Engineering Fracture Mechanics 127 (2014) 104–134

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

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

A floating node method for the modelling of discontinuities in composites

B.Y. Chen [a,b,*], S.T. Pinho [b], N.V. De Carvalho [c], P.M. Baiz [b], T.E. Tay [a]

[a] Department of Mechanical Engineering, National University of Singapore, 21 Lower Kent Ridge Road, Singapore 119077, Singapore
[b] Department of Aeronautics, Imperial College London, South Kensington Campus, London SW7 2AZ, United Kingdom
[c] National Institute of Aerospace, NASA Langley Research Center, Hampton, USA

ARTICLE INFO

Article history:
Received 1 January 2014
Received in revised form 16 May 2014
Accepted 21 May 2014
Available online 12 June 2014

Keywords:
Composites
Phantom node method
X-FEM
Multiple cracks
Crack interaction

ABSTRACT

This paper presents a new method suitable for modelling multiple discontinuities within a finite element. The architecture of the proposed method is similar to that of the phantom node method (which is equivalent to XFEM with Heaviside enrichment), and the solution of it is equivalent to local remeshing within the cracked element. The new method shows several advantages over the phantom node method, such as avoiding errors in the mapping of the crack geometry from the physical to the natural space and avoiding performing integrations over only part of an element. Compared to remeshing, the proposed method enables the representation of discontinuities through relatively closed FE codes (such as user-defined elements) without modifying the initial mesh and geometry, thus making it computationally more efficient. Additionally, the proposed method is particularly suited for modelling weak and cohesive discontinuities and for the representation of complex crack networks; it can model multiple plies and interfaces of a composite laminate, and both matrix crack and delamination, within a user-defined element; the information is shared between the plies and interfaces within such an element, allowing the direct implementation of interactive mechanisms. Verification examples show that the floating node method can predict stress intensity factors and crack propagation accurately. An application example shows that the proposed method can predict well the transition from matrix cracking to delamination and the subsequent saturation of matrix crack density in a c ross-ply laminate.

1. Introduction

With advantages such as light weight, high strength, and strong fatigue and corrosion resistance over traditional metallic materials, fibre-reinforced composite materials are becoming increasingly popular in industrial applications. However, the progressive failure of composites often involves several interacting damage mechanisms across different plies and interfaces of the laminate, which often lead to complex fracture paths [1–3]. Despite decades of research, the high-fidelity prediction of the progressive damage and failure of composites is still a challenging problem. The accurate simulation of the damage accumulation in simple cross-ply laminates [4,5] is already shown to be difficult [6].

---

* Corresponding author at: Block EA, # 02-21, 9 Engineering Drive 1, Singapore 117576, Singapore. Tel.: +65 90286157.
E-mail address: boyang.chen@nus.edu.sg (B.Y. Chen).

http://dx.doi.org/10.1016/j.engfracmech.2014.05.018
0013-7944/

Nomenclature

Latin characters

a	crack length
$A(\bar{j})$	crack area, stored in the dataset of edge j
$A_{\mathrm{W}}, A_{\mathrm{CT}}$	crack area in the crack wake and the crack tip elements, respectively
b	thickness, distance between cracks
$\mathbf{B}$	strain–displacement matrix of a finite element
$\mathbf{D}$	constitutive tensor
$E_{(i)}$	Young's modulus (of the direction $i, i = 1, 2, 3$)
Edge	array which contains the global indices of the edges of an element
$\mathbf{f}$	body force per unit volume
$\mathrm{fDOF}_{\mathrm{D}}/j$	array of internal/shared (on edge j) floating DoF of an element
$\mathbf{F}$	internal force vector at the crack tip
$G_{(ij)}$	shear modulus (in the plane $ij, ij = 12, 23, 13$)
$G_{\mathrm{I}}, G_{\mathrm{II}}$	mode I, mode II energy release rates
$G_{\mathrm{Ic}}, G_{\mathrm{IIc}}$	mode I, mode II critical energy release rates
H	Heaviside function
i_{elem}	global index of an element
$\mathbf{J}$	Jacobian matrix of a finite element
$\mathbf{K}$	stiffness matrix of a finite element
$K_{\mathrm{I}}, K_{\mathrm{II}}$	mode I, mode II stress intensity factors
$K_{\mathrm{Ic}}, K_{\mathrm{IIc}}$	mode I, mode II critical stress intensity factors
$\ell_{\mathrm{W}}, \ell_{\mathrm{CT}}$	crack length in the crack wake and crack tip elements, respectively
L	length
$\mathbf{n}(\bar{j})$	normal of the crack surface, stored in the dataset of edge j
n_W, n_L	number of elements in the width and length directions, respectively
$\mathbf{N}$	shape function matrix of a finite element
N_{edge}	number of edges in an element
$N_{\mathrm{fDOF}_{\mathrm{D}/j}}$	number of internal/shared (on edge j) floating DoF of an element
N_{node}	number of nodes in an element
Node	array of the global indices of the nodes of an element
N_{rDOF}	number of real DoF in an element
$\mathbf{q}$	nodal displacement vector of a finite element
$\mathbf{q}_i$	displacement vector of the node i
$\mathbf{Q}$	nodal force vector of a finite element
rDOF	array of real DoF in an element
S	shear strength for matrix cracking
$\mathbf{t}$	traction on the material boundary
$\mathbf{u}$	displacement vector of a point
$\mathbf{v}$	test function
W	width
W, CT	crack wake and crack tip elements, respectively
R, T	refinement and transition elements, respectively
$\mathbf{x}$	physical coordinates of a point
$\mathbf{x}_{\Gamma_{\Omega_c}}$	nodal coordinates of the cohesive element on Γ_{Ω_c}
$\mathbf{x}_{\Omega}$	nodal coordinates of the finite element on Ω
Y_{t}	transverse tensile strength

Greek characters

ϵ	strain; user-defined non-positive number
$\boldsymbol{\epsilon}$	strain tensor
ϵ_2^{f}	transverse failure strain of a composite lamina
$\bar{\epsilon}$	average strain in the domain
Γ_{Ω}	boundary of a physical domain
Γ_{Ω_c}	surface of a cohesive crack
Γ_{Ξ}	boundary of an integration domain
Γ_{Ξ_c}	integration domain for Γ_{Ω_c}
$\mu(j)$	edge status variable for edge j
ν	Poisson's ratio