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Failure mechanism based modelling of impact on fabric reinforced composite laminates based on shell elements

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ABSTRACT

A shell element based modelling strategy for simulating impact on fabric reinforced laminated composites within the framework of the Finite Element Method is presented. Thereby, each ply of the laminate is represented by its own layer of shell elements. The interfaces in-between are discretised by cohesive zone elements. Material nonlinearities within plies, i.e. fibre rupture, matrix cracking and plasticity-like effects, and interfaces, i.e. delamination, are accounted for by appropriate constitutive laws. Impact simulations of a rectangular laminated composite plate with quasi-isotropic layup in a drop tower test setup are conducted. The predictions are based on material parameters partly from corresponding material data sheets and partly estimated from the literature. Thus, no inverse model calibration is applied. The acquired simulation results are validated with accompanying experiments. The predicted spatial distribution of ply damage and delaminations, as well as the associated energy absorption agree very well with the experimental results. The approach shows excellent performance in terms of computational efficiency such that simulations of the impact behaviour of structural composite components become feasible.

1. Introduction

Many lightweight applications, ranging from aerospace structures over automotive components to sports equipment, demand materials with high stiffness-to-weight and strength-to-weight ratios. Laminated composites based on fibre reinforced polymers (FRPs) exhibit these beneficial characteristics and are widely used within in these industries. However, FRP composites show a complex damage and failure behaviour involving various modes of failure. These include debonding of individual plies, matrix cracking, fibre rupture and plasticity like effects. Considering out-of-plane impact loading, all of these mechanisms are likely to be observed. An overview of the general impact behaviour of FRP laminates is given in the review papers [1,2]. In order to understand the structural behaviour of FRP laminates subjected to out-of-plane impact, the extent of each mechanism and its effect on the overall mechanical behaviour needs to be investigated.

Experimental testing gives insight to the overall impact behaviour of certain specimens under certain loading conditions. However, it is very time consuming and expensive to investigate a variety of different impact scenarios. The experimental investigation of the impact behaviour of structural "real life" components involves even more difficulties. In this regard, numerical simulations by means of advanced methods within the framework of the Finite Element Method (FEM) provide a powerful tool for predicting the damage and failure behaviour of laminated composites subjected to impact.

FEM simulations of low velocity impacts and predictions of the general impact behaviour of unidirectionally reinforced FRP coupon specimens have been extensively reported in the literature, cf. [3–7]. These models feature ply-level discretisations using three dimensional continuum elements in combination with tri-axial constitutive models, where their main focus is put on the investigation of barely visible impact damage, i.e. delaminations and matrix cracking. A drawback of the continuum element discretisation within these models is a quite long computing time, even for models at coupon specimen level. Considering high velocity impact, most publications focus on the ballistic case, cf. [8–10], where impact of small projectiles with low mass is investigated. However, the authors haven't found any computational studies on impact scenarios at intermediate velocity in

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combination with intermediate impactor mass in the open literature. Moreover, to the authors' knowledge, studies dealing with the simulation of impact on fabric reinforced laminates up to complete perforation haven't been reported in recent years.

This paper presents a strategy for modelling and simulating the intermediate velocity/mass impact behaviour of fabric reinforced laminates up to complete perforation. Special attention is directed towards numerical efficiency in order to open the possibility for simulating impact on structural components much larger than coupon specimens within reasonable computation time. Therefore, a ply-level based discretisation in combination with shell elements is proposed. As an example of the proposed modelling strategy, numerical predictions of a rectangular laminated composite plate with quasi-isotropic layup in a drop-tower test setup are presented. The simulations are realised using the explicit FEM code Abaqus/Explicit v6.14 (Dassault Systemes Simulia Corp., Providence, RI, USA). Accompanying experiments are conducted in order to validate the proposed numerical model.

2. Modelling impact on laminated fabric composites

Impact on laminated composites, in general, is a highly dynamic loading scenario involving nonlinear material behaviour. An overview of occurring damage and failure modes within FRP laminates for different impact scenarios is given in Refs. [1,2]. The acting mechanisms can be categorised by their location of occurrence into intra-laminar and inter-laminar mechanisms. The intra-laminar failure mechanisms include matrix cracking, fibre rupture and plasticity like effects whereas inter-laminar failure denotes the debonding of adjacent plies, i.e. delamination. Each of these mechanisms contributes to the overall response of the laminate and their interaction results in penetration or even perforation of the laminate, depending on the actual impact scenario. Hence, meaningful predictions require a mechanism based modelling approach. This encompasses the modelling and simulation of propagating damage and failure of several mechanisms using suitable constitutive theories applied at appropriate geometrical length scales.

The proposed modelling strategy provides the ability to predict the overall energy absorption of a laminate subjected to transverse impact as well as the energy contributions of individual mechanisms. Furthermore, the approach is suitable to simulate complete perforation of the laminate. The modelling strategy is realised within the framework of the FEM, whereby an explicit time integration scheme is applied in order to simulate the highly nonlinear dynamic impact response of the laminate.

2.1. Geometrical modelling

Within this work, laminated composites consisting of several layers of fabric plies are considered. The smallest length scale to be resolved within the geometrical modelling is chosen to be the ply-level. Thereby, the laminate is modelled as a stack of various homogeneous orthotropic layers connected via inter-laminar interfaces, cf. [11]. The mid-plane of each ply is discretised by an individual layer of shell elements whereas the interfaces are represented by hexahedral elements in combination with a cohesive zone approach. These cohesive zone elements (CZE) share the nodes of the adjacent shell layers located at the corresponding plies' mid-planes. Hence, the in-plane dimensions of the CZEs are identical to the dimensions of the corresponding shell elements and their thickness corresponds to the normal distance between adjacent shell layers. It shall be noted that despite their finite geometrical thickness, the CZEs model the mechanical behaviour of a zero-thickness interface since a traction-separation based constitutive law is applied, as will be discussed in Section 2.2. The total mass of the laminate is distributed between the plies and the interfaces, since the explicit FEM code Abaqus/Explicit demands that every element within the computational domain is assigned some mass density. As Abaqus/Explicit uses lumped mass matrices, the nodal masses remain unchanged and the dynamic behaviour of the laminate is retained, regardless of the actual mass distribution between plies and interfaces. This arrangement is called stacked shell approach (SSA) in the following and is schematically depicted in Fig. 1. Major benefits in terms of computational efficiency of the proposed SSA arise from the use of shell elements for modelling the intra-ply behaviour of the composite. This way, the required amount of degrees of freedom is reduced significantly compared to an equivalent model discretised by three dimensional continuum elements, cf. [12]. Linearly interpolated continuum elements, as usually applied in explicit FEM codes, require aspect ratios close to one and considerably small element dimensions in order to alleviate the effect of shear locking which typically occurs during bending deformations. In the context of Fig. 1, moreover, each ply should be discretised by two or more continuum elements in thickness direction in order to describe the possibly nonlinear stress distribution over ply thickness. In this respect, a shell element based discretisation allows larger element dimensions due to its kinematic assumptions and, furthermore, the discretisation in the thickness direction of the plies is not necessary.

A further advantage of the use of a shell element based discretisation arises from the definition of the smallest stable time increment of the explicit time integration scheme. In general, it is dependent on the material properties and the smallest element dimension of the mesh. Considering a mesh composed of continuum elements, the smallest element dimension is governed by the usually small ply thicknesses of the laminate. However, when using shell elements the smallest element dimension is governed by the in-plane element dimensions which, typically, are significantly larger than the ply thicknesses. Hence, larger stable time increments arise resulting in shorter computation times. A limitation of the shell formulation lies in the fact that damage and failure within the shell layers representing individual plies results from in-plane stress and strain components only. However, the out-of-plane stress state is resolved within the CZEs at the interfaces between adjacent plies. This way, delamination due to transverse shear and out-of-plane tension is accounted for, provided appropriate constitutive theories are applied. Hence, impact scenarios where bending effects are dominating the overall response and ply damage and failure occurs due to in-plane stresses and strains are fully covered by the SSA. Scenarios where ply failure occurs due to transverse crushing of the laminate, as typically observed for high velocity impact, are beyond the scope of the SSA.

2.2. Constitutive modelling

The constitutive behaviour is described using individual constitutive laws for plies and interfaces. The fabric reinforced plies are modelled as homogeneous orthotropic material in combination with an energy based continuum damage mechanics approach to

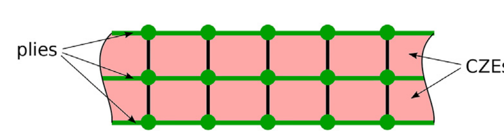

Fig. 1. Schematic illustration of the stacked shell approach (SSA). The plies are represented by the shell layers at the plies' mid-planes where the corresponding nodes are marked as dots. The CZEs are illustrated as shaded areas confined by black lines.