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Computational study on prestressed concrete members exposed to natural fires

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ABSTRACT

The present paper is aimed at investigating the structural behaviour in bending of prestressed concrete members exposed to natural fires, i.e. fires with a heating and a cooling phase. The fire scenarios considered are characterized by a heating phase that coincides with the ISO834 standard fire and a linear cooling branch. To accurately track the structural behaviour, the usual constitutive models for concrete, ordinary and prestressing steel at high temperature are adapted to account for the different behaviour of the materials upon unloading and cooling. Parametric analyses are carried out on typical prestressed sections (an I-girder and a double-tee), in order to highlight the detrimental effect of longer fire durations (up to 120 min) and lower cooling rates (3 °C/min) as well as the variability of the structural behaviour with the variation of the load level.

The results show that in members characterized by massive sections (I-girder in the present study) and exposed to natural fires, limiting the attention to the heating phase is not sufficient, as the maximum temperature in the prestressing steel may be reached long (even hours) after the onset of cooling (in accordance with tests reported in the literature), leading to delayed failure. Moreover, within the range of variation of the cooling rate (3–10 °C/min, ranging from slow to fast cooling) and load level ($M/M_u = 0.15–0.30$, ranging from low to high load ratio), the structural behaviour exhibits significant variations in the cooling phase of the fire, from an almost complete recovery of the initial configuration to runaway failure.

1. Introduction

Prestressed concrete members are widely used in a variety of structural applications. In comparison to ordinary reinforced concrete members, they offer several advantages, such as higher speed of construction and larger span-to-depth ratios [1]. The use of prestressing allows improving the mechanical performance of reinforced concrete members, by limiting cracking phenomena, and thus increasing the stiffness. Optimization of structural behaviour, which is typical of the prefabrication industry where prestressing is widely used, makes it also possible to reduce the overall dimensions of the members: in fact, several types of prestressed concrete members available on the market are characterized by thin webs.

In comparison to reinforced concrete members, prestressed concrete members are more sensitive to fire [2]. In detail: (a) cold worked prestressing steel is more sensitive to high temperatures than ordinary hot rolled steel; (b) the reduced thickness that characterizes prestressed concrete members results in lower steel protection: this is particularly true in structures that were built before the publication of the current standards, where the typical prescriptions concerning concrete cover are not respected; and (c) the lack of connectivity between the structural elements (which is directly related to construction time savings) results in statically-determinate structures, where the redistribution of the internal forces is not possible, to the detriment of the structure's global stability. Finally, prestressed concrete members in demanding structures (such as industrial facilities) are subjected to a higher risk of fire exposure, because of the higher availability of combustible materials. As previously mentioned, this is particularly dangerous for several existing structures, which do not comply with current code provisions as regards concrete cover.

The first systematic researches on the fire resistance of prestressed concrete members were reported by Troxell [3], who compared fire resistance tests conducted in Europe and in the United States. A basic finding was that prestressed members could resist fires lasting up to 4 h, by providing a suitable concrete cover. Moreover, the beneficial effects of the continuity over intermediate supports and of axial restraints were pointed out. Finally, no major differences were found between pre- and post-tensioned members (with bonded tendons). Another systematic

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research on the behaviour of prestressed concrete members exposed to fire was carried out by Gustaferro [4], who studied the behaviour of prestressed concrete members exposed to standard fires. Once again, the key role played by cover and restraint conditions was pointed out. Moreover, for continuous (and thus redundant) structures, the importance of providing negative reinforcement over the supports to allow moment redistributions was highlighted. A summary of the fundamentals concerning precast prestressed members can be found in Ref. [5]: as regards simply-supported members without end rotational restraints, a simple and straightforward method to determine the structural end point (and thus the fire resistance) is devised, which consists in comparing the applied moment with the moment capacity in the most stressed section (midspan).

In recent years, post-tensioned flat slabs with unbonded tendons and prestressed hollow core slabs have been the most investigated prestressed members among those available on the market. The reason for this is to be found in the high sensitivity to fire of the former (especially if there is no ordinary reinforcement to provide additional flexural capacity), and in the shear-deficient behaviour of the latter (since no transverse reinforcement is present).

One of the most significant studies on bonded and unbonded post-tensioned concrete slabs was carried out by Ellobody and Bailey [6], who investigated the influence on the structural behaviour of several parameters, such as aggregate type, duct material and restraint conditions. The results showed that the presence of boundary restraints and the use of aggregates without silica are beneficial. As for the duct material, slabs with metallic ducts exhibited larger deflections than those with plastic ducts.

Regarding hollow-core slabs, they have been the object of several studies in recent years [7–9]. The results show that the thermal and structural response can be adequately simulated by means of numerical models (despite some peculiarities, such as the presence of voids with the ensuing problems related to heat transfer), and that factors such as load level, concrete cover and hole size considerably affect fire resistance. Moreover, the failure of hollow-core slabs is primarily governed by the fire scenario, or, in fact, by strength and stiffness loss in the strands, which results in a decrease of the load-bearing capacity and an increase of deflections. Finally, as previously mentioned, another critical issue in hollow-core slabs is the shear strength [10], in consideration of the fact that these elements do not have transverse reinforcement.

More recently, extensive fire resistance experiments on nine bonded prestressed continuous concrete beams were performed by Hou et al. [11], investigating the influence of several variables, including concrete cover, load level and prestressing level. The test results proved that the influence of load level and concrete cover is very significant. Moreover, as should be expected, continuous beams are characterized by a higher fire resistance than simply supported beams.

All the aforementioned research works are focused on the standard fire (that is usually adopted in laboratory testing), i.e. a post-flashover cellulosic fire without cooling phase. When focusing on buildings consisting of prestressed concrete members, however, natural fires are undoubtedly more significant, mainly because of the large room and variable amount of fire load that characterizes this type of structures [12]. Within this context, in the design phase it may be advantageous from the economic point of view (and also more realistic) to resort to natural fires, based on the actual geometry of the compartment and on the available fire load. As a matter of fact, the most recent version of EN 1991-1-2 [13] allows resorting to performance-based design through the use of natural fires, taking as many significant parameters as possible into consideration, so as to eventually yield a more accurate representation of the real behaviour. Within this framework, it is clear that the structural behaviour of prestressed concrete members exposed to natural fires is definitely of interest for the designer.

Research works dealing with natural fires have been limited so far. The experimental research carried out by Gales and Bisby, reported in Ref. [14], who investigated the response of continuous and restrained post-tensioned concrete slabs, with unbonded tendons, exposed to natural fires, should be mentioned. Despite the relatively simple structural system, the deflection seems to be governed by several parameters, and is not yet fully understood.

More recently, the critical factors influencing the residual behaviour of reinforced concrete beams were investigated by Kodur and Agrawal [15]: a finite element model was set up to account for different material properties of both concrete and reinforcing steel, during the fire exposure phase (heating and subsequent cooling) but also during the residual phase (post-cooling phase). It was clearly pointed out that in natural fires the maximum ambient temperature does not give a clear indication of the maximum temperature in the rebars. As a matter of fact, the maximum temperature in the steel depends on the duration of the heating phase and on the cooling rate.

To date, no simplified methods are available for assessing the fire resistance of reinforced concrete members exposed to natural fires. EN 1992-1-2 [16] indicates the possibility of using the 500 °C isotherm method, but only if the thermal profiles inside the member are similar to those caused by the standard fire: this is certainly not the case in the cooling phase, when the external layers undergo cooling while the internal layers are still hot. As a matter of fact, the numerical studies carried out so far on concrete members all took advantage of advanced calculation methods, by using commercial softwares and performing demanding 3D thermo-mechanical analyses [15,17]. Simple approaches are thus needed, in order for practitioners to take advantage of the possibilities offered by the use of natural fires, without the need of computationally-demanding analyses (even in the case of members with simple structural layout).

The objective of this paper is to investigate the structural behaviour of simply supported prestressed members exposed to natural fires, in order to highlight the possibility of delayed failure (i.e. in the cooling phase of the fire), and to clarify the role played by duration of the heating phase, load ratio and cooling rate. To this end, the typical sectional approach used for simply supported concrete members, both pre- and post-tensioned with bonded tendons, is used. The constitutive models of concrete, ordinary and prestressing steel are suitably modified to properly take into account the different irreversible phenomena that take place in a full heating-cooling cycle. The modelling approach is validated against an experimental test showing satisfying agreement. The role of the different parameters coming into play is then investigated by means of parametric analyses carried out on two typical prestressed concrete sections, namely an I-girder and a double-tee, in order to highlight the peculiar features that characterize the structural behaviour of the studied members exposed to natural fires.

2. Analysis procedure

The failure of simply supported prestressed members in fire can be identified by taking into consideration the most stressed section, i.e. midspan (Fig. 1). This criterion is typically used for checking the safety under standard fires [4,5]. The same basic concept is applied in the following to the case of natural fires to identify the structural end point, i.e. the situation when the moment capacity is overcome by the applied moment. For simply supported members under distributed loads (or similar) and uniformly exposed to fire, failure is still governed by the most stressed section.

To this end, a sequentially-coupled thermo-mechanical analysis is carried out on the most stressed section. The first step is to perform a 2D thermal analysis of the section. In the numerical applications presented in the following, the thermal analyses were performed by means of the commercial software ABAQUS 6.16 [18]. Clearly, the thermal field could be worked out equally well by means of other softwares, or taking advantage of other approaches, such as the approximated analytical expressions by Wickström [19].

The output of the thermal analysis, consisting of the temperature values, is used as input for the mechanical analysis, in order to work out