ARTICLE IN PRESS

Composites: Part A xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Composites: Part A

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

Implementation of failure criteria for transverse failure of orthotropic Non-Crimp Fabric composite materials

Henrik Molker [a,b,*], Renaud Gutkin [c], Leif E. Asp [b]

[a] Durability CAE Body & Trim, Volvo Car Corporation, 405 31 Gothenburg, Sweden
[b] Department of Applied Mechanics, Chalmers University of Technology, 412 96 Gothenburg, Sweden
[c] Swerea SICOMP AB, Box 104, 431 22 Mölndal, Sweden

ARTICLE INFO

Article history:
Received 21 January 2016
Received in revised form 28 September 2016
Accepted 29 September 2016
Available online xxxx

Keywords:
Carbon fibres
Strength
Finite element analysis (FEA)
Failure

ABSTRACT

In this paper a set of failure criteria for Non-Crimp Fabric (NCF) reinforced composites is implemented in a Finite Element (FE) software. The criteria, implemented at the ply level, predict transverse failure of NCF reinforced composites, in particular accounting for their inherent orthotropic properties. Numerical simulations are compared with tests on specimens with a generic design feature found in automotive structures. The current implementation enables correct prediction of failure mode and location.

1. Introduction

The present research is part of a bigger effort aiming at identifying and further developing industrially efficient, yet scientifically based, Computer Aided Engineering (CAE) methods for vehicle structures made of high performance Carbon Fibre Reinforced Polymers (CFRP). CFRP automotive bodies today can be 50% lighter compared to corresponding steel alternatives and 30% lighter than aluminium alternatives with similar or improved stiffness, durability and crash worthiness properties. CFRP structures are therefore an outstanding alternative for lowering the weight of load carrying structures needed to meet future requirements on emissions and energy consumption.

Amongst the different types of composite materials available, Non-Crimp Fabric (NCF) reinforced composites manufactured by Resin Transfer Moulding (RTM) [1,2] are strong candidates for the automotive industry. NCF reinforced composite materials are orthotropic [3] in contrast to traditional transversely isotropic Uni-Directional (UD) fibre composites. In particular, uni-weave NCF reinforced composites have been found to have significantly lower out-of-plane strength compared to the transverse in-plane strength [4,5].[1] In tension in the out-of-plane direction, this is explained by the interbundle failure mode occurring at the interface between the fibre bundle and surrounding matrix [4,6]. Established physically based failure criteria developed for UD composites [7,8] do not take this orthotropic behaviour into account.

When composite structures are designed it is desirable to avoid out-of-plane loading conditions, or use guidelines to minimize the risk of out-of-plane loading [7]. However, avoiding this will not be possible within the automotive industry where many features and details are incorporated in the structures that are subjected to complex load cases. Being able to accurately predict failure initiation then becomes even more important when using materials with orthotropic properties, whose out-of-plane strength is lower than the transverse in-plane strength.

Current state of the art physically based failure criteria, e.g. Puck and Schürmann [8] and LaRC05 [9], assume transverse isotropy and cannot capture the orthotropic nature of transverse failure observed for NCF composites [4,6]. Consequently, to allow the use of NCF composites in automotive applications, failure criteria accurately predicting failure initiation under general 3D stress states were proposed and compared with other failure criteria by Molker et al. [6].

This paper presents the implementation of a set of physically based failure criteria for transverse failure initiation in NCF reinforced composites, taking the orthotropic nature into account. The implementation is done in the commercial FE code Abaqus/Standard. The criteria have been developed in a previous work [6] and are based on the LaRC05 criteria [9], adapted to

* Corresponding author at: Durability CAE Body & Trim, Volvo Car Corporation, 405 31 Gothenburg, Sweden.
E-mail address: henrik.molker@volvocars.com (H. Molker).

[1] The authors are not aware of any studies on multi-axial NCF reinforced composites to show if the low out-of-plane tensile strength is general to all NCF reinforced composites or limited to uni-weaves.

http://dx.doi.org/10.1016/j.compositesa.2016.09.021
1359-835X/

address the orthotropic properties with an additional failure mode. Assessment of the numerical approach is performed by comparison to test data from specimens with a generic design feature that can be found in real automotive applications.

2. Failure of NCF reinforced composites

NCF reinforced composites are not transversely isotropic as UD reinforced composites. Failure initiation criteria developed for UD reinforced composites cannot therefore be used to predict failure initiation in NCFs. A set of criteria presented by Molker et al. [6] addresses this for transverse failure by introducing an additional failure mode for transverse out-of-plane failure initiation.

The new failure criterion for out-of-plane transverse failure is added to the LaRC05 set of criteria [9] for initiation of transverse failure. LaRC05 has been chosen as it is physically based and its predictive capability has been verified in the World Wide Failure Exercise [10]. The material properties needed can be found from standard material tests. The additional criterion for out-of-plane transverse failure could also be used together with other criteria for UD reinforced composites, e.g. Puck and Schürmann [8], LaRC04 [11] or the criteria proposed by Catalanotti et al. [12], which address some additional aspects of failure initiation.

Interbundle failure has been found to initiate at the outer region of a fibre bundle propagating to the matrix surrounding the fibre bundles. Therefore, it is treated as a failure mode inside the composite material and not as delamination between plies of NCF reinforcements. However, it is noted that the criterion for the interbundle failure mode uses a polynomial stress based approach similar to Ye's delamination onset criterion [13].

The present article focuses on the implementation of the proposed set of criteria for transverse failure of NCF reinforced composites [6]. Comparisons to other failure criteria were made in Ref. [6] against a criterion for NCF reinforced materials proposed in the literature [14,15] and a meso-mechanical FE model, with good agreement.

2.1. Failure criteria for NCF reinforced composites considering two modes of transverse failure

NCF reinforced composites can be evaluated, taking the orthotropic strength and different failure modes into account, by introducing the failure criteria presented previously by Molker et al. [6]. In these criteria, an additional mode is introduced for transverse matrix related failure to complement the LaRC05 matrix failure criterion.

The additional transverse failure mode, denoted as transverse interbundle failure, is observed for out-of-plane tensile loading, at the interface between the impregnated fibre bundle and the surrounding matrix [6]. The fracture plane is perpendicular to the thickness direction, as illustrated for Bundle I in Fig. 1. The strength for this mode is significantly lower compared to the transverse intrabundle failure mode, shown in Fig. 1, Bundle II. The transverse interbundle failure mode in NCF reinforced composites is evaluated on a fracture plane perpendicular to the thickness direction. The failure initiation is evaluated using a failure criterion based on the traction acting at the Matrix Interface (MI), using the shear strengths $S_{T,MI}$ and $S_{L,MI}$ and out-of-plane strength Z_T. This failure index is denoted $FI_{M,MI}$.

$$FI_{M,MI} = \left(\frac{\tau_{T,MI}}{S_{T,MI}}\right)^2 + \left(\frac{\tau_{L,MI}}{S_{L,MI}}\right)^2 + \left(\frac{\sigma_{N,MI}}{Z_T}\right)^2 = 1, \quad \text{if } \sigma_{N,MI} > 0. \quad (1)$$

Interbundle failure initiation is only computed, using Eq. (1), if the out-of-plane normal stress is positive. Therefore, if a high level of out-of-plane shear stress combined with low out-of-plane compressive stress is applied to the material the model assumes that no interbundle failure can occur. This assumption has been made as no experimental results are available for such load cases. In Eq. (1), for convenience the shear strength $S_{T,MI}$ and $S_{L,MI}$ are assumed equal to the interlaminar shear strength (*ILSS*), as this failure occurs within the matrix material,

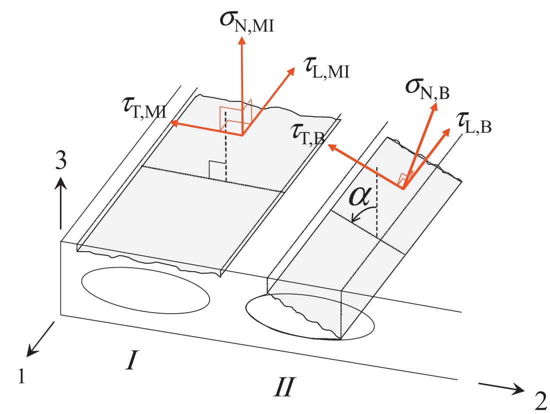

Fig. 1. Transverse fracture planes within a NCF lamina. Transverse interbundle failure at Bundle I, with a fracture plane perpendicular to the thickness direction. Transverse intrabundle failure at Bundle II, with a fracture plane at an angle α inside the fibre bundle. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$$S_{T,MI} = S_{L,MI} = ILSS. \quad (2)$$

The transverse intrabundle failure mode is evaluated using the LaRC05 criterion for matrix failure [9], denoted $FI_{M,B}$, and including in-situ effects, denoted by superscript is [9].

$$FI_{M,B} = \left(\frac{\tau_{T,B}}{S_T^{is} - \eta_T \sigma_{N,B}}\right)^2 + \left(\frac{\tau_{L,B}}{S_L^{is} - \eta_L \sigma_{N,B}}\right)^2 + \left(\frac{\langle \sigma_{N,B} \rangle_+}{Y_T^{is}}\right)^2 = 1 \quad (3)$$

where the transverse shear strength S_T is based on the transverse compressive strength Y_C as:

$$S_T = Y_C \cos(\alpha_0)\left(\sin(\alpha_0) + \frac{\cos(\alpha_0)}{\tan(2\alpha_0)}\right) \quad (4)$$

and where the friction parameters η_T and η_L are related to the shear strengths S_L and S_T as:

$$\frac{\eta_T}{S_T} = \frac{\eta_L}{S_L} \quad (5)$$

and Y_T denotes the in-plane tensile strength and S_L the longitudinal shear strength. In-situ values for the strength parameters, S_T, S_L and Y_T, are calculated according to Ref. [9].

The transverse failure index FI_M is evaluated as the highest of $FI_{M,MI}$ and $FI_{M,B}$ for all potential fracture planes (with angle α) for the current stress state.

$$FI_M = \max\left(FI_{M,MI}, \max_{\alpha=[0^\circ,180^\circ[}(FI_{M,B})\right) \quad (6)$$

2.2. Implementation in finite element software

Failure can initiate in any direction within the material and is determined by the current 3D stress state. Therefore, solid elements were used. Cohesive elements could have been used to trigger the interbundle failure as this occurs on a fracture plane perpendicular to the thickness direction. However, as only initiation is considered in the present work, this would create a more complex model that would increase the computational cost and the model preparation time.

The proposed failure criteria are implemented in Abaqus/Standard [16] using a user defined subroutine UVARM [16], which is