ALLEGATO n 1 al verbale n. 4

GRUPPO DOMANDE N. 1

1) L'ammissione ai corsi di Laurea e Laurea magistrale in Ingegneria Civile, Edile e Ambientale all'Univeristà di Padova.

2) Analisi degli stakeholders nella gestione di un progetto di formazione attuato in collaborazione con un'università africana.

GRUPPO DOMANDE N. 2

3) I rapporti internazionali del Dipartimento ICEA dell'Università di Padova nel settore della formazione.

4) Lo sviluppo di un progetto di formazione attuato in collaborazione con un'università africana.

GRUPPO DOMANDE N. 3

1) Il regolamento didattico dei corsi di laurea in Ingegneria Civile, edile e ambientale all'Università di Padova.

2) Il piano di gestione dei rischi di un progetto di formazione attuato in collaborazione con un'università africana.

GRUPPO DOMANDE N. 4

1) Le strutture di gestione dei corsi di Laurea e Laurea magistrale in Ingegneria Civile, Edile e Ambientale dell'Università di Padova.

2) Gruppi di processi e Linee guida nella gestione di un progetto internazionale.

ALLEGATO n. 3 al verbale n. 4

1. Introduction

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Concrete is the most widely used construction material in the world. It has a great variety of applications in the field of structural engineering. A realistic description of the failure mechanisms is very important to ensure the safety of the concrete structures [1] . However, due to the highly non-homogenous material with large heterogeneities, failure mechanisms of concrete structures are not well understood, especially under complex stress conditions. Unlike metal materials, there is a nonnegligible localized damage zone made of micro-cracks between aggregates or through aggregates around and ahead of the crack tip in concrete-like materials. This localized damage zone which is also known as the fracture process zone (FPZ) is deemed to have a direct relationship with the macro fracture behaviour of brittle materials including concrete and rock [2,3]. Macro-crack propagation in concrete and rock is actually caused by the initiation, micro-crack coalescence, and development of the fracture process zone [4]. As a consequence, some fundamental properties of concrete, including fracture energy and critical fracture toughness are affected by the evolution of the FPZ. Some researchers [5,6] also concluded that the existence of the FPZ in front of a growing crack in concrete structure might be the intrinsic reason for the size dependence of the fracture parameters.

Due to the important role of the FPZ during fracture process in concrete, various measurement techniques are already employed to track the fracture process in concrete experimentally, for example, the dye penetration method [7], the scanning electron microscopy method [8], acoustic emission (AE) techniques [9], and digital image correction (DIC) method [10]. Although all the experimental investigations described above can generally describe the shape and size of the fracture process zone, the limitation of the experimental technique itself as well as the composite nature of the concrete material makes it very difficult to thoroughly understand the detailed local behaviour during the evolution of fracture process in concrete. Thus, various numerical models which aim to delve the mechanisms underlying the evolution of fracture process zone have been developed (e.g. [11–13]). Particularly, Zhou and Chen [14] recently proposed a model in which a direct relationship between the FPZ parameters and the size-dependent nominal strength is established and then the role of the fracture process zone was discussed accordingly.

Modelling of concrete at the mesoscale which considers the concrete compositions as coarse aggregates, mortar matrix and the interface transitional zone (ITZ) is deemed to be a powerful means for the understanding of the physical processes underlying the macroscopic strength and failure behaviour of the composite materials under various loading conditions [15]. Generally, three types of mesoscale concrete models, namely distinct-element model (DEM), lattice-element model (LEM) and finite-element model (FEM) can be referenced in the literature.

However, a key factor that determines the extent to which the mesoscopic failure mechanisms may be realistically represented is the modelling of fractures. In lattice models, a fracture is generally represented by continuingly breaking (removing) the lattice members (beam or truss elements) when a failure criterion is met. This approach is suitable for crack opening, but it cannot accommodate possible crack closure which could happen during the complex evaluation of damage within the bulk of concrete, not to mention reversed loading. The discrete element or particle models possess inherent advantages in accommodating crack-induced discontinuity [16]; however its ability in modelling the continuum and partially damaged phases of concrete is very much subject to the equivalent description of the continuum properties through point contacts, and such equivalent description is difficult to generalize for different stress conditions.

Mesoscale models in a finite element framework are clearly superior in representing the nature of concrete as a non-homogenous continuum to start with. As in the general FE model of concrete as a homogeneous medium, cracks may be described using either a smeared or a discrete approach. Previous research has shown some long-lasting problems, such as mesh size dependency, and limited deformation modes of the standard continuum elements in the smeared crack approach when the softening behaviour is involved [17]. More recently, a continuum-based mesoscale concrete model, with enhancement by a nonlocal treatment is developed in [14], thus the evolution of the FPZ during the fracture process of notched concrete beams was successfully captured. In order to ensure a mesh independent result for both global response and local fracture process, a non-local approach with a micro characteristic length R_c was introduced into the continuum-based mesoscale concrete model. However, as it was pointed out in [18], the determination of the characteristic length for the mesoscale concrete model is not straightforward and can be case dependent. Moreover, there are still some inherent deficiencies of the nonlocal treatment at a mesoscale level, such as the boundary problem, the time-consuming calculation process and the 'blurred' damage process in terms of the initiation and propagation of the fracture process zone. All of these tend to render the non-local approach to be of a limited purpose. And non-local based approach performs more poorly in dynamic loading condition where stress wave effect is involved. To tackle these problems, a variety of techniques have been developed for regularization and tracking of cracks. But no universal method is in sight yet for solving a general fracture problem for concrete-like materials.

In contrast to the above continuum damage-based technique to model fracture within a finite element framework, the discrete approach can explicitly follow the initiation and propagation of multiple cracks. The potential cracks in this approach are introduced via zero-thickness interface elements equipped with a fracture based constitutive law, which may be inserted along all the grid lines of the mesh. These interface lines can branch, coalesce, and eventually form new free surfaces. Understandingly, because of the high heterogeneity of concrete composites, the local stress field within the FPZ is usually subjected to the mixed-mode I-II stress conditions instead of pure mode I or pure mode II loading even under ideal extern load. In the case of mixed-mode fracture, the evolution of micro-cracks within the FPZ is affected by the combination of the tensile and shear stress conditions. The shear response of micro-cracks often involves the sliding and friction mechanisms between the cracking surfaces.

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Most recently, Zhou and Lu [19] developed a robust mesoscale fracture model that decohesion and friction can be explicitly modelled in the transaction zone between aggregate and mortar phase during the fracture process. The model has shown its advantage in modelling the micro-crack initiation and macro-crack propagation during the fracture process in concrete-like materials under various complex loading conditions. In the present study, this model is further enhanced by extending the cohesive plus friction model into the mortar phase, since lots of microcracks can be also observed from experimental evidence. Therefore, by extending the cohesive plus contact approaches used in ITZ into the mortar matrix, the local fracture mechanisms including cohesion and friction developed during the failure process in concrete can be explicitly simulated.

The objective of this work is to contribute to the improved understanding of local fracture processes by numerically track the evolution of the FPZ for concrete structures. Three-point bending beams with different sizes and geometries were simulated using a mesoscale model, in which concrete is modelled as a random heterogeneous three-phase material consisting of coarse aggregate, mortar matrix and the weak interfacial transition zone (ITZ). Here, the fracture process zone is naturally described by the zone composed by microcracks which are between aggregates or through aggregates in the mesoscale framework during the fracture process. The macro response of stress-strain curves, as well as the shapes and sizes of fracture process zones calculated from numerical results are verified against experimental observations. The influence of the local stress field and friction effect, as well as the specimen size on the evolution of fracture process zone was identified and discussed accordingly. The remaining paper is organised as follows. In Section 2, a holistic 2D mesoscale model is developed in which cohesive elements and friction effect are incorporated to accommodate the initiation and evolution of the fracture process. The numerical model setup with parameters investigation and model verification are given in Section 3. In Section 4, the evolution of the fracture process zone and the size effect on the fracture process zone are investigated and discussed based on the numerical results. Finally, concluding remarks are presented in Section 5.

2. Numerical approach

2.1 Meso-structure generation

Several studies on the generation of random meso-structure in concrete specimen both in 2D and 3D can be found in the existing literatures [15,19,20]. Previous studies [14,19,21] have indicated that as far as attention on the evolution of fracture process zone is mainly focused, a 2D mesoscale concrete model is sufficient. Therefore, we shall confine ourselves to a 2D mesoscale model for the present investigation on the fracture process of concrete using a cohesion plus contact interface approach. The mesoscale structure of concrete is represented by a stochastic distribution of aggregates embedded in the mortar matrix. The aggregates are modelled by random polygon particles, and the nominal size of the individual aggregates obeys a given grading curve. The generation of the mesoscale geometry follows a commonly adopted take-and-place procedure [22], satisfying non-overlapping and minimum gap requirements. The procedure is programmed using Matlab. The density of the aggregates can be controlled by specifying a volume ratio. The detail procedure and steps for developing such a 2D mesoscale concrete model is provided in [22].

After generation of the mesoscopic geometric structure, ANSYS pre-processor is used to perform the FE-meshing. Triangular elements are used for better tracking the crack propagation path according to [21]. At this stage, only two components, i.e. aggregate and mortar are modelled. The meshed elements for aggregate and mortar components are shown in Figure 1.