COMPUTATIONAL MODELING OF IMPACT DAMAGE IN LAMINATED COMPOSITE PLATES

A. Ahmed*[1,2], L. J. Sluys[1]

[1] *Faculty of Civil Engineering and Geosciences, Delft University of Technology, The Netherlands*
[2] *Department of Civil Engineering, N-W.F.P University of Engineering & Technology, Pakistan*
* *Corresponding Author: A.Ahmed@tudelft.nl*

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Abstract

A time-dependent, meso-scopic laminate failure model is presented to simulate impact induced damage in laminated composite plates. The computational methodology uses three-dimensional solid-like shell elements to model individual plies of a laminate. Matrix cracking/splitting is modeled using the phantom node method which allows for mesh-independent crack propagation. Delamination damage is modeled using enriched shell interface elements. Numerical results on dynamic crack propagation in laminated composite plates are presented and compared with experimental results. Loading rate effects on damage initiation and growth in fiber-reinforced laminated composite plates are also discussed.

1. Introduction

Experimental studies have revealed that the stress-strain response, damage growth and damage modes in fiber-reinforced laminated composites are sensitive to strain rate effects [1, 2]. The structural response of the laminate is observed to be significantly different at low and high loading rates [3]. An increased loading rate may result in more damage and consequently larger energy dissipation [4]. In addition to this, cracks constrained to move along predefined locations in fiber-reinforced laminated composites (for example matrix cracks propagate along the fiber direction and delamination cracks grow along the interfaces of connecting plies) may propagate at speeds approaching the longitudinal wave speed of a material [1, 5]. Therefore, numerical modeling of initiation and propagation of individual damage processes in laminated composite plates requires efficient and accurate computational models. In addition to this, interaction between different damage mechanisms and their sensitivity to rate effects make computational modeling of these materials a challenge.

Delamination damage is one of the key damage mechanisms in composite laminates, which significantly reduces strength and stiffness of a laminate. Matrix cracks are often considered as precursors of delamination damage [6]. However, for laminates subjected to out-of-plane loading, the degree of anisotropy of individual plies and fiber orientation of the connecting plies also play a vital role in determining the initiation, location, size and extent of delamination damage [7]. Therefore, finite element models used to simulate thin plies of out-of-plane loaded laminates should be capable of accurately predicting the membrane and bending behavior of the laminates. Moreover, accurate predictions of three-dimensional stress states is crucial for accurate predictions of delamination damage in a laminate failure analysis.

Another important damage mechanism is the matrix cracking/splitting. Matrix cracks do not contribute significantly to the reduction of strength and stiffness of a laminate. However, they may induce delamination damage. Additionally, a strong interaction between matrix cracks and delamination damage is observed in [8]. Therefore, computational models should be capable of accurately predicting the initiation, location and evolution of matrix cracks.

In [8] an energy criterion is used to model initiation and growth of matrix cracks and delamination. In [9] interface elements are used to model matrix cracks and delamination damage with three-dimensional brick elements. However, these elements tend to lock (Poisson thickness locking) in thin shell applications. In [10] two-dimensional shell elements are used for laminate analysis. However, these elements do not provide a three-dimensional stress state, which is crucial for delamination.

This paper presents a meso-scopic laminate failure model for the simulation of damage in laminated composite plates subjected to dynamic loads. The three-dimensional computational methodology is based on solid-like shell elements. In this numerical model, two damage mechanisms i.e. matrix cracking and delamination damage are considered. The phantom node method is exploited for modeling matrix cracking in combination with shell interface elements for delamination damage. An impact test on a unidirectional laminated plate is performed to study the rate effects on damage initiation and growth. The effectiveness of the numerical model is demonstrated through an impact test on a cross-ply laminated plate and the results are compared with experimental observations.

2. Laminate failure model

A time-dependent, meso-scopic laminate failure model is presented to simulate impact induced damage in laminated composite plates. The progressive failure model presented in [7] is extended for the simulation of damage in laminated composite plates under dynamic loading conditions. Individual plies of the laminate are modeled using solid-like shell elements with orthotropic material properties, figure 1. The solid-like shell element gives a complete three-dimensional stress state in contrast to traditional Kirchhoff/Mindlin shells/plates. On the other hand, the solid-like shell element does not lock (Poisson thickness locking) in thin shell applications in contrast to the standard brick element. In the present contribution, rate effects are considered to be due to inertial effects and the presence of cohesive inter-ply/intra-ply cracking.

2.1. Matrix cracking

In order to simulate matrix cracking/splitting in laminates, propagating independently of the underlying finite element mesh, the phantom node method is exploited [11]. Damage processes ahead of a crack tip are modeled using the cohesive zone approach. An exponentially decaying cohesive law is used to model the nonlinear behavior of the material inside the cohesive zone. The crack direction is set to be equal to the fiber direction of the ply.

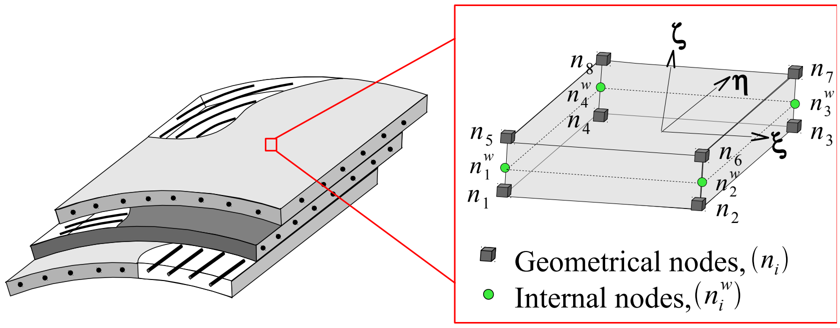


Figure 1. Solid-like shell element and meso-scopic laminate failure model

2.2. Delamination

Delamination damage is simulated using an enriched shell interface element [7]. The element allows for a complete kinematic description of interfaces as opposed to the traditional interface element. Moreover, the enriched interface element carefully takes the interaction between matrix cracking and delamination into account. This is crucial for accurate predictions of the fracture mode, energy dissipation and load capacity. The interface element is able to successfully represent cracked interfaces due to the presence of matrix cracks in the connecting plies.

Remark: The use of linear quadrilateral or linear brick elements for the modeling of cohesive cracking with the XFEM may result in an error in the approximation of the displacement jump field and an un-desirable rotation of the interface [12]. Figure 2 shows a comparison between the use of an interface element and the XFEM/phantom node method analysis results for a quadrilateral finite element containing a crack which is uniformly stretched in horizontal direction. The inaccuracy of the numerical results using the XFEM/phantom node method compared to using interface elements is evident from the figure. The numerical error is due to the unsuccessful transformation of the displacement jump from integration points to the element nodes as a rigid body motion in the XFEM/phantom node method. This is a direct consequence of using bi-linear/tri-linear element shape functions for the approximation of the displacement jump field as [11]

$$[\![\mathbf{u}]\!] = \mathbf{N}[\![\hat{\mathbf{u}}]\!] \quad , \quad [\![\delta\mathbf{u}]\!] = \mathbf{N}[\![\hat{\delta\mathbf{u}}]\!] \tag{1}$$

where $\mathbf{N}$ is a matrix of element shape functions. The shape functions of linear quadrilateral and linear brick elements represent the following polynomial functions

$$\Phi^{quad}(x, y) = \alpha_0 + \alpha_1 x + \alpha_2 y + \boxed{\alpha_3 xy} \tag{2}$$

$$\Phi^{brick}(x, y, z) = \alpha_0 + \alpha_1 x + \alpha_2 y + \alpha_3 z + \boxed{\alpha_4 xy + \alpha_5 xz + \alpha_6 yz + \alpha_7 xyz} \tag{3}$$

Due to the presence of bi-linear/tri-linear terms in these shape functions, the approximation fails to transmit the displacement jump as rigid body motion to the nodes.

The problem can be circumvented using different shape functions for the approximation of the displacement jump field and the continuous displacement field [13]. Alternatively, if the above bi-linear/tri-linear shape functions are used, the error in the approximation of the displacement jump field, and consequently in the stress/strain fields, can be minimized upon mesh refinement [12].

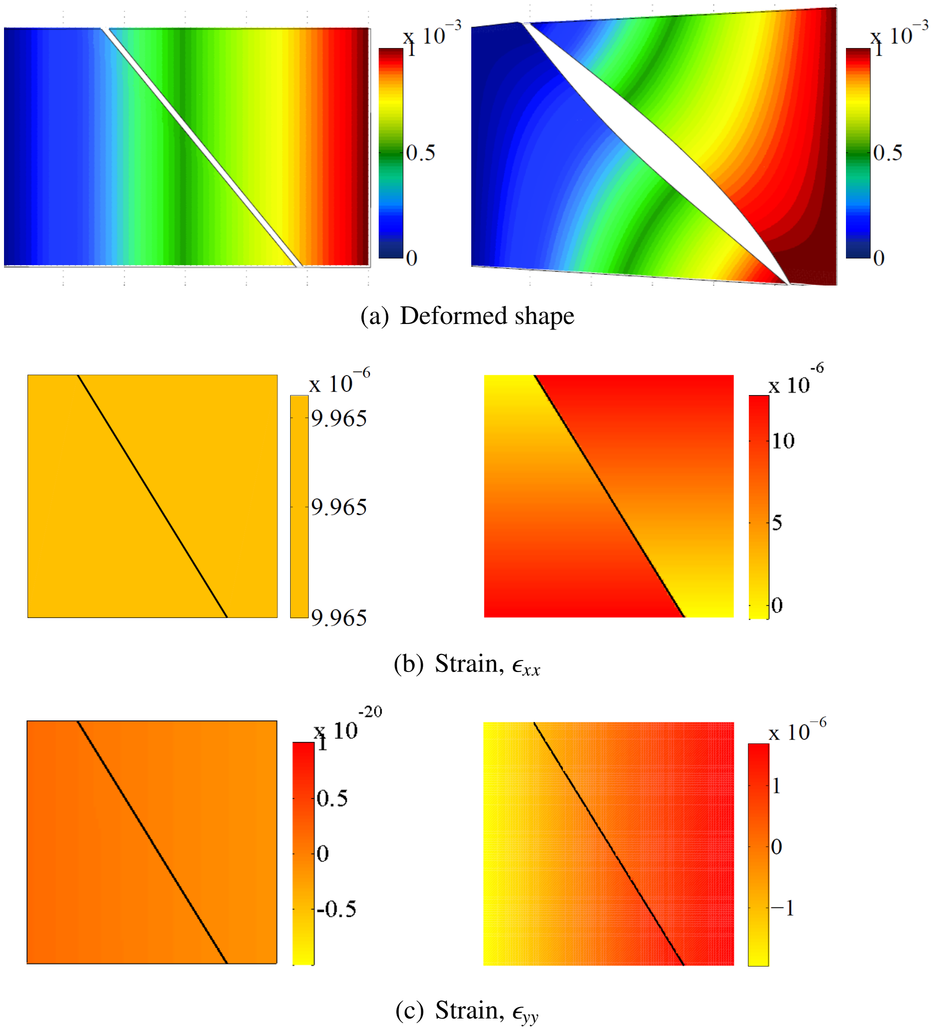


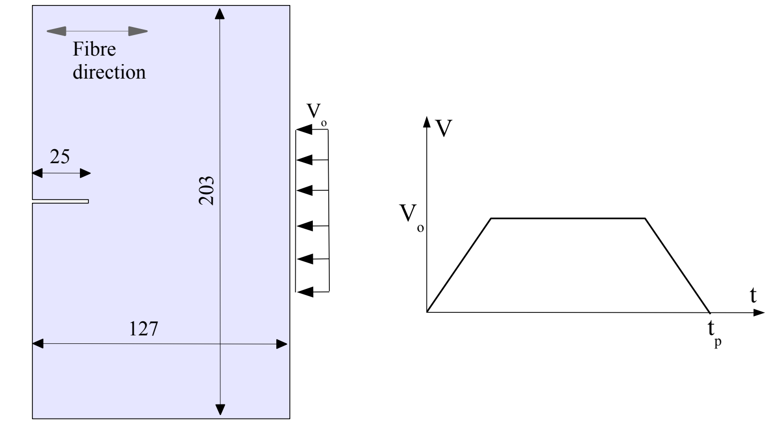
Figure 2. Comparison between interface element and XFEM/phantom node method analyses results; Left: interface element analysis, Right: XFEM/phantom node method analysis

3. Numerical examples

3.1. Mode-I crack propagation in a UD plate

In order to study rate effects on crack propagation in fiber-reinforced composites, numerical simulation of experiments in [5] is performed. Mode-I crack propagation is studied by impacting an edge-notch, unidirectional graphite-epoxy composite plate, figure 3a. The plate is impacted with a velocity V_o and an impact duration of t_p, figure 3b. Impact velocity V_o is reached in 1 μs. The numerical analysis is performed with a lumped mass matrix and the second order accurate central difference method is used for integration in the time domain. The analysis is performed with a time step , dt = 0.001 μs.

In order to study the effect of impact velocity, analyses are performed with V_o = 4, 8 and 12 m/s. Impact duration, t_p is taken to be 27 μs. Results of the analyses are presented in figure 4. Increasing the impact velocity results in earlier crack initiation, figure 4a. Moreover, the time to crack initiation is not varying linearly with increasing impact velocity. Increasing the impact



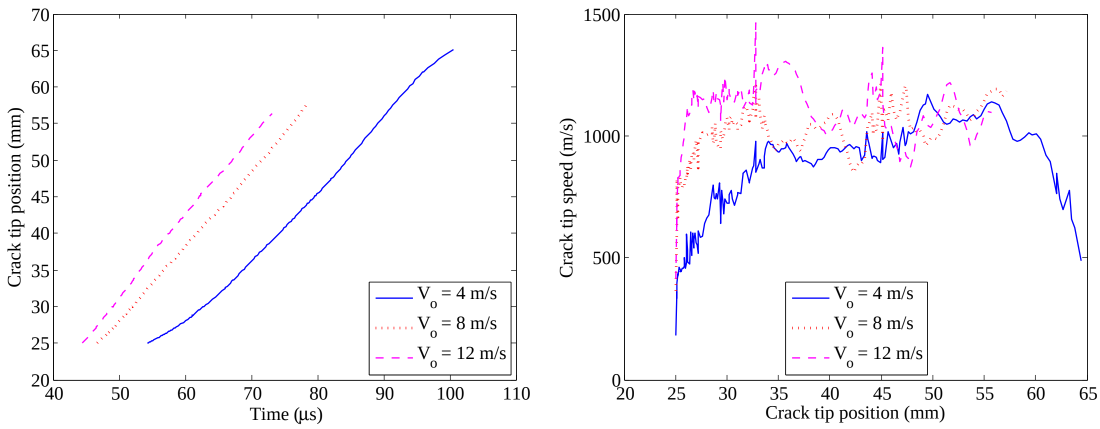
(a) Model geometry
(All dimensions are in mm)

(b) Load history

Figure 3. Impact loaded single-edge notch plate

E_{11} (GPa)	80	$\nu_{12} = \nu_{13}$	0.25	G_{Ic} (N/mm)	0.474
$E_{22} = E_{33}$ (GPa)	8.9	ν_{23}	0.43	G_{IIc} (N/mm)	0.344
$G_{12} = G_{13}$ (GPa)	3.6	ρ (kg/m^3)	1478	f_n (MPa)	35.8
				f_s (MPa)	26

Table 1. Material properties for laminated plate analysis



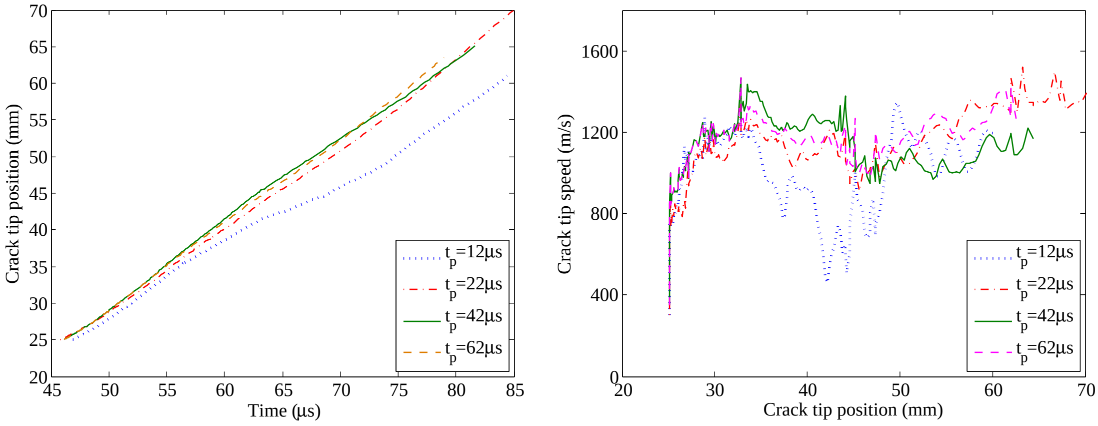
(a) (b)

Figure 4. Effect of impact velocity on crack propagation; (a) crack tip position and (b) crack tip speed

velocity also results in increased crack tip speed, figure 4b.

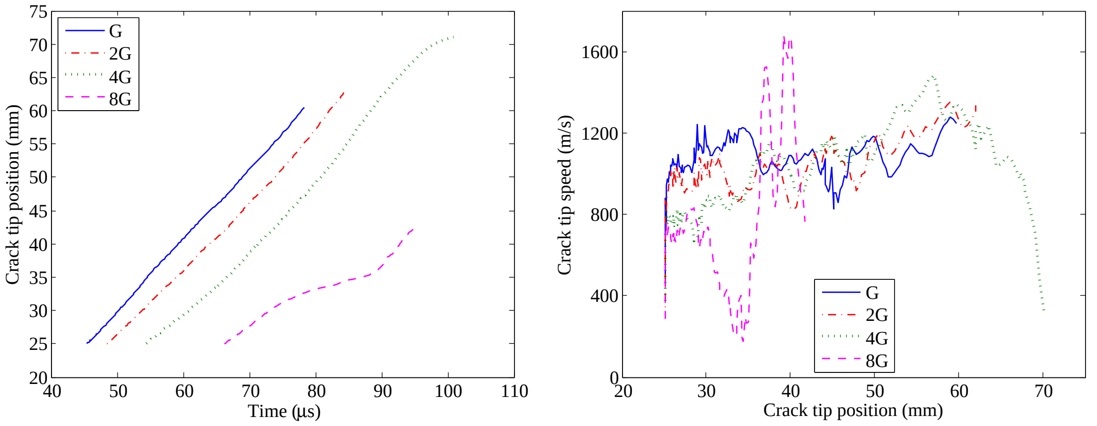
In order to study the effect of impact duration on crack growth, numerical analyses are performed with impact velocity V_o = 10 m/s and impact duration, t_p = 12, 22, 42 and 62 μs. For short impact durations, the crack first accelerates and then arrest for some time before accelerating again, figure 5.

The effect of the fracture toughness (G_c) on crack growth is investigated by scaling the fracture toughness of the material with a factor of 2, 4 and 8. An increased fracture toughness results in more resistance to crack growth, thereby, delaying the crack initiation time (figure 6a) and



(a) (b)

Figure 5. Effect of impact duration on crack propagation; (a) crack tip position and (b) crack tip speed



(a) (b)

Figure 6. Effect of fracture toughness on crack propagation; (a) crack tip position and (b) crack tip speed

decreasing the crack tip speed (figure 6b).

3.2. A square GFRP laminated plate

A square, $[0_{10}/90_{20}/0_{10}]$ graphite-fiber reinforced laminated plate is analyzed. Geometry and boundary conditions of the plate are shown in figure 7. The plate is simply supported on all edges and is loaded with a central transverse load. The load is applied at a rate of 1 N/s. Figure

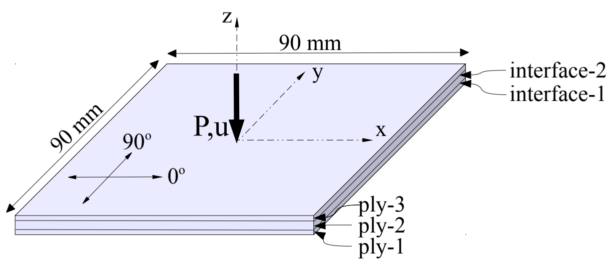


Figure 7. GFRP laminated plate under transverse loading

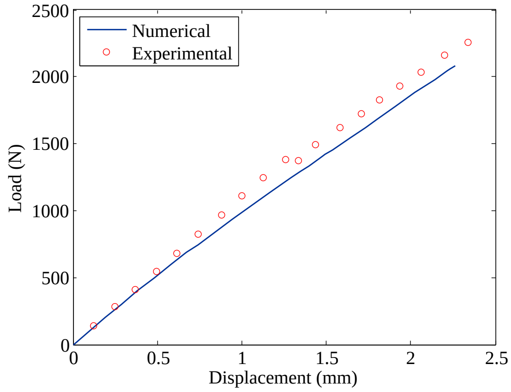


Figure 8. Load displacement curve (laminated plate)

8 shows the load displacement response in comparison with the experimental results [14]. The numerical results show good agreement with the experimental results. Delamination damage at the interface-1 and matrix cracking in ply-1 and ply-2 are shown in figure 9.

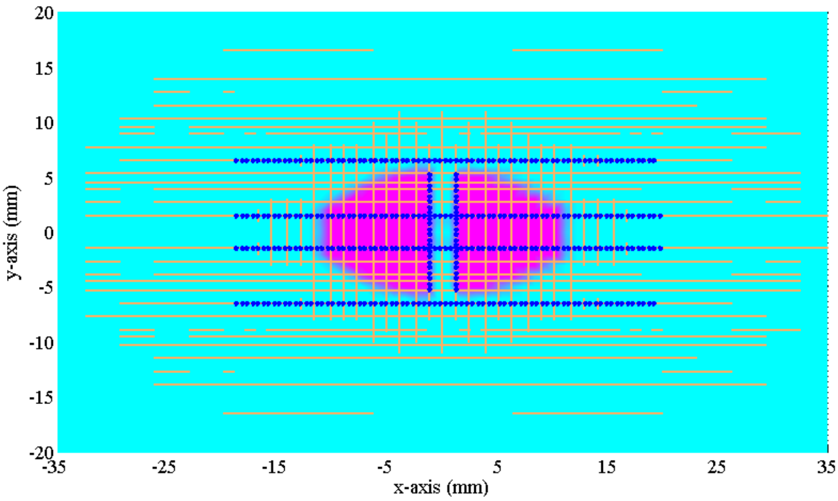


Figure 9. Delamination at interface-1 and matrix cracking in ply-1 (horizontal cracks) and ply-2 (vertical cracks). Dark lines indicate traction-free portion of the cracks

4. Conclusions

A laminate failure model is presented for the simulation of damage in laminated composite plates under dynamic loading. The model allows for a complete three dimensional analysis of laminate failure. The solid-like shell is used to model thin plies of a laminate without having the problem of Poisson-thickness locking, commonly found in traditional brick elements. The computational framework allows for an efficient simulation of matrix cracking/splitting, propagating arbitrarily through solid-like shell finite elements. Moreover, the coupling between different damage mechanisms is taken into account. The effectiveness of the model is demonstrated through an impact test on FRP laminated plates. Numerical results show good agreement with experiment results. Moreover, a rate effect on damage growth has been demonstrated.

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