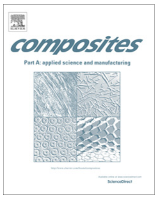
Composites: Part A 80 (2016) 194–203

Contents lists available at ScienceDirect

Composites: Part A

journal homepage: www.elsevier.com/locate/compositesa



A rate-dependent non-orthogonal constitutive model for describing shear behaviour of woven reinforced thermoplastic composites

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ARTICLE INFO

Article history:
Received 10 August 2015
Received in revised form 19 October 2015
Accepted 24 October 2015
Available online 27 October 2015

Keywords:
A. Prepreg
B. Mechanical properties
C. Finite element analysis (FEA)
E. Forming

ABSTRACT

A rate dependent constitutive model for woven reinforced thermoplastic matrix composites at forming temperatures is proposed in this work. The model is formulated using a stress objective derivative based on the fibre rotation. Nonlinear shear behaviour is modelled as a polynomial function and the rate dependence is described using a Cowper–Symonds overstress law formulated in terms of shear angle rate. The model parameters are determined by means of bias extension tests. The applicability of the material model is validated through a forming experiment.

1. Introduction

Woven composites exhibit challenging characteristic deformation modes during forming due to their textile structure. Fibre extensions are usually small and large angular rotation between the warp and the weft yarns is observed [1]. Shear behaviour is therefore very relevant when simulating forming behaviour of such materials. Two main approaches has been considered in literature to simulate draping/forming of woven materials, namely kinematic [2,3] and continuum mechanics approaches [4]. Kinematic methods, where the fabric is represented as a pin-jointed net with inextensible yarns, are widely used and provide a fast solution for several cases. However, they might not be accurate enough in some cases since they do not take into account the material constitutive behaviour. Another drawback of this method is that, as no forces are considered, effects of blank holders cannot be investigated. On the other hand, continuum mechanics approaches allow including all relevant aspects of constitutive behaviour, e.g. nonlinearities, rate-dependence, with the inherent disadvantage of being more time consuming in computation.

Vanclooster et al. [5] compared a kinematic model provided by a commercial software with their own biphasic constitutive model. They showed that kinematic approach fails in predicting the fibre orientation when unsymmetrical configurations are used, although the results are acceptable in some cases when the mould is symmetrical.

The field of constitutive modelling of woven composites has seen intense activity over the last fifteen years. Yu et al. [6] developed a non-orthogonal model based on a homogenization method considering properties of fabric and reinforcement showing good agreement with draping experiments of pre-impregnated woven. Xue et al. [1] considered a continuous model and analysed stresses and strains in orthogonal and non-orthogonal coordinates and rigid body rotation matrixes to obtain the stress–strain relationship in global coordinates. They proposed nonlinear functions for the tensile behaviour and a piecewise polynomial function to model the shear component. A more formal but similar approach was presented some years later by Peng and Cao [7]. Using similar functional expressions for the constitutive tensor, they obtained good results in comparison with bias extension test and shear frame test data. Their fibre orientation tracking model, where fibre frame is reoriented using the deformation gradient $\underline{\underline{F}}$ and material frame is rotated by rigid body rotation $\underline{\underline{R}}$ has been a notorious contribution to textile modelling and is still used in more recent works [8–11].

Mesoscopic approaches have been also investigated. Boisse et al. [12,13] introduced a mesoscopic approach where finite elements (FE) made of a number of woven unit cells are defined. They initially considered only tensile deformation energy in the model. Their work was posteriorly extended introducing in-plane rigidity

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http://dx.doi.org/10.1016/j.compositesa.2015.10.028
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[14]. The limitations of the previous approach were investigated and it was concluded that in-plane shear rigidity could be neglected as long as the local shear angle does not exceed the shear locking angle. More recently, Wang et al. [15,16] extended this approach further presenting a semi-discrete shell element model for thermoplastic matrix composites where tension, in-plane shear and also out-of-plane bending were considered. This approach showed good performance in predicting wrinkles appearance. Simpler approaches have also been addressed [17–19]. Abbassi et al. [19] performed a large experimental characterization on PPS/carbon and then used the data in a hemispherical surface forming simulation employing a regular orthotropic material model. They proposed a theoretical wrinkling model as an alternative to tackle the wrinkling prediction problem.

Continuous approaches are usually preferred since they can be easily implemented in FE codes using standard elements. To this aim, an important contribution was made by Badel et al. [8] who proposed a constitutive model where the objective derivative of the stress is based in the fibre rotation. The original formulation was made for unidirectional composites (i.e. one fibre direction) and was then extended to two fibre direction to model woven composites. They demonstrated that the use of objective derivatives of stress based on material rotations leads to wrong results when shear is superimposed with tensile stress states. This approach was also used in [9] confirming that the objective derivative based on the warp and weft fibre rotation tensors can describe the behaviour of the woven materials. Similar approach was again adopted in more recent works [10,11].

In spite of the intense work in the field of constitutive modelling of fabrics and woven reinforced thermoplastic composites, the rate dependence of their behaviour has been scarcely addressed. Harrison et al. [20] are within the few who specifically investigated this matter. They extended the model of [21] adding shear angle rate dependence in the shear component of the constitutive behaviour. This model needs as input several shear force vs. shear angle curves at different angle rates. Shear rigidity is then updated at each increment during the simulation depending on the local shear angle rate. Although the work delineated in [20] showed good performance in numerical simulations, still not many functional expressions have been tested to describe rate dependence.

In this work the rate dependence of a woven reinforced thermoplastic composite at two different temperatures was characterized using bias extension test [22–24]. A non-orthogonal model is proposed where the nonlinear shear behaviour is considered to depend on the shear angle rate obeying a Cowper–Symonds [25] overstress law. The model is implemented in the commercial FE software Abaqus/Explicit using a vectorised user material subroutine (VUMAT). Simulations of the bias extension test describe very well the characteristic strain distribution of this kind of test and the shear angle evolution. Furthermore, the model is validated comparing its predictions with results of an actual forming operation.

2. Shear characterization via bias extension test

2.1. Specimen preparation

The concepts behind bias extension test have been already explained in several works [22–24]. The main idea is to obtain a pure shear state in the central region C of the specimen as shown in Fig. 1 by applying axial displacement on a specimen with a ±45° fibre orientation. The main disadvantage of this test is the possible slippage between warp and weft yarns. Also, time-consuming image analysis post-processing is usually required to follow the sample deformation.

A polypropylene (PP)/glass fibre (GF, Twill – 50:50) commercial grade was analysed in this work. All tests were carried out at single ply level to avoid inter-ply effects on the mechanical behaviour. The specimens were cut out of plates using a StepFour Xpert 1800P CNC milling machine. The geometry of the specimens was defined according to the 16-yarn criterion introduced by Peng and Cao [26]. Every specimen contains 16 yarns along the $\overline{mn}$ segment indicated by a dotted line in Fig. 2. The aspect ratio of the specimens was modified to 2.5 (and not 2 as proposed in [26]) since previous test showed a more homogeneous distribution of the shear deformation in the pure shear region for higher aspect ratios as 2. The nominal dimensions of the employed specimens were $h = 250$ mm and $w = 100$ mm, where h and w are width and height, respectively, as shown in Fig. 1.

2.2. Experimental set-up

Bias extension test were carried out using a servo-hydraulic MTS 852 Damper Test System. Samples were tested inside a temperature chamber. Temperature was monitored using a temperature probe consisting of two layers of composite pressed together with a thermocouple inserted in between. The experimental set-up is shown in Fig. 3. The load-displacement response was recorded. Tests at three different crosshead speeds (100, 1000, and 10,000 mm/min, referred to as WE0, WE1, and WE2, respectively) and two different temperatures (180 °C and 200 °C, referred to as T180 and T200, respectively) were carried out. Each test was filmed using a PHANTOM V711 high-speed camera in order to follow the evolution of the shear angle during the test. The angle between warp and weft yarns at four different material points (identified as α_A, α_b, α_C, and α_D in Fig. 2) was computed using an image analysis code in Matlab especially programmed for this purpose. The average shear angle γ was then computed as:

$$\gamma = \sum_{i=1}^{4} \frac{|\alpha_i - 90^\circ|}{4} \tag{1}$$

2.3. Shear stress–shear angle curves determination

In order to characterize the shear behaviour of the material, the experimental data consisting of axial force and axial displacement must be post-processed to obtain shear force (and shear stress) evolution with the shear angle. Since the outcome of the bias extension test, the determination of the shear force has been a matter of intense discussion [4,27–30]. Cao et al. [30] deduced an expression to obtain the normalized shear force F_{sh} vs. shear angle γ from bias extension test data:

$$F_{sh}(\gamma) = \frac{1}{(2h-3w)\cos\gamma}\left(\left(\frac{h}{w}-1\right)F\left(\cos\frac{\gamma}{2} - sin\frac{\gamma}{2}\right) - wF_{sh}\left(\frac{\gamma}{2}\right)\cos\frac{\gamma}{2}\right) \tag{2}$$

where h, w and F are the sample height, the sample width and the axial force, respectively. Eq. (2) is based on the following four assumptions: (a) shear angles in each zone are considered to be uniform; (b) shear angle in zone C is considered to be twice that in zone B; (c) there is no shear deformation in zone A; (d) the initial fabric has a perfect orthogonal configuration (i.e. initial angle between warp and weft yarns is 90°).

An iterative procedure is needed since the current value $F_{sh}(\gamma)$ depends on $F_{sh}\left(\frac{\gamma}{2}\right)$. The first iteration is calculated considering $F_{sh}\left(\frac{\gamma}{2}\right) = 0$ and following iterations are calculated interpolating shear force values from the previous iteration. This process was repeated until the sum of squared differences between iterations was less than 10^{-20}. Once the normalized shear force was deter-