SIMPLIFIED ESTIMATION OF CRITICAL TEMPERATURES OF PORTAL FRAMES IN FIRE

by S.Y. Wong[1], I.W. Burgess[1] and R.J. Plank[2]
[1] Department of Civil & Structural Engineering, University of Sheffield, UK.
[2] School of Architectural Studies, University of Sheffield, UK.

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Abstract: The structural response of industrial portal-framed buildings to elevated temperatures caused by internal fires is poorly understood at present. A simplified approach is proposed to estimate the critical temperatures of portal frames in fire, based on plastic theory. The results from the approach are compared against detailed analyses from the finite element program VULCAN. It is shown from the comparison that the simplified approach always gives conservative results. The significance of these results and the limitations using the approach are discussed briefly.

1. INTRODUCTION

Portal frame construction is the most common structural form used in industrial single-storey buildings in the UK. A number of recent fires in industrial warehouses have drawn attention to a current lack of understanding about the structural response of portal frames to elevated temperatures. The UK Health and Safety Laboratories has collaborated since 1996 with the University of Sheffield in a research project to investigate this behaviour.

This paper presents a simplified approach based on Plastic Theory, which enables calculation of the failure temperatures of steel portal frames for different load cases and at different load levels, by inserting fire hinges (plastic hinges with reduced moment capacity) at appropriate locations. Different fire scenarios, including both localised and completely developed fires, are considered for a range of frame geometries. The results from this simplified approach are compared against detailed analytical results from VULCAN, a non-linear finite element program developed at the University of Sheffield. The analytical results from VULCAN have been validated against experimental results from fire tests conducted at the Health and Safety Laboratories, Buxton [1]. The results are briefly discussed including the effects of boundary conditions at the column bases.

The purpose of the work is to enable practising engineers to assess portal frame critical temperatures quickly and safely. Worked examples of simplified calculations are shown. Structures of this type are not usually required by legislation to have a minimum fire resistance period, but such a calculation is clearly of use in specific cases given either the usage of the building or its situation relative to other structures.

2. THE SIMPLIFIED METHOD

Since the mid-1950s portal frame design in the U.K. has been widely based on the principles of Plastic Theory, using a balance of internal and external work for strength calculation. Often these are designed as basic pitched-roof frames with pinned column-bases, avoiding high foundation cost as well as the complexity of forming a rigid base connection. Detailed illustrations of this design method can be found in many standard texts [2, 3, 4].

The simplified approach presented here simply follows the work balance procedure. The frame eventually creates sufficient plastic hinges as loads increase to form a mechanism which may include pre-existing hinged connections. Given a set of small displacements of this mechanism caused by the articulation of the hinges, the work done by the external loads in displacing is balanced by the work done by the internal plastic moments in rotation of their plastic hinges. The equilibrium equation work balance can be expressed as:

$$\sum W_j \delta_j \text{ (External work done)} = \sum M_i \theta_i \text{ (Internal work done)} \qquad (1)$$

Once a failure mechanism has been identified, the appropriate failure load can be found from equation (1). Finding the correct mechanism, which has the minimum value of this collapse load, involves testing all possible collapse mechanisms of the portal frame.

Under fire conditions the most common collapse mechanism for pitched-roof portal frames has been found from previous research [1] to be a rotational failure of part of the roof section, which is also the usual failure mode under vertical roof load at ambient temperature. The external work done is clearly dependent on the loading in the fire limit state, which can be determined from codes of practice for structural fire resistant design such as the British standard BS5950 Part 8 [5]. In fire vertical dead load is usually the dominant external load, since design imposed loading is considerably reduced by the partial safety factor for this accidental limit state.

The compatible internal work done is however induced by the forming of plastic hinges. Because of the elevated temperature, the yield stress of steel is reduced and this results in a reduction of the plastic moment capacity of the steel section. These hinges are regarded as “fire hinges”. By inserting these fire hinges into the portal frame, the level of reduction in plastic moment capacity required in order to reach the failure mechanism at given fire limit state load can be found. The strength reduction factors of steel at elevated temperature are given in fire resistance codes such as BS5950 Part 8 or the draft Eurocode EC3 Part 1.2 [6]. Provided that the fire hinges may be assumed to form in steel members which are at the same temperatures, it is possible to calculate the reduction factors required for the collapse mechanism to form in fire. The steel temperature giving this reduction can be found, and this is the failure temperature of the portal frame. If a fire resistance time is required, then the relationship between atmosphere temperature and steel temperature can be modelled simply using the incremental approaches given in Eurocode 1 Part 2.2 [7] for either exposed or passively protected steelwork. If the ISO834 [8] standard fire curve is assumed, as is conventional in fire testing of components, fire resistance times can be interpolated.

3. WORKED EXAMPLES

Using the simplified method presented in Section 2, this section will demonstrate two worked examples, determining the failure temperatures for a common form of pitched-roof portal frame with pinned bases, in an overall and a localised fire.

Considering firstly a widespread fire which results in the heating of the whole of a portal frame the collapse mechanism is illustrated in Fig. 1, with fire hinges forming at the apex and eaves.

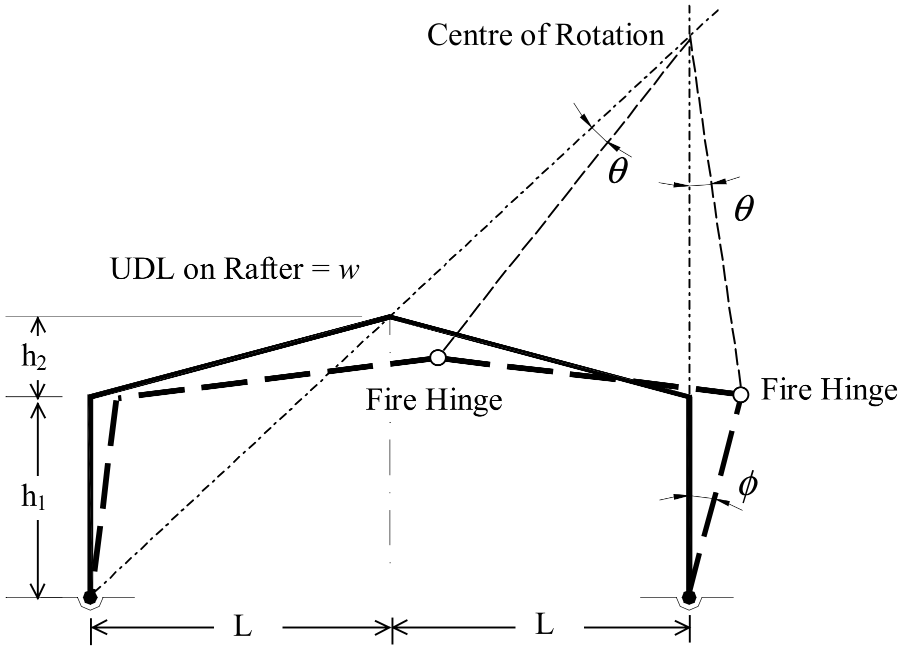

Fig. 1. Failure mechanism and location of fire hinges – frame heated overall.

The external work done = $wL^2\theta$

The internal work done = $M_p\eta(\theta + \theta + \phi + \theta)$

Where M_p is the plastic resistance moment of the rafter section at ambient temperature, η is the reduction factor and $\phi = \dfrac{h_1 + 2h_2}{h_1}\theta$.

Equating internal and external work and rearranging the equation,

$$\eta = \frac{wL^2}{M_p(3 + \frac{h_1 + 2h_2}{h_1})} \tag{2}$$

Using a portal frame of fairly practical dimensions (h_1 = 7m, h_2 = 4m, L = 15m) and loading, designed for ambient temperature limit states with dead, imposed and wind loads, the column section would be 533x210x92UB and the rafter section would be 457x191x89UB without haunches. An estimation of the vertical load at the fire limit state under BS5950 partial safety factors would be 2.4kN/m. Substituting these values into equation (2) gives η = 0.190, corresponding to a BS5950 Pt8 failure temperature at 0.5% strain of 697°C.

Considering also a localised fire near to one of the portal frame columns, the eaves region now has the highest temperature. The failure once again employs the rotational collapse mechanism shown in Fig. 1, with one plastic hinge forming near to the apex and a fire hinge forming near to the eaves. Using the same simplified approach:

The external work done = $wL^2\theta$
The internal work done = $M_p[\theta + \eta\theta + \eta(\phi + \theta)]$

Equating internal and external work as in the former example, the reduction factor can be shown to be

$$\eta = \frac{\left(\frac{wL^2}{M_p}\right) - 2}{1 + \left(\frac{h_1 + 2h_2}{h_1}\right)} \tag{3}$$

Using the same portal frame parameter values as for the previous case, the reduction factor value turns out to be negative. The significance of this will be discussed in the later sections. If a higher load level of 6kN/m is applied with the same frame geometry, the calculated η value is 0.140 and the failure temperature is 735°C.

4. VALIDATION OF THE SIMPLIFIED APPROACH

A non-linear finite element program VULCAN has been developed at the University of Sheffield for modelling the structural performance of steel and composite framed buildings exposed to fire. In this research project analytical results from VULCAN have been compared against a series of large-scale fire tests on a model frame at the Health and Safety Laboratories, Buxton [1]. The failure mechanism shown in Fig. 1 was confirmed by the analyses.

A series of VULCAN analyses were performed using the portal frame layout from the worked examples, applying different load levels and obtaining the failure temperatures. The load levels are presented in terms of their proportion of the failure load of the frame at ambient temperature, known as the Load Ratio. The results are compared against those calculated from the simplified approach in Table 1. It can be seen that the simplified approach compares well with the finite element results, particularly for the overall heating case. Further analyses were conducted to investigate the validity of the proposed method with various frame geometries, changing the spans and heights. It was found that the approach always gave close comparisons, especially for the cases of overall heating. The possibilities of inserting fire hinges at different locations for different fire scenarios were also investigated and are discussed later.

		Overall Heating		Corner (Local) Heating	
Load Ratio	Load (kN/m)	VULCAN Analysis	Simplified approach	VULCAN Analysis	Simplified approach
0.1	1.21	785°C	778°C	1137°C	Negative
0.2	2.42	700°C	697°C	900°C	Negative
0.3	3.62	650°C	642°C	851°C	Negative
0.4	4.83	605°C	598°C	740°C	Negative
0.5	6.04	560°C	556°C	715°C	735°C
0.6	7.25	516°C	519°C	650°C	635°C
0.7	8.46	473°C	476°C	589°C	565°C
0.8	9.60	415°C	425°C	526°C	503°C

Table 1. Comparison of failure temperatures from VULCAN and simplified approach.

5. DISCUSSION

It has been shown from the comparisons that the proposed simplified approach predicts the failure temperatures of portal frames with reasonable accuracy. However, for localised fire cases, negative reduction factors are obtained at the lower load levels, which is obviously unreasonable. In the localised fire scenario, after the formation of one fire hinge the low level of applied loading is not sufficient to cause the formation of a further, full-strength plastic hinge. A failure mechanism cannot be achieved, even when the fire hinge strength drops to zero. In such cases the finite element model continues until a much more localised hinge pattern occurs causing run-away deformation. The approach has also ignored the use of haunches at the eaves of the frame. Such frames should be capable of being treated in the same way, but the position of one of the hinges is moved away from the eaves to the haunch end, both at ambient temperature and in the fire case.

If the failure temperatures shown in Table 1 are compared with the limiting temperatures of isolated members given by Table 5 of BS5950 Pt8, it is seen that the values for "members in bending not supporting a concrete slab" form a lower bound to the critical temperatures of the portal frames in overall heating. It may be adequate to use the existing limiting temperature data for such cases. In localised fire scenarios fire hinges may need to be inserted at locations which are different from those at ambient temperature in order to identify the optimum mechanism. Beyond this the same approach is used.

Although most practical portal frames are designed with pinned bases, the real base connections and foundations actually provide some degree of rotational stiffness to the column bases. Four holding-down bolts are normally used to secure such a base to the foundation, and it is believed that this provides a certain amount of restraint which enables portal frames to perform better in fire than their idealisation. VULCAN was also used to study the effect of semi-rigid base connections, and it was found that critical temperatures of portal frames were increased significantly. This has not been considered in this proposed approach, but the current approach has the advantage for design of giving more conservative results.

6. CONCLUSION

An application of the normal principles of plastic analysis of portal frames has been attempted here, with the variation that fire hinges, which have reduced plastic moment capacity, are introduced into the work balance equation and the ultimate goal is to estimate the critical steel temperature in fire. The calculated results have been compared with VULCAN analyses, and the comparisons have shown that the proposed method gives a reasonably good estimation of the failure temperatures, particularly for the most usual and worst fire scenario in which the frame is heated overall.

In cases where a very localised part of a portal frame is subjected to fire the approach has not predicted any failure at very low load levels. This is a relatively specialised area where the proposed approach could be further developed. However, for the most usual fire case it provides a practical method of estimating critical steel temperatures, and by further interpolation a method of estimating fire resistance times in terms comparable to those used in design codes for isolated members.

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