Evaluation of the Internal Forces in a Plane Steel Frame under Fire Situation

Maria Eduarda S Piccolo[1], Dalilah Pires[1], Rafael C. Barros[2], Ricardo A. M. Silveira[2]

[1]*DTECH, Federal University of São João del-Rei*
Rod. MG 443, km 7, 36420-000, Ouro Branco/MG, Brazil
meduardafox@hotmail.com, dalilah@ufsj.edu.br
[2]*Dept. of Civil Engineering, Federal University of Ouro Preto*
Morro do Cruzeiro, 35400-000, Ouro Preto/MG, Brazil
rafael.barros@ufop.edu.br, ricardo@em.ufop.br

Abstract. The study of the high temperature effects on the steel structure systems analysis has been usual. The structural behavior under fire is an important part of fire protection engineering and the high degree of complexity and cost of experimental analyses under fire is remarkable. Thus, numerical analysis has been a widely used tool for investigating the structural behavior in fire. In this context, the present study has as objective to evaluate the behavior of the internal forces of a double steel frame, submitted to the action of fire. The temperature field in the cross-section of the structural elements that makes up the frame is obtained by the simplified method of NBR 14323 without thermal protection. Once the temperature of the structural elements is established, the behavior of the internal forces as a function of the temperature increase is evaluated using the Ftool software. Additionally, an analysis considering five different scenarios of exposure to fire is performed. The results showed that the magnitude of the internal forces increases with increasing temperature, which contributes to the loss of structural strength and, depending on how the fire reaches the structural elements, there is a significant difference in these forces.

Keywords: internal forces, fire, structural analysis, steel, Ftool.

1 Introduction

Knowledge of fire and related domains have contributed to human development. However, the loss of life and material damage caused by uncontrolled fires have highlighted, throughout history, the importance of considering fire safety in civil engineering designs [1]. Brazil had its phase of transition from rural to urban, industrial and service environments in an accelerated and unrestrained way, causing an increase in the risk of fire due to the inexistence of efficient ways to prevent the emergence and expansion of fire [2]. Lack of control over the emergence and spread of fire can have devastating consequences. Some disasters involving fire can be highlighted: the fires of the Andraus building, on February 24, 1972, Joelma building on February 1, 1974 and Grande Avenida building on February 14, 1981, all in São Paulo; the fire in the Andorinhas building, in Rio de Janeiro, in February 1986; nightclub Kiss in Santa Maria at dawn on January 27, 2013; the fires at the Museu da Língua Portuguesa and Cinemateca Brasileira in São Paulo in late 2015 and early 2016, respectively; the fire in a building in the Tehran city, Iran, in January 2017; the fire in a London residential building at dawn on June 14, 2017; the large fire that destroyed the Wilton Paes de Almeida building in São Paulo on May 1, 2018; the devastating fires with irreparable damage to the history of the National Museum in Rio de Janeiro in September 2018, the Notre-Dame Cathedral in Paris on April 15, 2019 and, recently, on July 29, 2021, the fire that reached one of the hangar of the Cinemateca Brasileira, in São Paulo.

The parameters surrounding a fire are mostly random, which makes them unique. The high temperature in fires alters the physical characteristics and mechanical resistance of materials. Both in steel and in other materials, for example, these characteristics deteriorate during exposure to fire and the loss of strength and stiffness increases considerably with increasing temperature. In this context, the objective of the present study is to verify the behavior of the internal forces in a steel frame subjected to a fire situation. The basic idea is to consider the temperature field in the structural element according to the simplified method prescribed by NBR 14323 [3] and, from this field, evaluate the internal forces (normal, shear and bending moment) using the educational software Ftool.

2 Analysis of a fire situation

An analysis in a fire situation basically consists of determining the temperature distribution in the structural elements (thermal analysis) and simulating the displacements, deformations and internal stresses in the structure (structural analysis), considering the loss of strength and stiffness of the structural material with the increase in temperature. Strength is related to the yield strength in steel, while stiffness is related to the modulus of elasticity of materials. In the Figure 1 is illustrated the behavior of these two properties as a function of temperature increase [3].

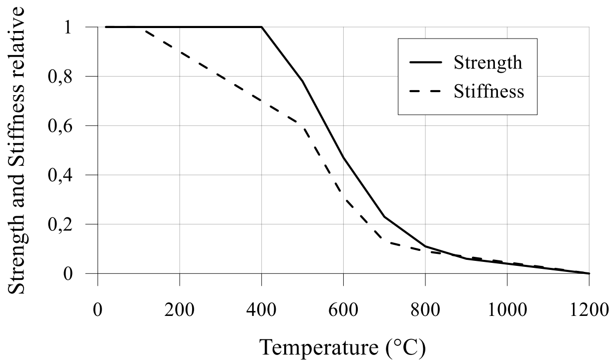


Figure 1. Steel strength and stiffness variation in function of temperature

The thermal analysis of a structural element subjected to a fire situation consists in determining the temperature variation or the temperature field in the element of interest, based on the boundary conditions of the adopted fire model. In structural problems in fire situations, the thermal analysis basically involves two parts: the determination of the heat transferred by convection and radiation, resulting from the fire, in the contour of the element of interest; and the determination of heat transfer by conduction inside the structural elements [4].

In the simplified calculation model, the temperature rise is considered homogeneously for the entire cross-section and along the length of the structural element of interest, using simple analytical equations in the case of steel. According to NBR 14323 [3], the temperature increase in structural steel elements located inside the building is given by Eq. (1), considering structural elements without thermal protection materials:

$$\Delta T_{steel,t} = k_{sh} \frac{(u/A)}{c_{steel}\rho_{steel}} \varphi \Delta t \quad (1)$$

where, k_{sh} is a correction factor for the shading effect, which can be taken as 1; c_{steel} is the specific heat of steel; ρ_{steel} is the specific mass of steel considered independent of temperature equal to 7850 kg/m³; Δt is the time interval in seconds and cannot be taken as greater than 5; u is the perimeter exposed to fire of the structural element, in meters (m); and A is the cross-section area of the steel structural element, in m². The relationship between the perimeter exposed to fire and the cross-section area (u/A), for prismatic bars of length L, defines the massivity factor. It is clearly seen that, for structural elements with a cross-section of the same area, the temperature increase will occur faster for those with a larger surface exposed to fire. Still from Eq. (1), φ is the heat flux per unit area, expressed in Watts per m² (W/m²) and depends on the temperature of the gases. Thus, the temperature in the steel structural element, at the current instant of time, is given as follows:

$$T_{steel,t} = T_{steel,t-\Delta t} + \Delta T_{steel,t} \quad (2)$$

The procedure presented for determining the temperature rise in steel structural elements is simple incrementation for any fire curve. The fire curve, which represents the temperature of the gases present in a certain compartment, adopted in this study, is the standard fire of ISO 834-1 [5] given by Eq. (3):

$$T_{gases} = T_0 + 345\log(8t+1) \tag{3}$$

where T_{gases} is the temperature of the gases in °C, T_0 is the initial ambient temperature, generally assumed to be 20 °C, and t is the fire exposure time in minutes.

The numerical simulation of the structural behavior in fire, performed with the help of the Ftool software, is divided into three steps: preprocessing, analysis and postprocessing. Preprocessing, which is the initial stage of computational analysis, consists of the complete definition of the steel frame to be analyzed. In this phase, the geometric and physical characteristics, the finite element discretization, the boundary conditions and the acting loading, including the thermal effect, are defined. Then, the actual numerical analysis begins. As a result of the analysis process, the nodal displacements, the support reactions and the internal forces in the structure are obtained. In a thermo-structural analysis, the results are determined at each instant of time.

3 Numerical example

In this section, the structural fire analysis of a steel frame is performed using the strategy presented in Section 2. It is a double portal where only the left compartment was fully heated, with the other elements kept at room temperature, as illustrated in Figure 2a. This frame is part of a series of tests on steel frames subjected to high temperatures carried out by Rubert and Schaumann [6]. The frame was loaded and then heated to collapse. All cross-sections of the elements that make up the frame are made of the IPE 80 and heated on all four faces (Figure 2a). The modulus of elasticity (E) of the steel was taken equal to 210 GPa and the yield stress (f_y) equal to 355 MPa. The reduction factors shown in Figure 1, referring to strength and stiffness, were also used in the analysis.

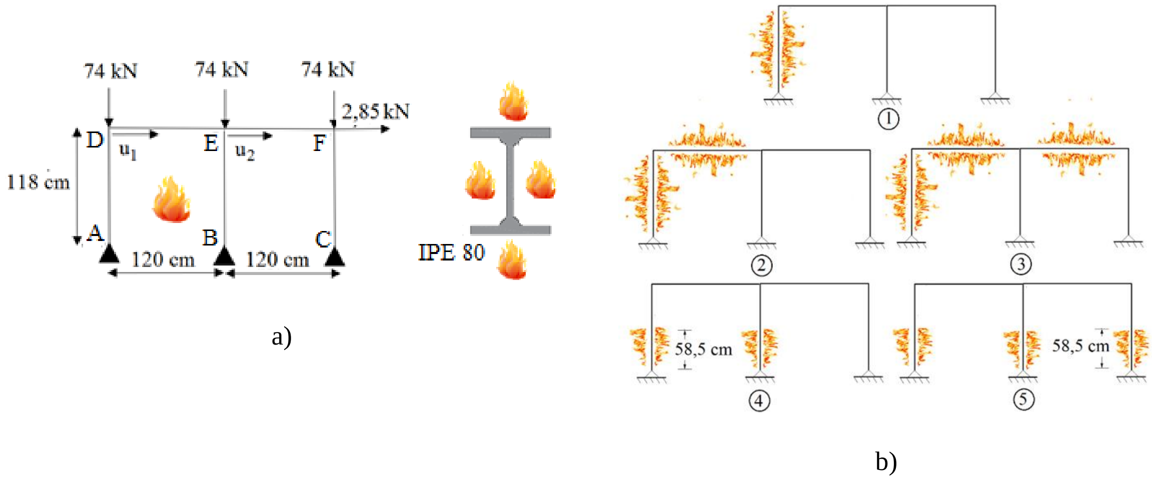
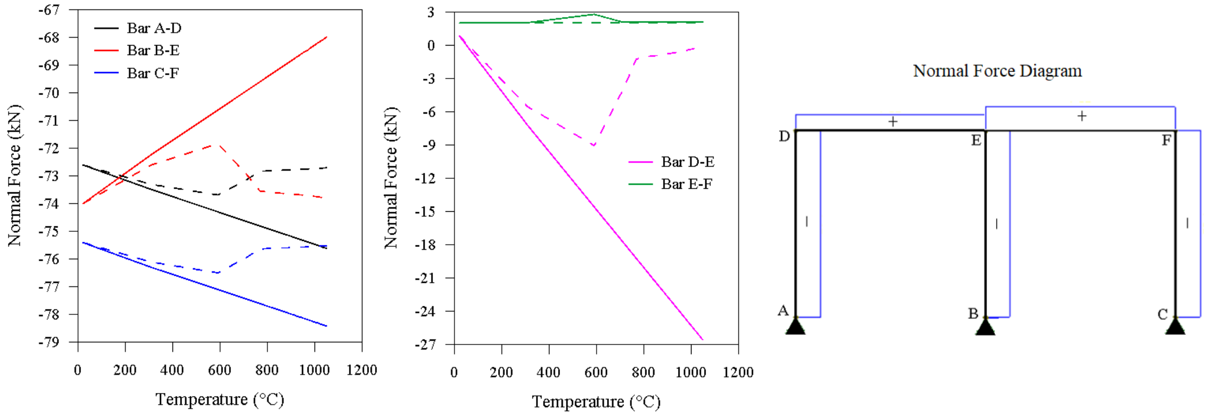
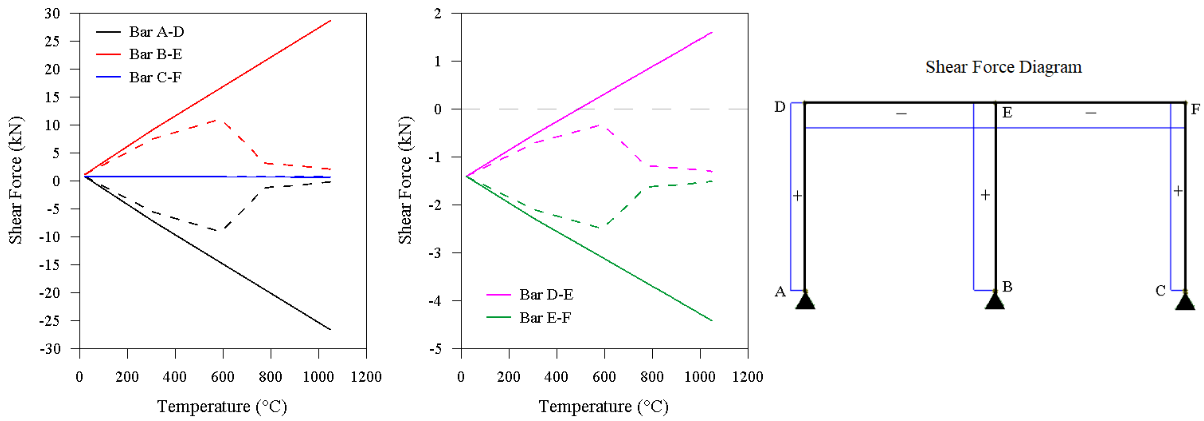


Figure 2. Double portal: a) characteristics and b) different heating

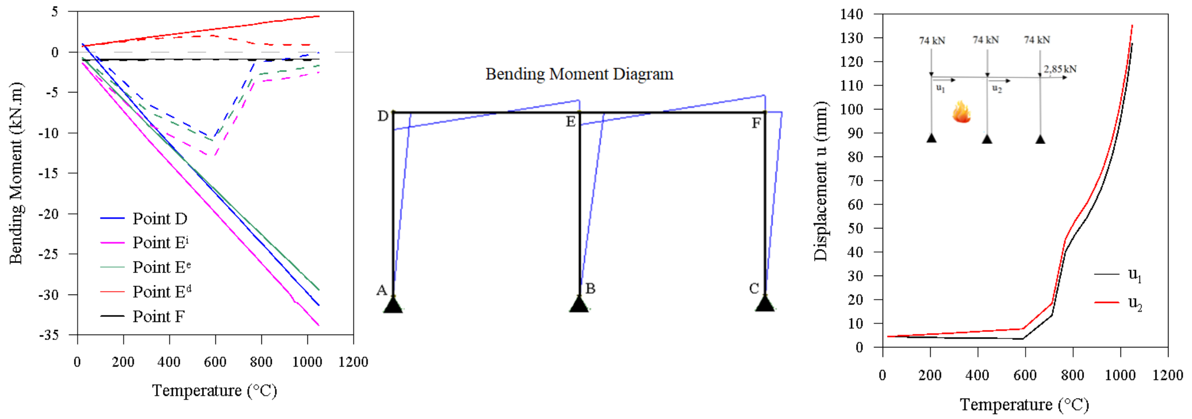
The graphs shown in Figure 3 represent the normal force (Figure 3a), shear force (Figure 3b) and the bending moment (Figure 3c) in the frame, varying with the increase in temperature. For all graphs, the solid line corresponds to the analysis without considering the reduction factor for f_y and E and the dashed line with the consideration. The results show that the internal forces in the frame tend to increase with increasing temperature. Another observation is the constant behavior of the increasing forces when f_y and E are not degraded. With the degradation of mechanical properties, it is possible to notice a sudden change in the behavior of the curves between the temperatures of 600 °C and 800 °C. This change may be related to the collapse of the frame, that is, when the displacements tend to infinity, as the displacements u_1 and u_2 increase significantly between these temperatures, according to the linear elastic analysis performed for each time interval, shown in the graph in Figure 3d.



a) Normal force versus temperature



b) Shear force versus temperature



c) Bending moment versus temperature

d) Displacement versus temperature

Figure 3. Internal forces variations and displacements with temperature

Barros et al. [7] evaluated the critical temperatures for different fire exposure scenarios of the double portal. The same loading condition shown in Figure 2a was maintained and five different scenarios as shown in Figure 2b were adopted. Here, the AD bar was chosen to verify the behavior of the internal forces according to the different heating conditions. In this analysis, f_y and E were degraded. It is possible to observe, through the results presented in Figure 4, that the way the fire reaches the structural elements, generates a significant difference in the behavior of internal forces. This raises the importance of being able to evaluate a structure in a fire situation for different configurations, since it is known that fire is a random event that can reach the structure and spread in different ways.

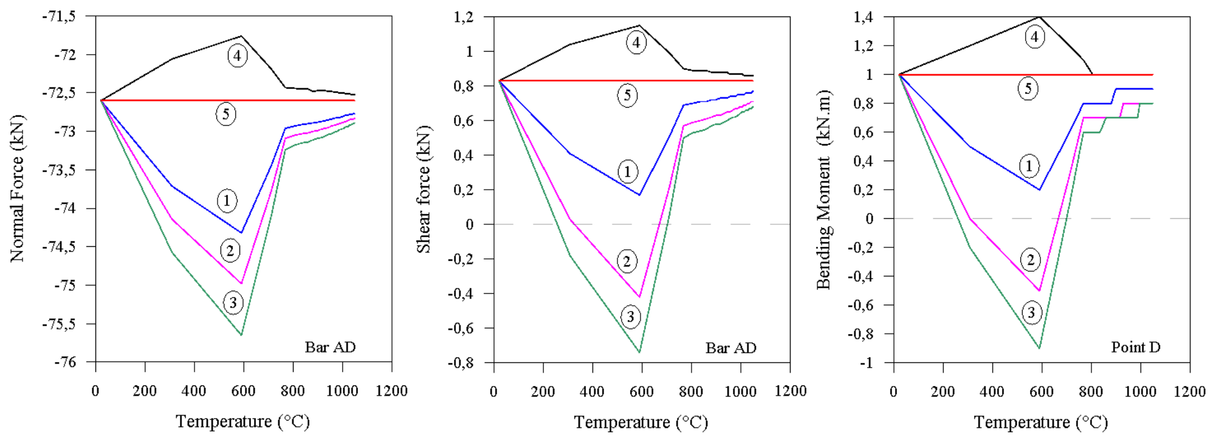


Figure 4. Internal forces variation considering different heating conditions

4 Conclusion

This work presented the evaluation of the behavior of the internal forces of a steel double portal subjected to fire action. The temperature field of the IPE 80 that makes up the frame was obtained by the simplified method of NBR 14323 [3] considering without thermal protection materials. Once the temperature of the structural elements was established, the behavior of the internal forces as a function of the temperature increase was evaluated using the Ftool software. Additionally, the analysis was carried out considering five different situations of heating the frame. Given the results achieved, it can be concluded that additional internal forces due to temperature emerged in the frame due to expansion restrictions, which promoted an increase in these forces acting on the structural system. Furthermore, the results showed that depending on how the fire hits the structural elements, there is a significant difference in the behavior of the internal forces. Such behavior reinforces the attention that must be paid to the analysis of a fire situation, since fire is a random event that can reach the structure and spread in different ways. Furthermore, additional unforeseen demands in projects at room temperature can significantly compromise the strength of the structural system.

Acknowledgements. The authors of this article thank CNPq, FAPEMIG, CAPES, UFSJ and PROPEC/UFOP for the support received in the development of this research.

References

[1] Morris, W.A., Mouço, D.L., “Aspects of fire precautions in buildings, Building Research Establishmen-BRE”. Fire Research Station, UK, 1988.
[2] Caldas, R. B. “Análise Numérica de Estruturas de Aço, Concreto e Mistas em Situação de Incêndio”, *Tese Doutorado - EE/UFMG*, Belo Horizonte, MG, Brasil, 2008 [in Portuguese].
[3] NBR 14323, “Projeto de estruturas de aço e de estruturas mistas de aço e concreto de edifícios em situação de incêndio”. *ABNT – Associação Brasileira de Normas Técnicas*, Rio de Janeiro, 2013.
[4] Maximiano, D. P. “Análise numérica avançada de estruturas de aço e de concreto armado em situação de incêndio”. *Tese Doutorado – Universidade Federal de Ouro Preto. Escola de Minas. Departamento de Engenharia Civil. Programa de Pós-Graduação em Engenharia Civil*, 197f., Ouro Preto, Minas Gerals, Brasil, 2018 [in Portuguese].
[5] ISO 834-1. “Fire resistance tests – Elements of buildings construction, Part 1: General requirements”. *ISO – International Organization for Standardization*, Geneva, 1999.
[6] A. Rubert, P. Schaumann. “Structural steel and plane frame assemblies under fire action”. Fire Safety Journal, vol. 10, pp. 173-184, 1986.
[7] R.C. Barros, D. Pires, R.A.M. Silveira, I.J.M. Lemes, P.A.S. Rocha, “Advanced inelastic analysis of steel structures at elevated temperatures by SCM/RPHM coupling”. Journal of Constructional Steel Research, vol. 145, pp. 368-385, 2018.