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Influence of the glass non-crimp fabric intrinsic undulation on the stiffness of the composite ply: A micromechanical approach

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Abstract. Load carrying components of modern wind turbine blades are manufactured from composites, consisting of non-crimp fabrics infused with polymer resins. The effective stiffness of the resulting laminate is a combination of the properties of its building blocks i.e. fibers, and matrix as well as from the fabric texture imperfections e.g. fiber undulations. Moreover, ply inherent boundary conditions, e.g. the restriction of the Poisson deformation of the matrix imposed from the adjacent fibers, are determining the in-situ orthotropic performance. Towards modelling the in-plane stiffness of a unidirectional (UD) infused non-crimp fabric, a two-step modular procedure is proposed, accounting for the aforementioned parameters, based only on experimental data and analytical formulations. Initially, a micromechanical model is predicting the stiffness of the ideal UD ply i.e. disregarding fiber undulations. Subsequently, a plate model is generated based on the classical lamination theory, approximating the UD laminate as a multiaxial configuration of ideal UD sub-plies. Each sub-ply thickness and orientation is based on the fiber angle density distribution of dry fabrics and cured laminates. These are derived experimentally with an integrated optical camera system and Computer Tomography scans respectively. The theoretical laminate stiffness is correlating very well with standard and thick UD laminate quasi-static tests.

1. Introduction

Wind turbine blades are subjected in high cycle fatigue loads over their operational life span [1]. Especially in the edge-wise direction these loads are driven from the blade mass [2]. Therefore, the weight optimization is of substantial importance. One of the parameters that are determining the total mass and its distribution along the structure is the specific stiffness of the employed materials, particularly of the UD plies which are the main building blocks for load bearing sub-components. The non-crimp fabrics that are employed in the manufacturing of wind turbine rotor blades are consisted of single fibres, bund into rovings and stitched for handling stability reasons to the so called backing plies. The fibers oriented along the blade length-axis are majorly responsible for its stiffness properties, although off-axis fibers contribute eventually when multiaxial fabrics are employed e.g. biaxial or triaxial. In the case of the UD fabric, due to the stitching of the rovings in the fabric configuration, the backing ply and the laminate stacking sequence, fiber angle often deviates from the absolute 0° roll direction which in turns is resulting in stiffness deviation from the ideal ply.

The in-plane stiffness properties are thoroughly studied in the international literature and several models are proposed particularly for the unidirectional ply, ranging from the rule of mixtures [3] up to
micro-mechanical models considering different levels of the composite details [4-6]. Chamis and Sendeckyj [7] are summarizing the predicting theories for the thermoelastic properties of UD materials in a review paper. They are concluding that due to the fabrication process and the statistic variability of the materials, the mechanical properties can be most reliably described with semi-empirical equations. Schürmann [8] proposes a semi-empirical model, considering the matrix Poisson ratio constraint in between the fibers, assuming a serial sequence of them. The model is corrected with a fitting on known test results. Krimmer [9] is stating that the fitting processes can induce errors that potentially could affect the theoretical outcome. Although he proposes similar physical assumptions to the aforementioned model, he alleviates though all fitting parameters by considering the roving geometry configuration in the UD ply, particularly for square or hexagonal pack schemes. This results in an improved prediction of the matrix dominated properties in comparison to all state of the art models. However, in order to incorporate the effect of the in-situ fiber undulations he introduces a knock-down factor for the stiffness of the single-fiber. Similar knock-down factor approaches are adopted in other analytical works [10-11].

In the present research it is attempted to predict the in-plane mechanical properties of the UD E-glass/epoxy laminate with an analytical methodology, implementing for the first time, to the author’s knowledge, a modelling procedure with no fitting or knock-down input parameters. The model is considering the matrix in-situ stiffening due to the Poisson deformation restriction, resulting from the adjacent fibers and the fiber in-plane angle distribution of the non-crimp fabric. Therefore, a modular procedure is unfolded in two succeeding steps based on well-established formulations [9] and the classical lamination theory [12]. First, the stiffness of the ideal UD ply i.e. with no fiber misalignment to the laminate 0°-axis, is estimated with a micromechanical model [9]. For this step, the input parameters are the fiber and matrix stiffness’s as well as the corresponding fiber volume fraction. The implementation of the intrinsic undulation of the non-crimp fabric is performed in a subsequent step. Therefore, the UD laminate is split into a multiaxial configuration, composed of ideal UD sub-plies that are stacked in variable orientations. The corresponding sub-plies thickness and angles are based on experimental data derived from the fibre in-plane angle distribution about the 0° laminate-axis. The angle deviations of dry UD fabrics and infused laminates, 4- and a 22-layer configurations, are recorded and analysed both with an integrated optical camera system and with micro Computer Tomography (microCT) scans. The optical camera is delivering 2-Dimensional (2D) the in-plane fiber orientation distribution while the microCT 3-Dimensional (3D). In order to enhance the comparison of the fiber-angle probability density derived from the two systems, the microCT results are transformed also in a 2D plane pattern. The theoretical effective mechanical properties of the UD plate model are validated against standard coupon (DIN EN ISO 527-5 [13]) and thick laminate quasi static tests with very good agreement.

The examined fabric consists of a 1134 gr/m² glass fibers in roll 0° direction, 36 gr/m² backing glass fibers and 12 gr/m² stitches (PES). The employed E-glass fibers are the SE2020 from 3B-fibreglass [14] and the infusion epoxy-resin is the RIMH035c/037 from Hexion GmbH [15]. All laminates were infused at 35 °C, cured at 40 °C for 10 hours and post-cured at 80 °C for 7 hours.

2. Methods for prediction of the composite stiffness of the ideal UD ply
A micromechanical approach is implemented for the prediction of the stiffness of the ideal E-glass/epoxy UD laminate manufactured with non-crimp fabrics and vacuum assisted resin infusion molding. For that ideal ply there is no fiber angle deviation from the 0° roll-axis. The model considers the ply in-situ fiber volume fraction, the backing fibers and the stitching material [9].

In the ply level, the orthotopic stiffness parameters and the corresponding indexes in the used mathematical formulations are described in Figure 1.
2.1. Analytical micromechanical model

In the current research, a micromechanical model is employed, as introduced by Krimmer [9], towards predicting the in-plane stiffness properties of the ideal UD, i.e. for the ply without fiber undulations. The laminate stiffness along the fibers, $E_{||}$, is estimated based on the rule of mixtures (RoM), by implementing the ply basic building block properties, the stiffness of the matrix $E_M$ and the fibres $E_F||$, see eq. (1),

$$E_{||} = (1 - FVF)E_M + FVF E_F||$$  

where FVF stands for the laminate fiber volume fraction. Diverging from the classical formulation of the RoM, the matrix stiffness $E_M$, is substituted in eq. (1) from its in-situ property parallel to the fibers, $E_M||$, see eq. (2). The latest is derived when considering the matrix Poisson ratio restriction due to the adjacent fibers, as described in [9],

$$E_{M||} = \frac{E_{Mh}(1-v_{M||}')+E_{MM||}'}{E_{Mh}(1-v_{M||}')+v_{M||}'+2v_{M||}'(1-E_{Mh})}$$  

where $v_{M||}'$, eq. (3) stands for the in-situ Poisson ratio of the matrix when pulling parallel to the fibers.

$$v_{M||}' = \left(1 - \frac{v_{FL||}E_M}{v_{MFL}}\right) v_M$$  

The model input parameters such as the matrix stiffness $E_M$ and the Poisson ratio $v_M$ are obtained through standard tensile tests [16]. $E_{Lh}$ stands for the composite stiffness in the direction transverse to the fibers. It is derived analytically in [9] as a function of the rovings pattern in the laminate. The assumption for the fiber-bundle packing geometry in the infused laminate configuration has a direct impact on the in-situ performance of the matrix dominated properties. Therefore, a hexagonal pack scheme is considered and thus the corresponding UD composite ply properties $E_{Lh}$, $G_{L||h}$, (stiffness transverse to the fibers and in-plane shear stiffness), are described in eq. (4) and (5).

$$E_{Lh} = \frac{2E_M}{\sqrt{3}} \left[\frac{\sqrt{3}}{2} - \frac{2\sqrt{3} FVF}{\pi} - \frac{\pi}{2 + \arctan \left(\frac{\sqrt{2\pi FVF}}{\pi \left(1 - \frac{E_M}{E_F}\right)^2} \right)} \right]$$  

$$G_{L||h} = \left[\frac{\pi}{2 + \arctan \left(\frac{\sqrt{2\pi FVF}}{\pi \left(1 - \frac{E_M}{E_F}\right)^2} \right)} \right]$$
\[ G_{\perp h} = \frac{2G_M}{\sqrt{3}} \left( \sqrt{\frac{3}{2}} - \frac{2\sqrt{3} FV_F}{\pi} - \frac{\pi}{2} \arctan \left( \frac{2\sqrt{3} FV_F}{\pi} \left( 1 - \frac{G_M}{G_{F \perp l}} \right) \right) \right) + \frac{\pi}{2} \arctan \left( \frac{\sqrt{3} FV_F}{\pi} \left( 1 - \frac{G_M}{G_{F \perp l}} \right) \right) \]

Matrix and fibers are assumed to be isotropic materials and therefore their shear stiffness is calculated accordingly, see eq. (6) and (7).

\[ G_M = \frac{E_M}{2(1 + \nu_M)} \]  \hspace{1cm} (6)

\[ G_{F \perp l} = \frac{E_F}{2(1 + \nu_F)} \]  \hspace{1cm} (7)

The in-situ properties of the matrix \( E_{M \perp l} \), \( \nu_{M \perp l} \) i.e. the stiffness transverse to the fibers and Poisson ratio of the matrix when pulling transverse to the fibers are derived under the same assumptions as described above and are listed for completeness purposes in Appendix A, see eq. (A.1) and (A.3).

2.2. Elastic properties of the multilayer laminate

Based on the fiber angle distribution measurements of the dry fabrics and the cured laminates, the UD configurations can be approximated as the summation of UD sub-plies with a range of fiber orientation. The measurement analysis is presented below in section 4. Due to the symmetric fiber distribution about laminate 0\(^\circ\) direction, the multiaxial laminate is considered to be balanced and symmetric. Therefore, any stiffness coupling terms are eliminated through the employed classical lamination plate theory analysis. The axial stiffness matrix \( [A_{ij}]_e \) is calculated for each ply with the respective fiber-angle orientation (\( \phi \)). The summation of the corresponding matrix terms weighted with the probability density of the angle distribution is resulting to the laminate axial stiffness matrix terms, eq. (8).

\[ A_{ij}^{Lam.} = \sum_{k=\phi_{min}}^{\phi_{max}} A_{ij}^k \cdot PD_k \]  \hspace{1cm} (8)

Given the axial stiffness matrix of the laminate, the effective elastic properties are derived as described in [12]. For completeness, the implemented formulas are listed below, see eq. (9-12).

\[ E_x = \frac{A_{xx}A_{yy} - A_{xy}^2}{hA_{yy}} \]  \hspace{1cm} (9)

\[ E_y = \frac{A_{xx}A_{yy} - A_{xy}^2}{hA_{xx}} \]  \hspace{1cm} (10)
\[ v_{xy} = \frac{A_{xy}}{A_{yy}} \quad (11) \]

\[ G_{xy} = \frac{A_{ss}}{h} \quad (12) \]

3. **Input parameters for the modelling procedure**

The required fiber input material properties are taken from the literature while the matrix mechanical properties are experimentally obtained in the context of this exercise. For the determination of the fibre angle distribution the materials, dry fabrics and cured laminates are subjected to optical and microCT scans.

3.1. **Constituent materials mechanical properties**

The glass-fiber stiffness \([14]\) and Poisson ratio \((\nu_{F,\|})\) \([9]\) are taken from the international literature and are listed in Table 1. The glass material is expected to perform isotropic and therefore the stiffness is considered to be equal along and transverse to the fibers, \(E_{F,\|} = E_{F,\perp}\). All properties are assumed to be the same both for the UD and the backing fibers.

**Table 1.** Fiber mechanical properties

|                        | Young’s mod. [GPa] | Poisson [-] |
|------------------------|-------------------|-------------|
| Average Value          | 81.0              | 0.22        |
| Standard deviation     | -                 | -           |

Standard DIN EN ISO 527-2 \([16]\) quasi-static tests are conducted for the derivation of the Young’s modulus and Poisson ratio of the cured matrix. The tests are performed in a 25kN calibrated universal machine of class 0.5, both for load cell and displacement, according to international standards \([17]\), \([18]\). The specimens are equipped with extra soft strain gauges in order to avoid local stiffness effects and thus influencing the recorded data. The measured mean values and the respective standard deviations are listed in Table 2. The corresponding glass transition and potential \((T_{g}, T_{g0})\) temperatures \([19]\) are included for completeness. Detailed mechanical properties of the test specimens are listed in Appendix B.

**Table 2.** Matrix mechanical properties

|                        | Young’s mod. [GPa] | Poisson [-] | \(T_g\) [°C] | \(T_{g0}\) [°C] |
|------------------------|-------------------|-------------|--------------|-----------------|
| Average Value          | 3.155             | 0.366       | 77.56        | 83.9            |
| Standard deviation     | 0.05              | 0.02        | 0.85         | 1.20            |

3.2. **Fibre distribution of dry non-crimp fabrics and cured laminates**

The fiber angle deviation \((\phi)\) is mapped for dry UD fabrics and UD infused laminates after curing. Typical fabric in-plane non-conformities i.e. undulations are shown in Figure 2. The measurements are conducted in 4- and 22-layer stacking sequences.
Figure 2. Typical in-plane undulation (φ) of the dry UD 1182 gr/m² non-crimp fabric.

For the quantification of the fibre angle distribution of the dry non-crimp fabrics, a camera (HP-C-V3D Apodius Vision System) integrated system is implemented, as shown in Figure 3. It consists of a mobile arm (Hexagon Absolute ARM 8335), a camera head which is installed at the end of the arm and a software (Apodius Explorer 3D) for digital analysis of the acquired photos. Before the infusion and during the preparation of UD stacking sequences, with 4- and 22- layers, each of them is scanned from the top view with an optical camera. Therefore, a 10x10cm measurement field is selected, located in the middle area of each ply. It is assumed that the defined area is representative for the fabric. A red tape line is attached on the table-form as a reference coordinate axis (x), assisting on the alignment of the dry UD fabric fibres and at the same time for the positioning of the Apodius System, see Figure 4. In order to assure the same position of the scanning head for all photos, the supporting arm is fixed on a station next to the infusion table. Because of the symmetric lay-up and the laying process, half of the plies are shot from the UD-fibre side and half from the backing-ply side.

Figure 3. Apodius vision System 3D

Figure 4. Coordinate system for the scans with the optical camera

The cured laminate is scanned using a Zeiss Xradia 520 microCT scanner with a 2000x2000 detector. The 4-layer and 22-layer laminate is scanned by means of a 20 mm and 13 mm FoV resulting in a voxel size on 9.8 microns and 6.4 microns, respectively. Both scans are based on a 8s exposer time using 6801 projections resulting in 20 hours scan time. The resulting 16 GB reconstructed scanning file was
analysed via a structure tensor method as described in [20]. The analysis step took around 1/2 hour for each scan.

The distribution of the fiber angle in the dry plies is averaged for the 4-layer and the 22-layer laminates, respectively. A bell-shaped fitting of the angle distribution probability $f(x)$, see eq. (5), is performed on the experimental data.

$$f(x) = a e^{-\frac{(x-b)^2}{2c^2}}$$

where $x$ is standing for the corresponding fiber angle and $a$, $b$ and $c$ bell-shape fitting parameters. All of them are listed in Table 3.

| Table 3. Fitting parameters of the Bell-shaped angle distributions |
|----------------------------|------------------|------------------|
|                           | optical camera   | microCT          |
|----------------------------|------------------|------------------|
| 4-layer                    | 5.3              | 13               |
| 22-layer                   | 5.4              | 5.3              |
|                            | 0.7              | 0.1              |
|                            | 8                | 3.1              |
|                            | -0.25            | -0.17            |
|                            | 7.8              | 1.8              |

The experimental in-plane angle distribution for the 4-layer and the 22-layer laminates before and after infusion with the corresponding bell-shaped probability densities are shown in Figure 5 and Figure 6.

**Figure 5.** Bell-shaped angle distribution of the 4-layer laminate before and after infusion

**Figure 6.** Bell-shaped angle distribution of the 22-layer laminate before and after infusion

### 3.3. Quasi-static tests for the derivation of UD composite mechanical properties

For the characterization of the principal Young’s Modulus $E_1$ and $E_2$, the Poisson ratio $\nu_{12}$ [13] and the shear stiffness $G_{12}$ [21] of the UD ply, three sets of specimens are tested with 4-layer symmetric layup. The average values and the corresponding standard deviations of the tested coupons are listed in Table 4. For completeness purposes the fiber volume fraction (FVF) and the glass transition temperatures ($T_g$) [19] are summarized too. The FVF values implemented in the model are derived according to [9] taking under consideration the stitches, the fiber sizing and the backing ply volumes. In brackets are listed the FVF’s derived according to the ISO standard [22]. For the derivation of the shear modulus, the shear strain range between 500-2500 µm/m is selected. This deviation from the range
1000-5000 µm/m proposed in the DIN EN ISO 14129:1998-02 standard [21] is chosen in order to account only for the linear deformation in the modulus calculation and eliminate non-linear effects which are observed over the 2500 µm/m limit.

| Table 4. UD ply mechanical properties |
|--------------------------------------|
| $E_1$ [GPa] | $E_2$ [GPa] | $v_{12}$ [-] | $G_{12}$ [GPa] | FVF [%] | $T_g$ [°C] | $T_{g\infty}$ [°C] |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Average:        | 42.35           | 12.61           | 0.301           | 4.59            | 54*             | 82.25           | 90.24           |
| St. dev.:       | 1.19            | 0.41            | 0.03            | 0.150           | -               | 1.70            | 1.41            |

* for the $E_2$ estimation, the theoretical FVF is 55%

3.4. Large scale coupon quasi-static test

Three large scale specimens are tested under tensile loading till rupture. To record the laminate deformation, four strain gauges are applied on each. Three linear with a measuring grid-length of 10mm are applied on one side, in the load direction at the middle of the coupon length i.e. at L=750 mm. They are located in 25 mm, 50 mm and 75 mm of the coupon width. The fourth is a cross-pattern strain gauge with a 0°- 90° orientation and 8mm measuring grid length applied on the other side of the specimen also at L=750 mm and centred at W=50 mm. The specimens are clamped in a 2,5 MN universal servo hydraulic coupon machine with 224 bar clamping pressure. The testing machine is calibrated with a load cell and displacement class of 0.5 according to [17], [18]. The coupon vertical angle to the machine load axis is measured with a calibrated digital angle recording device, with alignment tolerance of 0.1° (89.9° to 90.1°). The test is displacement controlled with a cross-head speed of 1mm/min. The specimen geometry and the experimental setup are illustrated in Figure 7 and Figure 8 respectively.

![Figure 7. Large scale coupon geometry](image1)

The average Young’s Modulus, the Poisson ratio, the glass transition and the potential glass transition temperatures are listed in Table 5.
4. Analysis results

4.1. Stiffness of the ideal UD ply

The predictions of analytical micromechanical model for the stiffness of the ideal UD ply (without undulations) by implementing the mean values and the standard deviation of the matrix properties are listed in Table 6.

Table 5. UD thick laminate mechanical properties

|       | $E_1$ [GPa] | $v_{12}$ [-] | FVF [%] | Tg [°C] | Tg∞ [°C] |
|-------|-------------|--------------|---------|---------|---------|
| Average: | 46.09       | 0.291        | 58      | 77.87   | 89.27   |
| St. dev.: | 1.35        | 0.006        | -       | 3.00    | 1.50    |

Table 6. Theoretical mechanical properties of the ideal UD ply

|       | $E_1$ [GPa] | $E_2$ [GPa] | $v_{12}$ [-] | $G_{12}$ [GPa] |
|-------|-------------|-------------|--------------|----------------|
| Prediction: | 43.48       | 12.01       | 0.26         | 3.87           |
| Standard Dev. | 0.11        | 0.50        | 0.01         | 0.14           |

4.2. Stiffness prediction of the UD laminate when incorporating the in-plane fiber bundle undulations

The proposed model predictions of the effective mechanical properties of the 4- and the 22-layer UD laminates are summarized below. Therefore, the laminate theory, see section 2.2, the stiffness of the ideal UD ply as presented in the previous section and the fiber-angle distribution as presented in section 3.2 both in the dry plies and the cured specimens, are combined. In Table 7 are listed the model predictions after employing the angle distribution measured on the dry fabrics with the optical camera system. In Table 8 are listed the model predictions after employing the angle distribution recorded with microCT on the cured specimens. Theoretical results are compared to the corresponding experimental.

Table 7. Effective laminate stiffness and difference from experim. (dry fabric angles)

|       | $E_1$ [GPa] | $E_2$ [GPa] | $v_{12}$ [-] | $G_{12}$ [GPa] |
|-------|-------------|-------------|--------------|----------------|
| 4-layer | 42.19       | -           | 11.72        | -              | 4.37    |
| 22-layer | -          | 47.03       | -            | 13.44          | -       | 5.11   |
| Standard Dev. | 0.12        | 0.13        | 0.49         | 0.57           | 0.005   | 0.14   | 0.17   |
| Differ. from exp. [%] | -0.39       | -           | -7.05        | -              | 0.70    | 4.68   |

|       | $E_1$ [GPa] | $E_2$ [GPa] | $v_{12}$ [-] | $G_{12}$ [GPa] |
|-------|-------------|-------------|--------------|----------------|
| 4-layer | -           | 2.35        | -            | 3.52           | -       | -      |
| 22-layer | -          | -           | -            | -              | -       | -      |
|                | $E_1$ [GPa] | $E_2$ [GPa] | $\nu_{12}$ [-] | $G_{12}$ [GPa] |
|----------------|-------------|-------------|----------------|----------------|
| 4-layer        | 43.15       | 11.77       | 0.272          | 4.00           |
| 22-layer       | -           | 46.31       | -              | 4.34           |
| Stand. Dev.    | 0.11        | 0.11        | 0.49           | 0.55           |
| Diff. from exp.| [%]         | [%]         | [%]            | [%]            |
| 4-layer        | 1.89        | -6.63       | -9.58          | -              |
| 22-layer       | -           | 0.49        | -              | 10.33          |

### 5. Discussion

To the authors' knowledge, this is the first attempt to benchmark the optical camera system and the angle density distribution with a microCT technique and vice versa. The comparison is highlighting a difference in the fiber angle probability between the dry fabrics and the cured laminate. This might be originating from the scale measurement level that the two techniques are zooming, assuming that in a macroscopic level higher degrees of angle deviations might be measurable. However, other effects, as fiber alignment after the vacuum application or even straightening due to the infusion and curing process cannot be excluded. Further microCT measurements of the dry fabric are planned in order to investigate the aforementioned issue.

In both cases the proposed model could predict the laminate in-plane stiffness along the fibers direction with very good precision. Nevertheless, the comparison to the matrix dominated properties is moderate. The model variant implementing the cured laminate angles distribution is deviating more especially for the thick laminate. This could be in line with the remark made above about the capacity of the technique to capture higher angle degrees.

When employing the higher end properties of the matrix material (standard deviation), the model predictions are improved approaching the test values in some cases with less than 4% difference for all mechanical properties. It has to be stated though the curing degree of the implemented matrix properties that were derived through static tests, is not totally the same with the composite test specimens, especially with the thick laminates. A curing kinetics model and a correlation model of stiffness with the curing degree could enhance future comparisons.

### 6. Conclusions

A theoretical model for the prediction of the in-situ stiffness of non-crimp laminates is successfully validated against quasi-static tests of different geometry scales and fiber volume fractions. The model is based exclusively in analytical formulations and well established mechanics without any knock-down or fitting parameters. As input parameters are required only the basic building block mechanical properties and the intrinsic fiber-angle probability distribution. Two fiber-angle distribution techniques are compared to each other, resulting in relative differences to each other. Further investigations have to be performed e.g. microCT scans on dry fabrics in order to conclude on the root causes.

Given these, the effective mechanical properties of any laminate with various fiber volume fraction could be predicted. Both sets of angle distributions results in very good along the laminate 0° direction i.e. less than 2.5%, however the model shows a higher deviation from the experimental results in the matrix dominated properties. These have to be investigated further.
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[16] DIN EN ISO, 527-2:2012-06, Plastics - Determination of tensile properties - Part 2: Test conditions for moulding and extrusion plastics
Appendix A

The analytical formulation of the in-situ matrix stiffness transverse to the UD fibers is described through eq. (A.1). For the formula derivation, a hexagonal-pack fiber geometry is assumed superimposed with the restrain of the matrix Poisson deformation due to the adjacent fibers.

\[ E'_{M\perp} = \frac{\bar{E}_{pl}|A \cdot FVF + E_{\perp}(1 - FVF)}{\bar{E}_{pl} E_{M} \left( \frac{E_{\perp}}{E_{M}} \left( 1 - 3v_{M\perp}^2 - 2v_{M\perp}^3 \right) + 2\left( 3v_{M\perp}^2 + v_{M\perp}^3 \right) \right) FVF + A(1 - FVF)} \]  
\[ A = \frac{E_{\perp}}{E_{M}} \left( 1 - v_{M\perp}^2 \right) + v_{M\perp}^2 \]  

(A.2)

Implementing the same assumptions as for the matrix transverse stiffness, the in-situ Poisson ratio of the matrix when pulling transverse to the fibers is described through eq. (A.3)

\[ v_{M\perp}' = \left( 1 - \frac{A \cdot FVF + E_{\perp}(1 - FVF)}{\bar{E}_{pl}| \frac{E_{\perp}}{E_{M}} \left( \frac{E_{\perp}}{E_{M}} \left( 1 - 3v_{M\perp}^2 - 2v_{M\perp}^3 \right) + 2\left( 3v_{M\perp}^2 + v_{M\perp}^3 \right) \right) FVF + A(1 - FVF)} \right) \]  

(A.3)
Appendix B

Table 9. Matrix DIN EN ISO 527-2 test results

| Specimen ID      | Young’s mod. | Poisson’s ratio |
|------------------|--------------|-----------------|
| 114774_019_09_007 | 3.13         | 0.36            |
| 114774_019_09_008 | 3.09         | 0.35            |
| 114774_019_09_009 | 3.19         | 0.37            |
| 114774_019_09_011 | 3.21         | 0.39            |
| 114774_019_09_012 | 3.15         | 0.37            |

Table 10. UD ply stiffness test results

| Specimen ID | Young’s mod. E₁ [GPa] | Poisson’s ratio ν₁₂ | Specimen ID | Young’s mod. E₂ [GPa] | Specimen ID | Shear mod. G₁₂ [GPa] |
|-------------|------------------------|---------------------|-------------|------------------------|-------------|----------------------|
| *_006_01_ 001 | 43.43                  | 0.29                | *_007_02_ 001 | 12.24                  | **_010_41_ 001 | 4.3                  |
| *_006_01_ 002 | 44.49                  | 0.32                | *_007_02_ 002 | 12.38                  | **_010_41_ 002 | 4.6                  |
| *_006_01_ 003 | 42.03                  | 0.35                | *_007_02_ 003 | 12.32                  | **_020_03_ 001 | 4.7                  |
| *_006_01_ 004 | 41.03                  | 0.30                | *_007_02_ 004 | 12.63                  | **_020_03_ 002 | 4.5                  |
| *_006_01_ 005 | 42.12                  | 0.30                | *_007_02_ 005 | 13.36                  | **_020_03_ 003 | 4.6                  |
| *_006_01_ 006 | 41.49                  | -                   | *_007_02_ 006 | 12.71                  | **_020_03_ 004 | 4.6                  |
| *_006_01_ 007 | 41.89                  | 0.25                | -           | -                      | -           | -                   |

* 114774, **111848