Analysis of the Progressive Collapse of Buildings under High Temperatures Using Successive Approximation Technique

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Abstract: This paper presents an investigation of the disproportionate collapse of multi-store steel buildings in a natural fire situation due to the progressive failure of their columns. For this purpose, it is intended to evaluate the effects of the redistribution of stress and vertical displacements of columns with the evolution of the temperature addressing, also, the impacts of the localized faults of these structural elements. In addition, another objective of this paper is the development of a practical analysis approach, which is called by successive approximations. As a methodology, advanced computational techniques were developed to predict the structural behavior of the building as the temperature reduces the strength and stiffness of its structural elements. For the parametric study, the overall response of the building was investigated through fire simulations in many columns. The results showed that the phenomenon of redistribution of stresses that occur during the heating period is essentially due to the reduction in the modulus of elasticity of the steel. In addition, the study pointed out that the use of advanced computational techniques through the use of successive approximations technique is an excellent alternative to study the progressive collapse of buildings subject to high temperatures.

Key words: Progressive collapse, fire, column.

1. Introduction

Highly relevant subject in the current scenario by the wave of crimes for terrorist attacks materialized in intentional explosions followed by fires in buildings, the investigation of fire-induced progressive collapse is treated as a further challenge of structural engineering because of the complexity involved in the study of the phenomenon.

Fire is an action of an exceptional nature, with a low probability of occurrence and duration, relatively low, reasons that lead to a generalized tendency on the part of the designers to despise their action in the structures [1]. However, statistics indicate that a fire is triggered in the world every 7 seconds, one person dies every 10 minutes in a fire and more than 80% of the North American companies that suffered a fire, left the market in less than 4 years structures [2].

It is emphasized that the temperature rise degrades the mechanical and thermal properties of the structural elements which in turn can lead the structure to partial or global collapse, in particular of structural configurations designed by steel elements, which are more susceptible to the phenomenon action [3].

Thus, intensive studies to identify the causes related to the progressive collapse of steel structures under very high temperatures have been carried out in the last years, surpassing investigations focusing on the analysis of the behavior in isolated elements. Thus, this work is expected to contribute to the study of the damage in steel structures caused by the phenomenon of fire and its effects on the stability conditions of
2. Methodology

Due to complexity involved in heat conduction problems in thermomechanics of structures added to the phenomenon of progressive collapse, obtaining a model that simulates such behavior is quite expensive. In this way, numerical simulations have been used because of their low operational and financial costs associated to the good adhesion and speed in obtaining the results.

In this research, with the use of advanced computational techniques, the goal is to address some of the main limitations imposed by the study of isolated structural elements in the analysis of the progressive collapse of buildings in a fire situation. In addition, it is known that in extreme situations it is not always possible to evaluate quickly, what extension at a multi-storey building under very high temperatures preserves its stability conditions to allow the escape of users. Thus, it is necessary to apply a method known as successive approximations, which although not as accurate as other numerical tools (ABAQUS, ANSYS), provides parameters for efficient and fast analysis.

Strategically, to achieve these objectives, many fire simulations were carried out in a structural model represented by a flat frame, where the elevation of temperature of its structural elements was conducted by a natural fire curve assuming the calculation requirements of NBR 14323:2013 [4] which considers, among other aspects, the reduction of the modulus of elasticity and the stiffness of the structural elements in the temperature elevation.

In this context, the parametric study was carried out by heating isolated structural elements in different building sites, so that it was possible to evaluate the phenomenon of the redistribution of efforts, the impacts of the critical temperature and the influence of the loads and the geometric characteristics of the columns in the conditions of building stability.

The numerical model of the phenomenon was carried out using SAP2000 software where the effects of the redistribution of efforts in the displacement diagrams × temperature and axial reactions × temperature of the heated columns and the surrounding structure, as well as the bending moment diagrams × temperature of the beams adjacent to the columns as the strength and stiffness of the structural parts were depreciated.

2.1 Fire Dynamics

Before investigating the parameters involved in the progressive collapse of multi-storey buildings of fire-induced steel, it is necessary to define the elements related to fire dynamics. With an explanation of the general characteristics of this phenomenon it is possible to determine the temperature of the gases established through standardized and natural curves, numerical simulations or real situations, representing the main peculiarity of a fire in what concerns the study of structures [5]. Figs. 1 and 2 present the fire models most used in the literature for the representation of the phenomenon.

The behavior of the structure in a fire situation depends in part on the mechanical and thermal properties of which the material is formed, where these factors change substantially within temperature ranges. As the structural elements are exposed to a thermal action, these parameters are progressively depreciated resulting in losses of resistance and stiffness, in the appearance of large structural deformations, and thermal curvatures [6].

ABNT NBR 14323:2013, considers heating rates between 2 °C/min and 50 °C/min for the adoption of reduction factors of yield strength and modulus of elasticity, during the design of structural steel elements in fire, which are shown in Fig. 3. However, the thermal properties of the materials are fundamental to quantify the heat that will be transferred to the solid elements and are discussed in Figs. 4-6, respectively.

Heat transfer from the hot gases to the surface of the structural elements occurs by a combination of the
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Fig. 1  Standard fire curve.

Fig. 2  Natural fire curve.

Fig. 3  Steel reduction factors under extremely high temperatures recommended by NBR 14323:2013.
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Thus, initially, the total heat flux that reaches the structure in a fire situation was determined by the sum of the heat flux by convection and by the heat flux by radiation, as shown in Eq. (1).

\[
\varphi = \varphi_c + \varphi_r
\]  (1)

where:

\(\varphi_r\) is the heat flux by radiation;

convection and radiation parameters, however the propagation of thermal energy inside the element is governed by the conduction mechanism [7]. In addition, the temperature that the structure reaches is strongly influenced by the relationship between the surface area exposed to heat and the mass of the profile, which is called the mass factor [8].
φ_c is the heat flow by convection.

There remains, therefore, the determination of the thermal equilibrium between the heat flux emitted by the phenomenon of the fire and the one absorbed by the steel structures. According to Nunes [1], this flux can be determined from Eq. (2) which postulates the variation of the amount of heat throughout the fire time.

$$\Delta Q_{abs} = m_a c_a \Delta \theta_{a,t}$$  \hspace{1cm} (2)

where:

- $\Delta Q_{abs}$ is the amount of heat absorbed by the structural element;
- $m_a$ is the mass of heated steel;
- $c_a$ is the specific heat of steel;
- $\Delta \theta_{a,t}$ is the temperature variation experienced by the steel element.

For this, it was determined the temperature rise of a structural element with a time interval of 5 seconds, as recommended by the design requirements of ABNT NBR 14323:2013 through Eq. (3).

$$\Delta \theta_{a,t} = k_{sh} \left( \frac{u_f}{A_g} \right) c_a \rho_a \varphi \Delta t$$  \hspace{1cm} (3)

where:

- $\Delta \theta_{a,t}$ is the temperature variation in a structural steel element, over a period of time (°C);
- $k_{sh}$ is the correction factor for the shading effect;
- $\frac{u_f}{A_g}$ is the mass factor for structural elements without thermal protection (m⁻¹);
- $c_a$ is the specific heat of steel (J/kg/°C);
- $\rho_a$ is the specific weight of steel (kg/m³);
- $\varphi$ is the heat flow (W/m²);
- $\Delta t$ is the time interval.

In order to illustrate the temperature increases of the steel in the standard and natural fire, so that it was possible to evaluate the influence of the mass factor, temperature curves were drawn for these two models of fire, which are shown in Figs. 7 and 8.

Analyzing the plots above it is noted that the greater the structural element’s mass factor is, the faster its heating will be. Although the influence of the geometric factor is well represented by this curve by the standard fire curve, its use does not allow a reliable representation of the maximum temperature reached by the structural element [9]. To circumvent this problem, the natural fire curve is used. When one considers the variation of specific heat as a function of the temperature of the steel, it is possible to observe a plateau in the curvilinear trajectory of the plot, as observed in the natural fire curve, indicating a latent heat input required to allow the phase change in the crystalline structure of the metal alloys [10].

The critical temperature is extremely important because it is a failure mode or in terms of modeling if it is the “removal” of the column during the simulation of the phenomenon or in real cases. The critical temperature can be calculated by Eq. (4).

![Fig. 7 Steel temperature in standard fire.](image-url)
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\[ \theta_{cr} = 39.19 \ln \left( \frac{1}{0.9674 k_{y,B}^{3.833} - 1} \right) + 482 \]  \hspace{1cm} (4)

where:

- \( k_{y,B} \) is the reduction factor associated to the flow limit of steels at high temperature.

The reduction resistance factor for the calculation of the critical temperature of the steel structural elements is obtained from expressions of the Simplified Sizing Method of ABNT NBR 14323:2013 which quantifies the maximum mechanical resistance of isolated parts in a fire situation.

2.2 Progressive Collapse

After defining the most important parameters involved in the fire dynamics and analyzing the consequences of temperature rise on the performance of the structural elements designed by steel components, it is evident that the fire action can trigger, through the loss of localized elements, global or partial multi-storey buildings.

Phenomenon is defined, according to Porcari et al. [11], such as the propagation of an initial failure from element to element, resulting in the destabilization of an entire structure or a significantly larger part that can be initiated by several abnormal loading scenarios such as: explosive charges, impact loads, seismic effects, etc. Figs. 9 and 10 show the progressive collapse of the Wilton Paes de Almeida building resulting from a major fire.

In this research the simulation of the progressive collapse will be conducted by the software SAP2000, by reducing the modulus of elasticity of some of its columns. The purpose of doing this is to simulate the heating of these structural elements and to evaluate the behavior of the main diagrams as the temperature rises.

2.3 Structural and Thermal Model

The investigation of progressive collapse in multi-storey steel buildings due to the action of fire cannot be carried out on isolated structural elements because it does not provide reliable answers with respect to its integral behavior [6]. In order to do this, hyperstatic structures were employed in this study, since they allow the transfer and the sharing of efforts as the temperature degrades the strength and stiffness of local elements [12].

For this, a commercial building of 16 floors with dimensions of 25 \( \times \) 15 meters and right foot of 2.85 meters per floor, where the columns and beams are designed by steel elements, was taken as a base model. Selecting one of the most overloaded frames of the building, it was admitted that 50% of the efforts of the slabs would be unloaded on their beams, adding also the own weight of the masonry. Fig. 11 shows the structural scheme with axis-to-axis distances between beams and columns, where the frame was used in the simulations of the phenomenon.

Initially, a preliminary survey of actions at room temperature was carried out. Next, we considered the
efforts of the slabs and beams due to their own weight, floor and ceiling cover, as well as the overloads of indicated office use and, finally, the efforts due to static wind actions. It should be noted that for the values of the weight of the beams and steel columns, the SAP2000 was obtained automatically.

In order to obtain the cross section of the profiles used in the beams and columns of the portal, the SAP2000 integrated design features based on ANSI/AISC 360-10 were used, which provides ideal section sizes (AISC and GERDAU standard, the latter being implemented). Table 1 shows the geometric characteristics of the profiles used in this study.

For the simulation of the thermal scenarios, the parametric fire curves were used, since it is one of the models that most closely approximate the actual fire phenomena, since it takes into account the performance of the main physical aspects used to determine the
temperature of the gases inside the compartment. These parameters are summarized in the fuel load, the degree of ventilation and the wall factor.

The fuel load inside the compartment is equivalent to 700 (MJ/kg), which was extracted from Annex C of NBR 14432:2000 [13] from the purpose (housing commercial offices) and height of the building. The degree of ventilation was determined for the largest external opening of a building compartment due to a window measuring 2 × 4 meters, which is supposed to be broken during the firing of the fire resulting in 0.10 m²/s. And, finally, the wall factor was extracted from the test of a natural fire model compartmentalized in a sealed environment, being taken equal to 1,160 J/m²/s², so that values below lead to against safety [9].

In the study of the temperature rise of the beams superimposed by slabs, the effects of the local radiation obstruction were considered, that is, the shading parameter \(k_{sh}\) of the profiles that are characteristic for acting in sections I and H determined jointly with the massivity factor from the geometric characteristics of the profile. Already for the columns, according to Neto [14], the correct behavior of these structural
elements inserted in masonry stems from the action of the temperature gradient along its cross section, which is capable of leading to the appearance of bending moments and curvatures. In this way, because it was in favor of safety, it was admitted that the columns of the building of this study were completely surrounded by the flames of the fire. The temperature curves of the beams and columns are represented by Figs. 12 and 13, respectively.

3. Results and Discussions

In order to understand the concepts applied to the phenomenon of redistribution of efforts and the mechanisms associated with structural interactions, the study of the progressive collapse of multi-storey steel buildings due to the phenomenon of fire will unfold in this article with the investigation of the global behavior of the edification by local failure of a column.

The simulation of this phenomenon in SAP2000 was carried out by reducing the modulus of elasticity and the parameter of resistance to the flow of steel, admitting a temperature range of 20 °C to 1,200 °C, only for the heating phase, per se to deal with a linear regime analysis. During the modeling, it was observed that when the rigidity of the structural element was exhausted, the redistribution of efforts to the columns of the lower floor was not taking place, indicating one of the limitations of this computational tool.

To circumvent this problem, the axial reaction that the last columns absorbed was determined when the other columns of that pavement failed, in order to capture and retransmit all the load absorbed by these elements. By replacing the axial reactions in the columns by statically equivalent forces and opposite directions it was possible to transfer the efforts to the lower pavements, simulating the phenomenon of

![Fig. 12 Beam temperature curve.](image1)

![Fig. 13 Column temperature curve.](image2)
Table 2 shows the steel profiles of the building that were used for the simulation stage of the thermomechanical study, with the loads acting at room temperature and the respective critical temperatures for each progressive structural element.

The structural model is discretized in Fig. 14, which shows the profiles adopted for frame columns and beams.

The analysis of vertical displacements versus steel temperature was the first study. Although the study was restricted in the heating phase, it was possible to analyze the impacts of the thermal action. The plot shown in Fig. 15 shows the variation of the vertical displacements obtained at the top of three columns with different geometries and loading conditions for the situations that characterize and disregard the performance of the critical temperature.

As observed in the plot above, up to 450 °C the displacements remained practically constant with the elevation of temperature, except for the situation of the column CS 350 × 119 that had the considered critical temperature. This means that the deformations were essentially due to the forces acting at room temperature.

On the other hand, from this section, one can observe a sudden increase of the vertical displacement rate, assuming that the thermal action has significant impacts on the modulus of elasticity of the structural elements. These displacements are more pronounced when the critical temperature of the structural elements is taken into account and serves to show that the structure will have its behavior significantly modified.

The study of the vertical displacements in cases in which the collapse temperature of the columns is considered fundamental to understand the influence of the geometric factors and of loadings exerts in the conditions of deformation of the structure. Thus, by observing the above plot, it is noticed that the greater deformations were alternating between the columns and CS 250 × 90 and CS 350 × 19, especially after 800 °C. Although these structural elements were subjected to a lower loading rate, their geometric characteristics were more determinant in the susceptibility of the steel profiles to the phenomenon of fire.

The investigation of the behavior of the axial loads in the heated column is another parameter approached in this study. Thus, a plot of the reaction (obtained in SAP2000) was drawn from the load acting on the column versus the profile temperature, as shown in Fig. 16.

As shown in the above plot, in the initial instants (up to 350 °C) the fire action is not severe in terms of axial stresses and the burden sharing is insufficient to trigger the failure of the adjacent structural elements before the critical temperature is reached. However, it should be noted that the structure, in this temperature range, could present large deformations which, if they were not free to occur, would lead to the appearance of an exceptional stress configuration at the beginning of the fire.

Nevertheless, from 400 °C a significant decrease of the resistant capacity of the abutments is observed, where the thermal effect is more aggressive to the structural elements. The phenomenon of redistribution of effort presents itself with more intensity at this stage and submits the structure to the abnormal design conditions, which can lead to partial or global ruin. Of course, the quantification of the load to be shared by the alternative paths of stresses is extremely dependent on the critical temperature. Such consideration justifies

| Column       | Loading (kN) | Critical temperature |
|--------------|-------------|---------------------|
| CS 250 × 90 | 1,259.49    | 482.64              |
| CS 350 × 119| 2,516.62    | 349.16              |
| CS 250 × 216| 4,105.28    | 490.23              |
Fig. 14  Structural model.
the importance of addressing the behavior of axial stresses at the time that such a warm-up is achieved.

In order to prove that the axial stresses of the heated columns would be redistributed, a chart was drawn showing the transfer of loads from the heated column to the adjacent columns that were at room temperature. This phenomenon is illustrated by Figs. 17 and 18.

As shown in the plots above the stress increase in the adjacent columns is insignificant until reaching the critical temperature or its mechanical resistance in a fire situation does not support the new design request. Upon reaching the critical temperature the column fails integrally and its efforts walk through the structural interactions until they reach the adjacent elements, which are more preserved from the thermal action. It is emphasized that this relocation of loading occurs, essentially, by the loss of rigidity of the column with the thermal degradation. In this case, it is observed that the redistribution of efforts due to the failure of the column causes the structural failure of the neighboring columns, since they did not present enough mechanical resistance to support the new configuration of efforts.

Last but not least, the phenomenon of inversion of stresses that occurs during the warm-up period is discussed. For this, the variation of the diagram of bending moments of the beams adjacent to the column heated during the fire is studied as shown in the plot of Fig. 19.

As can be seen in Fig. 19, the behavior of the bending moment diagram of the beams adjacent to the
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heated column is significantly modified with the evolution of temperature in the columns. When these structural elements are not sized to resist the inversion of stresses, the structural failure becomes eminent, which can lead to edification to progressive collapse. As the plot above does not take into account the critical
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temperature of the structural element, this means that
the inversion in the diagram can happen at temperature
intervals lower than the stipulated values, where the
considerations proposed by the analysis of the
diagrams of the axial reactions and vertical
displacements presented previously are also applied in
this situation.

4. Conclusion

The study of the behavior of isolated structural
elements under very high temperatures is fundamental
in the analysis of the progressive collapse of buildings
by the action of fire. Through it was possible to
understand how the thermal effects provide the
appearance of additional stresses and large
deformations in the structure, leaving it more
propitious to the formation of a new mechanism. In
addition to this, the investigation of the integral
behavior of the building requires the knowledge of
parameters that go beyond, for example, the
phenomenon of redistribution of effort, inversion in the
diagram of bending moments and other aspects related
mainly to structural interactions such as effects of
thermal expansion, discarded in this research.

It was possible to conclude that the phenomenon of
the redistribution of efforts that occurs during the
heating period will be exclusively due to reduce in the
modulus of elasticity of the steel. On the other hand,
the integral load sharing happens in the moment when
the structural element does not have more bearing
capacity due to the degradation of its strength to the
flow or when its critical temperature is achieved.

Despite the limitations of the numerical tool, the
study showed that the use of advanced computational
techniques is an excellent alternative to study the
progressive collapse of buildings induced by heating,
among several structural elements, that of their
columns. It is also added that for extreme situations,
where it is not possible to determine all the variables
involved in the investigation of the phenomenon, the
application of the successive approximations, which
takes into account the performance of the main
parameters, leads to satisfactory results and can
become an all fire engineering seeking, above all, the
preservation of human lives.

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