EFFICIENT SIZING METHODS FOR COMPOSITES PRIMARY STRUCTURES IN AUTOMOTIVE APPLICATIONS

H. Molker[a,c*], R. Gutkin[b], M. Oldenbo[a], L. E. Asp[b,c]

[a]*Volvo Car Corporation, Durability CAE Body & Trim, 405 31 Gothenburg*
[b]*Swerea SICOMP, 431 22 Mölndal, Sweden*
[c]*Chalmers University of Technology, Department of Applied Mechanics, 412 96 Gothenburg, Sweden*
**henrik.molker@volvocars.com*

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Abstract

In this paper, a set of failure criteria for Non Crimp Fabric (NCF) composites are presented. The proposed failure criteria are physically based and can take into account the orthotropic character of NCF composites by addressing the lost transverse isotropy. The criteria are compared to experimental data and show good agreement.

1. Introduction

To meet future 2020+ road vehicle energy consumption targets, a technology step by introducing Carbon Fibre Reinforced Plastics (CFRP) in vehicle structural parts, mainly body parts, has started in the automotive industry. This relates to the outstanding weight saving potential of these materials compared to metal alternatives. CFRP automotive bodies today are considered 50% lighter compared to corresponding steel alternatives and 30% lighter than aluminium alternatives with similar or better stiffness, durability and crash worthiness properties [1]. Further potential is anticipated by more recent studies, up to 60% [2] or even as much as 70% [3] with CFRP compared to steel.

The traditional way of making carbon fibre composites is through stacking of preimpregnated sheets (pre-pregs) using inexpensive tooling and curing the shaped structures in an autoclave. This is a time consuming process and to meet the requirements of the automotive industry, new processes will have to be used and need to be developed. Cost effective textile preforming techniques together with improved infusion techniques are promising methods [4]. One important family of such composites are Non-Crimp Fabric composites (NCF).

Car body development is simulation driven and requires efficient methodology to analyse and optimise the design. Current steel bodies are developed fully by virtual tools and a similar approach is needed for future CFRP bodies as well. This means that a cost-efficient, yet robust, design methodology for CFRP car components must be developed. The need for a rational design process will require models for prediction of failure initiation as well as damage progression up to final failure. For full-scale analyses, the methodology to be developed most likely needs to consider local-global analysis schemes as done in aircraft design today [5]. Furthermore, a procedure for composite car structural design validation including hot spot criteria must be developed and verified.

A common approach to analyse strength of laminated composites is to calculate a failure index for each ply within the laminate, and assume that failure occurs when the failure index in a given ply reaches one. This is referred as "first ply failure" which means that the highest loaded ply is the most critical for design. A wide range of failure theories is currently available, from polynomial fit as the Tsai-Wu criterion [6] to more advanced, and physically based, criteria like the Puck [7] or LaRC05 [8], for traditional Uni-Directional (UD) composites, like tape-based systems. However, these methods often need further development or refinement to be used for new types of composites with textile preforms, e.g. NCF composites, which are used and under development for use in high volumes in the automotive industry.

The focus of the research presented in this paper is preparing for enhanced analysis capability of textile based composites. The LaRC05 criterion developed for UD composites, is extended to be valid for textile composites suitable for the automotive industry. The failure criteria should be on a homogenised ply basis for each layer within a textile composite.

Once such failure criteria are established for NCF-composites, it can be the basis for hot-spot criteria that can be used when setting up a framework for the analysis procedure of structural components.

2. Background

2.1. Material physics of bundle based textile composites

Textile composites consisting of fibre bundles with UD fibres kept together with a knitting yarn are known as Non Crimp Fabric (NCF) composites, see figure 1. The advantage of these textiles compared to traditionally woven textiles, is that the waviness of the fibres is reduced, which improves the properties. The architecture of NCFs can be tailored to fit the needs of the structure. NCF blankets can consist of either a single layer of fibre bundles in one direction, called an NCF uni-weave, or several layers of bundles in different directions stacked on top of each other, i.e. a multi-axial NCF blanket. The layers are kept in place by knitting yarn (in the warp (longitudinal) and weft (transversal) directions).

The knitting yarn effects the properties of the composite such that the mechanical properties in the plane transverse to the fibres, *Y-Z* plane in figure 2, no longer are transversely isotropic [9]. In contrast to UD composites the stiffness and strength values are different in the *2* and *3* directions.

The strength in tension in the *3*-direction *(Z)* has been found to be close to half the strength in the *2*-direction *(Y)*, see figure 2. In compression the difference is less, the out of plane strength is approximately 10% higher in the *2*-direction compared to the *3*-direction. [9].

While the failure mechanism in longitudinal compression for NCF is similar to UD, i.e. fibre kinking [10], [11] the mechanisms are different for matrix related failure. From the experiments in [9] it has been observed that a NCF composite laminate loaded in transverse tension either fails in the matrix with a fracture plane close to the *1-2* plane, see figure 3b *I*, or inside the fibre bundles, see figure 3b *II*. Longitudinal cracks in the *1-2* plane have been found in [12], where they are observed in the interface between the bundle and matrix in NCF cross-ply materials under in-plane tensile loading.

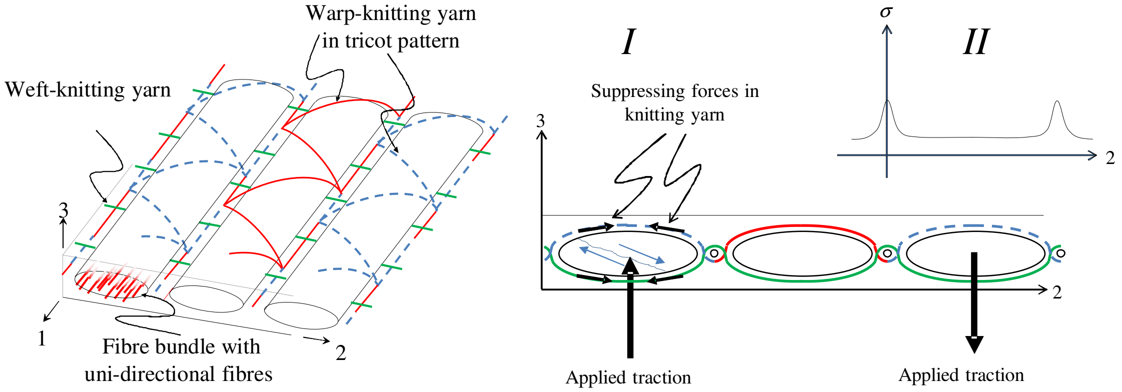

Figure 1. a) Schematic overview of an NCF uni-weave with tricot knitting, b) Schematic cross section of an NCF a uni-weave, *I* in compression and *II* in tension with stress distribution along the transverse binding yarn.

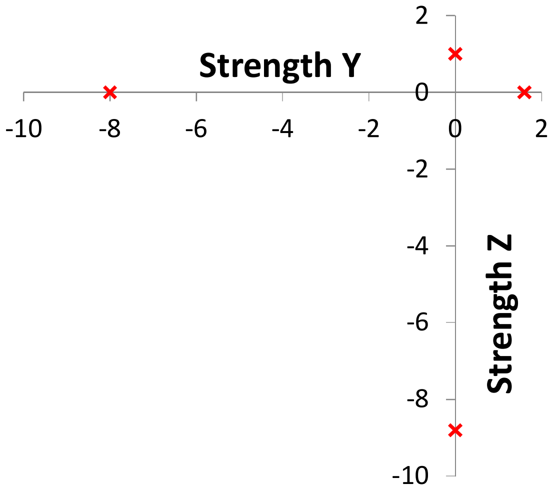

Figure 2. Strength values for an NCF-material, showing orthotropic properties. Normalised with Z_T.

2.1.1. Why is the strength of NCF composites not transversely isotropic?

The architecture of an NCF with bundle and matrix that are not symmetrically spaced indicates that the behaviour is not isotropic. Moreover, the *2-3* plane transverse to the fibre direction, see figure 1, is also orthotropic due to the binding yarn that is used to keep the bundles and plies together within the blanket. When loaded in tension, a stress concentration is formed at the warp of the binding yarn, that induces a fracture in the *1-2* plane [9].

The transverse binding yarn confines the bundles together when a load is applied [9], see figure 1 b). The suppressing forces are dependent on the architecture of the NCF composites, binding yarn and fracture plane angle.

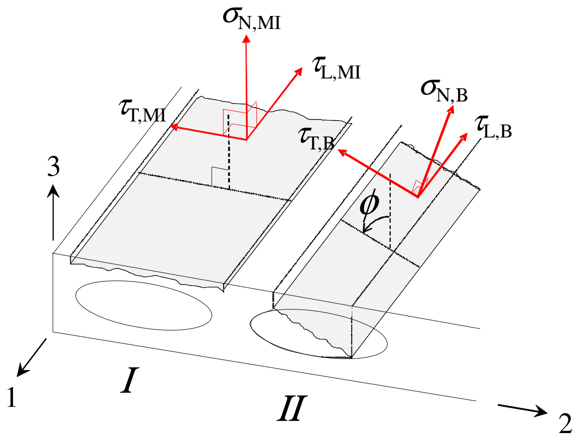

Figure 3. Fracture planes within an NCF lamina. Bundle *I* fracture plane parallel to the NCF layer in the matrix. Bundle *II* fracture plane inside the fibre bundle.

2.2. Current failure criteria

Physically based failure criteria have the possibility to capture the failure behaviour, not only predict onset of failure, but also to predict the mode of failure and the angle of fracture within a given ply. This is of great importance if subsequent damage analyses are to be performed. The LaRC05 [6] criteria performed well in the second World Wide Failure Exercise [13] for UD laminates, and the material parameters it uses are measurable from standard tests. It is therefore selected as a starting point for extension to NCF materials.

2.2.1. LaRC05

The LaRC05 failure criteria are based on three different failure modes; matrix failure, fibre kinking and fibre tension.

Matrix failure in LaRC05, is based on the transverse shear τ_T, longitudinal shear τ_L and the normal stress σ_N on the fracture plane, see figure 4. The strength values consider the in-situ effect, denoted with superscript *is*, and are based on the transverse tensile strength Y_T, transverse shear strengths, S_T and longitudinal shear strength S_L, as well as the failure angle for pure compression α_0.

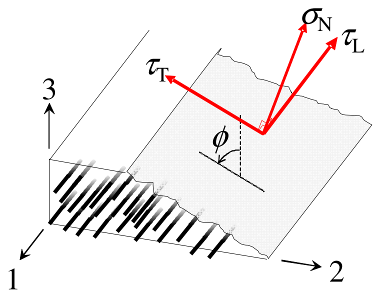

Figure 4. Tractions acting on the fracture plane for matrix failure in UD composites.

$$FI_{\mathrm{M}} = \left(\frac{\tau_{\mathrm{T}}}{S_{\mathrm{T}}^{\mathrm{is}} - \eta_{\mathrm{T}} \sigma_{\mathrm{N}}} \right)^2 + \left(\frac{\tau_{\mathrm{L}}}{S_{\mathrm{L}}^{\mathrm{is}} - \eta_{\mathrm{L}} \sigma_{\mathrm{N}}} \right)^2 + \left(\frac{\langle \sigma_{\mathrm{N}} \rangle_+}{Y_{\mathrm{T}}^{\mathrm{is}}} \right)^2 \le 1 \tag{1}$$

For matrix failure, the transverse shear strength S_T is evaluated against the transverse compressive strength Y_C as

$$S_{\mathrm{T}} = Y_{\mathrm{C}} \cos(\alpha_0) \left(\sin(\alpha_0) + \frac{\cos(\alpha_0)}{\tan(2\alpha_0)} \right). \tag{2}$$

The LaRC05 criteria capture fibre kinking or splitting, using failure criteria applied to the stresses transformed into the kinking plane. Kinking, or splitting, occurs in a coordinate frame with the *1*-direction aligned with the fibres misalignment and the tractions on this plane is denoted with the superscript, *m*. The stresses are calculated in this reference system through transformation. The failure mode, kinking or splitting, is distinguished by the magnitude of the compression stress along the fibres; if $\sigma_{11} < -X_C / 2$ then kinking occur and if $\sigma_{11} \geq -X_C / 2$ then splitting occur,

$$FI_{\mathrm{KINK}} = FI_{\mathrm{SPLIT}} = \left(\frac{\tau_{23}^{\mathrm{m}}}{S_{\mathrm{T}}^{\mathrm{is}} - \eta_{\mathrm{T}} \sigma_{22}^{\mathrm{m}}} \right)^2 + \left(\frac{\tau_{12}^{\mathrm{m}}}{S_{\mathrm{L}}^{\mathrm{is}} - \eta_{\mathrm{L}} \sigma_{22}^{\mathrm{m}}} \right)^2 + \left(\frac{\langle \sigma_{22}^{\mathrm{m}} \rangle_+}{Y_{\mathrm{T}}^{\mathrm{is}}} \right)^2 \le 1. \tag{3}$$

Fibre failure in tension occurs when the stress in the fibres exceeds the tensile strength,

$$FI_{\mathrm{FT}} = \frac{\langle \sigma_{11} \rangle_+}{X_{\mathrm{T}}} \le 1. \tag{4}$$

2.2.2. Juhasz criteria for 3D fibre reinforced plastics

A set of failure criteria for 3D composites, with orthotropic properties, have been proposed by Juhasz et al [14]. The criteria were used for composites with high in-plane fibre density and additional perpendicular reinforcements. The strength model distinguishes between fibre failure, FF, and inter-fibre failure, IFF. For loads applied close to one of the axes with parallel fibres, FF is evaluated, and when loaded at an off axis angle, $\alpha > 2^{o}$, IFF is evaluated. The IFF-criterion is based on strength parameters that are an interpolation of the basic strengths for the composite. The model is based on a simple parabolic criterion. However, the basic strengths need to be adjusted and are obtained from data fitting of experimental results.

3. Development of the failure criteria for NCF based on a two phase approach

In the LaRC05 criterion it is assumed that the transverse shear strength S_{T} is independent of the fracture plane angle, hence the compressive strength Y_{C} is independent on the fracture plane. Also the normal stress σ_{N} is evaluated against the tensile strength Y_{T} without any dependence on the fracture plane angle because of the transverse isotropy assumed for UD-composites.

3.1. Two phase model

The model for NCF developed here is founded on the LaRC05 criterion [8]. It is proposed that the strength parameters for the matrix are dependent on how the layer is loaded in a plane orthogonal to the fibre direction. For NCF materials, it has been found that the fracture plane are dependent on the tensile strengths, where $Y_T \neq Z_T$.

To address the two different failure modes in tension, two criteria are proposed. A criterion is proposed that evaluates the stress components against failure on a plane perpendicular to the layer thickness, independent of how the stress is applied in the transverse plane, see figure 3 bundle *I*. On this fracture surface, called matrix interface, *MI*, the out of plane strength Z_T is used,

$$FI_{\mathrm{M,MI}} = \left(\frac{\tau_{\mathrm{T,MI}}}{S_{\mathrm{T,MI}}}\right)^2 + \left(\frac{\tau_{\mathrm{L,MI}}}{S_{\mathrm{L}}}\right)^2 + \left(\frac{\sigma_{\mathrm{N,MI}}}{Z_{\mathrm{T}}}\right)^2 \leq 1 \text{, if } \sigma_N > 0, \tag{5}$$

where the shear strength $S_{T,MI}$ is based on the Z_C strength,

$$S_{\mathrm{T,MI}} = Z_{\mathrm{C}} \cos(\alpha_0)\left(\sin(\alpha_0) + \frac{\cos(\alpha_0)}{\tan(2\alpha_0)}\right). \tag{6}$$

A second criterion for failure in the bundle, and corresponding to the original LaRC05 equation, eq. 1, is used with the subscript *B*, see figure 3 bundle *II*,

$$FI_{\mathrm{M,B}} = \left(\frac{\tau_{\mathrm{T,B}}}{S_{\mathrm{T,B}} - \eta_{\mathrm{T}}\sigma_{\mathrm{N}}}\right)^2 + \left(\frac{\tau_{\mathrm{L,B}}}{S_{\mathrm{L}} - \eta_{\mathrm{L}}\sigma_{\mathrm{N}}}\right)^2 + \left(\frac{\langle\sigma_{\mathrm{N,B}}\rangle_+}{Y_{\mathrm{T}}}\right)^2 \leq 1, \tag{7}$$

where the shear strength $S_{\mathrm{T,B}}$ is based on the Y_{C} strength as:

$$S_{\mathrm{T,B}} = Y_{\mathrm{C}} \cos(\alpha_0)\left(\sin(\alpha_0) + \frac{\cos(\alpha_0)}{\tan(2\alpha_0)}\right) \tag{8}$$

and where the friction parameters η_{T} and η_{L} are related to the shear strengths S_{L} and S_{T} as:

$$\frac{\eta_{\mathrm{T}}}{S_{\mathrm{T}}} = \frac{\eta_{\mathrm{L}}}{S_{\mathrm{L}}} \tag{9}$$

Matrix dominated failure is evaluated as the lowest of $FI_{\mathrm{M,MI}}$ and $FI_{\mathrm{M,B}}$ for all angles.

4. Results and Discussion

The criteria with their implementation are developed for prediction of first ply failure of NCF composites. The criteria determine not only the onset of failure, but also the failure mode and fracture plane angle, which is useful for further analysis of a structure.

Predictions with the two different failure modes for matrix failure for an applied tensile stress are compared in figure 5. The stress is applied at on off axis angle θ from the Z-axis towards the Y-axis.

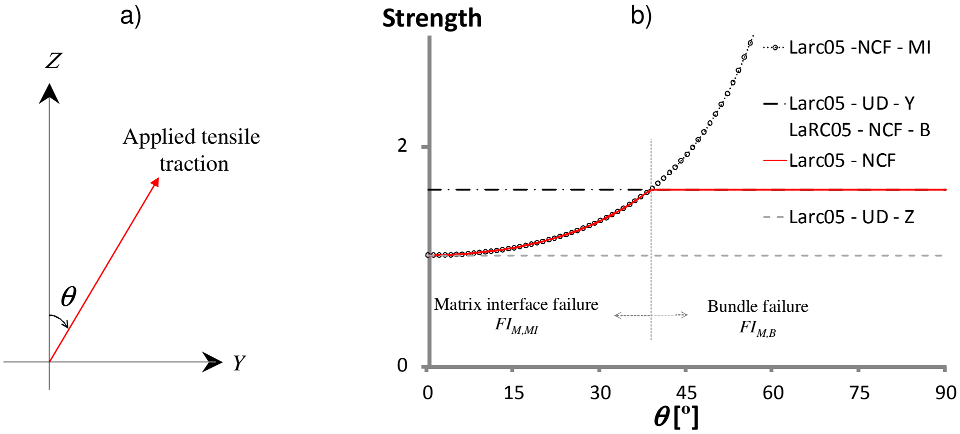

Figure 5. a) Application of the stress of at an off axis angle θ from the Z-axis to the Y-axis. b) Predicted failure envelope for a tensile stress at an angle θ. Normalised strength with Z_T.

A prediction with the model for the σ_{22}-σ_{33} plane is found in figure 6, together with LaRC05 and the data points from [9] marked. At each corner the fracture plane changes angle ϕ, see figure 3. The LaRC05 criteria overestimate the strength in the Z-direction. Both criteria underestimate the compressive strength in the Z-direction. This is due to that both criteria use the compressive Y-strength for calculation of the transverse shear strength, see eq. 2 and eq. 8.

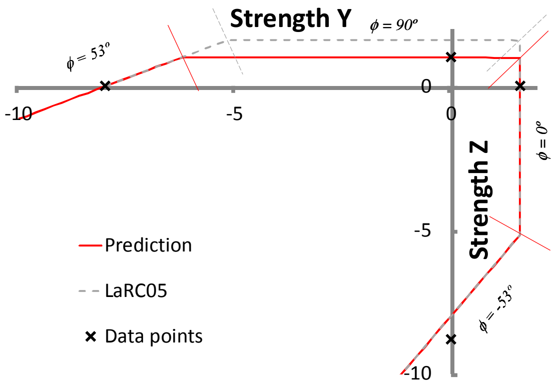

Figure 6. Predicted failure envelope in the σ_{22}-σ_{33} plane. The strengths are normalized with Z_T.

5. Conclusions

Automotive structural composite components are expected to be manufactured using NCF composites. In order to use these composites effectively, efficient design methods are needed. A first step of setting up such methods are to find working failure criteria. In this article a failure criteria for predicting failure in NCF composites with orthotropic properties are presented.

The criteria distinguish between two different failure modes for tension loaded layers in a NCF composite.

The model uses strength values that can be obtained from standard tests, but these values could also be obtained from FE meso-models of a desired NCF composite architecture.

6. Acknowledgement

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