EVALUATION OF PROCESS- AND LAYUP-INDUCED WARPAGE FOR TAILORED PPS/CF LAMINATES

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Abstract

This paper deals with rectangular PPS/CF laminates with a centered local reinforcement, orientated parallel to the long part edge. The laminates are produced from spot-welded tape layups which are consolidated subsequently to the automated thermoplastic tape-laying process. In the patched section these highly-tailored laminates contain asymmetric layups that cause component distortion. However, in order to exploit the full potential of thermoplastic advanced composites it is essential to understand such tailored structures to be able to design parts with i.a. optimized fiber orientations and profiled wall thickness.

As an excerpt from a more extensive study a selection of layup combinations of base plates and patches are investigated with regard to layup-induced shape distortions. For this purpose laser scanning is used to determine three-dimensional geometrical data of the samples and to derive the complex deformation modes. Furthermore, finite element modelling is applied to predict part deformation and to match simulation against measured 3D data.

Background and Motivation

In the past decades significant research has been conducted with regard to processing of thermoset and thermoplastic structural composites. Besides the fundamental challenges that come along with each individual process technology – such as ideal process parameter sets, cycle times or economic factors – implicit effects are to be considered as well. One of these implicit aspects of composite processing is the formation of residual stresses during the curing (thermosets) and cooling (thermoplastics) respectively. The most prominent cause of this effect is the highly anisotropic material behavior of continuous fiber-reinforced plastics, in particular the significantly different shrinkage behavior of matrix and reinforcing fibers.

Already in the early 1970s NASA Lewis Research Center conducted an extensive program that dealt with residual stresses in fiber reinforced composites and showed theirs influence on the mechanical performance of various material systems and layups [1]. More recently PARLEVLIEET et al. [2, 3, 4] presented a detailed overview of scientific publications with regard to residual stresses in thermoplastic composites. As far as structural mechanics of composite components is concerned, it is possible to conclude that residual stresses are of particular interest during the part dimensioning process due to their potentially weakening effect.

From a process perspective on the other hand, balanced residual stresses within a symmetric laminate are less critical. By contrast unbalanced residual stresses, especially in thin-walled components, can result in significant part deformation leading to difficult or even impossible assembly of composite parts. To avoid this issue common practice in the industry is to account for part warpage by adjusted mold cavities so that the warped part represents the desired shape. Oftentimes these tool modifications have to be implemented on a cost-intensive trial and error basis. Thus there is a high demand for solutions which are able to predict and describe part warpage in composite laminates prior to tool design.
There are two main aspects which create unbalanced residual stresses across a laminate's cross-section:

- First are processing conditions such as a gradient in cooling rate within thick laminates, forming pressure, uneven temperature of the upper and lower tool half, tool-part interaction and others. A wide variety of investigations dealing with these effects are available in literature, however oftentimes with a focus on thermoset composites. Some examples are given in [5-9].

- A second aspect is asymmetric layup design. Although ultimately avoidable, this kind of layup design allows for creating highly tailored components with additional material along the main load paths. Especially modern tape-laying technologies provide the required flexibility to produce such layups in an automated high-precision process. Nevertheless, the opportunities of such tailored structures are nowadays not yet exploited to their full extent, likely due to the challenges coming along with it. Furthermore recent research mainly focusses on case studies that are not application driven but describe the fundamental deformation principles of such asymmetric laminates [10-14].

**Study overview**

The contents covered by this article are part of a more extensive study that deals with a holistic approach for predicting and analyzing residual stresses and warpage of tailored laminates made from UD-tape, see Figure 1. For this purpose tailored laminates are manufactured with varying layups and process parameters in order to determine the effects of design and process. Subsequent to production, these components are scanned using a hand-operated laser scanner. Based on the 3D point cloud generated with this system it is possible to analyze the complex deformation modes which occur in highly-tailored composite structures and to validate results generated in finite element modelling. In addition to the predicted geometric deviation, simulation outputs stresses and strains resulting from the existing deformation state i.e. warpage. This information is of particular interest for subsequent structural analysis since process-induced residual stresses act as a preload of the component and might reduce loadability significantly. In order to verify and validate the output of finite element analysis (FEA), the residual stresses need to be measured. Although destructive as well as non-destructive methods exist, even today residual stress measurement of composite parts is, as described in [4], no standard task. Thus it is an important part of this study’s framework.
Experimental

Tailored laminates containing a local reinforcement (patch) are investigated to determine the influence of locally asymmetric layups on component distortion. The patch-reinforcement (P) is positioned centered on a baseplate (G) and orientated parallel to the longitudinal 1-axis, which also defines the 0°-fiber direction of the layups. Baseplates are 394 mm long (L) and 187 mm wide (W), with the patch being 50 mm wide. The ideal geometry without warpage is shown in Figure 2.

![Figure 2: Left: Schematic of the investigated tailored laminates; ideal geometry without warpage
Right: G+P tape layup produced with the RELAY 2000 technology](image)

The material investigated is Celanese’s Celstran® CFR-TP PPS CF60 (PPS/CF) unidirectional tape (UD-tape), a thermoplastic semi-finished product containing 60 % continuous carbon fibers by weight and 53 % by volume respectively. This single-ply material is processed using an automated RELAY® 2000 tape-placement machine1 to realize highly-accurate tape layups with any desired angle and stacking sequence. Using this technology flat tape layups are built up one ply after another, with each ply consisting of several tape courses. To allow handling of the tape layups after the stacking sequence, each course is tacked to the ply underneath by ultrasonic spot-welding. In order to minimize scrap and cycle times, large sheets are produced and cut to proper size afterwards. Furthermore, G- and P-sheets are separately produced and joint afterwards using ultrasonic welding. In Table 1 the G+P tape layups which are part of this paper are listed, representing two extreme cases for layup-induced warpage.

Table 1: G+P tape layup configurations

<table>
<thead>
<tr>
<th>G1P3</th>
<th>G2P6</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1 (\rightarrow (0_2,90_2)_s)/ P3 (\rightarrow (0)_s)</td>
<td>G2 (\rightarrow (90_2,0_2)_s)/ P6 (\rightarrow (90)_s)</td>
</tr>
</tbody>
</table>

Consolidation of the tape layups is performed in a HTP process (Heating - Transfer - Pressing) as illustrated in Figure 3. To avoid sticking of the molten material to the heating platens in process step 2, the tape layups are placed in between two pieces of 2 mm aluminum sheet metal that carry two G+P tape layups at a time. To fit the patch of the tape layup, grooves are milled into the lower sheet metal. Once processing temperature is reached the tape layups are carried into the mold (step 3) and cooled down under pressure before the consolidated laminates are taken out (step 4).

Table 2: Main set of process parameters

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>305</td>
<td>5</td>
<td>60</td>
<td>(p_1 = 150)</td>
<td>(T_1 = 100)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(p_2 = 450)</td>
<td>(T_2 = 150)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(p_3 = 750)</td>
<td>(T_3 = 200)</td>
</tr>
</tbody>
</table>

1 Developed by Fiberforge Corporation (CO, USA); in 2013 the technology was acquired by Dieffenbacher GmbH (Germany)
Table 2 summarizes the main set of process parameters as well as the process parameter variations that are investigated with regard to their effect on component warpage of G1P3 laminates. For the G2P6 laminate the p2 press force and T2 mold temperature are evaluated.

For determining the three-dimensional shape deformation of warped tailored laminates a hand-operated Descam ModelMaker Z laser scanner is used which is mounted to a FaroArm. To ensure high repeatability of the scanning procedure a jig, designed according to the 3-2-1 principle, is used. The generated point clouds are post-processed using the Geomagic Control software package. In a first step of scan-data analysis, the points within the point cloud are ordered to create a non-random structure. Subsequently, the amount of data is reduced during the so called wrapping procedure to limit the required computational time for further analysis. Details related to the pre-investigations leading to the number of points per component are part of the results section.

### Modelling warpage of tailored laminates

In order to predict the process- and layup-induced warpage of tailored laminates a model is created in Abaqus/Standard using a sequential thermo-mechanical analysis. This uncoupled model may be used since it is assumed that stress generation within the laminate does not generate heat and hence does not influence the local temperature. The material data used in the model is listed in the Annex.

### Modelling of the thermal analysis

In reference to Figure 3, the thermal analysis starts at the end of process step 2 when the material is at processing temperature. At this stage, the temperature distribution within the tailored laminate as well as the aluminum sheet metal is assumed to be uniform. The subsequent transfer of the stack into the press (step 3) is simulated with 10 s of radiation and convective cooling in motionless air at 25 °C room temperature. During the cooling under pressure (step 4) the process model includes a steel mold. Taking into account the actual mold design, the heating channels of the temperature control are included in the model according to Figure 4. For both halves of the mold, the heating channels are modelled as surfaces with permanently constant temperatures corresponding to the set values of the temperature control units (Top: 156 °C; bottom: 159 °C). The initial surface temperatures inside the cavity of the upper and lower mold are also assumed to be uniform. Based on measurements during the experiments, 150 °C is modelled for the top and 152 °C for the bottom. At the beginning of the thermal analysis a linear temperature profile is assumed between cavity surfaces and surfaces representing the heating channels. For the actual cooling phase the heat transfer of the interfaces steel-aluminum and aluminum-composite is considered to be ideal due to the applied press force.
To model the cooling process of the tailored laminates as described above, the steel mold components are meshed with first-order hexahedral diffusive heat transfer elements (DC3D8). The aluminum sheet metal on the other hand is meshed with DCC3D8 elements to account for the additional convective cooling during the transfer in process step 3. For the tailored laminates two variants are used: DCC3D8 solid elements and DS4 quadrilateral shell elements as a less computational intensive alternative.

![Figure 4: Mold design used in the thermal analysis](image)

**Modelling of the mechanical analysis**

The mechanical analysis follows the thermal analysis and calculates the deformation of the tailored laminates (G1P3 and G2P6) with a linear elastic material model, reduced integration elements and steps accounting for geometric non-linear effects. In accordance with the thermal analysis, meshing of tailored laminates is realized with two variants: C3D8R solid elements and S4R shell elements. To suppress rigid body movement while deformation develops, a node set in the center of the baseplate’s bottom surface is fixed using the “pin” boundary condition. The temperature history is implemented in the mechanical analysis as a predefined field.

Based on the shape deformation behavior of tailored laminates that was observed in the course of production, this paper presents a simplified approach for the mechanical analysis that does not take into account the steel mold, aluminum sheet metal, press force, part interactions or the pressing process itself. Instead, the tailored laminate is modelled solely and the mechanical analysis is initiated after the laminate and aluminum sheet metal is removed from the mold. Further details leading to this approach, as well as its boundaries, are part of the results and discussion section.

**Results and discussion**

**Interaction of processing and crystallization**

One key difference of thermoplastic composites compared to thermoset composites is the thermoplastics’ lack of a chemical curing reaction during solidification. Instead, the thermoplastic material is first heated above its melting temperature and then rapidly cooled down. Whilst temperature in the cooling process is above crystallization temperature, the mobility of molecular chains is sufficient for stress relaxation due to the visco-elastic behavior of the amorphous melt. As soon as the matrix is able to transfer shear stresses to the fibers residual stresses can develop. Thus thermal stresses can start to build up as soon as the laminate is cooled below its crystallization temperature. As long as the temperature is above approx. 125°C the amorphous portion still allows for stress relaxation to a certain extent. With falling below 125°C molecular chain mobility in the material becomes very low and thermal residual stresses start to build up due to the mismatch in thermal expansion of the thermoplastic matrix and the reinforcing fibers.

Using differential scanning calorimetry (DSC) [15] it is possible to determine the characteristic thermal properties of polymeric materials. Figure 5 shows a DSC scan of the
PPS/CF UD-tape conducted with a Netzsch DSC 204 F1 Phoenix at a constant heating rate of 10 K/min and cooling rates of 10 K/min and 60 K/min. Clearly visible is the shift of the crystallization temperature to lower temperatures with increasing cooling rate. However, in a processing environment as introduced in this paper peak cooling rates of up to 3750 K/min occur in the first seconds of cooling which cannot be realized by DSC.

Figure 5: DSC scan of PPS/CF UD-tape at cooling rates of 10 K/min and 60 K/min

To resolve the limitations of thermoanalytical methods with regard to very high cooling rates an experiment is conducted which is based on the characteristic crystallization behavior of the PPS matrix. Unlike other thermoplastics, the crystallization of PPS can be suppressed by quenching the material to low temperatures of e.g. 25 °C. This low mold temperature is required to realize sufficiently high cooling rates while falling below glass transition temperature. In consequence, two processing cycles of G1P3 tailored laminates are performed with a mold temperature of 25 °C and T2 = 150 °C. Figure 6 shows the cooling curves that are recorded with thermocouples embedded in the laminates during processing.

Figure 6: Left: Cooling curves of G1P3 tailored laminates with 25 °C and 150 °C mold temperature
Right: Warpage of a G1P3 tailored laminate right after de-molding and 3 mins later

Since the G1P3 sample quenched to 25 °C generates a laminate with amorphous PPS matrix the following can be concluded: in each point of the cooling curve belonging to the
150 °C mold temperature that overlaps with the cooling curve belonging to 25 °C mold temperature, the PPS matrix must in both cases be in an amorphous state. This means that for 150 °C mold temperature crystallization is very likely suppressed down to a temperature of approx. 175 °C and hence no residual stresses can build up earlier in the cooling process. Even between 175 °C and 165 °C the average cooling rate is approx. 100 K/min so that crystallization is likely suppressed as well. Furthermore, G1P3 tailored laminates do not show an instant deformation after de-molding but are flat (Figure 6, right). This also supports the assumption made and is in line with the fact that residual stresses can be relaxed to a certain extent as long as the material is above glass transition temperature. In summary, these observations lead to the approach for the mechanical analysis that is described in the corresponding paragraph. Since this approach is based on a hypothesis which takes the mold temperature into account it is only valid for the presented processing parameters. Transferability is probable as long as the laminate does not cool down below 125°C before de-molding. This assumption is yet to be validated in the course of the study framework.

3D-scanning results of warped tailored laminates

Before starting the 3D-scanning for an extensive study it is essential to verify the accuracy and hence reproducibility of the jig that is used to hold the components in position during scanning. For this purpose, a G1P3 tailored laminate that was processed with a p2T2 process parameter set (G1P3-p2T2) is scanned five times and analyzed in the following manner:

- Positioning tailored laminate in the jig.
- Laser-scanning of the warped tailored laminate.
- Removal of the tailored laminate from the jig.
- Restart with procedure.

Afterwards, each scan is imported as an ordered point cloud into the Geomagic Control software. Point density is thereby reduced to approx. 1,7 million points and then wrapped to create polygon objects. Using the reference points of the 3-2-1 jig, a best fit alignment of the tailored laminate’s CAD data and the scan object is performed before creating the 3D matching.

Judgment of the reproducibility builds up on the average positive and negative deviation and the consistency of the root mean square value (RMS) as well as the standard deviation. A summary of these evaluation parameters is presented in Figure 8 in which e.g. the standard variation is between 0,06 mm and 0,12 mm and average deviation is in each case consistently below 0,05 mm. Although a more comprehensive validation will be part of future experiments, the results show that a high accuracy can be achieved for a repeatedly scanned component.

Demonstrating the great influence of layup design on the component warpage, Figure 7 shows physical samples of G1P3-p2T2 and G2P6-p2T2 samples. After laser-scanning, the point clouds are processed according to the reproducibility experiment albeit the alignment, which is realized feature-based by three planes that are created using the jig reference points.

![Figure 7: Warped G1P3-p2T2 (left) and G2P6-p2T2 (right) components](image)
Figure 8: Summary of evaluation parameters for the reproducibility of 3D-scanning based on the used jig

In a first approach the component warpage is evaluated with regard to the global deformation mode and the maximum deflection that is present within a particular type of tailored laminate. The results described in the next paragraph thereby represent a single component of each type and hence are not yet statistically assured. This aspect is currently under investigation.

For all process parameter sets of G1P3 the main deformation mode corresponds to bending around the 1-axis, which is caused by the transversal contraction of the UD-patch during cooling. The maximum deflection on the other hand varies with the different process parameter sets. So is 14,5 mm measured for the p2T2 variant, which is significantly higher than for p1T1 (11,1 mm) and p3T3 (10,8 mm). While the trend of p1T1 in relation to p2T2 is according to expectations, an explanation for the lower maximum deflection of p3T3 is found in the increased material flow of the baseplate’s (G) 90° core-plies in 1-direction. This material flow occurs due to the combination of high press force as well as tool temperature and creates a burr that stiffens the short edge and in consequence suppresses deformation. Furthermore, the higher mold temperature might allow a stronger stress relaxation after de-molding which would also result in lower warpage.

In case of the G2P6 laminate, the main deformation mode corresponds to bending around the 2-axis. Contrary to G1P3 samples, the 90° patch governs warpage. Furthermore, the G2 baseplate’s outer plies are oriented in 90° direction as well, resulting in a lower bending stiffness compared to G1. In consequence, a maximum deflection of 30,0 mm is measured for G1P2. It is to be noted in this context that the component shows a significant torsional sub-deformation mode. This kind of divergences can be a result of disturbances such as fiber misalignment, varying process parameters or asymmetric material squeeze flow and need to be considered in future evaluations.

Figure 9 illustrates the deformation modes of the warped component. Supplementary, Table 3 summarizes the maximum deflection of the investigated samples.
Table 3: Maximum deflection of warped G1P3 and G2P6 samples

<table>
<thead>
<tr>
<th></th>
<th>G1P3-p1T1</th>
<th>G1P3-p2T2</th>
<th>G1P3-p3T3</th>
<th>G2P6-p2T2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. deflection [mm]</td>
<td>11.1</td>
<td>14.5</td>
<td>10.8</td>
<td>30.0</td>
</tr>
</tbody>
</table>

Results of the thermal analysis

The model that is used to predict the cooling behavior of tailored laminates during processing (see Figure 3) shows accurate results for shell as well as solid elements, as shown in Figure 10, left. As an indicator for the accuracy of the modelling, the right graph of Figure 10 draws the minimum and maximum deviation of the experimentally determined cooling curves from their mean value. In addition the graph shows the deviation of the calculated cooling curves compared to the experimental mean value which is below 10 K. Possible reasons for the larger difference during the convective cooling in air after de-molding are variations in the coefficients of convection and emission, inaccuracy in the used material’s thermal conductivity or a variation in room temperature during the experiments. The potential influence of a varying room temperature (RT) is included in the right graph of Figure 10.

Figure 10: Left: cooling curve of a G1P3 tailored laminated processed with mold temperature T2 = 150 °C  
Right: Divergence of the experimental and simulated cooling curves from the mean value
Results of the mechanical analysis

In order to evaluate the quality of the mechanical simulation model, the maximum deflection in the laminates’ thickness direction is considered. As presented in the paragraph of this section dealing with the 3D-scanning results, this maximum deflection occurs for the long (G1P3) and the short edge (G2P6) of the tailored laminates respectively.

Table 4: Maximum deflection (predicted and measured) of the warped tailored laminates produced with p2T2 parameter set

<table>
<thead>
<tr>
<th>Max. deflection [mm]</th>
<th>G1P3</th>
<th>G2P6</th>
</tr>
</thead>
<tbody>
<tr>
<td>C3D8R</td>
<td>13,8</td>
<td>97,0</td>
</tr>
<tr>
<td>S4R</td>
<td>13,8</td>
<td>96,5</td>
</tr>
<tr>
<td>3D scan</td>
<td>14,5</td>
<td>30,0</td>
</tr>
</tbody>
</table>

A summary of the results for the predicted and measured deflections is presented in Table 4. It can be concluded that both element types which are used for the mechanical analysis (S4R and C3D8R) show consistent results for both layup types G1P3 as well as G2P6, with a maximum difference of 0.5 % for the G2P6 layups. However, calculation time in both cases is approx. 2.2 times higher for solid elements compared to shells (taking into account thermal and mechanical analysis).

Results show that the mechanical model described in this paper is capable to predict the process- and layup-induced warpage of G1P3 layups with high accuracy. This applies to the absolute value of the maximum deflection (Table 4) as well as to the overall shape that is observed for the warped components (Figure 11).

For G2P6 laminates on the other hand, simulation generally shows a correct overall shape but overestimates the maximum deflection by a factor of approx. 3.2. However, cracks are present in the patch and, to a less pronounced extent, in the baseplate’s surface-ply of physical G2P6 laminates after de-molding. This leads to the assumption that the stresses perpendicular to the fibers within the patch (σ_{22}) of the tailored laminate exceed the material’s 90° strength. Although no validation of the stress output of the mechanical model is available at this point, simulation supports this assumption. Based on C3D8R calculations, stresses of up to σ_{22} = 100 MPa are present within the patch which is significantly higher than the material’s 90° strength of 20 MPa. To further investigate this effect, the maximum deflection of a representative G1P3 and G2P6 laminate is tracked over time. As illustrated in Figure 12, the G1P3 laminate shows virtually no change in its maximum deflection whereas the G2P6 suffers a strong decrease from 58 mm to 30 mm. Along with the decrease in maximum deflection an increase in the crack density is observed. Taking into account that even right after de-molding cracks are present in the patch of G2P6 laminates, a linear elastic result of 97 mm seems to be
more realistic. Hence, material degradation should be considered to be implemented in future modifications of the mechanical model to verify crack propagation and warpage relaxation over time.

![Figure 12: Maximum deflection of a G1P3-p2T2 and G2P6-p2T2 tailored laminates as a function of time; initial measurements represent the component after de-molding](image)

**Summary**

In this work, a study has been presented that aims to provide a holistic approach to predict, describe and evaluate the warpage of tailored laminates made from PPS/CF UD-tape. With G1P3 and G2P6, two examples were investigated with regard to process- and layup-induced warpage.

Based on laser-scanning three-dimensional shape information was gathered and evaluated with regard to the complex deformation modes that occur in warped tailored laminates. It has been shown, that the high accuracy and repeatability of such scanning systems, in combination with a properly designed jig are very well suited for this task.

Furthermore, a simplified modelling approach was presented that consists of an uncoupled thermal and mechanical analysis. Taking physical cooling curve measurements as a reference, the high accuracy of the thermal analysis was validated. However, the results of the mechanical analysis varied in accuracy with regard to the different layup types. Whereas the overall shape was correctly predicted for both layup variants, the maximum deflection was overestimated by a factor of approx. 3.2 for G2P6 laminates. For G1P3 samples on the other hand, high accuracy was achieved with both, solid and shell elements. From observations made on the physical samples was concluded that matrix cracking in the patch is likely responsible for the significantly lower remaining deformation of G2P6 samples compared to the result obtained by the linear elastic mechanical model. These aspects needs to be verified in future investigations.
Annex

The following abbreviations are used in Table 5 and Table 6:

- \( E_{11}, E_{22}, E_{33} \rightarrow \) Young’s moduli
- \( G_{12}, G_{21}, G_{23} \rightarrow \) Shear moduli
- \( \alpha_1, \alpha_2, \alpha_3 \rightarrow \) coefficients of thermal expansion
- \( \lambda_1, \lambda_2 \rightarrow \) thermal conductivities
- \( \rho \rightarrow \) density
- \( \nu_{12}, \nu_{13}, \nu_{23} \rightarrow \) Poisson’s ratios
- \( c_p \rightarrow \) specific heat capacity

Temperature dependent material properties are based on measurements and micro-mechanics (transverse isotropy).

The shear modulus \( G_{12} \) at room temperature is chosen according to [16] and its temperature dependent data is calculated based on BOTSIS’ statement that temperature data of \( G_{12} \) follows the trend of the Young’s modulus in 2-direction \( E_{22} \).

Poisson’s ratios \( \nu_{12}, \nu_{13} \) and \( \nu_{23} \) are also chosen according to [16].

Table 5: Temperature dependent material properties of PPS/CF

<table>
<thead>
<tr>
<th>Temperature [°C]</th>
<th>( \alpha_2 = \alpha_3 [10^{-6} \text{ K}^{-1}] )</th>
<th>( G_{12} = G_{13} ) [GPa]</th>
<th>( E_{22} = E_{33} ) [GPa]</th>
<th>( E_{11} ) [GPa]</th>
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<tr>
<td>118,3</td>
<td>3,01</td>
<td>5,70</td>
<td>8,97</td>
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<td>118,6</td>
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<td>107,6</td>
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<td>101,5</td>
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<td>Temperature [°C]</td>
<td>( c_p [\text{J/gK}] )</td>
<td>( \lambda_1 = \lambda_3 [\text{W/mK}] )</td>
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Table 6: Material properties without temperature dependency

<table>
<thead>
<tr>
<th>( \rho ) [g/cm³]</th>
<th>( \lambda_1 = \lambda_3 [\text{W/mK}] )</th>
<th>( \nu_{12} = \nu_{13} )</th>
<th>( \nu_{23} )</th>
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<td>0,5</td>
<td>0,3</td>
</tr>
<tr>
<td>2,5</td>
<td>0,49</td>
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[14] Palerosi A.C., de Almeida S.F.M., Curvature measurements of non-symmetric laminates using image processing, Proceedings of ICCM 15, Durban, South Africa, 2005
