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A performance indicator for structures under natural fire

T. Gernay *, J.-M. Franssen

Structural Engineering Department, Univ. of Liege, Ch. Des Chevreuils 1, 4000 Liege, Belgium

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ABSTRACT

Fires in buildings are characterized by a heating phase followed by a cooling phase, yet the effects of the latter on structures are not well covered in the current approaches to structural fire engineering. Indeed the actual requirement of non-occurrence of structural failure at peak temperature does not guarantee against a delayed failure during or after the cooling phase of a fire, which puts at risk the fire brigades and people proceeding to a building inspection after a fire. Therefore there is an urgent need to better comprehend and characterize the materials and structures behavior under decreasing temperatures. Sensitivity to delayed failure of a structural component depends on its typology and constituting materials. In particular, two structural components with the same Fire Resistance rating (R) under standardized fire may exhibit very distinct behavior under natural fire, one of them being more prone to delayed failure than the other. With the aim of quantifying this effect, a new indicator is proposed that characterizes the performance of structures under natural fire conditions. The paper presents the methodology to derive this new indicator as well as results for different typologies of structural components. Parametric analyses highlight the prime influence of constitutive material and thermal inertia of the element on the post-peak behavior. Used in conjunction with the Fire Resistance rating, it is shown how the new indicator carries additional and significant information for classifying structural systems in terms of their fire performance and propensity to delayed failure.

1. Introduction

Fire Resistance rating (R) has been widely used as the reference indicator for assessing the performance of structures in fire. It is defined as the duration during which a structural component fulfils predefined criteria with respect to structural integrity, stability and temperature transmission [1] under monotonically increasing standardized fire conditions. It has been used for several decades in fire engineering [2–4] and is the reference indicator of fire performance in many codes [5,6]. Practically, it gives comparative information for components in which the fire-induced temperatures would be monotonically increasing. The Fire Resistance is therefore a convenient and efficient indicator to characterize a structural component by mean of a single scalar, the quantity of information provided being deemed as sufficient in a prescriptive environment.

In a performance-based environment, a more realistic representation of the fire may be used that comprises a heating phase followed by a cooling phase during which the temperature in the compartment is decreasing back to ambient temperature. The influence of such realistic fire scenarios on the behavior of structural components is a key issue in the performance-based approach, as shown for example for concrete-filled hollow structural section columns [7] or for single-plate shear connections in which the tensile forces created during the cooling phase can lead to failure [8]. The required duration of stability may be longer than the duration of the heating phase. It may even be required that the structure survives the total duration of the fire until complete burnout, for instance in high-rise buildings due to requirements related to the egress time [9]. However, the fact that the structure exhibits stability at the time of maximum gas temperature does not guarantee against failure at a later stage. Typically, the load-bearing capacity of a structure continues decreasing after the maximum gas temperature is attained, finally reaching a minimum value and eventually recovering partially or completely when the temperatures in the structure are back to ambient. This delayed decrease in load-bearing capacity may be caused by the combination of various phenomena among which the delayed temperature increase in the sections due to thermal inertia and the non-recovery or additional loss of material mechanical properties during cooling. A previous research carried on the behavior of reinforced concrete columns under natural fires has indicated that there was a possibility of structural failure during and even after the cooling phase of a fire [10].

* Corresponding author. Tel.: +32 (0)43669253.
E-mail address: Thomas.Gernay@ulg.ac.be (T. Gernay).

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Natural fire scenarios are thus associated with a threat that was entirely disregarded as long as standardized fires were considered: the possibility of a structural failure arising after the time of maximum temperature in a compartment, referred to as delayed failure hereafter. A delayed failure has been observed, for example, in a full-scale fire test on a composite steel and concrete floor conducted in 2008 in the Czech Republic [11]. In 2004 in Switzerland, a delayed failure of an underground car park killed seven members of a fire brigade, who were present in the car park after having successfully fought the fire when the concrete structure suddenly collapsed [12]. Yet research works on structural behavior after the time of maximum temperature are very scarce and focus mainly on residual load-bearing capacity [13–16]. It is the opinion of the authors that more attention should be brought to the structural behavior during and right after the cooling phase of the fire, because the vulnerability of a structure is important in these phases during which the elevated temperature has not dissipated yet. In this purpose the definition of a suitable measure of performance for structures under natural fire is needed to allow for comparative analyses. Clearly, the Fire Resistance indicator is not suitable to characterize a structure sensitivity to delayed failure, as it is based on monotonically increasing temperatures. Therefore, a new indicator is proposed in this paper to complement the information carried by the Fire Resistance with information about the behavior under natural fire conditions. This indicator allows comparing and classifying structural systems in terms of their sensitivity to delayed failure.

The next Section presents the theoretical basis supporting the indicator definition. The definition allows associating an unequivocal value of the indicator for any given structural component under a given load. The method to derive the indicator is described in Section 3.

In Section 4, the indicator is numerically assessed for a series of applications with concrete, steel and timber materials. In a previous research [10], it was shown that for concrete columns the situations of delayed failure were more likely to arise for short-duration fires and columns with low slenderness or massive sections. It is shown here how these results can be interpreted in terms of the new indicator. The study is extended to other typologies of structural elements for comparing these typologies in terms of performance under natural fire. The results are discussed in Section 5.

2. Theoretical definition of the indicator

2.1. Capacity evolution under standardized and natural fire

Let us consider a structural component subjected to a certain load (demand) which is considered constant during the fire. During the fire, the temperature increase across the section of the component leads to a decrease of the mechanical properties of the constituting materials, resulting in a decrease of the load-bearing capacity of the component.

For a standardized fire, the temperature is continuously increasing in the compartment, so that the temperatures in the element are also continuously increasing and, assuming that all materials properties degrade under increasing temperatures, the load-bearing capacity is continuously decreasing. Failure occurs at the time when the capacity meets the demand, this time being defined as the Fire Resistance of the component. This is illustrated by the red[1] curve in Fig. 1 where, for the sake of simplicity, capacity is assumed to decrease linearly over time, which is usually not the case in practice.

[1] For interpretation of color in Fig. 1, the reader is referred to the web version of this article.

For a natural fire, the temperature in the compartment or, more generally speaking, the thermal solicitation to the elements, is first increasing until a maximum and then decreasing back to ambient conditions. In that case, the load-bearing capacity of the component is first decreasing until reaching a minimum and then it may remain constant or recover, partially or completely, after the temperature has come back to ambient. Importantly, the time of the maximum fire temperature and the time of the minimum load-bearing capacity are generally not simultaneous, the latter arising later than the former. Contrary to standardized fire in which failure will always happen, failure under a natural fire situation depends on the severity of the natural fire. Fig. 1 shows the evolution of capacity of a structural component for two different natural fires, the heating phase of which follows the standardized ISO fire for a duration of 20 min and 59 min respectively; failure arises for the longer natural fire only.

The following observations can be drawn, illustrated by this hypothetical example:

- Given a structural component submitted to a certain load, the component will fail under some natural fires while it will not under others, depending on the severity of the fire. The severity is a measure of natural fires to be established; it will be discussed later.
- Consequently, for any structural component submitted to a certain load, a "critical natural fire" can be defined as the natural fire with minimum severity that will lead to the failure of the component.
- This "critical natural fire" may have a duration of the heating phase shorter than the Fire Resistance of the component; the fact that a structural component is *R*90 does not give sufficient information to conclude whether the component will fail if it is subjected to a natural fire with a heating phase of, say, 80 min.
- The failure that occurs under a natural fire may arise long after the Fire Resistance time of the component, as seen for instance in Fig. 1 by comparing the time when the capacity meets the demand for the standardized fire and for the 59 min natural fire.

Note that the load in a structural component does not necessarily remain constant during a fire. The elevation of temperature in the materials produces thermal elongations together with a reduction of strength and stiffness, which may cause restraint forces when considering the interaction with the surrounding structure. As a result, the demand that is plotted in Fig. 1 could be a curve (in all generality) instead of a horizontal line. The demand was assumed constant in this hypothetical example to simplify the discussion. Assuming otherwise would not change the discussion of this section; in particular, it remains true that the capacity can meet the demand during the cooling phase of a fire which heating phase was shorter than the Fire Resistance of the component.

Hence, the Fire Resistance does not give enough information to characterize the performance of structures under natural fire and a new indicator is needed to complement it. This indicator must be related to a certain measure of severity of the natural fire.

The following section discusses the characterization of natural fires by a severity measure. Then the new indicator based on this severity measure is introduced in Section 2.3.

2.2. Measure of severity of a natural fire

Natural fires in a compartment can be characterized simply by a temperature–time relationship. Due to the variability in the parameters that affect the natural fire, an infinity of time–temperature relationships can be obtained in theory. For condensing the information contained in the full temperature–time curve into a characteristic measure of severity, several indicators can be