Approach to characterize the process depending mechanical properties of UD-braided CFRP laminates

C. Metzner[1], D. Gizik[1], Dr. J. Kaufmann[2] and Prof. L. Kroll[3]

[1]Airbus Defence and Space, Airbus Group Innovations, Willy-Messerschmitt Str. 1,
82024 Taufkirchen, Germany
Email: christian.metzner@airbus.com, Daniel.Gizik@airbus.com,
Web Page: http://www.airbus-group.com
[2]University of Chemnitz, Institute for Lightweight Structures (IST),
09111 Chemnitz, Germany
Email: joerg.kaufmann@mb.tu-chemnitz.de,
Web Page: http://www.textile-technologien.de
[3]University of Chemnitz, Institute for Lightweight Structures (IST),
09111 Chemnitz, Germany
Email: lothar.kroll@mb.tu-chemnitz.de,
Web Page: http://www.leichtbau.tu-chemnitz.de

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Abstract

The mechanical properties of braided composite materials are strongly influenced by the applied process parameters. To understand, adapt or improve the material behavior, methods are required to formulate the mechanical properties within the feasible process window. In this study a simple approach to characterize the process depending mechanical properties of unidirectional (UD) braided carbon fiber reinforced plastic (CFRP) laminates is presented. The key approach is based on coupon specimens, which were braided in different areal weights, braiding angles and bobbin set-ups. These laminates were characterized respectively the fiber architecture in CFRP state and the resulting tensile modulus and compression strength. The correlation of the calculated fiber undulations of the textile, the undulation angles in the CFRP and the resulting mechanical properties were used to formulate the process depending properties profile within the feasible process window. The property profile of the here investigated material combination is shown on an example.

1. Introduction

The direct processing of carbon-fibers (CF) with textile technics in combination with liquid resin impregnation can be seen as promising solutions for cost and weight optimized high performance structures e. g. for automotive or aeronautical applications. In contrary to the sequential technics, like the placement of preimpregnated fibers (AFP/ATL) or textile fabrics, direct technics, e. g. the braiding, processes low cost materials directly to complex geometries with high deposition rates [1]. Hereby, the plies with reinforcement fibers can be oriented in triaxial, biaxial and unidirectional direction. Due to the fiber crossings of the contrary running bobbin paths, braided fabrics show inherent vertical fiber undulations. Replacing the fibers of one bobbin path with non-load carrying support yarns, the fiber crimp can be significantly reduced [2, 3]. Therefore, the fiber dominated properties, as the tensile modulus and compression strength, are improved [4, 5]. In overbraiding technic, the reinforcement fibers are directly processed to the geometrical surface of the mandrel. Hereby, single plies are feasible in different braiding angle (β), areal weight (m_f) and bobbin set-up ($X_{set\text{-}up}$) [4]. As visible in Figure 1, changes of one of these parameters directly influences the fiber architecture of the processed fabric and therefore also the fiber dominated mechanical properties [5]. Weight and cost optimized structures can be achieved with a maximum material utilization, which is why a fundamental material knowledge is required even in an early design state. This study summarizes a simple method to describe the process parameter driven properties of UD-braided CFRP laminates. Hereby, experimentally determined trends are correlated with a formulation of the fiber architecture to define the tensile modulus and the compression strength.

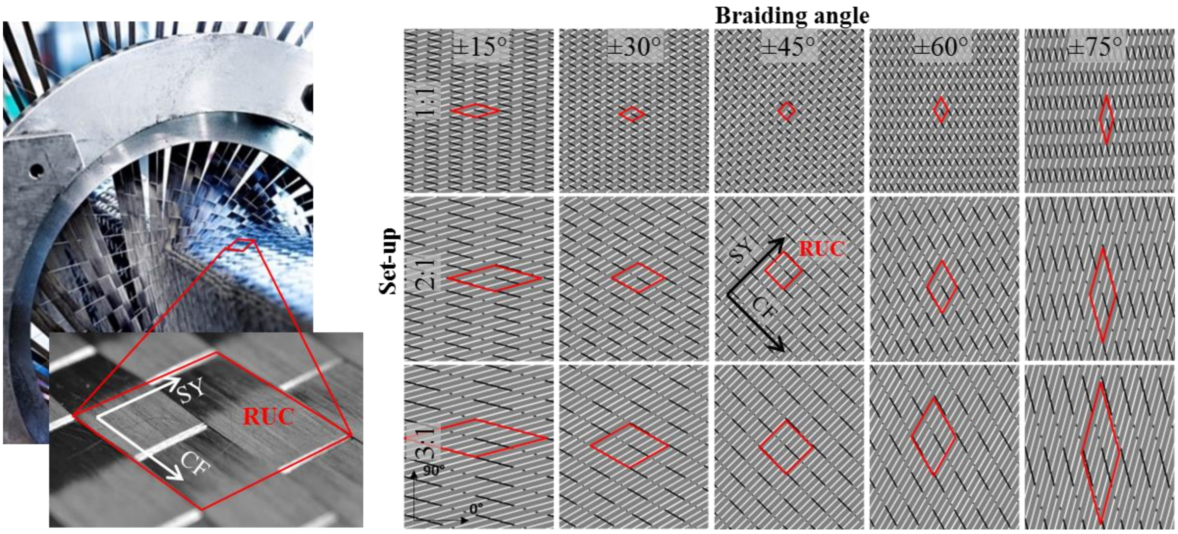

Figure 1: UD-braiding and the repeated unit cell (RUC) geometry depending on the braiding angle and set-up

2. State of the art

Several approaches were already developed to understand and formulate the process depending properties of braided and woven fabrics. The mismatch of the fiber orientation relative to the load direction, driven by the ply orientation and the mean undulation angle, significantly influences the tensile modulus [6]. The compression strength, in contrary, is limited by the crack initiation and therefore dominated by the loading direction. Although tensile loaded laminates are more influenced by fiber damage [7], compressive loads lead to shear buckling failure scenarios in areas with highest fiber undulation [8, 9]. Several formulations were developed to calculate the mechanical properties of braided or woven fabrics which base on the multiscale modelling approach (micro, meso, macro scale). The characteristics of the repeated unit cell (RUC) in weaves or braids can be well formulated with the meso scale approach. The RUC geometry is hereby defined with calculation models or measurements on micrographs of the processed CFRP laminates. Depending on the formulation approach, the waviness-geometry, waviness-ratio or also the maximum undulation angle is used in the models. Further calculation models were developed which discretize the RUC in segments with individual stiffness's which are composed in serial or parallel mode to the element stiffness [10]. Naik and Shembekar applied this kind of model for the formulation of the 3d material properties for biaxial braided CFRP laminates [13-16]. For UD-braids, Earle et al. [2] developed a simple model which base on the waviness ratio to calculate the relative E-moduli. Cox [11] determined best fit lines for digitized fiber undulations taken on micrographs. Hereby, the E-modulus was correlated with the mean undulation angle and the compression strength on the maximum undulation angle defined as the 90th percentile. Eisenhauer [12] and van den Broucke et al. [13] simulated the mechanical properties of UD-braids, whereas the architecture in textile as well as in CFRP state was taken as basis for the WiseTex model. The interaction of the mandrel geometry and applied process parameters dominate the undulation angle (out-of-plane, α) and the ply orientation angle (in-plane, β). Geometrical calculations can be applied to assess the ply orientation of the braided fabric e. g. with vectors [4] or numerical approaches [14]. Detailed fiber paths can be determined with the finite element method (FEM), whereas the braided ply angles but also local waviness angles are predictable. The appropriate definition of a representative unit cell can be seen as biggest challenge for the formulation approaches. Due to inhomogeneous and non-linear material effects e. g. imprints of the neighbored plies or the varying support-yarn amount, the RUC formulation isn't simply feasible in a geometrical matter.

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Addressing these issues, the here described approach deals with the evaluation of experimentally measured fiber undulations, which are correlated to the individual mechanical properties.

3. Experimental details

3.1. Specimen preparations

The textile preforms were produced on a radial braiding machine from Herzog type 1/144-100 with 72 horn gears and maximum 144 bobbin carriers. Unidirectional preforms were braided ply on ply to a flat CFRP mandrel (12 mm thickness) in different areal weights, braiding angles and set-ups to 1.9 mm nominal thickness in accordance to Table 1. The individual textile patterns were achieved with varied bobbin set-ups, whereas a multiple of 36 was applied due to the machine design. The reference laminate without any undulation was manufactured in winding technic. Therefore, CF's were wound to a mandrel to UD-plies with ca. 89° (3.2 mm feeding rate per round). The tenacity of the fibers during braiding and winding was adjusted to 5.25 N. The mandrels were manufactured with CFRP laminates in 12 mm thickness to reduce the thermal expansion effects to the textile preform during hot curing processing. Adjusting just one parameter in the produced unidirectional preforms, only the mandrel height was varied.

Table 1: Summary of manufactured material configurations

#	Textile technic	SY type	SY titer	CF type	CF titer	m_f	β	$X_{set\text{-}up}$	Specimen stacking	Mandrel perimeter
			[g/km]		[g/km]	[g/m²]	[°]	[CF:SG]		[mm]
1	Braiding	PET	2x 10	HTS40*	400	125	45	2:1	$[0]_{16}$	326
2					800	250	45	2:1	$[0]_8$	326
3					1600	500	45	2:1	$[0]_4$	326
4					800	250	60	2:1	$[0]_8$	461
5					800	250	75	2:1	$[0]_8$	890
6					800	250	45	1:1	$[0]_8$	163
7					800	250	45	3:1	$[0]_8$	489
8					800	250	60	1:1	$[0]_8$	230
9					800	250	75	1:1	$[0]_8$	445
10	Winding	-	-	HTS40*	800	250	89	-	$[0]_8$	524

* TohoTenax

3.2. Test methods

The fiber volume content of each material configuration was measured with wet chemical investigations in accordance to DIN EN 2564 on representative samples in 20 x 10 x 2 mm.

The vertical ply undulation angles of the cured laminates were determined on micrographs in length of 40 mm, which were scaled to 10% in length to improve the contrast of the waviness, Figure 2. With ImageJ [15], the micrographs were transformed to 8-bit pictures with 0.045 x 0.045 mm pixel size and 1:10 aspect ratio. The shape of the undulated plies was marked and reduced to a line with one pixel in height (skeletonized). The angles between the pixels of the digitalized lines were calculated, whereas min. 5 material samples per configuration were characterized according this method. In this study, the fiber architecture is defined with the mean ($\alpha_{\varnothing CFRP}$) and the maximum undulation angle ($\alpha_{0.99CFRP}$), calculated with the arithmetic average and the 99th percentile.

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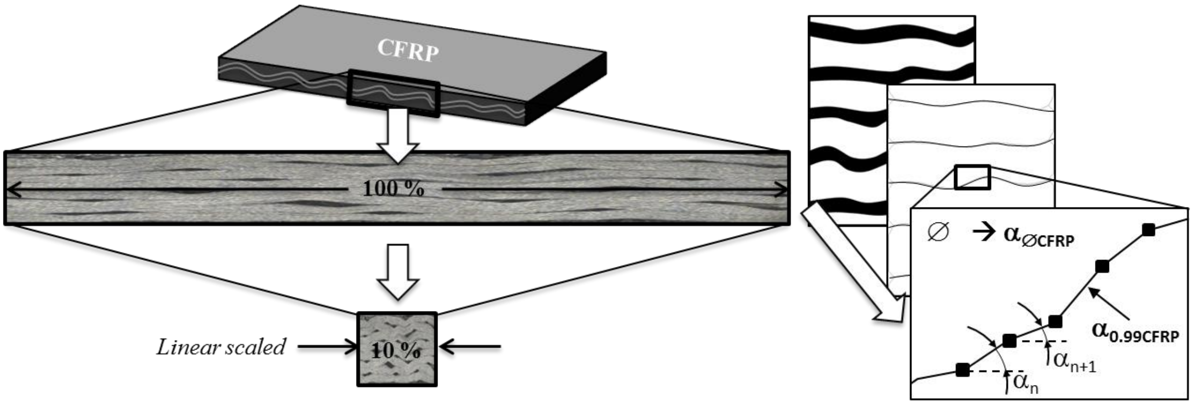

Figure 2: Measurement of the vertical ply undulation angle in the CFRP laminate

All here discussed mechanical properties are mean values, standardized to 60% fiber volume content, which were calculated with minimum 5 valid test values. The antennas represent the standard deviation in each direction. All specimens were tested as delivered without any pretreatments.

The compression strength (σ_{com}) was determined in accordance to EN 2850. The unidirectional specimens with 0° fiber orientation and geometry 110 x 10 x 1.9 mm were applied with tabs to improve the load introduction (10 x 10 mm gauging area). A constant loading of 1 mm/min was applied until failure, whereas the strength was calculated with the maximum force relative to the nominal laminate thickness and specimen width. The tensile modulus (E_{ten}) was measured referring to EN 2561 type A. As the required 250 mm specimen length wasn't feasible with all material configurations, shortened samples in 150 x 10 x 1.9 mm were tested. Tabs in 50 x 10 mm were applied to all specimens whereas the strain was measured with a length extensometer (MTS 634.31F-25) in 30 mm gauging length. E_{ten} was determined with the difference in stress relative to the difference in elongation in the constant load range of 1 to 15 KN.

3.2. Calculations

Fiber undulations in CFRP materials are oriented in all directions, whereas the braiding effects in vertical direction can be seen as most significant. The braiding angle of the textile is determinable with analytical methods, whereas the RUC geometry in terms of length (b/2), width and angle (α_{pc}) can be defined in dependency of m_f, X_{set-up} and the thickness of the fibers. The fiber thicknesses (t_{SY}, t_{CF}) can be calculated with the linear density and the volume content of the braiding yarns. With these relations, the vertical angle of the undulated segment in the RUC can be calculated in accordance to the model in Figure 3 and the equations 1 to 6. Addressing the different fiber tension of the CF and SY, $f_{ten} = 1$ describes the compensation of the SY and $f_{ten} = 0$ the undulated CF.

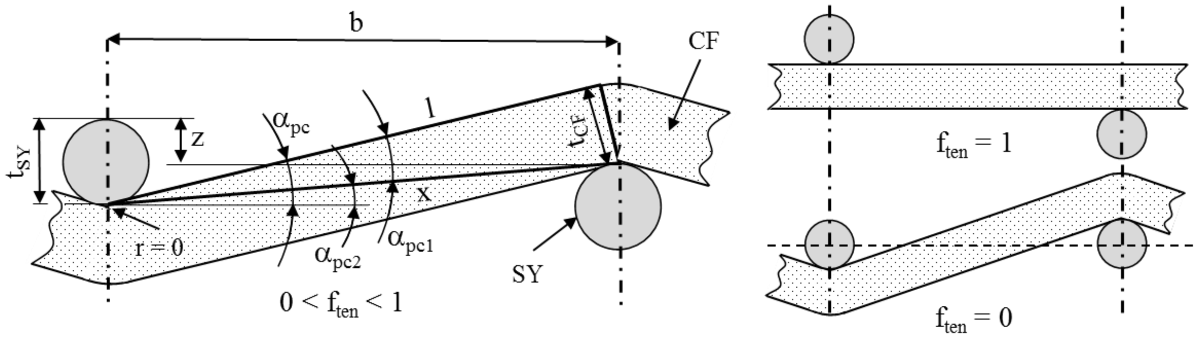

Figure 3: Model to calculate the vertical undulation angle in UD-braids

$$\alpha_{pc} = \alpha_{pc1} + \alpha_{pc2}$$ **Equation 1**

$$\alpha_{pc1} = \arcsin\left(\frac{t_{CF}}{x}\right)$$ **Equation 2**

$$\alpha_{pc2} = \left|\arcsin\left(\frac{t_{CF} f_{ten} - t_{SY}(1 - f_{ten})}{x}\right)\right|$$ **Equation 3**

$$f_{ten} = \left(\frac{z}{t_{CF} + t_{SY}}\right)$$ **Equation 4**

$$x = \sqrt{(t_{CF} f_{ten} - t_{SY}(1 - f_{ten}))^2 + b^2}$$ **Equation 5**

4. Material investigations on UD-braided specimens

In this chapter, the fiber architecture and the corresponding mechanical performance is discussed. The fiber undulation of the laminate is directly depending on the applied process parameters. Figure 4 shows scaled micrographs and digitized undulations of UD-braided laminates with varied X_{set-up}. The lowest set-up, with 1:1 bobbin ratio, leads to large resin nests and higher fiber undulations compared to higher X_{set-up}.

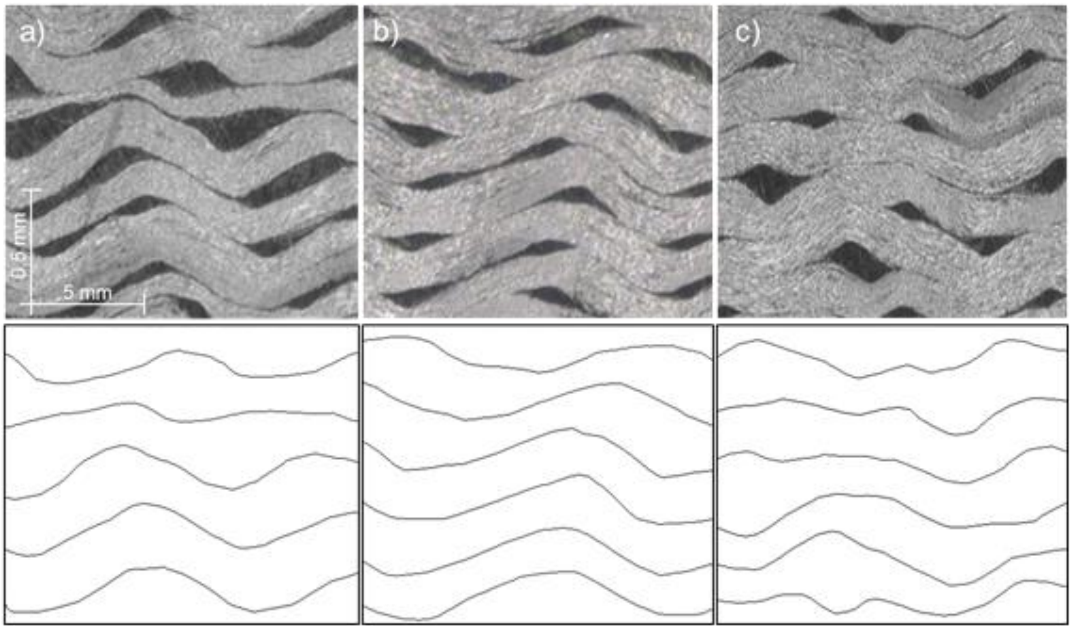

Figure 4: Scaled micrographs (top) and digitized undulations (bottom) of CFRP laminates produced in X_{set-up} a) 1:1, b) 2:1 and c) 3:1

The diagrams in Figure 5 represent the fiber undulation driven influence of E_{ten} relative to $\alpha_{\varnothing CFRP}$ (a) and σ_{com} relative to $\alpha_{0.99CFRP}$ (b). Basically, the laminate material configuration is defined as 250 g/m² areal weight, 2:1 set-up und 45° braiding angle, whereas the further data points show the performance of the given single parameter variation. All properties are shown as relative value with the wound material as reference values (E_{ten} = 154 GPa, σ_{com} = 1587 MPa). In general, tensile moduli are less influenced by locally fiber undulations, as this value is measured in the linear-elastic state. The compression strength, in contrary, is limited by the shear kinking failure mechanisms, whereas even locally fiber misalignments limit the breaking strain and ergo the compression strength.

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The minimum and maximum areal weight of UD-braids is strongly dependent on the feasible aspect ratio of the rovings, in terms of spreading or compression. Hereby, CF's with low linear density (400 tex) achieve single plies with closed surface in range of ca. 125 to 400 g/m² and higher linear density rovings (1600 tex) in range of ca. 250 to 500 g/m². Plies with low m_f generate less undulation angles due to the reduced ply-thickness driven vertical deflection at the CF/SY crossings. The reduced undulation angles significantly improve the compression strength ($\sigma_{com\ 500\ g/m^2}$ = 42%, $\sigma_{com\ 125\ g/m^2}$ = 86%), but also the tensile modulus increases from 81% (500 g/m²) to 86% (125 g/m²) relative to the reference.

The braiding angle can be adjusted in range of ca. ±15° to ±75°, whereas the RUC geometry is influenced in terms of angle and length (see Figure 1). Highest undulation angles can be found in braids with ±45°, because $\Delta\beta$ = 90° generates the shortest RUC length (case const. m_f). Therefore, the compression strength is reduced to 58% and the tensile modulus 85% of the reference value. Larger or also smaller braiding angles than ±45° show similar reduced undulation angles due to the geometrically driven effects of the RUC. The braid with ±75°, for example, shows a significantly increased compression strength and slightly higher tensile modulus (σ_{com} = 75%, E_{ten} = 87%).

The feasible bobbin set-ups are defined by the braiding device regarding number of horn gears and the quantity of bobbin slots. The here used braider (72 horn gears with each 4 bobbin slots) carries multiples of 36 bobbins on each path with a maximum total quantity of 144. The 3:1 set-up with 108 CF's and 36 SY's is the set-up with highest reinforcement fiber count. Other set-ups as multiples of 36 generate braids with an inhomogeneous material quality. Low $X_{set\text{-}up}$ with e. g. 1:1 show the shortest RUC length and ergo highest undulation angles with reduced compression strength (48%) and tensile modulus (83%). In contrary, the highest achievable $X_{set\text{-}up}$ significantly increases the mechanical performance in terms of strength and modulus significantly (σ_{com} = 84%, E_{ten} = 88%).

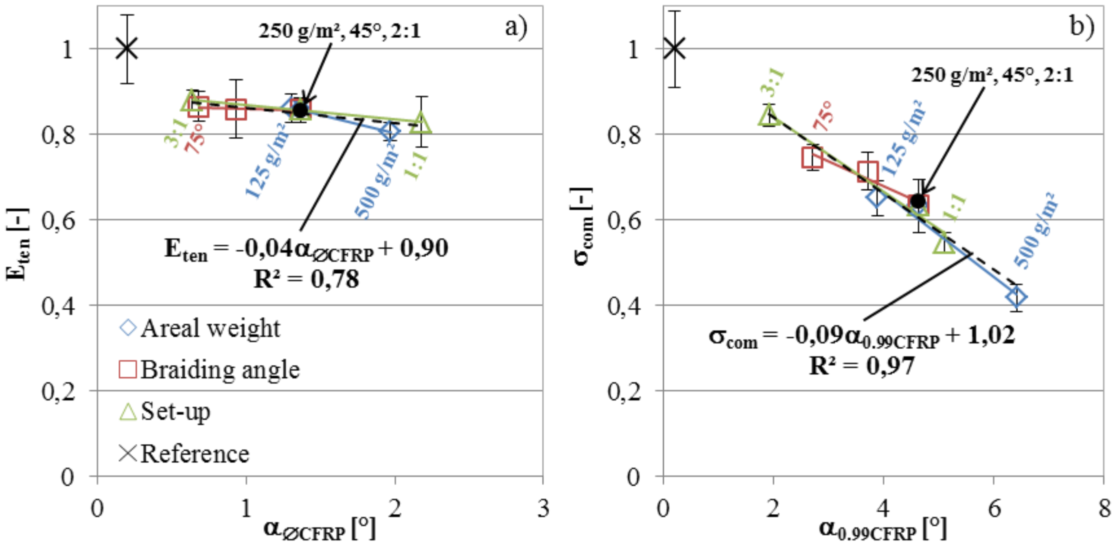

Figure 5: Relative tensile modulus (a) and compression strength (b) of a basic laminate with 250 g/m², 45° and 2:1 and laminates with varied single material parameters

5. Discussions & Synthesis

Chapter 4 discusses the influence of the single parameter changes, whereas linear regressions as formulation for E_{ten} and σ_{com} relative to $\alpha_{\varnothing CFRP}$ and $\alpha_{0.99CFRP}$ can be derived with a high regression coefficient (R^2). With the model in Figure 3, the undulation angles of the textile preform can be calculated. Figure 6 (a) shows the correlation of the calculated undulation angles of the textile and the in the laminate after infusion and curing process. The vacuum induced textile thickness shrink during

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processing reduces $\alpha_{\varnothing CFRP}$ to ca. 50% of α_{pc}. Locally inhomogeneities, in contrary, seem to get more significant, which explains the increased $\alpha_{0.99CFRP}$. With these correlations, the mechanical properties can be assessed relative to the process parameters. Figure 6 shows the relative E_{ten} and σ_{com} in dependency of the braiding angle and areal weight of UD-braids in 2:1 set-up. The green area marks the feasible process window in terms of minimum and maximum areal weight.

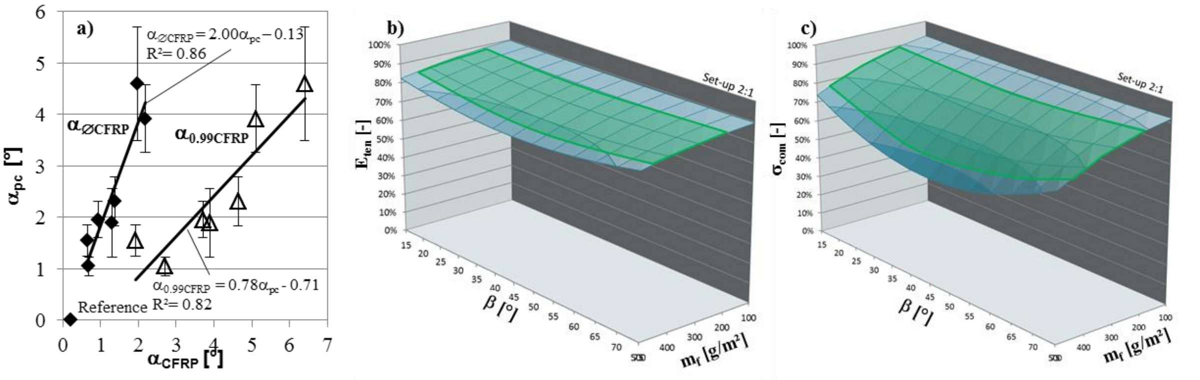

Figure 6: Relative tensile modulus and compression strength in dependency of the braiding angle and areal weight for UD-braids in 2:1 bobbin set-up

6. Summary & Conclusions

This study summarizes the experimental investigations on UD-braided laminates with the aim to characterize the process driven mechanical properties. Therefore, CFRP laminates were manufactured by means of braiding technology with different process parameters. The materials were characterized regarding the fiber undulation angles and mechanical performance. Depending on the process parameters, the RUC geometry and therefore the fiber dominated properties are influenced. Hereby, the property knockdown increases with higher areal weights, low bobbin set-up's and 90° fiber crossing angles (β = ±45°). For a generic formulation of the properties, the link between the calculated fiber architecture of the textile preform and the undulation angles of the processed laminate was evaluated with experimental trends. With this method, the process driven properties are determinable in a simplified approach, whereas the property profiles can be used as database to understand, improve or adapt the material. Furthermore, the development effort of new structures could be reduced, because the individual properties can be implemented in the simulation model in an early design stage.

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