Mechanics of cohesive interface: damage, contact, interlocking, dilatancy

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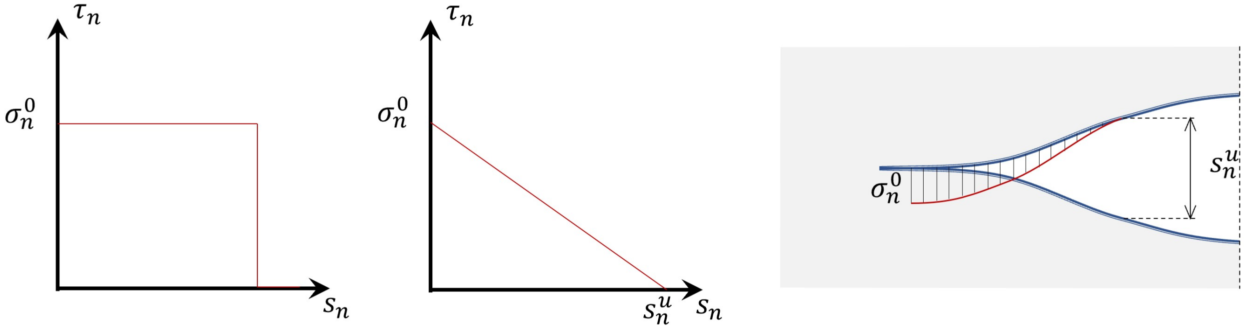
Interface mechanics refers to the study of the behavior of the link between materials or structures that are held together by cohesive forces. In other words, interface mechanics is concerned with the behavior of the connection between two materials or structures that are bonded together by adhesion forces. Interface mechanics plays an important role in a wide range of engineering applications, including adhesive bonding, composite materials, and fracture mechanics. In these applications, the performance of the structure is often strongly determined by the behavior of the interface between the materials or structural elements. Understanding the mechanics of cohesive interfaces is important for designing and analyzing structures that rely on adhesive bonding or other forms of cohesive forces. This involves studying the deformation, fracture, and failure of the interface under different loading conditions, as well as the influence of factors such as temperature, moisture, and chemical exposure on the behavior of the interface. Overall, interface mechanics is an important area of study that helps engineers and scientists design and optimize structures that rely on adhesion forces for their strength and durability.

The literature on the modeling of cohesive interfaces and of their use in the different fields of the application is absolutely huge. The models relating the relative displacement $\mathbf{s}$ with the traction $\boldsymbol{\tau}$ describe the degradation of the link between the two surfaces constituting the interface by accounting for the coupling of the normal and tangential effects, i.e. considering the mixity of the crack opening.

The interface modeling starts from the pioneering works concerning the fracture mechanics developed by Dugdale [11], who presented a theoretical model for analyzing the behavior of slits in steel sheets assuming a perfectly plastic response at the edges of a slit in a steel sheet, with a limited value of the maximum strain. Barenblatt [4] presented a theoretical framework for analyzing the behavior of cracks in brittle materials, introducing a relationship between the cohesive force and the opening of the crack lips increasing up to a maximum value of the tension and, subsequently, decreasing until it is zero. Hillerborg et al. [13] proposed a cohesive fracture mechanics approach for studying the crack growth in concrete structures in the framework of the finite element method accounting for a degradation law relating the traction to the crack opening. In figures 1(a) and 1(b), two possible interface opening responses considered by Hillerborg et al. are illustrated. The first one corresponds to the Dugdale [11] model, while the second illustrates a degrading response of the crack opening, as suggested by Barenblatt [4]. Figure 1(c), illustrates the schematic profile of the traction at the crack lips, for a softening behavior defining the so-called process zone.



(a) (b) (c)

Figure 1: Traction vs crack opening for (a) ductile and (b) cohesive material; (c) schematic of the traction profile on the crack lips for a softening crack opening response.

Among the most adopted interface models, Needleman [17] studied the void nucleation process from the initial detachment through the complete decohesion of rigid spherical inclusions in a composite material, proposing a nonlinear elastic interface model characterized by a maximum cohesion strength and a smooth softening branch for mixed mode decohesion. Tvergaard [25] developed an interface model able to account for different effects arising at the interface: mixity mode of decohesion, elastic unloading after degradation, frictional effect of the surface in contact. A very interesting aspect of the Tvergaard interface model is the possibility to consider the friction arising at the interface when decohesion is lost and shear and compressive normal stresses are present. Indeed, the proposed model is almost simple as it consider a Coulomb friction only after that the complete decohesion of the interface occurred, leading to a sharp discontinuity in the interface response. Chaboche et al. [8] proposed an improvement of the Tvergaard model introducing additional terms that force a continuity and monotonicity in the tangential stiffness degradation between the decohesion and the Coulomb frictional response occurring after complete separation. Ortiz and Pandolfi [18] proposed a three-dimensional interface damage model in the framework of finite strain assumption. The initial interface model has been then improved introducing also the effect of the unilateral contact and friction [20].

Mechanics of interface received great attention by Italian researches. Far to be exhaustive, among the others, Corigliano and Allix [10] adopted the interface model for investigating the interlaminar degradation of composite materials. Lenci [14] developed an interface model to study the crack growth between two elastic half-planes, showing that the derivative of the solution is logarithmically unbounded and that logarithmic stress singularities may exist. Giambanco et al. [12] formulated elasto-plastic non-standard interface model for reproducing the softening response occurring during the decohesion process in masonry, accounting for the dilatancy related to the roughness of contact surfaces after joint decohesion. Bertoldi et al. [5] presented a rigorous analytical derivation of a nonlocal interface model from the microstructure properties by considering the gradient approximation of the interface constitutive law. Carpinteri et al. [7] investigated the interface decohesion in double cantilever laminated beams. Paggi and Wriggers [19] developed a nonlocal cohesive zone model for finite thickness interfaces. Marulli et al. [16] combined a phase-field approach with the cohesive zone model for studying the crack propagation in layered structures. Bonetti et al. [6] derived a damaging interface model from asymptotic analysis of a micro-cracked layer. Parrinello and Borino [21] proposed an interface constitutive model based on the non-associative damage mechanics and frictional plasticity in a thermodynamically consistent framework. Confalonieri e Perego [9] formulated and validated an interface cohesive model for mixed mode I-mode II fracture proposing a bilinear traction-separation law.

A suitable way for introducing the coupling between damage and friction has been proposed by Alfano and Sacco [2] by developing a micromechanical analysis of the interface response. The proposed model has been successfully adopted in a wide range of engineering applications, such as hydraulic fracture mechanics [1], masonry structures [22].

The initial Alfano-Sacco interface model has been successively improved for accounting of the effects of the dilatancy and interlocking [24, 23]. As for the original model, the mechanical response of the interface has been derived developing a micromechanical analysis in the framework of 2D and 3D rough surfaces in contact and adhesion.

Recently, the Alfano-Sacco interface model has been implemented in a Virtual Element Method code to study the nucleation and evolution of the fracture in a cohesive solid [3, 15]. In figure 2, a numerical result concerning a L shape structural element is schematically illustrated.

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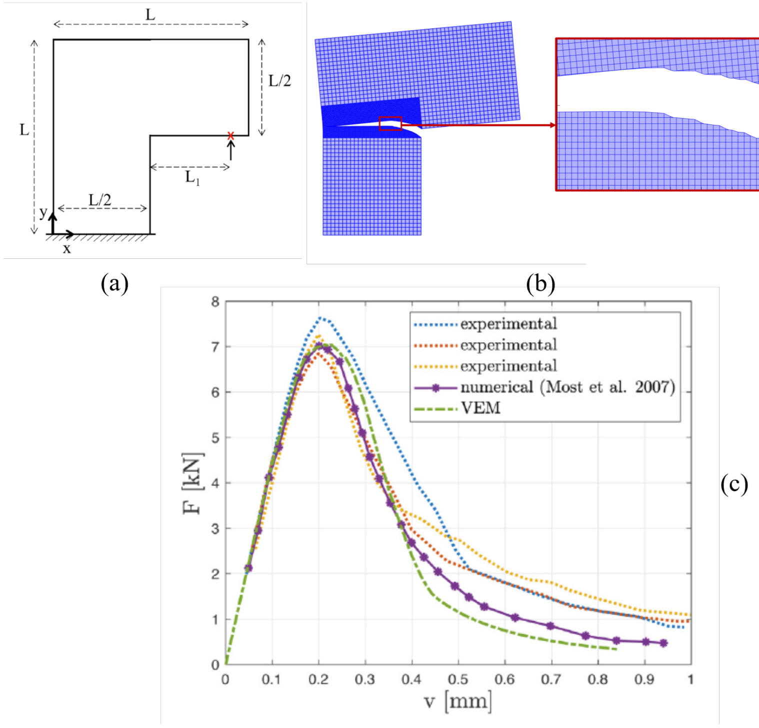

Figure 2: (a) L shape structural element; (b) deformed element with the crack opening; (c) mechanical response.

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