IMPROVED STRENGTH OF BOLTED JOINTS IN PULTRUDED FRP LAMINATES BY INTEGRATION OF LOCAL TEXTILE REINFORCEMENTS

Simon Boysen[1], Christoph Heimbucher[1], Alexander Marx[1], Patrick Schiebel[1] and Mareike Woestmann[1]

[1] FIBRE, Faserinstitut Bremen e.V., Am Biologischen Garten 2, 28359 Bremen, Germany,
Tel.: +49 (0) 421 218 59669, E-Mail: boysen@faserinstitut.de

Keywords: Pultrusion, Local Reinforcement, Tailored Fiber Placement

ABSTRACT

Pultrusion is an automated process for the continuous production of fiber-reinforced plastic profiles with high mechanical strength in the longitudinal direction. However, the predominantly unidirectional fiber orientation weakens the profiles when used in bolted joints due to interruptions in the fiber path. To address this, local multiaxial reinforcements or adaptions of fiber orientations are commonly employed but are not feasible in conventional pultrusion due to the continuity of the process. Pultruded profiles used in joints require reinforcements throughout their entire length, leading to drawbacks such as oversizing in most areas, reduced lightweight quality, slower process speeds and increased component costs. Due to these limitations, in many cases the potential of the pultrusion process cannot be fully exploited, which is why many areas of application have not yet been developed.

To overcome these limitations, textile semi-finished products with locally variable fiber orientations were developed and integrated into the pultrusion process. Various reinforcement structures were designed and produced using tailored fiber placement and crochet fabrics. The textile semi-finished products, produced on a continuous non-woven, allow a continuous integration into pultruded profiles. The locally reinforced pultrusion profiles were characterized by pin bearing, open hole and cyclic pin bearing tests and an evaluation of the reinforcement effect was carried out.

With local reinforcement contents of 13% to 15% of the local fiber volume content, the local pin bearing strengths could be increased by up to 86% (CFRP) and 35% (GFRP) compared to mainly unidirectional reinforced profiles. In addition, the reinforcement structures were transferred to a more efficient textile manufacturing process (crochet fabrics) and integrated into the pultrusion process. In this way, locally reinforced profiles with increased mechanical properties could be manufactured, paving the way for an industrial-scale implementation of the technology.

1 INTRODUCTION

Pultrusion is a well-established and highly efficient process for the production of fiber-reinforced composites. The name of the process is a combination of the terms “pull” and “extrusion” and is based on the continuous drawing of fibers impregnated with a polymer through a die, where the curing and shaping take place [1]. Reinforcing glass or carbon fibers are mainly used as starting materials; in certain cases, aramid or natural fibers are also used [2]. Various polymers, such as unsaturated polyester, vinyl ester, epoxies or polyurethane, are used for the shaping matrix in which the fibers are embedded. Mats, nonwovens and multiaxial fabrics are also used for reinforcement in highly stressed components [3].

The process is characterized by high productivity and low costs as well as high axial mechanical properties [4,5]. Applications for the materials range from construction and infrastructure to automotive, transportation, wind turbines and medical [6-10]. The materials exhibit properties such as corrosion resistance, good electrical and thermal insulation, and high fiber volume contents, which result in high mechanical properties [11].

The process was developed by W. B. Goldsworthy in the late 1950s [1] and accounted for a production volume of about 56 kt in 2021 [12], which is about two percent of the total composites market. Due to a high level of automation and value creation of the process as well as low production and energy costs, pultrusion is often considered to have an extremely promising future, as shown by a survey conducted by “Composites Germany” [12].

A critical design criterion of pultruded profiles is the load introduction area, the dimensioning of which must be carried out over the entire profile length due to the continuity of the process. This leads to oversizing of the profiles in most areas, resulting in an increased material consumption, lower pulling speeds and a higher energy consumption. To increase the efficiency of the pultrusion process, local adaptation of the fiber orientation to the multiaxial stress state in the area of joints is required [13]. By adapting the fiber orientations to the stress state, oversizing can be prevented and a more efficient part and process design can be achieved [14]. The implementation of locally adapted fiber orientations in pultruded profiles is not yet known and textile semi-finished products suitable for this purpose are not yet used in the pultrusion process.

2 MATERIALS AND METHODS

There are different approaches for the local reinforcement of fiber composites, one approach is the local adaptation of the fiber paths in the load introduction areas. One possibility for realizing locally variable fiber paths in pultruded profiles is the processing of textile semi-finished products, which have locally variable fiber orientations [15].

2.1 Development of TFP-Preforms and simulation

The use of the Tailored Fiber Placement (TFP) process is ideal for the production of load-adapted fiber reinforcements. With TFP technology, yarns can be placed on almost any two-dimensional paths and fixed to an embroidery base [16]. In this way, a preform for a multi-axis loaded component can be produced successively. The “roll-to-roll” variant of the process can also be used to produce reinforcing structures on a continuous carrier material [17]. In this way, semi-finished products with locally variable fiber orientations can be continuously processed by pultrusion.

One possibility for local reinforcement of areas with punctiform tensile and compressive loads is the loop joint, as used in load-bearing structures, for example. General design guidelines for the design of such reinforcing structures are given in [18]. The design guidelines were used to design different reinforcement patterns suitable for fabrication by the TFP process. The TFP structures were then analyzed for their reinforcing effect using an FEM simulation. The simulation model was built by adapting the material properties to the locally variable fiber volume fraction and orientation as it occurs in real production of the composite material. In the simulation, the force was applied via a bolt of the diameter 10 mm, which is located in a hole centered in the reinforcement structure. The linear elastic simulation was based on two load cases, tensile and compressive load, each with a force of 10 kN.

Within the framework of the simulation, the strain reductions due to the individual reinforcement patterns were determined, which served as the basis for evaluating the reinforcement effect. Based on the simulation results, a selection of suitable reinforcement structures was then made, which were manufactured on continuous embroidery base using the TFP process and then integrated into the pultrusion process. The TFP preforms were produced on a 2-head TFP embroidery machine from “ZSK Stickmaschinen GmbH”. This system can embroider continuous textiles with an embroidery frequency of up to 850 stitches/minute.

2.2 Materials (TFP-Preforms)

The TFP preforms were manufactured with both glass and carbon fibers. The materials used are listed below in Table 1:

Material	Name
Glass fiber	
Reinforcement rovings	ECR glass fiber 908, 1200 tex
Embroidery material	Evalith SH50 glass-nonwoven
Sewing thread	Amann Serafil 200/2 red

	Carbon fiber
Reinforcement rovings	Tenax HTS45 12K C-Faser E23, 800 tex
Embroidery material	Marubeni Carbon wet laid nonwoven, 30 g/m²
Sewing thread	Amann Serafil 200/2 red

Table 1: Materials used for the TFP-Preforms

2.3 Pultrusion process and equipment

The TFP preforms produced were then integrated into the pultrusion process and locally reinforced profiles were produced in this way. The tests were carried out on a pultrusion line of the company “Thomas GmbH + Co. Technik + Innovation KG” with a pull force of up to 80 kN. A wide range of different inline-measuring systems is available at the “Faserinstitut Bremen” for carrying out pultrusion trials. The pull forces and die temperatures are recorded by default. In addition, a laser profiler is used for scanning the surface topography in order to evaluate the roughness inline. An examination of the profiles, for example for inhomogeneities, can be carried out with an inline ultrasonic measurement system. In addition, pressure sensors are used to analyze the pressure inside the die at several positions, to analyze the effect of the local reinforcements on the process stability.

2.4 Materials (pultrusion process)

For the pultrusion trials carried out in this work, the epoxy resin system “LITESTONE” from the manufacturer “Olin” was used, which in preliminary tests proved to be “very robust” against fluctuating process parameters like fiber volume content. The exact composition of the resin system is summarized in Table 2:

Category	Name	Manufacturer	Parts
Resin	LITESTONE 3100E	Olin	100
Hardener	LITESTONE 3102H	Olin	105
Internal mold release	INT-1888LE	Axel MoldWiz	1
Filler material	Talcum powder	-	3

Table 2: Components of the resin system

In the pultrusion trials, glass fibers of the type “PS 4100” with 9600 tex by “Owens Corning” and Carbon fibers of the type “PX35” with 3740 tex by “Zoltek” were used. The impregnation of the fibers and semi-finished products was carried out in an open impregnation bath. The die used was a die for flat profiles (45x5 mm cavity) with a 5-zone heating system. The fiber volume content of the investigated profiles in the unreinforced areas was 62% for the GFRP profiles and 61% for the CFRP profiles. For both the GFRP and CFRP profiles, the fiber volume content in the locally reinforced areas was approximately 70%, corresponding to additional local reinforcement percentages of 13% for the GFRP profiles and 15% for the CFRP profiles. The test setup of the pultrusion tests carried out is shown below in Figure 1:

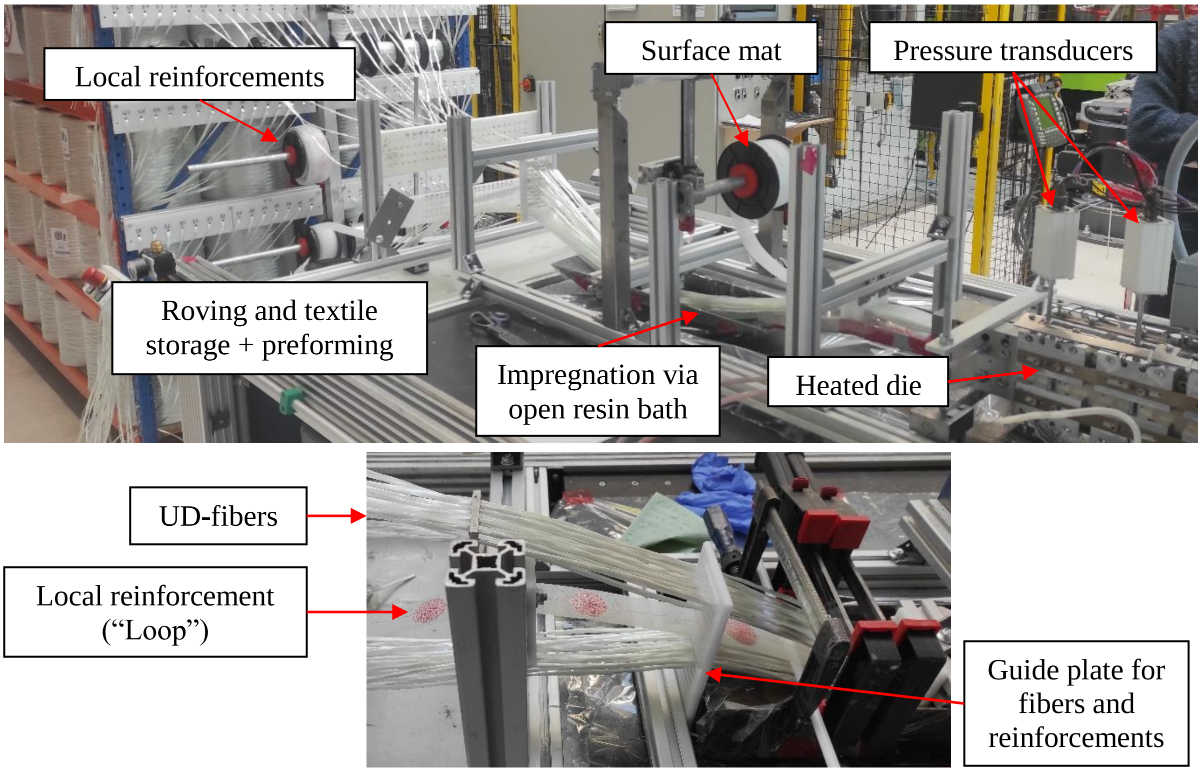

Figure 1: Pultrusion setup (top) and integration of the local reinforcements (bottom)

In order to enable a transfer of the process to an industrial scale, the developed reinforcement patterns were evaluated with regard to their transferability to an efficient and continuous textile manufacturing process. An interesting textile process in this context is the crochet galloon process, as it allows textiles with locally variable fiber courses to be produced. A reinforcement pattern suitable for transfer to a crochet gallon textile is the +/- 45° reinforcement. This can be transferred to a crochet galloon textile comparatively easily by locally adjusting the fiber orientations. The development and implementation of such a textile was carried out together with the company "Gustav Gerster GmbH & Co. KG", the developed textile is shown in Figure 2.

Figure 2: Crochet gallon textile with local oriented +/- 45 °-areas

The material data of the developed crochet gallon textile are listed below in Table 3:

Category	Name
Manufacturer	Gustav Gerster GmbH & Co. KG
Material	Glass fiber
Basic warp 90 ° and 0° layer	300 tex
0° und +/- 45 ° reinforcement	1200 tex
Crocheting yarn	PES 167/2 washed
textile-width	approx. 25 mm

Table 3: Material data of crochet gallon textile

The crochet gallon textile was processed in the pultrusion process to determine its reinforcing effect due to the locally varying fiber courses in the profiles. The textile was integrated into GFRP profiles with a fiber volume content of 62.4%. Glass fibers of the type “PS 4100” with 9600 tex by “Owens Corning” were used as reinforcing fibers of the UD laminate. For the profile surfaces the glass-nonwoven “Evalith SH50” was used, the used resin system was the epoxy “LITESTONE” by “Olin” in the composition shown in Table 2. The crochet gallon textile accounts for a fiber volume content of about 6.2%, so that the total fiber volume content is equivalent to 68.9%. Thus, the crochet-gallon textile accounts for a local share of approximately 8% of the fiber volume content.

2.5 Material testing of the pultruded profiles

Different investigation methods were used to characterize the locally reinforced pultruded products. Both an evaluation of the reinforcement effect and an analysis of the microstructure were carried out. The profiles produced were extensively characterized using mechanical testing methods in order to be able to make statements on the reinforcing effect of the TFP preforms. A common method for assessing the load-bearing capacity of bolted connections is the pin bearing strength tensile test [19], which is regulated by DIN EN 6037. In this test, a specimen provided with a hole is subjected to tensile loading via a bolt until it fails. The pin bearing strength determined in this way was used to compare the different reinforcement patterns. In addition, supplementary tests were carried out in the form of compression tests, open-hole tensile tests and tests with cyclic loads. The mechanical tests were carried out on a universal testing machine of the type “Zwick Z250” from “ZwickRoell GmbH & Co. KG”, the tests under cyclic loads were carried out on a universal testing machine from “Instron”.

Additionally, various investigations were carried out to analyze the microstructure. In order to evaluate the impregnation quality of the profiles, micrographs were taken which also allowed statements to be made on the shape and position of the reinforcement patterns within the profiles. The knowledge gained from this was supplemented by investigations using X-ray computed tomography.

3 RESULTS AND DISCUSSION

3.1 Simulative analysis

The initially designed reinforcement patterns were analyzed by an FEM analysis to estimate their reinforcement effect. In the simulation, different patterns were examined and an evaluation of the reinforcement effect was performed based on the simulated stress and strain reduction. In the simulation, the reinforcement patterns “Loop”, “Loop (double)”, “Loop + Radial” and “+/- 45°” were investigated. The results of the simulation are shown below in Figure 3. The patterns “Loop (double)”, “Loop + Radial” and “+/- 45°” performed best. With approximately 10% of the local fiber volume content, the patterns showed a significant reinforcing effect by the reduction of the maximum strain in the range of approximately 40% to 50%. The selected patterns were then used as a template in preform production using the TFP process.

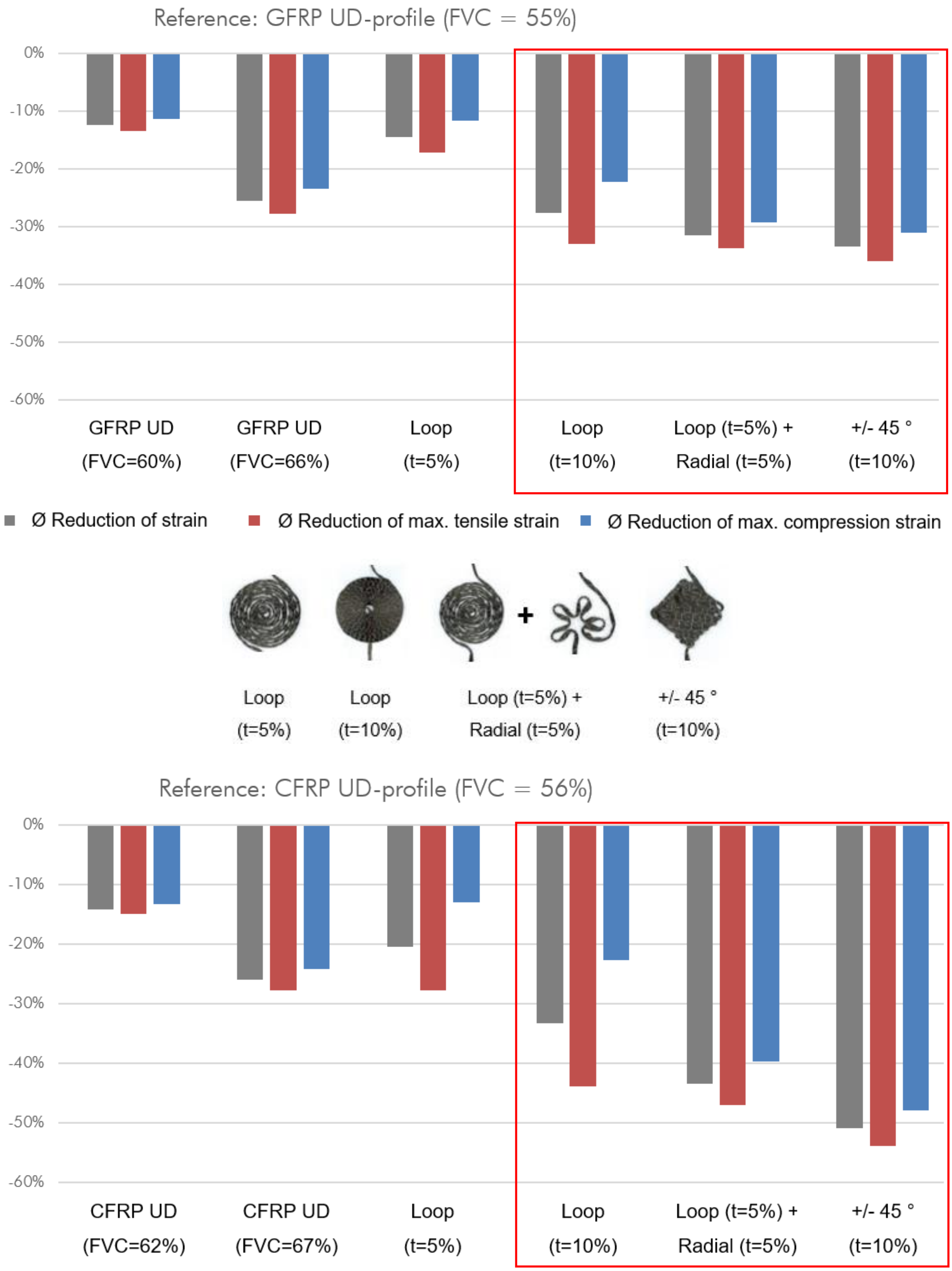

Figure 3: Results of the FEM-Simulation of the different reinforcement patterns

3.2 Pin bearing tests

For the investigation of the actual reinforcement effect, different preforms were produced on continuous embroidery base using the TFP process and then integrated in the pultrusion process for local reinforcement of the profiles. The locally reinforced pultruded specimens produced in this way were then used to make test specimens, which were mechanically characterized in bearing strength tensile tests. The determination of the bearing strengths was based on DIN EN 6037, and the tests were carried out on both GFRP and CFRP laminates. The dimensions of the specimens were 160x45x5 mm (LxWxH). The test specimens were provided with a hole for the test, which was loaded in the tensile direction via an inserted bolt. The hole and the bolt had a diameter of 10 mm for the test. The ratio of the lateral edge distance and the diameter of the hole (w/d) was 2.5, and the ratio of the edge distance of the hole in the tensile direction and the diameter (e/d) was 3.5. In addition to the locally reinforced pultruded specimens, specimens were taken from the unreinforced areas of the profiles. These had only one layer of the non-woven in the center of the profile and served as a reference for evaluating the reinforcing effect of the preforms.

The results of the pin bearing tests, which were carried out on the locally reinforced GFRP profiles, are shown below in Figure 4. In addition to the reinforcement patterns “+/- 45°” and “Loop”, which showed a promising reinforcement effect in the FEM simulation, further reinforcement patterns were investigated. The effect of a continuously increasing fiber volume content on the process stability over a larger area was to be investigated on the basis of two “extended” reinforcement patterns.

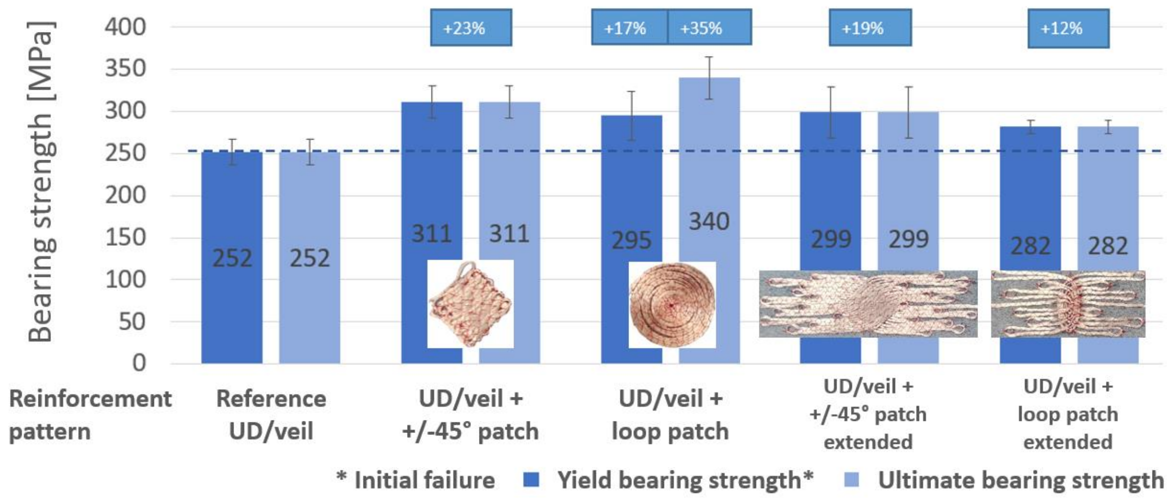

Figure 4: Pin bearing tests of GFRP-Laminates

The results show a comparatively low reinforcement effect of the introduced TFP preforms in the case of the GFRP preforms. The highest reinforcing effect was measured for the ultimate bearing strength of the “Loop” reinforcement pattern, which was improved by 35%. The maximum increase in the yield bearing strength is 23% and was achieved by the “+/- 45°” reinforcement pattern. The reinforcement effect of the extended reinforcement patterns which also have been examined in this case is somewhat lower. Increases of 19% and 12% in the yield bearing strength were achieved by the “+/- 45° extended” and the “Loop extended” patterns, respectively. In view of the reinforcing effect of the extended preforms, the additional increase in the amount of reinforcing material used is not considered reasonable.

In addition, the reinforcing effect of the different patterns on CFRP preforms was investigated in pin bearing tests. The results of the tests are shown in Figure 5:

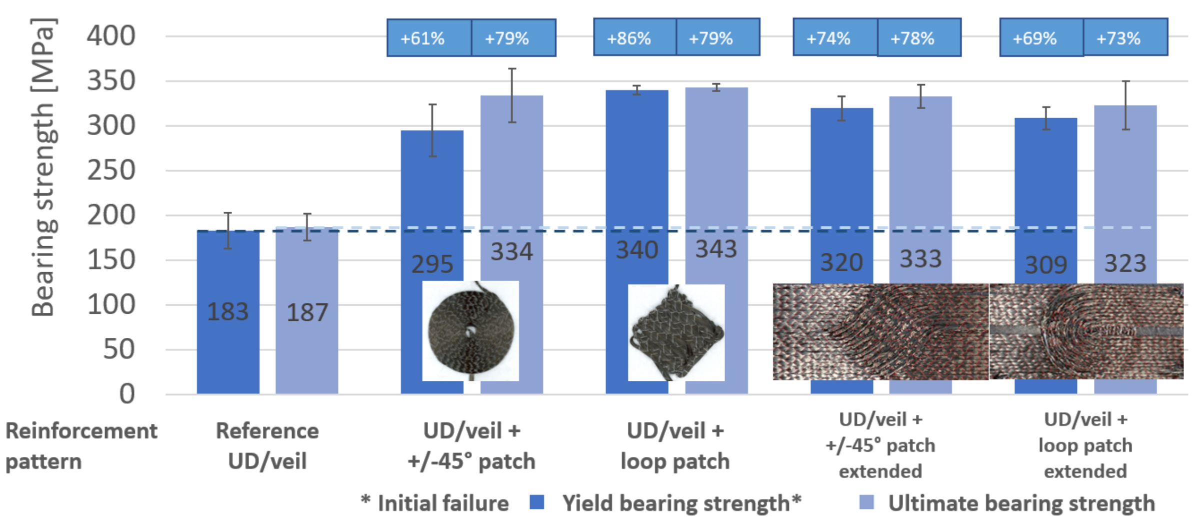

Figure 5: Pin bearing tests of CFRP-Laminates

The reinforcement effect for the locally reinforced CFRP pultruded parts is significantly higher than that for the GFRP laminates. Here, the highest increase in yield bearing strength is 86% in the case of "+/- 45°" reinforcement and the highest increase in ultimate bearing strength is 79% in the cases of "Loop" and "+/- 45°" reinforcements. It should be emphasized here that the level of the reference specimens from the CFRP trials is significantly lower than that of the reference from the GFRP trials. The UD laminates from the GFRP trials achieved a 37% higher limit hole frictional strength and 35% higher fracture hole frictional strength. In preliminary tests, a level of 248 MPa was achieved with unreinforced CFRP laminates, but with a larger edge distance (w/d = 3), which is why there is no direct comparability.

Furthermore, the introduced reinforcing structures changed the failure mode from an "abrupt" to a more "good natured" failure behavior. A comparison of the failure behavior of the unreinforced reference and one with the "+/- 45°" pattern is shown in Figure 6. It can be seen that in the locally reinforced case, the specimen has a certain residual load-bearing capacity after initial failure, and further elongation occurs until total failure. In the unreinforced case, on the other hand, the specimen fails abruptly and completely without any remaining load-bearing capacity.

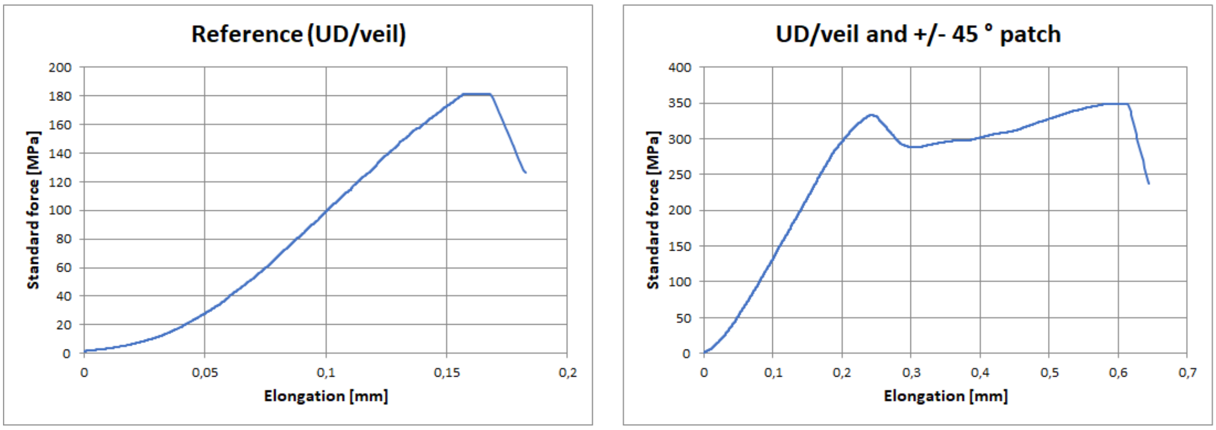

Figure 6: Comparison of failure behaviors (CFRP-laminates), UD/veil (left) and reinforced (right)

3.3 Supplementary tests

In order to provide a wide range of mechanical properties, tests of the locally reinforced profiles were carried out using supplementary test methods. The supplementary tests were carried out on specimens of locally reinforced GFRP profiles. These comprised the determination of the pin bearing strength when loaded in compression (according to DIN EN 6037) and the determination of the open-hole tensile strength. The dimensions of the specimens for the determination of the pin bearing strength were 160x45x5 mm (LxWxH) with a diameter of 10 mm for the hole. The specimens for the determination of the open-hole tensile strength had dimensions of 250x32x5 mm (LxWxH) with a hole diameter of 6.35 mm (1/4"). The results of these material tests are shown below in Table 4:

Property	Reference	+/- 45 °	+/- 45 ° (extended)	Loop	Loop (extended)
Yield bearing strength (compression, in MPa)	469	446	426	469	408
Standard deviation	34.8	38.9	44.11	26.3	51
Ultimate bearing strength (compression, in MPa)	469	452	436	469	411
Standard deviation	34.8	40.5	27.3	26.3	47.4
Open-Hole tensile strength (tension, in MPa)	597	Not tested	650	Not tested	Not tested
Standard deviation	17.8	-	13.9	-	-

Table 4: Results of the der supplementary mechanical tests

In addition, the pin bearing strength was determined with cyclic loads in fatigue tests (according to DIN 50100). The results of the mechanical tests with cyclic loads are shown in Figure 7.

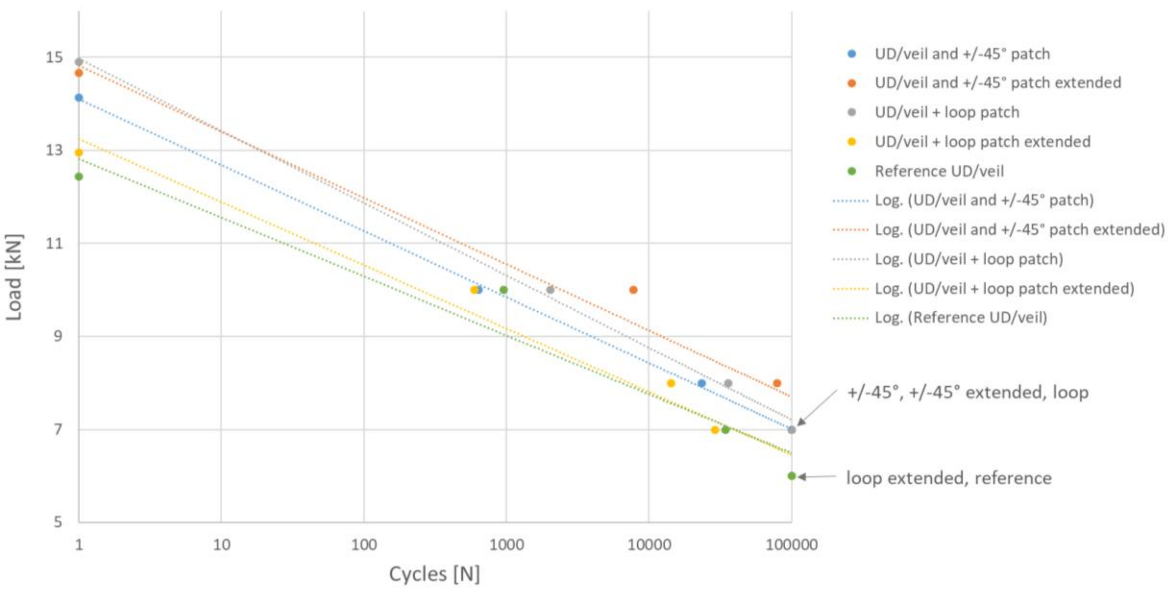

Figure 7: Results of cyclic pin bearing tests on local reinforced profiles

The compensation lines (dotted lines) show that, on average, the locally introduced reinforcements lead to an improvement in the fatigue behavior of the profiles. The straight line of the unreinforced reference sections is located below the straight lines of the locally reinforced sections in the diagram, which corresponds to a lower number of cycles withstood at the same load. The profiles reinforced with the pattern “+/- 45° extended” perform best here. Although the profiles reinforced with this pattern have a lower static pin bearing strength than the profiles reinforced with the “Loop” pattern, they can withstand a higher number of load cycles under cyclic loading.

3.4 Testing of the crochet-gallon textile

The profiles reinforced with the crochet-gallon textile were also tested in pin bearing tests to determine the reinforcing effect of the locally changed fiber orientations. The profiles were produced with die for flat profiles (cavity 25x4 mm). In order to obtain comparable ratios of the edge distances during testing, an adjustment of the hole diameter was made. This was therefore only 6 mm in this case, so that the ratios of w/d of 2.08 and e/d of 3.5 were present in the test. The results of the pin bearing tests on the profiles reinforced with the crochet-gallon fabric are shown in Figure 8:

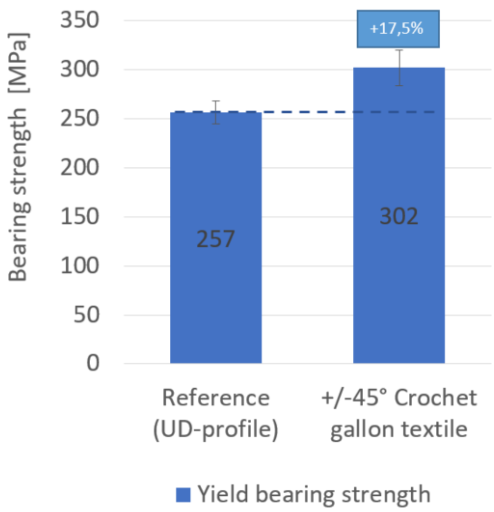

Figure 8: Results of Bearing strength tensile tests of Laminates reinforced with crochet-gallon fabric

The results show an increase of 17.5% in yield bearing strength due to the local adaptation of the fiber course in the crochet gallon textile compared to the unreinforced reference. The reinforcement effect is thus somewhat lower compared to the preforms produced by the TFP process (23%). However, it must be considered that the local reinforcement content here was approximately 13% of the fiber volume content, whereas in the case of the crochet-gallon textile it was only approximately 8%. With a comparably high reinforcement content, the crochet-gallon textile could therefore even perform better. Compared with the pure UD laminate, the integration of the crochet-gallon textile also brings an improvement in the failure behavior. The failure behavior can be described as good-natured, since it has a residual load-bearing capacity after the initial failure.

4 CONCLUSION AND OUTLOOK

This work presented a novel approach to overcome the weakness of pultruded FRP laminates in bolted connections by the integration of local textile reinforcements. In the conventional pultrusion process most of reinforcing fibers are oriented unidirectionally, resulting in reduced mechanical properties in bolted joints. To address this issue, textile semi-finished products with locally variable orientations have been developed. Using FEM simulation, the local reinforcement patterns “Loop” and

"+- 45°" showed significant improvements in the reduction of tensile and compressive elongation. The reinforcing patterns have been manufactured using the continuous "roll-to-roll" variant of the tailored fiber placement (TFP) process and were integrated into the pultrusion process.

By this, shares of the fiber volume content of 13% to 15% for the reinforcing patterns have been realized. The mechanical testing of the locally reinforced pultruded profiles showed significant improvements of pin bearing strengths by a maximum of 86% for CFRP and 35% for GFRP, while at the same time keeping the scatter of the measured values low. With this, the results of the mechanical testing confirm the FEM simulation: The reinforcing effect is higher for the CFRP variant compared to GFRP, and the "+/- 45°" and the "Loop" reinforcement also perform comparatively well.

Additionally, the transferability of the structures to more efficient textile manufacturing processes, such as crochet gallon, was investigated and successfully realized. The integration of a crochet gallon textile into pultruded GFRP profiles as a local reinforcement led to an increase in pin bearing strength of 17.5%. Considering the low share of the local fiber volume content of approximately 8%, the reinforcing effect of the crochet gallon textile could be described as comparably high. The use of more effective textile processes like the crochet gallon technology opens up possibilities for the industrial-scale implementation of the technology.

By locally adapting the fiber orientations in pultruded profiles, oversizing and associated drawbacks like an increased material consumption, lower pulling speeds and higher energy consumption can be reduced. The integration of local textile reinforcements enhances the overall mechanical performance of bolted joints in pultruded FRP laminates which leads to an expansion of potential applications of the pultrusion process and technical textiles.

Currently, the implementation of the technology in potential applications is being examined. Especially compression loaded CFRP profiles with a high stiffness requirement against buckling failure are technically and economically promising applications. For industrialization, an automated "patch-relocation" technology is reasonable which could be realized via an ultrasonic sensor or a laser-profiler. In addition, the transfer to other processes and materials is being investigated.

ACKNOWLEDGEMENTS

The work described was part of the IGF project "Patch-Pultrusion" (IGF-Nr. 21238 N/1). The project was funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK) within the framework concept "Central Innovation Program for SMEs". The authors are responsible for the contents of this publication.

REFERENCES

[1] T. F. Starr, *Pultrusion for engineers*, Band 2000. Woodhead Publishing Ltd, Cambridge, 2000

[2] D. Krebs, *Fundamentals of the Pultrusion Process for Production of FRP Components for the Requirements of Automotive Large-scale Production*, Dissertation, Karlsruher Institut für Technologie (KIT), Karlsruhe, 2018

[3] R. W. Meyer, *Handbook of Pultrusion Technology*, Chapman & Hall, London, 1985

[4] J. Fleischer, G. Lanza, P. T. Mativenga, H.-C. Möhring, R. Teti, A. Caggiano, *Composite Materials Parts Manufacturing*, 1st CIRP Conference on Composite Materials Parts Manufacturing, 2017

[5] M. Bannister, *Challenges for composites into the next millennium - a reinforcement perspective*, Composites Part A, 32(7):901-910, 2001

[6] J. Correia Ramôa, *Pultrusion of Advanced Fibre-Reinforced Polymer (FRP) Composites*, Advanced Fibre-Reinforced Polymer (FRP) Composites for Structural Applications, 2013

[7] S. C. Lange, *Miniaturisierung des Strangziehverfahrens am Beispiel der Herstellung von Kanülen aus kohlenfaserverstärkten Kunststoffen*, Dissertation, RWTH, Aachen, 2005

[8] X. Xu, L. He, B. Zhu, J. Li and J. Li, *Advances in polymeric materials for dental applications*, Polymer Chemistry, 8(5), 2017, 807–823

[9] R. Geiger, J. Pahl, *CFK-Strukturen in der automobilen Serienfertigung*. Lightweight Design 10, 2017, 52–57

[10] I. Baran, *Pultrusion: State-of-the-art – Process Models*, Smithers Information Limited, Shawbury, 2015

[11] S. C. Joshi, *The Pultrusion Process for Polymer Matrix,* Manufacturing Techniques for Polymer Matrix Composites, Woodhead Publishing, Philadelphia, 2012; pp. 381–413

[12] E. Witten, V. Mathes, *Der europäische Markt für Faserverstärkte Kunststoffe / Composites 2021: Marktentwicklungen, Trends Herausforderungen und Ausblicke*, AVK e.V., Frankfurt, 2022

[13] A. M. Girao Coelho, J. T. Mottram, *A review of the behavior and analysis of bolted connections and joints in pultruded fibre reinforced polymers*, Elsevier, Coventry, 2015

[14] R. R. Hizam, W. Karunasena, A. C. Manalo, *Effect of mechanical insert on the behavior of pultruded fibre reinforced polymer (FRP) bolted joint*, Fourth Asia-Pacific Conference on FRP Structures (APFIS), Melbourne, 2013

[15] V. Wang, *Bearing Behavior of Joints in Pultruded Composites*, Journal of Composite Materials, 36(18), 2013, 2199-2216

[16] R. Rolfes, J. Tessmer, R. Degenhardt, H. Temmen, P. Bürmann, J. Juhasz, *New Design Tools for Lightweight Aerospace Structures*, Seventh International Conference on Computational Structures Technology, Lisbon, 2004

[17] G. Gardiner, *Tailored Fiber Placement: Besting metal in volume production*, Composites World, Cincinnati, 2013

[18] H. Schürrmann, *Konstruieren mit Faser-Kunststoff-Verbunden,* Springer Verlag, Berlin/ Heidelberg, 2007

[19] Y. Cao, D. Zuo, Y. Zhao, Z. Cao, J. Zhi, G. Zheng, T. E. Tay, *Experimental investigation on bearing behavior and failure mechanism of double-lap thin-ply composite bolted joints,* Composite Structures, Volume 261, 2021