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On reliable predicting risk and nature of thermal spalling in heated concrete

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ABSTRACT

Thermal spalling is a deterioration phenomenon which is of fundamental importance during durability analysis of concrete structures exposed to high temperature, e.g. during a fire. To assess the risk of this damage mechanism for a real concrete structure, numerical simulations are usually applied since experimental tests are very costly. Some aspects related to predicting thermal spalling by means of numerical modelling of chemo-hygro-thermal and damage processes in heated concrete, are presented in this work. First, we propose a spalling index, validate it with some experimental results and show how it can be used in the quantitative assessment of spalling risk. Then, the results of numerical simulations of a slab, made of two types of concrete (NSC and HPC), heated with three different rates, are discussed from the energetic point of view in order to indicate the main physical causes and predict the nature of thermal spalling: slow, rapid or violent. The presented results allow to assess the contribution of energy due to constrained thermal strains and compressed pore gas into the thermal spalling for different types of concrete heated with different rates.

1. Introduction

Reliable prediction of durability and safety of concrete structures during a fire is of great practical importance, especially when designing concrete elements of high rise buildings or concrete lining of tunnels [1–3]. During heating of such structures, especially with a high rate, their integrity is endangered by the so-called thermal spalling. This paper addresses some issues concerning numerical simulations and prediction of this phenomenon (i.e. the interpretation and application of the numerical results), providing some possible solutions. The phenomenon of spalling is briefly described in Section 2. To assess the risk of thermal spalling occurrence for a concrete structure exposed to heating under given conditions, the evolutions of temperature, moisture content, pore

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pressure in the material and the degradation of its mechanical properties, should be known. To predict them with a sufficient accuracy, rather complex mathematical models are required taking into account the multiphysics nature of the system under consideration. Several models of such type were developed in the last twenty years, see e.g. [1,4–14]. One of the state-of-the-art mathematical models of concrete at high temperature was developed by Gawin et al. [9,11,12]. It was widely validated experimentally within some European Projects, e.g. *High Temperature Concrete – HITECO, Upgrading Existing Tunnels – UPTUN*. The model is based on Multiphase Porous Media Mechanics (MPMM). It takes into account several components and phases in the pore network, phase changes, the interactions between physicochemical processes, the transition through the critical point of water [8], as well as the most important material nonlinearities [9]. In Section 3 the main assumptions of this mathematical model are briefly summarized. In Section 4 we describe how the results of numerical simulations can be interpreted in order to assess quantitatively the thermal spalling risk. The analysis is based on the data from real laboratory tests, which are first numerically simulated and then appropriately elaborated. The evolutions of temperature, gas pressure, mechanical damage (concrete cracking) and constrained elastic energy fields are analyzed, in order to propose and validate a parameter (called spalling index) for assessment of the spalling risk occurrence in heated concrete.

Section 5 presents an analysis of the energy accumulated and then released during heating (with three different rates) of a slab made of two types of concrete, what allows to indicate the main physical causes of thermal spalling and to predict its nature (slow or violent or explosive) in the considered cases.

In the last section, some concluding remarks concerning the proposed energetic analysis of the results of numerical simulation are presented for predicting slow/violent/explosive nature of thermal spalling in heated concrete structures.

2. Thermal spalling of concrete

Spalling, in its most general form, is defined as the violent or non-violent breaking off of pieces (or layers) of concrete from the surface of a structural element when it is exposed to rising temperatures, e.g. during a fire [15–18]. A common classification of spalling phenomena leads to identifying the following five main types [16]: Violent Spalling, Sloughing Off, Corner Spalling, Explosive Spalling and Post-Cooling Spalling. Among them, one of the most dangerous is Explosive Spalling, which results in serious loss of material. Explosive Spalling is a very violent form of thermal spalling characterized by the forcible separation of pieces of concrete (the thickness of spalled-off concrete layer is usually of 0.5–2.0 cm [2]), accompanied by a typically loud explosive noise. It normally occurs above the temperature of 200 °C and is stochastic.

For concrete specimens from the same batch and under identical conditions, some could spall while others do not, e.g. [2,11]. Under suitable conditions, in terms of mechanical (external load stress) and thermal load (heating rate), all concretes can show the capacity for thermal spalling.

Spalling is due to different concomitant coupled processes: thermal (heat transfer), chemical (dehydration of cement products and the resulting water release), hygral (water mass transfer, in both liquid and vapor form, and pore pressure build up) and mechanical ones (release of the elastic energy stored during heating and loading and buckling effects in the external layer).

Velocity of spalled-off concrete pieces in fire conditions often exceeds 10 m/s [2], and for explosive spalling even 15 m/s. Considering the possible thickness of spalled-off concrete pieces (0.5–2.0 cm), the kinetic energy of 1 m^2 spalled concrete layer may reach 500–2000 J/m^2, and for explosive spalling even exceed 4500 J/m^2 [11]. Considering possible dimensions and mass of spalled-off concrete pieces (even greater than 0.1 kg), kinetic energy of a single piece may exceed 1 J, what creates the threat to people.

The extent, severity and nature of spalling occurrence are extremely varied. Spalling may be insignificant in amount and consequence, such as when surface pitting occurs. Alternatively, it can have a serious effect on the fire resistance of a structural element because of extensive removal of concrete which exposes the core of the section, and the reinforcing steel or tendons, to a more rapid rise of temperature, thus reducing the load-bearing cross-sectional area, like in the case of explosive spalling. These situations are emphasized and then much riskier in the case of High Performance and Ultra High Performance concrete. Their compactness and special composition result in high values of pore pressure and in a brittle behaviour of the matrix. To reduce the risk of concrete thermal spalling, some preventive measures may be applied [19,20], i.e. concrete of higher permeability (i.e. with higher w/c, without micro-silica) and/or addition of polypropylene fibres to concrete mix (up to 3 kg/m^3) in order to reduce pore pressure; protective layer made of a highly porous material (e.g. shotcrete or special plates) – to reduce heating rate of structure surface; aggregates of low thermal expansion – to reduce concrete cracking during heating. Then special protective steel nets may be applied on a structure surface to protect against spalled concrete pieces having high velocity (kinetic energy) [19].

3. Modelling thermal spalling

The model used in this work was formulated first in the framework of Hybrid Mixture Theories, and then extended to the Thermodynamically Constrained Averaging Theory [21], by considering cementitious materials as multiphase porous media and by supposing that all the phases and components are under equilibrium conditions [8,10,11]. The most important mutual couplings and material nonlinearities, as well as different physical behaviour of water above its critical temperature are taken into account. The model was extensively validated and its constitutive relationships were experimentally determined, e.g. [9,11,17]. The state of the material is described by 4 primary physical quantities, which are also the degrees of freedom in the FE code: gas pressure, p^g, capillary pressure, p^c, temperature, T, and displacement vector, $\mathbf{u}$. In addition, there is a set of internal parameters describing the advancement of the dehydration and deterioration