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The Composites Centre
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A 3-D MICROMECHANICAL MODEL FOR PREDICTING THE ELASTIC BEHAVIOUR OF WOVEN LAMINATES

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Abstract

This paper presents an analytical model for the prediction of the elastic behaviour of plain-weave composites. The fabric is assumed to be a hybrid plain weave with different materials and undulations in the warp and fill directions. The derivation of the effective material properties is based on Classical Laminate Theory (CLT). The theoretical predictions have been compared with experimental results and predictions using similar models available in the literature. Composite laminates were manufactured using the Resin Infusion under Flexible Tooling (RIFT) Process and tested under tension and in-plane shear loading for validating the model. A good correlation between theoretical predictions and experimental results for the in-plane properties was obtained.

3-D Micromechanical model formulation:

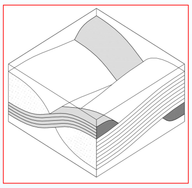


Fig.1 - Unit cell

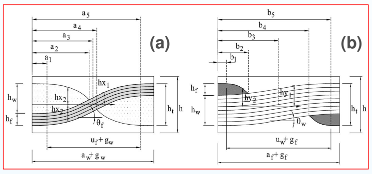


Fig.2 - Unit cell sections (Warp-(a),Fill-(b))

Homogenisation based on Series-Parallel model [1]

$$A_{ij}(x,y)=\int_{-z(x,y)}^{+z(x,y)}\bar{Q}^{e}_{ij}(x,y)dz$$

$$\bar{Q}^{e}_{ij}(x,y)=\left[T^{e}_{ij}(x,y)\right]^{-1}\left[Q^{e}_{ij}\right]\left[R_{ij}\right]\left[T^{e}_{ij}(x,y)\right]\left[R_{ij}\right]^{-1}$$

$$\bar{a}^{s}_{ij}(y)=\frac{1}{a_w+g_w}\int_{0}^{a_w+g_w}a_{ij}(x,y)dx$$

$$\bar{A}^{sp}_{ij}=\frac{1}{a_f+g_f}\int_{0}^{a_f+g_f}\bar{A}^{s}_{ij}(y)dy$$

$$\bar{a}_{ij}=\left[\bar{A}^{sp}_{ij}\right]^{-1}\longrightarrow\begin{cases}E_x=\frac{1}{\bar{a}_{11}h}, & E_y=\frac{1}{\bar{a}_{22}h}, & E_z=\frac{1}{\bar{a}_{33}h}\\ G_{xy}=\frac{1}{\bar{a}_{66}h}, & G_{zx}=\frac{1}{\bar{a}_{55}h}, & G_{yz}=\frac{1}{\bar{a}_{44}h}\\ \upsilon_{xy}=-\frac{\bar{a}_{12}}{\bar{a}_{11}}, & \upsilon_{xz}=-\frac{\bar{a}_{13}}{\bar{a}_{11}}, & \upsilon_{yz}=-\frac{\bar{a}_{23}}{\bar{a}_{22}}\end{cases}$$

Experimental work:

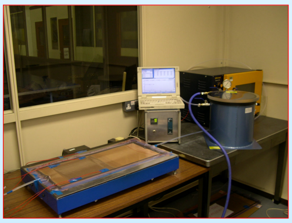


Fig.3 - RIFT setup [2]

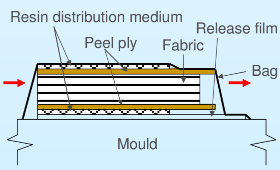


Fig.4 - Infusion arrangement

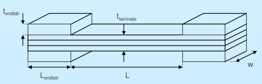


Fig.5 - Specimen configuration

Table 1 - Specimens dimension accordance to CRAG standard

Test specimen	Nominal dimensions [mm]				
	L	L_{endtab}	$t_{laminate}$	t_{endtab}	w
Tension warp	100	50	1.35	1.60	20
Tension weft	100	50	2.25	1.60	20
Tension ±45° shear	100	50	2.70	1.60	20

Model Validation:

Table 2 - E-Glass/vinylester plain-weave composite (Data from Scida et al. [3])

Results	$E_x=E_y$ [GPa]	E_z [GPa]	G_{xy} [GPa]	$G_{xz}=G_{yz}$ [GPa]	ν_{xy}	$\nu_{xz}=\nu_{yz}$
Experimental	24.80	8.50	6.50	4.20	0.10	0.28
Scida et al	25.33	13.46	5.19	5.24	0.12	0.29
Present model	25.80	13.26	5.12	5.02	0.15	0.31

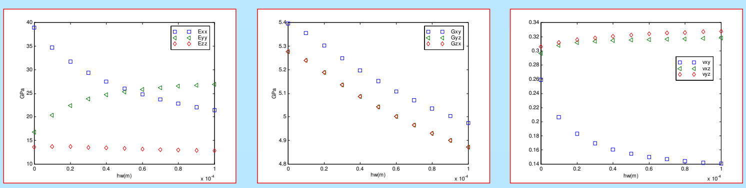


Fig.6 - Effects of the warp yarn thickness variation on the elastic properties of E-Glass/Vinylester plain-weave composite

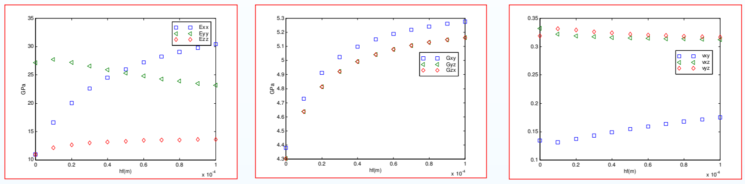


Fig.7 - Effects of the fill yarn thickness variation on the elastic properties of E-Glass/Vinylester plain-weave composite

Table 3 - Mechanical properties for the fibres

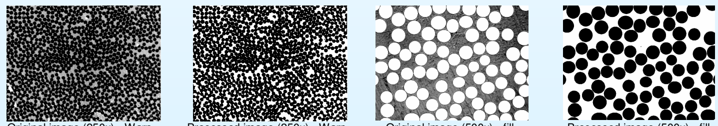
Fibre(1)	E_{11} [GPa]	E_{22} [GPa]	G_{12} [GPa]	G_{23} [GPa]	ν_{12}	ν_{23}
T700 (carbon)	232.00	23.10	8.96	8.27	0.20	0.40
PPG EC09 (Glass)(2)	72.40	72.40	29.67	29.67	0.22	0.22

(1) Fibre assumed to be transversely isotropic, $G_{23}=E_2/2(1+\nu_{23})$
(2) Glass fibre assumed to be isotropic

Table 4 - Mechanical properties for the matrix

Matrix(1)	E_{11} [GPa]	E_{22} [GPa]	G_{12} [GPa]	G_{23} [Gpa]	ν_{12}	ν_{23}
PRIME™ 20LV	2.97	2.97	1.08	1.08	0.38	0.38

(1) Matrix assumed to be isotropic, $G=E/2(1+\nu)$



Original image (250x) - Warp; Processed image (250x) - Warp; Original image (500x) - fill; Processed image (500x) - fill

Fig.8 - Microscope images of the fibre tows in the warp and fill directions

Table 5 - Mechanical properties for the strands based on area fibre fraction from Fig.8

Strand	E_{11} [GPa]	E_{22} [GPa]	G_{12} [GPa]	G_{23} [GPa]	ν_{12}	ν_{23}	V_f
T700/epoxy(1)	161.00	20.60	3.63	3.52	0.256	0.394	68.8
PPG EC09/epoxy(1)	43.20	12.40	3.61	3.61	0.287	0.281	58.0

(1) Predictions based on Halpin-Tsai equations

Table 6 - Geometric parameters for the micromechanical model

a_f [μm]	a_w [μm]	h_f [μm]	h_w [μm]	h_t [μm]	h [μm]	g_f [μm]	g_w [μm]	u_f [μm]	u_w [μm]
1112	2350	116	329	445	445	4900	60	1568	232

Table 7 - Comparison between theoretical predictions and experimental results

Results	E_x [GPa]	E_y [GPa]	E_z [GPa]	G_{xy} [GPa]	$G_{xz}=G_{yz}$ [GPa]	ν_{xy}	$\nu_{xz}=\nu_{yz}$
Experimental	100	8.11	---	3.88	---	0.36	---
Present model	114	9.11	14.40	4.39	4.23	0.38	0.428
Error (%)	14.0	12.3	---	13.1	---	6.0	---

Conclusions:

- The proposed 3-D micromechanical model enables the prediction of the elastic properties of woven laminates in a fast, accurate and effective way reducing the time scales associated with conventional mechanical testing;
- Good correlation between theoretical predictions and experimental results was obtained with errors within 14%;
- Micromechanical models based on CLT do not predict the through the thickness behaviour realistically therefore, a simple rule of mixtures is suggested for predicting the through the thickness behaviour;
- Manufacturing aspects associated with the RIFT process were also presented and discussed.

Acknowledgements:

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References:

[1] Naik, N.K., Shembekar P.S., Elastic behaviour of woven composites: I-Lamina analysis. *Journal of Composite Materials*, 26(15), 1992, pp. 2196-2225.
[2] Donadon M.V., Hodgkinson J.M., Falzon B.G., Iannucci L., Impact damage in composite structures manufactured using Resin Infusion under Flexible Tooling (RIFT) Process, *Proceedings of the ECCM-11, CD-ROM, Greece, 2004.*
[3] Scida D., Aboura Z., Benzeggagh M.L.,Bocherens E., A micromechanics model for 3-D elasticity and failure of woven-fibre composites, *Composite Science and Technology,* Vol. 59, 1999, pp. 505-517.