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Effects of residual stresses on the tensile fatigue behavior of concrete

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ABSTRACT

The influence of Eigenstresses due to drying shrinkage on the development of residual deformations characterizing the tensile fatigue behavior of concrete is analyzed. During the loading phase the Eigenstresses are locally released around the cracks inducing a mismatch between the crack surfaces which inhibits a perfect crack re-closure. The analysis is performed by means of a 2D mesoscale implicit finite-element model. The shrinkage strain is first applied determining the development of a diffused micro-damage and then quasi-static loading–unloading tests are simulated. Different microstructures and different values of shrinkage strain are considered. The results show that the presence of residual stresses increases the amount of total dissipated energy and naturally leads to the development of residual deformations. However, the obtained values are only a portion of the residual deformations experimentally measured. The possible concomitant effect of another mechanism, namely the formation of debris at a small scale, is therefore discussed.

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1. Introduction

Concrete is a material with a very complex mechanical behavior, that cannot be easily described by a simple constitutive law. Some of its peculiarities are: (*i*) a completely different behavior in tension and compression, with different peak stresses and dissipated energies; (*ii*) a mechanical response highly affected by the lateral confinement, with the consequent need of defining different constitutive laws for two- and three-dimensional problems [1,2]; (*iii*) a response under cyclic loadings characterized by a progressive development of damage [3]; and (*iv*) a dependence on the loading strain rate that is not yet fully understood [4]. This complex mechanical behavior is a consequence of the micro-structural heterogeneity of concrete, and the wide kaleidoscope of sizes of its ingredients which lead to interactions among mechanical phenomena, namely damage, cracking and contact, at different scales. An accurate and reliable modeling of concrete is still a challenge, and the derivation of empirical models from experiments remains the method of choice to define the constitutive behavior of concrete.

The analysis of the cyclic behavior in tension is a clear example of this kind of approach. It has been studied since the '80s of the past century, mainly from the experimental point of view [3,5-7]. The typical curve obtained from a deformation-controlled uniaxial tensile test with post-peak unloading and reloading cycles is shown in Fig. 1. Two main features stand out from this curve. First, the unloading path does not pass through the origin of the diagram since it intersects the abscissa with a residual deformation and, therefore, a compression stress has to be applied to recover the original condition of zero displacement. Second, the reloading path does not return to the same point of the envelope curve where it started from, but to a point which belongs to a lower stress. These phenomena are due to the damage which is developed during the loading–reloading loops, and make the definition of a constitutive law for the fatigue behavior complicated. Moreover, they depend on the position of the starting point of the unloading path along the softening curve. In particular, the residual deformation increases by delaying the starting point of the unloading path along the envelope curve. Such a residual deformation, or crack opening, has a fundamental practical relevance in the life of concrete structures since if cracks remain open also after unloading, water and humidity can more easily penetrate in concrete members, undermining their durability [8].

Based on the results of experimental tests, a number of empirical constitutive laws were proposed to model the cyclic behavior of concrete in tension [2,7,9,10]. They are mathematical formulations derived from the generalization of test results under various loading histories. Even though these models have been successfully applied to analyze the mechanical response of structural components, they do not give any explanation about the origin of this complex behavior. A possible reason for the development of the residual crack opening, which is investigated in this work, is the presence of a non-homogeneous Eigenstress state in the virgin unloaded material

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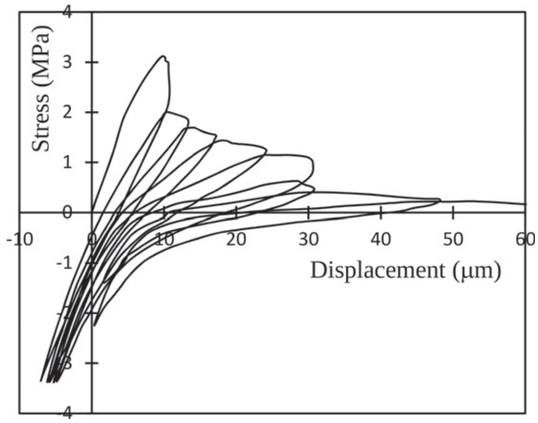

Fig. 1. Tensile cyclic behavior of concrete (experimental data taken from [7]).

due, for instance, to the drying shrinkage process. During the loading phase such stresses are locally released due to cracking, with a consequent impact on the deformation field. As a result, perfect crack closure cannot be achieved at the end of the unloading path due to a mismatch between the crack lips.

Drying shrinkage of concrete is caused by the moisture drying through the pore system of the hardened cement paste. Starting from the initial uniformly saturated state, moisture migrates towards the concrete surface in contact with the lower relative humidity environment driven by a nonlinear diffusion process. The variation of the moisture content determines shrinkage strains that, because of restraints to deformation given by the presence of stiff aggregates, lead to structural stresses and cracking. Initially, the shrinkage strains and the consequent Eigenstresses are non-uniform because of the hygral strain gradient between the inner and the outer layers of the specimen and they attain a uniform distribution only at the end of drying shrinkage. In the initial phase, the boundary conditions with respect to moisture evaporation play also a significant role. Drying shrinkage has been studied since many decades in order to experimentally measure the evolution of the strain and to identify the main variables involved in its development [11–16]. From the modeling standpoint, there is a number of papers contributing to the analysis of the shrinkage induced micro-cracking in concrete with the help of meso-mechanical models. Some of them concern the modeling of the hydration and drying processes [17,18], whereas others analyze the mechanical effects of shrinkage in terms of micro-cracking development and impact on the mechanical properties [19,20]. In the latter case, the shrinkage is modeled with simplified approaches, such as with uniform imposed strains. Then, there is a third kind of contributions which provide a complete coupling between the nonlinear diffusion process behind the development of drying shrinkage and the mechanical response of a representative volume element of concrete [21–23].

Within this context, the present work aims at contributing to understand the mechanical effects of residual stresses, for instance produced by drying shrinkage, on the tensile fatigue behavior of concrete. In particular, the main scope is to explore to which extent the presence of residual stresses may be the cause of the unrecoverable displacement characterizing the tensile cyclic behavior. This is the first time, to the best of our knowledge, that the influence of residual stresses on fatigue is modeled at the mesoscale. To this purpose a 2D meso-mechanical finite-element (FE) approach is adopted, in which aggregates and matrix are explicitly represented. A simple model is chosen, in which only large aggregates are explicitly modeled, whereas the small aggregates and other components are assumed to be mixed up with the cement paste establishing the matrix phase. In the proposed approach, damage and cracking are modeled by means of the cohesive method. An implicit solution scheme is adopted within a step-by-step analysis, with an extrinsic cohesive method approach, which means that cohesive elements are inserted during the step-by-step simulation where and when needed. Compared to more classical approaches, in which the concrete is considered as a homogeneous material and complex constitutive laws are implemented to model the real behavior, the proposed meso-mechanical model permits to use simpler constitutive relationships, since several other aspects contributing to the complexity of the response, namely material heterogeneity and crack roughness, are explicitly modeled.

The developed procedure characterized by the insertion of cohesive elements on-the-fly follows that recently used to analyze the dynamic cracking of concrete in tension and compression [24–26]. However, in those previous applications, due to the dynamic character of the problem, an explicit time integration scheme was adopted. In this regard, the use of the extrinsic cohesive element approach in the context of an implicit solution scheme to solve the step-by-step nonlinear problem is one of the novelty of the present work. Such a feature, which is an almost unique feature of the open-source code Akantu [27,28], is essential to analyze the effect of the Eigenstresses on the tensile fatigue behavior of concrete. The intrinsic cohesive approach, that was successfully adopted to analyze the micro-cracking induced by drying shrinkage [20,23], cannot be used for the scope of the present work because the interface elements introduced since the beginning accommodate the imposed strains and do not permit to capture residual displacements at the end of the unloading paths. On the other hand, the developed approach has a high computational cost since the cohesive elements are inserted one by one and at every insertion the nonlinear system is solved to find equilibrium. For this reason, a 2D model is used even though it is a strong idealization of real 3D situations. The main difference in the mechanical response is that micro-cracks can more easily percolate to create a macro-crack in 2D with respect to 3D, thus leading to a reduction of the load-carrying capacity and of the ductility for the same input parameters [29–31].

The paper is structured as follows: Section 2 describes the details of the cohesive law that has been used, while Section 3 outlines the numerical framework. The numerical model constituted by a heterogeneous specimen with two symmetric edge notches is defined in Section 4. The results of the numerical simulations are presented in Section 5, where focus is put first on the monotonic tensile behavior and then on the post-peak loading–unloading response. Finally, the results are commented in Section 6.

2. Mechanics

The concrete is modeled as a multi-phase solid material, whose components have a linear elastic behavior. Mechanical non-linearities are due to formation and propagation of cracks, which are modeled based on the cohesive zone model [32,33]. It consists in extending the cracks in front of their tips while applying surface tractions to keep it closed. The crack extension is called cohesive zone and the surface tractions are called cohesive tractions. These tractions gradually diminish in proportion to the crack opening according to a cohesive law, as originally proposed by Hillerborg for concrete [34]. In this work, the irreversible cohesive law, with a formulation which couple Mode I and Mode II crack propagation, proposed by Snozzi and Molinari [35] and shown in Fig. 2 was chosen. This law gives the possibility to define different values for the tensile and the shear strengths, as well as for the dissipated energy in pure opening mode $G_{c,I}$ and in pure sliding mode $G_{c,II}$. This is particularly useful for concrete-like materials, which behave differently in the two fracture modes.

The crack opening, represented by the vector $\boldsymbol{\Delta}$, contains a normal contribution Δ_n and a tangential contribution Δ_t with respect to the

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