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# A non-orthogonal material model of woven composites in the preforming process

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ABSTRACT

Woven composites are considered as a promising material choice for lightweight applications. An improved non-orthogonal material model that can decouple the strong tension and weak shear behavior of the woven composite under large shear deformation is proposed for simulating the preforming of woven composites. The tension, shear and compression moduli in the model are calibrated using the tension, bias-extension and bending experiments, respectively. The interaction between the composite layers is characterized by a sliding test. The newly developed material model is implemented in the commercial finite element software LS-DYNA® and validated by a double dome study.

## 1. Introduction

Carbon fiber reinforced plastics (CFRPs) have received growing attentions from transportation industry because of their high performance to weight ratio [1,2]. Due to its good geometric conformability, woven CFRP is most suitable for complex part geometries. The current manufacturing process for woven CFRP parts, however, relies on the manual layout of the material, leading to increasing human labor cost and low production rate, which confines the utilization of these materials in mass production.

A highly-automated process chain consisting of preforming and curing process is proposed to tackle this challenge. Materials used in the first preforming step is the stacked flat layers of prepregs, which are woven CFRPs impregnated with uncured thermoset resin in desired fiber orientations. These layers are heated above the resin melting temperature to fully soften the prepreg and formed into the part shape on a press. The formed part is then cured to harden the resin for the permanent shape [3]. The preforming step replaces the hand laying process and greatly reduces the human labor and time cost in mass production.

There exists ample design freedom in woven CFRP products in terms of parameters or options in material design and preforming processes, for example, geometry suitable for woven composites not necessary adapted exactly from its metal counterpart [4]. The large consumption of the test material and the extensive experimental trial out period could lead to high developing cost and long product development cycle. Numerical methods that can simulate the preforming process should be developed in order to solve this problem [5].

From the literature review, the first widely used computational method to predict the woven CFRP behavior during the preforming process is the pure kinematic-based pin-joint net (PJN) assumption [6]. However, the ignorance of the mechanical properties of the fabric and the resin results in inaccurate prediction, especially for wrinkling prediction. As an alternative, the finite element method (FEM) draws increasing attention. Simulations for the fiber orientation, draw-in amount and wrinkling behavior prediction during the preforming process have been documented in literatures. Jauffrès et al. [7] combined 1D beam elements and 2D shell elements to simulate the tensile and shear behaviors of the material separately. The meshing process for this hybrid element, however, was tricky and time-consuming. Hamila et al. developed a semi-discrete triangle shell element and handled this problem based on internal virtual work [5]. The drawback is that this element was applicable in an in-house FEM software, limiting its usage in the industry. In the LS-DYNA® software, there are built-in woven fabric material models, such as the MAT_234 and MAT 235. Both models, however, are based on meso-scale mechanics and require the input of meso-scale material parameters such as the yarn moduli and yarn–yarn interaction coefficient. It was found in practice that for these parameters, direct experimental characterization is difficult and reverse calculation is time-consuming.

For the potential of commercialization and user-friendly operation, our group proposed a non-orthogonal material model for the CFRP preforming simulation [8]. It was implemented into a commercial FEM code ABAQUS® as a user-defined material

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subroutine. Although the intention of coupling the tensile and shear behavior in the new constitutive law was applaudable [8] for having the most general form, it encountered inaccuracy especially when woven CFRP is subject to large shear deformation.

An improved non-orthogonal model for the woven CFRP preforming process is proposed in this work, which has been incorporated into the LS-DYNA® software as MAT_293 (MAT_COMPRF) through the joint effort of this academic and industry team. Following in this paper is the detailed illustration of the fundamentals of this model and its experimental validation conducted at an industrial lab. Additionally, the measurement of interaction between prepreg layers is also characterized.

## 2. Analysis of the material deformation mechanism

Woven CFRPs are highly anisotropic in mechanical properties. The prepreg used in this work has large tensile modulus (10 GPa level) along the warp and weft yarn directions because of the stiff carbon fibers, but small intra-ply shear modulus (0.1 MPa level), especially at the preforming temperature when the resin is molten as the shear resistance is mostly provided by the resin and the friction between the fiber yarns. During the preforming, the most dominant deformation mode is the intra-ply shear. To capture this mechanism, we propose to fully decouple the tension and shear deformation and the decoupling must hold well under large shear deformation.

### 2.1. Non-orthogonal woven composites material model

Stress analysis for the woven CFRP with the modified non-orthogonal model is shown in Fig. 1. $\sigma_{f1}$, and $\sigma_{f2}$ are the stress components caused by yarn stretch, and they are along the warp and weft yarn directions, respectively. $\sigma_{m1}$ and $\sigma_{m2}$ are the stress components caused by the yarn rotation. These stress components will be transformed into the local corotational coordinate, summed up as $\sigma_{XX}$, $\sigma_{XY}$, and $\sigma_{YY}$, and will be the stress outputs reported from the material model to the FEM software.

The deformation gradient tensor ***F*** is utilized in this model to trace the yarn directions and stretch ratios during the preforming via ***g*** = ***F***•***G***, where ***g*** and ***G*** are the final and initial orientations of the local fibers respectively. It can be used to calculate $\alpha$, which indicates the relative rotation between the local warp direction and the $X$-direction in the local corotational coordinate, and yarn angle $\beta$, which indicates the amount of shear deformation in the material.

In the FEM software, the stress tensor in the local corotational $X$–$Y$ coordinate is derived by $\sigma = \sigma^f + \sigma^m$. The calculation detail is demonstrated with the following Eqs. (1)–(9) in component form:

$$\sigma_{XX}^{f} = \sigma_{f1}\cdot\cos^2\alpha + \sigma_{f2}\cdot\cos^2(\alpha+\beta) \tag{1}$$

$$\sigma_{XY}^{f} = \sigma_{YX}^{f} = \frac{1}{2}\sigma_{f1}\cdot\sin 2\alpha + \frac{1}{2}\sigma_{f2}\cdot\sin 2(\alpha+\beta) \tag{2}$$

$$\sigma_{YY}^{f} = \sigma_{f1}\cdot\sin^2\alpha + \sigma_{f2}\cdot\sin^2(\alpha+\beta) \tag{3}$$

$$\sigma_{XX}^{m} = \frac{\sigma_{m1}+\sigma_{m2}}{2} + \frac{\sigma_{m1}-\sigma_{m2}}{2}\cos(2\alpha+\beta) \tag{4}$$

$$\sigma_{XY}^{m} = \sigma_{YX}^{m} = \frac{\sigma_{m1}-\sigma_{m2}}{2}\sin(2\alpha+\beta) \tag{5}$$

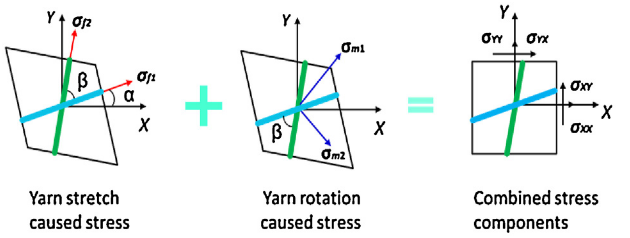

**Fig. 1.** Stress analysis of the woven CFRP with the modified non-orthogonal model.

$$\sigma_{YY}^{m} = \frac{\sigma_{m1}+\sigma_{m2}}{2} - \frac{\sigma_{m1}-\sigma_{m2}}{2}\cos(2\alpha+\beta) \tag{6}$$

$$\sigma_{XX} = \sigma_{XX}^{f} + \sigma_{XX}^{m} \tag{7}$$

$$\sigma_{XY} = \sigma_{YX} = \sigma_{XY}^{f} + \sigma_{XY}^{m} \tag{8}$$

$$\sigma_{YY} = \sigma_{YY}^{f} + \sigma_{YY}^{m} \tag{9}$$

These equations are derived based on the tensor coordinate transformation principle. The non-orthogonal stress components caused by yarn stretch and rotation at various deformation states will be characterized via a set of experiments.

### 2.2. Implementation of the model to finite element analysis

The modified non-orthogonal model was implemented into the FEM software LS-DYNA® as MAT_293 (currently in the testing phase before public release). MAT_293 enables users to directly input experimental data to define the stress–strain curves, as well as the shear locking angle, which indicates whether the shear deformation reaches to the extent that the rotation resistance between warp and weft yarns is no longer small compared to the tensile modulus of the material. The flowchart of the model is shown in Fig. 2.

In the material subroutine, the warp and weft directions for each element are calculated from the deformation gradient tensor. If the angle between the warp and weft yarns are smaller than the shear locking angle, then the small shear modulus condition will hold, and the total stress in the element will be updated via Eqs. (1)–(9). If the angle between the warp and weft yarns reaches to the shear locking angle, the resistance for further shear deformation will greatly increase because the contacted fiber yarns stiffen the woven structure. In this situation, the “yarn stretch caused stress” will still be calculated via Eqs. (1)–(3), while the shear components of the “Yarn rotation caused stress” will be derived with Eq. (10) in incremental form as:

$$d\sigma_{XY}^{m} = d\sigma_{YX}^{m} = E\cdot d\varepsilon_{XY} \tag{10}$$

where $E$ is the stable transverse compression modulus of the yarns, and $d\varepsilon_{XY}$ is the shear strain increment after shear locking.

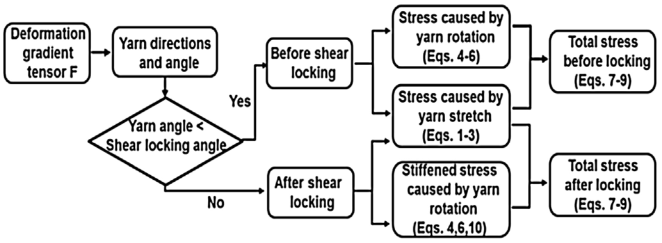

**Fig. 2.** Calculation flowchart of the LS-DYNA MAT_293.

## 3. Material characterization

Material characterization is essential for the FEM model to predict the behavior of the woven CFRPs during the preforming process. It can be seen from Fig. 1 that the stresses caused by both yarn stretch and yarn rotation need to be calibrated for any specific woven material that is of interest. The calibration can be performed experimentally by the uniaxial tension and bias-extension tests [9], as shown in Section 3.1. However, these two tests only provide the in-plane intra-ply properties of the material. During the preforming simulation, the bending behavior of the single layer and the interaction between the composite layers will also affect the in-plane strain distribution and consequently, the wrinkling initiation. Hence, experimental setups for the characterizations of bending stiffness and inter-ply interaction are developed and illustrated below in Sections 3.2 and 3.3, respectively.

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