

CONSTITUTIVE MODELLING OF UD REINFORCED THERMOPLASTIC LAMINATES

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ABSTRACT: Intra-ply shear is an important mechanism in thermoforming processes of UD fibre reinforced thermoplastic laminates. Various methods have been developed to characterise this shear mechanism, but measured properties differ for several orders of magnitude. The potential of another technique is shown in this paper. This approach considers a strip with a rectangular cross section, subjected to torsion. Several analyses have been carried out to determine the significant material properties for this loading mechanism. For clarity, isotropic and orthotropic elastic material behaviour was considered first. The response torque mainly depends on the in-plane shear modulus G_{12} . An extension was made to the analysis of anisotropic viscous material behaviour. Closed form solutions and FE simulations were compared, using a fibre reinforced viscous fluid model. The torsional response of a partially clamped strip was highly influenced by the fibre stiffnesses. Nevertheless, it is possible to relate the longitudinal viscosity to a closed form solution directly, if bulging is not suppressed and constant through the length of the strip. A smart clamping design is therefore required.

KEYWORDS: intra-ply shear, characterisation, thermoplastic, uni-directional, torsion, DMA, rectangular strip

INTRODUCTION

Simulation tools for the thermoforming process aim to reduce the number of optimisation cycles during the development phase of a product. Constitutive models are needed to describe the occurring deformation mechanisms, such as intra-ply shear, ply-ply and tool-ply friction, and out-of-plane bending. These models subsequently require material property data and corresponding characterisation methods. Different methods for intra-ply shear characterisation result in distinctly different material parameters, as was summarised clearly by Harrison [1]. This motivates the development of a different intra-ply shear characterisation technique. The objective is to characterise a uni-directional (UD) reinforced thermoplastic at high temperatures. In that case, visco-elastic behaviour has to be accounted for. For the sake of clarity, we will start with the analysis of an elastic strip loaded in torsion. Then, an extension to analyses with viscous material behaviour will be considered.

THEORY FOR INTRA-PLY DEFORMATIONS

The well accepted Ideal Fibre Reinforced Newtonian fluid Model (IFRM) can be utilised to describe the deformation behaviour of a UD reinforced ply with a matrix material in its molten state. This continuum theory was initially developed for elastic materials [2] and adapted by Rogers [3] to account for viscous fluids. A decomposed stress tensor is found by assuming incompressibility and fibre-inextensibility. The stress is the sum of a hydrostatic pressure $p\mathbf{I}$, an arbitrary fibre stress \underline{T} , and an extra stress tensor. Rogers [3] proposed a linear form of the extra stress tensor to describe the constitutive behaviour of a fibre reinforced viscous fluid, resulting in the following constitutive relationship:

$$\underline{\sigma} = -p\mathbf{I} + T\vec{a}\vec{a} + 2\eta_T \underline{D} + 2(\eta_L - \eta_T)(\vec{a}\vec{a} \cdot \underline{D} + \underline{D} \cdot \vec{a}\vec{a}), \quad (1)$$

in which $\underline{\sigma}$ is the stress tensor, \vec{a} is a vector that represents the fibre direction, and \underline{D} is the rate of deformation tensor. The parameters η_T and η_L represent the transverse and longitudinal viscosity of the UD reinforced ply respectively and are related to the shearing mechanisms of a fibre reinforced viscous fluid, as shown in Fig. 1. These shearing modes are associated with the shear moduli in case of elastic behaviour.

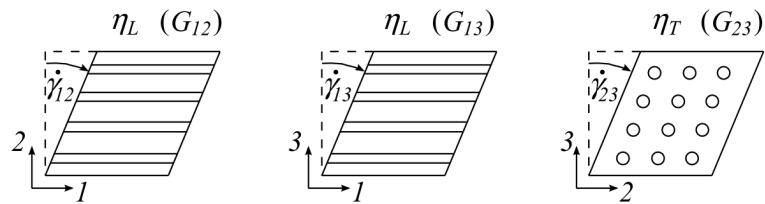


Fig. 1 Left and center, axial intra-ply shear. Right, transverse intra-ply shear.

INTRA-PLY SHEAR CHARACTERISATION

Several techniques were developed to determine the two viscosities in eqn. (1) for a UD fibre reinforced laminate at high temperatures. Some of them were described by Advani [4] and a comparison of many tests was presented by Harrison [1]. For example, plate-plate rheometry [5] and picture frame [6] tests were developed, but their resulting viscosities differ several orders of magnitude. Potter showed the potential of using off-axis tensile [7] and bias extension tests [8] for intra-ply shear characterisation. These can be used successfully for UD reinforced uncured epoxies. In-house, bias-extension tests were performed on UD reinforced thermoplastics at forming temperatures but non-uniform deformation, out-of-plane effects and poor reproducibility were encountered. Indeed, many tests involve difficulties due to the low integrity of fibre reinforced thermoplastics at high temperatures. Dealing with the laminate's integrity at high temperatures can probably be facilitated by exploiting the stiff and continuous nature of the fibres. To this end we examined the possibility of loading a fibre reinforced rectangular strip in torsion.

SHEAR CHARACTERISATION ALTERNATIVE

A Dynamic Mechanical Analysis (DMA) apparatus was utilised, to subject a fibre reinforced strip to torsional loading [9]. Similar loading mechanisms were used by Kennedy [10] to characterise the interfacial bond strength of fibre reinforced laminates. Here, a carbon fibre reinforced laminate with a 60% fibre volume fraction, a polyetherketoneketone (PEKK) matrix material and a $[0]_8$ lay-up was used to cut strips with dimensions $L = 35$ mm, $d = 1$ mm, and $w = 13$ mm (see Fig. 2, left). Table 1 shows the elastic material properties at room temperature. These were determined with the Composite Cylinder Assemblage model [13].

Table 1 Elastic material properties (stiffnesses in GPa) of the strip.

E_1	E_2	E_3	G_{12}	G_{23}	G_{13}	ν_{12} [-]	ν_{23} [-]	ν_{31} [-]
134	9.22	9.22	5.10	3.08	5.10	0.300	0.495	0.021

Amplitude sweep tests were performed at a relatively low frequency of 1 Hz, at room temperature, and with two distinct clamping conditions. Clamps were tightened at both sides of the strip for three repeatable tests with the results in Fig. 2 (□). Standard deviations were negligible. For this configuration, FE simulations showed a much stiffer response (not plotted in Fig. 2). Therefore, laminate slippage in the clamps is expected. The second configuration dealt with one tightened clamp and one loosened clamp, such that pronounced bulging appeared at one side. A smaller stiffness was measured, as indicated in Fig. 2 (○).

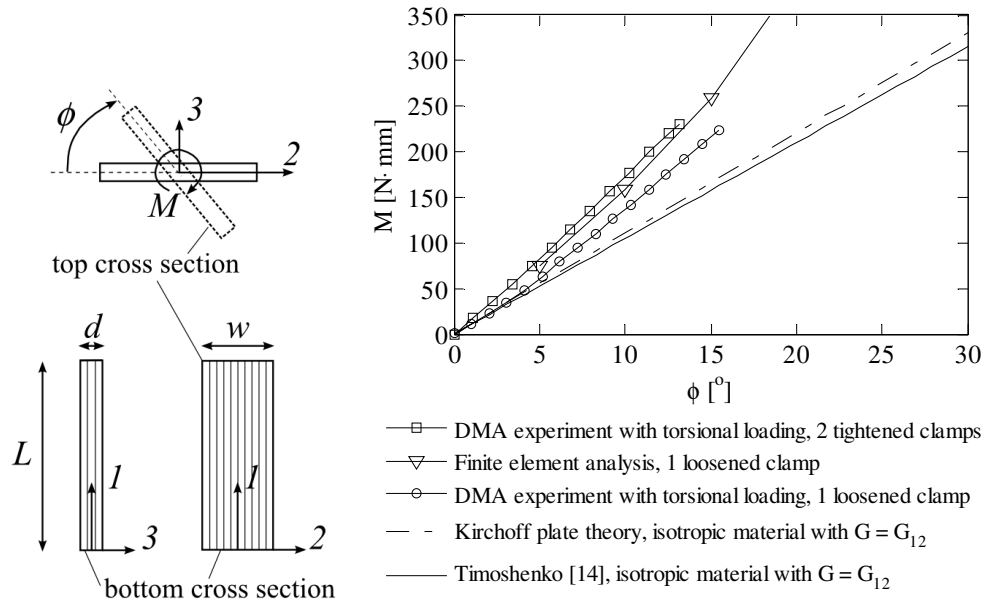


Fig. 2 Left, schematic representation of the UD reinforced thermoplastic strip.
 Right, torque versus rotation angle responses for several cases.

Elastic Approach

A sensitivity study is needed to reveal the dominant material parameters for a rectangular strip that is subjected to torsion. Closed form solutions were considered first. Bulging is assumed to be constant through the length of the strip. Isotropic material properties were assumed with a shear modulus G that equals G_{12} in Table 1. Kirchhoff's plate theory was employed to calculate the response of a rectangular strip with an

assumed constant curvature. The result is plotted with the dash-dotted line Fig. 2. The solid line in Fig. 2 shows the response of the solution for torsion of a rectangular bar, described by Timoshenko [14]:

$$M = \frac{1}{3} G_{12} \phi d^3 w \left(1 - \frac{192d}{w\pi^5} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^5} \tanh\left(\frac{(2n+1)\pi w}{2d}\right) \right), \quad (2)$$

Both solutions correspond with the experimental configuration with one loosened clamp, for small rotation angles below 5°. This already indicates a significant influence of G_{12} .

The AniForm finite element package [12] was used to analyse the response for larger rotations. In addition, an orthotropic elastic material model was used, using the material parameters from Table 1. Quadratic tetrahedra were used to mesh the geometry. Boundary conditions were applied to imitate the experimental situation (o) with a loosened clamp on top and a tightened clamp at the bottom of the strip. The response is shown in Fig. 2 (∇) and has a slightly stiffer behaviour, compared to the simulated experimental situation. Nevertheless, this FE model is employed to perform a sensitivity study on the orthotropic material parameters from Table 1.

In Fig. 3, each graph represents the response in which the magnitudes of one or several parameters were decreased to 10% of its original value. The torque M_0 from the original configuration is related to the torque M of the modified configuration. For small rotation angles, G_{12} is the most significant parameter. For larger rotation angles, the stiffness E_1 in the fibre direction shows an increasing significance.

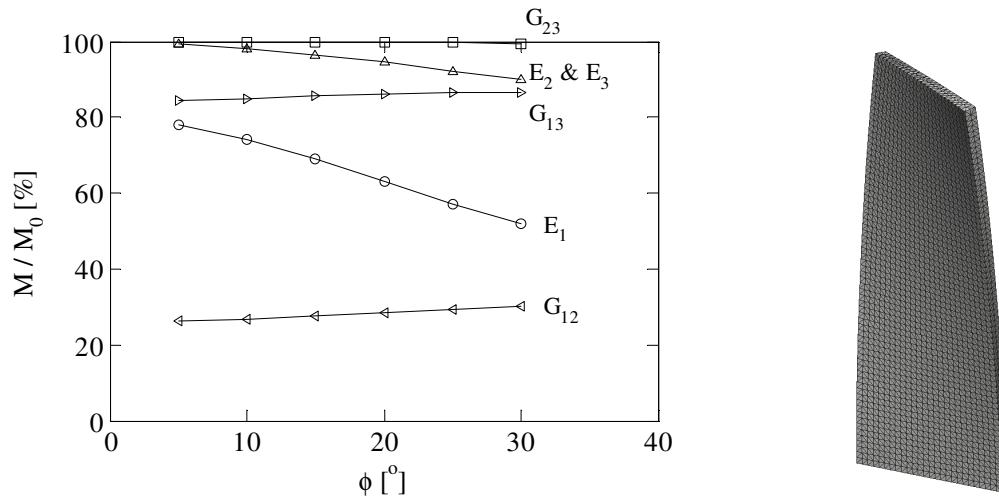


Fig. 3 Left, sensitivity on the material parameters, as indicated in the graph. The magnitude of the indicated parameter has been reduced to 10% of its original value from Table 1. Right, gives an impression of the deflection for $\phi = 30^\circ$.

Viscous Approach

To determine the viscosities that appear in the IFRM model in eqn. (1), a transition from elastic to viscous analyses is needed. This will show whether the pronounced shear mechanism in the elastic approach still holds for a fibre reinforced viscous fluid. The strip is subjected to a time dependent rotation $\phi = \phi_0 \sin(2\pi ft)$. The maximum rotation angle ϕ_0 was set to 3°, up to which linear responses in Fig. 2 were observed. The

maximum rotation rate $\dot{\phi}_0$ appears at $\phi=0$, where the contribution of an elastic response can be neglected. This rotation rate was determined by $\dot{\phi}_0 = 2\pi f \phi_0$, for several frequencies f .

As a first attempt, the closed form solution from Timoshenko [14] was simply converted by substituting $G_{12} = \eta_L$ and $\varphi = \phi$ in eqn. (2). Torsional responses were determined for several maximum rotation rates $\dot{\phi}_0$, as shown with the dashed line in Fig. 4. The previously mentioned FE model was employed as well. One loosened clamp was considered again. The IFRM constitutive model from eqn. (1) was used to describe material behaviour. A significant influence of the fibre stiffness (and thus of fibre stress \underline{T}) was observed. Increasing deviations from Timoshenko's solution were observed for realistic fibre stiffnesses. Additional responses (\triangleright) are shown for another FE model. Two loosened clamps were considered, such that bulging was less restricted than the former FE model. Results were not influenced by the fibre stress \underline{T} and good agreement with the modified closed form solution was found.

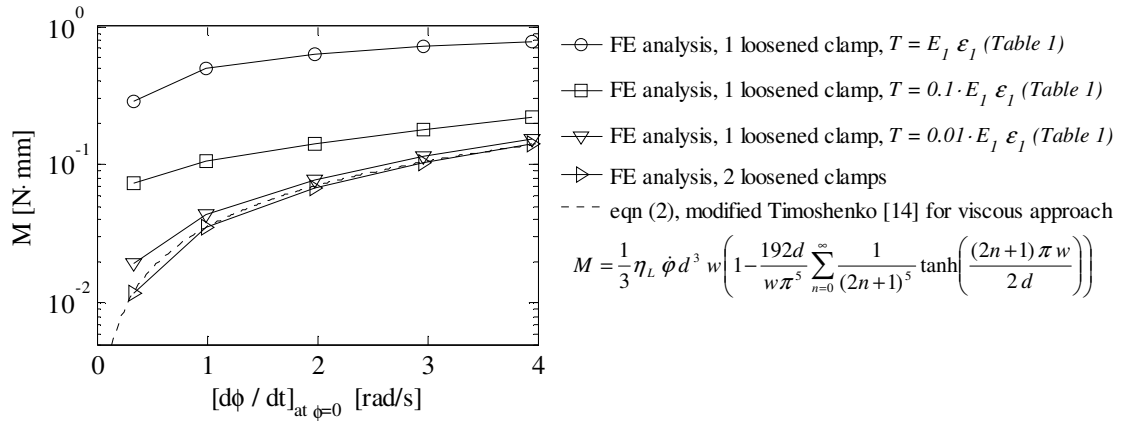


Fig. 4 Resulting torque, as a function of the rotation rate at $\phi=0$, which corresponds with a rotation frequency of $f \approx 0-12$ Hz. Viscosities were set to $\eta_L = 300$ kPa·s [5], and $\eta_T = 0$ kPa·s.

CONCLUSIONS AND FUTURE WORK

A torsionally loaded strip has been assessed for its potential to characterise its intra-ply shear properties. Firstly, elastic material behaviour was considered. Closed form solutions assumed isotropic material properties and constant bulging through the length of the strip. These showed good agreement with experimental results for small rotation angles, which already indicated the significance of G_{12} in case of elastic material behaviour.

An FE simulation was performed with an orthotropic elastic material model. Bulging was suppressed on one side of the strip only, which simulates the experimental situation. A sensitivity analysis on the elastic orthotropic material parameters revealed the significance of G_{12} as well. The influence of the fibre stiffness increased for larger rotation angles.

Further analyses dealt with viscous material behaviour. FE models were compared with a modified closed form solution for torsion of a rectangular bar [14]. The torsional response of a partially clamped strip was highly influenced by the fibre stiffnesses. This

was not the case for the analyses with elastic material behaviour. It is expected that this difference arises from the increased anisotropy.

Determining the viscosities from a DMA experiment is highly dependent on the clamping conditions. The longitudinal viscosity can be extracted directly with help of a closed form solution, if bulging is not suppressed and constant through the length of the strip. The actual clamping situation is not known for a molten thermoplastic strip at this moment. Bulging may be admitted by using a smart clamping design. Once the clamping condition is well controlled, further explorations are needed. Visco-elastic behaviour will be accounted for subsequently, distinguishing storage and loss terms.

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