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A thermo-mechanical cohesive zone model accounting for mechanically energetic Kapitza interfaces

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ABSTRACT

Interfaces can play a dominant role in the thermo-mechanical response of a body. The importance of interfaces is more pronounced as the problem scale decreases since the interface area to the bulk volume ratio grows. The objective of this contribution is to study computational aspects of modeling thermo-mechanical solids containing mechanically energetic, geometrically non-coherent Kapitza interfaces under cyclic loading. The interface is termed energetic in the sense that it possesses its own energy, entropy, constitutive relations and dissipation. To date, classical thermo-mechanical cohesive zone models do not account for elastic interfaces. Therefore we propose a novel interface model that couples the classical cohesive zone formulation to the interface elasticity theory under the Kapitza assumption within a thermo-mechanical framework. In other words, such an interface model allows for discontinuities in geometry, temperature and normal stress fields, while not permitting a jump in the normal heat flux across the interface.

The equations governing a fully non-linear transient problem are given. They are solved using the finite element method. The results are illustrated through a series of three-dimensional numerical examples for various interfacial parameters. In particular, a comparison is made between the results of the classical thermo-mechanical cohesive zone model and our novel (cohesive + energetic Kapitza) interface formulation.

1. Introduction

Interfaces play an important role in the overall thermo-mechanical responses of a body, firstly due to the fact that they possess different properties from those of the bulk and secondly because such a role becomes even more pronounced at small scales with increasing interface area to bulk volume ratios. Furthermore, due to increasing applications of thermo-mechanical interface materials, the task of developing more thorough theories of thermo-mechanical interfaces and studying the computational aspects becomes more pressing. With regard to interface, the following terminologies are frequently used in the literature:

- *Material interfaces* whereby the motion of the interface is bound to its surrounding bulk.
- *Energetic interfaces* implying that the interface possesses its own thermodynamical structure in the form of energy, entropy, constitutive relations and dissipation. Interfaces of this type are termed as thermodynamical singular surfaces by Daher and Maugin (1986).
- *Thermal interfaces* whereby the interface acquires heat conduction along the interface.
- *Standard interfaces* possess neither energetic structure nor heat conduction along the interface. These interfaces are termed free singular surfaces by Daher and Maugin (1986).

Within a thermo-mechanical setting, interfaces are often described using one of the following models:

- From a mechanical point of view, interfaces are either geometrically coherent or non-coherent. For a geometrically non-coherent interface the constitutive behavior is described by a traction–separation law. This approach is essentially based on the fact that local material degradation is associated with a displacement jump across the interface, i.e. $[[\boldsymbol{\varphi}]] \neq \mathbf{0}$. In

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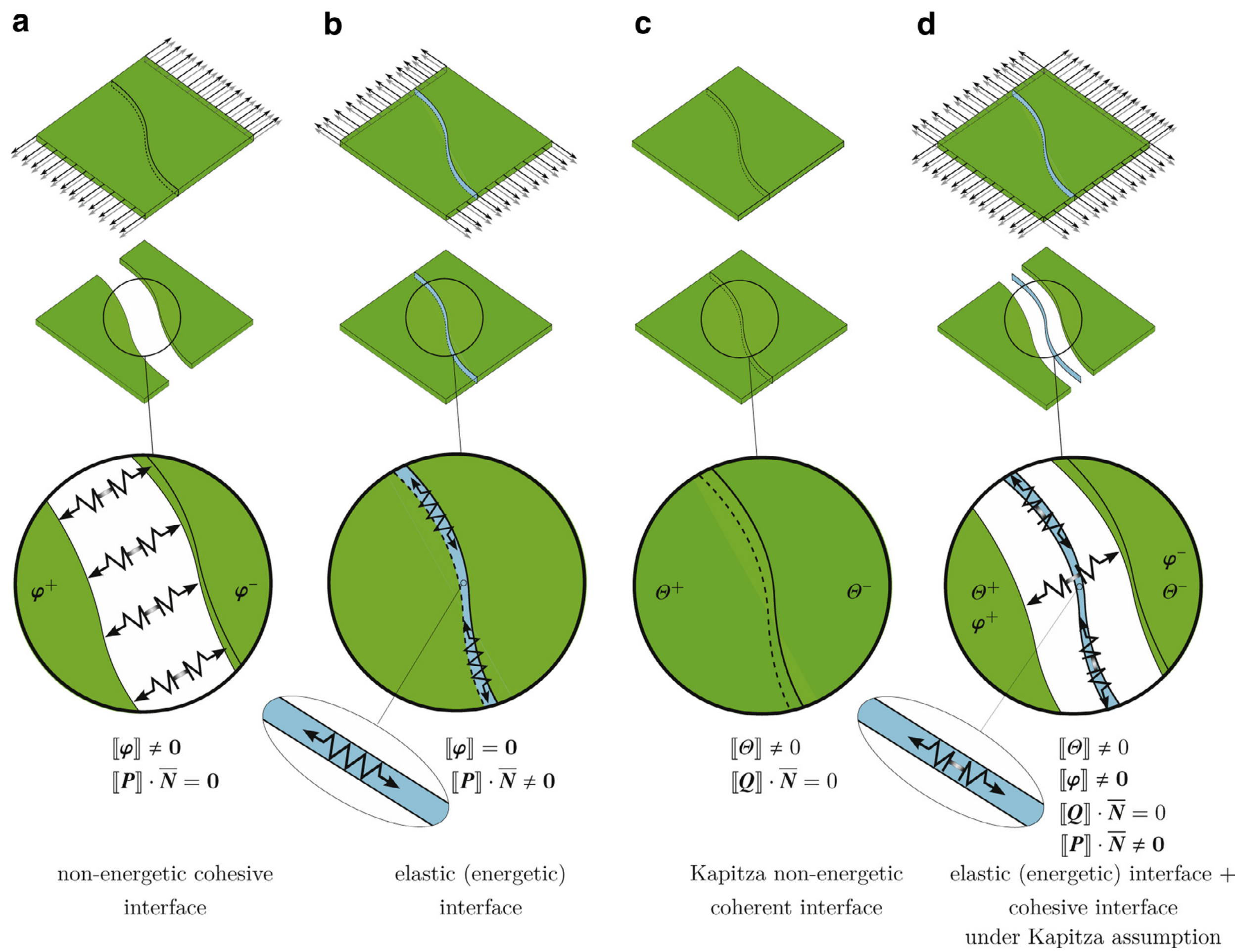

Fig. 1. Illustration of a geometrically non-coherent ($[[\boldsymbol{\varphi}]] \neq \mathbf{0}$), mechanically energetic ($[[\boldsymbol{P}]] \cdot \overline{\boldsymbol{N}} \neq \mathbf{0}$) interface under Kapitza assumption ($[[\Theta]] \neq 0$, $[[\boldsymbol{Q}]] \cdot \overline{\boldsymbol{N}} = 0$). (a) Geometrically non-coherent interface, (b) geometrically coherent elastic interface, (c) thermally non-coherent interface of Kapitza type, and (d) cohesive elastic interface under Kapitza thermal assumption (current contribution). In (d), cohesive degradation of the interface causes the degradation of mechanical and thermal properties of the interface through a cohesive damage variable $D_{\not\!I}$.

this approach the interface traction vector is a function of the displacement jump. Since these interfaces are not energetic, the traction continuity condition holds, i.e. the normal jump of Piola stress across the interface vanishes $[[\boldsymbol{P}]] \cdot \overline{\boldsymbol{N}} = \mathbf{0}$. For further details on cohesive interface models see Barenblatt (1962), Needleman (1990), Needleman (1992), Needleman (2014), Ortiz and Pandolfi (1999), van den Bosch et al. (2006), van den Bosch et al. (2007), Mosler and Scheider (2011), Aragón et al. (2013), Wu et al. (2014), Ottosen et al. (2015) and references therein. In the field of composite delamination many authors e.g. Corigliano (1993), Schellekens and Borst (1993), Allix et al. (1995), Allix and Corigliano (1996), Chaboche et al. (1997), Bolzon and Corigliano (1997), Ladevèze et al. (1998), Mi et al. (1998), Chen et al. (1999), Alfano and Crisfield (2001) employed classical cohesive zone models (CZM) to model the degradation of geometrically non-coherent interfaces. Nonetheless, these models lack any elastic resistance (mechanically energetic structure) along the interface (see Figs. 1(a) and 2(b)).
A coherent interface, on the other hand, may be endowed with its own elastic behavior or more precisely with its own energetic structure while it does not allow for a displacement jump across the interface, i.e. $[[\boldsymbol{\varphi}]] = \mathbf{0}$ (see Fig. 1(b)). The interface elastic response is a function of the superficial interface deformation gradient. For these interfaces, the traction continuity condition no longer holds, i.e. $[[\boldsymbol{P}]] \cdot \overline{\boldsymbol{N}} \neq \mathbf{0}$. Such interfaces are described by the *interface elasticity theory (IET)* proposed first by Gurtin and Murdoch (1975), Murdoch (1976). For further details see for instance, Moeckel (1975), Daher and Maugin (1986), dell'Isola and Romano (1987), Cammarata (1997), Gurtin et al. (1998), Steigmann and Ogden (1999), Fried and Todres (2005), Fried and Gurtin (2007), Steinmann (2008), Levitas and Javanbakht (2010), Javili and Steinmann (2010) and references therein. The effect of interface energetics in the size-dependent elastic state of the material has been widely investigated recently for instance in Benveniste et al. (2001), Sharma et al. (2003), Sharma and Ganti (2004), Dingreville et al. (2005), Sharma and Wheeler (2007), Duan et al. (2005a 2005b); 2009), Benveniste (2013), Huang and Sun (2007), Fischer and Svoboda (2010), Yvonnet et al. (2011b), Altenbach et al. (2012), Davydov et al. (2013) and references therein.

- From a thermal point of view, interfaces are either perfect or imperfect (see for instance Javili et al., 2013c; Fried and Gurtin, 2007, for further details). Recall that a thermal interface is non-energetic and allows heat conduction along the interface. A perfect interface does not allow for either the jump of temperature $[[\Theta]]$ or the normal heat flux $[[\boldsymbol{Q}]] \cdot \overline{\boldsymbol{N}}$ across the interface. An imperfect interface, on the other hand, permits discontinuities in either temperature $[[\Theta]]$ or normal heat flux $[[\boldsymbol{Q}]] \cdot \overline{\boldsymbol{N}}$, across the interface. Thus thermally imperfect interfaces can be further categorized into: