PREDICTIONS OF CARBON FIBRE SHEET MOULDING COMPOUND (CF-SMC) MECHANICAL PROPERTIES BASED ON LOCAL FIBRE ORIENTATION

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Abstract
Carbon Fibre-Sheet Moulding Compound materials (CF-SMC) are an innovative class of intermediate materials made of chopped carbon fibre strands dispersed in uncured (or partially cured) thermoset resin. These sheets are then compression moulded into the final desired shape. Currently, the more commonly used models for SMC mechanical properties were initially developed for injection moulded composites, where the reinforcement is in the form of individual fibres, rather than tows or bundles. However, the presence of an additional intermediate scale of inclusions in the SMCs is not considered by those models. Their accuracy is thus questionable, and their adoption challenging: the user should generally choose whether to consider inclusions as tows or fibres, and thus have access to different material parameters, not always available (for example, the volume fraction of the tows in the composite). This work aims to validate two different formulations of a mixed Mori-Tanaka iso-strain model: one where inclusions are considered to be fibres, one where inclusions are tows; in addition, stiffness predictions are compared with the ones obtained a shear-lag multiscale model, that involves description of both tows and fibres. The models are compared with experimental evidence.

1. Introduction

In the last years, the automotive sector has shown great interest in Carbon Fibre-Sheet Moulding Compound materials (CF-SMC) [1]. These materials are made of chopped carbon fibre strands dispersed in uncured thermoset resin. The resulting malleable sheets are then compression moulded into the final desired shape, allowing fast manufacturing and lightweight capabilities with fair mechanical properties. This material is thus characterised by two scales of inclusions: the chopped strands are the reinforcement phase, but they can be considered as UD composites themselves.

SMC mechanical properties are highly dependent on the orientation of the reinforcement [2]. This orientation is generally determined during the compression moulding, since the flow of uncured material tends to re-orient the fibres [3]. According to the amount of material flow in the cavity during the process, SMC can have either a quasi-isotropic behaviour [4] or show anisotropy [2].

This study investigates the capabilities of the commonly used models for stiffness predictions of CF-SMC. Three approaches were considered: two formulations of a mixed Mori-Tanaka iso-strain (MT-IS) model and a multiscale shear-lag model. The MT-IS model is currently used by many software adopted by industry for discontinuous composites design. Since this model was originally used for discontinuous injection moulded composite, only one inclusion description is possible, either as tow or fibre. Thus, the two formulations considered takes into account the two different cases. In addition, a shear-lag multiscale model is also tested, which can take into account the description of both individual fibres and tows. In section 2, experimental work performed to characterise the material according to the preferential orientation of the tows is presented. In the following section 3, the models are briefly described. Finally, results of predictions are compared in section 4.

2. Experimental

2.1. Specimen manufacturing

The CF-SMC material used in this work is provided by Mitsubishi Chemical Carbon Fiber and Composites GmbH, and is made of chopped strands of carbon fibres dispersed in vinyl ester resin. The filaments composing the tows have a nominal length of 25.4 mm and a nominal diameter of 6.8 µm. Each tow is made of 15000 filaments. Fibre volume content is 43%.

To manufacture oriented samples, rectangular plates, whose dimensions were 450 mm × 450 mm × 2.5 mm, were compression moulded by placing the initial charge in a very limited region of the cavity (Figure 1.a), with a mould coverage of 20%. Specimens were then waterjet cut from the region were flow occurred (specimen region, Figure 1.b), at angles θ=0°, 45° and 90° with respect to the prevailing flow direction. For the rest of the paper, they will be referred to as 0°, 45° and 90° specimens respectively. Specimen dimensions are 250 mm × 25 mm × 2.5 mm, following indications of [5] for discontinuous fibre composites.

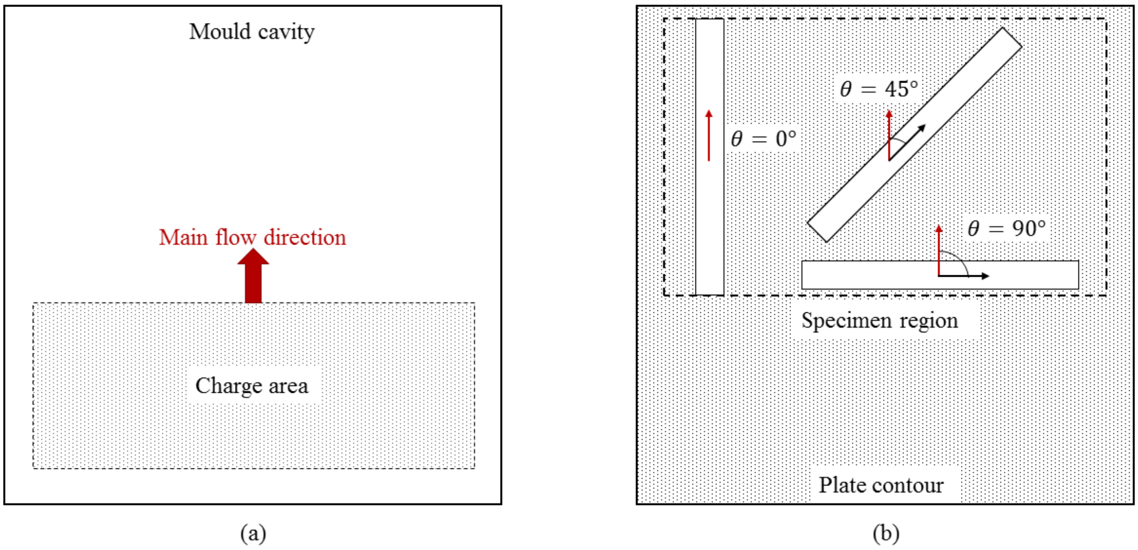

Figure 1. Specimen manufacturing: (a) initial material placement before compression moulding, and (b) moulded plate after compression moulding. Red arrows indicate, in both figures, the main flow direction.

To evaluate the second order orientation tensor, ellipsometry was used in combination with an automated microscopy acquisition technique, [3][6]. The result is:

$$A_{II} = \begin{pmatrix} 0.575 & 0 & 0 \\ sym. & 0.33 & 0 \\ sym. & sym. & 0.095 \end{pmatrix} \quad (1)$$

The first and the second axis of the tensor are in-plane, parallel to main flow direction and perpendicular respectively. Third axis is out-of-plane direction.

2.2. Tensile tests

Uniaxial tensile tests were conducted using an Instron 4505 machine, at 1 mm/min. Digital Image Correlation was used for strain measurements. Gauge length was 150 mm. Measured values of stiffness (with standard deviation) are reported in Figure 3, while stress-strain curves are reported in Figure 2.

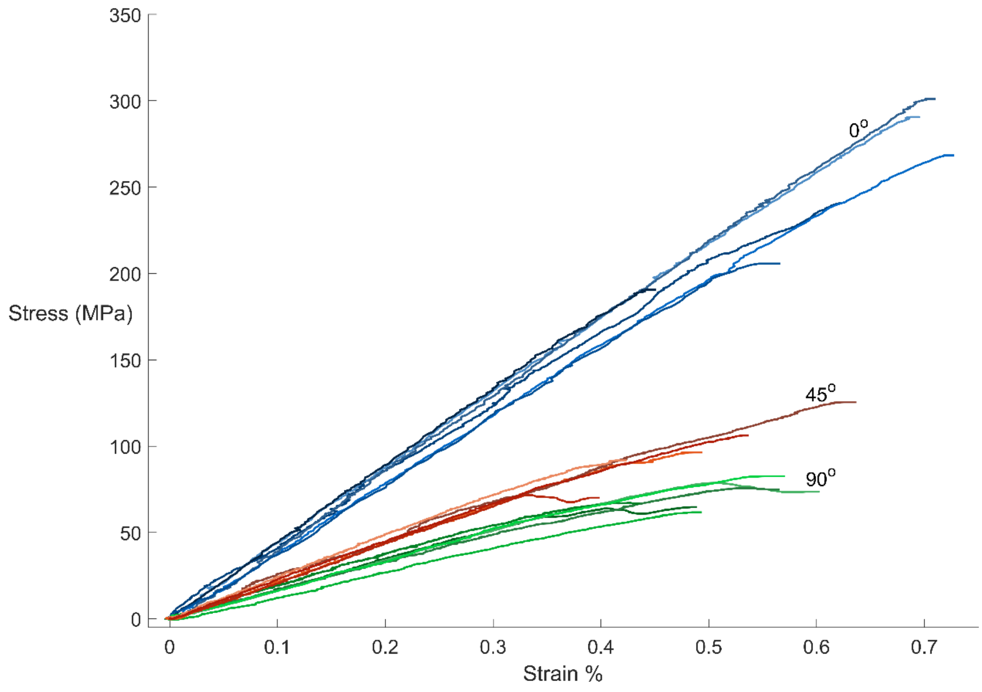

Figure 2. Stress-strain curves of specimens at different prevalent orientation

3. Model

3.1. Multiscale shear-lag model

This multiscale model is based on the equivalent laminate assumption [7], in which the discontinuous strand-based material is modelled as a laminate of UD discontinuous plies. At meso-scale, the elastic moduli of a 0° UD lamina are calculated using a shear-lag model [8]. The model evaluates the load transfer between the tows and the matrix; the tows properties are obtained from homogenisation of those of the individual fibres and matrix. The UD lamina properties are used, in combination with the orientation tensor of the material, to perform stiffness orientation averaging [3]. In this way, the stiffness at macro level of the whole composite is obtained. The input values to the procedure are reported in Table 1. In the table, superscript *'t'* indicates homogenised tow properties, while '*m*' indicates those relative to the matrix; tow geometry is described as length l^t, width w^t and thickness t^t; finally, V_{fl}

indicates volume fibre content in the composite and V_{ft} is the volume fibre content in the single tow. All the values come either from material supplier datasheet or indications or are based on values found in the literature for similar materials.

Table 1. Inputs for the shear-lag multiscale model. Values obtained from supplier are indicated as *****, while ˣ refers to an educated guess.

E_{11}^t*	E_{22}^t ˣ	G_{12}^t ˣ	ν_{12}^t ˣ	ν_{23}^t ˣ	E^m ˣ	G^m ˣ	ν^m ˣ	l^t *	w^t*	t^t*	V_{fl}*	V_{ft}*
GPa	GPa	GPa	-	-	GPa	GPa	-	mm	mm	mm	-	-
142	8.7	3.8	0.34	0.37	3.5	1.4	0.4	25.4	8	0.115	0.43	0.59

3.2. Mori-Tanaka iso-strain model

Mori-Tanaka formulation is now used to predict the 0° UD properties of the SMC material [9]. Mori-Tanaka approach makes use of the Eshelby solution for the single inclusion problem [10]. To compare the different modelling approaches, two formulations are used: one considers the inclusions at fibre level, thus using a prolate ellipsoidal shape for the Eshelby's tensor; the other considers the inclusions as tows, thus using a flat ellipsoidal shape. This distinction requires additional input at different level: both tow and fibre volume fraction are needed, as well as stiffness and aspect ratio. Once the 0° UD properties of the composite are obtained, orientation averaging is performed, as done for the previous model. The input values to both the procedures are reported in Table 2 and Table 3. In those tables the superscript 'f' refers to the fibres properties; fibres are described through diameter D^f and length l^f; finally V_{tl} is the volume tow content in the composite. Other parameters follow the nomenclature of Table 1. All the values come either from the material supplier datasheet or are based on values found in the literature for similar materials.

Table 2. Input values for the mixed Mori-Tanaka iso-strain model, considering inclusions as tows (stiffness in GPa, dimensions in mm). Values obtained from supplier are indicated as *, while ˣ refers to an educated guess.

E_{11}^t*	E_{22}^t ˣ	G_{12}^t ˣ	ν_{12}^t ˣ	ν_{23}^t ˣ	E^m ˣ	G^m ˣ	ν^m ˣ	l^t*	w^t*	t^t*	V_{tl}*
GPa	GPa	GPa	-	-	GPa	GPa	-	mm	mm	mm	-
142	8.7	3.8	0.34	0.37	3.5	1.4	0.4	25.4	8	0.115	0.72

Table 3. Input values for the mixed Mori-Tanaka iso-strain model, considering inclusions as fibres (stiffness in GPa, dimensions in mm). Values obtained from supplier are indicated as *, while ˣ refers to an educated guess.

E_{11}^f*	E_{22}^f ˣ	G_{12}^f ˣ	ν_{12}^f ˣ	ν_{23}^f ˣ	E^m ˣ	G^m ˣ	ν^m ˣ	l^f*	D^f*	V_{fl}*
GPa	GPa	GPa	-	-	GPa	GPa	-	mm	mm	-
240	14.7	6.4	0.3	0.35	3.5	1.4	0.4	25.4	0.0068	0.43

4. Results and discussion

Stiffness predictions coming from the three tested models (one shear lag and two homogenisation) are reported in Figure 3, and compared with the experimental results.

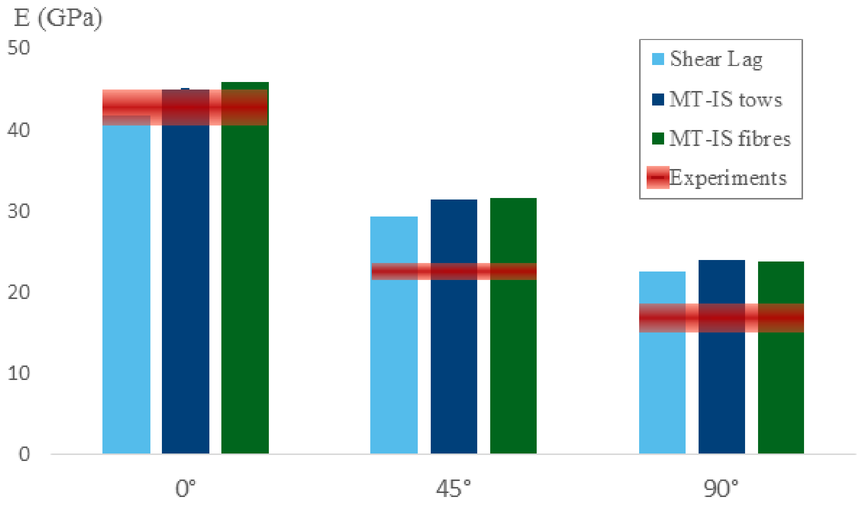

Figure 3. Results of model predictions compared to experimental results

Predictions proved to be quite accurate for the 0° case. However, all the models over-estimated the stiffness of the 45° and 90° samples: the Shear Lag multiscale model mismatch was respectively of 29.5% and 34%; for the MT-IS models the deviation was respectively of 39% and 43% when the inclusions were considered as tows, and of 39% and 42% when considering fibres inclusions. The fact that similar mismatch is found by using different material models, suggests that the source of inaccuracy is in the common part of all the approaches, that is the stiffness orientation averaging. This technique, in fact, is based on the assumption that the strain is uniform in the composite (iso-strain hypothesis). This is reasonably true for composites having fibres aligned with the load direction; in the other case, when a composite is loaded perpendicularly to the fibre direction, the opposite holds true: the stress in the fibres and matrix is the same (iso-stress hypothesis). This is in line with the result that overprediction does not affect the 0° calculations.

It is also interesting to observe that, in the MT-IS models, no significant difference is observed between the two formulations describing inclusions either as tows or fibres. This suggests that, when modelling CF-SMC, considering the orientation of the reinforcement is more crucial than taking into account its discontinuous nature.

4. Conclusions

Both formulations based on shear-lag and iso-strain Mori-Tanaka models were able to predict stiffness of the randomly-oriented discontinuous composite cut at 0° relatively the flow direction with a reasonable accuracy. However, stiffness orientation averaging has led to over-estimation of the transverse moduli. This study thus suggests that improvement is needed in predictions of CF-SMC stiffness when considering local fibre orientation: relying on an iso-strain assumption when trying to predict material properties might be effective only in a limited range of orientation. Care should thus be taken to consider the different orientation of the reinforcement when adopting predictive models, so that valid assumptions are used also when material is loaded perpendicularly to the preferential reinforcement direction. No significant difference was observed in the fibre-based or tow-based formulations of the MT-IS approaches. It is also worth noting that, in all cases, the shear-lag model performed slightly better than the MT-IS based homogenisation models.

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