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A thermomechanical interface description and its application to yarn pullout tests

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ABSTRACT

The paper introduces a novel finite deformation thermomechanical interface approach, containing a realistic physical description of the delamination behavior of heterogeneous materials at their designated failure layer. Considering the interfacial layer as consisting of breaking connections between different materials of a heterogeneous structure, when loaded above their connective strength, the model approach introduces a damage type formulation, reflecting the state of delamination. The paper introduces not only the model formulation, it also contains its numerical treatment and its validation on testing examples. The physical background of the interface approach leads to a simple determination of the interfacial model parameter, which is demonstrated at an aramid yarn pull out experiment using HNBR rubber at elevated temperatures.

1. Introduction

Different interface and cohesive zone models were developed in recent years. They are widely used in engineering applications dealing with fracture and delamination processes. First theoretical developments are made in Barenblatt (1962) and followed by Hillerborg et al. (1976), where finite element (FE) computations using a cohesive crack tip model are shown. Further on, different phenomena ranging from brittle fracture to ductile delamination within heterogeneous materials are modeled and used in structural applications. In Needleman (1987), a first consistent FE formulation, using Lagrangian kinematics at finite deformations is given. The publication of Tvergaard (1990) firstly deals with mixed-mode failure analysis. A reference surface in the middle of the interface is introduced in Ortiz and Pandolfi (1999), in order to identify normal and tangential directions at the interface. Recently, thermomechanical cohesive zone models are developed, see e.g. Hattiangadi and Siegmund (2004), Willam et al. (2004), Fagerström and Larsson (2008) and Fleischhauer et al. (2013). A novel kinematical framework is developed in van den Bosch et al. (2007) and van den Bosch et al. (2008), which directly determines the interfacial separation as a vectorial difference between the opening crack flanks. First damage-type cohesive zone laws are presented in Cazes et al. (2009). Inelastic and time dependent interface properties are introduced and developed in e.g. Geißler and Kaliske (2010) and Zreid et al. (2013). The interface approach presented in this paper is based on the interfacial kinematics given in van den Bosch et al. (2008) and the extension by including the thermal field given in Fleischhauer et al. (2013). The thermomechanical state of equilibrium is achieved in a fully coupled Newton-type solution scheme and based on the balance laws of thermodynamics, compare Coleman and Noll (1963) and Coleman and Gurtin (1967). In order to achieve physical meaningful interface parameters, a novel thermomechanical traction separation law is introduced, based on a discontinuous damage evolution adopted from Miehe (1995).

2. Thermomechanical interface element

In the following section, a brief summary of the interface element technology used is given, see Fleischhauer et al. (2013). The thermomechanical balance principle of linear momentum and the transient heat conduction equation are supplemented by the interface contributions related to the interface Ω, see Fig. 1.

2.1. Interfacial kinematics and temperature change in terms of finite deformations

Consider a solid body B consisting of various sub-bodies having different thermomechanical properties, where every sub-body is composed of material points $P \in B$. These material points are

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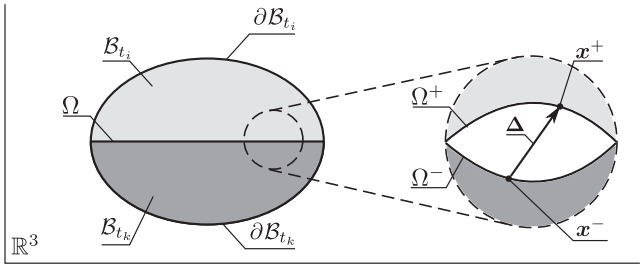

Fig. 1. Schematic graph of the current configuration of a heterogeneous solid body and illustration of an opened interface between the crack flanks Ω^+ and Ω^- and the separation $\boldsymbol{\Delta}$.

identically connected with the domain $\mathcal{B}$, consisting of the sub-domains $\mathcal{B}_i$ and $\mathcal{B}_k$. The configuration is a bijective mapping of P of B onto a position $\boldsymbol{x} \in \mathbb{R}^3$. The motion is a function of configurations. Thus, at current time $t \in \mathbb{R}$, the current configuration $\mathcal{B}_t$ is introduced. At a fixed time t_0, B possesses the reference configuration $\mathcal{B}_0$, being generally denoted by an undistorted, stress-free state, with a homogeneous temperature distribution. For an interface between the current configurations of two sub-domains, the boundaries $\partial\mathcal{B}_{t_i} \supset \Omega$ and $\mathcal{B}_{t_k} \supset \Omega$ are piecewise identical along the connective interface $\Omega \subset \mathcal{B}_t$, see Fig. 1 for their current configurations in the Euclidean space $\mathbb{R}^3$. The opening displacement between two points $\boldsymbol{x}^+ \in \Omega$ and $\boldsymbol{x}^- \in \Omega$ can be described by the opening vector $\boldsymbol{\Delta} = \boldsymbol{x}^+ - \boldsymbol{x}^-$, where $\boldsymbol{x}^+ \in \mathcal{B}_{t_i}$ and $\boldsymbol{x}^- \in \mathcal{B}_{t_k}$, as depicted in Fig. 1. The related points are initially connected having the same coordinates $\boldsymbol{X}^+ \in \mathcal{B}_{0_i}, \boldsymbol{X}^- \in \mathcal{B}_{0_k}$ at Ω^+_{ref} and Ω^-_{ref}. Both points start to separate as soon as the bonding between them is smaller than its connective forces. Additionally, no penetration between the solid parts B_i of B is assumed.

The absolute temperature of a material point of B is denoted by θ, while the change of temperature with respect to a reference absolute temperature θ_0 is denoted by $\vartheta = \theta - \theta_0$. The same notation is used for the interface, where the temperature difference between to initially connected points $\boldsymbol{x}^+ \in \mathcal{B}_{t_i}$ and $\boldsymbol{x}^- \in \mathcal{B}_{t_k}$ is denoted by $[\![\theta]\!] = \theta^+ - \theta^-$.

2.2. Kinetical equilibrium under consideration of interfacial mechanisms

The balance of linear momentum, describing the kinetical equilibrium of the observed solid body, is now supplemented by the interface contributions, reading

$$\int_{\mathcal{B}_t} \boldsymbol{\sigma} : \operatorname{grad}(\delta\boldsymbol{u})\,\mathrm{d}v - \int_{\partial\mathcal{B}_t} (\boldsymbol{\sigma}\delta\boldsymbol{u}) \cdot \boldsymbol{n}\,\mathrm{d}a + \int_{\mathcal{B}_t} \delta\boldsymbol{u} \cdot (\rho\ddot{\boldsymbol{u}} - \rho\boldsymbol{b})\,\mathrm{d}v - \int_{\Omega^+} \delta\boldsymbol{u}^+ \cdot \boldsymbol{t}^+\,\mathrm{d}\Omega^+ - \int_{\Omega^-} \delta\boldsymbol{u}^- \cdot \boldsymbol{t}^-\,\mathrm{d}\Omega^- = 0. \tag{1}$$

The integrals over Ω^+ and Ω^- are the contributions coming from the opening interface. The test function $\delta\boldsymbol{u}^+$ is defined at Ω^+ and the test function $\delta\boldsymbol{u}^-$ is defined at Ω^-. Now, Eq. (1) has to be discretized for the observed body B, using e.g. linear ansatz functions $\boldsymbol{N}(\xi)$ for the shape of the elements, where e.g. $\boldsymbol{\xi} = [\xi_1, \xi_2, \xi_3]^T$ are the local coordinates according to the isoparametric concept of the finite element method (FEM), see e.g. Zienkiewicz and Taylor (2000). Subsequently, the finite element equations of the discretized equilibrium condition can be formulated

$$G_k = \mathop{\mathsf{A}}_{E=1}^{N} \left[\delta\boldsymbol{d}^{E^T} \left\{ \int_{\mathcal{B}_{t_E}} \boldsymbol{B}^T\boldsymbol{\sigma}\,\mathrm{d}v + \left(\int_{\mathcal{B}_{t_E}} \boldsymbol{N}^T\rho\boldsymbol{N}\,\mathrm{d}v \right) \ddot{\boldsymbol{d}}^E - \int_{\mathcal{B}_{t_E}} \boldsymbol{N}^T(\rho\boldsymbol{b})\,\mathrm{d}v - \int_{\partial\mathcal{B}_{t_E}} \boldsymbol{N}^T\boldsymbol{t}\,\mathrm{d}a - \int_{\Omega^+_E} \boldsymbol{N}^T_{\Omega^+}\boldsymbol{t}^+\,\mathrm{d}\Omega^+ - \int_{\Omega^-_E} \boldsymbol{N}^T_{\Omega^-}\boldsymbol{t}^-\,\mathrm{d}\Omega^- \right\} \right] = 0, \tag{2}$$

considering the discretized test function $\delta\boldsymbol{u} = \boldsymbol{N}(\xi)\delta\boldsymbol{d}^E$. The test function, defined at the boundary Ω^+, is discretized by

$$\delta\boldsymbol{u}^+ = \boldsymbol{N}_{\Omega^+}\delta\boldsymbol{d}^E. \tag{3}$$

The test function at the Ω^- surface is discretized by

$$\delta\boldsymbol{u}^- = \boldsymbol{N}_{\Omega^-}\delta\boldsymbol{d}^E. \tag{4}$$

Eqs. (3) and (4) introduce $\boldsymbol{N}_{\Omega^+}$ and $\boldsymbol{N}_{\Omega^-}$. Both functions are standard shape functions, which are fixed for the local coordinate ξ_i of $\boldsymbol{\xi}$ pointing from the bottom surface Ω^- to the top surface Ω^+. Thus, the appropriate $\boldsymbol{\xi}$ entry takes the value -1 for the bottom surface ($\boldsymbol{N}_{\Omega^-}$) and $+1$ for the top surface ($\boldsymbol{N}_{\Omega^+}$). To achieve the entire finite element equations, Eq. (2) can be reconsidered

$$\boldsymbol{G}_k = \mathop{\mathsf{A}}_{E=1}^{N} \left[\int_{\mathcal{B}_{t_E}} \boldsymbol{B}^T\boldsymbol{\sigma}\,\mathrm{d}v + \left(\int_{\mathcal{B}_{t_E}} \boldsymbol{N}^T\rho\boldsymbol{N}\,\mathrm{d}v \right) \ddot{\boldsymbol{d}}^E - \int_{\mathcal{B}_{t_E}} \boldsymbol{N}^T(\rho\boldsymbol{b})\,\mathrm{d}v - \int_{\partial\mathcal{B}_{t_E}} \boldsymbol{N}^T\boldsymbol{t}\,\mathrm{d}a - \int_{\Omega^+_E} \boldsymbol{N}^T_{\Omega^+}\boldsymbol{t}^+\,\mathrm{d}\Omega^+ - \int_{\Omega^-_E} \boldsymbol{N}^T_{\Omega^-}\boldsymbol{t}^-\,\mathrm{d}\Omega^- \right] \tag{5}$$

$$\boldsymbol{G}_k = \mathop{\mathsf{A}}_{E=1}^{N} \left[\boldsymbol{f}^E_{int} + \boldsymbol{m}^E\ddot{\boldsymbol{d}}^E - \boldsymbol{f}^E_{ext} - \boldsymbol{f}^E_{ifc} \right] = \boldsymbol{0}, \tag{6}$$

since it should be fulfilled for any arbitrary test function. Eq. (6) fully describes any body B, containing interfaces.

2.3. Energetical equilibrium under consideration of interfacial mechanisms

In order to achieve thermomechanical equilibrium in terms of a fully coupled numerical solution, the transient heat conduction equation has to be processed e.g. by the Galerkin method, by multiplying a time independent test function. The consideration of opening cracks within B results in

$$\int_{\mathcal{B}_t} \delta\theta\rho c\dot{\theta}\,\mathrm{d}v - \int_{\mathcal{B}_t} \delta\theta\rho r\,\mathrm{d}v + \int_{\partial\mathcal{B}_t} \delta\theta \cdot (\boldsymbol{q} \cdot \boldsymbol{n})\,\mathrm{d}a - \int_{\mathcal{B}_t} \operatorname{grad}(\delta\theta) \cdot \boldsymbol{q}\,\mathrm{d}v - \int_{\mathcal{B}_t} \delta\theta \cdot w_{\mathrm{ext}}\,\mathrm{d}v + \int_{\mathcal{B}_t} \delta\theta \cdot w_{\mathrm{int}}\,\mathrm{d}v + \int_{\Omega^+} \delta\theta^+ \cdot (\boldsymbol{q}^+ \cdot \boldsymbol{n}^+ - w^+)\,\mathrm{d}\Omega^+ + \int_{\Omega^-} \delta\theta^- \cdot (\boldsymbol{q}^- \cdot \boldsymbol{n}^- - w^-)\,\mathrm{d}\Omega^- = 0. \tag{7}$$

The additional contributions at the boundaries Ω^+ and Ω^- have to be considered, since they are caused by the opening crack flanks. The heat flows $q^+_n = (\boldsymbol{q}^+ \cdot \boldsymbol{n}^+)$ and $q^-_n = (\boldsymbol{q}^- \cdot \boldsymbol{n}^-)$, as well as the power terms $w^+ = w^+_{ext} - w^+_{int}$ and $w^- = w^-_{ext} - w^-_{int}$ describe the rate of energy of the surfaces Ω^+ and Ω^-, since they are originated in the heat flux and the power terms of the bonds between the opening flanks. The next step towards a numerical solution of the partial differential equation, describing the heat conduction, is the discretization of the temperature field. The temperature field test function defined at the boundary Ω^+, is discretized by

$$\delta\theta^+ = \boldsymbol{N}_{\Omega^+}\delta\boldsymbol{\theta}^E. \tag{8}$$

The temperature field test function at the Ω^- surface is discretized by

$$\delta\theta^- = \boldsymbol{N}_{\Omega^-}\delta\boldsymbol{\theta}^E, \tag{9}$$

see Section 2.2 for the introduction of the shape functions. Finally, one can formulate the entire set of finite element equations of the energetical equilibrium