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Experimental and numerical characterization method for forming behavior of thermoplastics reinforced with woven fabrics

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Abstract

The automotive and aviation industry has to achieve significant weight reduction in order to fulfil legal obligations. This leads to an increasing use of new materials or new material combinations like fibre-reinforced plastics (FRP) as they provide a high lightweight potential due to the combination of low density and high tensile strength. Meanwhile pre-impregnated sheets with a thermoplastic matrix reinforced with woven carbon fibres are commercially available. This has led in a significant cost reduction and hence, the FRP have become affordable for large scale production. The material properties, in particular the forming and failure behaviour of the FRP, differ strongly from that of conventional metal materials like steel or aluminium. Therefore, new material characterisation techniques, investigation methods as well as numerical models are required. The main focus of this paper lies on the development of a non-orthogonal material model for the FRP, its implementation in a commercial FE-software as well as on the use of a combined experimental-numerical procedure for material characterisation. Since the properties of these materials are strongly temperature dependent, the forming process of reinforced thermoplastics is typically carried out at elevated temperatures. Thus, temperature sensitivity has to be taken into account during experimental testing as well as in the model approach. The model parameterisation is carried out based on an iterative numerical optimization procedure. For this purpose, the experimentally obtained results are investigated by means of digital image correlation and linked with the numerical model in combination with an automated optimization process.

Keywords: Fabric-Reinforced Thermoplastics; FE-Modelling; Material Characterisation

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1. Introduction

New materials, like woven composites, offer a combination of low density and high specific tensile strength. Thus, they provide a high light-weight potential and are increasingly used. However, the high strength is only offered in the fibre direction. This strong anisotropic behaviour differs from commonly used metal materials. Due to their woven fibre arrangement, organic sheets offer a higher overall stiffness as compared with UD-laminates. Furthermore, the formability is increased by yarn rotation and stretching of the undulated fibres [1]. The use of thermoplastics as a matrix material is gaining more importance particularly in the automotive industry, since it can be formed to a complex geometry under elevated temperatures [2; 3].

The used material, organic sheets, consist of a thermoplastic PA6 matrix and woven glass fibres as reinforcement. The overall properties are a superimposition of matrix properties and fibre properties [4]. This leads to a strong anisotropic behaviour, where the highest strength is observed in the fibre direction. Therefore, the shearing of the fibres at the cross points is the main in plane forming mode of woven fabrics [5]. During the deformation, the angle between the fibres changes and once it reaches a critical value, referred to as locking angle, the shear stress undergoes a substantial increase due to shear locking. In the molten state, the shear resistance can be assumed to be negligible until reaching the specific locking angle of the woven fabric [6]. In contrast to the glass fibres, the forming behaviour of the thermoplastic matrix material is strongly temperature dependent [2]. Above the melting temperature, the stiffness and strength are significantly reduced. However, in case of a matrix solidification during the forming phase, the influence of the matrix on the overall forming behaviour increases significantly. The influence of temperature evolution has been investigated in [7] by means of the draping behaviour of a double dome geometry. The authors have concluded that the temperature evolution over the entire process including the heating, transfer and forming phase has a decisive impact on the precise prediction of the draping process. The bending properties of reinforced thermoplastic sheets were measured in [8] by means of cantilever test, which were performed in an environmental chamber. In order to characterise the main in plane forming mode, the shear deformation, the picture frame or bias extension test can be applied. Both methods are discussed in [6] and [9] and lead to similar results. The material properties of the glass fibres are analysed by means of uniaxial tensile tests, whereby the loading is introduced in fibre direction. This contribution deals with experimental investigations to determine the mechanical properties of organic sheets. Considering of the temperature dependency the tests have been performed in a wide temperature range. Based on the experimental findings, a numerical model has been developed and implemented into the commercial FE-Software Abaqus CAE 6.14. The model parameterisation has been subsequently carried out by a numerical optimisation process.

2. Material characterisation of organic sheets

In the scope of this work organic sheet with a PA6 matrix reinforced with woven glass fibres (2/2 twill) and a thickness of 1 mm was investigated. Since the considered thermoplastic PA6 is strongly temperature dependent the tests were carried out inside an environmental chamber at temperatures between RT and 240 °C and a test speed of 1 mms-1. In order to take the effect of fibre direction into account tensile tests in fibre direction as well as bias extension tests have been performed. The experimental tests have been carried out at LMT, ENS Paris-Saclay and for each parameter combination up to 5 repetitions have been conducted. During the bias extension test the load is introduced with an initial angle of 45° to the fibres, which leads to pure shear in the middle of the sample. A detailed explanation of the bias extension test is given in [5]. During the tests the displacements have been captured by means of an optical measurement system with a frame rate of 4 pictures/mm. The ratio of height (H) to width (W) was chosen to 2.33 and thus higher than 2.0 in order to achieve more homogeneous shear deformation in the bias extension tests like proposed in [5]. Furthermore, heating tests have been carried out in order to ensure a homogeneous sample temperature. The used test setup as well as the fibre orientations for the different tests are shown in Fig. 2. In Fig. 2b, c measured force displacement curves for uniaxial tensile test and bias extension tests are presented for different testing temperatures at a test speed of 1 mm/s. The comparison between tensile test (b) and bias extension test (c) shows the strong influence of the fibre direction. During tensile testing, the introduced load is borne by the fibres. The observed maximum forces are in general higher as compared to the bias extension test and only small strains exist before fracture. The temperature dependency is also small.

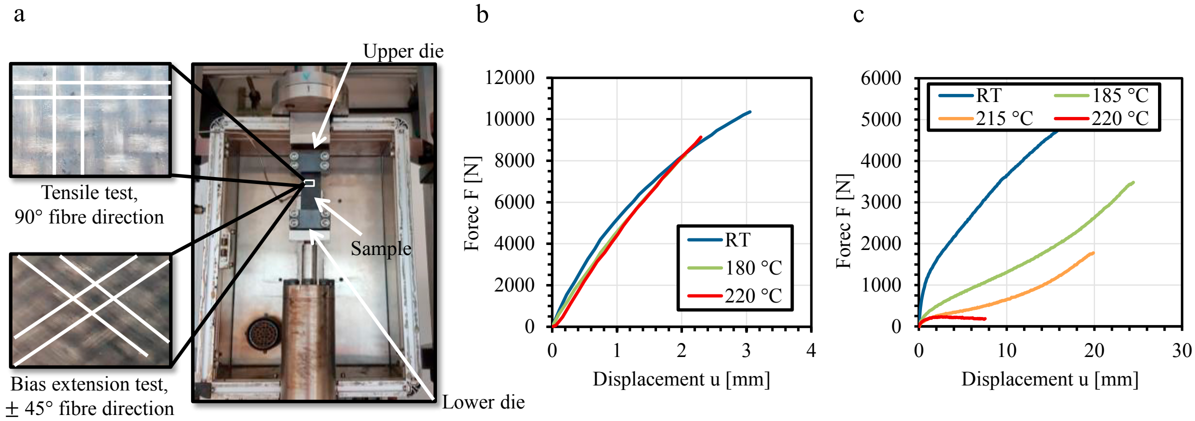

Fig. 1. (a) Experimental test setup for uniaxial tensile test and bias extension test with corresponding fibre directions; (b) Experimental obtained force-displacements curves for various temperatures at a test speed of 1 mm/s: uniaxial tensile tests with 90° fibre direction; (c) bias extension tests with ± 45° fibre direction.

In contrast, the results of bias extension test demonstrate a more complex material behaviour. Due to the loading direction the mechanical behaviour is a superimposition of matrix and fibre properties. A high temperature dependency can be seen due to the increased influence of the thermoplastic matrix material. The initial fibre orientation in the bias extension test is ±45°. However, the shear deformation leads to fibre rotation with increasing displacement and the fibre get more and more aligned in loading direction. Friction between the fibre bundles themselves as well as between the fibre bundles and the matrix influence the movement. If the specific lock angle is reached, further deformation leads to a sharp increase of force as well as out of plane wrinkling due to compaction of fibre bundles. For a detailed material description the change of shear angle with increasing displacement is of great interest. The current shear angle γ has been calculated based on optical measurement data by means of digital image correlation with following equation (1) [10]:

$$\gamma = \frac{\pi}{2} - 2 * \arctan\left(\frac{1+\varepsilon_x}{1+\varepsilon_y}\right) \quad (1)$$

$$F_{SH}(\gamma) = \frac{1}{(2H-3W)\cos\gamma}\left[\left(\frac{H}{W}-1\right) F_{ax}\left(\cos\frac{\gamma}{2}-\sin\frac{\gamma}{2}\right) - W\, F_{SH}\left(\frac{\gamma}{2}\right)\cos\frac{\gamma}{2}\right] \quad (2)$$

where ε_x and ε_y are the engineering strains. Furthermore, the material description requires the actual shear stress which depends on the shear angle. This dependency leads to a high non-linear behaviour. In this work a constant test speed of $1 mms^{-1}$ has been investigated. Therefore, the matrix viscosity is assumed to be rate independent. Following the basic research of [11] the normalised shear force $F_{SH}(\gamma)$ per unit length can be calculated based on the geometric properties of the bias extension sample with equation (2), whereby H and W are the specimen height and width, respectively. The current value of $F_{SH}(\gamma)$ depends on $F_{SH}(\gamma/2)$, hence the shear force needs to be calculated in an iterative procedure by means of a Matlab code. The shear angle is taken into account by correlating the measured axial force F_{ax} with the optical measured shear angle. The shear angle dependent shear stress τ_{12} can be derived by referring the shear force on the specimen thickness. The Fig. 2 presents exemplary calculated shear stress - shear angle curves for the temperature of 185 °C, 200 °C and 215 °C and a test speed of 1 mm/s. The shear angles distribution calculated by means of digital image correlation (DIC) show some variation at the sides. This is caused by loose fibre ends, which are not sheared but captured by the DIC and lead to failures in this region. Therefore, during the investigations, three regions of interest (ROI) have been chosen on the sample surface and a representative mean shear angle has been calculated and subsequently used for further calculation steps (Fig. 2a). The nonlinear dependency between shear stress and shear angle can be described by means of a polynomial function. In order to obtain numerical stability a continuous description of the temperature dependent material behaviour is necessary.

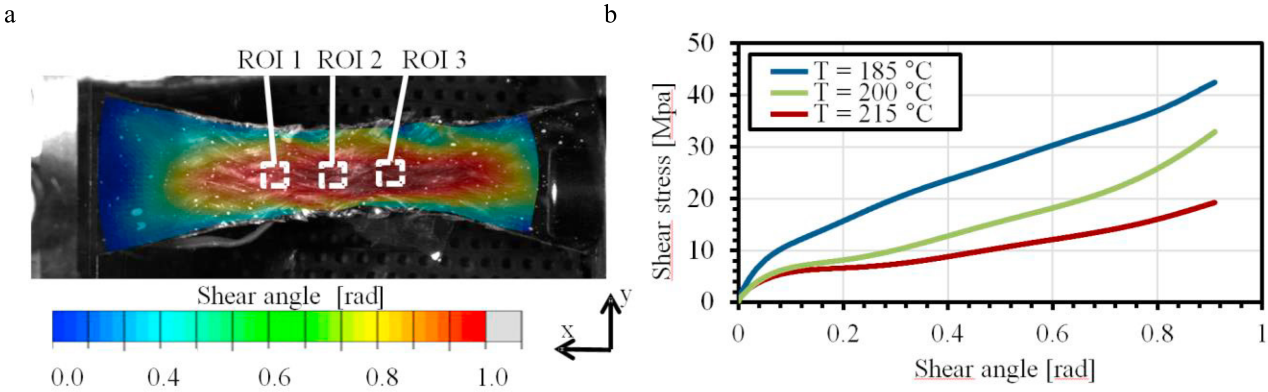

Figure 2 (a) Shear angle obtained by means of DIC at a displacement of 18 mm for a temperature of 215 °C ; (b) shear stress - shear angle curve for the temperatures of 185 °C, 200 °C and 215 °C.

Therefore, the polynomial function has been extended by an multiplicative term, considering an exponential relationship, whereby the coefficients $p_1 - p_5$ are material specific constants and T_0 is a scaling factor for the temperature dependency (Fig. 3a). The Fig. 3b presents the predicted shear stress surface as well as the experimental optained shear angle – shear stress curves, marked with black dots. The correlation coefficient is determined to R^2=0.99, thus the introduced model provides a good description of the material behaviour under consideration of elevated temperatures.

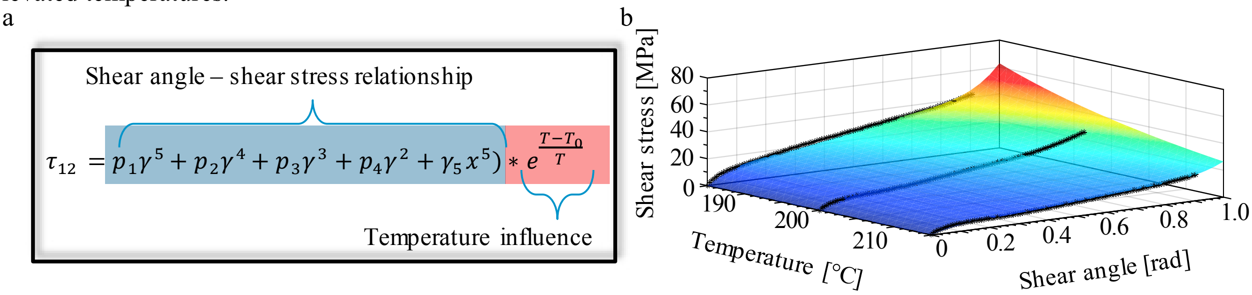

Fig. 3. (a) Polynomial function for the description of the nonlinear relationship between shear stress and shear angle under consideration of temperature dependency; (b) Comparison between experimental data and the model predicted shear stress.

3. Numerical model and material data optimisation

For numerical description of organic sheets deformation, a non-orthogonal hypo-elastic material model has been established and implemented in the FE-Software Abaqus CAE 6.14 by means of a user defined routine. Hypo-elastic material models are widely used in FE codes to describe the material behaviour at large strains [12]. Due to strong changes of the fibre direction during the forming process the shear stiffness needs to be described as a function of the shear angle. Taking into account the works [1; 13] the current fibre direction during deformation can be calculated by means of fixed body rotation matrix and deformation gradient. A schematic representation of fibre rotation is given in Fig. 4. The deformation caused change of fibre direction is considered by transforming the obtained strain increment from the global orthonormal frame (*g*) to the fibre frames (*f*). The stress and strain increments for both fibre directions (*f1, f2*) are calculated within the fibre frames based on the updated stiffness matrix and subsequently transferred back to Cauchy stress. The update of the stress increments is carried out by using the Hughes and Winget formulation [14]. The shear stress increment is calculated in the non-orthogonal frame defined by the two fibre directions f_{1x}^1 and f_{2x}^1 based on the change of the angle ψ and the updated nonlinear shear modulus. Finally, the shear stress increment is also transferred back to the global orthonormal frame. The stress tensor is updated by a superimposition of the calculated stress increments of the different frames. The superimposition is carried out in the global orthonormal frame. As an initial approach only tensile modulus in fibre direction and shear modulus depending on shear angle have been considered. The effect of poisson's ratio has been neglected.

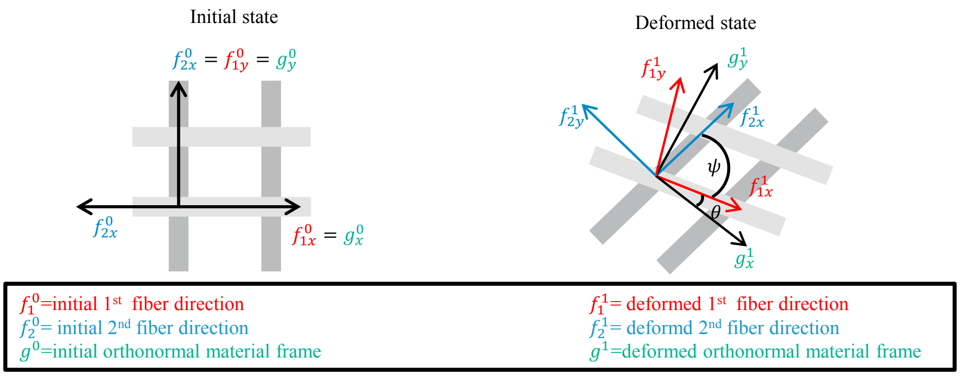

Fig. 4. Schematic representation of fibre orientation during deformation of woven fabrics.

Due to the superimposition of matrix and fibre properties, the nonlinear relationship between shear angle and shear stress as well as the calculation of the shear angle based on DIC-data, the parameterisation of the numerical material model is challenging. Therefore, an iterative numerical optimisation process has been developed. The process itself is controlled by a Python file, which modifies the user defined input parameters, the base points p_1-p_5 inside the Abaqus job file, submit the job as well as perform post processing operations on the results file. The shear stress – shear angle behaviour is described by the base points. To modify the material behaviour in fibre direction, the experimental determined elastic modulus E_{11} in fibre direction is multiplied by a scaling factor A. is introduced, which is multiplied by the elastic modulus in fibre direction. The sum of squared errors of the experimental measured and numerical calculated axial forces has been chosen as target figure. The optimisation is carried out by means of multi objective genetic algorithm (MOGA), which can be used efficiently for multi objective optimisation problems. In order to meet the shape of the force – displacement curve the deviation at characteristic displacements as well as the total deviation have been chosen as objectives. For a first approach, the optimisation process has been performed for bias extension test at a temperature of 215 °C and a test speed of 1 mms^{-1}.

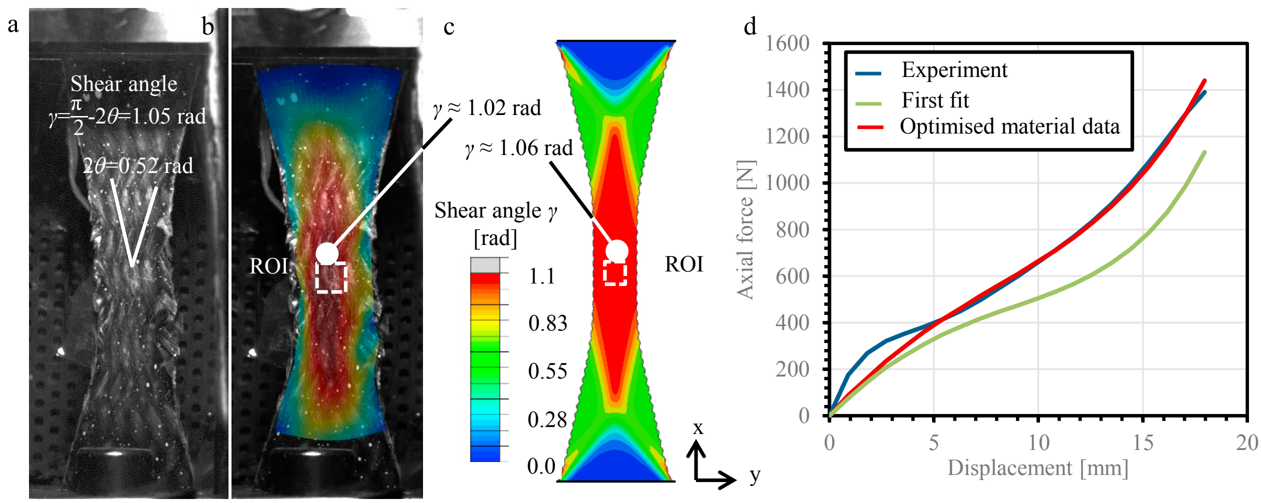

Figure 5 Comparison of manually measured shear angle (a), the shear angle distribution obtained by (b) DIC and by (c) numerical simulation at a displacement of 18 mm; (d) force – displacement curves based on experimental data and numerical simulation at a temperature of 215 °C.

The determination of the shear angle evolution by means of DIC analysis as well as the numerical model itself and the numerical optimisation process are validated by a comparison of numerical calculated data with experimental data. Fig. 5 shows a comparison between manually measured angle between the fibre direction (Fig. 5a), the shear angle obtained by optical measurement and DIC analysis (Fig. 5b) as well as the numerical calculated shear angle at the ROI position in the middle of the sample (Fig. 5c) for a bias extension tests at 215 °C and a displacement of 18 mm.

The numerical results, presented in Fig. 5c, are calculated based on the optimised material data. An overview over the initial material parameters, determined based on the experimental data and the finally used optimized data is given in table 1.

Table 1 Overview over initial and optimised material data for the numerical simulation

	p_1	p_2	p_3	p_4	p_5	A	E_{11} [GPa]
Initial data	97.00	-524.00	1332.00	-1485.00	609.00	1.00	8000
Optimised data	106.89	-513.22	1343.39	-1610.50	637.09	1.19	8000

The determined shear angles show a good qualitative agreement. A comparison of experimental measured and numerical calculated force displacement curves is presented in Fig. 5d. The numerical calculated curves are based on the initial determined material data as well as on the material data which has been obtained after the numerical optimisation. The optimised material data shows a good agreement with the experimental measured curve. Furthermore, it can be seen that the optimisation process leads to a strong increase in the quality of the numerical results.

4. Conclusion

In this research the complex material behaviour of organic sheets, which consist of a thermoplastic matrix with woven glass fibres, has been characterised by means of uniaxial tensile tests and bias extension tests under consideration of a wide temperature range. The results show a strong dependency on fibre direction, shear angle and temperature. A continuous model approach, which takes the change of fibre direction into account, has been implemented by means of a user subroutine. The model has been parametrized under consideration of the nonlinear relationship between shear angle and shear modulus. The change of the shear angle has been determined by means of digital image correlation in an incremental procedure based on the optical measured displacement data. The material model has been parameterised by means of an iterative optimisation process. The comparison of experimental measured and numerical calculated shear angle distribution showed a good qualitative agreement. Furthermore, the optimisation of the material data by means of a genetic optimisation algorithm leads to estimation of force displacement curves.

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