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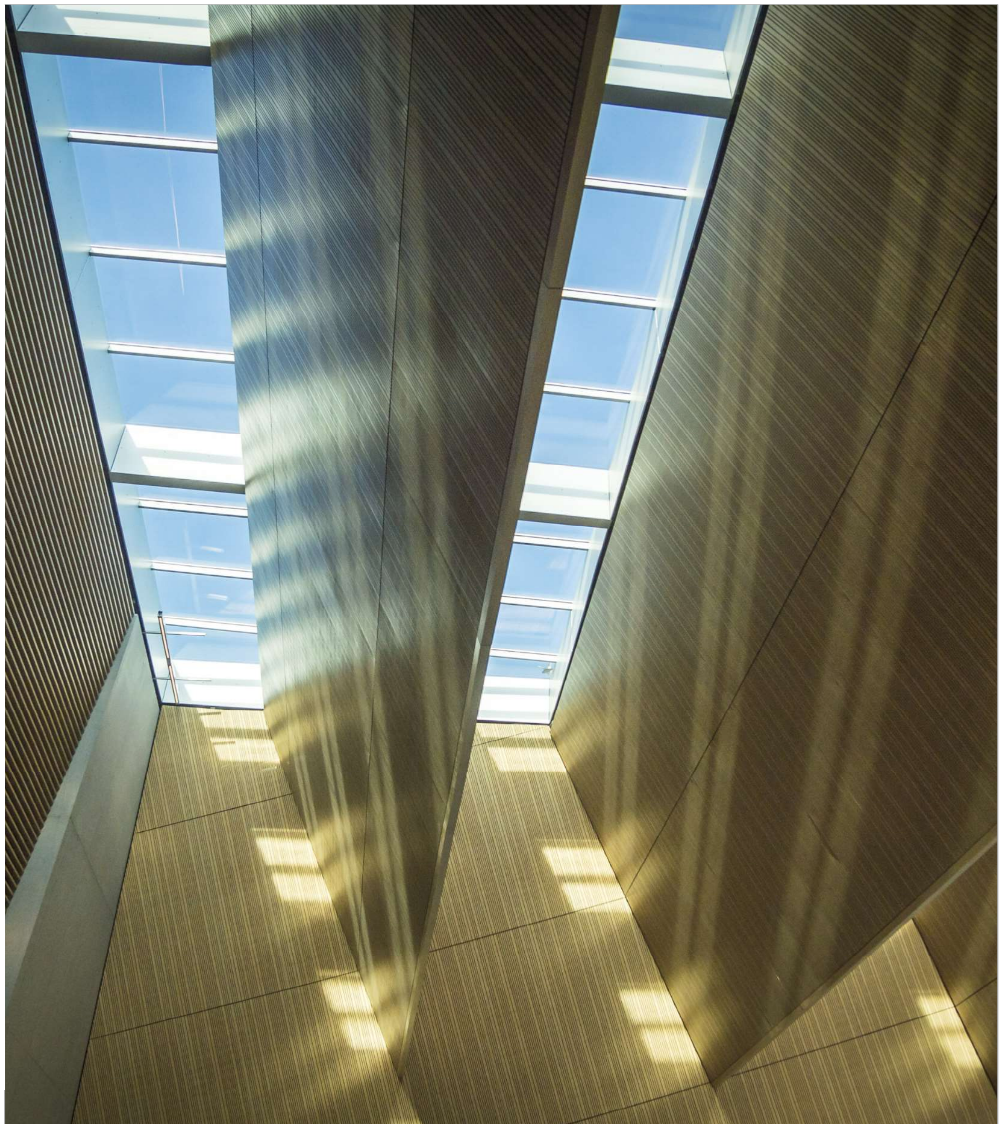

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Tailoring mechanical properties of randomly oriented tape composites: An experimental study

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Abstract: Discontinuous tape composites (DTC) have properties such as notch insensitivity, short processing times, and large shaping freedom. However, the mechanical behaviour of randomly oriented tape (ROT) composites is less predictable compared to continuous fibre composites due to the mesoscopic heterogeneity of the material. Controlling the tape alignment is a compelling approach for tailoring the mechanical properties of ROT composites, enabling better control and prediction of the material properties such as tensile strength and stiffness. However, for a successful implementation of the alignment method in industry, a fast tape alignment method is needed. A quantitative assessment has been made between different alignment methods. The presented alignment method has been used to manufacture aligned DTC samples for the characterisation of the material. This study showed an average tensile stiffness of randomly orientated, 0˚ centred, and ±45˚ centred tapes of 32.5, 79.5, and 25.3 GPa respectively.

Keywords: Randomly Orientated Tapes; Discontinuous Fibre Composites; Tow alignment; Computer vision; Mechanical Properties

1. Introduction

Discontinuous tape thermoplastic composites can contribute to waste reduction, low-cost production in the aerospace and automotive industries, and allow for large shaping freedom. However, mechanical performance of DTC show high variability due to their discontinuous structures [1]. To apply this material group with higher confidence into structures, more knowledge has to be gained on how to predict and improve their material properties. By aligning the properties of the tapes with the direction of loading, the mechanical response can be influenced [2]. This can be done by orienting the fibres inside the material in the loading direction to make the material stronger and stiffer.

This study focuses on the alignment and the effect of alignment of DTC. Tapes have been aligned by means of a mechanical alignment method as suggested by Gan et al [3]. The selected tape alignment method makes use of vertical slits to align and deposit tapes into a mould. This method is a fast and dry method which is suitable for large-scale manufacturing processes. For this study, tapes with dimensions 22.5 x 7.5 x 0.2 mm made out of carbon fibre with a thermoplastic matrix and a fibre volume fraction of 55% have been used. In this paper, a tape alignment technique is described and characterized by means of measuring the orientation distribution of tapes on a surface. These measurements have been obtained using the OpenCV library in Python [4].

For the determination of the effect of alignment on the mechanical response, three type of samples have been manufactured with a random, 0° centred, and ±45° centred tape orientation distribution. For the latter two, the alignment technique has been applied to create a single

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aligned layer and a $[+45°,-45°]_s$ quasi-layup. The test samples have been tested in tensile loading for the determination of the tensile and shear response of the material.

The recorded tensile stiffness where found to be 32.5, 79.7, and 25.3 GPa respectively for the randomly orientated, 0˚ centred and ±45˚ centred tape distributions respectively. The obtained results give insight in the effect of tape alignment in discontinuous fibre composites on the tensile modulus. The effect of manufacturing on the overall tape orientation distribution has become more quantifiable than research has shown until now.

2. Experimental Procedure

Discontinuous tapes were obtained by cutting unidirectional continuous tape composites with a fibre volume ratio of 55%. The dimensions of tapes are 22.5 x 7.5 x 0.2 mm.

2.1. Tape Alignment Method

The used alignment method has been proposed by Gan et al. [3]. Although this method was used for thermoplastic composite tapes, the design has been altered to be suitable for thermoplastic tapes with the described dimensions. This alignment method has been selected from a group of potentially successful concepts which have been graded based on their process time, development time and level of alignment that each of them reached. With OpenCV as image recognition software, a large number of measurements have been executed for the determination of the tape orientation distribution.

The final method has been selected due to its fast and dry deposition of tapes which makes it suitable for large scale manufacturing. The method uses an alignment tool which exist out of multiple parallel walls. These walls have varying height and chamfers at the edges to ensure that the tapes do not clog the tool and are evenly spread out into the mould. This resulted into the alignment tools as shown in Figure 1a. This design has been used for the development of alignment tools for the +45˚ and -45˚ direction which can be seen in Figure 1b/c. All three different tools have been designed for manufacturing with FDM.

(a) (b) (c)

Figure 1, Alignment tools for manufacturing, a) 0° orientation, b) +45° orientation, c) -45° orientation.

For the manufacturing of aligned DTC plates, an alignment tool is placed in a mould cavity after which tapes are deposited. By shaking the tool, the tapes align between the walls of the tool and are left inside the mould when the tool is removed (as can be seen in Figure 2). The spacing between the walls has been set at 1 mm more than the width of the tapes. This allows for good alignment of tapes in combination with easy deposition and avoids clogging of the tool.

(a) (b) (c)

Figure 2, Deposited tapes inside mould, a) Random tape distribution, b) 0° centred tape distribution, c) ±45° centred tape distribution.

2.2. Alignment Characterisation Using Digital Image Recognition

The selection and characterization of the alignment method has partially been executed by means of position (1,1) of the orientation tensor [5-6]. For this, aligned tapes have been deposited onto a moving surface. Of these tapes, images have been captured which allows for the determination of their orientation by means of the OpenCV library in Python. During this characterization, multiple test runs have been executed with the alignment tool which resulted in the tape orientation distribution as shown in Figure 3 and an in-plane orientation tensor as shown in equation 1 [5-6].

$$a_{ij} = \frac{1}{N_t}\sum_{k=1}^{N_t} p_i^k p_j^k \quad [1]$$

Hereby N_t is the number of measured tapes and p is the component of the unitvector of the measured tape projected onto one of the principle axis. This study used the first position of the orientation tensor, a_{11} which is zero when all tapes are perpendicular to the loading direction and one when they are all aligned in the loading direction. With a random orientation, this value is assumed to be 0.5. The orientation vector below shows the values of the selected alignment method. In here it can clearly be seen that the use of the alignment tool resulted in an overall alignment of the deposited tapes into the 0˚ direction.

$$a_{in-plane} = \begin{bmatrix} 0.87 & 0.00 \\ 0.00 & 0.13 \end{bmatrix}$$

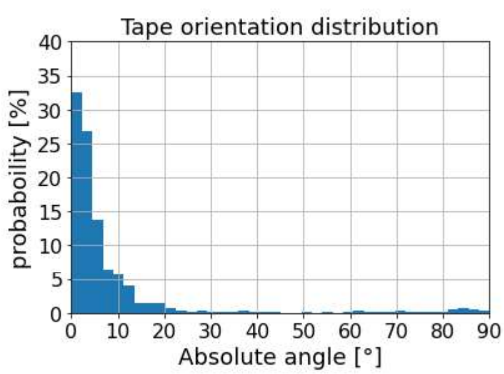


Figure 3,Measurements orientation distribution of alignment tool

2.3. Sample Manufacturing

Three different types of DTC samples have been manufactured; six with a random layup, six with 0° centred alignment, and four with ±45° centred alignment. For each sample type, the corresponding alignment tool has been used as described in section 2.1. The mould has been heated up to 385°C at 45 bar followed by a 20 minute dwell and cool-down to room temperature. The manufactured plates are cut with a Proth diamond blade cutting machine according to Figure 4. These dimensions are based on previous studies [4,7,8], and the available mould size. Tabs have been glued onto the 30 mm of each end for better load transfer resulting in a gauge length of 80 mm.

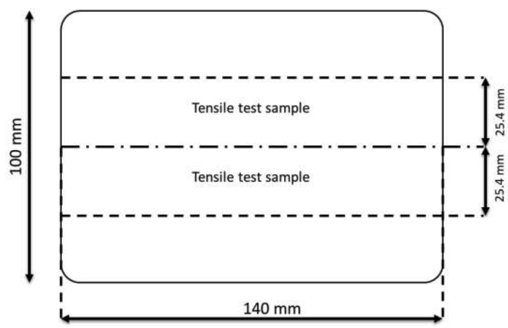


Figure 4, Cutting pattern for sample manufacturing.

3. Test Methodology and Results

3.1. Tensile response

The tensile test setup has been shown in Figure 5. The test samples have been hydraulically clamped in a *250KN Zwick tensile test machine* and elongated with displacement control with a displacement rate of 1 $mm\ s^{-1}$. Two 5 MP cameras have been used with the ViC3D DIC system of Correlated Solutions Inc. With this, the force readings of the load cell are linked to the measurements of the DIC system for the determination of the average tensile modulus in the range between 1000 micro-strain [9] to half the failure load [10].

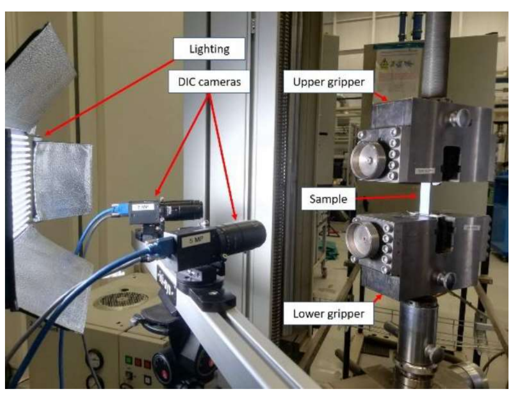
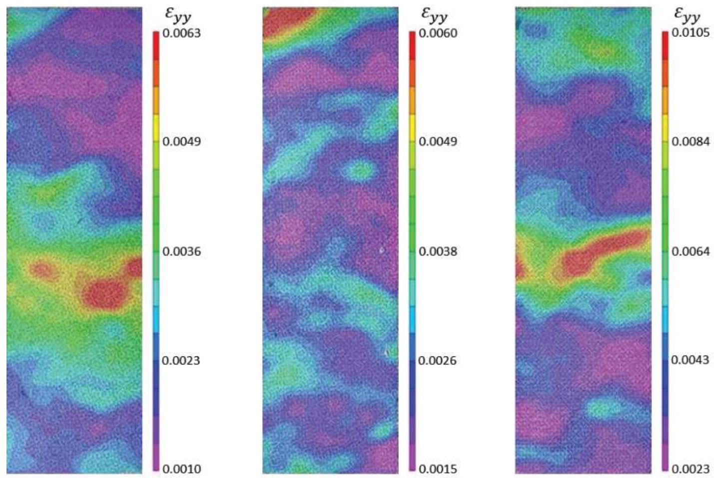


Figure 5, Tensile test setup.

During the study, the effect of tape orientation on strain distribution was investigated. For this, only tensile tests have been performed, and thus, only the strains in loading direction is presented. In Figure 6 and 7, the strain characteristics are shown which shows similar variety in the strain field found in literature [11]. Based on the strain patterns in Figure 6, significant varieties in distributions could not be identified. When comparing the strains of the three types of samples in Figure 7, it is found that the randomly orientated tapes have the highest spread in strains. This stochastic distribution is most likely caused by the large variety in local stiffness due to the deposition process. The samples with tapes aligned in the loading direction show the smallest spread.



(a) (b) (c)

Figure 6, Examples of strain distributions, a) Random tape distribution, b) 0° centred tape distribution, c) ±45° centred tape distribution.

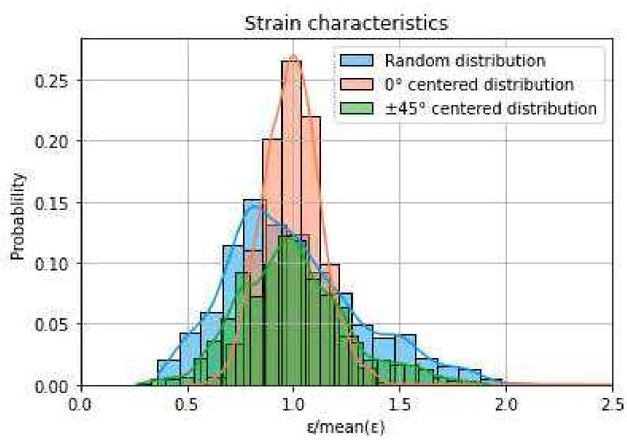
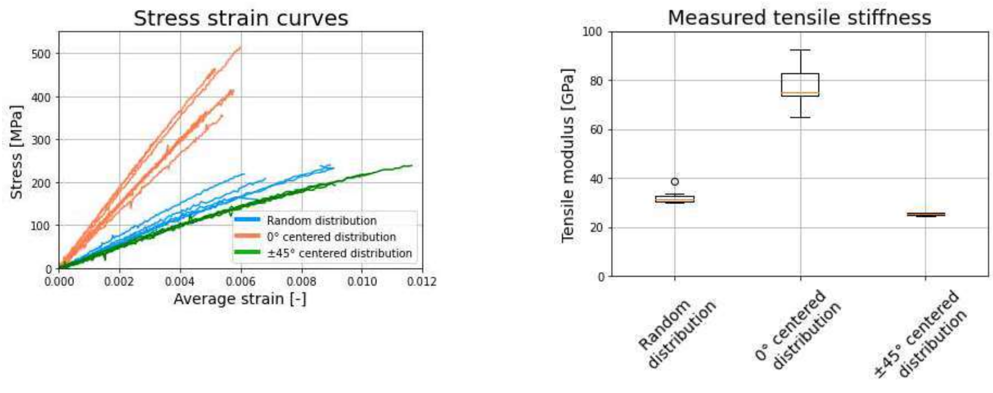


Figure 7, Longitudinal Lagrange strain characteristics of tape orientation distributions at half the failure load. Strains are normalized to the mean value of each sample

By combining the DIC strain data and the tensile force measurements, the stress strain curves of the samples have been obtained as shown in Figure 8. Within the different tape orientation distributions, differences are observed with regards to the stiffness, ultimate tensile stress, and strain at failure. These can be caused by the stochastic nature of the material but is most likely also caused by the manufacturing process. This is assumed because the tensile response of samples from the same plates are relatively similar.



(a) (b)

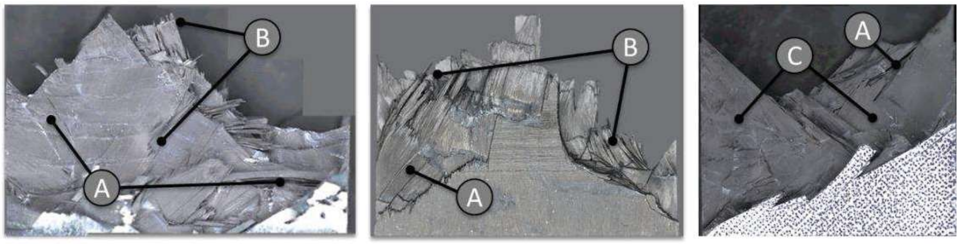
Figure 8. Tensile response of mechanical test, a) stress strain curves b) statistical results of tensile modulus.

As mentioned, the tensile modulus is taken as the average slope of the curves between 1000 micro-strain and half the failure stress. On average, it was found that the samples with randomly orientated tapes and 0° centred tapes have a tensile modulus of 32.5 GPa and 79.7 GPa respectively. The ±45˚ orientation centred samples showed an average tensile stiffness of 25.3 GPa. What should be noted is that the ±45˚ samples showed the lowest spread in stiffness. This is expected to be because tape misalignment in both directions compensate each other, while the alignment tool limits the possible variations in tape orientations as well.

Based on the measurements, the minimal average UTS of 0° centred tapes is 396 MPa compared to 202 MPa for the random tape orientation. Due to failure at the tabs of the samples, the UTS of 0° centred tapes is expected to be higher. The ±45˚ centred samples show a tensile strength comparable to the randomly orientated samples of 210 MPa. This tape orientation showed the highest strains at failure. Because the main failure modes of this type was matrix failure, it is assumed the failure was in shear. This results in a shear strength of the material of 105 MPa.

3.2. Failure analysis

The failure surfaces of the tested samples have been inspected using optical microscopy to see the differences in failure modes that are present in each of the samples. Three of the observations are shown in Figure 9. It was found that the samples with randomly orientated tapes show a large variety of failure modes that are (A) tape splitting, (B) fibre failure , and (C) matrix failure. The samples with a 0˚ centred tape orientation showed a more fibre related failure and less matrix failure which is linked to the tensile stresses in the fibre direction. Opposite to this was ±45˚ centred samples which showed mainly matrix failure whereby the different orientation layers have been separated from each other.



(a) (b) (c)

Figure 9, Fracture surfaces, a) Random tape distribution, b) 0° centred tape distribution, c) ±45° centred tape distribution. (A) tape splitting, (B) fibre failure , and (C) matrix failure.

4. Conclusions & Recommendations

Recent research into DTC has resulted in many insights into the mechanical behaviour and design parameters. This study has documented the tools and manufacturing needed for a fast dry alignment of DTC (in 0˚, +45˚, and -45˚ direction) and quantified the tensile modulus of the material with random, 0° centred, and ±45˚ centred DTC.

First an alignment method has been presented which is quantified using the tape orientation distribution using OpenCV. With the described method, test samples have been manufactured and tested in tension. By means of the obtained DIC data, it was found that the differences in tape orientation caused differences in strain characteristics. Hereby the randomly orientated tapes showed the largest spread and the 0˚ centred tape distributions showed the lowest.

By combining the tensile force readings and DIC strain measurements, stress strain curves have been obtained for all the samples. It was found that due to the alignment in loading direction, the average tensile modulus in loading direction was increased by 145% compared to randomly orientated tapes, from 32.5 to 79.7 GPa. The samples with the ±45˚ centred tapes showed a tensile stiffness and strength of 210 MPa and 25.3 GPa respectively.

The described alignment method and its characteristics can be used for the development and testing of more complicated tape alignment (such as steering). The results of the material characterization can be used for large scale alignment, reference values for design, or for validation of future research in numerical and experimental material characterisation.

3. Acknowledgements (For Clemens)

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4. References

[1] Pimenta, S., & Robinson, P.. An analytical shear-lag model for composites with 'brick-and-mortar'architecture considering non-linear matrix response and failure. Comp. Science and Technology, 104, 111-124, 2014.

[2] Martulli, L. M., Muyshondt, L., Kerschbaum, M., Pimenta, S., Lomov, S. V., & Swolfs, Y. Carbon fibre sheet moulding compounds with high in-mould flow: Linking morphology to tensile and compressive properties. Comp. Part A: Applied Science and Manufacturing, 126, 105600, 2019.

[3] Gan, K. W., Ho, Y. W., Ow, Z. Y., Israr, H. A., & Wong, K. J. Aligned discontinuous carbon fibre tows in hybrid composites and their tensile behaviour: An experimental study. Journal of Comp. Materials, 53(26-27), 3893-3907, 2019.

[4] Bradski, G., & Kaehler, A. Learning OpenCV: Computer vision with the OpenCV library. " O'Reilly Media, Inc.", 2008.

[5] Advani, S. G., & Tucker III, C. L. The use of tensors to describe and predict fiber orientation in short fiber composites. Journal of rheology, 31(8), 751-784, 1987.

[6] Ranganathan, S., & Advani, S. G. (1990). Characterization of orientation clustering in short-fiber composites. Journal of Polymer Science Part B: Polymer Physics, 28(13), 2651-2672.

[7] Yamashita, S., Hashimoto, K., Suganuma, H., & Takahashi, J. Experimental characterization of the tensile failure mode of ultra-thin chopped carbon fiber tape-reinforced thermoplastics. Journal of Reinforced Plastics and Comp., 35(18), 1342-1352, 2016.

[8] Feraboli, P., Peitso, E., Deleo, F., Cleveland, T., & Stickler, P. B. Characterization of prepreg-based discontinuous carbon fiber/epoxy systems. Journal of reinforced plastics and comp., 28(10), 1191-1214, 2009.

[9] Siddiqui, M. Z., Tariq, F., Naz, N., & Ahmed, M. F. Determination of Young's modulus of metallic and composite materials by digital image correlation. Journal of Space Technology, 1(1), 32-37, 2012.

[10] Cuartas, VM, Perrin, M., Pastor, ML, Welemane, H., Cantarel, A., & Karama, M. Identification of the elastic properties in CFRP composites. In International Symposium on Aircraft Materials ACMA 2014 (pp. pp-61), 2014, April.

[11] Feraboli, P., Cleveland, T., Stickler, P., & Halpin, J. Stochastic laminate analogy for simulating the variability in modulus of discontinuous composite materials. Comp. Part A: Applied Science and Manufacturing, 41(4), 557-570, 2010.