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Multi-scale identification of concrete material parameters

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ABSTRACT

A multiscale method for determining fracture related material parameters in concrete is presented. A homogenized constitutive law is used in the coarse-scale while the fine-scale accounts for the meso-scopic features of concrete, i.e. the cement matrix, micro-cracks and aggregates. The fine-scale and the coarse-scale is coupled by the Lagrange multiplier method. A meshless method is applied where material failure is modeled by the extended element free Galerkin method. The well-posedness of the boundary value problem is restored by means of cohesive zone approach. The interface between the cement matrix and the aggregates are also modeled through the cohesive zone approach. The validity of the method is shown for two benchmark problems with available experimental results.

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1. Introduction

Concrete is an important material in bridges, buildings and other Civil Engineering applications. Its ingredients are cement matrix, micro-cracks and aggregates. The coarse-scale (i.e. macroscopic) material parameters are dependent on the fine-scale (i.e. mesoscopic) features. One important feature is the behavior of the interface between the porous cement matrix and the aggregates which has to be taken into account in the computational formulation. Coarse-scale constitutive model consider concrete as homogenized material and do not account for fine-scale features. Therefore, they cannot predict coarse-scale material parameters based on fine-scale features. Nevertheless, there are numerous contributions modeling larger concrete structure based on macroscopic material models, also accounting for fracture [1–11]. The focus on this manuscript is to provide a multi-scale approach to predict coarse-scale parameters rather than determining them experimentally.

Fracture is an important feature in concrete at all scales. It was shown for instance by [12] that the large characteristic length of the fracture process zone in concrete materials does not allow a linear elastic fracture model. Furthermore, concrete is characterized by the nucleation, propagation and coalescence of micro-cracks that form into a macroscopic crack band. Early approaches model the fracture behavior of concrete with so-called smeared crack approaches [3,4,13,14]. However, the poor description of the crack kinematics, stress locking and mesh-bias prohibit the use of smeared crack approaches to complex problems. Discrete crack models, in particular discrete crack approaches based on enrichment, are strong competitor to smeared crack models [15–27]. Those methods are commonly used for material failure in homogenized continua. We will use those methods to model fracture in the heterogeneous concrete which remains challenging due to the huge number of cracks and complex fracture patterns [28,29].

As modeling the entire concrete material as heterogeneous material is prohibitively expensive, we use a multiscale method. Only the domain where fracture occurs are considered as heterogeneous while other domains are treated as homogeneous material. The material properties in those domains are obtained by computational homogenization. The two domains are coupled with the Lagrange multiplier methods. We assume fracture occurs only in the cement matrix; the aggregates behave linear elastic. The extended element free Galerkin (XEFG) method [30,31] is used to model material failure. This method has advantage over other mesh-based computational methods for fracture due to its mesh-free character (ease in adaptive refinement, large deformations [32–39], etc. [40]) and has been applied to several interested problems [41–52] and will be used here for the first time in the context of a multiscale method for fracture in concrete. Other effective methods such as the extended finite element method [17,53], smoothed finite element method [54–59], phantom node method [60–63] or other FE methods for fracture based on edge rotation [64–68] could be employed as well. Our methodology is validated by two benchmark problems. We also predict macroscopic material parameters and show the influence of the interface model between the cement paste and aggregates.

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The manuscript is structured as follows: First, the extended element free Galerkin method is described. The cohesive zone approach is explained next before the multiscale method is described. Two computational results are presented and compared to experiments before this paper is concluded in the last section.

2. Extended element-free Galerkin method

The approximation of the displacement field in the extended element free Galerkin method is given by [31]:

$$\mathbf{u}^h(\mathbf{X}) = \mathbf{u}^h_S(\mathbf{X}) + \mathbf{u}^h_E(\mathbf{X}) \tag{1}$$

where $\mathbf{u}^h_S(\mathbf{X})$ is the "standard" EFG approximation while $\mathbf{u}^h_E(\mathbf{X})$ denotes the enriched or extended part accounting for the jump in the displacement field. The approximation of the continuous displacement field in the EFG method can be written as

$$\mathbf{u}^h_S(\mathbf{X}) = \sum_{I=1}^{m} p_I(\mathbf{X})\ a_I(\mathbf{X}) = \mathbf{p}^T(\mathbf{X})\ \mathbf{a}(\mathbf{X}) \tag{2}$$

$\mathbf{p}^T(\mathbf{X})$ denoting the vector of basis functions and m indicating the number of basis functions in $\mathbf{p}$; $\mathbf{a}(\mathbf{X})$ is the vector of unknowns. In a Galerkin method, at least linear basis functions are needed, i.e. $\mathbf{p}^T(\mathbf{x}) = [1\ X\ Y]$. Note that all quantities are expressed in terms of material co-ordinates $\mathbf{X}$ instead of spatial co-ordinates $\mathbf{x}$ that is also common in meshfree methods [35,69,70]. Hence, the shape functions need to be evaluated only at the beginning of the calculation. The EFG shape functions are obtained by minimizing an error norm $\mathcal{L}_2$ with respect to the unknown coefficients $\mathbf{a}$:

$$J = \sum_{I=1}^{n} \left(\mathbf{p}^T(\mathbf{X}_I)\ \mathbf{a}(\mathbf{X}) - \mathbf{u}_I\right)^2 w(\mathbf{X} - \mathbf{X}_I) \tag{3}$$

that will finally yield to the well known EFG approximation (similar to an FE interpolation):

$$\mathbf{u}(\mathbf{X}) = \mathbf{N}(\mathbf{X})\ \mathbf{D} \tag{4}$$

where the shape functions $\mathbf{N}(\mathbf{X})$ are given by

$$\mathbf{N}(\mathbf{X}) = \mathbf{p}^T(\mathbf{X})\ \mathbf{A}^{-1}(\mathbf{X})\ \mathbf{C}(\mathbf{X}) \tag{5}$$

with

$$\begin{aligned} \mathbf{A}(\mathbf{X}) &= \sum_{I=1}^{n} w(\mathbf{X} - \mathbf{X}_I)\ \mathbf{p}(\mathbf{X}_I)\ \mathbf{p}^T(\mathbf{X}_I) \\ \mathbf{C}(\mathbf{X}) &= [w(\mathbf{X} - \mathbf{X}_1)\mathbf{p}(\mathbf{x}_1)\ w(\mathbf{X} - \mathbf{X}_2)\mathbf{p}(\mathbf{x}_2) \dots w(\mathbf{X} - \mathbf{X}_n)\mathbf{p}(\mathbf{x}_n)] \\ \mathbf{D} &= [\mathbf{u}_1\ \mathbf{u}_2 \dots \mathbf{u}_n] \end{aligned} \tag{6}$$

$w(\mathbf{X} - \mathbf{X}_I)$ being the weighting function and $\mathbf{u}_I$ and $\mathbf{X}_I$ are the nodal values of the displacement field at node I and its position, respectively; n is the number of neighbors within the domain of influence of particle I. We use the following weighting function:

$$w(d_I) = \begin{cases} \frac{e^{-(d_I/c)^2} - e^{-(d_{mI}/c)^2}}{1 - e^{-(d_{mI}/c)^2}} & d_I \leqslant d_{mI} \\ 0 & d_I > d_{mI} \end{cases} \tag{7}$$

d_{mI} denoting the support size of node I, often called domain of influence, and c controls the dilation of the weighting function. Note that in contrast to the FEM, EFG is not interpolatory complicating the imposition of essential boundary conditions.

The approximation of the enriched displacement field $\mathbf{u}^h_E(\mathbf{X})$ can be further decomposed into a step enrichment $\mathbf{u}^h_{ES}$ and a crack tip-enrichment $\mathbf{u}^h_{ET}$:

$$\begin{aligned} \mathbf{u}^h_E(\mathbf{X}) &= \mathbf{u}^h_{ES} + \mathbf{u}^h_{ET} \\ &= \sum_{I}^{n_C} N_I(\mathbf{X})\ \psi(f_{\mathbf{X}})\ \mathbf{a}_I + \sum_{J}^{n_T} N_I(\mathbf{X})\ \phi(\mathbf{X}(\theta, r))\ \mathbf{b}_J \end{aligned} \tag{8}$$

n_C being the number of nodes with completely cut domain of influence and n_T denote the number of nodes with partially cut domain of influence; $\mathbf{a}$ and $\mathbf{b}$ are additional degrees of freedom. The enrichment functions $\psi(f_{\mathbf{X}})$ and $\phi(\mathbf{X}(\theta, r))$ are given by:

$$\begin{aligned} \phi(\mathbf{X}(\theta, r)) &= r\ sin\frac{\theta}{2} \\ \psi(f_{\mathbf{X}}) &= \begin{cases} 1 & f(\mathbf{X}) > 0 \\ 0 & f(\mathbf{X}) < 0 \end{cases} \end{aligned} \tag{9}$$

We use a level set $f_{\mathbf{X}}$ in order to model the crack topology where r in Eq. (9) denotes the distance of a point to the crack tip; the angle θ is defined in Fig. 1. The crack tip enrichment can be avoided but special techniques are required [19,71,72] complicating the implementation, especially when the cracks propagate.

3. Constitutive and cohesive crack model

The cement paste as well as the aggregates are modeled by a linear elastic constitutive model.

We adopt the cohesive crack model from [73] that is briefly reviewed in this section. It is based on the potential Φ:

$$\Phi = \frac{t_{c0}}{2\Delta} exp\left(-\alpha\Delta^{\beta}\right)(i_4 + a[i_1 - i_4]) \tag{10}$$

with

$$\begin{aligned} i_1 &= \mathbf{I} \cdot ([[\mathbf{u}]] \otimes [[\mathbf{u}]]) \\ i_4 &= ([[\mathbf{u}]] \otimes [[\mathbf{u}]]) : \mathbf{n} \otimes \mathbf{n} \end{aligned} \tag{11}$$

$\mathbf{n}$ denoting the crack normal vector and $[[\mathbf{u}]]$ the discontinuity in the displacement; α, t_{c0}, β and a are parameters. Differentiating Φ with respect to the discontinuous displacement field $[[\mathbf{u}]]$ yields

$$\mathbf{t}_c = \frac{t_{c0}}{\Delta} exp\left(-\alpha\Delta^{\beta}\right)(\mathbf{u}_n + a\mathbf{u}_t) \tag{12}$$

$\mathbf{u}_n$ and $\mathbf{u}_t$ denoting the normal and tangential jump in the displacement field, respectively:

$$\begin{aligned} \mathbf{u}_n &= \underbrace{[[\mathbf{u}]] \cdot \mathbf{n}}_{u_n}\ \mathbf{n} \\ \mathbf{u}_t &= \underbrace{[[\mathbf{u}]] \cdot \mathbf{e}_t}_{u_t}\ \frac{[[\mathbf{u}]] - \mathbf{u}_n}{|[[\mathbf{u}]] - \mathbf{u}_n|} \end{aligned} \tag{13}$$

where the vector $\mathbf{e}_t$ corresponds to a crack surface (or crack segment) and Δ can be derived from the yield surface:

$$\Psi = |[[\mathbf{u}]]| - \Delta \tag{14}$$

It can be shown that the consistent material tangent stiffness of the cohesive model is obtained by

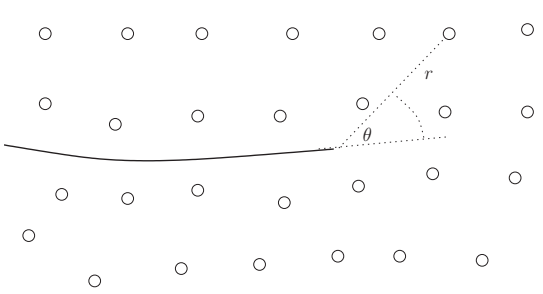

Fig. 1. Modeling of crack by XEFG.

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