Influence of temperature on in-plane and out-of-plane mechanical behaviour of GFRP composite

M. Grubenmann¹, J. Heingärtner¹, P. Hora², D. Bassan³

¹ inspire - ivp, Technoparkstrasse 1, 8005 Zurich, Switzerland
² ETH Zurich, Institute of Virtual Manufacturing, Tannenstrasse 3, 8092 Zurich, Switzerland
³ C.R.F. S.C.p.A, Strada Torino 50, 10043 Orbassano (TO), Italy

E-mail: grubenmann@inspire.ethz.ch

Abstract. In this work, the challenges in forming of glass-fibre reinforced PA6, from experimental material characterization and parameter identification to numerical modelling using Finite Element Analyses (FEA) is reviewed and results are presented. Mechanical in-plane behaviour is characterized by tensile and bias extension tests. Out-of-plane characteristics are determined using the cantilever test. The constitutive model is set-up using LS-DYNA™, in which the fibre and matrix properties are considered separately. Therefore separate tensile experiments with unreinforced PA6 are performed. FEA is used to model the tensile and cantilever tests in which the strain-stress curves, influence of displacement on shearing angle and different approaches in modelling the bending stiffness are compared. The advantages and drawbacks of the model are shown and discussed. It is shown that the conducted experiments can be reproduced by using the implemented material model and reasonably good results are achieved.

1. Introduction
The focus on reduction of CO2 emissions in the automotive industry has led to an increased usage of new materials. The application of glass-fibre reinforced thermoplastics enables new lightweight solutions but also new challenges in material modelling. Woven-fabric reinforced composites have high specific strength and stiffness and supreme formability characteristics and have proven their potential in structural applications. Thermoforming of such thermoplastics reinforced with fibre fabrics, called organosheets, allow low cycle times and a good recyclability [1]. FEA is a useful engineering tool to avoid trial and error approaches in designing an appropriate process and therefore safe time and costs. Several approaches exist in FEA to model the macroscopic material behaviour [2-5]. This study is focused on the modelling of Tepex dynalite 102-RG600(2)/47 % in LS-DYNA™ considering in-plane and out-of-plane deformation. LS-DYNA™ offers *MAT_249 to simulate a woven reinforced thermoplastic in dependence of temperature and strain rate. This approach is based on an additive split between anisotropic fibre and isotropic matrix behaviour. The matrix is described by an elasto-plastic formulation with a von-Mises yield criterion, whereas for the fibres a hyperelastic material definition is used [6].

2. Material characterization
In this study, the experimental investigation concerns the characterization and validation of the organosheet. First, quasi-static tensile tests and biaxial extension tests from room temperature to 200 °C were performed to show the in-plane deformation behaviour. Furthermore, cantilever tests in the same temperature range were performed to determine the out-of-plane behaviour. The results from these basic experiments are used to determine *MAT_249 in LS-DYNA™.
2.1. Material properties

The considered organosheet consists of a polyamide 6 matrix reinforced with 47 vol. % fibre content. The fabric is an E-Glass roved in twill 2/2 style. One layer has a thickness of 0.5 mm and the laminate consists of two layers to build an overall thickness of 1.0 mm. The two layers are rotated by 90 degrees as they form a symmetrical layup. This leads to the assumption of identical mechanical properties in the first two principal directions.

To model the contribution of the matrix material to the compound behaviour, separate material tests with PA6 were performed. Specimens were produced according to EN ISO 527-1 and tensile tests according to EN ISO 527-4 were performed under the same conditions as the organosheet. The results of these tests are shown in Figure 1.

![Figure 1. Uniaxial tensile tests of matrix material Polyamide 6.](image)

The calculated material properties are listed in Table 1.

| Temperature [°C] | Young’s Modulus [MPa] | Poisson’s ratio [-] |
|------------------|------------------------|--------------------|
| 24               | 2968                   | 0.35               |
| 80               | 529                    | 0.41               |
| 140              | 367                    | 0.39               |
| 200              | 169                    | 0.46               |

With the rule of mixture (ROM) introduced by Krenchel [7], the elastic properties of the final layup can be predicted considering the single material properties. The ROM includes the effect of fibre length and fibre orientation and is given by

\[ E_c = \eta_l \eta_\theta E_f V_f + E_m V_m \]  

(1)

with the fibre length distribution factor \( \eta_l = 1 \) in case of continuous fibres and fibre orientation distribution factor \( \eta_\theta \) calculated using

\[ \eta_\theta = \sum a_n \cos^4 \theta. \]  

(2)

For a biaxial woven material in the direction parallel to the fibres, \( \eta_\theta \) is given by 0.5. In the case on the bias angle which is at \( \pm 45 \) to the fibres, \( \eta_\theta \) is given by 0.25. The Young’s modulus of a single glass fibre has been considered based on supplier data as \( E_f = 73000 \) MPa. With the aforementioned properties of the fibre and matrix properties, a Young’s modulus of \( E_c = 17245 \) MPa is predicted at the temperature of 200 °C. This calculated value agrees well with the measured value shown in Figure 3.
2.2. In-plane experimental investigation

To determine the in-plane behaviour, quasi-static tensile tests according DIN EN ISO 527-4 and biaxial extension tests according DIN EN ISO 14129 were performed. The characteristic mechanical properties were averaged from three valid results. Figure 2 shows the technical stress-strain diagram in 0° and the shear stress in dependence of the shear angle in 45° to the main fibre direction.

![Figure 2](image)

Figure 2. Experimental results of uniaxial tensile tests in fibre direction (left) and bias extension tests (right).

Tests are performed at room temperature, 80 °C, 140 °C and 200 °C. It can be seen that the properties in fibre direction are dominated by the fibres as they have a high strength and small strain to failure. Due to the two-layers laminate in which the weft and warp are oriented in the same direction, properties in direction 1 and direction 2 show similar results. In the bias extension test, the fibres are oriented at 45 degrees to the extension direction for pure shear behaviour. It can be seen, that the matrix strongly influences the shearing interaction of the fibres as the shear stress $\tau_{12}$ decreases with increasing temperature. It can be assumed that at a temperature of 200 °C only the interactions of the fibres are dominating and the influence of the PA6 can be neglected. Using this experiment, the shear locking angle is determined as $\theta = 38°$. The obtained mechanical properties are listed in Table 2.

### Table 2. Material properties of considered organosheet.

| Temperature [°C] | Tensile strength [MPa] | Elongation at break [%] | Shearing modulus G [GPa] | Shearing strength [MPa] | Shearing angle at break [°] |
|-----------------|------------------------|-------------------------|--------------------------|------------------------|---------------------------|
| 24              | 375                    | 2.1                     | 0.90                     | 62.8                   | 29.2                      |
| 80              | 311                    | 1.8                     | 0.58                     | 49.7                   | 26.6                      |
| 140             | 321                    | 1.9                     | 0.34                     | 49.4                   | 41.4                      |
| 200             | 317                    | 2.0                     | 0.25                     | 27.2                   | 51.3                      |

The results of the determination of the Young’s modulus is shown separately in Figure 3. In a first step, Young’s modulus was calculated according the norm in a strain range of 0.05 % and 0.25 %. In this range, it is not possible to determine the correct stiffness of the fibres because the fibres are woven and therefore have to be stretched first. This range is strongly influenced by the properties of the matrix material. To show this process of stretching, an additional Young’s modulus was determined in a range between 0.5 % and 1.0 %. Resulting from this study, the effective Young’s modulus of the woven composite, without the influence of the matrix, is determined as 16.6 GPa at a temperature of 200 °C.
2.3. Out-of-plane experimental investigation
The bending behaviour of the material is characterized by performing cantilever tests. The test specimen is clamped at one end and is under gravity load. As the specimen is heated in the oven up to 240 °C, at specific temperature levels pictures are taken. These pictures are transferred to a two-dimensional space to be compared with the simulation results. The experimental results are shown in Figure 4. It can be seen, that on one hand significant deflection occurs in both cases at a temperature of 200 °C and on the other hand the specimen with a 45 degrees fibre orientation show a higher bending moment compared to the 0 degree orientation.

3. FEA Analysis and material model validation
The finite element analyses are performed in LS-Dyna™ using an explicit solver. Belytschko-Lin-Tsai shell elements with an edge length of 0.5 mm and one integration point per layer were chosen. One integration point per layer is given by default by using *PART_COMPOSITE. To compare the influence of integration point location, own integration rules are defined with the same number of integration points. The matrix and fibre properties are considered separately.
3.1. In-plane results
The matrix properties are taken from Table 1 and Figure 1. The Young’s modulus is chosen as the value calculated with the Krenchel equation. It is assumed that at a temperature of 200 °C the influence of the matrix is negligible and therefore the shearing interaction curve from Figure 2 is used for the shearing interaction of the fibres. The results of the simulations are shown in Figure 5.

![Figure 5](image-url)

**Figure 5.** Comparison of experimental and simulation results in fibre direction (left) and in 45 degrees to fibre direction (right).

In the case of zero degree fibre orientation the deformation is dominated by the Young’s modulus of the laminate and therefore the simulation results show good agreement with the experiments. In the case of pure shearing, it is shown that the shearing deformation is described in a reasonable manner. The shear locking angle agrees with the before determined angle of 38 degrees.

3.2. Out-of-plane results
The out-of-plane behaviour is determined by the elastic properties of the laminate. In the material card, the transversal shear modulus orthogonal and along to the direction of the fibre can be used. Variation of this parameter show no significant influence on the bending stiffness. Using *PART_COMPOSITE, one integration point in the middle of each layer is defined. As a consequence, the bending stiffness is hereby determined. Alternatively, own integration rules using *INTEGRATION_SHELL can be defined to model the bending stiffness of the composite. Figure 6 shows the schematic layup of the composite and the possibility of a modified integration rule (IR). Both integration points are symmetrical to the middle surface and defined by the relative distance s (Initial composite IR $s = 0.5$).

![Figure 6](image-url)

**Figure 6.** Composite layup with comparison of integration rules.

The influence of integration point positions in the thickness direction is shown in Figure 7. Considering the low bending stiffness of the used material, the initial IR configuration using *PART_COMPOSITE shows a too high bending stiffness. As a consequence, a modified IR is defined
in which the two integration points are varied in thickness direction. It can be seen that the distance of the integration points to the middle layer has a significant influence on the bending behaviour. The experimental results show that the orientation of the fibres result also in different bending stiffnesses. As the shearing deformation in 45 degree orientation is the dominating deformation mode, the position of the integration points is determined using the cantilever experiment at 200 °C. The relative distance of the integration points to the middle layer is chosen as 0.075, which shows reasonable agreement with the measurements in 0 and 45 degree fibre orientation.

Figure 7. Influence of integration point locations in thickness direction on bending behaviour in the case of 0 degree fibre orientation (left) and 45 degree fibre orientation (right) along cantilever at 200 °C.

4. Conclusions
Tests at different temperatures were performed to show the in-plane and out-of-plane behaviour of the organosheet. It is shown that the conducted experiments can be reproduced in a reasonable manner. The extension of the material in fibre direction is dominated by the Young’s modulus of the woven structure and can be well estimated by the ROM by Krenchel. Considering the shearing behaviour of the composite, the shearing stress in dependence of the shearing angle can be well reproduced. The bending behaviour is more strongly affected by the integration point positions than the elastic material properties. With a relative distance of the integration points of 0.075 to the middle layer, reasonable results can be achieved.

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