A Continuum Damage Model for the Simulation of Delamination under Variable-Mode Ratio in Composite Materials

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Motivation and Objectives

Delamination is one of the predominant forms of failure in many laminated composites systems, especially when there is no reinforcement in the thickness direction. The numerical simulation of delamination can be developed within the framework of Damage Mechanics by means of a cohesive crack model: a cohesive damage zone -or softening plasticity-develops near the crack front. The critical driving force for delamination, G_c, strongly depends on the crack propagation mode. Therefore, it is important to formulate the cohesive models so that do not exhibit inconsistencies (i.e. restoration of the cohesive state) when the mode of propagation changes. Therefore, a thermodynamically consistent damage model for the simulation of progressive delamination under variable-mode ratio has been developed in this work.

Approach

The model is formulated in the context of the Continuum Damage Mechanics (CDM). The constitutive equations that result from the variation of the free energy with damage are used to model the initiation and propagation of delamination. Interfacial penetration of two adjacent layers after complete decohesion is prevented by the formulation of the free energy. The equations of the Constitutive Damage Model are:

Table 1. *Equations of the constitutive damage model.*

Free Energy	$\psi(\Delta, \mathrm{d}) = (1-\mathrm{d})\,\psi^0(\Delta_i) - \mathrm{d}\psi^0\left(\bar{\delta}_{3i}\langle -\Delta_3\rangle\right)$
Constitutive equation	$\tau_i = \frac{\partial\psi}{\partial\Delta_i} = (1-\mathrm{d})\,\bar{\delta}_{ij}K\Delta_j - \mathrm{d}\bar{\delta}_{ij}K\bar{\delta}_{3j}\langle -\Delta_3\rangle$
Displacement jump norm	$\lambda = \sqrt{\langle\Delta_3\rangle^2 + (\Delta_{shear})^2}$
Damage criterion	$\bar{F}(\lambda^t, r^t) := \mathfrak{G}(\lambda^t) - \mathfrak{G}(r^t) \le 0 \quad \forall t \ge 0$ $\mathfrak{G}(\lambda) = \frac{\Delta^f(\lambda-\Delta^0)}{\lambda(\Delta^f-\Delta^0)}$
Evolution law	$\dot{\mathrm{d}} = \dot{\mu}\frac{\partial\bar{F}(\lambda,r)}{\partial\lambda} = \dot{\mu}\frac{\partial\mathfrak{G}(\lambda)}{\partial\lambda}\ ;\ \dot{r} = \dot{\mu}$
Load/unload conditions	$\dot{\mu} \ge 0\ ;\ \bar{F}(\lambda^t, r^t) \le 0\ ;\ \dot{\mu}\bar{F}(\lambda^t, r^t) = 0$ $r^t = \max\{r^0, \max_s \lambda^s\} \quad 0 \le s \le t$

A bilinear constitutive equation is used to model the behaviour of the interface. The bilinear constitutive equation is defined by the initiation and propagation criterion. A new delamination initiation criterion is developed to assure that the formulation can account for changes in the loading mode in a thermodynamically consistent way. The propagation criterion used is the same proposed by Benzeggagh and Kenane.

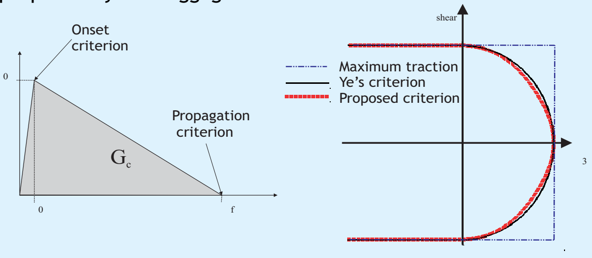

Figure 1. *(a) Bilinear constitutive equation (b) Onset damage surface.*

The formulation presented assures a smooth transition for all mixed-mode ratios between the initial damage surface to the propagation surface through damage evolution.

Results

The model is implemented in the ABAQUS Finite Element code as a user-written element subroutine (UEL). To verify the element under different loading conditions, the double cantilever beam (DCB) test, the end notched flexure (ENF) test, and the mixed-mode bending (MMB) tests are simulated. The numerical predictions are compared with experimental data. (Fig. 3) A good agreement between the numerical predictions and the experimental results is obtained.

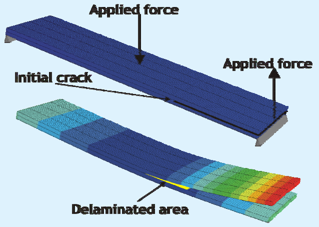

Figure 2. *Undeformed and deformed mesh for a MMB test FE simulation*

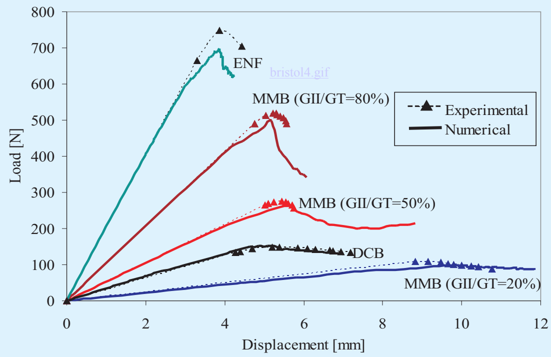

Figure 3. *Numerical and experimental results*

Conclusions

The formulation proposed can predict the strength of composite structures that exhibit progressive delamination, even when the loading conditions, including the mixed-mode ratio, change.

The model is easily implemented in a FE element environment. Currently, it is implemented using decohesion element, but it also can be used in other element technologies such as continuum elements with embedded discontinuities.

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