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# Coupled thermo–mechanical interface model for concrete failure analysis under high temperature

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**Abstract**

A thermo–mechanical interface model for failure analysis of concrete subjected to high temperature is presented in this work. The model is an extension of a fracture energy-based interface formulation which now includes thermal damage induced by high temperature and/or fire. The coupled thermal–mechanical effect in the interface model is taken into account through the formulation of a temperature dependent maximum strength criterion and fracture energy-based softening or post-cracking rule. In this sense, the strong variation of concrete ductility during failure processes in mode I, II or mixed types of fracture is described through the consideration of temperature dependent ductility measures and of the specific work spent in softening. Moreover, a temperature-based scaling function is introduced to more accurately predict the thermal effect affecting the interface strength and post-cracking response. After outlining the mathematical formulation of the interface model, numerical analyses are presented to validate its soundness and capability. A wide range of experimental results, available in the scientific literature, are analyzed at both material and structural scale of analysis using the proposed interface model and in the framework of the discrete crack approach. The results demonstrate the predictive capabilities of the proposed interface constitutive theory for temperature dependent failure behavior of concrete.


*Keywords:* High temperature; Fracture; Interface; Cracking; Discontinuous approach; Coupled thermo–mechanics

## 1. Introduction

The exposure to high temperature and fire is one of the most destructive actions that concrete material may suffer [1]. Under elevated temperature, the chemical composition, the physical structure as well as the moisture content of concrete drastically change [2,3]. Such changes deal with the dehydration of hardened cement paste and the conversion of calcium hydroxide into calcium oxide with the subsequent release of bond water to become free water [4,5]. As a consequence, during and after long term exposure to high temperature, the most important mechanical features of concrete can be adversely affected. Experimental evidences demonstrate the substantial changes of cohesion, tensile

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and compressive strengths [6,7], Young modulus and Poisson's ratio [8,3] of concrete materials due to the long term exposure to fire and/or high temperature.

The relevance of high temperature exposure and its severe consequences for the safety conditions and integrity of concrete structures is well recognized by several design codes which, at the same time, provide simplified guidelines or rules for the concrete design under elevated temperature, see a.o. the ACI-216.1-07 [9] and EN-1992-1.2 [10].

Several theoretical models are currently available in the scientific literature to simulate the failure processes of concrete structures subjected to the combined action of high temperatures and mechanical loads. Most of the existing proposals follow the so-called smeared crack approach. As a reference we may report the works by Nechnech et al. [11] who describe an elastic–plastic damage model for plain concrete subjected to high temperature, by Schrefler et al. [12] and Pont et al. [13] who take into account the thermo-hydro-mechanical effect in the description of concrete behavior at elevated temperature and also by Tenchev and Purnell [14] whereby an application of a damage constitutive theory is performed for predicting spalling phenomena in concrete.

In this work, and in the framework of the discrete crack approach, an elasto–thermo–plastic interface model is proposed to predict the concrete cracking and failure behavior when subjected to combined thermo–mechanical actions under high temperature.

Zero-thickness interface elements, formulated in terms of contact stresses versus opening relative displacements, have been historically employed for modeling both the response behavior of material discontinuities such as mechanical contacts [15,16], bonds [17–19] and crack evolutions in quasi-brittle materials like concrete [20,21]. Also, several plasticity-based interface formulations have been proposed to predict failure behaviors of discontinuities in soil/rock mechanisms [22]. One of the most frequent use of interface elements in computational concrete mechanics is related to mesoscopic failure simulations. Thereby, the use of non-linear interfaces can be limited to model the aggregate-mortar joints [23]. This strategy is combined with the use of non-linear continuum models for the mortar in between aggregates. Alternatively, the use of non-linear interfaces may involve both the aggregate–mortar and the mortar–mortar joints while linear elastic models are considered for the continuum mortar elements. This strategy was proposed by Lopez et al. [24,25] for rate independent failure behavior analysis of concrete and by Lorefice et al. [26] for time dependent simulations of concrete failure behavior. Recently, the approach and interface model by Lopez et al. [24,25] was extended by the authors, see [27–29], to model the behavior of mortar-to-mortar interfaces of fiber reinforced cementitious composites. Regarding the modeling of transport problems in concrete through interfaces we may refer here to the works by Segura and Carol [30] who take into account moisture diffusion problems and coupled analysis, the fluid flow through discontinuities by Idiart et al. [31] which is related to coupled hygro-mechanical analysis of concrete drying shrinkage, the proposal by Idiart et al. [32] whereby a chemo-mechanical analysis of concrete cracking and degradation due to external sulfate attack is performed, and by Liaudat et al. [33] who outline a diffusion–reaction model for Alkali–Silica Reaction (ASR) processes.

The elasto–thermo–plastic interface model proposed in this work is used in computational analysis of concrete materials and related structures when subjected to long term exposure of high temperatures. The interface model is formulated within the general framework of the flow theory of plasticity which is embedded in fracture mechanics concepts to account for the objectivity of the fracture energy release during post-peak regimes of concrete. Based on the original model by Carol et al. [34], the interface formulation is extended to take into account the temperature effects in the maximum strength criterion and in the softening rules under both mode I and mode II types of failure, which are differently and independently treated in the constitutive model. A relevant novel aspect in this interface model formulation is the inclusion of the thermal effects in the softening rules. It is worth mentioning that under monotonic thermo–mechanical loading, the increasing damage of cohesive-frictional materials like concrete gives rise to the development of macroscopic cracks representing first order discontinuities of both displacement and thermal fields. Therefore, the fixed (discrete) crack approach, based on coupled thermo–mechanical interfaces, represents the most straightforward and direct procedure to model jumps of velocities and thermal rate fields in quasi-brittle materials like concrete. A fundamental advantage of this approach, based on zero-thickness interfaces, is the related objectivity of the Finite Element (FE) predictions of localized failure processes regarding mesh-size and orientation, provided when a sufficient and appropriated mesh density is considered. An additional advantage of zero thickness interfaces is the inexistence of element locking which constitutes a relevant shortcoming of "thin-layer" FEs.

It is important to remark that strength criterion degradation due to temperature effects is strictly related to the interaction between drying shrinkage, high temperature and cement (de-)hydration. Actually, a classical way for modeling drying processes in porous media like concrete deals with calculating the moisture diffusion which takes place in