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Towards a standard measure of the ability of a structure to resist a natural fire

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ABSTRACT

Fire brigades face a major threat when intervening in a building in fire: the possibility of structural collapse during the cooling phase of the fire, or soon thereafter. In the current approaches to structural fire engineering, the fire resistance rating (R) is generally the only measure taken into consideration to characterize the fire performance of structural elements, although this measure does not reflect the response in real fire conditions. In this work, a standard measure is proposed to characterize the ability of structural members to resist a natural fire including the decay phases. This measure yields information about the potential occurrence of delayed failure as a function of the duration of the fire before it started to decrease, whether by self-extinction or due to the action of the fire fighters. The paper presents the method to derive this new standard measure as well as results for different typologies of structural elements. Finally, the interpretation and practical consequences are discussed, in particular regarding the safety of fire fighters during an intervention.

INTRODUCTION

In a performance-based approach, a realistic representation of the fire needs to be considered in the analysis. This representation should include the successive fire development stages until burnout. Yet, this demands a shift in perspective on the response of structures to fire, because structural members that perform well under continuously increasing time-temperature curves (such as the standard ISO fire) do not necessarily perform well when subjected to heating-cooling sequence. Meanwhile, collapse of buildings during the cooling phase of a fire occurred in the past, highlighting the importance of filling this lack of knowledge.

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Several recent studies have focused on the residual load bearing capacity of structural members after exposure to fire, e.g. [1]. However, the analysis of the transient evolution of capacity during the decay phase has rarely been addressed. This aspect needs further investigation as the capacity continues to decrease after the time of maximum gas temperature in a building compartment [2], which particularly endangers the fire fighters and first responders. Other researchers have made contributions to determine equivalent fire resistance based on performance based methods [3]. In this work, the objective is to propose an original and pragmatic concept to characterize the structural fire performance under realistic, natural fires. A novel standard measure is derived and applied to different structural members subjected to natural fire. The goal is also to define a measure that can be helpful for fire fighters education and for increasing their safety on site.

POSSIBILITY OF DELAYED COLLAPSE

Factors Promoting Failure after the Time of Maximum Gas Temperature

When a structural member is exposed to natural fire, its load bearing capacity decreases during the heating phase of the fire, but it also decreases after the maximum gas temperature is attained. As a consequence, structural failure may occur during or after the cooling phase. This delayed decrease in load bearing capacity may be caused by the combination of various phenomena, such as:

- the delayed temperature increase in the sections, due to thermal inertia;
- the non-recovery or additional loss of material properties during cooling;
- the built-up and reversal of thermal forces in a structure subjected to heating-cooling (e.g. tensile forces in connections).

For instance, Figure 1 depicts the evolution of temperature in the section of a reinforced concrete (RC) column exposed to a natural fire. The fire corresponds to the Eurocode parametric fire with a 60-minutes heating phase and a coefficient $\Gamma = 1$ [4]. The maximum temperature in the corner steel rebars (A) is reached after 92 minutes, i.e. during the cooling phase of the fire. In the core of the concrete section (C), the maximum temperatures are reached long after the end of the fire. Hence due to this thermal inertia, the concrete core of the section continues to lose part of its mechanical properties after the gas temperature in the compartment is back to ambient. Besides, concrete material is known to also lose part of its residual strength during cooling [5].

Example: Structural Response of a Column under Natural Fire

The effects of the phenomena listed in the previous section on the possibility of delayed failure are illustrated here for a RC column. Figure 2 shows the evolution of the vertical deflection at the top of a column that is subjected to constant applied load and to natural fire exposure. The column is analyzed under three different values of the load using the nonlinear finite element software SAFIR® [6]. As can be seen, depending on the applied load, structural failures during the cooling phase or even after the end of the fire may be observed. The goal of the standard measure that is introduced in this paper is to quantify the sensitivity to these delayed failures.

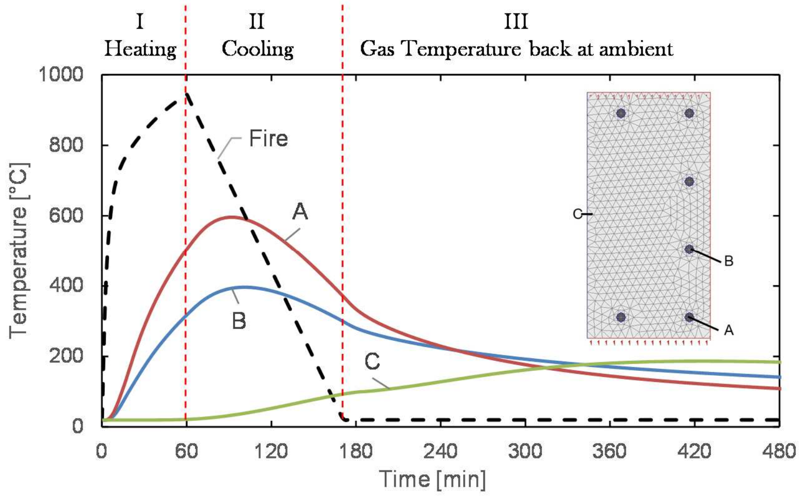

Figure 1. Evolution of temperature in a RC column section exposed to a natural fire (1/2 modeled).

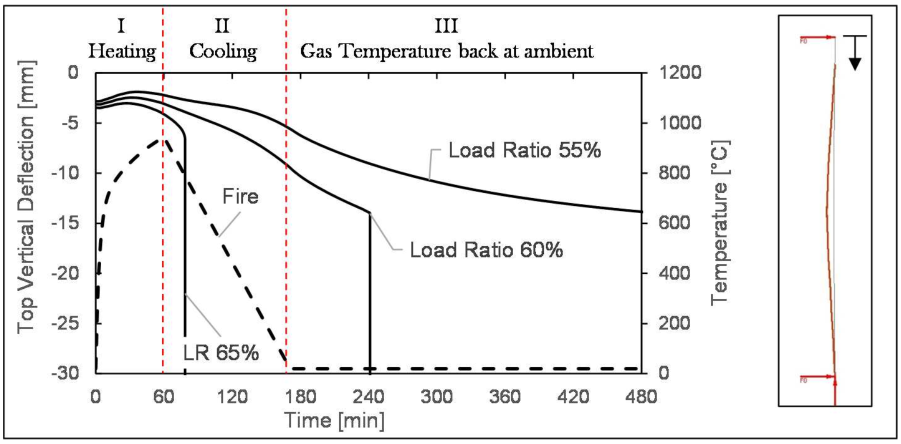

Figure 2. Time evolution of top vertical displacement for a RC column exposed to a 60-minutes heating phase natural fire, for different levels of applied compressive load.

STANDARD MEASURE FOR PERFORMANCE UNDER NATURAL FIRE

Duration of the Heating Phase (DHP)

The fire resistance rating (R) relates the applied load ratio (LR) on a member with the duration of exposure to a standard fire until failure. By similarity, the key idea behind the proposed measure is to relate the applied LR with a duration that is characteristic of a natural fire and that causes failure. It is chosen to work with the duration of the heating phase of the natural fire based on the parametric fire model of Eurocode 1 with $\Gamma = 1$. Selection of this value for Γ makes the heating phase approximate the standard ISO curve.

Using this set of natural fires, a standard measure can then be defined to quantify the response of a structural member under natural fire exposure. This measure is referred to as Duration of Heating Phase (DHP). The DHP of a member under a given applied LR is defined as the minimum exposure time to standard ISO fire (followed by cooling phase in accordance with the Eurocode parametric fire model) that will eventually result in the failure of the structural component, even if the fire stops thereafter. It has a straightforward interpretation for fire brigades: if their intervention (which ends the heating phase) starts earlier than the DHP of the structure, the structure is theoretically safe; if it starts later, they should be particularly careful as the structure is expected to eventually collapse even though the gas temperatures are decreasing. Note that failure can occur several minutes or hours after the time corresponding to the DHP. The DHP only informs about the occurrence of failure (not the time at which it will occur), based on the extent of fire exposure that the member has experienced. The reader is referred to [7] for more details about the theoretical definition of the DHP.

Adopting a measure in time unit is convenient for comparison with the Fire Resistance indicator. Besides, the duration of the heating phase of a natural fire has a direct practical significance and can be easily comprehended by the different stakeholders involved in fire safety. Also, this is a quantity that, to some degree, can be estimated on site during a real fire.

It is recognized that the adopted natural fire model represents a specific type of fire and is not necessarily representative of the real fire that would develop in a building. However, defining a standard natural fire provides significant advantages. It allows quantifying and comparing the performance of different members. The time-temperature relationships that represent the fire are simplified and comprise only one varying parameter, the duration of the heating phase.

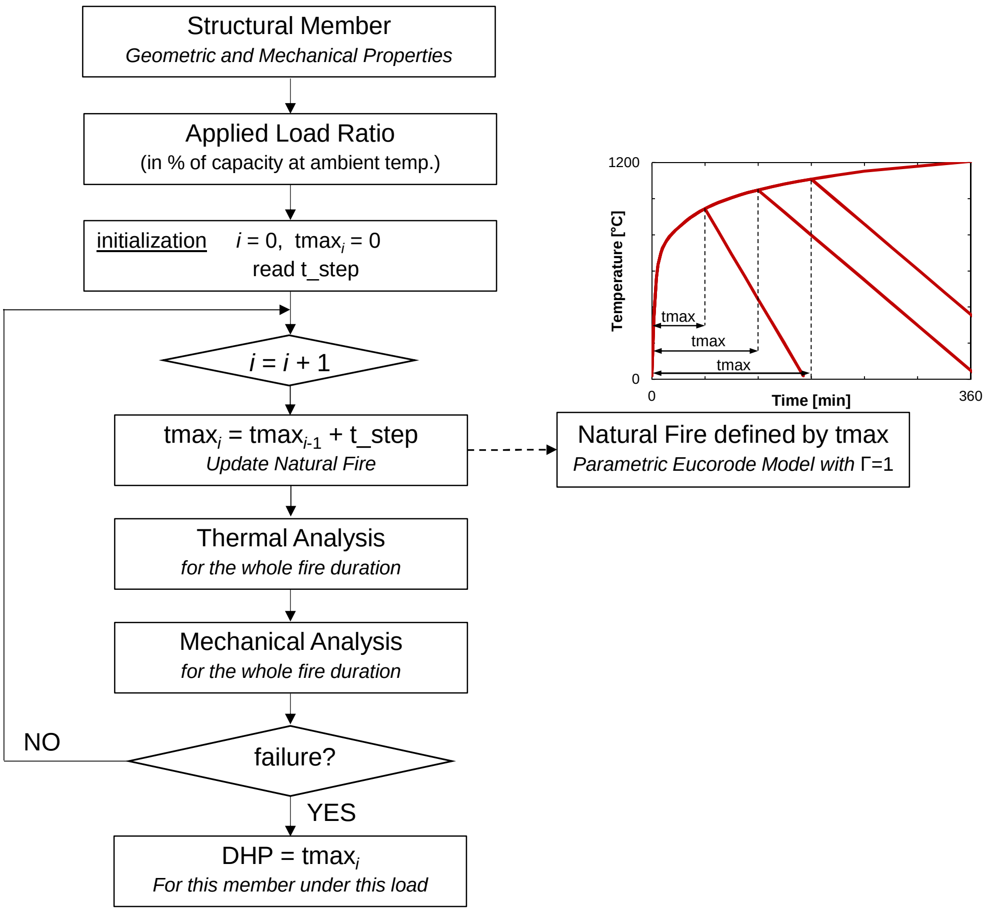

Figure 3. Flowchart to obtain the DHP of a member – fixed load ratio method.

Method to Derive the DHP

The method to obtain the DHP of a structural member subjected to a given LR is illustrated by the flowchart in Figure 3. It can be seen that this method is a more complex operation than the method to obtain the Fire Resistance, for two reasons.

First, searching for the DHP of a member is searching for a fire curve. The process is thus iterative, consisting of several analyses under different applied parametric fires for the search of the minimum value of parameter tmax that leads to structural failure (where tmax is the duration of the heating phase).

Secondly, except for the simplest members, the analysis of a structural member under natural fire necessarily requires a verification in the entire time domain by a step-by-step method, since verification in the load domain at the time of maximum gas temperature does not guarantee against failure at a later stage. Therefore, the “thermal analysis” and “mechanical analysis” in the flowchart need to be transient analyses. These are usually performed by means of advanced numerical methods such as the non-linear FEM. The parameter t_step dictates the degree of accuracy of the process and should not exceed a few percent of the value of DHP.

RESULTS - COMPARISON BETWEEN DHP AND R

Load Bearing Capacity Criterion

For illustration, the DHP and R of various structural members are determined under different applied load ratios. The following members are considered:

- A RC square column of 4 m length and 45 cm side, exposed to natural fire on its four sides;
- A HEB 400 steel column of 4 m length, in S355, exposed to natural fire on its four sides, with a thermal protection designed to provide a fire resistance of 60 minutes under 50% LR (P1);
- The same steel column but with a thermal protection designed to provide a fire resistance of 120 minutes under 50% LR (P2);
- A softwood timber beam, simply supported with 4 m span, exposed to natural fire on 3 sides.

The response of the structural members under natural fire exposure is analyzed using SAFIR® [6]. The material properties are taken according to the Eurocodes. For concrete modeling, the Explicit Transient Creep Eurocode model is adopted to take into account the transient creep strain irreversibility during cooling [8]. Concrete compressive strength is reduced during cooling by an additional 10% of the value corresponding to the maximum temperature according to Eurocode 4.

The fire resistance rating R under standard ISO fire and the DHP under natural fire are obtained for the members. The results are given in Table I. This allows drawing the following main conclusions:

- For all the studied members, the DHP is always lower than the fire resistance R. This reveals the possibility of delayed failure, for any constituting material.
- The difference between the DHP and R is higher for certain members than for others. This is due to the different mechanisms influencing delayed failures,

such as the thermal inertia brought by the insulation in a protected steel member or the delayed charring process in a timber member.

- A member that has a longer fire resistance than another may nevertheless have a shorter DHP.

These conclusions have important implications. In particular, they demonstrate that the fire resistance R is not relevant for estimating the structural performance to fire when considering natural fires. A specific typology and/or material that happens to perform better than another under standardized fire conditions (higher R) might in fact perform worse under a realistic fire (lower DHP).

Insulation Criterion

The discussion so far has focused on the load bearing capacity criterion under fire. Typically, the fire performance of building members may be evaluated based on more than one criterion. For instance, the insulation criterion can also be critical when assessing the fire performance of a concrete slab or wall. It is interesting to examine how this insulation criterion is affected by the cooling phase of a fire.

The Eurocode states that the following requirements apply to the verification of the separation function for the average temperature rise, assuming that the normal temperature is 20°C:

(a) The average temperature of the unexposed side of the construction should be limited to 160°C during the heating phase until the maximum gas temperature in the fire compartment is reached.

(b) The average temperature of the unexposed side of the construction should be limited to 220°C (recommended value) during the decay phase.

Numerical analyses are used to evaluate the heat transfer across the depth of a concrete slab subjected to fire at its lower face. To satisfy the criterion related to the heating phase for 120 minutes, the minimum required thickness is found to be equal to 117 mm. This means that a concrete slab of 117 mm subjected to ISO fire at its lower face reaches an average temperature of 160°C after 120 minutes. If the simulation is continued with the decay phase of the fire (where the cooling phase after 120 min follows the parametric Eurocode fire model), the average temperature of the unexposed side reaches up to 252°C. In order to satisfy the criterion related to the decay phase, the slab thickness needs to be increased to 138 mm, see Figure 4.
Inversely, if the slab has a fixed thickness of 117 mm, the maximum duration of the heating phase that allows satisfying the criterion during the decay phase is 85 min. Therefore, the 117 mm slab has a DHP of 85 min with respect to the insulation criterion (decay phase requirement), whereas it has a R of 120 min (heating phase requirement). Note that those analyses are based on the assumption that the decay phase of the natural fire is according to the Eurocode parametric fire model.

TABLE I. INDICATORS DHP AND R FOR DIFFERENT STRUCTURAL MEMBERS

Time in min	**RC column**		**Steel Column (P1)**		**Steel Column (P2)**		**Timber Beam**	
Load Ratio	**DHP**	**R**	**DHP**	**R**	**DHP**	**R**	**DHP**	**R**
60%	60	88	35	54	72	108	15	51
50%	89	120	43	61	84	120	26	71
40%	116	164	50	69	97	135	39	92
30%	168	218	60	79	111	153	53	116

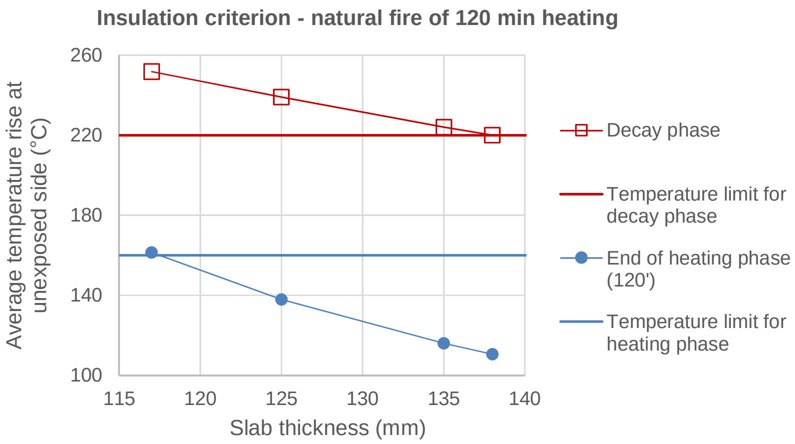

Figure 4. The insulation criterion in Eurocode (average temperature at the unexposed side) for a concrete slab is more severe during the decay phase than during the heating phase.

DISCUSSION

The indicator DHP quantifies the sensitivity of structural members to fire decay phases. The characterization of a structural member by the couple of indicators (DHP, R) can prove useful and have practical implications for the fire brigades.

Figure 5 shows on a timeline the standard measures DHP and R for the steel column (P1) and the timber beam subjected to a 50% LR. The timber beam has a higher R but a lower DHP than the steel column. These measures suggest that, should an intervention of the fire brigade take place between 26 min and 43 min after the time of flashover (scenario b), the timber beam would experience a delayed failure, whereas the steel column would not fail. This conclusion could not be obtained based on the values of R. If R was the only indicator considered, one would disregard entirely the higher sensitivity to cooling phases of the timber beam.

On a conceptual level, the couple of indicators (DHP, R) allows dividing the post-flashover time domain in three parts for a structure in fire:

1) The first part of the time domain starts at the flashover and lasts until the time corresponding to DHP. In this part, the structure is theoretically safe. It is able to withstand the effects of the fire and, should the gas temperature start cooling down in this part, the structure would then survive indefinitely.
2) The second part of the time domain lies between the times corresponding to DHP and R. In this part, the structure is still standing even if the gas temperature has been continuously increasing from the flashover. However, if the fire is still in its heating phase, the structure has been affected to such an extent at that time that it will fail even if the fire starts decreasing soon thereafter.
3) The third part of the time domain starts at the time corresponding to R. In this part, if the gas temperature has not started cooling down yet, the structure is theoretically collapsed.

This means that, for the fire brigades, the DHP of a structure is a key information. When arriving on site, they can relate the DHP with the information they can get about the duration of the fire and use it for mitigating the risk during their intervention.

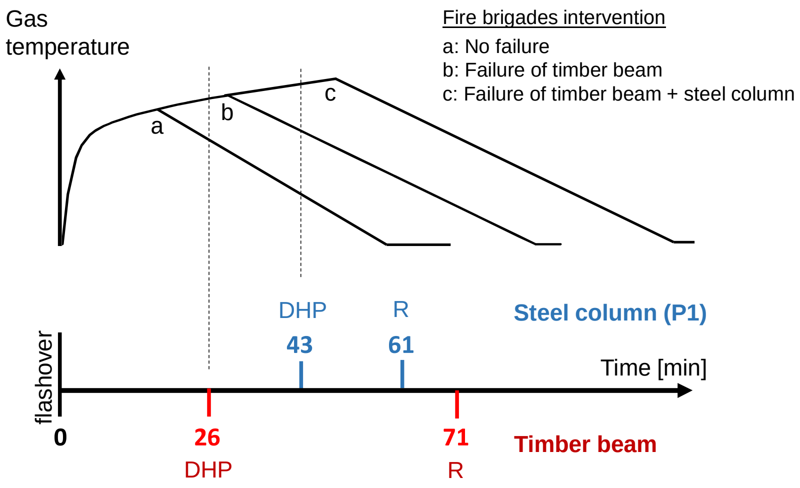

Figure 5. DHP and R for a steel column and a timber beam, for an applied LR of 50% on the members.

CONCLUSION

This research aims at better comprehending and characterizing the fire response of structural members during the decay phases. A methodology has been developed to determine the maximum duration of heating phase of a natural fire that can be withstood by a member without leading to delayed failure. This leads to the definition of a novel standard measure, called Duration of Heating Phase (DHP). The DHP has a straightforward interpretation for fire brigades: if their intervention (which ends the heating phase) starts earlier than the DHP of the structure, the structure is theoretically safe; if it starts later, they should be particularly careful as the structure is expected to eventually collapse even though the gas temperatures are decreasing.

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