevated temperature

Figure 2 shows the normalized effective yield strength and elastic modulus of steel at different temperature. The normalization is done against the corresponding value at ambient temperature. As can be seen, there is no loss in effective yield strength at temperatures up to 400^{o}C. However, the elastic modulus starts to decrease at 100^{o}C Figure 3 shows stress-strain curves of steel grade S275 at different temperature in accordance to Eurocode 3 (BS EN 1993-1-2: 2005). 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 effective yield strength of steel at ambient temperature is retained at while the steel is subjected to a temperature of 890^{o}C. The coefficient of thermal expansion is set 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.

4. Fire model

Fig.4 shows the standard fire rating curve in accordance to ISO834 and Eurocode 3. 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 faster heating as compared to the section temperature based on the simple calculation method of EC3. This is because the surrounding air temperature is assumed equal to the standard temperature while the temperature is rising inside the steel section due to the heat conduction and radiation.

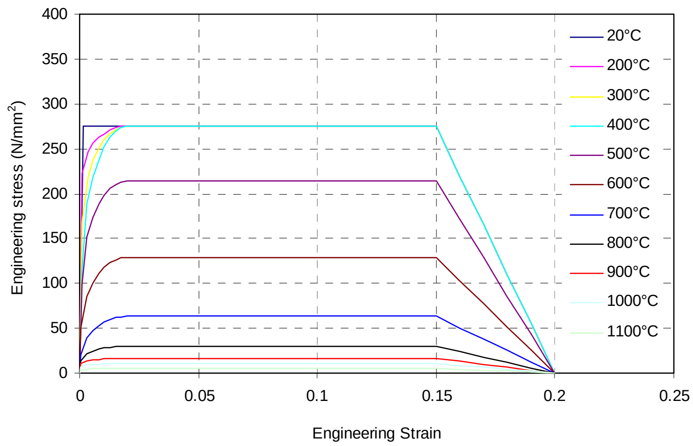

Figure 3. Engineering stress-strain curves for steel grade S275 at different temperature after Euro code 3.

5. Abaqus model details

The present study uses the numerical simulation method by using a general purpose commercial finite element package Abaqus (Abaqus user's manual, 2006) in order to observe behaviour of portal frame under fire boundary conditions in various scenarios. The analyses methods that have been used are static, implicit dynamic and explicit dynamic analyses. Explicit dynamic analysis is used throughout the remaining of the analysis for further study. Static and implicit dynamic analyses have been used for validation purposes up-to unstable and post-unstable, i.e. post snap-through-buckling behaviour respectively.

Instead of using shell or solid elements, as they require extremely large computational time without showing any major improvements in results, beam elements of type B21 have been selected in order to keep the model simple and accurate. This element consists of two nodes with two translational and one rotational degree of freedom. Moreover, this element is capable of showing temperature gradient throughout the section, or different temperatures at gauss point integrals. Five Gauss point integrals are used throughout the web of both columns and rafter of portal frame.

In static method of analysis, large-strain material non-linearity is included. With *ELASTIC and *PLASTIC options, the yield and ultimate tensile strength of structural steel components are converted to the true stress and plastic strain with appropriate input format for Abaqus.

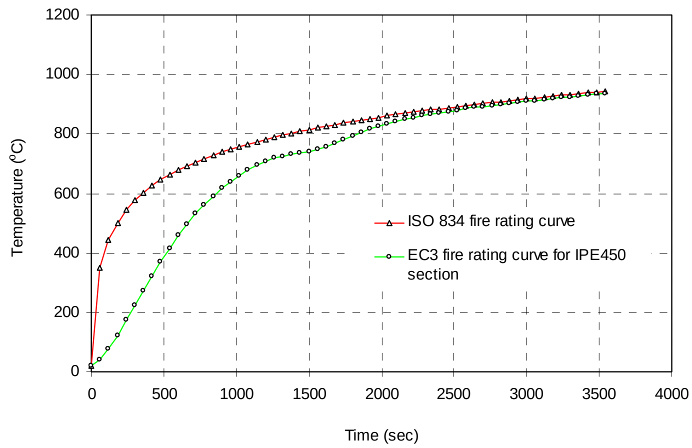

Figure 4. Time-temperature curves.

Out of two generic ways (Wang, 2002) for a structure under fire conditions, namely transient state method where loads are applied first and held constant and then structure is exposed to gradually increased temperature, and steady state method where the structure is exposed to gradually increased temperature first and then constant load is applied, we have selected the transient state method.

For numerical simulations in Abaqus using the transient state method, the structural load is applied and held constant in the first step, and steel temperature is gradually increased in the next analysis step.

Ambient temperature of the whole structure at 20^{o}C is applied by means of *INITIAL CONDITION option. Structural load in the first step is applied through *DLOAD and *CLOAD option. Temperature is increased gradually in the next step using the *TEPERATURE option.

Static method of analysis is stopped when the structure started to show structural instability. Either of the parameters, RIKS and STABILIZE with *STATIC option, have been used to overcome the problem. Both of these parameters are valid as long as the model is static in nature. Since the considered portal frame model is dynamic or at least quasi-static in nature, use of these parameters is of no use to overcome the convergence and continuation of computational problem, and use of dynamic methods of analysis seem to be the best option.

Implicit dynamic method of analysis is stopped as well when the structure started to show structural instability. In order to overcome this structural instability and continue calculation up-to post snap-through-buckling behaviour of structure, HAFTOL and ALPHA parameters with *DYNAMIC option are used. These options are related to convergence and damping within the analysis. ALPHA adds extra numerical damping to the model. An analysis with no extra numerical damping was terminated after a significant amount of time with very little or no advancement in result. Increments of time were so little that it was deemed pointless to continue the analysis. Altering this value has no considerable impact on the analysis result, however, increase of the value of ALPHA parameter allowed significant savings in computational time. HAFTOL parameter helps achieve faster convergence by limiting the size of increment. It uses the residual forces left from the solution from previous increment of time to affect the increment size. Altering this value virtually has no impact on the analysis results; however, the main effect of altering of this value is significant savings of computational time. Roughly, a value in the range of 10 to 100 times helps achieve faster solution. A too small or too large HAFTOL parameter adversely affects the convergence and computational time.

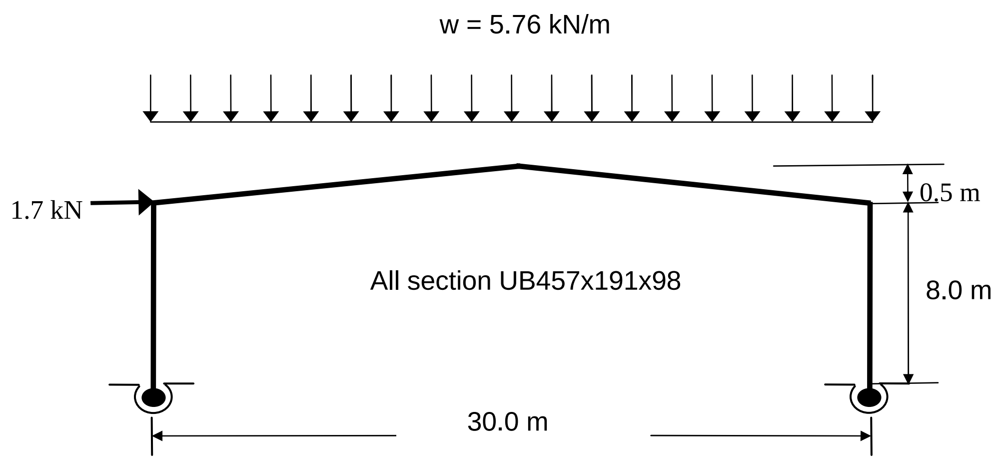

Figure 5. Details of single span portal frame after Song et al (2007).

Explicit dynamic method of analysis may show numerical instability for a quasi-static analysis. In such cases, to obtain a numerically stable solution, mass scaling procedure has been adopted. It alters the mass matrix used in the acceleration equation used in the model and adds extra damping. A similar effect can be obtained by increasing the density of the material, but mass scaling method gives more control over the analysis. *FIXED MASS SCALING option is used for this purpose.

Rotational stiffness at column base is modeled using a spring element at the column base whose stiffness for the rotational degrees of freedom can be varied.

Density of steel is necessary for either implicit or explicit dynamic analysis in order to accommodate inertia forces.

Rayleigh mass proportional damping is used in this analysis in order to introduce some mechanism to dissipate kinetic energy to get quantitatively accurate results in an unstable structure. A value of 5% Rayleigh mass proportional damping is chosen for our analysis. Rayleigh stiffness proportional damping is not considered as the stiffness of the structure is lost at higher temperature and makes the structure mass dependent.

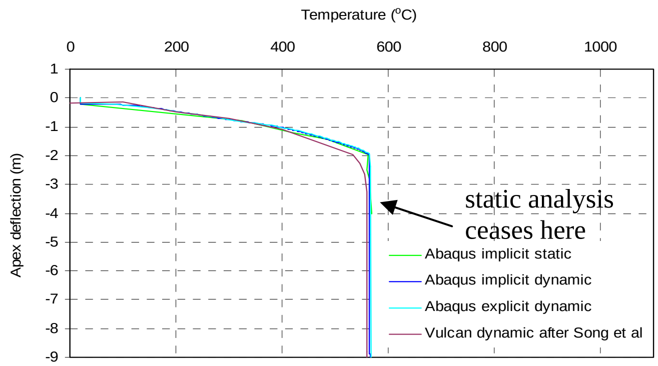

Figure 6. Variation of apex deflection against temperature for single span portal frame.

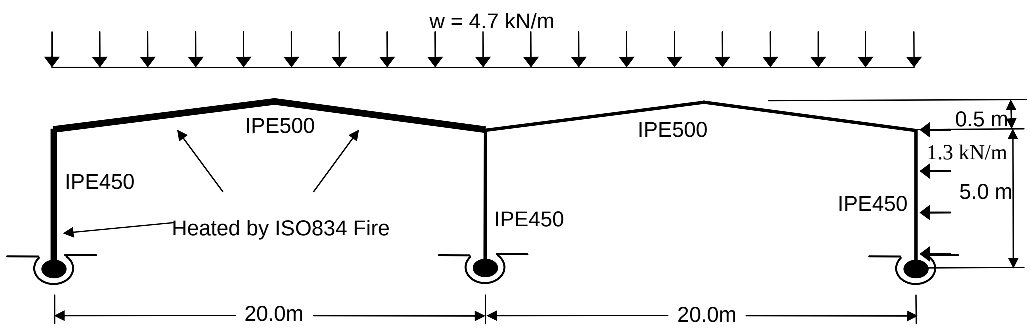

Figure 7. Details of double span frame after Vassart et al (2007).

6. Benchmark models

The dynamic finite element model described the previous section of this paper needs first to be validated against the results of two benchmark models: a single span frame after Song et al (2007) and a double span frame after Vassart et al (2007). For both cases, non-linear elasto-plastic implicit dynamic analyses were used. Song used Vulcan finite element analysis program for analysis of the single bay portal frame, and Vassart used Abaqus for analysis of the double bay portal frame.

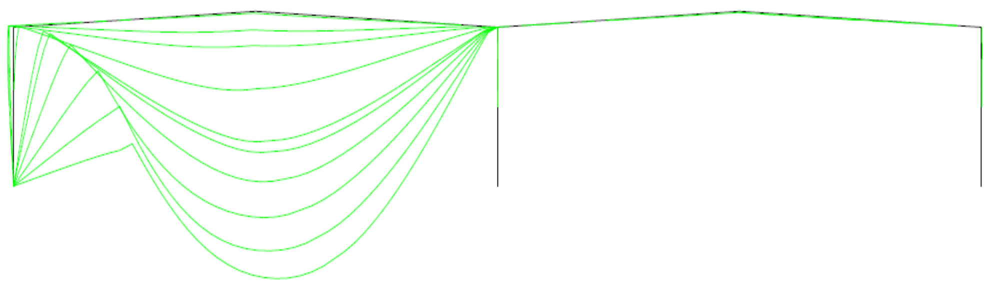

Figure 8. Deformation of double bay portal frame at various stages of elevated temperature (left frame is at elevated temperature).

6.1 Single span portal frame

Figure 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. Sixteen beam elements are used for each column and thirty-two beam elements for each side rafter. A fixed mass scaling factor of 2 is used for explicit dynamic analysis.

Figure 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 2.3 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 using Vulcan. The apex of the frame experiences snap-through-buckling at a temperature around 561^{o}C.

6.2 Double span portal frame

Figure 7 shows the 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 Figure 8 that only the left hand side of the portal frame will experience snap-through-buckling. Figure 9 shows details of the variation of left hand side apex deflection against temperature. As can be seen, the results between implicit dynamic and explicit dynamic are quite close the results obtained by Vassart using Abaqus. The apex of the left rafter experiences snap-through-buckling at around 26 minute of time.

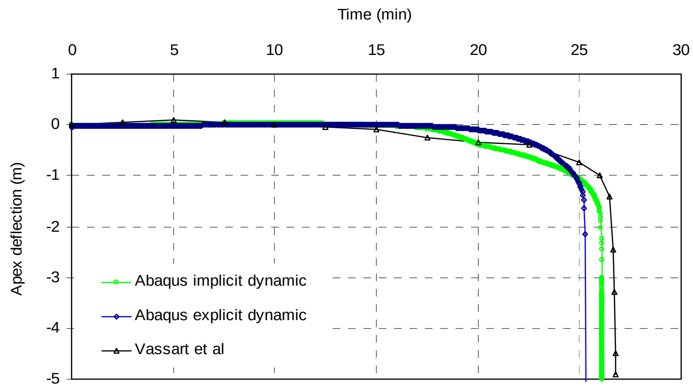

Figure 9. Variation of apex deflection of left hand side frames against time of double bay portal frame.

6.3 Analysis time

In the present analyses, explicit method of analysis solves quite faster than the implicit method. In case of single bay portal frame, explicit method has taken 3 minutes to solve the model when fixed mass scaling factor is 2 and for the same model implicit analysis has taken almost half an hour to finish. In the case of double bay portal frame, the explicit method solves the model in six minutes and implicit analysis takes almost one hour. In both cases, static analysis fails to converge when the model becomes unstable. This clearly indicates that explicit method of analysis is a viable alternative to an implicit method of analysis.

6.4 Discussion of results

For single span portal frame model, it has been demonstrated that the implicit dynamic and explicit dynamic analysis results are similar, as shown in Figure 6. But for double span portal frame model, though the results obtained by implicit and explicit dynamic methods of analysis are almost similar, there is a small difference between the results of implicit and explicit methods of analyses as shown in Figure 9. This is mainly caused by the difference in the methods of solution procedure. However, the difference is within the range of 2% of the results which can be considered as acceptable.

7. Parametric study

A parametric study is conducted for the SCI portal frame (Newman and Simms, 2002) where- *level of fire protection in column*, *loads on rafter* and *column base rotational stiffness* is varied. The detail of the portal frame is shown in Figure 10.

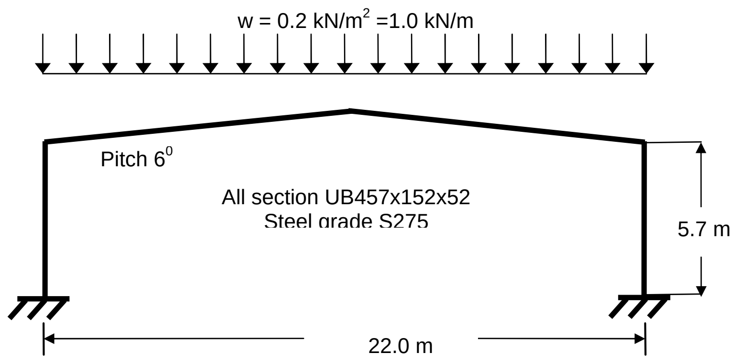

Figure 10. Details of SCI examplar single span portal frame.

7.1 Effect of level of fire protection and support conditions

It is assumed that the rafter is not surrounded by any fire protection material in order to ensure that in the event of fire it will collapse within portal frame structure. It means that rafter temperature is always at elevated temperature. However, the column may or may not be surrounded by any fire protection material which may or may not allow the column temperature to be kept at either at ambient temperature or be at elevated temperature. The column base support can be either fixed or pinned. As a consequence, four cases can be considered for analysis a shown in Table 1. The rafter is kept at elevated temperature at all cases.

Table 1: Different cases based on fire protection at column and column base support condition.

Cases	Description
case 1	Column is at ambient temperature, column base support is fixed
case 2	Column is at elevated temperature, column base support is fixed
case 3	Column is at ambient temperature, column base support is pinned
case 4	Column is at elevated temperature, column base support is pinned

Figure 13 shows the variation of apex deflection against temperature for different cases. As can be seen from the figure, the apex of the portal frame experiences snap-through-buckling within the range of temperature of 805^{o}C to 811^{o}C for cases 2, 3 and 4. However, for case 1, the apex of the portal frame experiences snap-through-buckling at higher temperature at around 936^{o}C, and shows some stabilization at a vertical deflection of apex of 2.47 m , which again experiences another snap-through-buckling at around 1069^{o}C. When column base is pinned, the level of fire protection has no effect on snap-through-buckling temperature; however, when the column base is fixed, the snap-through-buckling temperature is shifted to a higher value. These means that type of column base support condition has a considerable influence on snap-through-buckling temperature. Fixed column base is more suitable for structure to be designed for fire resistance as it increases the snap-through-buckling temperature.

Figure 14 shows the variation of overturning moment (OTM) at column bases for cases 1 and 2. According to the SCI method, the maximum OTM will be 61 kNm. This clearly indicates that the SCI method is over-conservative and less predictable as can be seen from this figure, the structure experiences OTM of 307 kNm at 727°C and 146 kNm at 406°C for case 1 and 2 respectively, which in both cases are over the SCI value; and more than 5 times and 2 times of the SCI value for case 1 and 2 respectively. In case 1, the structure even experiences nearly the plastic moment capacity of the section, which is 301 kNm. The OTM drastically falls when the apex of the structure experiences snap-though-buckling at 936°C and 805°C respectively.

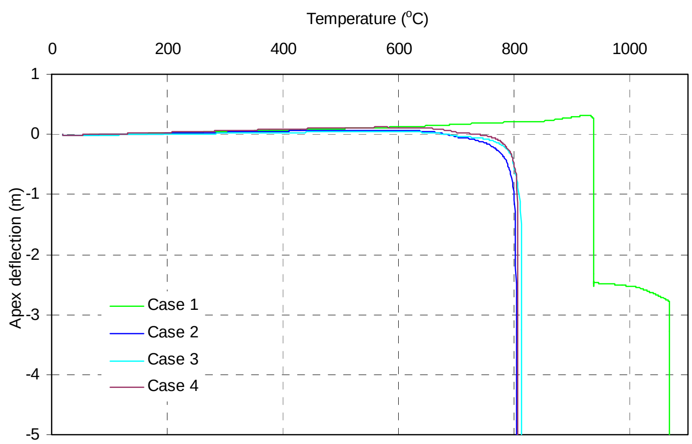

Figure 13. Variation of apex deflection against temperature for single span SCI portal frame for various cases.

7.2 Effect of loads on rafter

The loads on rafter is varied between 1 N/ m to 5000 N/m and self-weight is not considered as additional load. Figure 15 shows the variation of apex deflection against temperature for different loads on rafter. As can be seen from the figure, that the structure experiences snap-through buckling at around 425 N/m load. It means that at elevated temperature the structure will always experiences snap-through-buckling as the self-weight of structure is 506 N/m which is higher than 425 N/m. However, in reality, there will always be some loads on rafter in addition to its self-weight, which will come from the roofing and purlins. As the load increases on rafter, the temperature of snap-through-buckling decreases as can be seen in Figure 12. The snap-through-buckling temperature for this structure is within the range of 584°C to 1095°C.

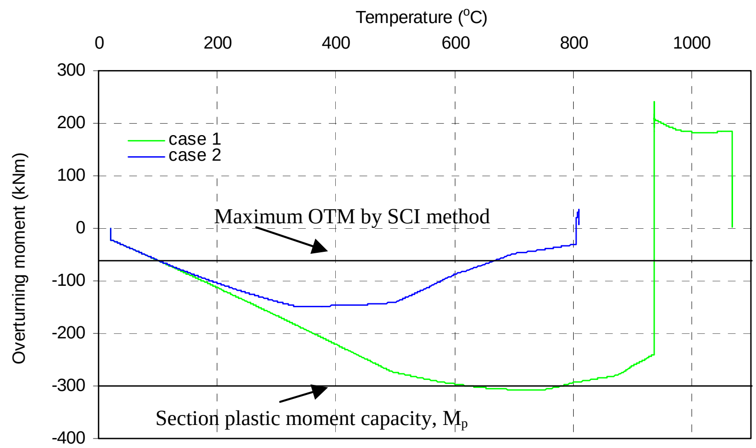

Figure 14. Variation of resisting moment against temperature at the column base for single span SCI portal frame for case 1 and case 2.

7.3 Effect of column base rotational stiffness

At ambient temperature it is quite reasonable to assume the column base support condition is either fixed or pinned. But in real cases, while the structure is at elevated temperature there is no absolute fixed or pinned support existed, rather, the column base support will behave somewhere between the fixed or pinned support. It simply means that the rotational stiffness of the column bases will be varied from 0 to infinity, which according to the SCI guidelines will be somewhere between 8 to 25 time of EI/h of column of portal frame. E stands for modulus of elasticity, I for cross-sectional moment of inertia, and h is the height of column.

Figure 15 shows the variation of apex deflection against temperature for different rotational stiffness. As can be seen from the figure, the apex deflection varies within the range of column base K=0 (column base pinned) and K=25 (column base fixed), where, K is the normalized value rotational stiffness. As can be seen from Figure 16, at lower rotational stiffness, the structure experiences snap-through at lower temperature; and increase of rotational stiffness provides some sort of stabilization on the structure and, consequently, it experiences snap-through-buckling at higher temperature. It is interesting to note that, at higher rotational stiffness, the structure experiences some sort of stabilization after its first snap-through-buckling, as can be seen from Figure 15.

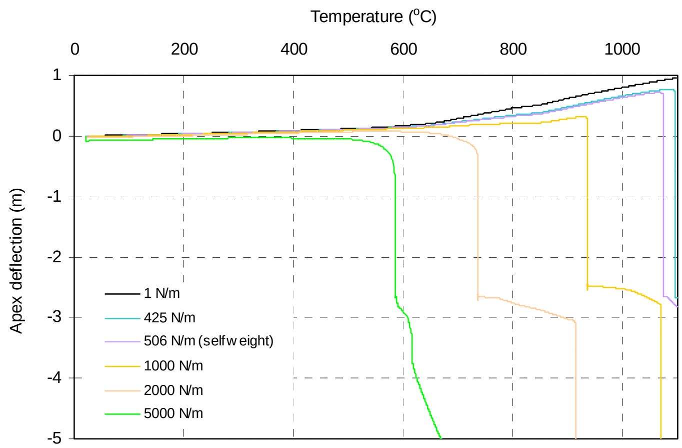

Figure 11. Variation of apex deflection when load is varied for single span SCI portal frame for case 1.

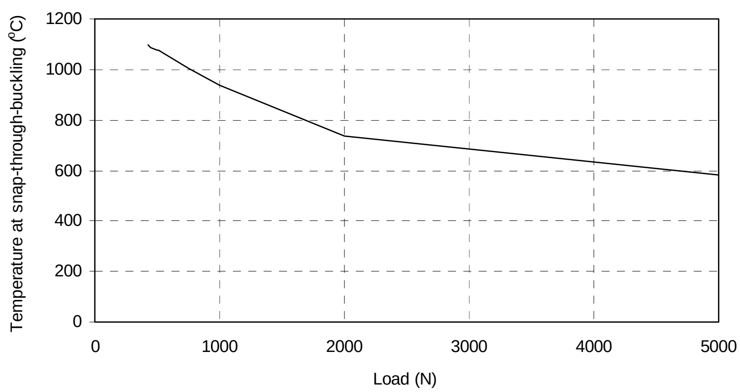

Figure 12. Relationship between applied load on rafter and snap-through-buckling temperature for the SCI rafter for case 1.

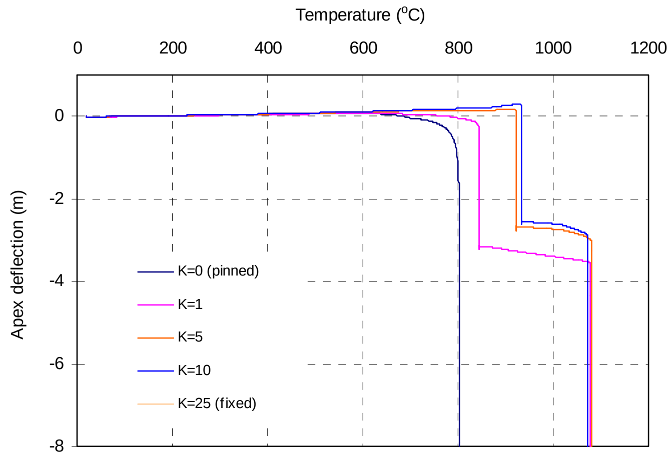

Figure 15. Variation of apex deflection when column base rotational stiffness is varied for single span SCI portal frame for case 1.

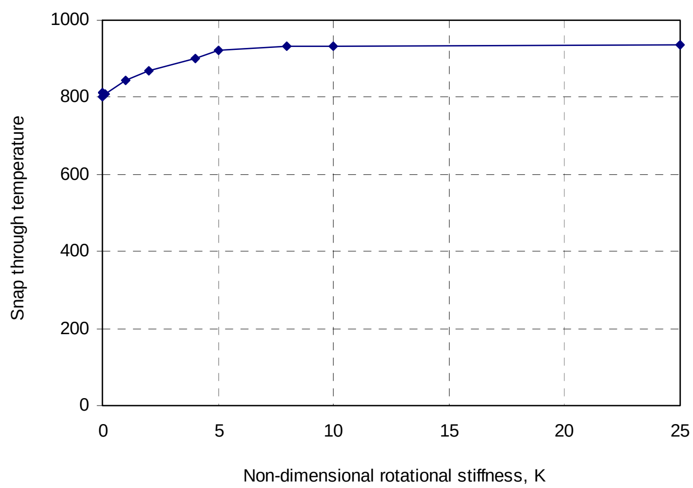

Figure 16. Relationship between rotational stiffness at column bases and snap-through-buckling temperature for the SCI rafter for case 1.

8. Conclusions

Behavior of a portal frame at elevated temperature is numerically investigated using dynamic method of analysis. Both geometrical and material nonlinearity is considered at elevated temperature. The model is validated against two benchmark models where satisfactory agreement is achieved. It is capable to capture the large-strain, large-displacement, and most importantly the instability behavior of portal frame structure, and these sort of behaviors are quite common in any structure at elevated temperature.

It is established that the snap-through-buckling temperature is susceptible to the level of fire protection, loads on rafter and rotational stiffness of column base.

When column base is pinned, the level of fire protection has no effect on snap-through-buckling temperature; however, when the column base is fixed, the snap-through-buckling temperature is shifted towards a higher value. These means that type of column base support condition has a considerable influence on snap-through-buckling temperature. Fixed column base is more suitable for fire resistant structure as it increases the snap-through-buckling temperature.

SCI method is over-conservative and less predictable as compared to the OTM of 61 kNm calculated by SCI method which is far less than OTM of 307 kNm for case 1 and 146 kNm for case 2.

The structure is experiences snap-through-buckling even by its self-weight and when there is no additional load on rafter. When the load is increased on rafter, the snap-through-buckling temperature decreases.

At lower rotational stiffness, the structure experiences snap-through at lower temperature; and increase of rotational stiffness provides some sort of stabilization on the structure and, consequently, it experiences snap-through-buckling at higher temperature. At higher rotational stiffness, the structure experiences some sort of stabilization after its first snap-through-buckling.

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10. Acknowledgements

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