Composite Structures 126 (2015) 196–206

Contents lists available at ScienceDirect

Composite Structures

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

An enriched shell element formulation for efficient modeling of multiple delamination propagation in laminates

Jim Brouzoulis, Martin Fagerström *

Department of Applied Mechanics, Division on Material and Computational Mechanics, Chalmers University of Technology, Gothenburg, Sweden

ARTICLE INFO

Article history:
Available online 25 February 2015

Keywords:
Multiple delamination
XFEM
Computational efficiency
Shells

ABSTRACT

In the modeling of progressive damage in fiber reinforced polymers, the kinematical representation of delamination is normally treated in one of two ways. Either efficient or accurate modeling of delamination is considered. In the first case, delamination is disregarded or implicitly included in the material modeling. In the second case, delamination is explicitly modeled at a significant numerical cost where all plies are represented by separate elements in the thickness direction, connected by interlaminar cohesive zone elements. In this paper, we therefore aim to take one step closer to more efficient FE analyses by presenting a modeling concept which supports laminate failure analyses requiring only one shell element through the thickness. With this concept, arbitrary delamination propagation is accounted for only in areas where it is needed. In addition, by using this concept, the model preparation time is reduced. We show that the current shell formulation proposed can be utilized to accurately simulate propagating delamination cracks as well as to accurately describe the kinematics of a laminate containing multiple delaminations through the thickness. Thus, we see significant potential for this modeling concept in analyses in which computationally efficiency is of major importance, such as for large scale crash analyses.

1. Introduction

To meet the sharpening targets from regulatory bodies[1] on CO_2 emissions from cars, the automotive industry is currently very active in reducing vehicle weight, where one significant step is to increase the amount of Fibre Reinforced Polymers (FRPs) due to their superior specific properties (e.g. specific strength and specific energy absorption in axial crushing) compared to conventional metals. The superior energy absorption capability of FRPs has been analyzed experimentally by many authors, cf. e.g. the reviews by Carruthers et al. [1] and Jacob et al. [2]. From these studies, it can be concluded that for Carbon Fibre Reinforced Polymers (CFRPs) the specific energy absorption in axial compression can be higher or significantly higher compared to aluminium and steel grades used in crash structures today, cf. e.g. Hamada et al. [3]. Furthermore, it has been shown, cf. Hull [4] and Grauers et al. [5], that this beneficial material characteristic is the consequence of a very complicated fracture process in the material involving many competing failure mechanisms, e.g. fiber kinking (and breaking) in compression, compressive matrix failure and significant (mixed-mode) delamination. Interestingly, it can be concluded from the paper by Grauers et al. that delamination is one of the governing failure mechanisms. Not as a primary energy absorbing mechanism but definitively in the sense that propagating delaminations significantly influence the overall deformation pattern and thereby, indirectly, the occurrence of the other failure mechanisms. From these observations, it is clear that to achieve accurate predictions of the crashworthiness performance of FRP components in simulations – which is an absolute requirement in the automotive development process today if these materials are to be used – the delamination process needs to be explicitly accounted for in an accurate way.

In addition to accuracy, computational efficiency of the structural Finite Element (FE) analysis is equally important to facilitate full scale crash simulations. Thereby, an efficient approximation and solution method for the modeling of propagating delamination cracks is absolutely crucial to meet today's requirements on virtual development lead times in the automotive industry. Up until now, there have been two variants of how to account for delamination progression in crash (or crush) applications reported in the literature, focusing on *either* efficiency *or* accuracy. With efficiency in

* Corresponding author at: Hörsalsvägen 7, SE–412 96 Göteborg, Sweden. Tel.: +46 31 772 1300.
E-mail address: martin.fagerstrom@chalmers.se (M. Fagerström).

[1] As an example, within the European Union new legislations setting mandatory emission reduction targets for new cars are enforced by the European Commission. According to these reduction targets, the fleet average to be achieved by all new cars is 95 g/km by 2021, corresponding to a reduction of 40% compared with the 2007 fleet average of 158.7 g/km.

http://dx.doi.org/10.1016/j.compstruct.2015.02.055
0263-8223/

focus, shell models with one element through the thickness are used where the delamination propagation is implicitly accounted for by using phenomenological material models which are not based on the physical mechanisms but rather mimicking the total failure process including effects of delamination, cf. e.g. Feraboli [6]. In contrast, with more focus on the accuracy, laminates are modeled with many elements through the thickness (possibly one per ply) connected by cohesive interface elements or similar, cf. Bussadori et al. [7] and Greve and Pickett [8], although with the obvious drawback of increased numerical cost. In this paper, we therefore aim to take one step closer to more efficient FE analyses, while maintaining good accuracy, by presenting a modeling concept which supports laminate failure analyses requiring only one shell element through the thickness, and where arbitrary delamination propagation is accounted for only in areas where it is needed.

The modeling concept we propose is based on the eXtended Finite Element Method (XFEM) [9,10] which allows for mesh independent representations of discontinuities (e.g. cracks and delaminations) by introducing kinematical enrichments locally in the vicinity of the propagating crack(s). Several researchers before us have successfully utilized the XFEM framework to model failure propagation in composites, cf. e.g. Van der Meer et al. [11] modeling matrix cracks and delaminations by combining XFEM enhanced solid elements (matrix cracks) and interconnecting classical cohesive elements (delaminations), Ahmed et al. [12] proposing a geometrically nonlinear discontinuous solid-like shell element for the modeling of intralaminar crack propagation in thin shell structures and Larsson [13] and de Borst and Remmers [14] modeling arbitrarily located single delaminations. In fact, the currently proposed modeling concept is an extension of the works in [13,14], with similarities also to the method proposed for modeling two delamination cracks in beams by Batra and Xiao [15]. However, in contrast to the above mentioned works, the current modeling concept allows not only one but arbitrarily many delaminations to be included in one and the same shell. As a consequence, a structural model of a thin-walled laminate can, by using this modeling concept, initially be built up by a single layer of shell elements through the thickness. During loading, the model is then dynamically enriched in critical areas where delamination is predicted. This means that a significant reduction of total degrees of freedom of the model needed to describe a potentially very complex state of deformation can be achieved, compared to the case where each ply is to be modeled by separate elements (shells or solids) connected by cohesive elements. Thereby, the computational cost is reduced since the total number of degrees of freedom are kept to a minimum.

In the numerical section of this paper we show that the current shell formulation proposed can be utilized to accurately simulate propagating delamination cracks in both mode I and mode II situations. Moreover, we also show that the formulation accurately describes the kinematics of a laminate containing multiple delaminations through the thickness with different sizes. These results thereby indicates that the level of detail in the present approach is such that individual delaminations can be analyzed accurately where present. Moreover, the level of detail (and computational cost) of the model is only increased in areas where delamination actually occurs thereby reducing the computational effort required in large scale analyses. Thus, we foresee the use of this modeling concept in analyses in which computationally efficiency is of major importance.

2. Initial and deformed shell geometry in terms of convected coordinates

As described in the introduction, the primary focus of the current paper is to propose a modeling concept which kinematically can represent arbitrarily many delaminations. We start by presenting the kinematical shell framework which has been considered in the developments of the current modeling concept. The framework consists of three interrelated domains; the inertial Cartesian domain $\mathcal{B}_C$, the undeformed (reference) domain $\mathcal{B}_0$ and the deformed (current) domain $\mathcal{B}$ with pertinent mappings, cf. Fig. 1.

As a staring point, the reference configuration $\mathcal{B}_0$ of the shell is considered parameterized is in terms of convected (co-variant) coordinates $\boldsymbol{\xi}$ as

$$\mathcal{B}_0 = \{\boldsymbol{X} := \boldsymbol{\Phi}(\boldsymbol{\xi})\}, \tag{1}$$

where we introduced the contracted notation $\boldsymbol{\xi} = (\xi^1, \xi^2, \xi^3 = \xi)$ and $\bar{\boldsymbol{\xi}} = (\xi^1, \xi^2)$ for a point in the shell and on the mid-surface respectively[2] Furthermore, the outer boundary of the domains are denoted as Ω with an appropriate subscript depending on configuration. As can be seen from Eq. (1), the mapping $\boldsymbol{\Phi}(\boldsymbol{\xi}) \in \mathcal{B}_0$ maps a point $\boldsymbol{\xi}$ in the inertial Cartesian domain to the corresponding point $\boldsymbol{X}$ in the undeformed reference domain. Associated with the mapping $\boldsymbol{\Phi}$, we also have that the co-variant base vectors $\boldsymbol{G}_i$ in the reference domain are expressed in a general sense as

$$\boldsymbol{G}_i = \boldsymbol{\Phi}_{,i}, \tag{2}$$

where $\bullet_{,i}$ denotes the partial derivative of $\bullet$ with respect to $\xi^i, \quad i = 1,2,3$.

In a similar fashion, the deformed geometry is described by the deformation map $\boldsymbol{\varphi}(\boldsymbol{\xi}) \in \mathcal{B}$ from the inertial Cartesian frame as

$$\mathcal{B} = \{\boldsymbol{x} := \boldsymbol{\varphi}(\boldsymbol{\xi})\}. \tag{3}$$

The pertinent co-variant base vectors in the deformed domain thereby becomes

$$\boldsymbol{g}_i = \boldsymbol{\varphi}_{,i}. \tag{4}$$

Associated with the deformation from the undeformed to the deformed configuration, we obtain the deformation gradient $\boldsymbol{F}$ as

$$\boldsymbol{F} = \boldsymbol{x} \otimes \nabla_X = \boldsymbol{g}_i \otimes \boldsymbol{G}^i, \quad i = 1,2,3 \tag{5}$$

where we have also introduced the contra-variant base vectors $\boldsymbol{G}^i = \partial \xi^i / \partial \boldsymbol{X}$ in the reference configuration which are obtained (in a standard manner) as

$$\boldsymbol{G}^i = G_{ij}^{-1} \boldsymbol{G}_j \tag{6}$$

using the metric tensor $G_{ij} = \boldsymbol{G}_i \cdot \boldsymbol{G}_j$.

3. A concept for modeling multiple delaminations in shells

To describe multiple delaminations within one and the same shell element, the above defined deformation maps need to be extended to allow for displacement discontinuities across delamination interfaces. To do so, we propose to locally enrich the displacement approximation of the shell in the vicinity of interlaminar cracks in line with the XFEM, cf. SubSection 3.2 below. However, as a basis for this extension of the deformation maps, we first discuss the geometric description of interlaminar cracks in this context.

3.1. Geometric description of interlaminar cracks using level sets

Consider a laminate built up from a number of plies, each defined by lying at a constant distance from the mid-surface. Let this laminate contain N_{del} delamination surfaces, where Γ_k represents such a surface in the reference configuration, with

[2] To avoid confusion, we will from here on only use $\bar{\xi}$ to denote the in-plane coordinates and ξ to denote the out of plane coordinate. As a consequence, any appearance of e.g. ξ^2 should be interpreted as $(\xi^3)^2$.