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Cohesive zone length of orthotropic materials undergoing delamination

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ABSTRACT

Polymer-based laminated composite materials can fail by delamination. Cohesive zone development occurs during delamination, where dissipation mechanisms take place. Within a numerical framework, a fine discretization is needed along the cohesive zone length to accurately capture the non-linear stress distribution. Knowing the cohesive zone length beforehand is important for meshing purposes. This paper presents a literature review of existing analytic expressions. The limitations and range of applicability of the analytic formulas are discussed. Novel empirical formulas are proposed to predict the cohesive zone length of homogeneous orthotropic materials with a crack growing under pure mode I or pure mode II.

1. Introduction

The use of cohesive zone model (CZM) has been widely used to model the non-linear processes which take place at the near tip of cracks. The CZM has satisfactorily overcome some of the limitations of linear elastic fracture mechanics (LEFM) based methods. It takes into consideration the failure process zone (FPZ), which in many engineering applications is not negligible in comparison with other dimensions of the structure (i.e. composite materials).

The CZM was introduced in the early sixties by Barenblatt [1] and Dugdale [2] to model different non-linear processes while avoiding the stress singularity at the front of an existing crack. Barenblatt focused on brittle fracture while Dugdale focused on plastic fracture. Later in the seventies, Hillerborg [3] extended the concept by proposing that a cohesive crack may develop despite the absence of an existing flaw, by introducing crack initiation rules. The CZM assumes that the entire FPZ is lumped into the crack plane. It becomes very efficient in situations where the crack path is known beforehand. For this reason, it is widely used to model delamination in laminated composite materials.

The CZM concept is sketched in Fig. 1. The CZM represents the FPZ (damaged material) through a fictitious crack (dashed line) able to transfer cohesive forces from one face to another. These forces are given by the so-called cohesive law (see Fig. 2), which relates them with the crack opening displacements (COD). The cohesive zone length (CZL) is the distance at the crack plane where the cohesive forces are acting.

Focusing on quasi-brittle materials and within the finite element method (FEM) framework, a fine discretization is needed to correctly capture the stress distribution along the CZL in order to account for accurate energy dissipation. Some researchers state that the range needed along the CZL is from three to ten elements [4,5]. Considering large structures or

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Nomenclature

E_1, E_2	Young's moduli
E'_1, E'_2	plane strain Young's moduli
$\nu_{12}, \nu_{13}, \nu_{23}, \nu_{21}, \nu_{32}, \nu_{32}$	Poisson's ratios
$\nu'_{12}, \nu'_{13}, \nu'_{23}, \nu'_{21}, \nu'_{32}, \nu'_{32}$	plane strain Poisson's ratios
G_{12}, G_{13}, G_{23}	shear moduli
λ, ρ	dimensionless parameters which define the orthotropy of the material
E'_I, E'_{II}	equivalent elastic moduli
τ_I, τ_{II}	interface stress
τ_{Ic}, τ_{IIc}	interface maximum strength
G_{Ic}, G_{IIc}	critical energy release rate
K_{Ic}, K_{IIc}	critical stress intensity factor
l_{chI}, l_{chII}	characteristic length of the material
l^0_{czI}, l^0_{czII}	cohesive zone length in a slender body
$l^\infty_{czI}, l^\infty_{czII}$	cohesive zone length in an infinite body
M^0_I, M^0_{II}	dimensionless parameter of the cohesive zone length for slender bodies
$M^\infty_I, M^\infty_{II}$	dimensionless parameter of the cohesive zone length for infinite bodies
δ_I, δ_{II}	crack opening displacement
$\delta_{Io}, \delta_{IIo}$	onset crack opening displacement
$\delta_{Ic}, \delta_{IIc}$	critical crack opening displacement
k	penalty stiffness
h	specimen thickness
x, y	coordinates
N_e	number of elements within the numerical cohesive zone length
l_e	element length within the numerical cohesive zone length
l_{czim}	modified cohesive zone length
τ_{im}	modified interface strength
n_I, n_{II}	fitting parameter for a given cohesive law type where applicable, subscripts 1, 2, 3 are used to denote principal axes while subscripts I and II denote properties under mode I and II loading, respectively

Acronyms

C-ELS	Calibrated End Load Split
COD	Crack Opening Displacement
CZL	Cohesive Zone Length
CZM	Cohesive Zone Model
DCB	Double Cantilever Beam
ENF	End Notched Flexural
FEM	Finite Element Method
FPZ	Failure Process Zone
LEFM	Linear Elastic Fracture Mechanics
MMB	Mixed Mode Bending

multiple crack paths this requirement might involve a high computational effort. Consequently, it is desirable to know the size of the CZL beforehand in order to have a good compromise between accuracy and computational effort.

On the other hand, different strategies in the literature, reviewed by Bak et al. [6], can reduce this effort using coarser meshes while ensuring accuracy. Turon et al. [4] proposed reducing the strength in order to enlarge the CZL and consequently allow the use of coarser meshes. Strength modification reduces the accuracy on the damage onset prediction. However, once the cohesive zone is developed, the crack propagation is mainly controlled by the fracture toughness rather than the strength of the material [4]. Nevertheless, an accurate CZL expression is required to know how the CZL scales with the strength. Otherwise, the modified strength might lead to convergence problems or incorrect results.

Analytic expressions in the literature predict the CZL of isotropic materials for centrally notched specimens under pure mode I and pure mode II loading. However, these expressions are for limiting scenarios such as a large crack in an infinite sheet or a crack in a slender structure. Numerical investigations [5,7] show that the range of their applicability is not clearly known. Based on the analytic bounds, this paper proposes a general expression to predict the CZL of orthotropic materials under pure mode I and pure mode II loading for any structure size and material property.