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A mesoscale interface approach to modelling fractures in concrete for material investigation

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HIGHLIGHTS

- A mesoscale model for concrete with heterogeneity and aggregate-mortar interface.
- Interface (ITZ) modelled with independent cohesive and contact-friction mechanisms.
- Model allows holistic and explicit simulation of fracture in a mesoscale framework.
- Model is generally applicable without restriction to loading/stress conditions.
- Model is well suited for concrete material characterisation and investigation.

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ABSTRACT

Advanced computational modelling can provide a powerful tool for material investigation and characterisation. For concrete materials, appropriate description of the heterogeneity and realisation of complex fractures are two challenging aspects in high fidelity numerical simulations. This paper presents a new mesoscale model for concrete with the ability of simulating natural evolution of fracture at the interface between the aggregates and mortar matrix and without restriction to the loading conditions. To this end, a combined cohesive and contact interface approach is employed. The contact-friction process at a fractured interface is treated as an independent process that complements the general cohesive law, thus allowing the closure of cracked surfaces and the development of residual shear resistance in a realistic manner. Parametrisation is conducted to examine the effects of pertinent interface parameters on the macroscopic behaviour of concrete. The modelling approach is demonstrated to be capable of simulating the behaviour of concrete under a variety of loading conditions, including confined and dynamic compression. The new mesoscale model provides a comprehensive numerical means for investigating into the micro-mesoscale mechanisms underlying the macroscopic behaviour of concrete.

1. Introduction

Concrete is a non-homogeneous composite with large heterogeneities. The behaviour of concrete is fundamentally affected by the fracture mechanisms, particularly at interfaces between aggregates and the mortar matrix, i.e. the interfacial transition zone or ITZ. Modelling of concrete is complicated because of the development of fractures, in that at the initial stage concrete behaves primarily like a heterogeneous continuum solid, but when fractures grow it gradually becomes discontinuous.

Modelling of concrete at the mesoscale makes it possible to describe the composition of the material, and it has been a subject of continuous interest in the research community concerning brittle and quasi-brittle solids (e.g. [1–3]). As summarised in [4], three distinctive approaches have been employed in mesoscale modelling of concrete, namely lattice model, discrete element model (DEM), and continuum finite element (FE)-based model.

A key factor that determines the extent to which a mesoscale model may be capable of realistically representing the intrinsic failure mechanisms is the modelling of fractures. In lattice models [5,6], fracture is generally represented by continuingly breaking the lattice members, which may be beam or truss elements, when a failure criterion is met. This approach is suitable for crack opening; but it cannot accommodate possible crack closure. The discrete element or particle models possess inherent advantages in accommodating crack-induced discontinuity; however its ability in modelling the continuum and partially damaged states of concrete is subject to the equivalent description of the continuum

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properties, and such equivalent description is difficult to generalize for different stress conditions [4].

Finite element-based mesoscale model is well suited for representing the intact concrete as it is essentially a non-homogenous continuum. As in the general FE model of concrete, cracks may be described using either a smeared or a discrete approach. However, previous research has shown some well-known issues with the standard continuum elements, such as the mesh size dependency and the limited deformation modes in the smeared crack approach when the softening behaviour is involved [7].

The incorporation of cohesive interface elements within a finite element framework makes it possible to follow the initiation and propagation of multiple cracks. These interface lines can branch, coalesce, and eventually form new free surfaces. The mechanical properties of the interface can generally be described using a cohesive law, which represents a gradual loss of the strength with increasing separation and can also be related to the work of separation, or fracture energy that is required for the complete formation of a free surface [8]. Fig. 1 depicts the formation of a separation (crack) over an interface with cohesive zone elements.

As the macroscopic failure in concrete is much dependent on the interface between aggregate and mortar, a sound representation of the mechanical properties and the fracture at the ITZ is crucial for a realistic modelling of the mesoscopic damage mechanisms for concrete-like materials. Therefore in the present study the focus has been placed to develop a holistic interface approach to capture the complex damage process at the ITZ for any stress conditions.

It is generally understood that the real ITZ has a very thin thickness of 20–50 μm [9,10], and it has a different mechanical property from the cement paste. Because of its thin thickness, it may be reasonably represented by zero-thickness cohesive elements.

The adequacy of using cohesive elements for modelling the ITZ in a general mesoscale model depends upon the capacity of the cohesive elements in catering to complex stress conditions. A classical cohesive model is suited for modelling the interface failure involving model I and mode II fractures. Applying this cohesive element model proves to work well under tension-dominated loading, but it performs poorly in other loading conditions including axial compression [2]. The reason is deemed to relate to the inability of the cohesive element in representing the shear failure of the ITZ under a complex stress condition.

Some other techniques have also been developed in attempt to address the coupled effect of normal and shear stresses at a cohesive interface. An interface element which incorporates the interaction of cohesion, tensile strength and the friction angle in a constitutive model has been proposed [7] to investigate the concrete fracture mechanisms under complex loading conditions. The main feature of this interface element is that it introduces a friction dissipative mechanism between two potential crack surfaces into the cohesive law intrinsically. By defining several loading fracture surfaces at different loading stages with shape parameters, such a model can generally simulate the whole process from fracture to pure friction. However some of the parameters used in the model cannot be obtained easily and some are also case-dependent. Moreover, as Ruiz et al. [11] suggested, the contact and friction process should be regarded as independent phenomena outside cohesive law. This is because physically fracture and friction are two independent processes, and in particular the presence of friction may result in a steady frictional resistance while the normal cohesive strength simultaneously weakens. Thus a contact-friction algorithm is deemed to be more appropriate to represent the interaction resistance at cracked surfaces.

In this paper, a holistic interface approach combining the cohesive mechanism with the contact-friction mechanism is developed to explicitly represent the behaviour of ITZ in a mesoscale concrete model. Relatively simple and explicit physical laws are employed for individual mechanisms. In conjunction with the mesoscale description of the complex geometric interface between the mortar and random aggregates, which allows for the fracture path to develop in a more realistic manner, the combined framework provides a comprehensive method to capture the detailed damage processes in concrete under all general loading conditions. The application of the model for material investigations is demonstrated by numerical simulation of concrete under different loading conditions in comparison with experimental observations.

2. Modelling approach for ITZ in a mesoscale framework

2.1. Overview of the mesoscale model and meso-structure generation

The present study is focused on fracture modelling of concrete in a two-dimensional (2D) mesoscale model framework, with a holistic interface description for the ITZ. The mesoscale structure of concrete is represented by a stochastic distribution of coarse 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 [12], satisfying non-overlapping and minimum gap requirements. The density of the aggregates can be controlled by specifying a volume ratio, e.g. 45% in this paper. For normal concrete, the coarse aggregates are defined as those with a minimum nominal size of 4.75 mm [1]. Herein the procedure is programmed using MATLAB.

After the generation of the mesoscale structure, the geometrical data can be brought into a finite element meshing processor. In the present study, ANSYS pre-processor is used to perform the FE-meshing. Fig. 2 illustrates a typical mesoscale model geometry. In this figure, only two material components, namely aggregates and the mortar matrix, are shown. The third component, i.e. the interface transition zone (ITZ) between aggregates and mortar matrix can be created subsequently. To overcome the issues with

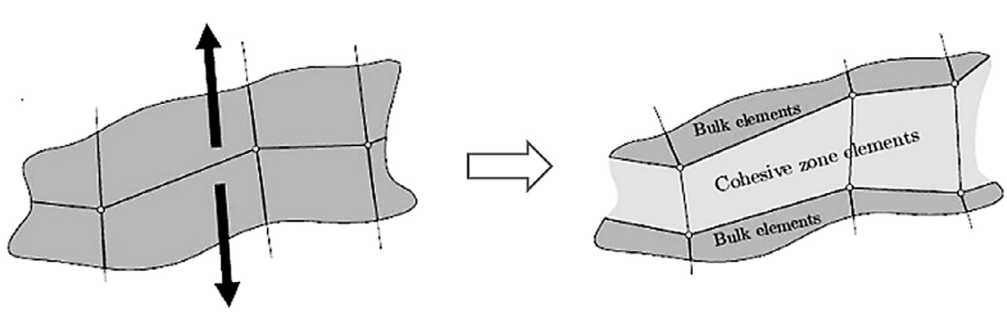

Fig. 1. Cohesive elements along mesh lines (after [8]).