BENDING RESISTANCE OF COMPOSITE STEEL-CONCRETE BEAMS IN FIRE SITUATION

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Abstract. *The objective of this paper is to determine the bending resistance of composite beams in fire situation. The study was carried out in two stages: the first one represented the thermal analysis and the second the structural analysis. The thermal analysis was done in a commercial software based in the finite element method. The structural analysis was based in the simplified method of calculation recommended by the NBR 14323. Three cases has been studied: profile without protection, profile with full protection and the profile with partial protection. As the result, the development and the distribution of temperatures at the composite cross-section was determinated. In the same way, the mechanical behavior of the simply supported beam was investigated, mainly, detaching the partial fire protection, whose its use as thermal isolate is an alternative to the reduction of costs, but it needs to be used with critical sense.*

Keywords: *composite beams, fire resistance, finite elements, simplified mehod of calculation.*

1. Introduce

In a general way, it is necessary to have knowledge about the structural performance of buildingds in fire. Thus, the mechanical properties of the materials used in the civil construction, as steel and concrete, are debilitated gradually with the increase of the temperature. So, it can cause the premature collapse of a structural element (composite beam, for example) and/or linking (Fakury, 1999).

The structural resistant capacity under high temperatures depends of three basic components: the fire model, the heat transfer model and the structural model. Figure 1 shows the calculation stages of the load capacity for a structure exposed to fire.

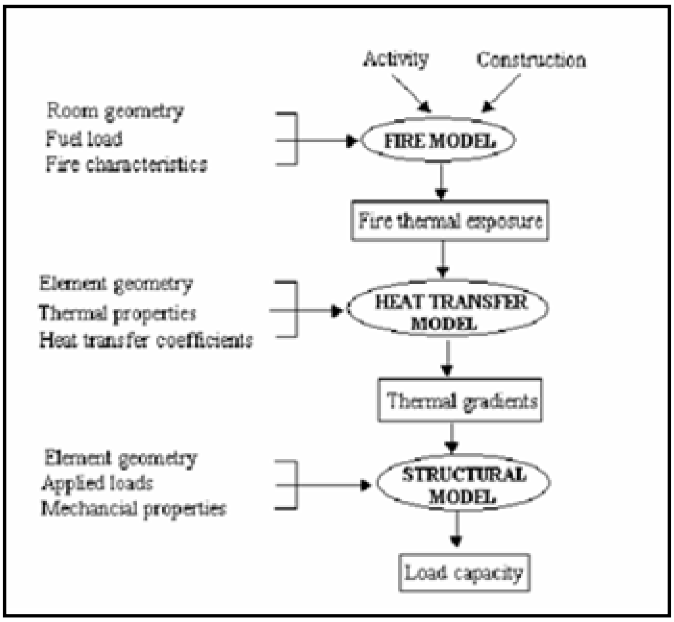


Figure 1. Flow chart for calculation the load capacity of a structure exposed to fire

The fire model tries to reproduce the fire´s scenario through time-temperature curves. The heat transfer model corresponds the stage of heat transference between the hot gases and the structural member. The structure absorbs heat and suffers a temperature rise. The structural model intends to determine the resistant capacity as a function of the temperature reached by the structural member. In this stage, it is necessary to take into account the reduction of strength and rigidity on its constituent materials.

2. Standard fire

Nominal time-temperature curves represent the set of curves that try to reproduce furnace tests on structural elements for determining its fire resistance. And the standard fire represents one of these nominal curves. The International Organization for Standartization by means of code ISO 834 (1994), and also NBR 14432 (2000), recommends to the use of the following expression for calculation the standard fire curve:

$$\theta_g = \theta_0 + 345 \cdot \log(8 \cdot t + 1) \tag{1}$$

where θ_g is the temperature of the standard fire curve (°C), θ_0 is the ambient temperature (°C) and t is the time in minutes. Figure 2 illustrates the fire model that is represented by the standard fire curve.

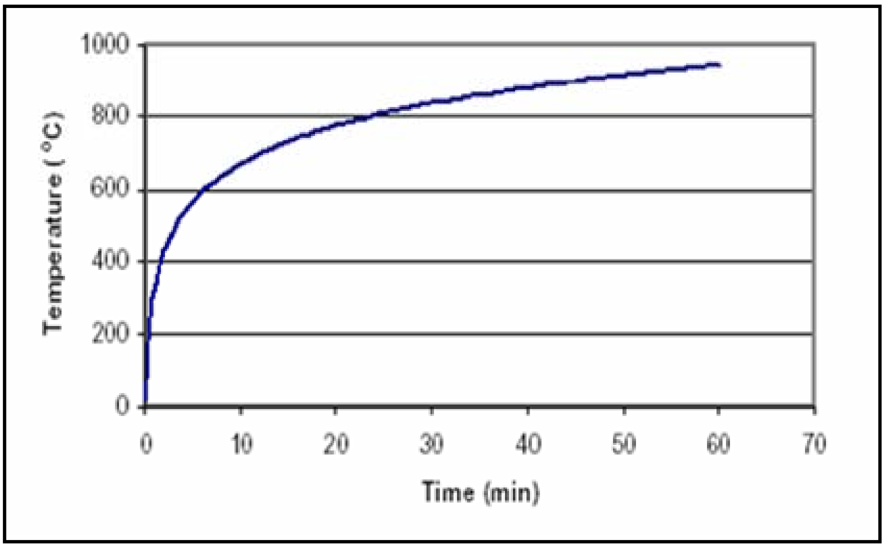


Figure 2. Time-temperature curve of the standard fire

3. Heat transfer between the fire hot gases and the structural member

The temperature difference enters the hot gases of the fire and the structural member generates a heat flow that, by convection and radiation, is transferred to the structure (thermal action) provoking a gradual increase of temperature. The heat flux by convection, q_{conv}, in Watt for square meter, can be determined by the Newton´s Cooling Law, as follows:

$$q_{conv} = h_c \cdot (\theta_i - \theta_j) \tag{2}$$

where h_c is the coefficient of heat transfer by convection (W/m2.°C), and θi and θj are, respectively, the temperatures in warm surfaces i and j. The heat flux by radiation, q_{rad}, in Watt for square meter, is given by (Pitanga, 2004):

$$q_{rad} = h_r \cdot (\theta_i - \theta_j) \qquad \therefore \qquad h_r = \varepsilon_{res} \cdot \sigma \cdot (\theta_i^2 + \theta_j^2) \cdot (\theta_i + \theta_j) \tag{3}$$

where h_r is the coefficient of heat transfer by radiation (W/m2.K), ε_{res} is the resulting emissivity of the furnace and σ (= 5,67.10^{-8} W/m^2.K^4) is the constant of *Stefan-Boltzmann*. When the structure absorbs the heat flow induced by the convection and radiation, it suffers a temperature rise on time. The form in wich the heat is conducted inside the solid is object of the heat transfer by conduction. The *heat conduction equation*, or simply *heat equation*, can be used to get the distribution of temperature in a bidimensional and isotropic medium in function of the time. For the specific case of structures in fire situation, as generation of internal heat does not exist, it is allowed to write for the equation of heat the following expression:

$$\frac{\partial}{\partial x}\left(\lambda(\theta)\cdot\frac{\partial\theta}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda(\theta)\cdot\frac{\partial\theta}{\partial y}\right)-\rho\cdot c(\theta)\frac{\partial\theta}{\partial t}=0 \tag{4}$$

where $\theta = \theta(x,y,t)$ is the temperature, ρ is the density (kg/m^3), c is the specific heat (J/kg.°C) and λ is the thermal conductivity (W/m.°C) of the body. However, to be solved, it needs certain special conditions that they need to be specified in the contour of the body.

4. Heat equation discretization

The FEM is an important computational tool that solves problems described for partial differential equations, whose domain of interest can be represented as an assembly of subdomains called finite elements (Nikishkov, 2001). Figure 3 illustrates the following bondary conditions that can be specified in the closed contour surface Γ:

$$\theta=\theta_s(x,t) \qquad in\ \ x=(x,y)\in\Gamma_s,\ t>0$$

$$q_n=h_c\left(\theta_g-\theta_{\sup}\right)+h_r\left(\theta_g-\theta_{\sup}\right) \qquad in\ \ x=(x,y)\in\Gamma_{q_n},\ t>0$$

where θ_s is the prescribed field of temperature, θ_g is the temperature of the Standard fire curve, θ_{sup} is the temperature at the closed surface of contour Γ_{qn} and q_n represents the heat flux by convection and/or radiation.

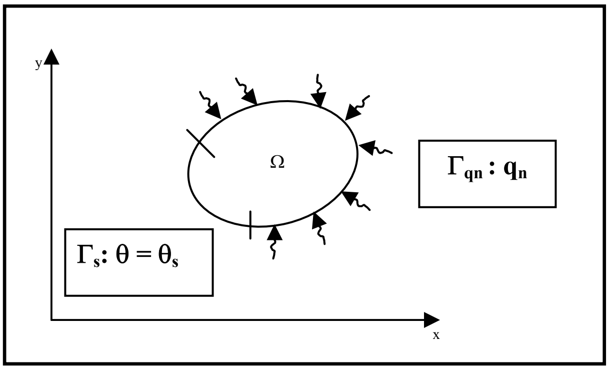


Figure 3. Bondary conditions for the incial value problem

In transient problems it is necessary to specify the field of temperature for the solid in a certain instant of time, that it is assumed as being the start point for the analysis (initial condition), i.e.:

$$\theta=\theta_0(x) \qquad em\ x=(x,y)\in\Omega,\ \ t=0$$

where $\theta_0\,(x)$ represents the field of temperature into the solid in $t = 0$, that it is the initial time. Problems of this type are generally known as *initial value problems*, whose the required solution needs to be valid in all space-time domain. According to Zienkiewicz & Morgan (1983), it is more convenient to use the technique of the partial discretization. First, it is solved the contour value problem (spatial approach), and after the time-dependent problem (temporal approach). At a first moment, considering only the spatial approximation, it is possible to arrive the following expression through the Galerkin´s Finite Elements (Pitanga, 2004; Reddy and Gartiling, 1994):

$$[M(\theta)]\cdot\left\{\frac{\partial\theta}{\partial t}\right\}+[K(\theta,t)]\cdot\{\theta\}=\{Q(\theta,t)\} \tag{5}$$

where M is the thermal capacity matrix, K is the thermal conductivity matrix and Q is the vector of the heat flux by convection and/or radiation. Equation (5) represents a system of ordinary differential nonlinear equations in time. For the specific case of heat transfer between the hot gases and the structural member, the thermal conductivity matrix and the vector of heat flux are dependents of temperature and time, because, both, possess the coefficient of heat transfer by radiation, h_r, in its formulations. In the end of this stage, the FEM´s model is called "semidiscrete", because only the spatial approximation was formulated.

In the last stage, known as temporal approximation, the equation solution is calculated through the direct integration method, where the ordinary differential equations in time can be represented by finite differences into the interval of interest (Polivka & Wilson, 1976). From Eq. (5) and using the approximation by backward finite differences for the instant of time "n+1" (Zienkiewicz & Morgan, 1983), is allowed to write the following expression (Pitanga, 2004):

$$\left\{\frac{\left[M\left(\theta_{i-1}^{n+1}\right)\right]}{\Delta t}+\left[K\left(\theta_{i-1}^{n+1}\right)\right]\right\}\cdot\left\{\Delta\theta_i\right\}=\left\{Q\left(\theta_{i-1}^{n+1}\right)\right\}-\left[K\left(\theta_{i-1}^{n+1}\right)\right]\cdot\left\{\theta_{i-1}^{n}\right\} \qquad (6)$$

In wich:

$$\left\{\theta_i^{n+1}\right\}=\left\{\theta_{i-1}^{n+1}\right\}+\left\{\Delta\theta_i\right\} \qquad (7)$$

Where:

n+1 represents the time step number;
i represents the number of the required iteration to reach the solution convergence in “n+1”**;**
Δt is the time interval..

5. Plastic moment capacity

Full shear connection happens when the number of shear connectors is sufficient to develop the plastic bending resistance of the cross-section. In this case, the bending resistance is determined by the plastification of concrete or steel section and not by the cut resistance of the shear connectors, that is, the increase on number of connectors does not produce bending resistance addition. Thus, the bending moment resistance, according to NBR 14323 (1999), is calculated using the simple plastic theory. It is calculated by dividing the composite cross-section into many smalls blocks and summing their contributions. Figure 4 shows the three possible cases for the plastic neutral line (LNP) at the composite section, where:

Cfi is the resultant of compression tensions in the concrete;
Tfi is the resultant of compression tensions in the steel;
C´fi is the resultant of compression tensions in the steel;
yp is the distance of the plastic neutral line until the superior face of the steel beam;
a is the compressed thickness of the concrete slab;
b, *tc*, *d*, *bfi*, *bfs*, *h*, *tfi*, *tfs*, *tw* e *hF* represent geometric characteristics of the composite beam.

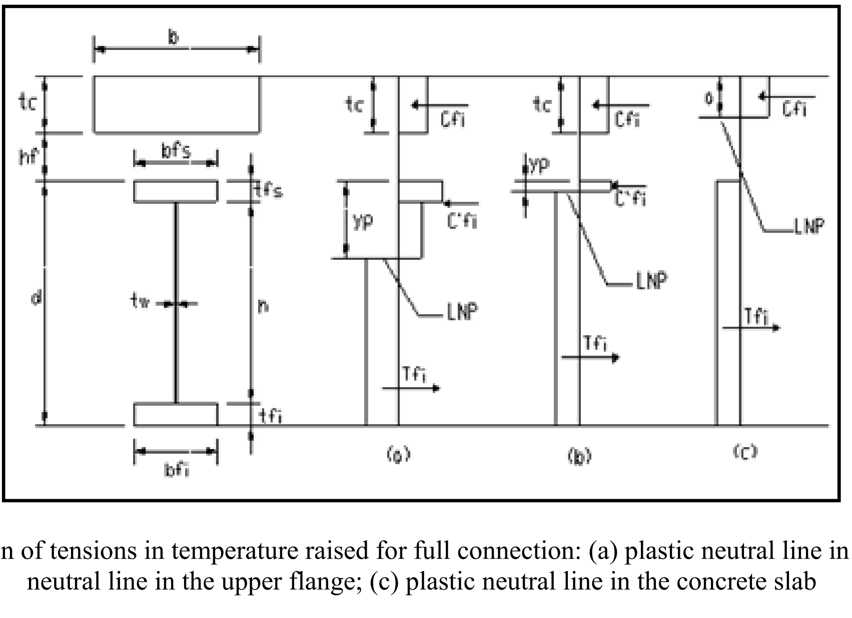


Figura 4. Distribution of tensions in temperature raised for full connection: (a) plastic neutral line in the web; (b) plastic neutral line in the upper flange; (c) plastic neutral line in the concrete slab

6. Thermal-mechanic behavior

This section intends to determine the bending moment resistance of the simply supported composite beam in fire situation. The study was carried out in two stages: the first one represented the thermal analysis and the second the structural analysis. ANSYS was the program used to carry out the thermal analysis through FEM, while the simplified method of NBR 14323 was used to investigate the structural behavior of the composite beam.

6.1. Calculation hypotheses

It is assumed that the structural member is totally involved by flames from the compartment and that the temperature of the hot gases respects the standard fire temperature-time curve. This is the "side exposed to fire", where it places the steel beam and the lower part of the concrete slab. The upper part of the concrete slab is called "side not exposed to fire", in which is considered that it does not have fire and the air is at the ambient temperature (natural convection). Table 1 brings a summary for initial and contour conditions adopted in this work. The coefficient of heat transfer by convection on the side not exposed to fire follows what was recommended by Kruppa and Zhao (1995). The others coefficients correspond those ones from NBR 14323.

Table 1. Initial and contour conditions for the composite beam with and without material of thermal protection

Coefficient of heat transfer by convection on the unexposed side to fire (W/m^2.°C)	9
Resulting emissivity between the furnace and the structural member	0,5
Coefficient of heat transfer by convection on the exposed side to fire (W/m^2.°C)	25
Inicial temperature (°C)	20

Figure 5 presents the physical model considered for thermal analysis. It can be observed two distinct physical situations in the contour surface of the composite beam, the side exposed and the other unexposed to fire.

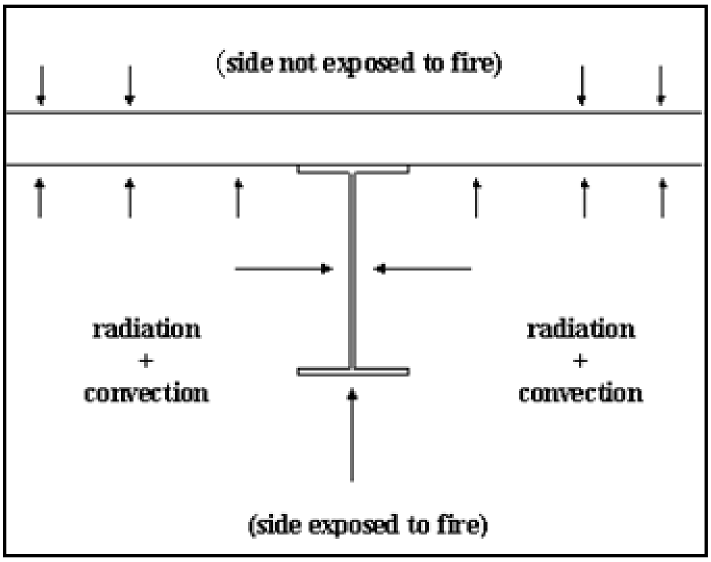
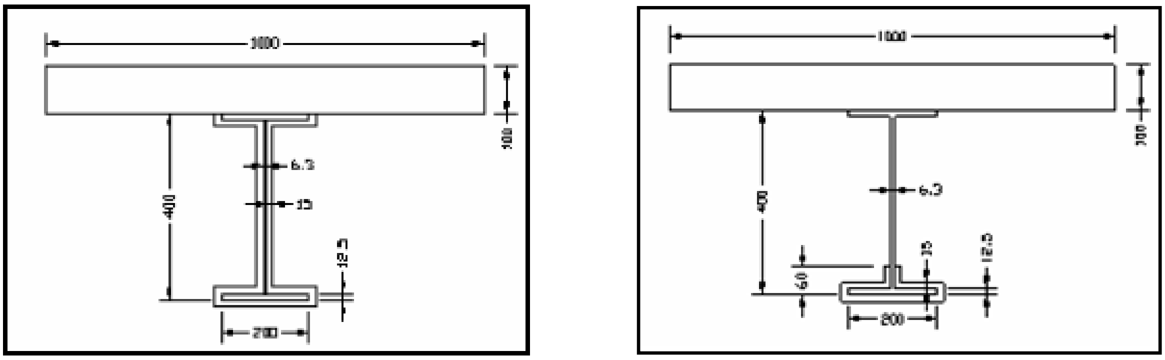


Figure 5. Model considered for numerical modeling of composite beam in fire situation

6.2. Field of temperature obtained from FEM

Three cases have been studied: profile without protection, profile with full protection and the profile with partial protection. It is understood as total protection the thermal protection that involves all the metallic section. Composite beams partially protected are those where only the lower flange and a fraction of the web on steel section is protected against to fire (Wang, 1998). Figure 6 presents the dimensions (mm) and the geometry of two studied cases. Tables 1 and 2 present the properties of the steel, the concrete and the protection used in the transient thermal analysis.



(a) (b)

Figure 6. Geometric characteristics of two studied cases: (a) beam with full protection; (b) beam with partial protection

Table 1. Properties of the steel and the concrete

Properties	Steel	Concrete
Density (kg/m^3)	7850	2400
Specific heat (J/kg.°C)	600	1000
Thermal conductivity (W/m.°C)	45	0.90

Table 2. Characteristics of the thermal protection

Thickness (mm)	15
Specific heat (J/kg.°C)	1100
Thermal conductivity (W/m.°C)	0.15
Density (kg/m^3)	350

The element used in the thermal analysis was the PLANE35, that is a quadratic triangular finite element formed by six nodal points, which it can be find on elements library of ANSYS. It is very used in bidimensional problems of heat transfer. In the steel profile, the points that represented the centroids of the upper flange, web and lower flange has been chosen for extracting the temperatures. In the concrete slab, the section placed at the vertical symmetric axis of the composite beam was chosen, which was divided in five equal slices of 20 mm. The increment on time adopted was 60 seconds. Figure 7 shows the fields of temperature for two cases analyzed. It was considered 40 minutes for the fire duration . The colors vary from blue to red, representing, respectively, the low (20 to 140°C) and high (980 to 1100°C) temperatures.

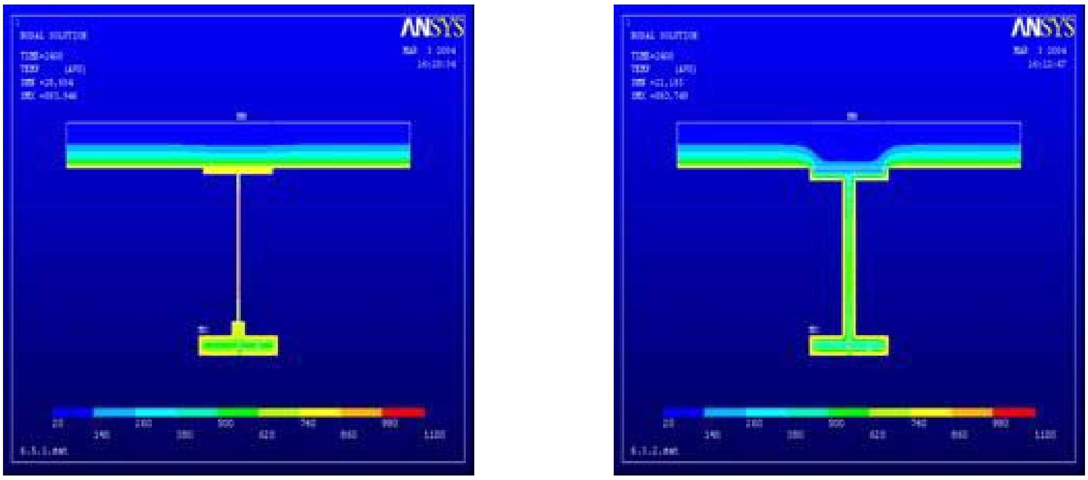


Figure 7. Colors map for fire duration of 40 minutes

6.3. Bending resistance under high temperatures

The model of a composite simply supported beam pertaining to a commercial building was adopted. The steel yield strength and the concrete compression strengh were assumed, respectivily, as 250 Mpa and 18 MPa. It has been used 21 stud bolt connectors with 19 mm of diameter, whose steel had 415 MPa limit of rupture. The connectors were duly spaced between the central section (of maximum moment) and the end section (of null moment) in way that if had satisfied the condition of full shear interaction (NBR 8800, 1986). The temperatures gotten in the previous section has been used to determine the bending moment resistance.

Figure 8 presents the development of the positive bending moment under high temperatures for the three studied cases. The bending moment on initial time (t = 0) corresponds that one at the ambient temperature (20°C). As the lower flange answers for an important parcel of the resistant moment, in the specific case of the profile with partial protection, its thermal isolation was necessary to guarantee more resistance than the profile without protection, at least until the first thirty minutes of fire duration.

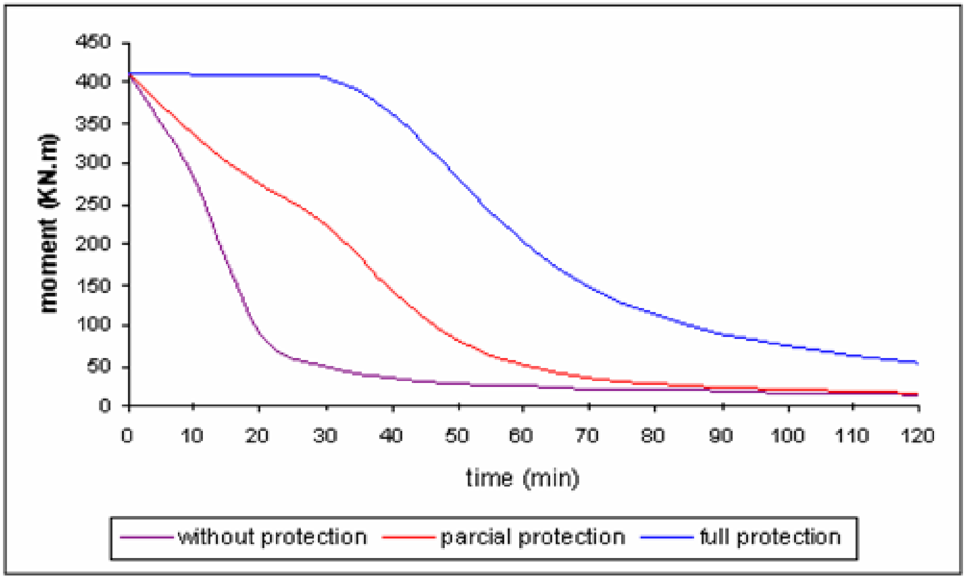


Figure 8. Graphical moment *versus* time of the composite beam during the exposition to fire

7. Conclusions

At 60 minutes of fire duration, the bending moment capacity of the composite simply supported beam with no thermal protection is about 5% in relation that one at ambient temperature. Thus, the ideal would be to protect all the beams against the fire, however, the inherent cost to this constructive process is excessively expensive (Claret, 2000). Since it is necessary to coat the beams with full protection, an alternative would be the use of the partial protection. For the situations whose the material cost of full and partial protection is similar, the partial protection is justified, because the cost of the material installation is well lesser than the total protection. The partial fire protection is acceptable as an alternative to the reduction of costs since that used with critical sense, although the ideal is the full thermal protection.

8. References

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