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Numerical methods for the modelling of interface delamination in composites.

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Summary

Composite materials have been used in structures for centuries. The available software enable us to model composite materials with specialized elements called layered elements, thus we can assign different properties and orientations for the various layers. The failure mechanism discussed in this paper is the interface delamination at the contact surface between two materials. This has motivated considerable research on the failure at the interface.

Interface delamination can be modelled by traditional fracture mechanics methods such as nodal release techniques. Alternatively, we can use techniques that will directly establish the fracture mechanism, by introducing a critical fracture energy that is also the energy required to break apart the interface surface, called cohesive zone model (CZM). In the second part of this paper will be discussed a more recent method to numerically model the delamination, namely discontinuous Galerkin model. This approach offer advantages over the more traditional approach that uses interface elements, as will be discussed in more detail.

KEYWORDS: debonding, interface delamination, composites, cohesive zone model, discontinuous Galerkin model

1. INTRODUCTION

A major failure mode in composite structures is debonding, either between two structural components, or between different layers within a structural part. Conventionally, special interface elements methods are placed a priori between the continuum finite elements to capture debonding at locations where they are expected to emerge. More recently, discretization methods have been proposed, which are more flexible than standard finite element methods, while having the potential to capture propagating debonding cracks in a robust, efficient and accurate manner, two of them being presented in the present paper, meaning cohesive zone model and discontinuous Galerkin method.

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Composite materials are somewhat more difficult to model than an isotropic material such as iron or steel. Because each layer may have different orthotropic material properties, extra-care must be exercised when defining the properties and orientations of the various layers. Both fiber and particulate composite materials provide applications in materials science where the multiscale microstructure leads to the need for multiscale modeling. Using this approach, the various aspects of the entire structural problem are considered at different levels of observation, each of them characterized by a well-defined length scale. The different levels at which analyses are carried out, are connected either through length scale transitions, in which the structural behaviour at a given level is homogenised to arrive at mechanical properties at a next higher level [1], or through finite element analyses which are conducted at two levels simultaneously and in which are connected by matching the boundary conditions at both levels [2, 3].

This paper will not focus on the methods for length scale transition or approaches for carrying out multi-level finite element analyses. Instead, we shall focus on so-called meso-level approach, in which delamination is assumed to be the main degrading mechanism. For this purpose, the different levels of analysis – macro, meso and micro – are defined in the context of laminated composite structures. At the meso-level as well as at the micro-level, fracture along internal material boundaries, delamination and debonding, respectively, governs the failure behaviour. Most constitutive relations for such interfaces have in common that a so-called work of separation or fracture energy plays a central role. For this reason the subject of cohesive zone models, which are equipped with such a material parameter, is included in the discussion.

At the meso-level, the plies are modelled as continua and can either be assumed to behave linearly elastically or can be degraded according to a damage law, and are discretised using standard finite elements – while the delamination is modelled in a discrete manner using special interface elements [4, 5]. Generalised plane strain elements are often used to model free-edge delamination [6], while stacks of solid or shell elements and interface elements are applicable to cases of delamination near holes or other cases where a three-dimensional modelling is necessary [3, 7].

2. COHESIVE ZONE MODEL

Recently, the concept of cohesive zones has received revived interest and the cohesive zone modelling (CZM) approach has emerged as a powerful analytical tool for nonlinear fracture processes. This type of model has been widely used for studying the so-called quasi-brittle fracture process zone, which arises prior to complete fracture in, e.g., concrete materials and macromolecular based polymer

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materials [8, 9]. Applications to other material systems such as adhesively bonded joints [10, 11], bimaterial interfaces [12], and the dynamic fracture of homogeneous materials [13] have also been very successful. Cohesive zone models have also been used to analyze composite delamination problems. Problems of delamination in the absence of large notches or holes have been studied [14, 15, 16] and also, more pertinently to the present work, in the presence of a notch [17].

CZM involves representing the adhesive bonded interface by a layer of special elements whose constitutive properties describe the traction (or cohesive stress) evolution as the interface is being opened [18]. Thus the core of CZM is the traction-separation law (also called cohesive law) that describes the evolution of interface stresses as functions of interface separations.

2.1. Traction-separation law

The cohesive traction is related to the cohesive separation of the surfaces by a traction-separation law (TS-law). In initially rigid models the cohesive zone is inactive as long as a certain stress level has not been reached. Barenblatt [19] was the first to propose a cohesive zone model for brittle fracture. Another popular model assumes that the cohesive stress remains constant up to a critical separation distance at which it drops down to zero. The second type of model assumes an initially elastic response of the cohesive zone. Most TS-laws of that type follow a similar scheme: the cohesive traction is zero at the beginning of the deformation. With increasing separation, the traction across the cohesive zone reaches maximum, then decreases and eventually vanishes allowing for complete decohesion. Crack growth under increasing external loading occurs when the crack surfaces separate gradually to the point where separation at the crack tip exceeds the critical value Δ_c and the cohesive traction vanishes [20].

In CZM, the potential crack propagation plane or the cleavage plane is idealised as a cohesive zone or cohesive interface and is assumed to support a nominal traction field T (force/unit reference area). This traction field, in general, has components both normal and tangential to the cohesive interface. The mechanical response of the cohesive interface is described through a constitutive law (in terms of a potential function) relating the traction field T with a separation parameter. The constitutive equations are such that, with increasing interfacial separation, the traction across the interface reaches a maximum, decreases and eventually vanishes so that complete decohesion occurs. It should be emphasized here that this constitutive description is a continuum one, and thus does not represent the interaction of two individual atoms across the interface. Also, it does not account for discrete dislocation effects. Consequently, the functional dependence of the traction field on interface separation is not uniquely determined [21].

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Typically the cohesive stress increases initially with the opening displacement, reaches a peak and then drops continuously to zero again at a certain critical displacement, as shown in Figure 1, and where the peak cohesive stresses represent the maximum load bearing capability of the adhesive [22].

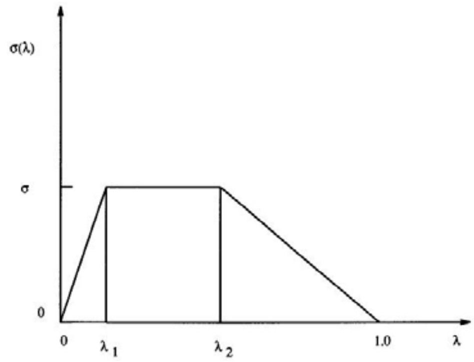

Figure 1. Traction-separation law in cohesive zone model

The TS-law relates the cohesive normal traction N to the normal separation displacement Δ. In principle, TS-laws of any shape can be implemented with little modification. The reason for choosing a TS-law with straight segments is due to the computational costs. An exponential law would require updating the systems matrix continuously. The shape of the law consists of a rising, a constant and a falling segment and is determined by five parameters; the area under the curve defines the fracture energy:

$$\Gamma = 0.50\sigma_{th} \cdot \Delta_c \cdot (1 - \delta_1 + \delta_2) \tag{1}$$

where σ_{th} is the cohesive strength, Δ_c is the crack opening separation above which the cohesive interaction vanishes and δ_1, δ_2 are the shape parameters that define the corners of the trapezoid.

2.2. Interface elements

The interface fracture phenomena play an important role in a number of applications especially in laminated composites. When modelling interface fracture phenomena, the use of discrete approach is advocated to achieve a better representation of the entire fracture process. If failure takes place along well-defined surfaces, a standard way to solve fracture problems with finite element methods consists of inserting interface elements (or cohesive layers) with zero thickness in the mesh at places where cracking is expected to occur [23, 24].

For interface elements, the interfacial separation is defined as the displacement jump, δ, i.e., the difference of the displacements of the adjacent interface surfaces:

$$\delta = u^{top} - u^{bottom} \tag{2}$$

Note that the definition of the separation is based on local element coordinate system, Figure 2. The normal of the interface is denoted as local direction **n**, and the local tangent direction is denoted as **t**. Thus:

$$\delta_n = n \cdot \delta \tag{3}$$

$$\delta_t = t \cdot \delta \tag{4}$$

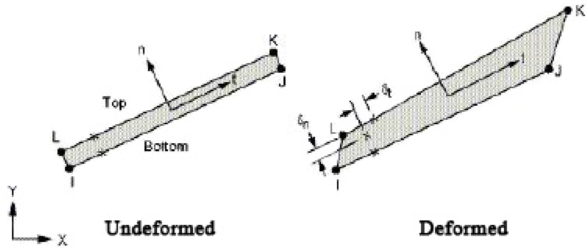

Figure 2. Interface elements

An example where the potential of cohesive-zone models can be exploited fully using conventional discrete interface elements, which is an analysis of delamination in layered composite materials [6]. Since the propagation of delaminations is restricted to the interfaces between the plies, inserting interface elements at these locations permits an exact simulation of the failure mode [3].

3. DISCONTINUOUS GALERKIN MODEL

The discontinuous Galerkin (dG) method is a class of finite element methods, which uses discontinuous, piecewise polynomial spaces for the numerical solution and the test functions. This method has classically been employed for the computation of fluid flow, but more recently, attention has been given to their potential use in solid mechanics, and especially for problems involving cracks [25], or for constitutive models that incorporate spatial gradients [26].

According to Stan [27] the main advantages of the discontinuous Galerkin finite element methods are:

- the shape functions are discontinuous along the element edges;
- the dG methods are locally mass conservative at the element level;

- each element can be thought of as a separate entity (the element topology, the degree of approximation and even the choice of governing equations can vary from element to element and in time over the course of calculation without loss of rigor in the method).

Consider a body that occupies a bounded Lipschitz domain Ω in $\Re^3$ (Figure 3). The continuum problem is governed by the following equations stated in terms of the Cauchy stress:

$$-\nabla \cdot \sigma = b \text{ in } \Omega \tag{5}$$

$$\sigma \cdot n = g_N \text{ on } \partial_N \Omega \tag{6}$$

$$u = g_D \text{ on } \partial_D \Omega \tag{7}$$

where b is the body force, n - the unit vector outward normal to the boundary $\partial\Omega$, g_D and g_N are the boundary conditions applied on the displacement $\partial_D \Omega = \Gamma_D$ and traction $\partial_N \Omega = \Gamma_N$ parts of the boundary, respectively.

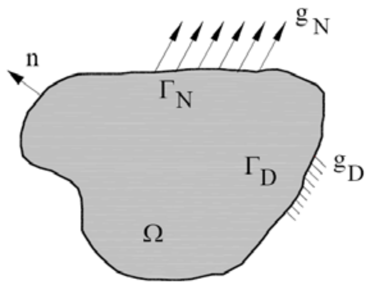

Figure 3. Body with a discontinuity

Let $\Omega_h = \{T\}$ be a shape-regular partition of Ω, where T are finite elements. Let e denote an arbitrary element edge, and $\varepsilon_h = \{e\}$ be the set of all edges. Each element boundary e is shared by two elements T^+ and T^- such that $e = T^+ \cap T^-$, with n^+ being the unit normal vector to T^+ (Figure 4).

We decompose ε_h into three disjoints subsets such that $\varepsilon_h = \varepsilon_I \cup \varepsilon_D \cup \varepsilon_N$, where ε_I is the set of all internal edges, $\varepsilon_I = \{e \in \partial T \setminus \partial\Omega : T \in \Omega_h\}$; ε_D is the set of all element edges on the Dirichlet part of the boundary $\partial_D \Omega, \varepsilon_D = \{e \subset \partial T \cap \partial_D \Omega : T \in \Omega_h\}$; ε_N is the set of all element edges on the Neuman part of the boundary $\partial_N \Omega, \varepsilon_N = \{e \subset \partial T \cap \partial_N \Omega : T \in \Omega_h\}$.

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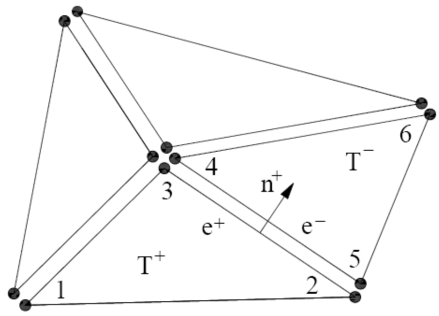

Figure 4. Discontinuous Galerkin mesh

The following approximation space is introduced:

$$V_h = \left\{ \upsilon \in L^2(\Omega) : \upsilon|_T \in P^k(T), \forall T \in \Omega_h \right\} \tag{8}$$

where $P^k(T)$ is the space of polynomials of degree at most k supported on T.

To facilitate construction of a numerical scheme with high order accuracy in the vicinity of discontinuities, we require all discontinuities to lay on the element boundaries.

The stabilized discontinuous Galerkin weak formulation results in the following form: Find $u_h \in V_h$ such that:

$$a(\upsilon_h, u_h) + j(\upsilon_h, u_h) = l(\upsilon_h), \forall \upsilon_h \in V_h$$

in which

$$\begin{aligned} a(\upsilon_h, u_h) = {} & (\varepsilon(\upsilon_h), \sigma(u_h))_T - ([\upsilon_h], < \sigma(u_h) \cdot n >)_{\partial_I \Omega_h} \\ & + \alpha(< \Omega(\upsilon_h) \cdot n >, [u_h])_{\partial_I \Omega_h} - (\upsilon_h, \sigma(u_h) \cdot n)_{\partial_D \Omega_h} \\ & + \alpha(\sigma(\upsilon_h) \cdot n, u_h)_{\partial_D \Omega_h} \end{aligned} \tag{9}$$

$$j(\upsilon_h, u_h) = \left(\frac{\beta}{h_e} [\upsilon_h], [u_h] \right)_{\partial_I \Omega_h} + \left(\frac{\beta}{h_e} \upsilon_h, u_h \right)_{\partial_I \Omega_h} - \left(\frac{\beta}{h_e} \upsilon_h, g_D \right)_{\partial_D \Omega_h} \tag{10}$$

and

$$l(\upsilon_h) = (\upsilon_h, b)_T - (\upsilon_h, g_N)_{\partial_N \Omega_h} + \alpha(\sigma(\upsilon_h) \cdot n, g_D)_{\partial_D \Omega_h} \tag{11}$$

In the above equations β is a positive penalty parameter assumed constant across Ω_h, and h_e denotes the characteristic length of the mesh. The parameter α is either

+1, or -1, corresponding to non-symmetric and symmetric interior penalty methods, respectively.

4. CONCLUSIONS

It is worth remarking that, in this paper, a powerful analytical tool for composite delamination was used, namely the cohesive zone model. Normally, delamination is defined as the separation of two plies of a laminated composite, but also delamination can occur exactly at the interface between two phases. Fracture or delamination along the interfaces plays a major role in limiting the toughness and the ductility of the multi-phase materials, such as composites or laminated composite structures. In this concern the interface surfaces of the materials can be modelled using a special set of interface materials or contact elements, and CZM can be used to characterize the constitutive behaviour of the interface.

Another approach, which offers advantages over the more traditional approaches, is the discontinuous Galerkin method that can handle cohesive cracks very naturally. Some of their main advantages are including good stability and consistency, and absence of traction oscillations and spurious reflections. One of the downsides of the dG methods is the computational cost since a loop over the boundaries in the mesh in necessary. Also, an important yet unresolved problem is the automatic selection of the stabilization parameter. However, the presented dG finite element formulation with cohesive models can simplify the computational modeling of failure along well-defined surface.

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