Phase-Field Simulation of Crack Propagation at Adhesive Interfaces in Brittle Materials

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When it comes to failure of a heterogeneous material, the adhesive interfaces linking the different constituents can crucially influence its mechanical behavior. In this contribution, a diffuse description of interfaces in the context of the phase-field approach to brittle fracture is outlined. Two- and three-dimensional simulations of crack phenomena are presented and serve for validation of the model against LEFM.

1 Phase-field modeling of heterogeneous materials

1.1 Diffuse modeling approach for adhesive interfaces

Starting point for the phase-field modeling of brittle fracture is the total pseudo energy functional

\[ \psi = \int_{\Omega} \left( (1-d)^2 \psi_{el}^i + \psi_{el}^c \right) + G_c(x) \cdot \frac{1}{4\ell_c} [d^2 + 4\ell_c^2|\nabla d|^2] \, dV, \]  

in which the MIEHE split [1] of the strain energy into a fraction \( \psi_{el}^i \) attributed to the tensile part of the deformation and a compression part \( \psi_{el}^c \) is applied. Over a finite width governed by the crack length scale parameter \( \ell_c \), the phase-field variable \( d \) bridges between the intact (\( d = 0 \)) or fully broken (\( d = 1 \)) material state.

Following the previous work of HANSEN-DÖRR et al. [2], adhesive interfaces are incorporated defining space-dependent functions for the fracture toughness \( G_c(x) \). For this purpose, the interface is described in a diffuse manner in analogy to the regularization of the crack over the length scale \( \ell_c \). In addition to the fracture toughness \( G_c^0 \), it is assigned a finite characteristic width \( \ell_i \). Accordingly, the fracture toughness function depicting the interface can be interpreted as static phase-field. In principle, a GAUSSIAN-like jump between the fracture toughness values \( G_c^0 \) and \( G_c^i \) assigned to the interface and the bulk material, respectively, can be assumed, see Fig. 1 (a). However, a jump of the fracture toughness values negatively influenced the convergence of numerical solvers. Therefore, a smooth, GAUSSIAN-like transition is prescribed for the simulation of crack phenomena. For the case of heterogeneous elastic properties in the bulk material, a hyperbolic tangent-like approximation of the jump of the elastic constants at the interface midline is assumed as an approximation.

1.2 Bulk material influence on effective interface properties

For adhesive interfaces which are incorporated in the phase-field model as described above, an influence of the fracture toughness of the bulk material \( G_c^0 \) on the dissipation due to an interfacial crack arises from the diffuse description of both the crack and the interface. For a one-dimensional setting and the HEAVISIDE-like interface description, this effect can be described analytically considering the dissipation per cross-section

\[ G_c^{i,act} = \int_{\ell} G_c(x) \cdot \frac{1}{4\ell_c} [d^2 + 4\ell_c^2|\nabla d|^2] \, dx, \]

which corresponds to the effective fracture toughness of the interface. When evaluating the functional (2) for a heterogeneous fracture toughness, the alteration of the crack phase-field profile with respect to the homogeneous case has to be taken into account, cf. Fig. 1 (a). In addition to the analytical investigation, a numerical study on this lengthscale interaction effect has been conducted for both the HEAVISIDE-like and the GAUSSIAN-like fracture toughness functions. In this study, a crack propagating along an interface in a two-dimensional setting has been considered and the concept of configurational forces [3] has been employed. The results of this study are depicted in Fig. 1 (b) together with the analytical results from (2) for the HEAVISIDE-like interface description and in Fig. 1 (c) for the GAUSSIAN-like fracture toughness function, respectively. Based on the numerical results, a compensation procedure is established: An artificially lowered value of the interfacial fracture toughness is defined such that the actual fracture toughness \( G_c^{i,act} \) recovers the physical value, cf. [2, 4] for details.

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Section 3: Damage and fracture mechanics

Fig. 1: Diffuse modeling of interfaces: The phase-field profile of a crack within an interface (---) described by the HEAVISIDE-like fracture toughness function (−−−−) is altered with respect to the homogeneous case (−−−−−−−−−−) − (a). The bulk material influence on the actual interface fracture toughness is the more pronounced the smaller the ratio of the interfacial to the crack length scale is \(\ell_i/\ell_c = 0.625\) − 1.25 − 1.875 − 2.5 − 3.125 − 4. For the HEAVISIDE-like interface description, good agreement between analytically (lines) and numerically (points) determined values of the actual interface toughness is obtained − (b). For the GAUSSIAN-like fracture toughness function, numerical data is available only − (c).

2 Simulation of crack phenomena

In order to demonstrate the predictive capability of the present model, two- and three-dimensional simulations of crack phenomena have been conducted. The setup and the numerical results are shown in Fig. 2. Good qualitative agreement between the simulations and analytical predictions from LEFM [5] is obtained.

Fig. 2: Simulation of crack phenomena: (a) – A box-shaped or quadratic, respectively, domain with a GAUSSIAN-like interface (−−−− interface midline) and an initial crack \(I^0\) is considered. Displacement boundary conditions are applied on the side edges \(\partial \Omega_u\). (b) – For the interface rectangular to \(I^0\), \(\psi_b/\psi_{b,\text{act}} = 8\), and homogeneous elastic constants, crack branching into the interface is simulated (− − \(d > 0.8\)) in accordance with LEFM [5] which is followed by kinking of one of the tips out into the bulk. (c) – Elastic heterogeneity \((E_2/E_1 = 1/3\) − 1, \(\ell_i/\ell_c = 3\)) has a significant impact on the crack path. For a constant ratio \(\psi_b/\psi_{b,\text{act}}\), interfacial failure becomes the more energetically favorable the stiffer the material beyond the interface is. Furthermore, approaching the interface, the crack is deviated towards the interface midline for \(E_2/E_1 < 0\) and vice versa which coincides with LEFM predictions [5].

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