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SYMCOMP 2019

ECCOMAS
Thematic Conference

4th International Conference on
Numerical and Symbolic Computation
Developments and Applications

PROCEEDINGS

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SYMCOMP 2019 – 4th International Conference on Numerical and Symbolic Computation: Developments and Applications

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April, 2019

1 – Introduction

The Organizing Committee of SYMCOMP2019 – 4th International Conference on Numerical and Symbolic Computation: Developments and Applications, welcomes all the participants and acknowledge the contribution of the authors to the success of this event.

This fourth International Conference on Numerical and Symbolic Computation, is promoted by APMTAC - Associação Portuguesa de Mecânica Teórica, Aplicada e Computacional and it was organized in the context of IDMEC - Instituto de Engenharia Mecânica, Instituto Superior Técnico, Universidade de Lisboa. With this ECCOMAS Thematic Conference it is intended to bring together academic and scientific communities that are involved with Numerical and Symbolic Computation in the most various scientific areas

SYMCOMP 2019 elects as main goals:

To establish the state of the art and point out innovative applications and guidelines on the use of Numerical and Symbolic Computation in the numerous fields of Knowledge, such as Engineering, Physics, Mathematics, Economy and Management, Architecture, ...

To promote the exchange of experiences and ideas and the dissemination of works developed within the wide scope of Numerical and Symbolic Computation.

To encourage the participation of young researchers in scientific conferences.

To facilitate the meeting of APMTAC members (Portuguese Society for Theoretical, Applied and Computational Mechanics) and other scientific organizations members dedicated to computation, and to encourage new memberships.

We invite all participants to keep a proactive attitude and dialoguing, exchanging and promoting ideas, discussing research topics presented and looking for new ways and possible partnerships to work to develop in the future.

The Executive Committee of SYMCOMP2019 wishes to express his gratitude for the cooperation of all colleagues involved in various committees, the Scientific Committee, the Programm Committee, Organizing Committee and the Secretariat. We hope everyone has enjoyed helping to consolidate this project, which we are sure will continue in the future. Our thanks to you all.

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NUMERICAL SIMULATIONS OF INDUSTRIAL STEEL PORTAL FRAMES UNDER FIRE CONDITIONS

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Keywords: Steel portal frames, industrial buildings, numerical simulations, fire

Abstract *To protect human lives and prevent against failure of structures, the collapse of industrial buildings under fire should always occur inward with a minimum failure time. The main objective of this study is to investigate the behaviour of industrial structures with steel portal frames under the effect of fire. In order to achieve this goal, numerical simulations on portal frames with haunches at the ends of the rafters are conducted using finite element software ANSYS®. The structures are studied with decoupled thermal and mechanical analyses. For this purpose, geometric and material nonlinearities are taken into account in the analysis using the standard ISO 834 as the fire model. The parametric study is carried out taking into account the parameters influencing the time resistance and the failure modes such as fire scenarios, length of haunches and geometrical dimensions of the portal frames. The comparison results with the simple calculation method R15, in term of time resistance, show a close agreement.*

1. INTRODUCTION

For practical reasons of exploitation, durability and cost efficiency, industrial buildings are in general made with steel portal frames using hot-rolled sections or welded sections with haunches at the ends of the rafters. However, steel although being a ductile material, it remains vulnerable to the effect of excessive temperatures. The tragic fire events that have affected industrial buildings in Algeria in recent years remind us of the real risk of fires. European standards [1] [2] give an overview of simplified design rules, which are common for the evaluation of the fire resistance of steel structural elements. However, for industrial and warehouse buildings, specific requirements defined in terms of structural behaviour have been imposed to meet the safety objectives of occupants and firefighters. In this context, the criteria of non-collapse outward of the structure exposed to fire and non-progressive collapse must be verified.

In order to meet these performance criteria, a European project [3] covered the structural behaviour of industrial buildings and warehouses exposed to fire. The project aimed to demonstrate that, given the 3D behaviour of the structure in case of fire, these structures can offer better structural strength. Based on the numerical results, simplified calculation methods have been proposed.

The actual behaviour of the industrial buildings in fire situation requires some parameters such as material and geometrical nonlinearities as well as variation in thermal and mechanical behaviour in time. However, only numerical analysis using finite element programs provide a comprehensive analysis of such structures by providing various fire scenarios [4] [5] [6] [7].

This article proceeds by numerical simulations to study the behaviour of industrial steel portal frames with haunches under standard fire ISO834 [8]. A model is developed using ANSYS program [9] to determine the time resistance and the collapse mode considering particularly the effect of fire scenario, haunch length and geometrical dimensions of the portal frames. The parametric study was performed by both shell elements to model the portal frames in 3D and non-uniform temperature within the structural beam-column elements.

2. FIRE MODEL AND THERMAL RESPONSE

Although the governing parameters of a real fire are numerous such as fire load density, ventilation condition and material compartment, the ISO834 standard time-temperature curve [8] is assumed testing purposes and numerical simulations. It represents the action of a fire in a confined compartment of building and the gas temperature evolution given according to the formula of the EC1 [1]:

$$\theta = 20 + 345\, log_{10}(8t + 1) \tag{1}$$

It is known that for thermal response, the governing equation for the three-dimensional non-linear transient heat conduction within the cross section of a structural element takes the following form:

$$\frac{\partial}{\partial x}\left(\lambda_a \frac{\partial \theta_a}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_a \frac{\partial \theta_a}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda_a \frac{\partial \theta_a}{\partial z}\right) = \rho_a C_a \frac{\partial \theta_a}{\partial t} \tag{2}$$

where λ_a and C_a are respectively the thermal conductivity and the specific heat of steel both are expressed as a function of the temperature in EC1 [1], θ_a is the steel temperature in x, y and z directions at time t, ρ_a is the density of steel equal to 7850 kg/m3.

Since the solution of equation (2) is non-linear, simplified solution for the temperature rise of an unprotected steel member is provided by EC3 [2], assuming a lumped thermal model for non-massive elements, with the following equation:

$$\Delta\theta_{a,t} = \mathrm{k_{sh}}\ \frac{A_m/V}{c_a\rho_a}\,\dot{h}_{net,d}\ \Delta t \tag{3}$$

where k_{sh} is the correction factor for the shadow effect, A_m/V is the section factor for unprotected steel elements, $\dot{h}_{net,d}$ is the net heat flux or heat transfer by convection and radiation per unit area, Δt is the time interval in seconds ($\Delta t \leq 5$ s).

3. PARAMETRIC STUDY

A parametric study is conducted using numerical simulations with ANSYS [9]. The industrial portal frame, shown in Fig. 1, is analysed based on the variation of the following parameters: fire scenarios, haunch length and portal frame dimensions.

This structure is illustrated in the CTICM guide [10] where both frame and purlins are checked for 15 minutes of fire exposure. Load combination on the rafter take into account G (dead load, roof, industrial equipment under roof and cladding) equal to 4.16 kN/m and S (snow) equal to 4.4 kN/m. According to EC0 [11], a total uniformly distributed load q in fire situation is calculated using G and 0.2S which gives 5.04 kN/m. Elements are chosen using hot rolled sections with IPE400 for the rafter and IPE500 for both columns. The steel grade is taken as S235 with a density of 7850 kg/m^3 and Poisson's ratio equal to 0.3. Haunches, with IPE400 section, are added at the ends of the rafter. Column bases are supposed fully pinned.

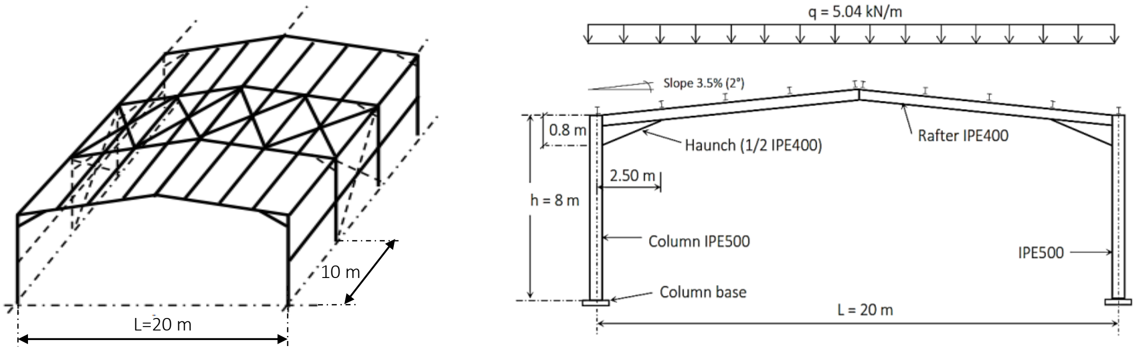


Figure 1. Portal model to be analysed.

3.1. Finite element modelling

The frame model is created using 3D finite elements with SHELL131 for thermal analysis and SHELL181 for mechanical analysis. The task is solved as a combined one using material nonlinear thermal analysis and geometry and material nonlinear static analysis in the ANSYS software [9]. In the thermal analysis, the temperature distribution is obtained in the section. In the nonlinear static analysis, the corresponding displacement, internal efforts and stress-strain state of the structure caused by both applied loads and constrained thermal dilatation are solved for each time step Δt, corresponding to temperature increments.

After a convergence test, the columns and beam are subdivided into 60 elements and 86 elements respectively along their lengths. Along the height, the section is subdivided into 12 elements (figure 2). Lateral-torsional buckling of the rafter has been prevented by adding appropriately lateral supports to the flanges. The fixation of the columns to their base are considered pinned, see figure 2.

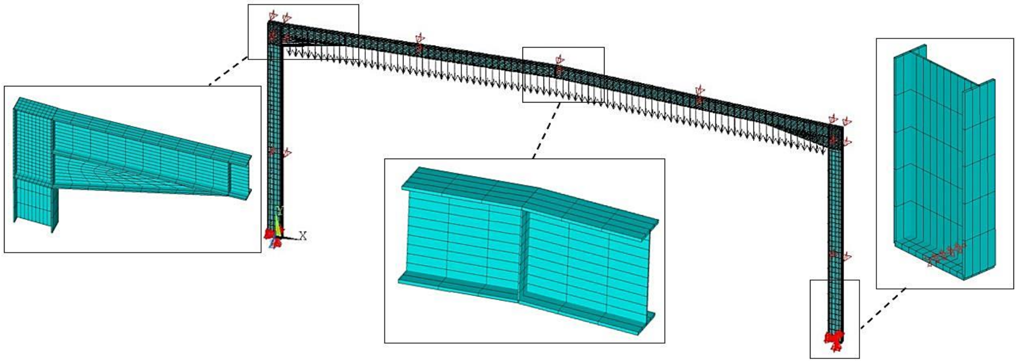


Figure 2. Numerical model, discretization of the portal frame.

3.2. Thermal analysis

The nonlinear transient thermal analysis is performed using the resolution of equation 2. Figure 3 shows the temperature distributions in the portal frame after 15 minutes of a standard ISO834 fire. It is important to note that all the four sides of the elements are under fire load.

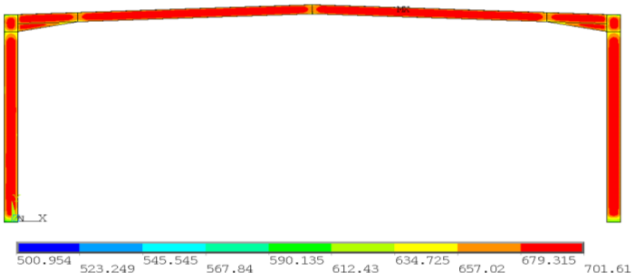
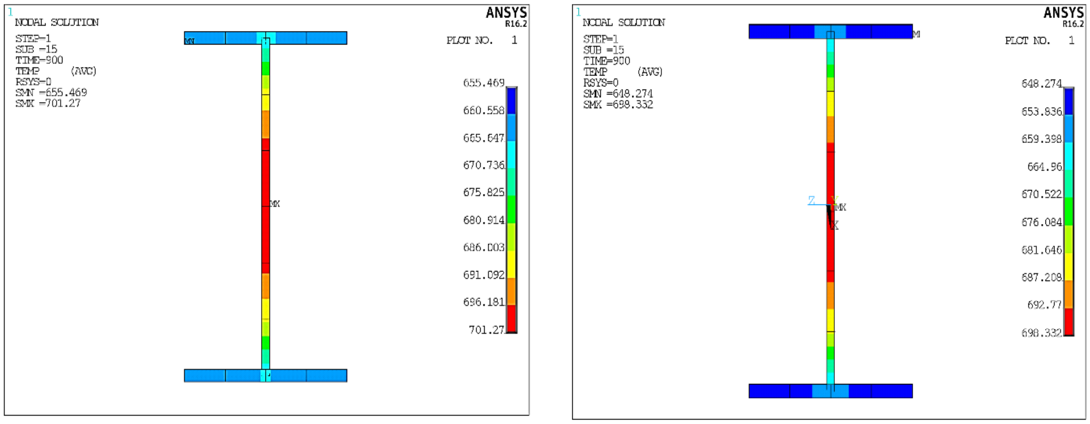


Figure 3. Temperature field in the portal frame at time t = 15 minutes.

The temperature distributions in both sections, columns (IPE 500) and rafter (IPE 400), is given in figure 4.



(a) **(b)**

Figure 4. Temperature distributions in the rafter section (a) and column section (b) at t = 15 minutes.

The temperature field is recorded for the corresponding resistance class and applied as body load to the mechanical model.

3.3. Mechanical analysis

The thermal loading was set in steps on the deformed state of the portal frame with simultaneous change of all necessary mechanical properties of the material depending on the temperature in the structure. The nonlinear material response of steel at elevated temperature is provided by EC3 [2] as shown in figure 5.

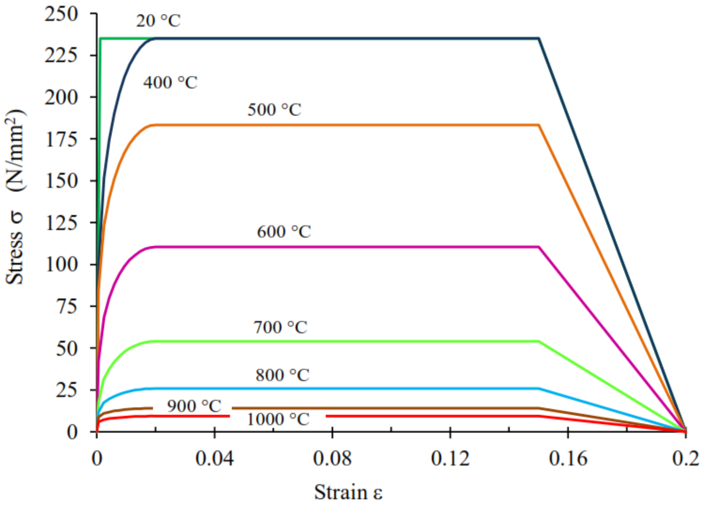
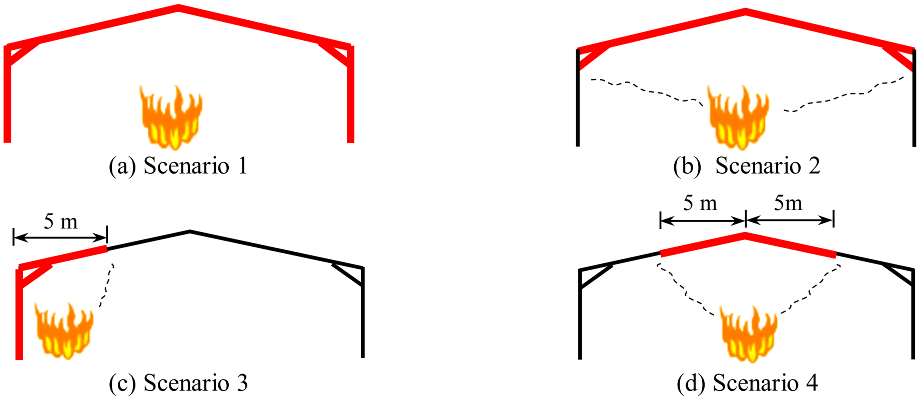


Figure 5. Stress-strain curve for steel grade S235 at different temperatures.

The results in term of displacements (vertical and horizontal) of the portal frame, failure time and Von Mises stresses at the developed hinges are illustrated in the next section.

3.3.1. Effect of fire scenarios

Fire scenarios can have a great influence on the behaviour of the structure and consequently its resistance time and failure mode. In this analysis, four fire scenarios have been considered. The first scenario (1) represents a generalized fire or flashover. The second scenario (2) considered that both columns are protected against fire. The third and fourth scenarios assume that portal frame is subjected to a localised fire involving one column and part of the beam (scenario 3) and the central part of the beam (scenario 4), see figure 6.



(a) Scenario 1

(b) Scenario 2

(c) Scenario 3

(d) Scenario 4

Figure 6. Heating profiles of the frame model.

Figures 7, 8 and 9 show the variations of the vertical (at ¼ and ½ of the rafter) and the horizontal displacements at the top of both columns according to the four scenarios.

According to these figures, the failure times are estimated to be 16.32 (min), 19.08 (min), 20.22 (min) and 33.63 (min) respectively for scenarios 1, 2, 3 and 4. This gives an improvement of 16.91%, 23.90% and 106% respectively for scenarios 2, 3 and 4 compared to scenario 1 (generalized fire). These results confirm the severity of generalized fires in comparison with localized fires.

From the results of the horizontal displacements at the top of both columns, figures 8 and 9, only scenario 1 confirms the beginning of collapse of the structure towards the inside. For the other fire scenarios 2, 3 and 4, the horizontal displacements of the columns do not confirm the collapse modes (inside or outside). The simulations are stopped before the top of the columns come back to the inside region of the structure. According to the work of Vassard *et al* [12] and Song [5], only simulations with dynamic approach can solve this problem and go further in the analysis so the collapse mode can be predicted.

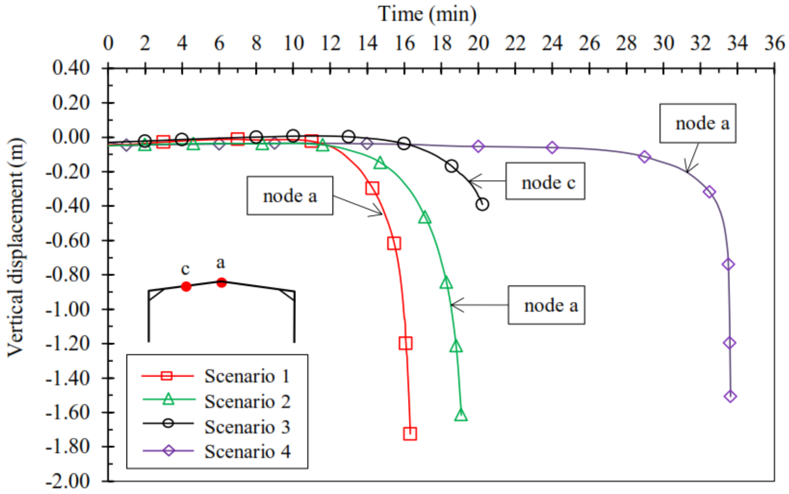


Figure 7. Vertical displacement/time at node a (fire scenarios 1, 2, 4) and node c (fire scenario 3).

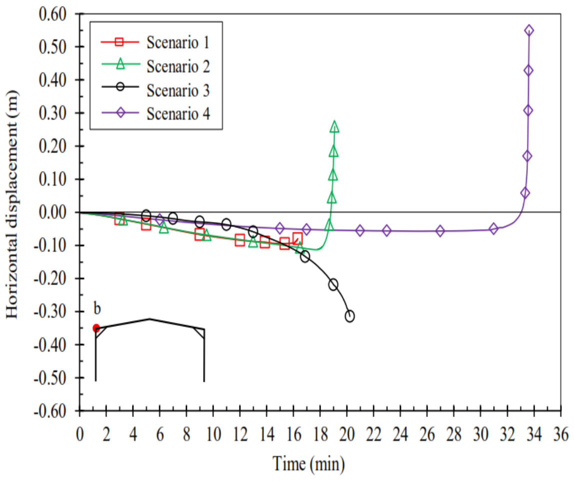


Figure 8. Horizontal displacement of node (b)

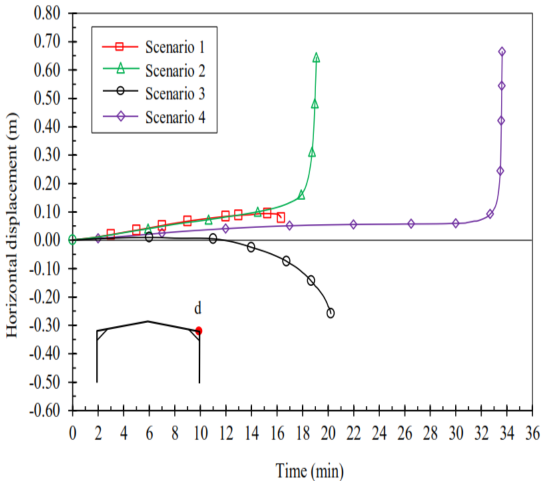


Figure 9. Horizontal displacement of node (d)

3.3.2. Effect of haunch length

Haunches in the rafters at the eaves are used to reduce the depth of the rafter and achieve efficient moment connection between column and rafter. To analyse the influence of haunches on the fire resistance of single portal frame, five different lengths are considered: 0 m, 0.5 m, 1 m, 2 m, 3 m and 4 m. The profile section of the haunch is taken constant (1/2 IPE400). The scenario 1 (generalized fire) is considered in this section.

The displacement-time curves, vertical at apex and horizontal at eaves, are presented in figures 10 and 11.

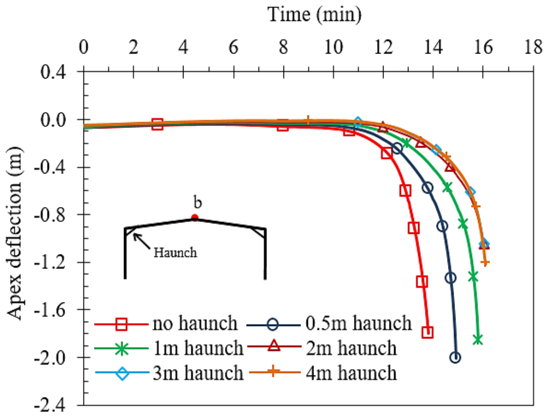


Figure 10. Apex vertical deflection (node b) for different haunch lengths

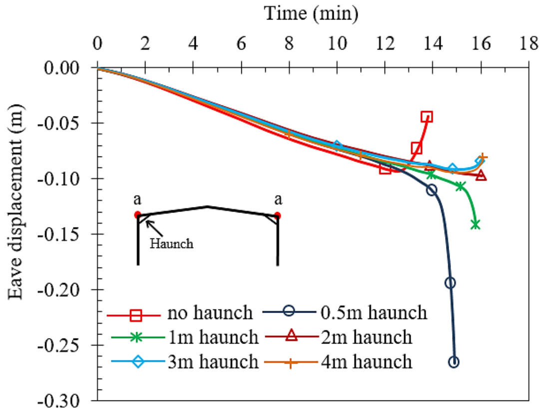


Figure 11. Eave horizontal displacement (node a) for different haunch lengths

The figures above show that the use of haunches until one-tenth of the span (2 m) increases the time resistance of the portal frame. With the same rafter profile (IPE400), time resistance without haunches is about 13.81 minutes and with 2 m haunches (one-tenth) time resistance increases to 16 minutes (16% increase). We notice that beyond this distance (2 m), no improvement can be seen. This may be explained by the fact that weakest section can be located at the end of the haunch when shorter haunch is used (less than one-tenth) to rafter end when haunch reached one-tenth and more.

Results from figure 11 show that when the lengths of haunches are less than one-tenth of the rafter span, the collapse of the structure tends to happen in the outward direction.

The maximum Von Mises stresses developed in the rafter at different locations (haunch end, rafter ends and rafter mid-span) are shown in figures 12 to 15.

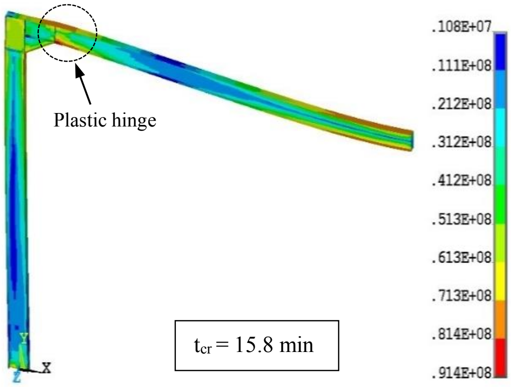


Figure 12. Von Mises stresses in the half portal frame (1m haunch)

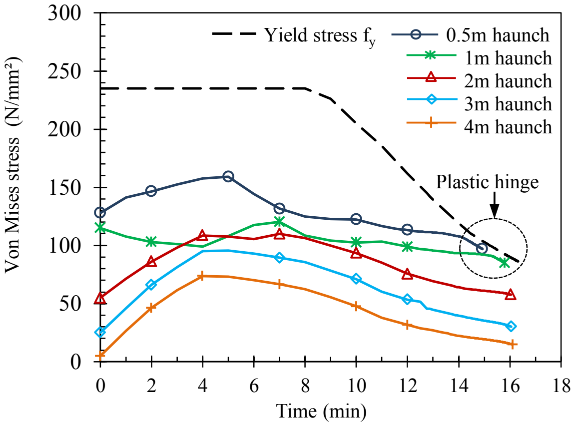


Figure 13. Von Mises stresses at haunch end for different haunch lengths

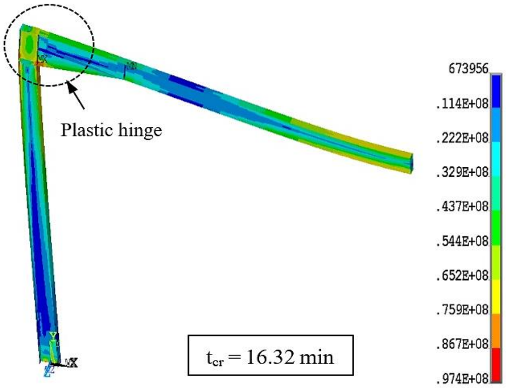


Figure 14. Von Mises stresses in the half portal frame (2.5 m haunch)

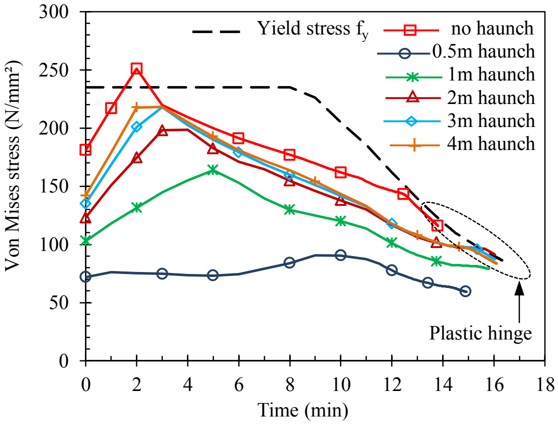


Figure 15. Von Mises stresses at eaves (nodes a) for different haunch lengths

From figures 14 and 15, the yielding stresses are obtained at the eaves when haunch length is one-tenth (2 m) and more. For shorter haunches (less than one-tenth), the yielding stresses appear at the ends of the haunches, see figures 12 and 13. This is due to the weakest section on the rafter, which change from the eaves to the ends of the haunches.

As expected, when no haunch is used, maximum stresses are located at the eaves, see figure 15. A value of 250 N/mm² is obtained at 2 minutes heated time, which is greater than the yield stress (235 N/mm²) and this has favourably leads to the collapse of the portal frame at early time.

3.3.3. Effect of geometrical dimensions

Different geometries for frames are investigated in this section, see table 1, looking at the influence on failure modes. A series of frames with h/L ratio (h: is column high and L: is rafter span) taken equal to 0.2, 0.3, 0.4, 0.5 and 0.6. The other parameters of the portal frames, such as the haunch length and the rafter slope are taken respectively 1/10 of portal's span and 3.5%. For all portal frames, the haunch's section is the same as the rafter's section. Table 1 summarises the details of these frames.

Portal frame	L (m)	h (m)	h/L	Column section (Grade S235)	Rafter section (Grade S235)	Load ($q_{fi,Ed}$) (kN/m)
(1)	25	5	0.2	IPE 500	IPE 500	3.660
(2)	30	9	0.3	HEA 600	HEA 600	4.230
(3)	20	8	0.4	IPE 500	IPE 400	5.040
(4)	16	8	0.5	IPE 360	IPE 330	4.804
(5)	10	6	0.6	IPE 330	IPE 300	3.180

Table 1. Characteristics of the portal frames.

Figures 16, 17 and 18 show the variations of the vertical displacement at apex and the horizontal displacements at eaves.

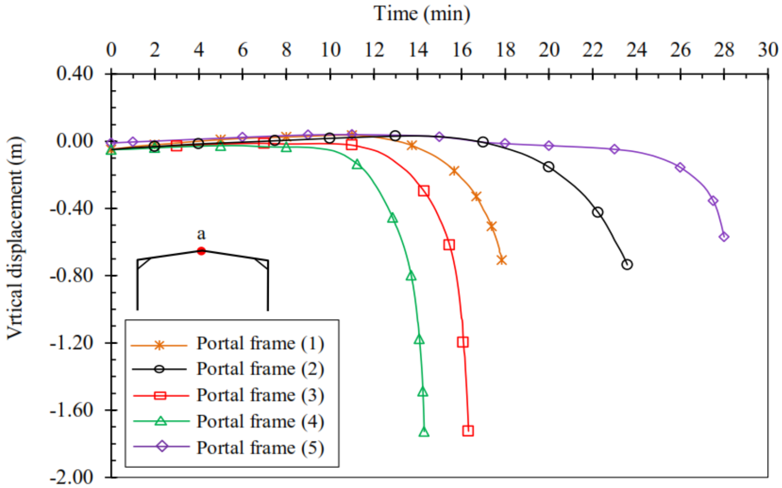


Figure 16. Vertical displacement / time at apex (node a) for the five portal frames.

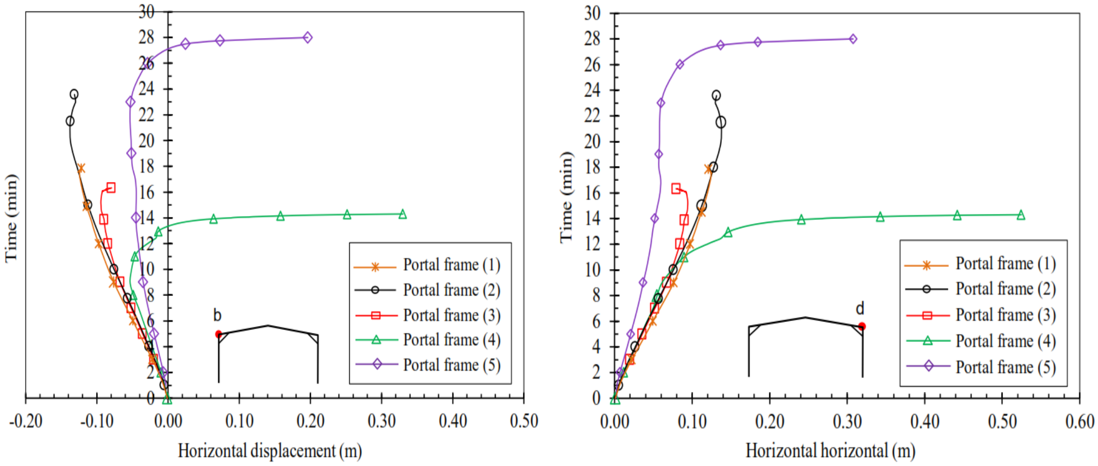


Figure 17. Horizontal displacement / time of node (b) Figure 18. Horizontal displacement / time of node (d)

According to figures 17 and 18, the horizontal displacements at eaves indicate that when the h/L ratio is greater than 0.4 (case of the portal frames 4 and 5), the collapse of the portal frames is developed outwards of the structure. This is confirmed by the positive values of the horizontal displacements of both eaves. For portal frames (1), (2) and (3), with h/L ratio less or equal than 0.4, the horizontal displacements at eaves are developed towards the outside of the structures until the time of collapse when a reversal movement towards the inside of the structure is found. This collapse mode (inward) is considered safe according to the European standards [3].

4. COMPARAISON OF RESULTS USING THE PARAMETRIC STUDY AND THE SIMPLIFIED METHOD (R15)

For industrial steel buildings such as warehouses, simplified methods are used to verify frames and purlins for fire stability of 15 minutes [10]. According to these methods, for sections of class 1 and 2, the critical temperature is determined using equation 4 and table 2.

$$k_{y,\theta} \geq \frac{q_{fi,Ed}\ L^2}{14\ W_{pl,y}\ f_y} \tag{4}$$

θ (°C)	20 ÷ 400	500	600	700	800	900	1000	1100	1200
$k_{y,\theta}$	1	0.78	0.47	0.23	0.11	0.06	0.04	0.02	0

Table 2. Reduction factor $k_{y,\theta}$ for yield strength at elevated temperatures.

Where $q_{fi,Ed}$ is the uniformly distributed load applied to the rafter under fire condition, $k_{y,\theta}$ is the reduction factor for the yield strength f_y, $W_{pl,y}$ plastic modulus and L is the length of the rafter outside haunches.

Critical time t_{cr} of the portal frame can be calculated using equation 3. For the comparison purpose, the correction factor K_{sh} obtained from equation 3 is taken equal to 1.

Tables 3, 4 and 5 present the values of time resistance obtained using this study and those calculated with simplified method R15 [10].

Numerical simulation (ANSYS)		Simplified method (R15)
Fire Scenarios	t_{cr} (min)	t_{cr} (min)
1	16.32	15.95
2	19.08	
3	20.22	
4	33.63	

Table 3. Time resistance using different fire scenarios.

Haunch length (m)	Numerical simulation (ANSYS)	Simplified method (R15)
	t_{cr} (min)	t_{cr} (min)
0	13.81	12.20
0.5	14.92	12.87
1	15.80	13.61
2	16.04	15.14
2.5	16.32	15.95
3	16.05	16.92
4	16.11	23.49

Table 4. Time resistance using different haunch lengths.

Portal frame	Numerical simulation (ANSYS)	Simplified method (R15)
	t_{cr} (min)	t_{cr} (min)
(1)	17.85	18.90
(2)	23.58	22.33
(3)	16.32	15.95
(4)	14.30	14.28
(5)	28.00	28.85

Table 5. Time resistance using different portal frames.

These results indicate that the fire resistance determined by the simplified method (R15) are approximately in agreement with those of the present study when generalized fire (scenario 1) is considered and haunch length varying up to one-eight of the rafter span. Beyond this length, the results are overestimated.

5. CONCLUSIONS

This article investigates the behaviour of industrial steel portal frames under standard ISO834 fire using numerical simulations. The following conclusions can be drawn:

- Fire scenarios can have a great influence on the fire resistance of industrial steel portal frames. An improvement varying from 16% to 106% is observed with localized fire scenarios compared to the generalized fire scenario.
- The use of haunches until one-tenth of the span increases the fire resistance of the portal frame around 16%. Beyond this length, no improvement can be observed.
- The geometrical dimensions of the portal frames have a significant effect on the structural behaviour of industrial buildings. When column height to span length ratio is greater than 0.4, the collapse of the portal frames tends to happen toward the outside of the structure, which is considered unsafe according to the actual codes.

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