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MULTI-SCALE VISCOELASTIC BENDING ANALYSIS OF LAMINATED COMPOSITES WITH SOFT INTERFACES

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Abstract: *This study investigates the bending behaviour of the orthotropic elastic and viscoelastic multi-layered plates with resin rich inter-plies to improve our understanding of the effects of shear deformation and ply slippage on wrinkle formation. This is accomplished by employing a three-dimensional (3D) multi-scale modelling framework that incorporates analysis at different scales (micro-, meso-, and macro-scale). The variation of resin viscoelastic characteristics at the early stage of cure and its effect on the bending properties of the composite is investigated numerically. The results highlight the importance of considering the material's rate dependency in describing the bending behaviour of composite prepregs accurately. Moreover, the bending response of the thin uncured prepregs is found to be dominated by their ply bending stiffness rather than inter-ply friction.*

Keywords: Bending; Viscoelasticity; Multi-scale modelling; Orthotropic properties; Resin.

1. Introduction

Wrinkle formation during the forming process of laminated composite components poses obstacles to fully exploiting the potential of advanced composites. In literature, much attention has been paid to deformation mechanisms behind wrinkle formation during consolidation such as in-plane shear, out-of-plane bending and inter-ply slippage [1, 2]. It is now well-understood that bending properties of uncured thin laminates can influence the occurrence of wrinkles including the shape, magnitude and intensity of wrinkles [3]. Analyzing the bending and buckling deformations of uncured thermoset composites is crucial to understand contributing mechanisms and underlying physics of the wrinkle formation during hot drape forming process of laminated composites [4, 5]. Recently, Le et al. [4] developed an efficient multi-scale approach for viscoelastic analysis of single-ply woven composites under bending. In addition to from bending stiffness, inter-ply slippage has been considered as an important deformation mechanism during the process of forming composites, particularly for multi-layered textile composites [2]. Therefore, the proposed method has been expected to expand the investigation into the bending behaviour of multi-layered textile composite separated by relatively soft interfaces.

Recently, some researchers (e.g. [2]) have employed Aniform Finite Element (FE) software with shell elements to model the viscoelastic bending behaviour of composite plies under conditions relevant to the forming process. Several time-consuming characterization tests (i.e. bias extension, bending) are required to determine the material parameters for a suitable constitutive model. Unlike previous studies, the influence of various parameters including fibre stiffness, ply anisotropy, resin properties, and loading rates on the viscoelastic bending behaviour of laminated composites are analyzed in this study. The weaving pattern and the stacking sequence of plies are considered at the meso-scale while the effect of ply slippage is captured by introducing a thin interface layer between the plies at the macro-scale. Section 2 briefly introduces the methodology for simulating the bending behaviour of prepregs using the analytical homogenization techniques at micro- and meso-scale for material properties combined with the DF of viscoelasticity at macro-scale for numerical analysis. The details of the FE model and its verification are provided in Section 3. The capabilities, limitations of the developed model, and future work are discussed in Section 4.

2. Methodology

The viscoelastic behaviour of multi-layered cantilever plates subjected to tip displacements has been modelled using the multi-scale approach proposed in Malek [6] for orthotropic composites. At the micro-scale, the analytical micromechanics equations described in Malek [6] are used to predict the effective viscoelastic properties of a representative volume element (RVE) of a composite with circular long fibres (see Fig. 1).

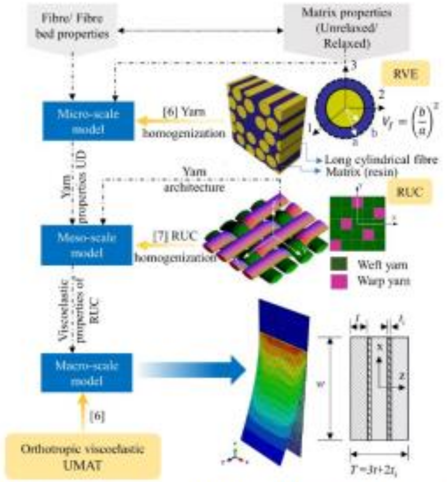

Figure 1: Schematic of the multi-scale modelling approach for bending behaviour of 5-harness satin weave multilayered composites from micro-scale to macro-scale.

The fibre's elastic and resin's viscoelastic properties are required as inputs for the micro-scale model. Since fiber-bed characteristics are essential in describing the behaviour of prepregs at the early stage of cure, the fibre-bed properties are incorporated into the micromechanics equations [6]. The effective properties obtained from the micromechanics model along with fabric architecture are then used to estimate the properties of a representative unit cell (RUC) of a woven fabric at the meso-scale. The method for calculating three-dimensional effective parameters was adapted from Naik [7]. Once the effective meso-scale properties of the composite are obtained, they are employed directly for structural analysis at the macro-scale. A differential form (DF) of orthotropic viscoelasticity implemented as a UMAT is used for structural level (macro-scale) simulations. For further details, the reader is referred to [4].

3. Results

The composite plate selected for this study is based on a bending test of a three-layer textile composite conducted by Alshahrani & Hojjati [2]. Each ply has dimensions of 50 mm in width (*w*), 0.55 mm in thickness (*t*) and an un-gripped length of 120 mm, out of 150 mm in total length (*L*). Assuming that each ply is separated by a very thin interface, t_i = 0.01 mm (see Fig. 2). The three-layer cantilever plate is restrained from all displacements in a length of 30 mm as it was gripped along this distance [2]. A 20-node solid quadratic brick element with reduced integration elements (C3D20R) is used. A tip displacement of 30 mm is applied to introduce high curvature in the sample [2].

For simplicity, the effective material properties of the uncured layers under bending are assumed isotropic (E_p =700 MPa and υ_p = 0.4) first. Such effective bending stiffness were computed employing the in-plane properties of uncured prepreg under bending with known compressive and tensile moduli based on the transformation method discussed in [4]. The Young's modulus of the interface, E_i may vary within a range of values shown in Table 1. Identical Poisson's ratios are used for plies and the interface (i.e. υ_p = υ_i). The laminated plate has an overhang that may be treated as a cantilever wide beam subjected to a uniform displacement at the free end. Using Roark's formulas [8] for wide beams, the force, *F*, required to reach the tip displacement of 30 mm is calculated and results are presented in Table 1. Calculations for the upper and lower bound are obtained by assuming the layers to be fully bonded or disconnected. As shown in Table 1, the FE results for the homogeneous and isotropic case (E_i = E_p) are very close but below the upper bound. This verifies the present FE model in terms of mesh size, applied load and boundary conditions.

To better understand the role of ply anisotropy on the plate's bending response, parametric studies with transversely isotropic layers were conducted. The elastic constants of such layers for two specific transversely isotropic sets are listed in Table 2. As noted in Fig. 3, irrespective of very low interface stiffness (e.g. 70 kPa), the effect of shear deformation on the bending behaviour is less than 6.5% for the dimensions of the selected multi-layered plates. In other words, bending is the dominating deformation mechanism in this case study. Also, it seems that the anisotropy nature of plies affects the bending behaviour of laminated plates with thin and soft interfaces more considerably than their shear properties. The ply anisotropy nature (assumed in Table 2) reduces the apparent flexural rigidity of the entire plate up to 14 % (see Fig. 3). Recognizing the role of the ply's anisotropy as mentioned above along with the variation of resin viscoelastic characteristics [9] at the early stage of cure that may affect the deformation behaviour, the orthotropic viscoelastic properties are considered in the followings.

The mechanical properties of the resin, fibre and fibre-bed that have been used for viscoelastic analysis at micro-scale are listed in Table 3 [4]. It should be noted that the selected low value for fibre bending stiffness (i.e. 1.5 GPa) is an apparent value based on the micro-buckling of individual fibres arising from the low compressive modulus of the uncured composites [4]. It should be highlighted that such a low value of the longitudinal fibre modulus considered here (1.5 GPa) is in agreement with data previously reported in the literature [4].

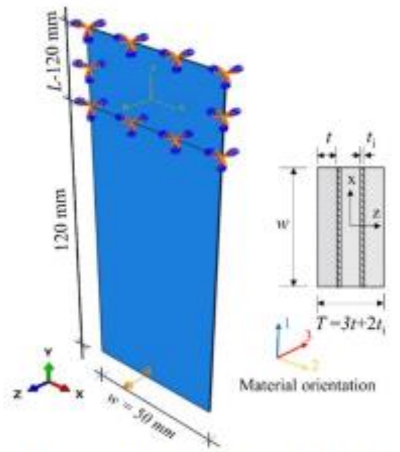

Figure 2: Bending model of a three-layer plate

Table 1: Comparisons between current FE predictions and analytical estimates [8].
E_p = 700 MPa, $\upsilon_p = \upsilon_i = 0.4$

E_i (MPa)	F (N)		
	FE (Isotropic)	Upper bound	Lower bound
700	9.372×10^{-1}		
70	9.335×10^{-1}		
7	9.317×10^{-1}	9.324×10^{-1}	9.993×10^{-2}
0.7	9.232×10^{-1}		
0.07	8.757×10^{-1}		

Due to the lack of experimental data for uncured resin (i.e. Cycom 5320), Prony series constants for MTM45-1 [9] are assumed to validate the model against the experimental data reported in [2]. First, the fibre-bed elastic properties are incorporated into the micromechanics equations [6] at micro-scale to estimate the effective viscoelastic properties of the uncured UD prepreg. The effective properties obtained from analytical homogenization at this scale are then used to predict the properties of the fabric at the meso-scale [7]. The estimated mechanical viscoelastic constants for 5-harness satin weave composite ply are provided in Table 4. Similar to previous cases for assumed elastic constants, five interface properties, E_i, ranging from 70 kPa to 700 MPa are introduced to investigate the influence of interface stiffness on the overall bending behaviour. Fig. 3 compares the required loads for the multi-layered plates with five different interface properties to reach a tip displacement of 30 mm at room temperature. As seen in Fig.

3, the apparent flexural rigidity of the viscoelastic plates is reduced by almost 30% compared to the corresponding elastic cases while the effect of ply-slippage on the overall bending behaviour is still negligible.

Table 2: Input properties of transversely isotropic plies.

Properties	Set[a]	Set[b]	Unit
$E_{1p} = E_{2p}$	700	700	MPa
E_{3p}	136	13.6	MPa
G_{12p}	40	4.0	MPa
$G_{13p} = G_{23p}$	40	4.0	MPa
υ_{12p}	0.2	0.2	-*
$\upsilon_{13p} = \upsilon_{23p}$	0.7	0.7	-*

Notes: The 12-plane is the plane of woven fabric

As a next step towards validating the proposed model, bending of four fabrics with different layups (as shown in Fig. 4) published in the literature were investigated. Note that by employing the analytical technique [7] for the homogenization technique at the meso-scale, the stiffnesses in warp and weft direction are assumed the same for simplification. Therefore, this study neglects the difference between weft and warp yarns in woven fabric structure as concerned in [2]. The load value required to achieve a tip displacement of 30 mm is used to calculate the bending moment along the length of the beam. By capturing the bending curve corresponding to the maximum displacement reached, deflection profile *z*(*y*) is fitted using a proper polynomial function. The expression for the curvature is subsequently calculated as $\kappa = z''(y)/(1 + z(y)'^2)^{3/2}$[10]. Finally, the moments at each point can be plotted against the corresponding curvature values as shown in Fig. 5.

As shown in Fig. 5, the stacking 1 [0°/0°/0°] with respect to fibre direction requires the highest load to reach the desired displacement. Fig. 5 also demonstrates that rotating ply 2 and ply 3 by 45° (stacking 3) decreases the bending stiffness by approximately 15% compared to stacking 1. Stacking 2 and stacking 4 give slight differences from stacking 1 and stacking 3, respectively. It is noted that FE simulations of multiple plies under bending are considered at room temperature with a speed of 3 mm/s and assumed the interface stiffness of 7 MPa for all cases. Nevertheless, the moment against curvature relation captured by the experiment for selected stacking sequences [2] was conducted at 70°C only, hence, they are not included in Fig. 5 for comparison purposes. At room temperature, the maximum bending moment for stacking 1 with a speed of 3 mm/s was measured about 55 N.mm in [2], compared to the present FE prediction of 75 N.mm (see Fig. 5). This discrepancy can be attributed to the assumed input parameters for the fibre bending stiffness, resin viscoelastic characteristics and yarn architecture due to the lack of experimental data for material properties at micro- and meso-scale. However, the proposed multi-scale approach should be emphasized as a rapid method for estimating the effect of various parameters on wrinkle formation. Moreover, it appears to be rather difficult to precisely predict the bending behaviour of uncured laminated prepregs using FE analysis because the simulation outcome is dependent on precise material inputs at smaller scales that may be missing in the literature. It should be noted that the simulation model using Aniform software in [2] underestimates the maximum bending moment for stacking 1 at room temperature .

Table 3: Input material properties of fibre, resin and fibre bed used in the bending simulation of textile prepregs [4].

V_f = 0.600

Property	Unit	Fibre	Resin		Fibre bed
			Relaxed	Unrelaxed	
E_1	GPa	1.50×10^{0}	3.00×10^{-6}	1.65×10^{-1}	1.50×10^{0}
$E_2 = E_3$	GPa	1.72×10^{-1}	3.00×10^{-6}	1.65×10^{-1}	1.12×10^{-4}
$G_{12} = G_{13}$	GPa	27.60	1.00×10^{-6}	5.52×10^{-2}	1.13×10^{-4}
G_{23}	GPa	0.07	1.00×10^{-6}	5.52×10^{-2}	4.49×10^{-5}
$\nu_{12} = \nu_{13}$	-	0.2	0.495	0.495	
ν_{23}	-	0.25	0.495	0.495	0.250

Table 4: Meso-scale predictions of 5HS prepreg mechanical properties under bending using the analytical technique of Naik [7].

Laminate type	Material	E_{xx}, E_{yy}	E_{zz}	G_{xz}, G_{yz}	G_{xy}	ν_{xz}, ν_{yz}	ν_{xy}
		MPa	MPa	MPa	MPa		
5HS	Relaxed resin	412.60	8.40	5.10	3.80×10^{-1}	0.800	2.94×10^{-4}
	Unrelaxed resin	680.20	394.10	126.20	187.20	0.676	0.212

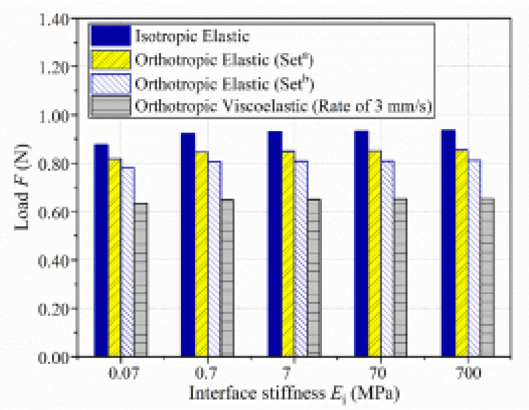

Figure 3: The effect of interface properties on the bending loads. Required loads to reach a tip displacement of 30 mm at room temperature are compared using various material models. Resin viscoelastic properties selected for the orthotropic viscoelastic material model are provided in [9]. The composite has the length of 150 mm, the width of 50 mm and the thickness of 1.67 mm.