Cohesive modeling of mixed mode delamination in paperboard laminates

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ABSTRACT

Paperboard and paperboard products, such as carton packages, generally present a layered structure. Paperboard is often produced in the form of multi-plies, with coatings, decor layers and possible layers of other materials, such as aluminum layers for food protection. Delamination between any of these layers is a common problem during the different phases of the converting process. Ink-tack delamination [1] can e.g. occur during printing, while delamination is intentionally induced during creasing and folding [2,3]. Delamination is also frequent in the converting of corrugated boards, particularly in the die-cutting of multi-ply materials.

A distinctive feature of this variety of scenarios is that in most cases delamination occurs under mixed-mode, non-proportional loading, with varying mode ratio. For design purposes, numerical simulations of different phases of the converting process are often carried out using cohesive interfaces to account for possible delamination. Even though a large number of cohesive models for mixed-mode delamination is available in the literature (see e.g. [4] for a comparative review of different models), in many cases these are based on strong assumptions on the loading path and on the mixed-mode failure properties, or lack of thermodynamic consistency.

A robust cohesive model, suitable for the simulation of mixed-mode delamination, should possess a number of requisites, such as those listed hereafter. It should produce a positive dissipation under any loading path (thermodynamic consistency); it should be able to reproduce correctly the growth of fracture energy in passing from Mode I to Mode II failure; it should not make any assumption on the loading path (e.g. freezing the mode mixity ratio after reaching the activation surface); it should be based on a small number of physically meaningful parameters; it should allow for a simple and effective parameter identification strategy.

A new, thermodynamically consistent, isotropic damage cohesive model for mixed mode delamination under variable mode ratio, satisfying the above listed requisites, is discussed in this work. In the model, the normal and shear modes are coupled through the consideration of an internal friction-like term, which gives rise to an activation surface, defined in the plane of dimensionless cohesive tractions, of the type shown in Figure 1. This type of surface is typical of materials exhibiting a pressure dependent failure behavior, such as paperboard. In the case of polymeric interfaces, e.g. low-density polyethylene, a possible interpretation of these activation modes is that they account for the typical progressive failure modes, i.e. shear and crazing [5], of many thermoplastic polymeric materials.

Each one of the three surfaces in Figure 1 defines a distinct damage mode: the projection of the cohesive tractions onto the three normals allows for the decomposition of the energy release rate in terms of three contributions, each one related to one of the three damage modes. An additive decomposition of the damage variable is also introduced accordingly. The activation function is classically expressed in terms of a combination of the decomposed energy release rates. The overall fracture energy, i.e. the dissipated energy at complete decohesion, is, at any mode ratio, an outcome of the model, without the need to introduce any empirical laws.

The model can make use of different evolution equations for damage, leading to different softening branches in the traction-opening displacement plane, such as bi-linear softening or exponential softening. The definition of the model requires the knowledge of the fracture energies and of the activation tractions in pure Modes I and II and the knowledge of the fracture energy evolution with the mode mixity ratio.

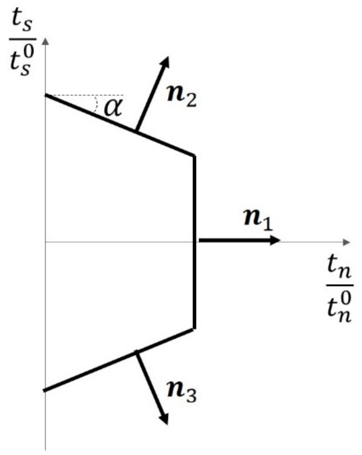

Figure 1. Three surfaces activation domain.

The proposed model has been validated on a number of benchmark tests proposed in the literature. The results of numerical simulations of mixed-mode experimental tests (more specifically Mixed-Mode Bending (MMB) tests, performed with the experimental setup shown in Figure 2 and proposed in [6]) are compared with the corresponding experimental data. As a representative example, Figure 3 shows the results of the application of the proposed model to the test reported in [7].

It can be observed how the proposed model is capable to reproduce correctly the non-monotonic growth of the fracture energy with the mode mixity ratio γ. The "bump" occurring at about $\gamma = 0.4$, typical of many interfaces in composite materials (see e.g. [8]) and which is not reproduced by the empirical Benzeggagh-Kenane [9] model, corresponds in the proposed model to the transition from the opening dominated failure mode to the shear one.

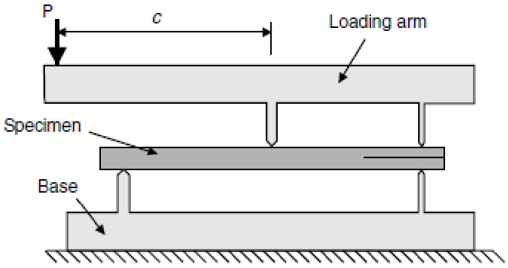

Figure 2. Mixed-Mode Bending (MMB) testing apparatus [6].

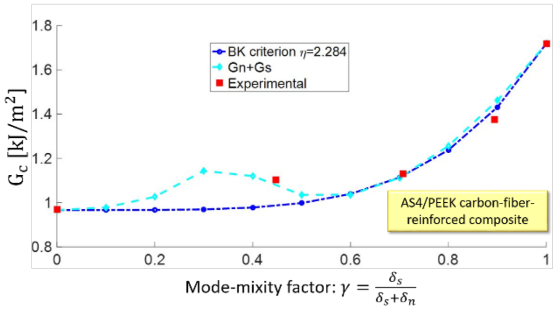
[*Camanho, Dàvila and de Moura, 2003*]

Figure 3. Results of simulation of MMB test. Square dots are experimetnal results. Dark dashed curve is obtained with Benzeggagh-Kenane [7] empirical law. Light dashed curve obtained with present model.

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