8th. World Congress on Computational Mechanics (WCCM8)
5th European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS 2008)
June 30 –July 5, 2008
Venice, Italy

Multiscale Modeling of Heterogeneous Adhesives: Effect of Particle Decohesion

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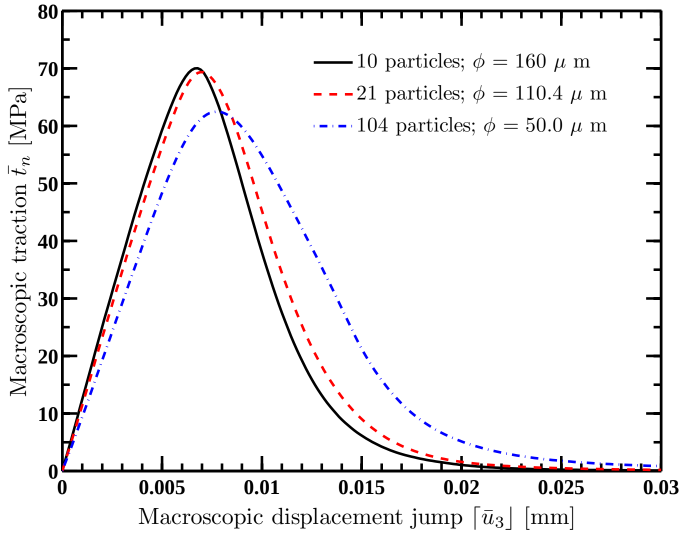
Key Words: *multiscale cohesive, heterogeneous adhesives, fracture, finite elements*

ABSTRACT

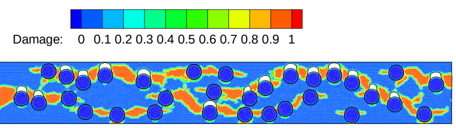
The addition of heterogeneities in thermoset polymer-based adhesives has received increasing attention in a wide range of engineering applications. In many of these applications, second-phase particles are added to improve the fracture properties of the usually brittle adhesive layer, often considered as the weak link of the bonded structure. Examples include thermosetting polymers reinforced with rubber particles [1], carbon-nanotubes [2], self-healing microcapsules [3], etc. The addition of heterogeneities introduces several micro-toughening mechanisms that may lead to a change in the failure pattern from *cohesive* (at the interface between adhesive and adherend) for neat polymeric adhesives to *adhesive* (contained within the adhesive layer) [4]. While the microscale toughening mechanisms have been well studied and documented for the bulk particulate modified polymers, there is only limited information about use of reinforcements in thin adhesive systems. In this work, we study the different failure/toughening mechanisms and analyze the effect of inclusion volume fraction, particle size, and particle-matrix interface properties on the macroscopic response of heterogeneous adhesives made of stiff particles combined with brittle epoxy using a multiscale cohesive finite element scheme.

At the macroscale, the cohesive finite element (CFE) method, which collapses the adhesive layer to a line (in 2D), is a natural choice for numerical analyzes of bonded structures. Although attractive for their simplicity, the phenomenological and/or mathematically convenient cohesive laws proposed in the literature do not represent the complex failure processes occurring at the micro-level in heterogeneous adhesives. A multiscale cohesive scheme, which has an ability to relate the microscopic failure details in heterogeneous adhesive layers to the macroscopic effective traction-separation law, has been developed [5]. The multiscale scheme relies on Hill's energy equivalence lemma, implemented in a computation homogenization framework. At the microscale, we use an isotropic damage model to describe the failure taking place in the matrix and inclusions, while the particle-matrix interface is modeled using a rate independent, exponential cohesive law.

Figure 1(a) shows the effect of particle size on the macroscopic traction-separation law under mode I loading for the case of stiff particles weakly bonded to a brittle matrix. The fracture toughness, which



(a)



(b)

Figure 1: Effect of particle size on macroscopic traction-separation curve (a) and microscale damage pattern (b) under mode I loading.

is the area under macroscopic constitutive response, increases for smaller particle sizes. Increase in the fracture toughness is accompanied by reduction in the maximum failure strength. We observe a complete *cohesive* (contained within the layer) failure pattern at the microscale for a representative heterogeneous adhesive layer (Figure 1(b)).

The multiscale cohesive tool can be used to tailor and optimize the design of particulate reinforced adhesives by correctly choosing the inclusion size, volume fraction, and inclusion-matrix interface properties.

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