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Statistical modeling of cracking in large concrete structures under Thermo-Hydro-Mechanical loads: Application to Nuclear Containment Buildings. Part 1: Random field effects (reference analysis)

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ABSTRACT

In the case of homogeneously distributed stress loads, the intrinsically random distribution of voids and defaults in the concrete volume is one of the driving factors of strain localization, crack initiation and propagation. In this contribution, a macroscopic approach based on a stochastic and continuous damage model is suggested to describe concrete's cracking under simultaneous Thermo-Hydro-Mechanical (THM) loads. Statistical and energetic size effects at the structural scale are taken into account by (a) reducing the mean tensile strength of the considered concrete's effective volume according to a probabilistic-based Size Effect Law (SEL) adapted to local models, (b) performing an energy-based regularization for mesh independency and (c) describing the spatial distribution of the Young's modulus property using autocorrelated lognormal Random Fields (RF). The proposed strategy is applied to the first lift of the VeRCoRs Nuclear Containment Building mock-up (the gusset) which undergoes, at early age, restrained endogenous and thermal shrinkages and, during the Operational Phase (OP), several pressurization tests leading to possible concrete cracking and damage increase. Different cracking patterns are predicted and their evolution in time due to the concrete's ageing phenomena is analyzed. The predicted numerical results (i.e. temperature, strains and cracking patterns) are in line with in situ observations and support the need for statistical description of concrete cracking rather than classical deterministic analyses.

1. Introduction

The prediction and modeling of concrete cracking in large concrete structures, especially those with a containment role such as dams and Nuclear Containment Buildings (NCB), is a critical issue to the assessment and prediction of their state of serviceability and longevity. For those applications, it is crucial for the modeling strategies to describe accurately, first, the global structural response (i.e. the structural behaviors' evolution in time and size effects) under realistic Thermal, Hydric and Mechanical (THM) loads and second, but mostly, the local response related more to the concrete's heterogeneous nature and ageing behavior in time (i.e. crack initiation, opening and spacing).

For such large structures, cracking may occur during the first hours after concrete casting (early age phase) Conceição et al., 2014; Briffaut et al., 2011; Benboudjema and Torrenti, 2008. As it hardens, restrained early age (thermal and endogenous) shrinkages develop leading to possible critical tensile stresses. This damage state can be altered later on as the concrete ages due to the continuous creep and drying under operational loads. With that regard, numerical analyses covering both the early age and operational phases are lacked, despite the existence of adapted numerical tools (as shown later on). At the structural scale and to the author's knowledge, existing contributions (for example Foucault, 2012; Pape, 2003; Asali et al., 2016) seem to overlook the effects of early age damage on the long term behavior of concrete in NCBs and analysis in (Conceição et al. (2014), Briffaut et al. (2011), Benboudjema and Torrenti (2008), Briffaut et al. (2012a)) are limited to the early age phase without exploring its effect on the long term behavior. For the long term simulations, it is presumed that early age damage does not influence the global and long term behavior nor influence, locally, the stress distribution around a cracked area. These are, indeed, strong and questionable hypotheses that are yet to be attested in the presence of early age cracks that are, paradoxically,

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Nomenclature

CI	Confidence Interval
EHM	Equivalent Homogenized Material
FE	Finite Elements
NCB	Nuclear Containment Building
OP	Operational Phase
PDF	Probability Density Function
POP	Pre Operational Phase
RF	Random field
RH	Relative Humidity
RSV	Representative Structural Volume
SEL	Size Effect Law
SSEL	Statistical Size Effect Law
THM	Thermo-Hydro-Mechanical
VeRCoRs	French acronym for ‘’ VErification Réaliste du COnfinement des RéacteurS ‘’ meaning ‘’ Realistic assessment of the nuclear reactors' tightness “
WL2	Weakest Link and Localization

supposed to be critical for the delayed performance of a large structure. Therefore, a global analysis covering both the early-age and delayed behavior phases is needed to, first; accurately describe the cracking patterns of concrete and their evolution in time under realistic THM loads and, second, account for the early age damage while computing the delayed behavior under operational loads.

Depending on the selected modeling scale, various strategies exist in the literature to model concrete cracking and introduce some randomness with regards to cracks position and propagation. Such uncertainty is due to the heterogeneous nature of concrete and random distribution of voids and defaults within its volume at the micro/*meso*-scopic scale. At this (mesoscopic) scale, some authors consider concrete as a biphasic material of which crack initiation is due to the contrast in terms of mechanical properties between the cement paste and aggregates (Briffaut et al., 2013) and its associated randomness is mainly due to the random spatial distribution of the aggregates' size (Nguyen et al., 2010). Due to the required spatial discretization, which needs to be as small as the smallest aggregate's size, the computational time is only reasonable when small and intermediate specimen scales ($\sim 10^{-2}$ m) are considered. The use of mesoscopic approach for large scales (~ 1 m) remains numerically hard to achieve which justifies the interest in macroscopic approaches for large concrete structures (~ 10 m) Conceição et al., 2014; Asali et al., 2016; Briffaut et al., 2011. By “macroscopic”, it is meant that concrete is modeled by an Equivalent Homogenized Material (EHM) of which the properties are representative of all concrete's phases (cement paste, aggregates, voids and defaults). Classical methods consist of using a homogeneous field to describe concrete's mean properties. This shows accurate results when the global structural response is of interest (concrete's thermal behavior (thermo-hydration) Briffaut et al., 2012a; Briffaut et al., 2012b; drying (Mensi et al., 1988; Bažant and Najjar, 1972) and viscoelastic response to mechanical loadings (Foucault, 2012). However, for the concrete's local behavior and particularly its cracking process, the use of a homogeneous field leads to a constant and deterministic cracking pattern (if any) as it cannot reproduce the heterogeneity of concrete observed at the *meso*-scale. To overcome such limitation, some authors suggest using random fields (RFs) to describe the spatial distribution of concrete's mechanical properties (especially the Young's modulus (de Larrard et al., 2010) and the tensile strength (Rossi and Wu, 1992; Tailhan et al., 2010), others offer to couple homogeneous or RFs with stochastic approaches (Llau et al., 2016) to deduce a distribution of the cracking patterns. In all cases, the use of RFs requires numerous simulations (as many as the considered random field realizations) which might also lead to heavy computational time. So far and to the author's knowledge, being limited to the mechanically loaded concrete, the random field's pertinence and its capacity to predict all cracking patterns is yet to be demonstrated for simultaneous THM loads and yet to be positioned within a global structural modeling approach covering both the early-age and long term phases.

Another important structural aspect when dealing with concrete cracking in large concrete structures is size effects (Bažant, 1999). It can be defined, generally, as the dependence of the concrete's strength to its effectively stressed volume (Rossi et al., 1994). A recurrent approach to define such dependence is the probabilistic Weibull theory (Weibull, 1939); a so called probabilistic ‘’ Size Effect Law’’ (SEL) is then derived based on the weakest link theory. Being a 1D and fragile law, it stipulates that the tensile strength tends to zero as the structural volume increases (Bažant, 1999). This obviously contradicts experimental observations showing that beyond a certain maximal structural characteristic length, the tensile strength of concrete has a constant and non-null lowest value (Sellier and Millard, 2014). Eventually, this questions the hypotheses of a 1D and fragile SEL. Indeed, for concrete, the SEL should also account for the stress distribution (which can be 3D) and mostly for its quasi-brittle nature. By definition this leads to a non-local formulation of the SEL where a finite and limited zone is considered to define the maximum domain of stress distribution and then its associated structural tensile strength as shown for example in the WL2 model (Sellier and Millard, 2014). Nevertheless, even if they are based on a probabilistic approach, the previous WL2 SEL provide a given tensile strength for a given structural volume and a given stress distribution. When applied at the structural scale, the resulting cracking pattern remains then ‘’deterministic’’ defining the mean model's response (in the sense of a Maximum Likelihood Estimation) for a Weibull distribution associated with the tensile strength. In other words, the SEL – as presented in Bažant (1999), Sellier and Millard (2014) – accounts for the energetic part of size effect and cannot reproduce the statistical size effect which might be achieved thanks to the use of RF. Reciprocally and as used in the reference works considered for this contribution (de Larrard et al., 2010; Rossi and Wu, 1992; Tailhan et al., 2010), the use of RF cannot fully replace the use of SEL since they only induce a variation around (and do not reduce nor change) the mean response. In that sense, SEL and random fields are complementary and are both needed for a statistical description of cracking at large structural scales.

Consequently, the purpose of this contribution is threefold:

(a) Define a statistical modeling strategy of concrete cracking under simultaneous THM loads: The general weakly coupled THM strategy is detailed in the first section §2. The descriptive equations are provided for both the concrete's behavior at early age and as it ages when exposed to hydric fluxes and prestressing loads. Since several simulations are foreseen (due to the use of RF), regularized local damage models (Mazars et al., 2015) are preferred herein compared to non-local ones (Sellier and Millard, 2014; Giry et al., 2011; Breysse, 1990) to diminish the required computational time. The second section §3 focuses on the modeling of size effects (both energetic and statistical): A Statistical Size Effect Law (SSEL) is suggested for local damage models in order to define the mean tensile strength of large structures and is then coupled to spatially correlated RF associated with the Young's modulus property.

(b) Validate the statistical strategy based on a Representative Structural Volume (RSV) under realistic THM loads: In section §4, the proposed statistical modeling strategy is applied to the VeRCoRs (Corbin and Garcia, 2015) Nuclear Containment Buildings (NCB) using original and realistic TH boundary conditions issued from in situ measurements. The case study is limited to the gusset's RSV