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Adaptive floating node method for modelling cohesive fracture of composite materials

X. Lu[a,*], B.Y. Chen[b], V.B.C. Tan[a], T.E. Tay[a]

[a] Department of Mechanical Engineering, National University of Singapore, 117576, Singapore
[b] Faculty of Aerospace Engineering, Delft University of Technology, 2629HS Delft, Netherlands

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ABSTRACT

The cohesive element has been widely employed to model delamination and matrix cracking in composite materials. However, an extremely fine mesh along the potential crack path is required to achieve accurate predictions of stresses within the cohesive zone. A sufficient number of cohesive elements must be present within the cohesive zone ahead of the crack tip, resulting in very high computational cost and time for application to practical composite structures. To mitigate this problem, an adaptive floating node method (A-FNM) with potential to reduce model size and computational effort is proposed. An element with adaptive partitioning capabilities is designed such that it can be formulated as a master element, a refined element and a coarsened element, depending on the damage state in the progressive damage process. A relatively coarse overall mesh may be used initially, and by transforming the element configurations adaptively, the local refinement and coarsening schemes are applied in the analysis. The localized stress gradient ahead of the crack front within the refinement zone is captured by the refined elements. The refinement and coarsening operations are performed at the elemental level with fixed nodal connectivity, so that global successive remeshing in adaptive mesh refinement (AMR) techniques is avoided; this is the key difference between AMR and A-FNM. It is demonstrated that, without loss of accuracy, the present method simplifies the modelling procedure and reduces computational cost.

1. Introduction

Delamination and matrix cracking are two of the most common failure mechanisms for laminated composite materials arising from low-velocity impacts, bearing loads or manufacturing defects. Their interaction and propagation significantly affect the strength and integrity of composite structures [1].

Two explicit approaches are commonly adopted to model fracture in composite materials: the virtual crack closure technique (VCCT) [2,3] and cohesive zone model (CZM) [4,5]. Assuming self-similar crack propagation, VCCT may be performed to calculate the strain energy release rate and predict crack propagation. It has been applied to model delamination migration in composite laminates [6] with an accompanying failure criterion for matrix crack initiation. In general, however, the assumption of an initial crack and requirement for successive remeshing operations make the application of this method rather cumbersome. The other alternative, the cohesive element (CE) method, is formulated based on the CZM and has been widely used to model the onset and propagation of cohesive cracks [7–15]. A cohesive zone (or fracture process zone) is introduced in front of the crack tip to model the material damaging mechanisms. Combined with other numerical methods such as the extended finite element method (XFEM) and

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[*] Corresponding author.
E-mail address: xinlu@u.nus.edu (X. Lu).

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Nomenclature

$\mathcal{A}$	assembly operator	ε	strain
$\boldsymbol{D}$	constitutive matrix	$\boldsymbol{\sigma}$	stress
e	relative error	A-FNM	adaptive floating node method
$\boldsymbol{K}$	stiffness matrix	AMR	adaptive mesh refinement
l_{ch}	characteristic length	B-K	Benzeggagh–Kenane
l_{CE}	length of cohesive element	CE	cohesive element
l_{CZ}	length of cohesive zone	CZM	cohesive zone model
l_{rf}	length of refinement zone	DCB	double cantilever beam
$\boldsymbol{N}$	shape function matrix	DoF	degree of freedom
$\boldsymbol{Q}$	nodal force vector	DM	delamination migration
$\boldsymbol{t}$	traction	ENF	end notch flexure
$\boldsymbol{u}$	displacement	FE	finite element
U	strain energy	FNM	floating node method
δ	variation operator	MMB	mixed-mode bending
Δ	separation	OHT	open-hole tension
ζ	tolerance	SE	solid element
		VCCT	virtual crack closure technique
		XFEM	extended finite element method

floating node method (FNM) [16–25], modified or enhanced CEs have been used to predict the coupled interaction between matrix cracking and delamination propagation.

However, to achieve accurate predictions with the CZM, sufficient number of CEs must be used within the moving cohesive zone ahead of the crack front, which is extremely small compared with the scale of most structures [26,27]. It has been found that significant mesh dependency and over-prediction of structural strength can be expected if coarse CE meshes are adopted in the simulations [12]. Consequently, application of the CE modelling requires an excessively refined mesh (usually determined by the cohesive zone length) along the potential crack path, leading to very high computational expense.

To address the strict mesh size requirement, which is the significant drawback of CE modelling, several numerical techniques have been proposed. Guiamatsia et al. enriched the CE with analytical solutions obtained from the beam on an elastic foundation and hence increased the size requirement in the simulation [28–30]. Turon et al. introduced an engineering solution: by artificially reducing interface strength, CE models with relatively coarse meshes may provide satisfactory results [12]. On the other hand, globally fine meshes can be avoided by employing adaptive mesh refinement (AMR) techniques [31–33]. The meshes ahead of the crack tip were refined to the required length scale while, in the far field, relatively coarse meshes could be used [34–38]. To reduce the number of CEs in the model, Shor et al. adaptively inserted and deleted the CEs around the crack tip region during delamination propagation [39]. Other adaptive modelling techniques and enriched formulations have been researched in the literature [40–44]. Although these techniques may, to some extent, overcome the difficulties of CE modelling, there are also significant limitations. For instance, if reduced interface strength is used, the cohesive traction fields in front of the crack tip could not be faithfully captured and user experience is needed to choose the appropriate mesh size and the corresponding reduced strength parameters. AMR techniques generally require continuing global mesh regeneration and the associated nodal mapping, which in turn increases overall computational cost and implementation complexity.

Within the very small cohesive zone, it is necessary for the mesh to be very fine; however, in the intact and the extensively failed regions, there is no need for such refinement. Based on this understanding, an efficient adaptive floating node method (A-FNM) is developed in this study. The floating node method (FNM) is a recently developed discrete crack method for modelling progressive failure of fiber-reinforced composites [19–21]. In the FNM, besides the standard element nodes, additional floating nodes are included in the formulation to potentially capture discontinuities introduced by the cracks. The performance and accuracy of the FNM have been validated in previous work [19–21]. Based on the same framework, the A-FNM is proposed and an adaptive element is formulated, which may be interchangeably partitioned into one of three configurations (namely, the master element, refined element and coarsened element), depending on the stage of damage evolution experienced by the element. The master and coarsened elements are used in fields far from the critical damaged region while the refined elements are assigned ahead of the crack tip. By altering the element configurations adaptively in the analysis, local refinement and coarsening are achieved within an originally coarse mesh. The refined region moves together with the propagating crack front, more accurately modelling the progressive damage process. This would be particularly useful in cases of advancing delamination or concentrated damage fronts.

Although the presented A-FNM shares some features in common to the AMR, several drawbacks of AMR have been overcome:

- Global successive remeshing is not required: the refinement and coarsening operations in A-FNM are performed on the elemental level. By simply transforming the element configurations, local refinement and coarsening with fixed nodal connectivity is achieved.
- Mapping of nodal information is not required: all the nodal information, e.g., the displacements and the failure indices, is stored in the same element throughout the simulation. Mapping information between different meshes is avoided.
- Specially-designed solvers are not required: the proposed A-FNM can be generally implemented as a user-defined element in commercial finite element (FE) software packages such as Abaqus.