29th Nordic Seminar on Computational Mechanics
NSCM-29
R. Larsson (Ed.)
2016

DELAMINATION INITIATION AND PROPAGATION MODELLING WITH AN ENRICHED SHELL ELEMENT FORMULATION

JOHANNES FRÄMBY*, MARTIN FAGERSTRÖM AND JIM BROUZOULIS

Department of Applied Mechanics
Chalmers University of Technology, Gothenburg, Sweden
*e-mail: johannes.framby@chalmers.se, web page: http://www.chalmers.se/am

Key words: shells; delamination; XFEM; computational effciency.

1 INTRODUCTION

To meet the increasing demands from regulatory bodies on CO_2 emissions from automotive vehicles, the automotive industry is currently very active in reducing vehicle weight. One significant step is to increase the amount of laminated composites made of Fibre Reinforced Polymers (FRPs) due to their superior specific properties compared to conventional metals. However, the lack of numerical finite element (FE) tools for making accurate predictions of the crash response of structures in FRPs is a major obstacle for the introduction of FRPs in future cars

Traditionally, FE crash simulations are performed using equivalent single-layer (ESL) shell element models, which are well suited to model the thin-walled metal structures in automotive bodies while at the same time being computationally cost effective compared to continuum solid (3D) element models. However, to achieve good predictability of the deformation of laminated composite components in crash simulations, a proper modelling of the delamination process is crucial. At the same time, industrial restrictions on the simulation time of crash simulations implies that detailed modelling of each ply as represented by separate elements through the thickness is not feasible.

Thus, to be able to perform large scale simulations of progressive crash failure in FRPs (*e.g.* to capture delamination) while maintaining a good level of predictability, better suited types of FE-models need to be adopted. Prerequisites for such models are that they need to be both accurate and computationally efficient – a challenge addressed in this contribution.

2 SHELL FORMULATION AND IMPROVED PREDICTION OF TRANSVERSE STRESSES

To address the challenge of accuracy and efficiency, we choose to adopt an ESL shell formulation and describe the delamination failure using local extension of the element formulation following the work by Brouzoulis and Fagerström[1]. In their work the ESL formulation is locally enriched using the eXtended Finite Element Method (XFEM) in order to model an arbitrary number of delaminations.

In order to predict the occurrence of delaminations, an accurate prediction of the delamination driving transverse (out-of-plane) stress components must be achieved. However, a known drawback of traditional shell element formulations is the low accuracy of the through-the-thickness predicted transverse stress components.

In this contribution we utilise a traditional post-processing recovery method, where the transverse stresses are determined from the in-plane variation of the in-plane stresses using the 3D equilibrium equations. The in-plane variations are approximated using a polynomial fit to the stress values in the integration points within a patch of elements. The recovered transverse stresses are then used to locate critical areas where the shell formulation can be locally enriched, such that the kinematics of a delamination can be captured even using an ESL model.

3 ADAPTIVE ENRICHMENT CONCEPT

By combining the adopted enrichable ESL formulation[1] with the stress recovery method we have developed an adaptive methodology for modelling initiating and propagating delaminations[2]. In short the methodology involves the following steps:

1. The laminated structure is built up by a single layer of shell elements through the thickness;

2. The interlaminar transverse stresses, calculated using the stress recovery method, are used in an interlaminar failure criterion

$$f_{\mathrm{I}} = \left(\frac{\langle \hat{\sigma}_{33} \rangle_+}{\sigma_{\mathrm{fn}}} \right)^2 + \frac{\hat{\sigma}_{13}^2 + \hat{\sigma}_{23}^2}{\sigma_{\mathrm{fs}}^2} \geq r_{\mathrm{I}}^2, \quad 0 < r_{\mathrm{I}} \leq 1 \tag{1}$$

   in order to locate any critical elements where delamination will occur. To avoid potential numerical problems at the point of intiation, we propose to enrich new delmination zones at a stress state somewhat lower than the critical state ($r_{\mathrm{I}} < 1$).

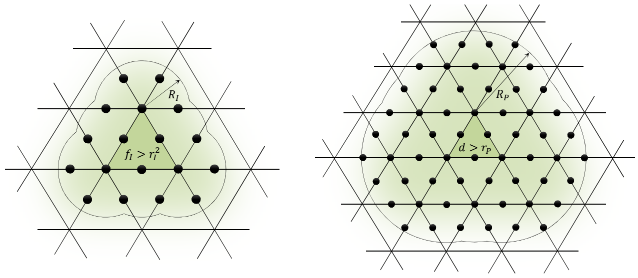
3. The nodes of the predicted initiation element, including a distance R_{I} outside, are locally refined by inserting delamination enrichments and associated cohesive zone models, cf. Figure 1a.

4. In order to model propagating delaminations an expansion criterion is used. This indicates that if any of the elements associated with the delamination reaches its interlaminar failure strength and has started to evolve damage, *i.e.*

$$f_{\mathrm{P}} = 1 \quad \text{if} \quad d > r_{\mathrm{P}} \text{ in } \Gamma^{\mathrm{del}}, \tag{2}$$

   where r_{P} is a small number close to zero and Γ^{del} represents the surface of a delamination, the enrichments are expanded a certain distance R_{P}, cf. Figure 1b.

In this way the additional computational expense, associated with the complicated fracture process in laminated composites, can be limited while at the same time maintaining a high level of accuracy.



(a) (b)

Figure 1: (a) When the initiation criterion in Eq. (1) is met in an element the associated element nodes are enriched (marked by •) along with the nodes within a distance R_{I}. (b) When the expansion criterion in Eq. (2) is activated in an element in the delamination enrichment, the associated element nodes are enriched along with the nodes within a distance R_{P}.

4 NUMERICAL EXAMPLE

To illustrate the methodology we consider a simply supported beam in which delamination enrichments are first to initiate and then allowed to expand.

The beam, which consists of four UD layers, all having the fibre direction along the beam, is loaded by a triangular traction load on top, cf. Figure 2. The beam has a thickness to length ratio of $\frac{h}{L} = 0.5 \times \frac{4}{9}$, which using uniform interlaminar tensile normal and shear strength will result in mode II delamination initiation in mid interface at the supports. The initiation criterion in Eq. (1) is used with a threshold of $r_{\mathrm{I}} = 0.9$

The resulting reaction forces for different values of the initation radius R_{I} and expansion radius R_{P} are in Figure 3 compared to a reference solution, where cohesive zones have been introduced in all interfaces from the start. From Figure 3 it is obvious that the choice of initiation radius R_{I} does not affect the results as much as the choice of expansion radius R_{P}. This is likely due to the fact that the initiation criterion has already enriched a sufficient amount of nodes, allowing the delamination process to be accurately resolved. On the contrary, the expansion radius R_{P} must be set large enough such that it does not obstruct the propagation of the delamination. The relative computational costs for some of the simulations are shown in Table 1.

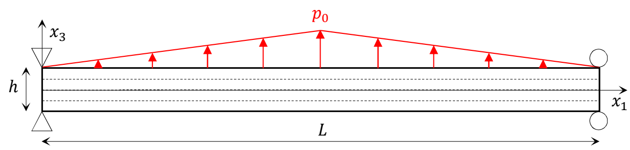


Figure 2: Geometry of the simply supported beam. A vertical traction load is applied on the top surface.

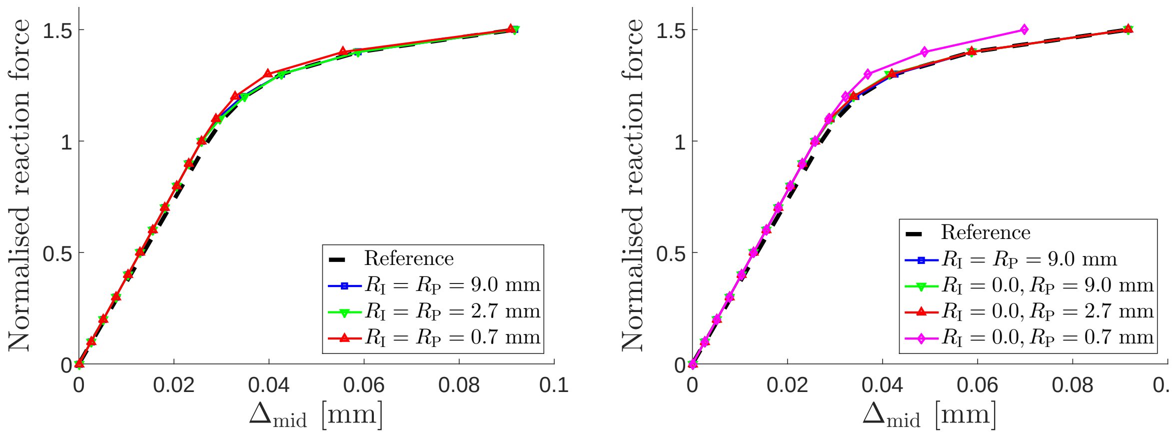


Figure 3: Force versus vertical deflection results from using different initiation and expansion radii. Initiation criterion evaluated using recovered stresses at a threshold of $r_{\text{I}} = 0.9$.

Table 1: CPU-time (normalised in relation to the reference) for simply supported beam with triangular traction load. More than 50 % is saved compared to the reference case.

r_{I}	R_{I}	R_{P}	t_{CPU}
Reference			1.00
0.9	9.0 mm	9.0 mm	0.47
”	0.0 mm	9.0 mm	0.46
”	”	2.7 mm	0.47

5 CONCLUSION

In this contribution we present an adaptive enrichment methodology for the modelling of multiple and arbitrarily located delamination cracks in a laminated structure using an equivalent single-layer shell model. We can conclude that, with proper choice of the expansion parameters, the proposed methodology has the potential to enable computationally efficient *and* accurate simulations of progressive failure in laminated composites.

REFERENCES

[1] Brouzoulis, J. & Fagerström, M. An enriched shell element formulation for efficient modeling of multiple delamination propagation in laminates. *Composite Structures* **126**, 196–206 (2015).

[2] Främby, J., Fagerström, M. & Brouzoulis, J. Adaptive modelling of delamination initiation and propagation using an equivalent single-layer shell approach. *Submitted for international publication* (2016).