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Generalized interfacial energy and size effects in composites

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ABSTRACT

The objective of this contribution is to explain the size effect in composites due to the interfacial energy between the constituents of the underlying microstructure. The generalized interface energy accounts for both jumps of the deformation as well as the stress across the interface. The cohesive zone and elastic interface are only two limit cases of the general interface model. A closed form analytical solution is derived to compute the effective interface-enhanced material response. Our novel analytical solution is in excellent agreement with the numerical results obtained from the finite element method for a broad variety of parameters and dimensions. A remarkable observation is that the notion of size effect is theoretically bounded verified by numerical examples. Thus, the gain or loss via reducing the dimensions of the microstructure is limited to certain ultimate values, immediately relevant for designing nano-composites.

1. Introduction

Homogenization (Hill, 1963; 1972; Ogden, 1974) is a commonly accepted methodology to explain the overall response of composite materials based on its constituents at the microscale. While the classical homogenization is well-established today, the influence of interfaces at the microscale remains elusive and poorly understood. This contribution investigates on the impact of interfaces at the microscale on the effective material response through an interface-enhanced homogenization scheme from both analytical and numerical perspectives.

The interphases between various constituents of a heterogeneous microstructure can play a crucial role on the overall material response. The general interface model here represents the finite thickness interphase. Note, the idea of the general interface model follows the seminal work of Hashin (2002) where he distinguishes between perfect and imperfect interface models. Furthermore, McBride et al. (2012) show that classical interface models cannot capture the response of heterogeneous material layers, see Fig. 1. Emerging applications of nano-materials require better understanding of interfaces since the influence of lower-dimensional media on the overall material response increases with decreasing size.

Interfaces can be categorized into four models according to their kinematic or kinetic characteristics, as shown in Fig. 2. The *perfect interface model* does not allow for the displacement jump nor the traction jump across the interface. The *elastic interface model* is semi-imperfect in the sense that it is kinematically coherent but kinetically non-coherent. Interface elasticity theory (Daher and Maugin, 1986; Dell'Isola and Romano, 1987; Fried and Gurtin, 2007; Gurtin and Murdoch, 1975; Moeckel, 1975; Murdoch, 1976) endows the interface with an elastic resistance along the interface. The traction jump across the interface is due to the interface stress (see Chen et al., 2006; Javili et al., 2013c, among others). Interface and surface

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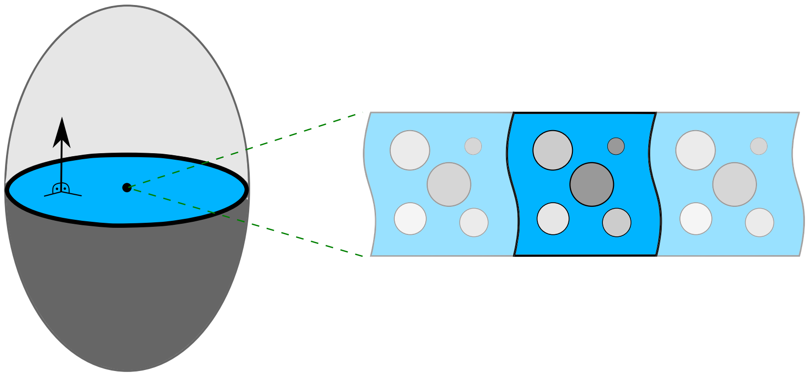

Fig. 1. Motivation for the need of a general interface model. Homogenization of heterogeneous material layers shows that even the simplest elastic response requires a general interface model to be properly captured McBride et al. (2012). The zero-thickness interface model (left) is representative of a finite thickness interphase (right).

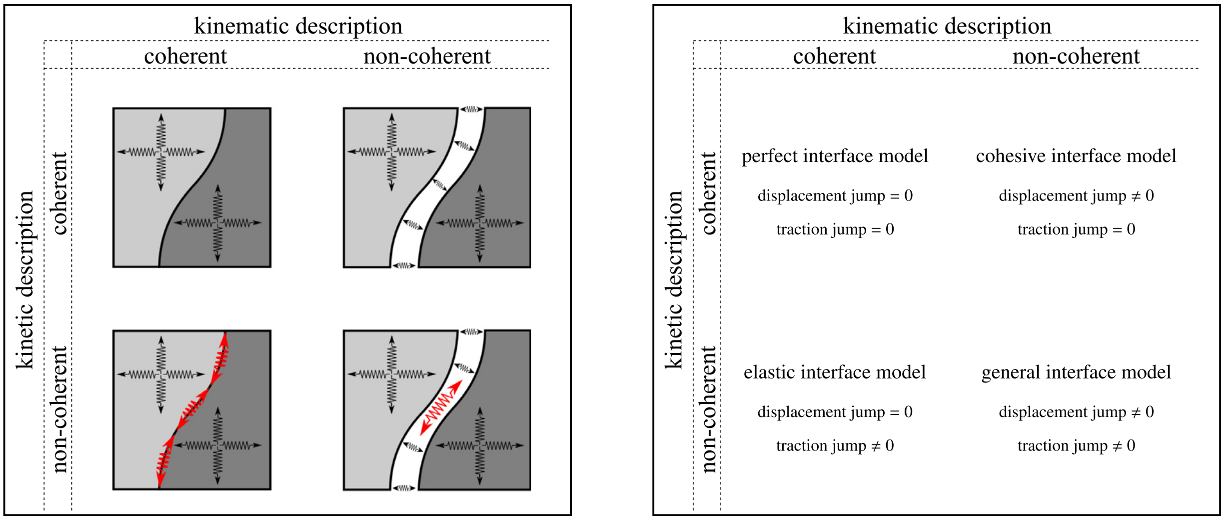

Fig. 2. An overview of interface models. Graphical illustration (left) and mathematical explanation (right). From the viewpoint of continuum mechanics, interfaces can be divided into four categories depending on their kinematic or kinetic characteristics. The elastic interface model does not allow for the displacement jump, but the traction may suffer a jump across the interface. The cohesive interface model on the contrary, allows for the displacement jump but assumes the continuity of the traction field across the interface. The intersection of elastic and cohesive interface model is the perfect interface model for which both the traction and displacement across the interface are continuous. This contribution formulates the general interface model which encompasses all other interface types.

elasticity theory is a mature field investigated in Altenbach and Eremeyev (2011); Chhapadia et al. (2011); Cordero et al. (2016); Dingreville et al. (2014); Dingreville and Qu (2008); Duan et al. (2009); Fried and Todres (2005); Gao et al. (2014); Gurtin et al. (1998); Huang and Wang (2006); Javili et al. (2013a); Liu et al. (2017); Steigmann and Ogden (1999); Steinmann (2008); Wang et al. (2010a); 2010b) among others.[1] The *cohesive interface model* allows for the displacement jump across the interface, but remains kinetically coherent hence, semi-imperfect. The cohesive interface model dates back to the seminal works (Barenblatt, 1959; 1962; Dugdale, 1960) and has been extensively studied (Alfano and Crisfield, 2001; van den Bosch et al., 2006; Charlotte et al., 2006; Despringre et al., 2016; Dimitri et al., 2015; Fagerstr and Larsson, 2006; Gasser and Holzapfel, 2003; Mosler and Scheider, 2011; Ortiz and Pandolfi, 1999; Park and Paulino, 2013; Park et al., 2009; Qian et al., 2017; Tijssens et al., 2000; Wu et al., 2016; Xu and Needleman, 1994) in the past. The perfect interface model is the intersection of the two semi-perfect interface models. From the perspective of deriving interface models as asymptotic limits of thin interphases, the cohesive interface model is derived as the limit case of soft interphases and is termed spring

[1] An important Erratum Huang and Wang (2010) on Huang and Wang (2006) was later published by its authors. Furthermore, the same authors published a more comprehensive version of their work on interfacial energy and micromechanics with interface effect in Huang and Wang (2013).