EXPERIMENTAL ANALYSIS OF DRAPING PROCESS GENERATED MATERIAL IMPERFECTIONS IN TEXTILE PREFORMS

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Abstract
Two dimensional textile reinforcements, e.g. non-crimp-fabrics (NCF), are preformed into complex three-dimensional shapes to be used in fibre reinforced parts for medium to high volume composite applications. The structural performance of NCF reinforced composite parts is significantly influenced by the local fibre architecture of the NCF preform which is formed during the draping process. The resulting local imperfections, their size and their impact on mechanical properties of the composite material has not been fully addressed by present research. To solve this problem, a generic mold for investigations on the draping behaviour of NCF on structural level as well as specific tools for reproducing fibre waviness, fibre gapping and transverse compression due to shear on coupon level, were developed and tested. Major draping effects observed on structural level for 0/90° stacks were shearing and fibre gapping while ±45° layups also showed fibre waviness. With this set of tools, it is possible to investigate the formation of draping effects on structural level and to reproduce selected individual effects on coupon level for mechanical testing of CFRP specimen.

1. Introduction

During the forming of textile fabrics to create preforms for the resin-transfer-molding (RTM) process, draping effects occur. Draping effects influence the local fibre orientation and the local fibre volume content (FVC) and therefore have a great influence on the local mechanical properties of fibre reinforced polymers (FRP). So far, these effects are not represented by macroscopic forming simulations. Maron [1] and Schirmaier [2] conducted experiments to validate forming simulation models. They observed non quantifiable draping effects which their simulation models could not predict. Draping effects are on the one hand fibre waviness, which can be divided into out-of-plane and in-plane-waviness. The former is often present in thick laminates whereas the latter occurs in thinner laminates. Fibre waviness can be described by a wave length λ and an amplitude A. On the other hand, the effects fibre gapping and transverse compression of the fibres due to shear are observed. Both effects are of opposing nature in regard to fibre volume content: fibre gapping reduces the local FVC as the distance between fibre bundles decreases and transverse compression due to shear increases the local FVC as the fibres are forced towards each other. Because these effects observed on complex geometries cannot be created by forming simulation on part level, it is necessary to characterize these effects experimentally. For material testing it is essential to create draping effects on coupon level. The literature describes several approaches to create out-of-plane waviness and its influence on compressive strength [3–5]. Out-of-plane waviness is present and critical in thick

laminates e.g. for fan blades [6]. In plane-waviness occurs in thinner structures. To create in-plane-waviness, Hsiao et al. [3] suggest to cut thick (70 to 150 ply) laminates with out-of-plane-waviness into slices. However; the manufacturing of thick laminates is very time consuming and difficult in terms of air-entrapment. To create in-plane waviness, Bröekl [7] describes two methods - a sliding and a swivel mechanism. The first mechanism deforms the fibres by moving sliders perpendicular to the fibre direction while the fibres are not actively compressed in longitudinal direction in which they contract. The second mechanism uses swivel arms, which form parallelograms and actively move the fibres in perpendicular and longitudinal direction. Bröekl [7] found that the swivel mechanism is more suited, since it induces fewer irregularities in the deformed fabric. The tools described by [7] create fibre waviness with A/λ ratios of 0.05 to 0.135 with large wavelengths (λ= 55 to 120 mm) which is large compared to the very local draping effects. No studies were found which describe the manufacturing of gapped specimen.
The goal of this work is to present new tools for the reproducible creation of the draping effects fibre waviness, fibre gapping and transverse compression due to shear for coupon tests. Furthermore, a forming tool on structural level is proposed which allows to adjust draping effects while preforming a complex geometry.

2. Materials

A unidirectional carbon fibre non-crimp-fabric (NCF) of the type PX 35 from Zoltek was used for preform manufacturing. It is a unidirectional reinforcement fabric with a pre-applied powder binder and 5 mm wide rovings (50K). The target areal weight is 330 g/m². Adjacent rovings of this fabric are connected by a tricot loop type stitching which forms a characteristic zigzag pattern on one side of the fabric and gives the fabric a high shearing resistance. The powder binder is an epoxy based adhesive which is pre-applied at the factory on one side of the fabric. In this case binder technology is used to freeze the draping effects after deformation. The binder is a thermoset with thermoplastic properties: this means it can be melted several times.

3. Process on Coupon Level

The goal was to design simple and flexible tools to adjust fibre waviness, fibre gapping and transverses compression due to shear for the manufacturing of coupon specimen for mechanical testing using a high pressure RTM process. Draping effects are considered to be in the same order as the width of the roving bundles. Therefore, waves with a wavelength λ = 20 to100 mm and an A/λ =0.05 to 0.1 mm must be possible to manufacture. The target for gap size is half the roving width (w_{gap} = 2.5 mm) and shear angles of α = 0 to 35°.

3.1. Tools and Preform Manufacturing

Fibre waviness for fibre misalignment

Due to the small dimensions of the waves and the adjustability of the A/λ-ratio, a sliding mechanism was chosen. In contrast, a swivel mechanism consists of numerous parts for all the joints and hinges and several mechanisms would be required, because one mechanism can only adjust one single A/λ-ratio for a given amplitude. The sliding mechanism comprises 20 ledges between two guide plates. The needle ledges are 5 mm wide, 600 mm long and feature a needle every 5 mm. Galvanized fine wire staples with a diameter of 0.7 mm, glued into an aluminum strip, are used for the needles. The fabric is applied on top of the needles and pushed downwards so that the needles penetrate the fabric. By pushing the ledges the roving bundles are displaced in transverse direction. To adjust the wavelength and amplitude, corresponding master plates with the desired wave pattern are pressed simultaneously against the ledges from opposite directions (Figure 1). To prevent the needle ledges from buckling in out-of-plane direction, they are placed under a grid. The 10 mm long needles penetrate the grid and catch the fabric.

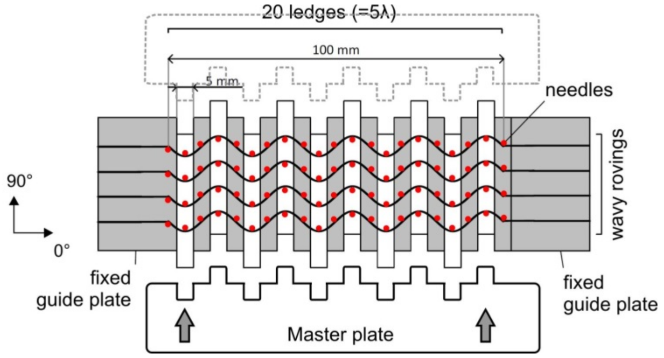


Figure 1. Principle of tool to induce fibre waviness with different A/λ-ratios

Preforms are manufactured in a two-step preforming process. In a first step, a single fabric layer with a fibre orientation perpendicular to the direction of the needle ledges is pressed downwards with a sponge like tool. After forming, the wavy pattern is fixed by activation of the powder binder on the fabric. Binder activation can be performed by infrared heating or a hot air gun while the fabric is still attached to needle ledges. After careful removal from the tool, the waves remain in the preform. In a second step, all plies are accurately stacked upon each other and joined in a membrane press by activating the binder for the second time.

Fibre gapping for reduced fibre volume content

To induce gaps between the roving bundles and in thus way to reduce the FVC, a modified sliding mechanism is used, which is based on the first tool. This time, the roving bundles of the fabric are oriented in parallel to the needle ledges and one guide plate on the side is removed. Instead of moving the needle ledges in parallel, small spacer ledges are inserted inbetween them to create a transverse movement to separate the fibre bundles (Figure 2). The gaps size is determined by the width of the spacer ledges. Spacer ledges of several widths are used to adjust different gaps sizes. For a gentle forming process the spacer ledges have to be inserted one after another.

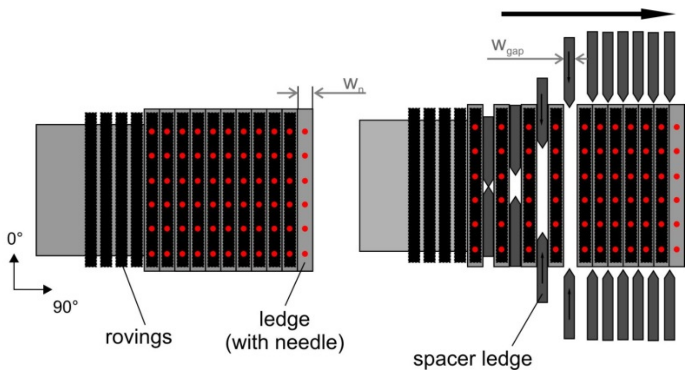


Figure 2. Principle of tool to induce fibre gapping

The manufacturing comprises the same two-step process as described for waviness. Because binder activation on a single fabric layer would not fix the gap size as the gap acts as a void between rovings and the stitching cannot maintain the gap size, an additional fixation layer must be added. An undeformed ply is attached on top as a fixation layer for preform cohesion.

Fibre shearing for increased fibre volume content

For the manufacturing of sheared preforms with an increased fibre volume content, a shear frame is used. A characteristic feature is that 6 plies of fabric are sheared at once. To fix and compress all layers, binder activation is performed in the membrane press with the fabrics still in the shear frame. Therefore, a low profile shear frame was designed without sharp pointy clamps to prevent harming the membrane. To successfully impregnate the preform with a higher FVC, the resin flow direction needs to be within the fibre direction of the preform. Hence, the preforms for the RTM tool are cut according to Figure 3.

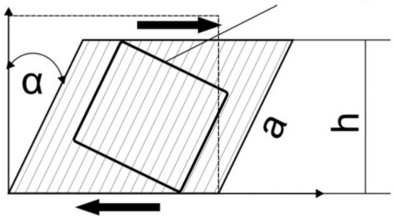


Figure 3. Principle of tool to create transverse compression due to shear

3.2. Forming Results and Discussion

To evaluate the forming results, the preform's outer layers can only visually be assessed. To inspect the inner layers, computer tomography (CT) scans are performed in order to check if the curves of the waves are located one upon another. Changes in wavelength or amplitude can be evaluated by measuring the distance between the crests of a wave. Gapping distance and fibre orientation are verified for gapped preforms. To check the quality of the preform before infiltration, the FVC of the preform is calculated by measuring the fibre mass of a precisely cut out area with draping effects comparing it to the theoretical fibre volume content determined by analytical equations.

The analytical solution for the fibre volume content of a preform with an assumed thickness of the final coupon can be written as

$$\varphi_{\mathrm{exp},i} = \frac{n_L}{\rho_f \cdot t} m_{A_i}. \quad (1)$$

with the weight per unit area of the preform m_{A_i}(index i: w = wavy, g = gapped, s = sheared), n_L the number of fabric layers, ρ_f the density of the fibres, and t as the assumed laminate thickness.

Exemplary, the comparison of the experimental results isshown for wavy preforms where the theoretical fibre volume content is calculated by (2)

$$\varphi_{\mathrm{w}}(\lambda, A) = \frac{n_L}{\rho_f \cdot t} \cdot m_{A_0} \cdot \frac{l_{\lambda,\mathrm{A}}}{l_0}, \quad (2)$$

where m_{A_0} is the mass per unit area of the undeformed fabric, l_0 is the length of a straight roving bundle and $l_{\lambda,A}$ is the arc length of fibre bundle with a sinusoidal wave. For a wavy pattern with a wave length of $\lambda = 20$ mm and the generated amplitudes, there is a good correlation between experimental and analytical results (Table 1). It can be shown that for $A/\lambda > 0.1$ the experimentally determined fibre volume content deviates from the analytical values. This is due to the tricot loop pattern of the stitching yarn restraining the movement of the fibres. In combination with the simple shear induced by the sliding mechanism (the roving bundles are not guided in fibre direction while they are displaced in transverse direction) the forming limits for this configuration are reached. This was observed during preform preparation as gaps between the roving bundles started to appear in the wavy section.

Table 1. Analytical and experimental results of fibre volume content for wavy preforms with a wave length $\lambda = 20\ mm$, number of plys $n_L = 6$ and an assumed laminate thickness of $t = 2.25\ mm$

		Analytical			Experimental (n=5)		
Amplitude [mm]	A/λ	$l_{\lambda,A}$ [mm]	φ_w [%]	m_{Aw} [g/m²]	φ_w [%]	m_{Aw} [g/m²]	Deviation [%]
0.0	0.000	100.00	47.9	325.00	47.8	324.31	-0.21
0.5	0.025	100.61	48.2	327.00	48.1	326.11	-0.27
1.0	0.050	102.42	49.0	332.88	49.0	332.42	-0.14
1.5	0.075	105.34	50.4	342.36	50.3	341.05	-0.38
2.0	0.100	109.24	52.3	355.02	51.9	352.00	-0.85
2.5	0.125	113.98	54.9	370.45	52.2	354.11	-4.41
3.0	0.150	119.45	57.2	388.20	52.2	354.32	-8.72

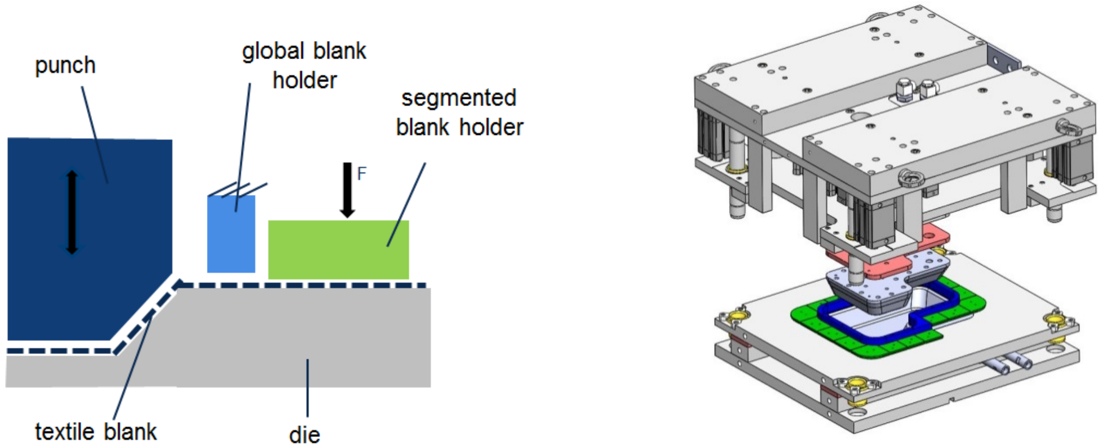
For the CT scan, the dry preforms were compressed to the theoretical laminate thickness. CT scans confirmed that the maximum A/λ-ratio that could be reproduced was 0.1 for λ = 20 mm. Furthermore the CT scans showed that uniform deformation results for all plies of a 10-ply stack could be achieved. Individual plies were difficult to differentiate because the waves lie directly on top of each other. CT scans of gapped preforms showed the gap size for preforms above 2.5 mm varies as the roving bundles are deflected into a wavy shape due to the transverse stretch of the stitching yarn.

4. Process on Structural Level

A tool to form and consolidate draping effects in a complex L-shaped geometry is presented. It consists of three parts: a negative mold, a draping unit and a consolidation unit for high-pressure-resin-transfer-molding (HP-RTM) infiltration. By combining each of the latter with the negative mold, with the first configuration the preforming step and with the second configuration the consolidation step can be performed.

4.1 Tool for Preforming a Complex Geometry

To study draping effects on a more complex geometry than a hemisphere, this L-shaped mold in combination with the draping unit (Figure 4 (b)) was designed. The L-geometry is 280 mm long, 200 mm wide and 40 mm deep for a preform thickness up to 3 mm. The mold comprises different draft angles (shallower draft angles on the left and bottom side and steeper draft angles on the right and upper side). Due to the L-shape and the different draft angles, the running length of adjacent fibre bundles differentiates which will lead to fibre shearing. Furthermore, the mold features 5 inside and 1 outside corner C3 (Figure 5 (a)) where the outside corner is intended to lead to gapping effects. Figure 4 (a) shows the preforming concept: A punch forces the fabric, which is placed over the mold surface, into the L-shaped cavity. To avoid wrinkling, a 10 mm wide global blank holder with a constant distance to the die surface is positioned around the circumference of the L-shape. To influence the draping behaviour – avoiding or creating draping effects – 19 adjustable segmented blank holders (40 mm wide) are placed around the outside contour of the L. When not active, the segmented blank holders act as an extension of the global blank holder, to avoid wrinkles without exerting a force on the textile. If the segments are active, each can exert a force between 25 to 250 N. Each segment is activated by a pneumatic cylinder connected to a pressure reducing valve and controlled by a main valve. The cylinders are connected in a way that they are controlled by one main switch, however each force can be set from zero (inactive) to 250 N individually. The clamping configuration is set at the start of the process, but individual cylinders could be added manually during the forming process. The punch and die have flow channels for oil heating and by connecting a heating/cooling temperature control unit, a variothermic process is possible. The tool is set up in a mold carrier/press and the punch movement is controlled by the motion of the upper press platen. The possibility for tool set-up in a press is mandatory to realize high locking pressures required in the consolidation step (HP-RTM).



(a) (b)

Figure 4. Illustration of the draping concept to investigate draping effects, (a) schematic of the mold concept with the basic parts, (b) draping mold for experimental investigation of draping effects (partially exploded view)

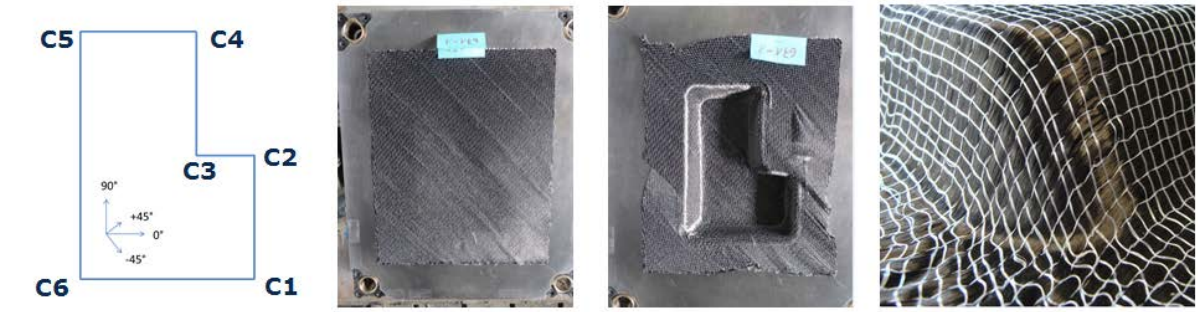
4.2 Draping Process of Complex Preforms

With the bindered fabric and the tool, two preforming process variants are possible: type one is a variothermic process which involves cold forming of the preform stack with an additional heating and cooling step for binder activation. Type two is an isothermic process which includes external heating of the preform stack and a transfer of the hot stack into the tool followed by the forming process. The variothermic process is very simple as it does not require an external preform heater and no preform handling, however it is very energy and time consuming. Heating of the tool to activation temperature and cooling to a consolidation temperature takes 20 min. The isothermic process is faster and more efficient. With a contact heater activation, a temperature of 170 °C is reached within 20 s (2 fabric layers). For the first trials, the preform was transferred manually within approx. 10 s to the mold. The actual forming where the fabric is in contact with blank holders takes a few seconds only, while the time form open to closed mold is 15 s. A major challenge is the fast transfer of the hot preform to prevent a temperature drop below the binder activation temperature of 150 °C. Tool temperature is set at 70 °C to demold a consolidated preform.

4.3 Evaluation of Forming Effects for Complex Preforms

So far, forming studies were conducted for single UD-NCF layers (0°, 90°, -45° and +45° fibre orientation) and 2-ply stacks (0/90° and -45/+45°) using the global blank holder with inactive clamping of the segmented blank holders. For the isothermic process variant, a temperature drop during transfer time was measured to 15-20 K and therefore the binder is still active while forming. Single fabric layers were formed using both processes and draping effects were observed at the same locations. Only fibre gaps were found to be slightly larger for the isothermic process. Fabrics with molten binder are more flexible compared to a cold formed fabric and would explain these effects. For identical test configurations, equal preform qualities and little variability in the shape and the position of draping effects can be reported, this also applies for the preform outline and material intake.
On single fabric layers with -45° orientation, almost no draping effects were observed. Waves were

only observed in C4 and C6 where the fibres were compressed. For 0° and 90° orientation, gapping was found to be within 1-2 mm in the area between C2 and C3. In the inside corners C1 and C3-5 shearing occurs. In general, single ply layers are difficult to handle. The binder cannot fix the shape of single layer preforms because there is no second layer it can connect to. Inherently stable preforms can only be accomplished with two or more layers.
On 2-ply stacks, the -45/+45° stacks showed less draping effects than the 0/90° stacks. The -45/+45° showed fibre waviness due to compression of the roving bundles in the corners C1 and C3-5. On 0/90° stacks, mainly gapping and shearing was observed. A major wrinkle was observed outside of the mold at corner C2 for 0/90° 2-ply stacks. This area is not covered by a global blank holder and does not prevent wrinkle formation. Material accumulations here influences draping effects in other locations.



fiber orientation and corner nomenclature (a) | before forming (b) | after forming (c) | detail of C1 (outside) (d)

Figure 5. Draping a complex preform (a) nomenclature of corners, (b) a single layer of fabric before forming, (c) single layer of fabric (-45°) after forming in the mold, (d) detail of a 2 layer 0/90° stack

As a next step, the blank holder configuration needs to be modified by adding a second global blank holder between corner C2 and C4 to avoid major wrinkles outside the mold to improve forming results. This will have an effect on fibre orientation within the mold and further preforming experiments need to be executed. To find draping effects in the inner structure of a complex shaped preform standard CT scan evaluation software is appropriate. However, an improved analysis strategy needs to be devised to accurately quantify draping effects.

5. Conclusions

During the forming process of fabrics, so-called draping effects, like fibre waviness, fibre gapping or transverse compression due to shear, change the local fibre volume content. Tools with sliding needle ledges to reproduce variable waviness and gapping on coupon level were developed and tested in this work. For unidirectional non-crimp fabrics, fibre waviness with a wavelength of $\lambda = 20$ mm was reliably replicated for A/λ-ratios up to 0.1 mm. For unidirectional non-crimp fabrics it was shown by comparing analytical and experimental results that fibre waviness with a wavelength of λ = 20 mm and A/λ-ratios up to 0.1 mm can be reliably reproduced. On structural level, a complex L-shaped forming tool with 19 segmented active blank holders was designed and first forming trials were conducted. When forming 1- and 2-ply, stacks repeatable draping results could be reached. With CT analysis qualitative analysis of the fabric preform structure is possible. However, for a quantitative analysis an enhanced evaluation method must be established. With the developed new tools it is possible to investigate the formation of draping effects on structural level and to reproduce selected individual effects in order to determine their influence on mechanical properties of FRP.

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