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Virtual elements and zero thickness interface-based approach for fracture analysis of heterogeneous materials

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Abstract

A novel procedure for analyzing fracture processes in quasi-brittle materials and consisting in combining the discrete crack approach by means of interface elements with the Virtual Element Method is proposed and developed in this work. In particular, the proposed procedure is used in the simulation of non-linear mechanical response and cracking of cement-based composites at the mesoscopic level of observation. Thereby three components are recognized: mortar, coarse aggregates and mortar–aggregate interfaces. In this regard VEM constitutes a powerful and efficient tool to represent the complex geometries of the inclusions in composite materials, such as coarse aggregates in concrete. Actually, patches with any number of edges (not necessarily convex), hanging nodes, flat angles, collapsing nodes, etc., can be easily handled in the VEM framework while retaining the same approximation properties of FEM. On the other hand, classical zero-thickness interface elements (IEs) are employed for modeling stress-crack opening processes. A series of numerical results, not only at the mesoscopic but also at the macroscopic level of observation, are presented to demonstrate the soundness and capabilities of the proposed approach based on combinations of VEM and IEs.

Keywords: Virtual element method; Zero-thickness interfaces; Meso-scale; Fracture; Discontinuous approach

1. Introduction

Meso-scale analysis and the consideration of complex micro/meso-structural geometries in composite systems and materials has become increasingly attractive in the last years in the field of computational methods [1,2]. Plenty of computational approaches, based on the Finite Element Method (FEM), have been actually employed in several fields of solid mechanics and failure simulations [3,4].

From all possible composites considered in engineering designs and, moreover, in the field of computational solid mechanics, concrete and cementitious mixtures are amongst the most attractive ones based on the extensive use of

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these materials in civil constructions worldwide. In the last decades, the analysis of concrete failure and cracking behavior at the mesoscopic level of observation emerged as a promising and extremely effective technique. However, the viability and capability of meso-scale numerical tools for concrete failure analysis are deeply dependent, on the one hand, on the accuracy of the considered non-linear constitutive equations of the composite constituents and, on the other hand, they are also strongly dependent on the considered approach for modeling the interaction between these constituents [5]. Finally, and very importantly, a proper and efficient meshing of the considered micro/mesoscopic geometry and of the involved constituents is of key importance, particularly in lower scale analysis [6]. In the case of concrete composites, the constituents may include coarse and fine aggregates, cementitious mortar or paste, fibers and interfaces.

A large amount of theoretical models and numerical tools have been proposed in literature with the aim to realistically model and predict the pre- and post-cracking behavior of concrete at the meso-scale level. Some of these proposals have traditionally been implemented by means of the classical continuum-based procedures (namely, Smeared Crack Approaches — SCAs) in which the fracture zone is distributed in a certain region of the solid [7]. Other techniques follow the well-known discrete approach whereby cracks are directly represented or modeled as a jump in the kinematic field within the analyzed material [8]. Different procedures or FE techniques were proposed to materialize the discrete approach, such as the Embedded strong discontinuities (E-FEM) [9], eXtended Finite Element Method (X-FEM) [10], lattice approaches [11], particle models [12], Discrete Element Method (DEM) [13] and zero-thickness interfaces [14].

These numerical schemes incorporate meso-scale inclusions and/or heterogeneities by means of the description of a certain region of the body which has been meshed (or discretized) by using standard FEs. Nevertheless, in most cases this process becomes very difficult and inefficient when the shape, geometry and aspect ratio of the particles present high distortions and superficial tortuosity. This is one of the reasons why the majority of the available works only explicitly consider coarse aggregates but neither the medium nor the small ones [15] and, sometimes, only quite regular geometries have been handled in the scientific literature. In this regard, the Virtual Element Method (VEM) offers a very reliable and efficient alternative procedure to account for geometrically more complex inclusions and, consequently, is more suitable for arbitrary non-structured discretizations [16,17]. This issue represents one of the main advantages of the application of VEM in mesoscopic numerical analyses. In this paper, a novel and efficient procedure for numerical analysis of cracking processes in composites, characterized by geometrically complex inclusions, is proposed. It encompasses the use of two fundamental discretization strategies such as the VEM and IEs which provide relevant advantages regarding both the domain discretization and the simulation of post-cracking failure mechanisms of dissipative, brittle and quasi-brittle composites.

After the problem overview and literature review provided in this section, the paper is organized as follows: Section 2 summarizes the meso-scale approach for taking into account the composite nature of the quasi-brittle composites like concrete which are considered in this research. The basic equations and constitutive rules behind the use of zero-thickness interface elements for discrete cracking analysis are formulated subsequently, in Section 3. Afterwards, the mathematical framework and the main ingredients of the VEM applied to elasticity problems are outlined in Section 4. Some practical information behind the implementation of the proposed approach is then given in Section 5, while Section 6 deals with the numerical applications and some examples for assessing the potential and capability of the proposed approach. Some concluding remarks are finally reported in Section 7.

2. Finite element strategy for discrete failure analysis of composites with inclusions

In this section the strategy proposed in this work for discrete failure simulations of boundary value problems of composites with embedded inclusions such as the mesoscopic structure of cementitious mixtures and concrete is presented. These meso-scale structures are characterized by large aggregates embedded in mortar matrix as schematically indicated in Fig. 1.

One standard approach is to obtain a convex polygonal representation for representing the large aggregates surrounded by the mortar matrix. Traditionally, these polygons can be numerically generated through performing the so-called Voronoi/Delaunay tessellation [18] in a set of points, initially ordered in a regular array, which are slightly perturbed before the tessellation procedure as shown in Fig. 1a–b. Coarse aggregates are thus obtained by resizing and randomly rotating the Voronoi polygons as represented in Fig. 1c–d–e. The input data for the discretization procedure outlined in Fig. 1 mainly consist in the 2D specimen dimensions (based x height), mixture design parameters,