CURVATURE ANALYSIS OF ASYMMETRIC SPECIMENS FOR THE RESIDUAL STRESS QUANTIFICATION IN FIBER METAL LAMINATES

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KEYWORDS

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ABSTRACT

Residual stresses inevitably develop during the manufacturing process of most material layups like fiber metal laminates (FML). The main contributor to these stresses is the anisotropy or difference in thermal expansion behaviour.
Residual stress states can be made visible by laminates with asymmetric layups which results in a certain curvature after manufacturing. The evaluation of this curvature has proven to be a particularly suitable quantification method for the residual stress state since it is highly dependent on intrinsic and extrinsic parameters. This paper discusses the curvature evaluation in a general context with a focus on FML and a comparison to carbon fiber reinforced polymers (CFRP).

1. INTRODUCTION

Fiber reinforced laminates which either consist of different materials, like FML, or material with anisotropic thermal behaviour are widely used within lightweight structures.
During manufacturing processes like autoclave curing, the materials are heated which consequently results in thermal expansion. The materials bond at elevated temperatures and shrink as a compound material during the cooling step in the process [1,2]. This results in residual stresses, because the single plies are hindered to deform back into their initial state. Residual stresses can lead to early component failure as they can be as high as 20% of the material strength depending on the materials being used [3,4]. Therefore, it seems crucial to know the residual stress to determine the appropriate laminate strength for high performance structures.
Different methods for the residual stress quantification exist and are either destructive, non-destructive and are conducted either during the manufacturing process or afterwards. Especially, in-situ strain monitoring like using fiber optical sensors is capable of delivering precise results [1]. Their main disadvantage is their need of a rather complex experimental setup which makes them unattractive to frequent usage during industrial manufacturing processes. Therefore, a different measurement technique is needed to quantify the internal stress state. Curvature measurement for asymmetric FML demonstrated its capability of being suitable for residual stress evaluation if boundary conditions are considered [5].
The curvature of asymmetric layups can occur in any in-plane direction whenever the in-plane coefficients of thermal expansion (CTE) differ between the single plies. Therefore, it is necessary to pay attention to the specimen’s geometry. Specimens with a small width to length ratio is preferably to be used for an easy evaluation [6,7]. Width to length ratios close to 1 produce saddle-shape curvatures. Furthermore, a laminate thickness of 1mm is chosen to reduce the influence of warpage, which mainly affects thin laminates [8].
It is possible to transform the resulting curvature into the stress-free temperature of the curved asymmetric specimen. Stress-free temperature and curvature are equally sensitive towards stress inducing factors [3].
This paper discusses the relevance of intrinsic influencing factors on the curvature of multi-material layups like the ratio of CTE, Youngs modulus and thickness. The work builds upon previous investigations [5], where only FML layups were investigated. This paper extends the findings to pure CFRP materials and aims at giving a rather general overview on the curvature evaluation for arbitrary laminates.
With the help of analytical approaches, a wide variety of intrinsic parameter spectra and their influence on specimen’s curvature is evaluated. The influence of extrinsic parameters like toll material and manufacturing process is investigated experimentally for the two material FML and CFRP.

It is expected, that the influence of the extrinsic parameters tends to show the same behaviour in CFPR as in FML.
Specimen manufacturing and evaluation is based on a highly automatable workflow [5].

2. MATERIALS AND METHODS

The following section describes the materials and specimens which have been used for the experiments (Section 2.1). The used measurement methods are defined in Section 2.2, while Section 2.3 outlines the relevant analytical calculations. Section 2.4 describes the direct correlation between stress-free temperature and curvature.

2.1 Material and specimen definition

The FRP and FML laminates used in this work are manufactured with the prepreg Hexply 8552-AS4 from the Hexcel company. Its properties as well as the ones of the used steel (1.4310) are taken from literature and depicted in Table 1.

Table 1: Material properties for Hexply 8552-AS4 and steel 1.4310. Index 1 indicates the fiber direction (CFRP) or the direction of rolling (steel).

Value	Unit	Hexcel 8552-AS4	Steel 1.4310
E_1	GPa	132 [10]	187 [5]
E_2	GPa	9.2 [10]	194 [5]
G_{12}	GPa	4.8 [10]	71.2 [13]
ν_{12}	-	0.3 [10]	0.3[13]
t_{ply}	mm	0.13_{cured} [11]	0.12
α_1	ppm/K	0.4 [12]	19.0 [4]
α_2	ppm/K	31.2 [12]	19.15 [4]

The ratio of the width to length is important for the curvature analysis and has to be rather small in order to minimize the two-dimensional curvature. Therefore, a width to length ratio of 0.07 is used.
The size of the manufactured specimens is originally 300mm x 30mm but they are trimmed to 290mm x 20mm in order to reduce edge effects (Figure 1).

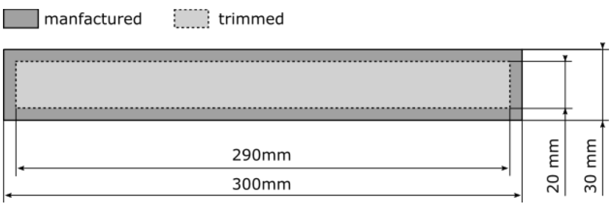

Figure 1: Dimensions of the manufactured and trimmed asymmetric specimens in their plane state.

The CFRP specimens are cut with a circular saw and a diamond blade, whereas the FML specimen are waterjet cut which reduces the risk of delamination.

Table 2: Layup asymmetric FML

Layer	Material	Orientation	Thickness
1-7	CFRP	0°	7x0.13mm
8	steel	rolling	0.12mm

Every specimen has to possess a minimum thickness to avoid warpage. The FML specimens of interest features a nominal thickness of 1.03mm and contains one steel layer and seven CFRP layers (Table 2).

Pre-testing of asymmetric CFRP manufacturing outlined that the layer ratio between 0° and 90° needs to be greater compared to FML with only one steel layer. The 90°-CFRP layers possess reduced stiffness (E_2) compared to steel. Therefore, a layup with four layers in 0° and four layers in 90° is applied (Table 3) which accumulates to a thickness of 1.04mm. This thickness is comparable to the thickness of the manufactured FML.

Table 3: Layup asymmetric CFRP

Layer	Material	Orientation	Thickness
1-4	CFRP	0°	4x0.13mm
5-8	CFRP	90°	4x0.13mm

2.2 Measurement methods

This section describes the measurement method which has been used for the curvature determination and the measurement of the stress-free temperature in an oven.

2.2.1 Curvature measurement

A 3-dimensional scanning head (GOM ATOS) is used to determine the resulting geometry of each specimen after curing. The main advantage of this technique is the quick set up for industrial implementation and the high accuracy. The measurement produces a point cloud which is analyzed by the software GOM-Inspect.

Figure 2: 3D point cloud representation of a specimen with GOM ATOS. [1]

This measurement technique has the additional advantage of delivering the specimen thickness distribution to consider its influence as shown in Figure 2. To get the curvature of the specimen, a cylinder is fitted into the point cloud to determine the corresponding radius.

2.2.1 Stress-free temperature measurement

The stress-free temperatures of all specimens are determined in a lab oven with a glass window. Each specimen is positioned on a metal plate, the curvature is facing upwards.

Thermocouples (Type K) are used to measure the temperature in the oven at different locations. The stress-free temperature is defined as the temperature when a specimen reaches the flat state. Although this process is rather subjective, it can be assumed to reach an accuracy of about ± 2K.

All specimens are heated with a heating ramp of 4K/min until a temperature of 140°C is reached. This temperature is held constant for 30min before a second heating step with a gradient of 0.7K/min is applied to allow the temperature to equalize within the specimens.

2.3 Analytical calculation

It is possible to calculate the stress-free temperature if the radius of the curved asymmetric specimens and further parameters are known.

The results of the curvature measurement can be either transformed to T_{SF} using analytical or numerical methods. It was shown in [5] that analytical and numerical simulation do not differ significantly and both match the experimental results. Therefore, this work relies on the analytical evaluation of the parameter variation for intrinsic and extrinsic parameters.

Different analytical models exist in literature [14-16]. These models inherit different material and geometry parameters and are originally designed to calculate the deformation of bimetals, where two different metallic layers are joined together and produce thermomechanical bending.

The most prominently used analytical description is given by Timoshenko [16]:

$$r = \frac{h(3(1+m)^2 + (1+mn)(m^2 + \frac{1}{mn}))}{6\,(\alpha_2 - \alpha_1)(T_{sf} - T_r)(1+m)^2} \qquad (1)$$

where h is the specimen's thickness, α_1 and α_2 are the coefficients of thermal expansion for the two materials, T_r is a mandatory reference temperature (temperature of curvature measurement), and T_{sf} is the stress-free temperature, $m = t_1/t_2$ represents the ratio of the thicknesses (t_1 and t_2) of the two constituents (CFRP and steel / 0° and 90°), whereas $n = E_1/E_2$ indicates the ratio of the elastic moduli of the two constituents (CFRP and steel / 0° and 90°), respectively. This equation is used to correlate stress free temperature and curvature for all specimens [6].

2.4 Correlation between stress-free temperature and residual stress

Residual stress can be calculated using the classic laminate theory. Pure linear thermoplastic behaviour is assumed. The residual stress for unidirectional symmetric layups can be calculated using Equation (2) [4]:

$$\{\sigma_{res}\}_k = [Q]_k \cdot (\{\alpha\}_{lam} - \{\alpha\}k) \cdot (T_R - T_{sf}) \qquad (2)$$

with the reduced stiffness matrix $[Q]_k$ for each ply k, the coefficients of thermal expansion $\{\alpha\}_k$ per ply and for the entire laminate $\{\alpha\}_{lam}$. The parameter T_R specifies the reference temperature, e.g., operating temperature or room temperature, whereas T_{sf} indicates the stress-free temperature derived from experiment or calculation. The in-plane laminate thermal expansion coefficient $\{\alpha\}_{lam}$ can be derived from the ply CTEs with equation 3 for an arbitrary laminate [4]:

$$\{\alpha\}_{lam} = [R]^{-1} \cdot [A]^{-1} \cdot \sum_{k=1}^{n} Q_k \cdot [R] \cdot [T]_k^{-1} \cdot t_k \cdot \{\alpha\}_k \qquad (3)$$

$$[R] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 2 \end{bmatrix} \; and \; [T] = \begin{bmatrix} c^2 & s^2 & 2sc \\ s^2 & c^2 & -2sc \\ -sc & sc & c^2 - s^2 \end{bmatrix}$$

where $[A]$ is the laminate extensional stiffness matrix, Q_k the ply stiffness in global laminate coordinates, $[T]$ the transformation matrix and t_k the thickness for each ply respectively. Again, $\{\alpha\}_k$ indicates the coefficients of thermal expansion for the respective ply. In the transformation matrix, s and c indicate the $sin(\alpha)$ and $cos(\alpha)$ terms, where α is the ply angle in the laminate coordinate system. Further information can be found in the literature [17, 18].

The CTE of the CFRP in fiber direction differs from the CTE of the metal layers and the CTE of the CFRP orthogonal to the fiber direction. Both, the CTE of steel and of CFRP orthogonal to the fiber direction is much higher than the CTE of CFRP in fiber direction.

During manufacturing under temperature exposure, all layers expand according to their individual CTE. All layer bond at a specific temperature higher than room temperature. Cooling leads to layer contraction but as the different layers cannot slide among each other stresses build up.

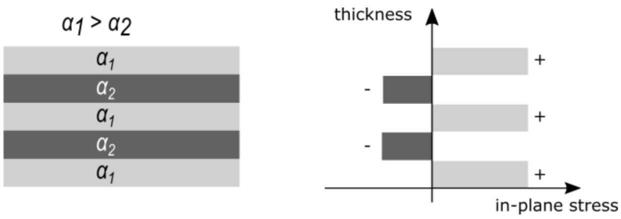

Figure 3: Residual stress state through the thickness in a generic symmetrical layup after manufacturing at elevated temperatures and cool down to room temperature.

Figure 3 depicts the stress state for each layer in a symmetrical layup which is manufactured in a heated curing process.
The same layer wise stress state can be assumed to be valid for asymmetric FML or asymmetric CFRP specimens. Figure 4 clarifies the reason for bending of asymmetric specimen. If only two layers are contained within a specimen, the specimen bends towards the layer with the higher (positive) stress to equalize (Figure 4). The curvature results towards the steel respectively the 90° layer, as they posses a higher CTE than the 0° layers.

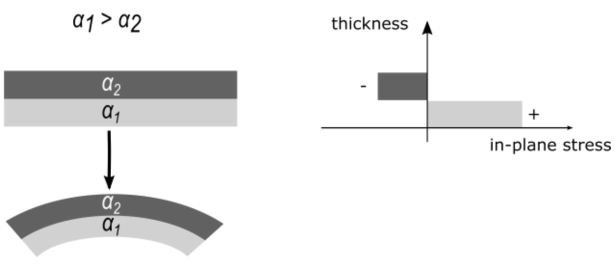

Figure 4: Residual stress state through the thickness in an asymmetrical layup after manufacturing at elevated temperatures and cool down to room temperature. The laminate deforms after demoulding to reduce interlaminar stresses.

2.5 Specimen manufacturing
This section describes the manufacturing-analysing workflow for the curved specimens (Section 2.5.1) to outline the proposed steps of the evaluation process. Furthermore, the manufacturing and the labelling is described in Section 2.5.2.

2.5.1 Workflow for the manufacturing and the analysing process
The manufacturing and evaluation follow the proposed workflow of [5] shown in Figure 10. This workflow suggests to place an asymmetric sample within every manufacturing process of symmetric layups in order to conclude on the residual stress state within the laminate.
Asymmetric and symmetric layups are manufactured using the same material or material combination. During manufacturing, both layups are influenced simultaneously by the same extrinsic parameters, whereas the intrinsic parameters are mainly originating from the materials itself.
The resulting curvature of the asymmetric specimens is evaluated and consequently transformed into a corresponding stress-free temperature considering the appropriate material properties. The residual stresses can be calculated with the stress-free temperature in any laminate manufactured within the same process and hence, their influence on the mechanical strength of the laminate can be estimated.

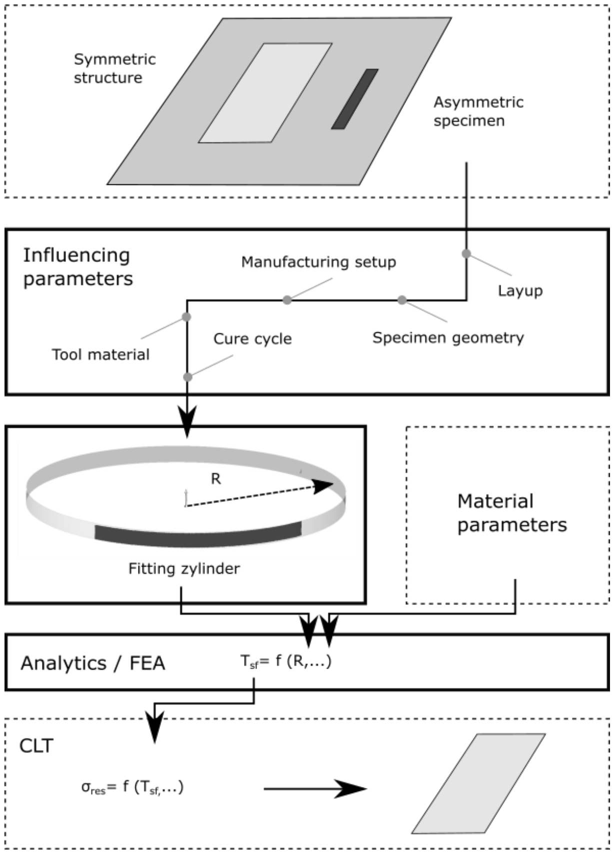

Figure 10: Proposed workflow to use asymmetric specimens for residual stress quantification of FML structures. The focus of this paper is indicated by the boxes framed with thick lines (based on [5])

2.5.2 Specimen manufacturing and labelling
The specimens are manufactured using prepreg CFRP and steel layers. The single plies are stacked on top of each other and a cover plate is placed on top of the stack. A release foil is used to prevent adhesion between laminate and cover plate. The laminate is transferred onto the tool and covered with a vacuum-bag, before curing in an autoclave.
The asymmetric FML specimens are labelled using the nomenclature explained in Table 4, whereas the asymmetric CFRP specimens are labelled according to Table 5.

Table 4: Logic used to label the asymmetric FML with ID17SR as an example

1	No. of steel plies	-
7	No. of CFRP plies	-
S	Tool material	S: steel / A: aluminium
R	Cure cycle	R: recommended / M: modified

Table 5: Logic used to label the CFRP specimens with ID090 SR as an example

090	Layup	-
S	Tool material	S: steel / A: aluminium
R	Cure cycle	R: recommended / M: modified

Every specimen is built at least 3 times to be able to evaluate scattering of the results. Less specimens could be evaluated for 17 AR and 090 SR due to manufacturing issues. Half of the specimens manufactured in each curing cycle are covered by aluminium tooling, the other half by steel tooling.
Table 6 lists all evaluated FML specimens as well as the built CFRP specimen.

Table 6: Overview of the specimen program and its parameter variations in this work

ID	Layup	Tool	Cure Cycle	Quan-tity
17 SR	asym. S/C	steel	MRCC	4
17 SM	asym. S/C	steel	MOD	3
17 AR	asym. S/C	alum.	MRCC	1
17 AM	asym. S/C	steel	MOD	3
090 SR	asym. C	steel	MRCC	2
090 SM	asym. C	steel	MOD	3
090 AR	asym. C	alum.	MRCC	3
090 AM	asym. C	alum.	MOD	3

The whole specimen setup is built twice to analyse the extrinsic parameters, as [5] already demonstrated the significance of this variation.
Hexply, the supplier of the CFRP material, recommends a curing cycle (Figure 11: MRCC). It was shown in [5] that a modification (Figure 11: MOD) of the cycle can lead to a lower stress-free temperature for FML [5, 19]. The modified process implements a temperature drop after it reaches a temperature of 145°C) to a temperature of 45°C. The final temperature step is a 180°C plateau.

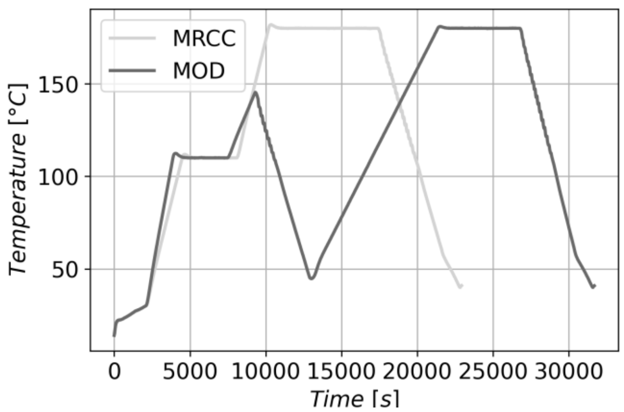

Figure 11: Two different temperature profiles during autoclave cure for the two considered manufacturing processes MRCC and MOD

The MOD curing cycle takes longer than the MRCC cycle because of the intermediate cooling step. This cooling step reduces the gel point temperature of the resin.

3. INTRINSIC PARAMETER VARIATION

Intrinsic influences are driven by the internal material properties and the layup. These parameters are known in advance. Therefore, they can be varied in an analytical approach to evaluate their influences analytically. The following section determines the change of the expected curvature using the already known material properties and Equation (1).
The parameter variation is conducted for the relevant radius range between 200-500mm. Different parameters of this equation are varied. Figure 5 displays the different parameters for the two sections used.

Figure 5: Generic layup for an asymmetric specimens

Table 7 presents the different variations which are conducted in the following paragraphs. The reference temperature T_r is set to 23°C for all variations.

Table 7: Parameter variation of the specimen's parameters in Equation1 (x: set, v: variable)

Parameters	Fig. 8	Fig. 9	Fig.10	Fig. 11
h	**v**	x	x	x
n (E_1/E_2)	x	**v**	x	x
m (t_1/t_2)	x	x	**v**	x
$\Delta\alpha$	x	x	x	**v**

3.1 Variation of thickness

The thickness is a linear term in Equation (1) and influences the bending stiffness of a specimen. Therefore, the absolute thickness is a leading factor for the absolute curvature [5].
Two layups are depicted in (Figure 6). Each layup represents the setup for one of the used asymmetric specimens, either FML or CFRP. The layups use the values from Table 1 for all parameters that are not varied in this section.
Both layups behave very similar, for a change in thickness h. The manufactured CFRP specimen possess a thickness of 1.04mm, the FML specimen 1.03mm.
A change in r results in a change of T_{sf} in a hyperbolic pattern. Different thicknesses result in different radii for the same stress-free temperature. The depicted behaviour shows the dependency of the radius from the thickness. Therefore, the absolute specimen`s thickness needs to be considered evaluating the absolute radius.

(layup 2, n=1.61) has a greater change in radius for a given change in T_{sf} than the same temperature change for CFRP (layup1, n=0.079).

3.3 Variation of layer section thickness ratio

Different layer sections not necessarily possess the same thickness and therefore contribute to the formation of the curvature. The layer section ratio is defined as $m = t_1/t_2$.

Again, the influence of n is non-linear. It can be derived from Figure 8, that the smaller m, the less change in radius is needed to account for a defined change in T_{sf}.

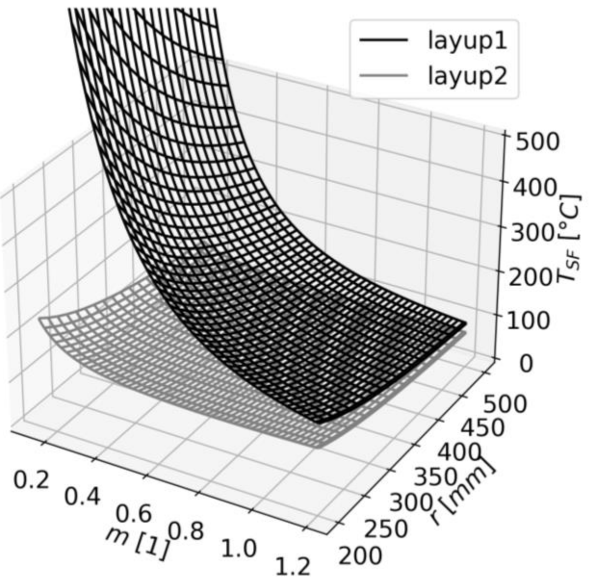

Figure 8: Comparisson of layer section ratio sensitivity for the used layup 1 (CFRP) and layup 2 (FML) laminates for different radii. (n_1=0.079, h_1=1.04, n_2=1.61, h_2=1.03,)

Although, FML possess a layer thickness section ratio of m=1/7 which is much smaller than the one of the manufactured CFRP samples (m=1), the absolute behaviour of the CFRP specimens shows a similar behaviour of the T-R relationship. It is important to consider the radius range of interest for a specific comparison. The less curvature, the more change in radius is needed to compensate a defined change in temperature.

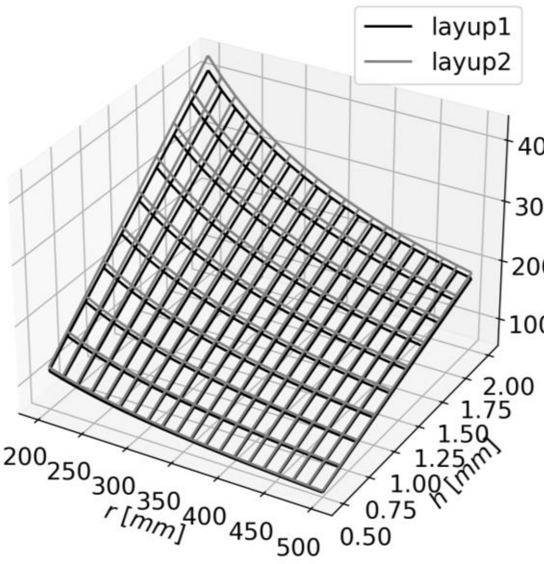

Figure 6: Comparisson of thickness sensitivity for the used layup 1 (CFRP) and layup 2 (FML) for different radii. (m_1=1/7, n_1=1.61, m_2=1, n_2=0.079)

3.2 Variation of stiffness ratio

Multi-material layups usually possess different stiffnesses. These stiffnesses influence the bending behaviour and therefore its ratio needs to be evaluated to interpret the resulting curvature. The stiffness ratio is defined as $n = E_1/E_2$. Its influence is non-linear.

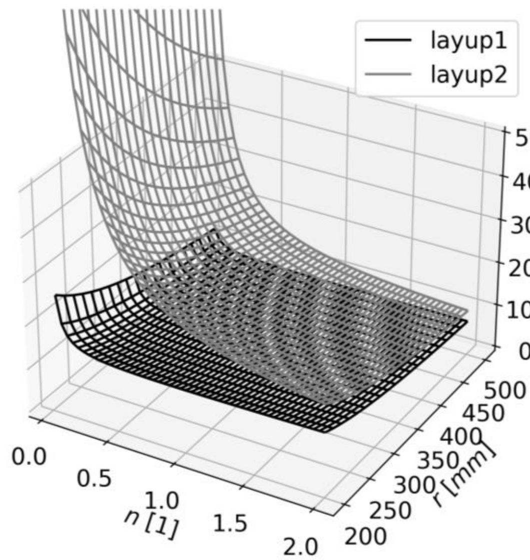

Figure 7: Comparisson of stiffness ratio sensitivity for the used layup 1 (CFRP) and layup 2 (FML) laminates for different radii. (m_1=1, h_1=1.04 m_2=1/7, h_2=1.03,)

Small ratios result in a greater influence on the radius - stress-free temperature relationship (Figure 7). The greater n, the more change in radius is needed to account for a changed stress-free temperature. Hence, the manufactured FML

3.4 Variation of layer section thickness ratio

Figure 9 depicts the behaviour of a change in $\Delta\alpha$. Both layups possess materials with two different CTEs which have a difference which is covered by the depicted $\Delta\alpha$.

It is obvious, that both layups behave very similar.

A change in $\Delta\alpha$ dominates the T-R relation. The greater $\Delta\alpha$, the more change of the radius is needed to account for a change of the stress-free temperature. The processed FML has a $\Delta\alpha$ of $1.86e^{-5}$ppm/K, the CFRP specimens possess $\Delta\alpha = 3.08\ e^{-5}$ppm/K.

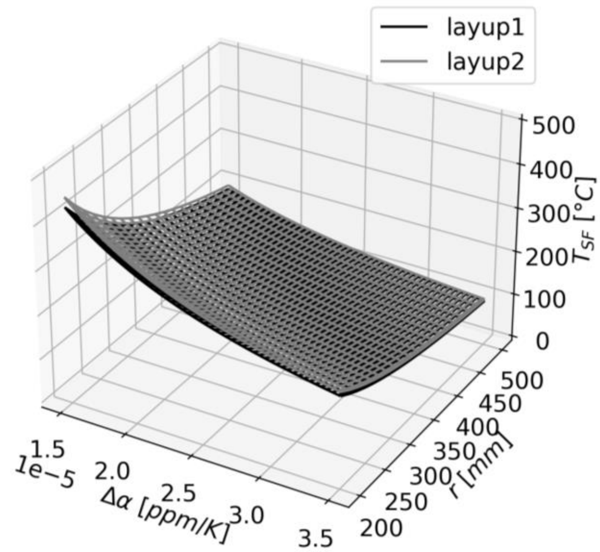

Figure 9: Comparisson of the change of Δα for the used layup 1 (CFRP) and layup 2 (FML) laminates for different radii. (m_1=1, h_1=1.04, n_1=0.079, m_2=1/7, h_2=1.03, n_2=1.61)

The absolute sensitivity of the radius against a change of T_{sf} is higher for small $\Delta\alpha$, nonetheless this sensitivity is highly radius range dependent again. The calculated behaviour of the parameter variation for the produced FML and CFRP, especially the change of the stiffness ration, the change of the layer section thickness ratio and the variation of $\Delta\alpha$ lead to the assumption that the manufactured asymmetric CFRP specimens will not show such a distinct curvature distribution as FML do but the general behaviour of the samples is expected to be the same. The more curvature, the greater is T_{sf} and consequentially the residual stress within the corresponding symmetric specimen.

These findings show the influence of the specimen set up and the material combination used. The results help to choose the specimens setup to get the best possible results in terms of sensitivity and correctness of the specimen's stress dependent curvature. This is important to evaluate T_{sf} correctly to determine the residual stress state within a manufactured laminate.

4. EXTRINSIC PARAMETER VARIATION

The following chapter discusses the curvature analysis of the asymmetric manufactured specimens of the CFRP and the FML. The manufacturing on either steel or aluminium tooling and the usage of the two different processes manly affects the extrinsic parameter influence on the specimen`s curvature and hence their residual stress state.
Each batch is investigated depended of its tooling and its curing cycle influences. Additionally, the correlation between the curvature and its corresponding stress-free temperature is examined.

4.1 Influence of tooling material on the curvature

Tooling is a major influence on curvature as shown in [5]. All resulting radii for both tooling setups are pictured in Figure 12. The use of an aluminium tool results in a smaller radius compared to the steel tooling does, except for the CFRP specimen, which have been manufactured in the recommended process.
The increased radius on a steel tool for one specimen set (090 SM), displays absolute curvature values which are very similar to the curvature of its steel counterpart. The standard deviation of both sets overlap. This behaviour and the fact that the radii of the CFRP specimen display in a small range lead to the assumption that this reversed behaviour is not a sign for a completely different effect. Measure and manufacturing uncertainties can lead to such a behaviour.
The diagram additionally depicts that the FML specimens result in less curvature (larger radius) than the CFRP specimen. This behaviour is mainly influenced by the intrinsic material properties as investigated in Section 3.

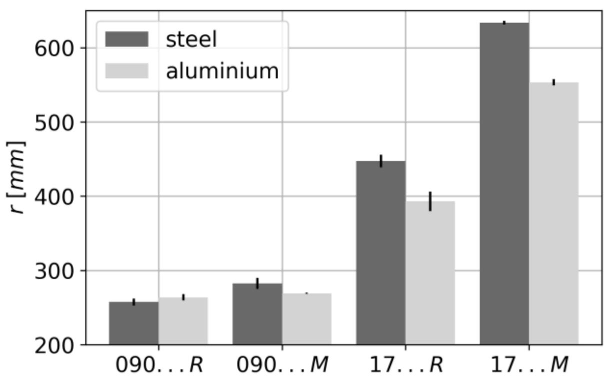

Figure 12: Comparison of the radius of the specimens manufactured on either the steel or the aluminium tooling.

FML shows more significant changes of the radii due to a change of tooling material than CFRP. These FML samples are not only influenced by two different materials, the setups with aluminium tools are influenced by a third material and hence, another CTE. Aluminium possesses a thermal expansion coefficient of 24 ppm/K, more than steel (19 ppm/K). This causes the aluminium to stretch more during heating than steel.
A pressurized contact, like autoclave curing, introduces forced interaction and hence, introduces additional strain on the CFRP and the metal side of FML. The $\Delta\alpha$ between steel and aluminium is a lot smaller than the difference between the outer CFRP layer and steel. This supports the elongation of the steel and therefore of the CFRP on the metal side as well.
Steel tooling does not introduce this additional force into a specimen. The steel tooling still supports the

elongation of the metal side as it expands similar to the specimen's metal sheet.

The steel tooling manufacturing setup tends to be a more symmetric layup (steel-steel-CFRP-steel) than the aluminium tooling setup (aluminium-steel-CFRP-aluminium) is which underlines the investigated smaller curvature in these specimens.

4.2 Influence of the curing cycle on the curvature

The specimens were manufactured using the two described autoclave processes. The modified process is developed to reduce the stress-free temperature as demonstrated in [5].

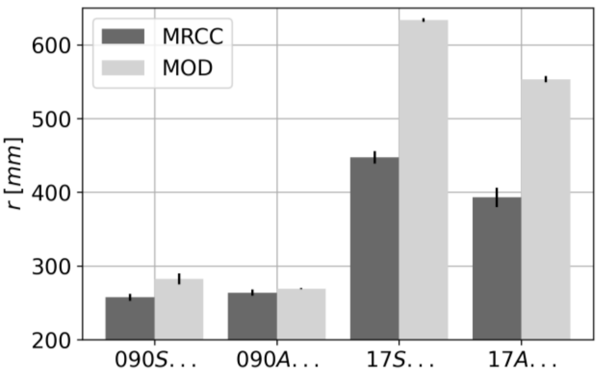

Figure 13: Comparison of the radius of the specimens manufactured in the recommended and the modified curing cycle.

Every specimen set, which is cured in a modified curing cycle, shows a larger radius. This indicates the expected lower T_{sf} and hence lower residual stress.

It can be concluded from the diagram (Figure 13) that the radius changes between the two curing processes of the same manufacturing setup is much higher in FML than it is in CFRP specimens.

It was already shown in Section 3 that FML demonstrate a greater change in radius for a given change of the stress-free temperature.

The bonding temperature is a main influence on T_{sf} as the bonding prevents the layers from sliding amongst each other.

4.2.3 Correlation of curvature and stress-free temperature

The radii of the different specimens are determined in a 3D-measurement setup. Additionally, the stress- free temperatures are measured in an oven. These temperatures and the corresponding radii are plotted in Figure 14. The mean of each differently manufactured specimens set is outlined within the diagram.

A calculated analytical solution for the specimen's is plotted additionally to demonstrate the behaviour more clearly. The measured temperatures follow these trends although they do not match perfectly.

Asymmetric CFRP specimens show a steeper gradient of the T-R relation. Reasonable low change in radius changes T_{sf} significantly. This relationship underlines the evaluation in Section 3.

All manufactured CFRP specimens show within a small stress-free temperature range. The FML specimens show differently. Its trend supports the investigation in Section 3 as well that FML are more sensitive towards an internal stress and result in a greater change of radius.

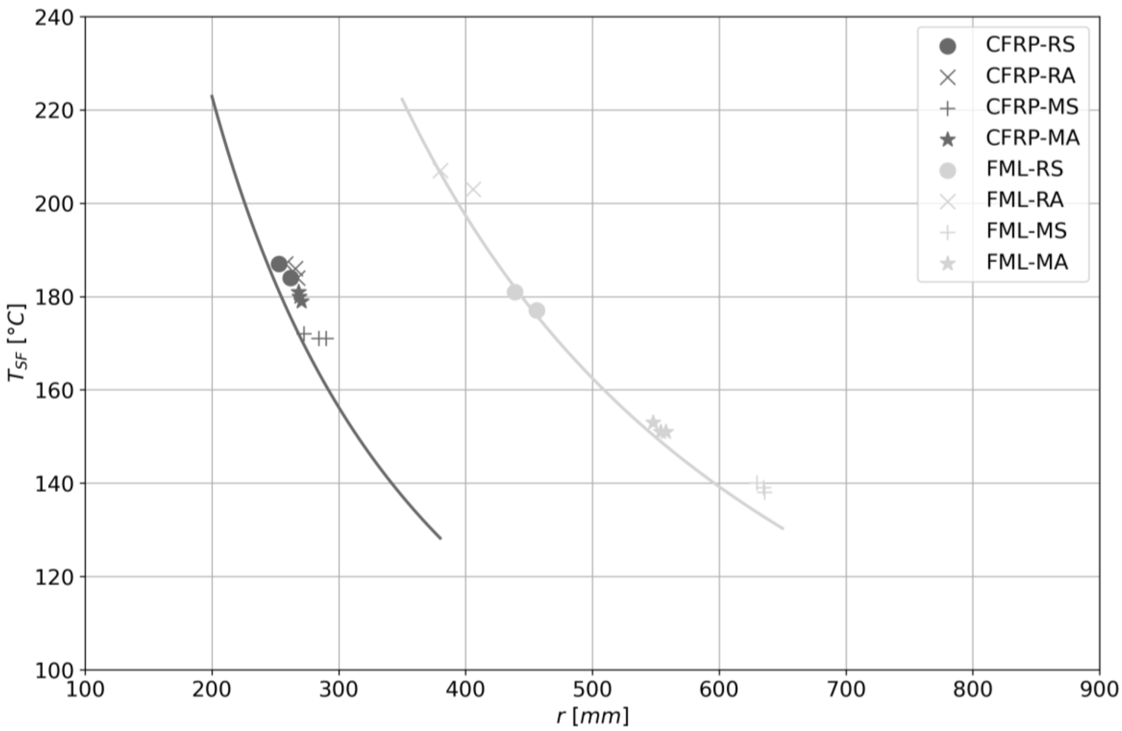

Figure 14: Correlation of radius and the corresponding calculated stress-free temperature

The measured stress-free temperatures are close to the calculated temperatures for the measured radii for FML. Whereas these temperatures differ more for the CFRP specimen. Curvature is not only a result of thermal behaviour but also from phenomena like chemical shrinking. This shrinking affect is matrix dominated. The manufactured asymmetric FMLs do not have layers whose behaviour is dominated by the matrix. The UD 0° layers are dominated by the fiber properties and steel is not impacted by chemical shrinking at all.
Unlike FML, the asymmetric CRFP specimens are matrix dominated in the 90° layers. These 90° layers are influenced by chemical shrinking, which is not covered by Timoshenko's equation.
FML seems to be impacted much more by the change of external manufacturing influences. A temperature step of about 20K appears due to a tooling material change using the same process. The process changes results in a shift of T_{sf} by about 50K. CFRP specimens show a far smaller T_{sf} range. 5-10K are evoked by a changed tooling material, a varied process causes a maximum shift of the stress-free temperature of about 15K.
Figure 14 and Section 3 lead to the conclusion of the curvature analysis that asymmetric CFRP is more sensitive against intrinsic influences (e.g. chemical shrinking) whereas external manufacturing influences do not impact the stress-free temperature and the residual stress state as intensively as they do for FML. FML is not as heavily impacted by the intrinsic influences as the CFRP specimens are.

5. CONCLUSION

This paper demonstrated the influence of internal and external parameters on the stress-free temperature and hence the residual stress state. The conducted research focuses on the intrinsic and extrinsic parameters for asymmetric CFRP and asymmetric FML specimen.

An analytical evaluation of parameter variation was outlined and demonstrated the significance of the intrinsic parameters for each layup. CFRP specimens display a given delta T_{sf} in a smaller change of its radius than FML. The layup changes the stress state of a CFPR specimen more than in FML. The analytical variation outlined the significance of $\Delta\alpha$. This parameter dominates all other parameters of the analytical equation. Its actual value is crucial for the specimen's sensitivity towards a change in its stress-free temperature. The stress-free temperature is manly changed due to extrinsic factors. The analytical evaluation explains the behaviour of FML specimens compared to CFRP specimens. It could be successfully demonstrated that the extrinsic parameter tooling and curing cycle impact CFRP specimens in a similar way than they effect FML although the influence is less important.

Additionally, it could be clearly outlined, that the extrinsic parameters influence the stress-free temperature and hence, the residual stress state in FML significantly, more than in CFRP.
Therefore, the importance of the residual stress consideration, especially for FML, is emphasized.
It can be derived from Section 3 and 4, that behaviour due to residual stress influence is vital for FML, as the residual stress state is more dependent on intrinsic and extrinsic factors than for CFRP.

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