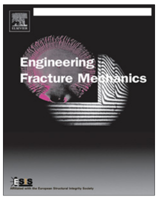
Engineering Fracture Mechanics 146 (2015) 121–138

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech



Adaptive insertion of cohesive elements for simulation of delamination in laminated composite materials

Ofir Shor, Reza Vaziri [*]

Department of Civil Engineering, The University of British Columbia, Vancouver, Canada

ARTICLE INFO

Article history:
Received 22 February 2015
Received in revised form 18 July 2015
Accepted 22 July 2015
Available online 29 July 2015

Keywords:
LS-DYNA
Adaptive element-splitting
Delamination
Cohesive zones
Adaptive cohesive zone
DCB
ENF
MMB

ABSTRACT

A novel technique for efficient simulation of progressive delamination in large-scale laminated composite structures is presented. During the transient analysis, continuum elements within regions where delamination has the potential to initiate are adaptively split through their thickness into two shell elements sandwiching a cohesive element. By eliminating the a priori requirement to implant cohesive elements at all possible spatial locations, the computational efforts are reduced, thus lending the method suitable for treatment of practical size structures. The methodology is verified here through its application to Mode-I, Mode-II and Mixed-Mode loading conditions for which benchmark solutions exist.

1. Introduction

Composite materials are increasingly being used in advanced structural applications. Failure of these materials involves evolution of various damage mechanisms, such as fibre breakage and matrix cracks [38,14], where the debonding of adjacent laminate layers, also known as delamination, is considered to be one of the most dominant damage mechanisms affecting the behaviour of composite laminates. Delamination will usually lead to a reduction in structural stiffness and load carrying capability, and can also lead to instability and premature structural failure under compressive loading [2]. This raises the necessity to predict its initiation and propagation.

Various numerical approaches are aimed at simulating delamination in composite materials. Early methods were based on stress-based criteria, where the inter-laminar and out-of-plane stresses ($\sigma_{13}, \sigma_{23}, \sigma_{33}$) were used to predict the initiation and growth of delamination damage in the material [5]. These models were proven to be effective in capturing the initiation of delamination, but could not capture the scale-effects as in a fracture-based model [7]. Since the delamination damage mode is discrete in nature, it is widely accepted in the scientific community that fracture mechanics principles should be implemented in order to accurately predict delamination initiation and growth.

The Virtual Crack Closure Technique (VCCT), originally developed by Rybicki et al. [34,33], is based on fracture-mechanics principles. Using this method, the strain energy release rate G is calculated numerically, and is compared to some critical value G_c in order to determine whether or not the delamination crack propagates in a given timestep. VCCT was proven

---

[*] Corresponding author.
E-mail addresses: ofir@composites.ubc.ca (O. Shor), Reza.Vaziri@ubc.ca (R. Vaziri).

http://dx.doi.org/10.1016/j.engfracmech.2015.07.044
0013-7944/

Nomenclature

a	length of initial crack
A_{TSLC}	area under the normalised traction–separation law, used as an input to the cohesive material model.
E_{11}	Young's modulus, axial direction
E_{22}	Young's modulus, transverse direction
E_{33}	Young's modulus, normal (out-of-plane) direction
G_{12}	shear modulus, 12 plane
G_{23}	shear modulus, 23 plane
G_{31}	shear modulus, 31 plane
G_{Ic}	critical strain-energy release rate, mode I
G_{IIc}	critical strain-energy release rate, mode II
h	thickness of beam
i	first element to reach the critical value of the element-splitting criteria
l	length of beam
L	length of beam
P	reaction force monitored during the transient analysis
Q	element satisfying the radial search criterion,
R	geometrical radius used by the radial search algorithm
S	parameter used for the element-splitting criterion
S_c	parameter used for the critical value of the element-splitting criterion
t	thickness of beam
$\bar{t}$	normalised traction-stress
XMU	failure parameter used in the cohesive material law
α	user-defined interaction term for cohesive damage growth
β	mode-mixity of the cohesive load
δ_I	crack-opening in the normal direction
δ_{II}	crack-opening in the shear direction
Δ	displacement monitored during the run
λ	normalised crack opening
ν_{12}	major Poisson's ratio, (in-plane)
ν_{13}	major Poisson's ratio, (out-of-plane)
ν_{23}	Poisson's ratio, (transverse plane)
σ_{13}	out-of-plane shear stress in the 13 local material's coordinate system
σ_{23}	out-of-plane shear stress in the 23 local material's coordinate system
σ_{33}	out-of-plane normal stress in the local material's coordinate system
σ_{max}	maximum normal stress in the cohesive interface, before softening begins
σ_{zz}	stress in the global *zz* direction
σ_{zz}^c	critical value of the stress in the global *zz* direction, at which element splitting takes place, in the numerical DCB verification case
τ_{xz}	shear stress in the global *zx* plane
τ_{max}	maximum shear stress in the cohesive interface, before softening begins

to be capable of predicting the evolution of delamination damage under various loading conditions [34,32,37]. Complex delamination patterns were also predicted by the VCCT method, where the strain-energy release rate was used to predict delamination induced damage during a low velocity impact event [22,23]. An overview of the VCCT method and its numerical implementation into finite element codes can be found in [20,21]. A major drawback of the VCCT method is that it requires the presence of an initial crack in the finite element mesh prior to the analysis, which makes the method useful for cases where the exact location of the delamination crack is explicitly known. For cases involving large structures where delamination crack location is unknown, the method becomes less favourable. In addition, since VCCT is based on Linear Elastic Fracture Mechanics, it is limited to cases where the size of the fracture process zone is negligibly small compared to the other structural dimensions. This assumption is not valid for many quasi-brittle materials. In such cases, the fracture process zone, as well as the embedded cohesive tractions have to be modelled explicitly. Cohesive zone models have been developed over the past decades to address the above issues.

In contrast to VCCT, the cohesive zone method, described in detail in [29], allows modelling delamination crack propagation without introducing delamination cracks into the model prior to the analysis. Using this method, the need to calculate the non-physical singular stress field at the crack tip is eliminated by using a force–displacement relation between the nodes in the finite element mesh (traction–separation law) [8]. This law is the basis for computing the delamination crack initiation, propagation, and opening. Thus, cohesive zone models can deal with the nonlinear zone ahead of the crack tip,