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Experimental Investigation on the Bending Behavior of Weft Interlaced Multilayered Woven Fabrics for Composite Applications

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Abstract
Direct preforming processes have potential for fiber-reinforced semi-finished products, creating 3D structures with strong delamination resistance using double-flat-steel-healds. However, the shedding method limits pattern variety, necessitating alternative options for interlacing diversity. One approach is using weft yarn instead of warp yarn for interlacing. This study explores its impact on mechanical properties, focusing on bending behavior, fiber volume content, and micrograph analysis of infiltrated warp and weft interlaced structures. The result shows interesting differences in mechanical behavior regarding different weave types and test direction as well as communalities within the individual structures.

Keywords
textile reinforced composite, integrally woven structure, double-flat-steel-healds, direct preforming, weft interlacement, warp interlacement, delamination resistance, stacked yarns, 3D-weave.

1. Introduction

Fiber-reinforced plastics (FRP) are widely used as structural components in numerous industries, such as aerospace, automotive and plant engineering. In most cases, high-performance fibers such as glass and carbon fibers are used and meet the high requirements regarding stiffness and mechanical strength with the lowest possible mass [1]. In general, FRP components are manufactured by the use of two-dimensional single layers of a certain textile reinforcement structure, which is cut to the component dimensions, stacked on top of each other, and then draped according to the component contour. This process, known as sequential preforming, is labor-intensive and time-consuming. In addition, FRP components produced in this way have no out-of-plane reinforcement. This means that if the fiber-plastic composite component is subjected to bending or shear stress, e.g. due to impact events, the component may fail under resulting delamination effects, since there are no reinforcing fibers running between the stacked individual layers to promote uniform stress distribution in all the reinforcing layers of the component.

The use of modern weaving technology, on the other hand, enables the single-stage production of final-contour, multilayer and three-dimensional preforms that can be processed directly into a FRP without further preforming steps [2]. This process is referred as direct preforming and has already been successfully transferred into industrial practice for certain applications, e.g. fan blades for the new generation of engines called LEAP-1C [3].

Multilayered woven preforms produced by the direct preforming process using weaving technology have a variable volume content of out-of-plane fibers. The arrangement of the warp and weft yarn systems is defined by the fabric weave and other process specific conditions, e. g. yarn tension, during the weaving process. For the production of multilayer woven preforms, the following three basic multilayer weaves can be used: through-the-thickness, layer-to-layer and angle interlock. These weaves differ in the way the different fabric layers are interlaced with each other. All weaves have in common that they are connected by a specific yarn system, whose arrangement within the multilayer fabric and the latter FRP significantly influence its mechanical properties [4–6, 1] (Figure 1-1).

The production possibilities of multilayer fabrics from transverse force sensitive high performance fibers (like carbon and glass) are currently still limited, since the warp thread density increases linearly with an increasing number of fabric layers. This leads to unavoidable damage, especially to the warp yarn system, due to abrasion caused by yarn/yarn friction and friction between yarn and yarn guiding elements [7–11].

Therefore the use of double-flat-steel-healds is presented in [12], which enables the significant reduction in weaving process-related fiber damage and, in principle, allows the damage-minimized production of multilayer fabrics from high-performance fibers. However due to the staggered arrangement of the warp yarns in the double-flat-steel-healds, the warp yarns cannot be moved as desired in the high or low position, as is the case, e.g. when using a Jacquard module with conventional healds.

Therefore, alternative methods are needed to produce the multilayer fabric with the required variety and structure. A promising approach to avoid the described limitation (yarn damage, weave restrictions) is the use of the weft system as an intelacing yarn system that connects

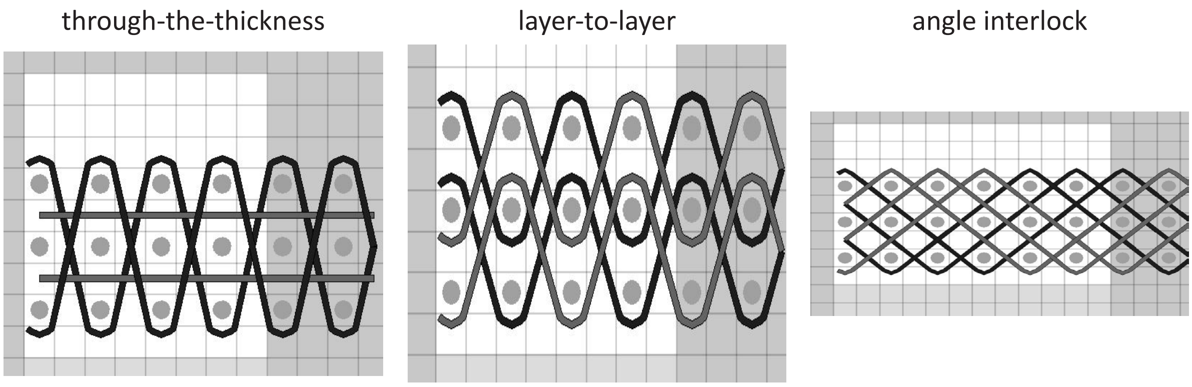


Fig. 1-1. Three basic multilayer weaves (cut along the warp direction: weft dot, warp line)

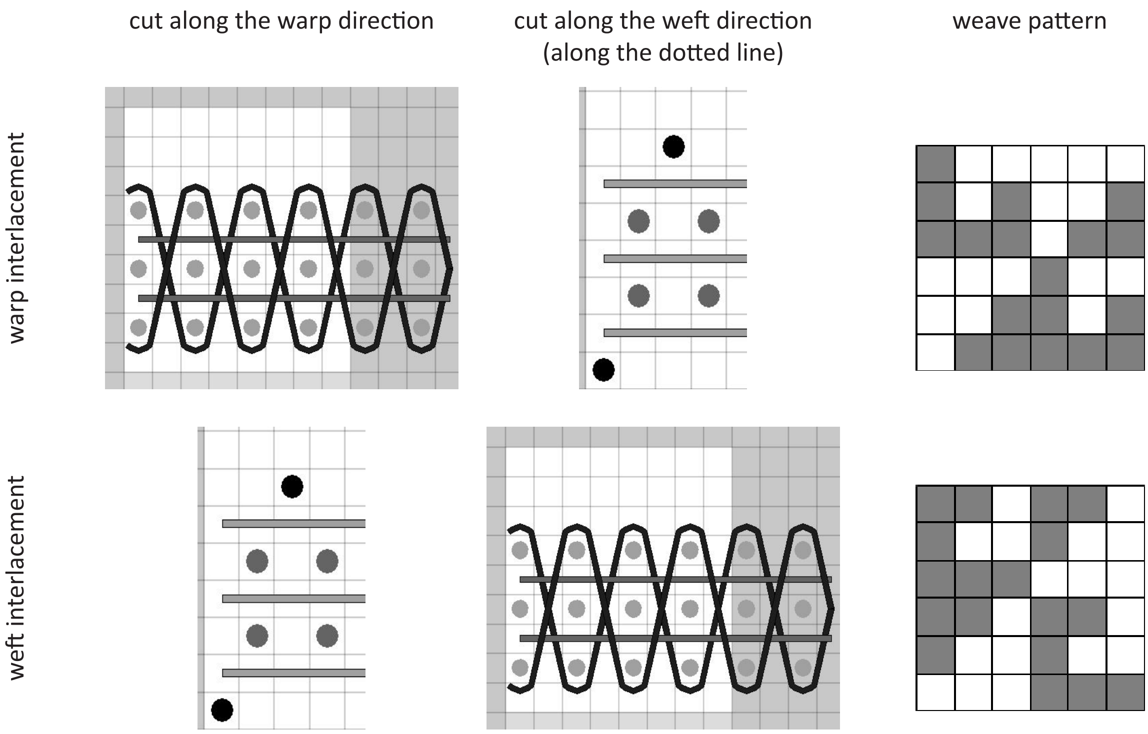


Fig. 1-2. Through-the-thickness weave structure and pattern in warp and weft direction

the individual fabric layers to form a multilayer fabric instead of the commonly used warp yarns. The following example illustrates the difference between warp and weft interlacement. In conventional multilayer fabrics, the weft is not involved in keeping the layers together and the interlacement is only done by the warp yarn system (Figure 1-2). However, the interlacement could be done in a similar manner by the rearrangement of the weft as in the interlacing yarn system, while the warp yarns run straight through the fabric. As shown in Figure 1-2, the structural composition of the fabric can remain meanwhile the same. Thus, for each conventional warp interlaced weave, a corresponding weft interlaced structure can be derived, e.g. by means of suitable software like EAT DesignScope Victor or comparable [13].

Thus, this approach appears promising for extending the process limitations in the production and utilization of multilayered fabrics. However, the lack of fundamental knowledge about the extent to which the property spectrum of weft-bonded weaves is equal to that of warp-bonded structures is an argument against its use. Significant differences can occur in this respect, since the structure in the fabric preform depends on the force equilibrium between warp and weft yarns during production. An example of this is the crimp of the warp yarns when their tension is set too low compared to a significantly higher weft tension.The crimp is the ratio of yarn consumption to a certain reference distance within the fabric, e. g. between two weave points or a repeat. The higher the ratio, the more the respective yarn is crimped. As a result of that, the reinforcing fibers are not aligned in the warp direction in accordance with the load (e. g. tension, pressure, etc.), which has a significant negative effect on the subsequent FRP properties, such as stiffness and strength.

With regard to the production of multilayered woven fabrics, the interlacing yarn system has to be processed with a significantly higher yarn requirement compared to other yarns. Due to the simultaneous processing of the warp yarns in the weaving process, this difference can be compensated with warp interlacing weaves by providing additional material from the warp yarn supply. With weft interlacing weaves, on the other hand, the weft thread is inserted into the fabric with a constant length, which means that similar compensation effects cannot take effect, because there is no supply of additional material on the one hand, and on the other hand friction effects between yarn systems preserve the balancing of warp and weft crimp. In case of doubt, this leads to so-called warping, whereby excessive crimp is introduced into the remaining non-interlacing yarn systems, which reduces the mechanical properties.

The objective of this work was, therefore, the experimental investigation of the relationship between mechanical properties (evaluated by means of bending tests) and the use of weft interlaced multilayered weaves. The stiffness and strength of the FRP produced from the weaves serve as evaluation criteria. A comparison is made with conventionally warp interlaced weaves and FRP specimens made of them. In combination with microscopy-based examination of the samples, a basic assessment of the applicability of weft interlaced multilayered fabrics for FRP will be made.

An extensive literature search showed that investigations of the mechanical properties of multilayer fabrics have been carried out e. g. the change in mechanical properties when using organic fibers [14], or filling threads [15]; also the comparison of stacked fabrics and 3D-fabrics in ballistic tests [16], tensile tests on dry multilayer fabrics with flax fibers [17], and impact resistant and 3-point-bending on dry multilayer fabrics [18] were studied. For the use of natural fibers such as jute fibers in combination with a biodegradable matrix, it was shown that weft or warp binding lead to similar mechanical properties [19]. However, none of these studies investigate the influence of the direction of the binding yarn for high performance fibers.

2. Materials and Methods

2.1. Sample and Specimen Preparation

For the production of the fabric samples, carbon fibers of the manufacturer Toho Tenax with a linear density of 800 tex were used in the warp and weft. A MAGEBA shuttle rapier loom SL RTEC 1200/1 with a Stäubli jacquard machine was used to produce the fabric samples.

224 warp threads were used, which corresponds to a fabric width of 146 mm and, thus, a warp density of 15.34 threads per cm. The same density was realized in the weft direction. The objective of this study was to determine the fundamental relationships between mechanical FRP-properties and the configuration of the fabric reinforcement using a warp or weft interlaced structure. Regarding this, a through-the-thickness and a layer-to-layer weave were chosen, because they show the highest and respectively the lowest crimp of the binding thread. The four weave patterns required were produced with "EAT DesignScope Victor" software.

The samples were consolidated by vacuum-assisted resin infusion (VARI), see Figure 2-2, using a plate-shaped tool on both sides, as already described in [20]. The sides of the specimen surfaces were therefore equal, which is a requirement for the later bending test of the specimens. The resin EPIKOTE RIMR 136 was used for infiltration.

After curing, the specimen plates were cut to standard nominal dimensions [21], see Figure 2-3, for the bending test by water jet processing.

2.2. Tests

Prior to the mechanical investigations, material samples were taken from the consolidated FRP sample plates and the fiber volume content (FVC) determined according to ISO 1172:2023 "Textile-glass-reinforced plastics – Prepregs, moulding compounds and laminates – Determination of the textile-glass and mineral-filler content using calcination methods" [22]. Experience has shown that different textile reinforcing materials, such as fabrics of different weave, exhibit significant differences in compaction behavior, which also leads to differences in the FVC achievable in VARI at 1 bar pressure. With the determined FVC, the results from the mechanical investigation

Fig. 2-1. MAGEBA shuttle rapier loom SL RTEC 1200/1

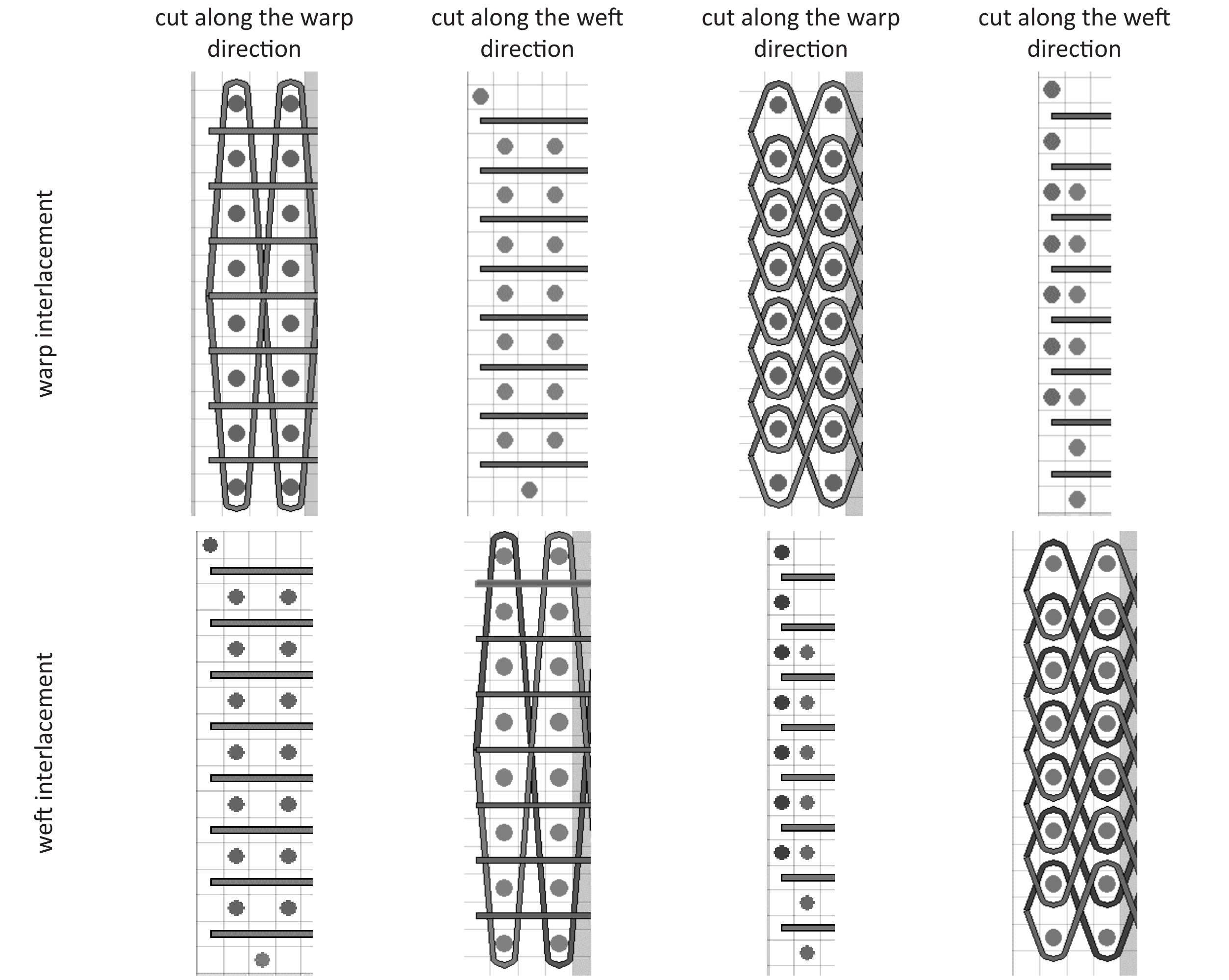


Fig. 2-2. Weave structure for the produced samples in warp and weft direction

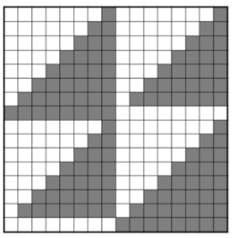
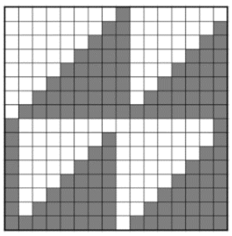
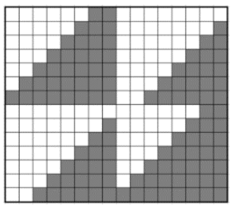
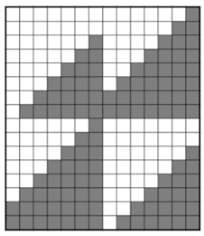
	through-the-thickness weft interlacement	**through-the-thickness warp interlacement**	**layer-to-layer weft interlacement**	**layer-to-layer warp interlacement**
				
WeD	16	16	14	16
WaD	16	16	16	14
Sample batch	1	2	3	4

Table 2-1. Four weave patterns with warp (WaD) and weft densities (WeD) in threads per cm

can be compared with other work and with each other.

The mechanical properties were determined using the 3-point bending method according to ISO 14125:1998 “Fiber reinforced plastic composites – Determination of flexural properties” [21] with a universal testing machine (Zwick Z100) in combination with a standardized bending jig for composite materials. To document the test, the resulting force on the loading piston and the deflection in the middle of the specimen were determined with a Zwick displacement transducer.

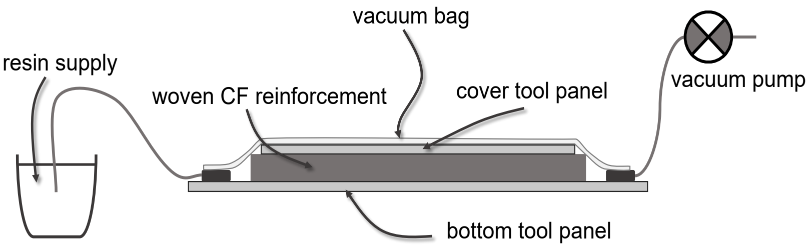


Fig. 2-3. Setup for sample infiltration

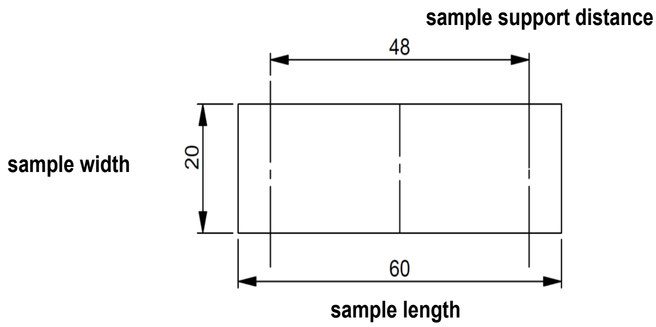


Fig. 2-4. Sample geometry

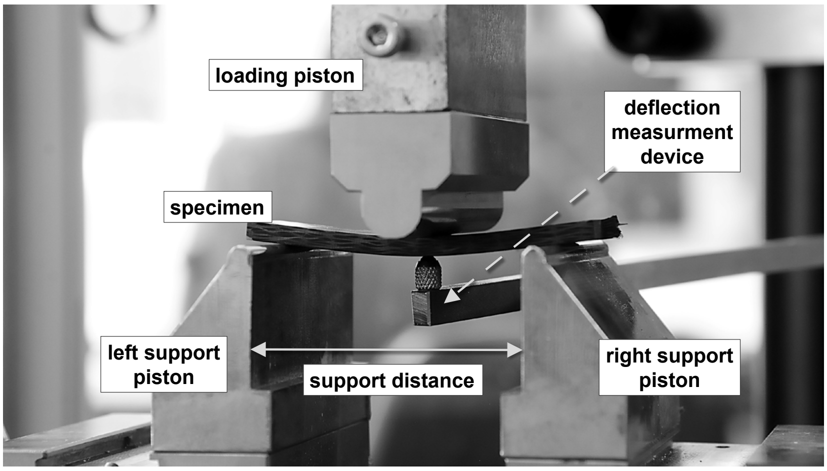


Fig. 2-5. Flexural test setup

The data were used to evaluate the following mechanical bending properties of the FRP specimens: the strain in the outer surface of the specimen ε_f, flexural stress σ_f during the test, the mechanical parameters modulus of elasticity in flexure E_f, the flexural strength σ_{fM}, and the corresponding strain at the flexural strength ε_{fM} with the following equations:

$$\varepsilon_f = \frac{6sh}{L^2} \tag{3.1}$$

$$\sigma_f = \frac{3FL}{2bh^2} \tag{3.2}$$

$$E_f = \frac{\sigma_f'' - \sigma_f'}{\varepsilon_f'' - \varepsilon_f'} = 500(\sigma_f'' - \sigma_f') \tag{3.3}$$

with

$\varepsilon_f' = 0.0005$ $\quad$ $\varepsilon_f'' = 0.0025$

In addition to the determination of FVC and mechanical characteristics, cross-sectional images of all fabric types were prepared. For this purpose, an additional white marking thread made of polyethylene (660 tex) was used as weft thread, thus making the course of the weft threads in the respective weave visible. In this way, the results of the mechanical test can be compared and evaluated with the internal structure of the fabric.

3. Results and Discussion

3.1. Fiber Volume Content

As already mentioned, the compaction behavior of the consolidated fabrics is strongly dependent on the respective weave. The values determined for the FVC can be seen in Table 3-1. It is evident that the FVC of the through-the-thickness 10 % lower, because the threads cannot slide against each other as those of the layer-to-layer weave. Furthermore, during the infiltration, additional resin filled the gaps caused by the binder yarns in the through-the-thickness weaves. The numbering of the sample batches and the certain FVC values are further used for the following parts of the paper.

3.2. Flexural Bending Behavior

According to the standard applied [23], two essential failure mechanisms are accepted for the determination of the bending properties. These are either tensile or compressive fractures on the outer surfaces of the specimens. In comparison, failure that occurs in combination with interlaminar shear is not accepted. Accordingly, the failure behavior of all sample series was investigated in more detail. It was found that the through-the-thickness specimens very often fail due to tensile fracture on the underside. The layer-to-layer specimens, on the other hand, showed fractures only on the upper side due to buckling of the outer fiber layers.

As can be seen from the results in Table 3-2, significant differences in mechanical behavior occur in the bending test partly depending on the weave and interlacement types examined, but partly also on the test direction. Table 3-2 shows the determined mechanical test results with regard to the weave used and the test direction. As already shown in section 2,

Sample batch	Weave	Interlacement type	Fiber volume content (FVC)	Sample thickness
01	Through-the-thickness	Weft interlacement	43.5 %	3.4 mm
02	Through-the-thickness	Warp interlacement	39.4 %	3.4 mm
03	Layer-to-layer	Weft interlacement	50.2 %	2.8 mm
04	Layer-to-layer	Warp interlacement	52.0 %	2.8 mm

Table 3-1. Fiber volume content, determined according to EN ISO 1172

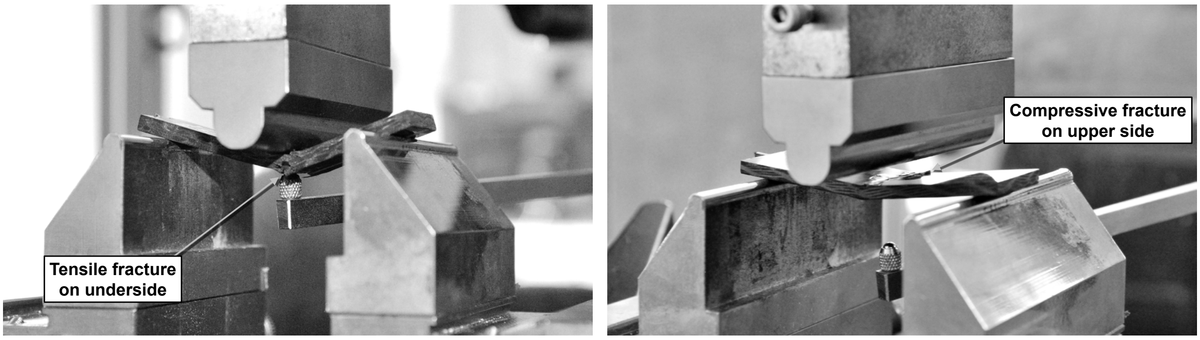


Fig. 3-1. Fracture behavior during the bending tests (left: tensile fracture, right: compressvie fracture)

the sample batches are made up as follows:

– Batch 01: through-the-thickness, weft interlacement
– Batch 02: through-the-thickness, warp interlacement
– Batch 03: layer-to-layer, weft interlacement
– Batch 04: layer-to-layer, warp interlacement

The combination of weave and interlacement type results in 4 different sample batches. The bending properties are again determined in both warp and weft direction, resulting in 8 sample series. The highest normalized values for the flexural modulus can be obtained for weft interlaced layer-to-layer in the weft direction (No. 3, Figure 3-2). The characteristic properties determined for stiffness and strength are similar or even identical during testing in the direction of the interlacing yarn system (03 - weft interlacement, 04 - warp interlacement) or in the direction of the non-interlaced yarn system at a similarly high level. Using the weaves examined, good mechanical properties can be achieved in the FRP by considering the angle changes in the fiber orientation. Despite the differences the principle of the angle-transformed weave described in section 1 can be used very well for the layer-to-layer type.

With the weave, similar values of elasticity in flexure are achieved in different test directions, both for warp an weft interlacing. With the layer-to-layer weave, there are differences in the test direction for both interlacing variants. In both cases the result in the direction of interlacing is significantly lower. Here the high crimp comes into play and causes breakouts due to buckling. Against the interlacing direction the crimp is significantly lower due to the more stretched position of the fibers allowing a higher load, similar to the behavior of the through-the-thickness weave.

The stiffness and flexural strength of the through-the-thickness weaves are generally lower than that of the layer-to-layer. When comparing the results within the batches, it is noticeable that the values are lower when tested in the direction of the interlacing yarn system than in the direction of the non-interlacing yarn system (Figure 3-3). In general, the parameters for the weft interlaced weaves (batch 01) are worse than those of the conventional warp interlaced through-the-thickness samples (batch 02). It can be seen that the method of angle-transformation of the weaves cannot be used without restrictions regarding the comparability of properties. While the method is suitable for layer-to-layer, it cannot be used for through-the-thickness with their characteristic strong crimp of the binding threads. Accordingly the method is only applicable depending on the type of weave.

A direct comparison of the test results (Table 4-2) shows that the specimens with a through-the-thickness weave can take a significantly higher strain at the maximum bending stress than those with a layer-to-layer weave. From the comparison of these results with the failure behavior of the specimens, two results can therefore be concluded:

1) The layer-to-layer samples have a more compact structure and stronger normalized stiffness independent of the interlacement type used (weft or warp). However, they fail at smaller elongations due to the higher crimp in the outer layers.

2) The through-the-thickness specimens can absorb higher strengths and elongations at break, which prevents the compression failure of the outer fibers due to the binder thread system and the comparatively elongated arrangement of the fibers. Instead, tensile fractures or intermediate fiber fractures occur on the bottom.

3.3. Cross-Sectional Analysis

In the following, an analysis of the micrographs of the samples is performed.

Sample batch	Test direction	Modulus of elasticity in flexure		Flexural strength		Strain at flexural strength
		Test result	Normalized1)	Test result	Normalized1)	
		E_f in 10^3 N/mm²	$E_{f,norm}$ in 10^3 N/mm²	σ_f in N/mm²	$\sigma_{f,norm}$ in N/mm²	ε_{fM} in %
01	Warp	31.4 ± 4.3 2)	36.1 ± 4.9	407 ± 68	468 ± 78	1.9 %
	Weft	29.5 ± 1.1	33.9 ± 1.3	473 ± 16	544 ± 18	1.9 %
02	Warp	33.8 ± 2.0	38.9 ± 2.3	522 ± 25	600 ± 29	1.6 %
	Weft	36.6 ± 0.4	42.1 ± 0.5	490 ± 18	563 ± 21	1.8 %
03	Warp	57.4 ± 5.7	57.2 ± 5.7	578 ± 43	576 ± 43	1.1 %
	Weft	36.1 ± 1.8	36.0 ± 1.8	483 ± 30	481 ± 30	1.5 %
04	Warp	36.9 ± 3.8	35.5 ± 3.7	494 ± 30	475 ± 29	1.5 %
	Weft	48.7 ± 0.2	46.8 ± 0.2	601 ± 34	578 ± 33	1.2 %
1) Normalized to 50 % FVC; 2) Single standard deviation						

Table 3-2. Results of the flexural bending test

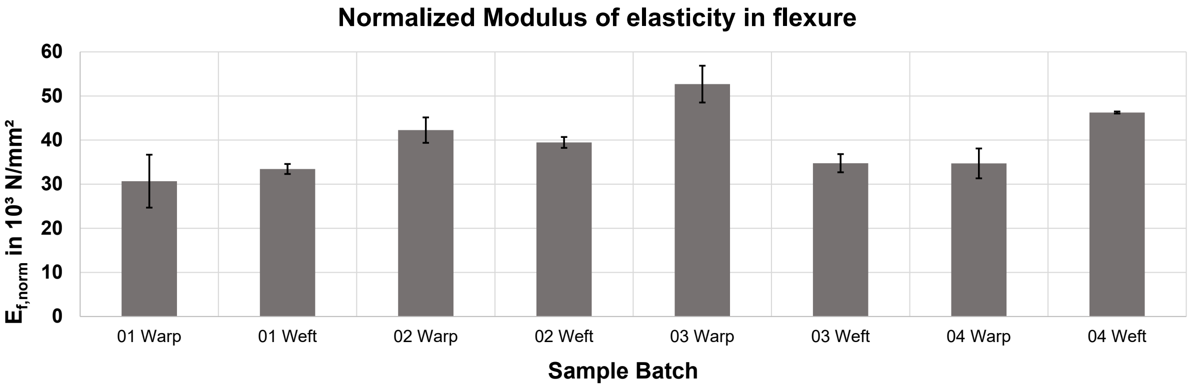


Fig. 3-2. Normalized modulus of elasticity in flexure

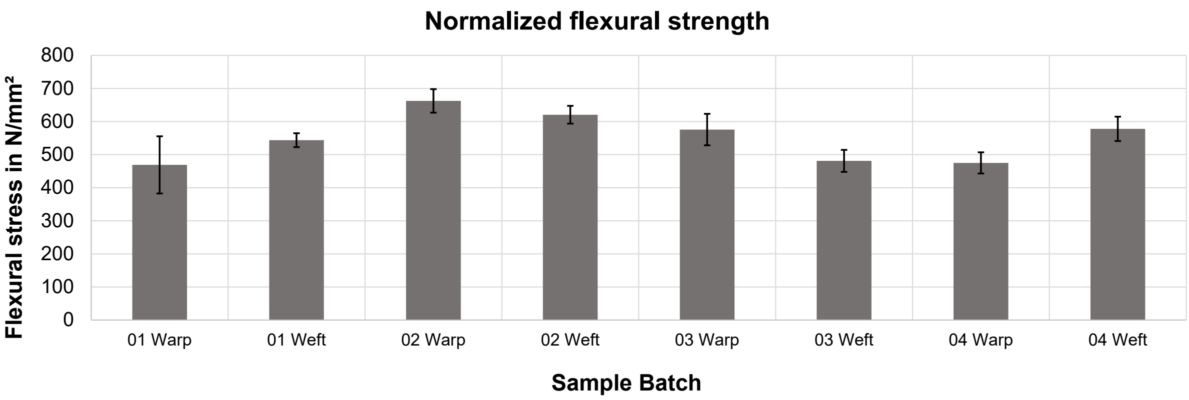


Fig. 3-3. Normalized flexural strength

It is assessed to which interlacement induced effects the determined bending properties of the samples can be traced. The following figures show the polished side surfaces of resin-embedded samples of the weave types investigated. In contrast to the specimens for the bending test, the fabrics for the microsection specimens were manufactured with a weft thread of polyethylene (660 tex) to make the course of warp and weft visible.

The images in Figure 3-4 show cross-sections of the through-the-thickness specimens. A comparison of the cut sides shows that the course of the threads clearly depends on the type of binding used (Weft/Warp Interlacement). Thus, the parallely sliced CF warp threads in 1) show a narrowed course. Rotated at 90° in 2), the course of the weft can be seen. On the left edge of the cross section, an initial crimp is still visible. This decreases in the further course, however, which confirms

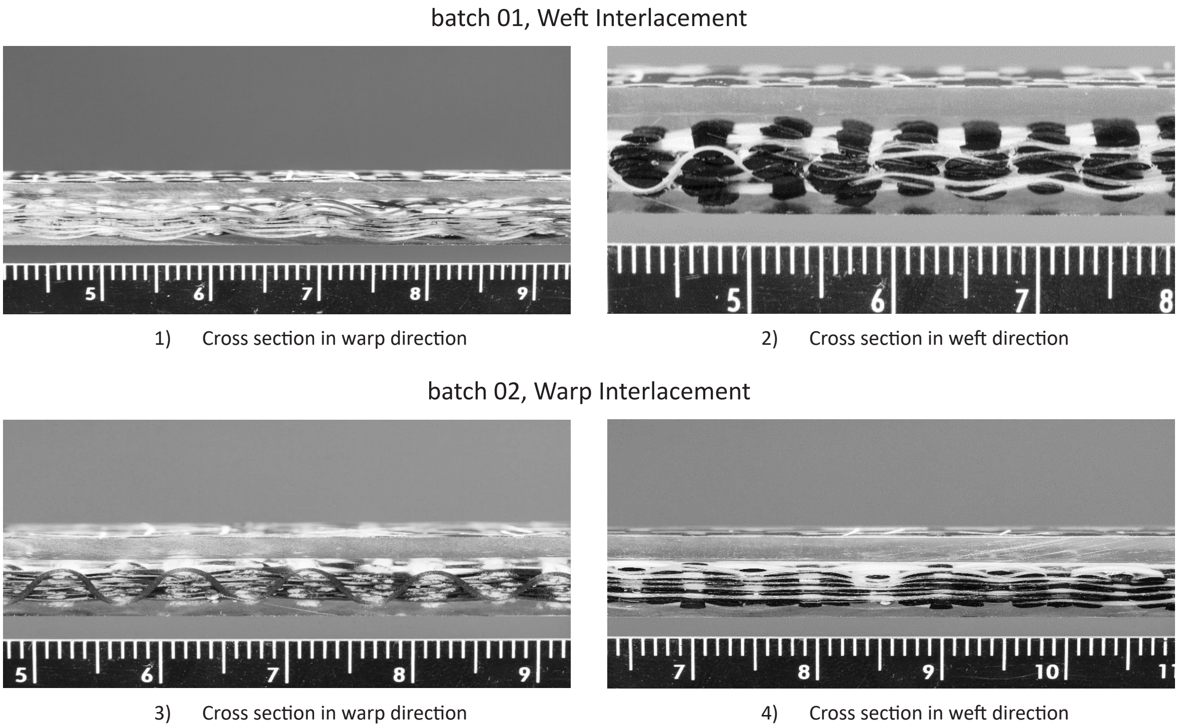


Fig. 3-4. Cross section of the through-the-thickness samples

the hypothesis at the beginning of the paper, that the crimp/insertion of the weft thread is hindered by the increasing interlacing with the warp thread system and the resulting friction effects between the thread systems. The resulting tensile forces on the weft thread lead to the deflection of the warp threads visible in 1). Another resulting effect is a high unevenness in the interlacing of warp and weft. Accordingly, the measured values in Table 3-2, Figure 3-2 and Figure 3-3 show high standard deviations.

In comparison, warp and weft threads are arranged with high regularity in the warp interlaced through-the-thickness sample. In 3) the warp threads are bound into the fabric with constant crimp. Similarly, the weft threads in 4) are arranged in an even and as far as possible stretched arrangement. This arrangement is reflected in the results from the bending test, where the best strength values were achieved for this fabric type with a comparatively low standard deviation.

The images in Figure 3-5 show microsections of the layer-to-layer samples. In comparison with the through-the-thickness samples, there is no distinct dependence between warp and weft binding. The arrangement of the threads between 5) and 8) or 6) and 7) is similar. Also, the test values for the corresponding samples match very well, thus it can be assumed that the difference in thread orientation is not statistically significant in both cases. Furthermore, the interlaced threads are more crimped in both fabric weaves, so that a higher bending strength can be obtained in the direction of the uninterlaced thread system.

4. Conclusion

Four different fabric samples were prepared to investigate the influence of the weave pattern on the mechanical properties of the FRP. For these, weave patterns through-the-thickness and layer-to-layer were selected because they have the highest and the lowest incorporation of the binding threads. The weave patterns were made in the warp and weft directions. The manufactured fabrics were infiltrated in a VARI set-up with two-sided tools. Cutting of the actual specimens was done by water jet. The mechanical properties were determined using the 3-point bending method with a universal testing machine (Zwick Z100) in combination with a standardized bending jig for composite materials. It could be shown that the layer-to-layer samples have a more compact structure and stronger normalized stiffness, irrespective of the interlacement type used (weft or warp). However, they fail at smaller elongations due to the higher crimp in the outer layers. The through-the-thickness specimens can absorb higher strengths and elongations at break, which prevents compression failure of the outer fibers due to the binder thread system and the comparatively elongated arrangement of the fibers. The comparision of the interlacement type within a bach shows that the method of angle-transformation has a partial impact on the mechanical properties: While the method does not effect the bending behavior for layer-to-layer and through-the-thickness, a difference in strength is observed. The generally high values of all samples allow the use of angle-transformed weaves, suitable for high performance applicatuion. For comparable properties of the transformed weave, only the layer-to-layer is applicable.

The Authors declares there is no conflict of interest.

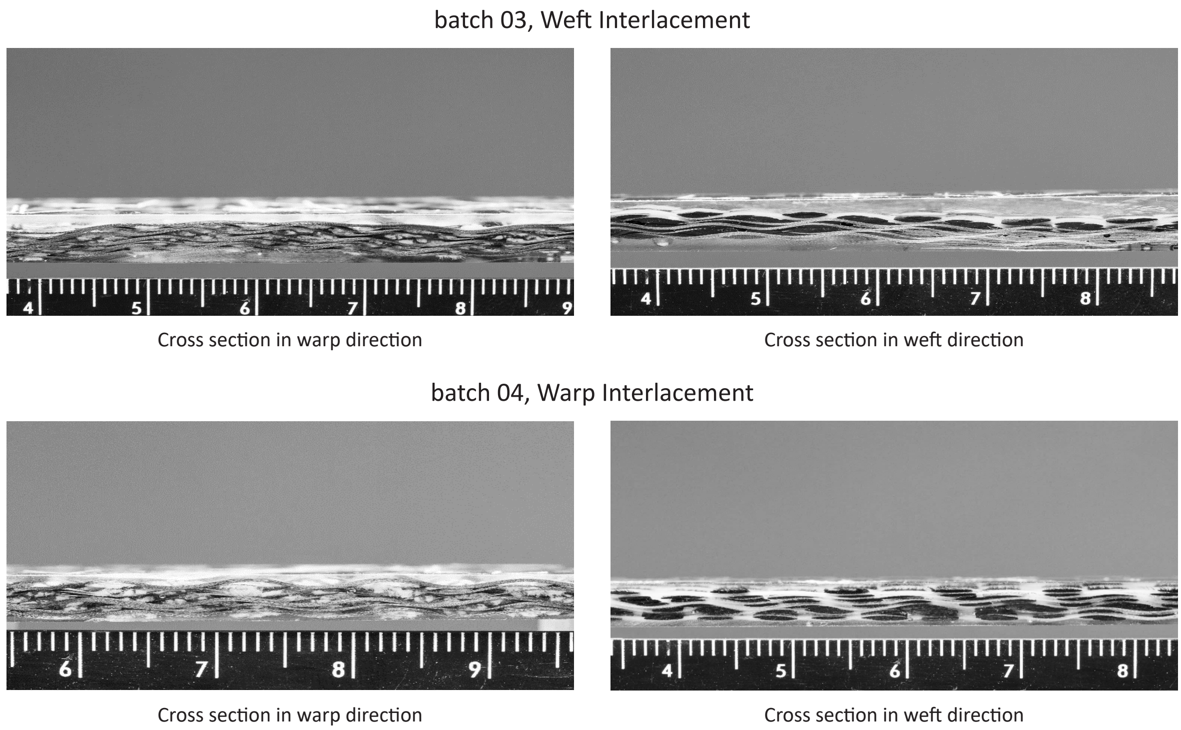


Fig. 3-5. Cross section of the layer-to-layer samples

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References

1. Cherif C. Textile Werkstoffe für den Leichtbau. Berlin, Heidelberg: Springer Berlin Heidelberg; 2011.
2. Schegner P, Fazeli M, Sennewald C, Hoffmann G, Cherif C. Technology Development for Direct Weaving of Complex 3D Nodal Structures. Appl Compos Mater 2019; 26(1):423–32.
3. Safran. LEAP-1C engine for single-aisle commercial jets; 05.25.2021 [cited 2022 Feb 11]. Available from: URL: https://www.safran-group.com/products-services/leap-1c-new-generation-engine-single-aisle-commercial-jets.
4. Corbin AC, Kececi A, Boussu F, Ferreira M, Soulat D. Engineering Design and Mechanical Property Characterisation of 3D Warp Interlock Woven Fabrics. Applied Composite Materials 2018; 25(4):811–22. Available from: URL: https://doi.org/10.1007/s10443-018-9715-z.
5. Maqsood M, Hussain T, Nawab Y, Shaker K, Umair M. Prediction of warp and weft yarn crimp in cotton woven fabrics. The Journal of The Textile Institute 2015; 106(11):1180–9.
6. Umair M, Nawab Y, Malik MH, Shaker K. Development and characterization of three-dimensional woven-shaped preforms and their associated composites. Journal of Reinforced Plastics and Composites 2015; 34(24):2018–28.
7. Archer E, Buchanan S, McIlhagger AT, Quinn JP. The effect of 3D weaving and consolidation on carbon fiber tows, fabrics, and composites. Journal of Reinforced Plastics and Composites 2010; 29(20):3162–70.
8. Li M, Wang P, Boussu F, Soulat D. Investigation of the Strength Loss of HMWPE Yarns During Manufacturing Process of 3D Warp Interlock Fabrics. Applied Composite Materials 2021.
9. Lefebvre M, Francois B, Daniel C. Influence of high-performance yarns degradation inside three-dimensional warp interlock fabric. Journal of Industrial Textiles 2013; 42(4):475–88.
10. Gloy Y, Renkens W, Herty M, Gries T. Simulation and Optimisation of Warp Tension in the Weaving Process. J Textile Sci Eng 2015; 05(01).
11. Bessette C, Decrette M, Tourlonias M, Osselin J-F, Charleux F, Coupé D et al. In-situ measurement of tension and contact forces for weaving process monitoring: Application to 3D interlock.

Composites Part A: Applied Science and Manufacturing 2019; 126:105604.
12. Vorhof M, Weise D, Sennewald C, Hoffmann G. New method for warp yarn arrangement and algorithm for pattern conversion for three-dimensional woven multilayered fabrics. Journal of Industrial Textiles 2018; 45:152808371881353.
13. EAT GmbH "The DesignScope Company". 3DWeave Comp [cited 2022 Apr 11]. Available from: URL: https://www.designscopecompany.com/3dweave-comp/.
14. Yang X, Fan W, Ge S, Gao X, Wang S, Zhang Y et al. Advanced textile technology for fabrication of ramie fiber PLA composites with enhanced mechanical properties. Industrial Crops and Products 2021; 162:113312.
15. Jabbar M, Shaker K, Nawab Y, Umair M. Effect of the stuffer yarns on the mechanical performance of novel 3D woven green composites. Composite Structures 2021; 269:114023.
16. Abtew MA, Boussu F, Bruniaux P, Loghin C, Cristian I, Chen Y et al. Ballistic impact performance and surface failure mechanisms of two-dimensional and three-dimensional woven p-aramid multi-layer fabrics for lightweight women ballistic vest applications. Journal of Industrial Textiles 2021; 50(9):1351–83.
17. Corbin A-C, Boussu F, Ferreira M, Soulat D. Influence of 3D warp interlock fabrics parameters made with flax rovings on their final mechanical behaviour. Journal of Industrial Textiles 2020; 49(9):1123–44.
18. Li M, Wang P, Boussu F, Soulat D. A review on the mechanical performance of three-dimensional warp interlock woven fabrics as reinforcement in composites. Journal of Industrial Textiles 2020:152808371989438.
19. Kashif M, Hamdani, Syed Talha Ali, Nawab Y, Asghar MA, Umair M, Shaker K. Optimization of 3D woven preform for improved mechanical performance. Journal of Industrial Textiles 2018; 48(7):1206–27.
20. Weise D, Vorhof M, Unger R, Hoffmann G, Cherif C. Studying the influence of different carbon-fibre-reinforced polymer patches on the mechanical properties of carbon-fibre-reinforced polymer composite. Journal of Industrial Textiles 2018; 48(3):539–58.
21. Internationale Organisation für Normung. Fibre-reinforced plastic composites - Determination of flexural properties.
22. Internationale Organisation für Normung. Prepregs, moulding compounds and laminates - Determination of the textile-glass and mineral-filler content.
23. Internationale Organisation für Normung. Rubber and plastics test equipment - Tensile, flexural and compression types (constant rate of traverse) - Specification.