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A multiscale model for the numerical simulation of the anchor bolt pull-out test in lightweight aggregate concrete

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HIGHLIGHTS

- A concurrent multiscale approach is used for studying fracture phenomena in LWAC.
- An ad-hoc path following method is proposed to simulate crack propagation in LWAC.
- The competition between different damage mechanisms in LWAC is considered.
- The overall nonlinear response of LWAC for anchor bolt pull-out tests is obtained.
- The influence of aggregates' quality and content on LWAC's response is studied.

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ABSTRACT

Lightweight aggregate concrete (LWAC) has been increasingly used as a construction material in civil and building engineering, especially in earthquake hazard zones, due to its higher strength-to-weight ratio and efficient handling with respect to ordinary concrete. The aim of the present work is to perform complete failure analyses in LWAC taking into account the effects of the underlying microstructure on its overall structural behavior. To this end, a concurrent multiscale method is adopted, in conjunction with an innovative crack modeling framework. Continuous crack propagation along a non-prescribed path is modeled in the LEFM setting, taking advantage of a shape optimization method coupling a moving mesh strategy and a gradient-free optimization solver. The crack penetration through a material interface is also taken into account, by means of a novel re-initiation criterion at interface, based on a material characteristic length. Numerical computations have been carried out with reference to the complete failure analysis of a LWAC specimen subjected to the anchor bolt pull-out test; the related results have shown that the peak and post-peak response is strongly affected by volume fraction and Young's modulus of lightweight aggregates. Their validation has been performed by means of comparisons with a fully homogenized model uniquely based on LEFM approach.

1. Introduction

Lightweight aggregate concrete (LWAC) has gained popularity in recent years as an alternative to ordinary normal weight concrete for both structural and nonstructural purposes; its distinctive feature is an oven-dry density of less than 2000 kg/m^3, typically achieved by substituting normal weight aggregates by a combination of fractions of both lightweight coarse and fine materials or lightweight coarse material with an appropriate content of natural fine aggregate. The main advantages of lightweight aggregate concrete over ordinary concrete are higher fire resistance, ease of handling, efficient transportation, and reduced dead loads; due to its high strength-to-weight ratio, lightweight concretes are used for civil and mechanical applications calling for small structural masses, as in earthquake engineering.

High performance lightweight concretes are typically produced using expanded clay, shale or slate as aggregates. These aggregates are characterized by a relatively low density due to their intrinsic cellular microstructure; in order to assure a reasonable compressive strength for the finished concrete (typically more than 20 MPa), the lightweight aggregates are produced to have an optimum balance between their density and crushing strength (strongly related to the resistance to fragmentation); as a consequence, the density of a finished oven-dry lightweight concrete should not be smaller than 1500 kg/m^3, if used for structural purposes [1–3].

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Several experimental and numerical works have been carried out in the past in order to study the overall mechanical behavior of structural LWAC [4–21]; in detail, the role of different design variables on the peak and post-peak softening response has been investigated, such as the aggregates' quality [9,18,21], size [13,14,20], and volume fraction [8,15,16,18,19]. Most of these works are of an experimental nature, but there exist a few studies based on micromechanical modeling [8,13–16,21].

The mechanical characteristics of the lightweight aggregate are more similar to those of the cement paste matrix than to the normal weight aggregate, and variations in aggregate quality and content will be more directly reflected in the finished concrete characteristics. Moreover, the transition zone between the aggregates and the matrix, i.e. the weakest zone in normal weight concretes, is not present or is very small, since the cement paste penetrates inside the aggregates due to their porous nature; as a consequence, the bond between the aggregate and the matrix is stronger in the case of LWAC than in normal weight concrete. This fact has a strong connection with the final aspect of the crack path: the crack trajectory is characterized by a small tortuosity, since, once trapped by an aggregate, does not propagate along the interface (unlike in the case of ordinary concretes, where the aggregate/cement paste interface is a weaker component than the aggregate itself) [3,6,10–12]. In this paper, the adjective "strong" for an interface refers to its stress threshold, unlike other works where the same adjective refers to the assumed continuous character of the displacement field across the interface itself (for distinguishing it from the opposite discontinuous character referred to as "weak interface", corresponding to a finite stiffness value). Due to the presence of strong interfaces in LWACs, the hypothesis of perfect bond between the different constituents is considered to be valid, whatever the stress level acting on the material interfaces.

In this work the influence of the aggregate quality and content on the effective strength and toughness of lightweight concretes is investigated, by performing numerical experiments concerning the Round Robin pull-out test, provided in [22] and already studied by many researchers [23–34] for normal weight concrete. Here, a multiscale model has been developed in order to perform complete failure analysis for this test; such a model contains a fully microscopic description within a target region, referred to as the "zone of interest", whereas outside this region the microstructure is replaced by an equivalent homogenized material, whose elastic properties are obtained via a first-order homogenization technique. A finite element discretization has been employed for both regions, and used in conjunction with a fracture criterion based on Linear Elastic Fracture Mechanics (LEFM). Comparisons with a purely homogenized analysis have been carried out, in order to assess the validity of the proposed multiscale approach and the accuracy of related numerical results for both peak and post-peak structural response.

The paper is organized as follows: in Section 2 a description of the proposed multiscale model is given; Section 3 illustrates the main theoretical and numerical tools for simulating fracture in LWAC at the mesoscopic scale; then Section 4 is entirely devoted to the presentation of the numerical results obtained by means of the proposed method, in terms of peak and post-peak behavior during a pull-out test of an LWAC specimen; finally in Section 5 some concluding remarks are provided.

2. Description of LWAC's multiscale model

Lightweight aggregate concrete (LWAC) as well as ordinary normal weight concrete possesses a highly heterogeneous microstructure, thus resulting in an extremely complex mechanical behavior; in fact, its overall structural response is strongly affected by the individual components and their mutual interactions. Generally speaking, LWAC is considered to be consisting of three different phases: a continuous phase., i.e. the cement paste matrix, a discontinuous phases, made of coarse and fine aggregates, distributed into the matrix phase according to a given granulometry, and an interfacial phase placed in between, referred to as the "interfacial transition zone" (ITZ).

As is well known, a suitable numerical simulation of concrete at a mesoscopic level should take into account the effect of the shape, size and distribution of coarse aggregates within the mortar matrix on the concrete's overall mechanical behavior. Several mesoscale models have been proposed in the literature for ordinary concrete, most of which are based on a random generation of its underlying microstructure [35–38].

However, such fully microscopic models are not pursed in engineering practice due to the required large computational effort; as a consequence, simplified models are usually preferred to predict failure in concrete and other quasibrittle heterogeneous materials, most of which belong to the class of multiscale approaches (see [39] for a concise review). Generally speaking, multiscale models have gained popularity due to their advantages, consisting in a higher degree of accuracy and reduced computational costs with respect to single-scale models. Following [39], such methods can be grouped in three main classes depending on the type of coupling between the microscopic and macroscopic sub-problems: sequential, semi-concurrent and concurrent methods. Sequential methods are efficient in determining the macroscopic behavior of heterogeneous media in terms of stiffness and strength, but have a limited predictive capability for problems involving the damage and other nonlinear phenomena (see, for instance, [40]). When dealing with geometrical and/or material nonlinearities, semi-concurrent approaches are preferred, in which an incremental-iterative nested solution scheme is used for establishing the desired scale transition (see, for instance, [41–45]). In the present work, a concurrent multiscale method is adopted, based on a domain decomposition approach, as in [46,47]; the principal feature of this strategy is to decompose the original problem into smaller and more manageable sub-problems to be solved simultaneously, as described in the author's previous works [48,49]: a fine-scale description, presented in Section 2.1, is used within the "zone of interest", i.e. the zone subject to cracking and/or other nonlinear phenomena, whereas a coarse-scale resolution is kept outside this region, as shown in Section 2.2. In order to assure perfect continuity between the sub-models, a suitable micro–macro connection has to be established; in the present work, where a standard finite element approach is employed, this condition lead to a gradual transition between the two meshes, without the insertion of hanging nodes.

2.1. Fine-scale modeling of LWAC's microstructure

Our attention is devoted to a lightweight aggregate concrete with natural sand (Sand LWAC or SLWAC), where only the coarse aggregate is made of lightweight material; thus, a numerical model of concrete's microstructure can be obtained by explicitly considering only coarse aggregates; sand and cement paste are homogenized together with their ITZ, giving rise to a simplified homogeneous model of mortar phase. Due to the thinness of the ITZ between cement paste and lightweight aggregates, the considered mesostructure is regarded as a bimaterial system with randomly distributed particles with perfectly bonded interfaces; moreover, due to the sintered nature of aggregates, for the sake of simplicity spherical aggregates can be considered (see Fig. 1a), thus neglecting all shape effects.