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Hydraulic fracture at the dam-foundation interface using the scaled boundary finite element method coupled with the cohesive crack model

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ABSTRACT

The scaled boundary finite element method coupled with the cohesive crack model is extended to investigate the hydraulic fracture at the dam-foundation interface. The concrete and rock bulk are modeled by the scaled boundary polygons. Cohesive interface elements model the fracture process zone between the crack faces. The cohesive tractions are modeled as side-face tractions in the scaled boundary polygons. The solution of the stress field around the crack tip is expressed semi-analytically as a power series. Accurate displacement field, stress field and stress intensity factors can be obtained without asymptotic enrichment or local mesh refinement. The proposed procedure is verified by the hydraulic fracture of a rectangular embankment on rigid foundation and applied to the modeling of hydraulic fracture on the dam-foundation interface of a benchmark dam. Different distributions of water pressure inside the crack are investigated. It is found that the water pressure inside the crack decreases the peak overflow to less than 20% of the case without water in the crack. Considering the water lag or not is significant to the response, while different distribution of pressure following the water lag region in the fracture process zone has negligible influence.

1. Introduction

The interface between concrete dam and its underlying rock foundation is a weak link of the dam-foundation system. The stress concentration at the interface is a source for nucleation of micro-cracks. In practice, micro-cracks are inherently present at the dam heel. These cracks can potentially coalesce to develop a major crack that propagates along the concrete-rock interface, which increases the permeability of concrete, harms the drainage system and reduces the shear bearing capacity of the dam. Moreover, water inflow from the reservoir into the crack faces further promotes the crack propagation through hydraulic mechanisms. Rescher [1] reported that the penetration of water into the concrete-rock interface exerts an uplift pressure on the dam, which affects its structural stability. Therefore, hydraulic fracture at the dam-foundation interface is an important phenomenon for the safety evaluation of concrete dams.

The distribution of the water pressure within the crack is an important parameter in hydraulic fracture modeling. Generally, two approaches are usually used to determine the water pressure distribution within the crack during hydraulic fracture. The first approach employs coupled hydro-mechanical simulations, in which, the water pressure distribution is determined from the equilibrium conditions of fluid flow in a control volume [2]. The second approach idealizes the water pressure distribution as a purely mechanical load [3,4]. A mathematical model for the water pressure distribution is usually derived analytically based on experimental observations. This approach is suitable for crack propagation in materials with low permeability. The latter approach is adopted in this paper.

In treating the water pressure as a purely mechanical load, initial studies using this approach assumed a uniform distribution of the water pressure within the crack [5]. Independent numerical studies by Dewey et al. [6] and Plizzari [7], however, reported that the stress field in the vicinity of the crack is sensitive to the assumed water pressure distribution within the crack. Bruhwiler and Saouma [8] studied the distribution of water pressure within a crack by experimenting on wedge splitting specimens. They reported that the water pressure increased from zero to full hydrostatic pressure along the fracture process zone. An empirical model for the water pressure distribution expressed as a function of the crack opening displacement was proposed. Slowik and Saouma [9] studied the effect of water pressure in fast propagating cracks using wedge splitting tests subjected to dynamic loads. They reported that the rate of the COD influences the water pressure distribution inside the

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crack and that the trapped water has a wedging effect that increases the magnitude of the tensile stresses in the vicinity of the crack tip. A model for the fluid flow in concrete cracks was proposed based on experimental observations and simplifying assumptions based on, for example, the fluid flow velocity, the size of crack widths and the impermeability of the concrete at the fracture process zone.

Hydraulic fracture at the dam-joint foundation is usually investigated using the cohesive zone model [10–12] in combination with the finite element method (FEM). Bolzon and Cocchetti [3] developed a friction-cohesive softening interface model with coupled degradation of normal and tangential strength to model the joint in low permeability materials. Two models of water pressure distribution within the crack was studied i.e. piecewise linear and exponential. Alfano et al. [4] developed a multi-scale interface model to simulate crack propagation in dams considering the effect of water pressure in the crack. The water pressure distribution was assumed as an exponential function of the crack opening displacement, consistent with the experimental observations of Bruhwiler and Saouma [8]. Barpi and Valente [13] modeled the water penetration at a dam-foundation joint using the cohesive zone model. The model for the water pressure distribution inside the crack was described by polynomial functions and was based on the models proposed in [8,14,15]. Barpi and Valente [16] also derived the asymptotic expansion of the stress field around the crack tip of a dam-foundation joint. Consistent with the model developed by Desroches et al. [17], their analysis assumed water lag near the crack tip where the hydrostatic pressure penetrates only to the knee-point of the cohesive law. Using a similar approach, Alberto and Valente [18] derived the asymptotic fields around a cohesive frictional crack at the bi-material interface between a dam and the rock foundation.

Efficient simulations of hydraulic fracture at the dam-foundation interface require accurate modeling of the stress field in the vicinity of the crack. Compared with homogeneous materials, the stress field at the crack on a concrete-rock interface is more complex and is highly influenced by the mismatch of the two constituent materials. Although the FEM can be used to model such behavior, its polynomial-based shape functions necessitate the use of a sufficiently dense mesh in the vicinity of the crack tip, as was demonstrated in the numerical examples reported in e.g. [4,13]. To improve the performance of the FEM in modeling quasi-brittle fracture, the finite element shape functions can be enriched with the asymptotic expansion of a cohesive crack [19,20].

The scaled boundary finite element method (SBFEM) is an alternative approach that can effectively model the fracture behavior of quasi-brittle materials. The SBFEM is a semi-analytical method and was developed by Song and Wolf [21]. Its unique characteristics make it very efficient in modeling problems of unbounded media [22,23], thin plates [24], heat problem [25] and fracture problems [26–28]. Application of the SBFEM to model quasi-brittle fracture was reported in [29,30,33]. When modeling fracture, the SBFEM does not require a fine mesh at the crack tip such as the FEM e.g. [13] [34] or asymptotic enrichment functions such as the extended FEM [19,35]. The asymptotic fields in the vicinity of crack tips, notches, material junctions and cohesive cracks are analytically represented in the formulation.

In this paper, the SBFEM is applied to model hydraulic fracture at the dam-foundation interface. The concrete and rock are assumed to be linear elastic and impermeable. The fracture process zone and the water pressure distribution in the vicinity of the crack tip is modeled using the cohesive zone model via interface elements. The water pressure distribution is applied to the crack surfaces as a purely mechanical load and is assumed to be an exponential function of the crack opening displacement, similar to [3,4]. The interface elements are coupled to the SBFEM by a shadow domain procedure [29]. The SBFEM solution using generalized coordinates [36] is adopted to model the cohesive tractions acting on the crack faces. To facilitate the modeling of crack propagation, the SBFEM is used together with polygon meshes having arbitrary number of sides [44]. Crack propagation is modeled by a simple modification of the polygons along the interface.

This paper is organized as follows. Section 2 describes the cohesive zone model and interface elements used to model the cohesive tractions and water pressure distribution acting in the fracture process zone of the interface crack. Section 3 details the fundamental theory of the SBFEM and its solution using generalized coordinates. Section 4 describes the shadow domain procedure used to couple the SBFEM and the interface elements, the stress field in the vicinity of the crack tip and the condition of stability of the cohesive crack. In Section 5, the developed approach is validated by standard numerical bench marks. The influence of the water pressure on the fracture behavior at the interface crack is investigated numerically. The major conclusions of this study are summarized in Section 6.

2. Modeling of cohesive crack and water pressure in the process

2.1. Cohesive traction distribution

The cohesive zone model [10–12,49] is commonly used to model the fracture behavior of quasi-brittle materials such as concrete, rocks and ceramics. This model idealizes the fracture behavior in the process zone as a line that is characterized by nonlinear constitutive relations of the cohesive traction and the relative displacements of the crack surfaces. The constitutive relation at the fracture process zone is determined by the mode I and mode II fracture energy, G_{fI} and G_{fII}, and the tensile and shear strength, $t_n^{(u)}$ and $t_s^{(u)}$. The exact relation between the normal and tangential cohesive tractions, t_n and t_s, with the relative crack opening and sliding displacements, w_n and w_s, are not known explicitly. For homogeneous materials, the experimentally measured G_{fI}, G_{fII}, t_n and t_s are fitted into various simplified models assuming linear, bi-linear, exponential and trapezoidal decaying relations have been proposed and studied e.g [37].

For bi-material interfacial fracture, there is a lack of consensus on the form of the constitutive relation at the interface and its related fracture parameters. For example, the determination of G_{fII}, the coupling between the constitutive relation in the normal direction and that in the shear direction, still remain to be further investigated. Mahalingam presented a cohesive law for the NFU-SiN interface, in which the parameters for the normal component and shear component were obtained through independent experiments. The shape of the traction-displacement law for both normal and tangential components was assumed to be the same [38]. Toftegaard et al. studied the interface between two dissimilar composite materials by mixed mode cohesive laws. They considered linear and exponential softening cohesive laws for both the normal and shear components, and a parametric analysis was provided [39].

The authors previously investigated the quasi-brittle fracture behavior at the interface between concrete and rock using four-point-shear specimens [40]. By assuming a set of unique parameters, the constitutive relations relating the normal and tangential cohesive traction to the relative displacements of the crack faces at the interface were determined by calibrating the experimentally measured load-crack opening and sliding displacements with numerical simulations. In order to be able to use the interface constitutive relations previously determined in [40] to model interface fracture of practical dams, the experimentally determined relations between the cohesive traction and the crack opening and sliding displacements, and the fracture energies, G_{fI} and G_{fII}, have to be augmented to account for the size effect [41].

Due to the lack of experimental results on specimens with aggregate sizes typical in practical dams, the tails of the cohesive curves determined in [40] are elongated so that the energy dissipation in the process zone due to larger crack opening and shearing can be modeled. The augmented constitutive relations of the concrete-rock interface are shown in Fig. 1. Note that for the shear constitutive relation, only the positive part of the anti-symmetric curve is shown. In these curves, the knee points remain unchanged. For the case of shear case, since there is no knee point, the first half of the descending section remains unchanged. The size of the fracture process zone, w_n and w_s, is assumed