Moniruddoza Ashir*, Georg Bardl, Lars Hahn, Andreas Nocke, Chokri Cherif

Technische Universität Dresden, Institute of Textile Machinery and High Performance Material Technology,
01069 Dresden, Germany
* e-mail: moniruddoza.ashir@tu-dresden.de

Mechanical Characterisation of Carbon Fibre-Reinforced Plastics with Defined Defects

DOI: 10.5604/01.3001.0012.5173

Abstract
A steadily increasing application of fibre-reinforced plastics in the field of lightweight construction has been observed in the course of the past two decades. Currently a major challenge in the growing high technology market is the quality assurance of manufactured fibre-reinforced plastic components. During different stages in the manufacturing process of fibre-reinforced plastics, defects of different types and sizes are enclosed in them, exerting a destructive influence on the performance of fibre-reinforced plastics in various practical applications in terms of strength, stiffness and brittleness. Thus the aim of this research project was to investigate the effect of defined local defects on the mechanical properties, such as tensile, flexural and impact properties, of fibre-reinforced plastics, in particular carbon fibre-reinforced plastics. Results show that these mechanical properties depend significantly on the type and size of defect.

Key words: *carbon fibre-reinforced plastics, defects, mechanical characterisation.*

Introduction

Lightweight materials have been enjoying growing popularity in various industrial sectors, especially in the aerospace, automotive and mechanical engineering, resulting from, among other things, rising oil and energy prices in the last twenty years. The current focus of lightweight material industries is on fibre-reinforced plastics, particularly on carbon fibre-reinforced plastics (CFRPs), since they offer higher relative specific tensile strength and stiffness as well as a weight reduction of up to 70% compared to steel [1, 2]. Different CFRP components currently available on the market are manufactured from textile reinforcing fabrics consisting of carbon fibres built up in layers. Remarkable examples of CFRP components include the series production of the Airbus A350XWB (wing and fuselage are made of CFRPs) and the BMW i series (car bodies of BMW i3 and BMW i8 are made of CFRPs) [3]. Other fast-growing market sectors with possible applications for CFRPs are wind turbine and marine engineering. Various market studies expect the growth rate of CFRPs to rise from 13% to 17% in the next 10 to 15 years [4, 5].

Currently a major challenge for this high technology market is the quality assurance of manufactured CFRP components. The BMW Group – the manufacturer of the CFRP-based i-Series – claims that due to internal quality issues, occurring mainly during the different stages of CFRP production, only about half of the CFRP components produced in total are actually utilised [6]. Because of the relatively new and complex manufacturing process, internal quality issues or defects occur in CFRPs.

Defects in CFRPs are classified as minor and major defects. A minor defect is tolerable, while a major defect is intolerable and must be avoided. Major and minor defects are categorised by the defect damage threshold, which depends on the structural complexity of CFRPs [7]. These defects in CFRPs are produced during their manufacturing or in-service performance [8]. Voids, foreign bodies, incorrect fibre volume due to insufficient or excess resin, bonding defects, fibre misalignment, wavy fibres, ply cracking, delamination, and the fracture or buckling of fibres are some examples of defects occurring in CFRPs [8, 9]. These appear randomly in CFRPs. A systematic analysis is therefore necessary in order to evaluate the quality of CFRPs.

Thus the fabrication of CFRPs with defined defects for quality evaluation by destructive and non-destructive methods has received considerable attention [10-21]. Zöcke *et al.* [15] produced CFRPs with flat bottom holes of different diameters and depths for quantitative evaluation of optical lock-in thermography measurements of CFRPs. The development of CFRPs with defined defects containing Poly Tetra Fluoro Ethylene (PTFE) for comparison of different non-destructive testing methods was described in [16]. In this case, the man-made delamination between different layers of CFRPs was produced with different sizes of PTFE. Kochan [17] developed CFRPs with defined local defects containing aluminum oxide hollow balls and polystyrol balls for ultrasonic and thermographic non-destructive testing. However, all efforts regarding the production of CFRPs containing local defects have been limited to qualitative and quantitative evaluation by non-destructive testing (NDT), ultrasonic testing, thermographic testing,

Table 1. Specifications of unidirectional non-crimp fabrics used (UD-NCFs).

Parameter	Value
Areal weight, g/m^2	300
Thickness, mm	0.33
Width, mm	600
Fineness of individual roving, tex	800 (12k)

the eddy current scanning system, x-ray testing, and phase array or sampling phase array technology, for instance.

Developments regarding the delamination of CFRPs made from unidirectional non-crimp carbon fabrics using a pendulum impact tester were reported in [17]. Numerical and experimental trials regarding the critical buckling load of laminated glass fibre-reinforced plastics with strip delamination were investigated in [18]. The effect of the position of the defined local defect and the influence of a defined amount of voids on the mechanical properties of CFRPs was also described in [19, 20]. The comparability of NDT methods in detecting defects strongly depends on the type of defect. Whereas conductive foreign objects, for instance copper (Cu) sheet, can be easily detected with eddy current testing [21], and non-conductive defects like PTFE foil can only be detected well with ultrasonic methods [14]. However, it is not clear if the effect of these different defects is comparable.

Thus the aim of this research project was to systematically investigate the relationship between different types and sizes of defects and the mechanical performance of CFRPs. In order to establish this relationship, CFRPs with defects of different types and sizes were fabricated. Next mechanical characterisation of CFRPs with and without defects was undertaken by means of tensile, bending and impact tests.

Experimental

Materials

Unidirectional (UD) non-crimp reinforcing fabrics (NCFs) of carbon rovings (SGL Group, Germany) were selected for this research project due to their excellent mechanical properties in the warp direction compared to other types of reinforcing fabrics, such as woven or knitted fabrics [22]. Furthermore UD-NCFs have been used in the aerospace industries for many years due to their superior mechanical properties [23]. Specifications of the UD-NCFs used are listed in ***Table 1*** [24].

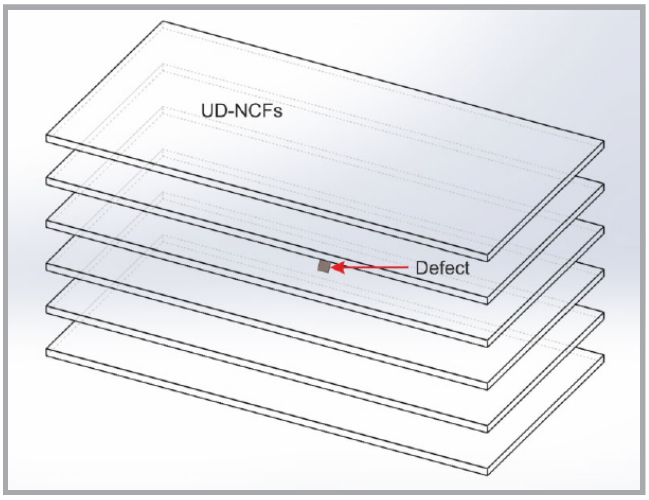

Figure 1. Defect laying in the middle of the six layers of UD-NCFs.

Different types of defects, such as metal and plastic particles, hollow balls, liquid drops, packaging materials, fibre particles and auxiliary materials of impregnation, can be incorporated into CFRPs during the processing stage. In this research project, example defects – Cu sheet (noll electronik, Germany) and PTFE foil (Rump Folien GmbH, Germany) were used. Additionally in order to create the delamination between UD-NCF layers in CFRPs, a liquid defect – separating agent (Mikon®700 MC, Münch Chemie International GmbH, Germany) was adopted.

The thickness of Cu and PTFE was 0.03 and 0.05 mm, respectively. The density of the liquid separating agent at 20 °C was 0.78 g/cm^3. Infusion resin MGS RIMR 135 and hardener RIMH 137 (Hexion, Sokolov, Czech Republic) were utilised as resin systems. Before initiating the impregnation process, the matrix and hardener were mixed at a ratio of 10:3 by weight. The density, flexural strength, tensile strength, compressive strength and impact strength of the resin-hardener mixture applied were 1.18 g/cm^3, 90 N/mm^2, 60 N/mm^2, 80 N/mm^2 and 70 kJ/m^2, respectively [25].

Fabrication of CFRPs with defined defects

In order to fabricate CFRPs with different defects, UD-NCF was cut to 300×600 mm^2, which is an appropriate size for samples in the process of mechanical characterisation. In order to achieve the required thickness of the CFRP, i.e. 2 mm during mechanical testing, six layers of UD-NCFs were used during impregnation. The size of the defects was varied in order to reveal the change in mechanical performance of the CFRP. Hence the Cu sheet and PTFE foil were tailored to the size of 1×1, 2×2, 3×3 and 6×6 mm^2. As the separating agent is naturally liquid, it was applied between the layers of UD-NCFs using a brush on hard paper. The hard paper was cut to the same size as the Cu and PTFE. The Cu, PTFE and liquid separating agent in the dimensions mentioned above were placed in the middle of the six layers of UD-NCFs parallel to the fibre length direction. A representative laying of the defect in the middle of the test sample is shown schematically in ***Figure 1***.

Moreover UD-NCFs were arranged perpendicular to a metal mould and in parallel to each other during the laying process, consequently all carbon fibres were tensioned in the same direction during mechanical characterisation. The impregnation of UD-NCFs with defined defects was executed by means of the Seemann Composites Resin Infusion Molding Process (SCRIMP). A systematic representation of the fabric laying and impregnation process is shown in ***Figure 2***. Details of the SCRIMP process can be found in [26]. In order to compare the change in mechanical performance of CFRPs with defects to those without defects, 6 layers of UD-NCF without defects were impregnated as well. A CFRP without defects was defined as the reference.

After the impregnation, the treated UD-NCFs were cured in an oven at 50 °C for 15 hours. After curing, the CFRP was tailored to the required size in accord-

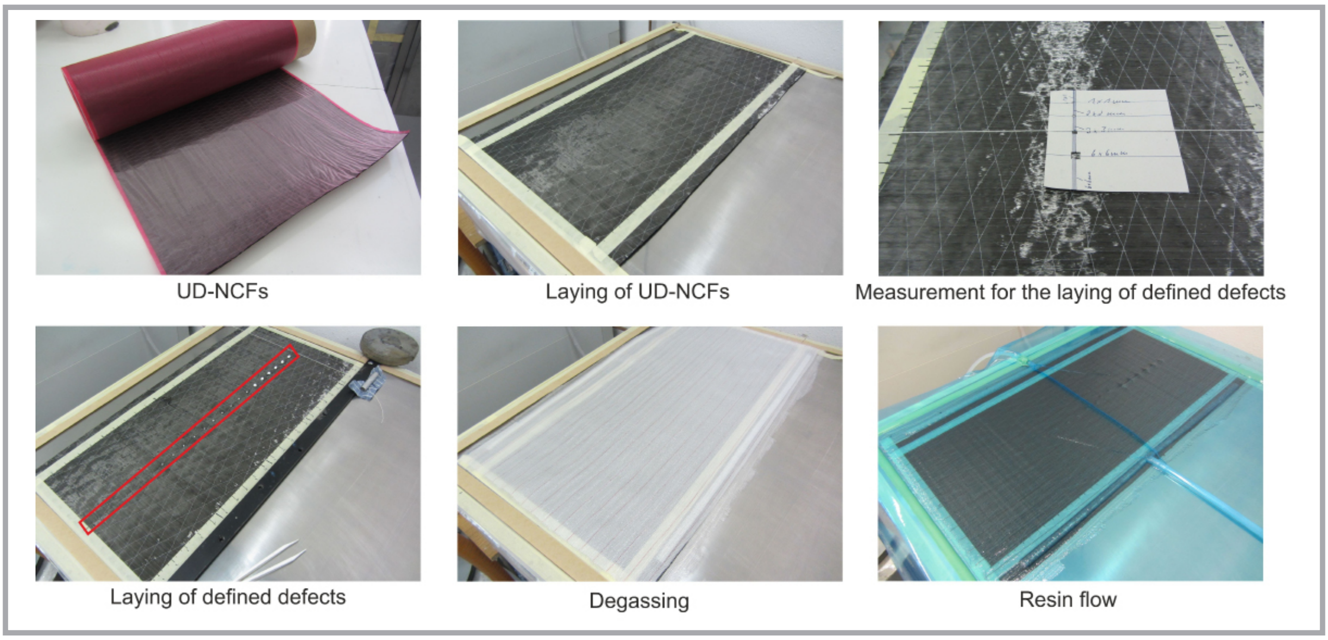

***Figure 2.** Laying of defects and impregnation process for the fabrication of CFRPs with defects.*

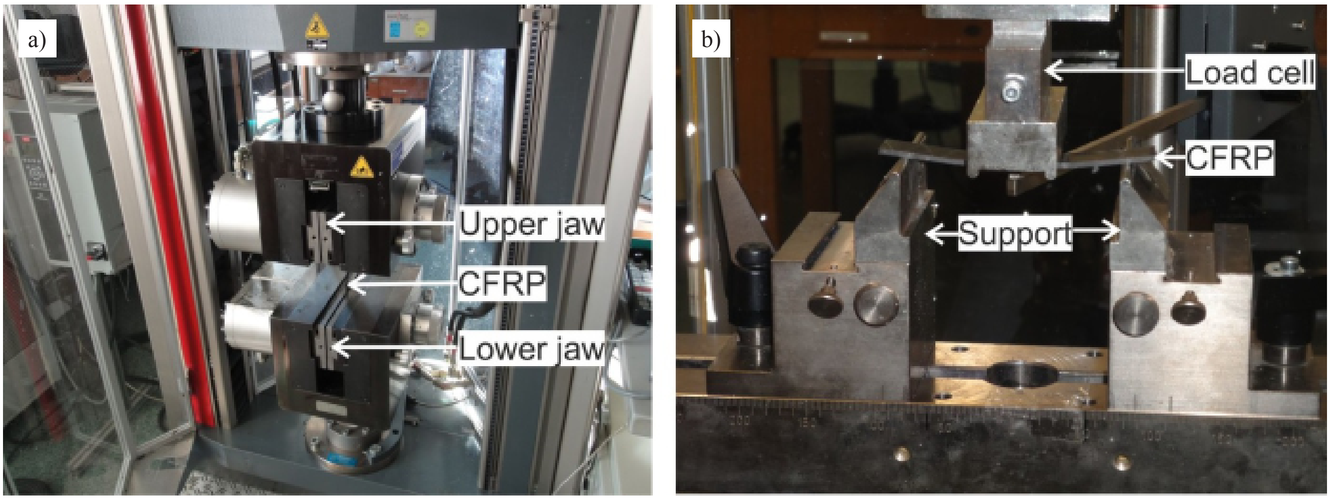

***Figure 3.** Testing machine Zwick Z100 for the a) tensile and b) bending testing [19].*

ance with mechanical testing standards (c.f. ***Table 2***) by means of a laboratory wet saw.

Mechanical characterisation

In order to investigate the influence of defects of different types and sizes on the strength, stiffness and brittleness of CFRPs, mechanical characterisation was undertaken by means of tensile, bending and impact tests. The tensile and bending tests were performed using the testing machine Zwick Z 100 (Zwick GmbH & Co. KG, Germany). The testing device with a test setup for tensile and bending testing is shown in ***Figure 3***. A 4-point bending test was performed in order to characterise the stiffness of the CFRPs. The impact test was based on the principles of Charpy impact test technology, and carried out on a Charpy pendulum impact tester CEAST 9050 (Instron GmbH, Germany). A 15 J pendulum with a fall speed of 3.8 m/s was used to break the specimens. All tests were performed at 23 °C temperature and 50% relative humidity (RH) according to DIN EN ISO 291. The test standards applied during the tensile, flexural and impact tests are listed in ***Table 2***. Each test was performed seven times, and their average was calculated.

***Table 2.** Norm and dimensions of mechanical characterisation of CFRPs.*

Test	Norm	Dimension, mm		
		Length	Width	Thickness
Tensile	DIN EN ISO 13934-1	250	15	2
Bending	DIN EN ISO 14125	100	15	2
Impact	DIN EN ISO 179-1	40	15	2

Results and discussion

The results of tensile, bending and impact testing are described for both reference CFRPs and CFRPs with defects in this section. In addition, the loss of mechanical performance of CFRPs with defects depending on their type and size is discussed and compared to the performance of reference CFRPs.

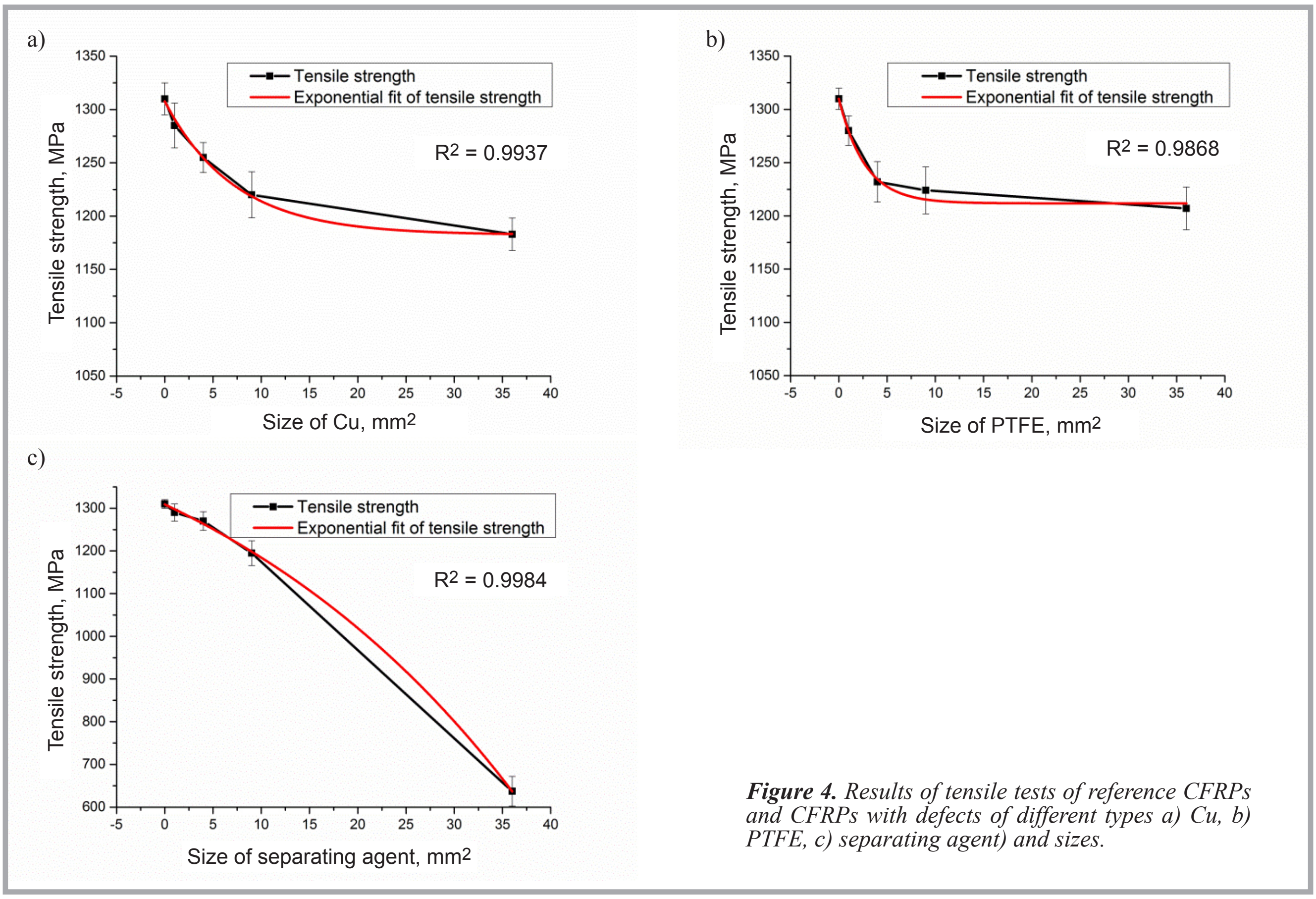

Figure 4. *Results of tensile tests of reference CFRPs and CFRPs with defects of different types a) Cu, b) PTFE, c) separating agent) and sizes.*

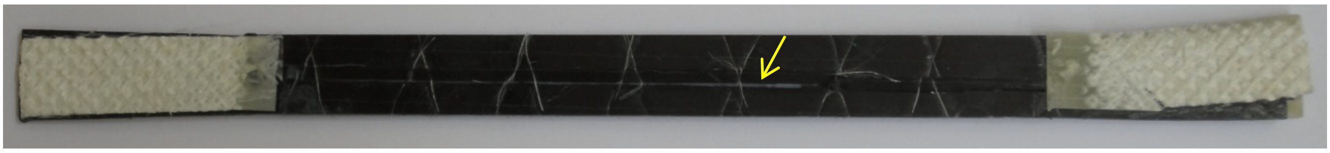

Figure 5. *Rupture of CFRP with copper after the tensile test. The rupture line is marked by a yellow arrow.*

Tensile tests

Results of the tensile tests of reference CFRPs and CFRPs with defects of different types and sizes are shown in ***Figure 4.***

As displayed in ***Figure 4***, the maximum tensile strength occurred in the case of reference CFRPs. A tendency towards a slight reduction in tensile strength with an increasing size of defects is apparent in ***Figure 3***.

The size of the defect influenced the results of the tensile tests. Since the defect was very small in comparison to the sample size, the tensile strength of reference CFRPs and that of CFRPs with a defect the size of 1×1 mm^2 were almost the same for all types. The CFRP produced with a 6×6 mm^2 defect showed less tensile strength than that containing a defect with a size of 1×1 mm^2. This resulted from the greater size of the defect interrupting adhesion between the fibre and matrix to a greater degree, thus causing delamination. The delamination affected load transmission from the matrix to fibres, and consequently the material strength was reduced. Some deviations can be seen in ***Figure 4***, which presumably resulted from manual processing.

Figure 4 gives a comparison of the loss in tensile strength of CFRPs with different types of defects. Due to the surface or chemical state of the defects and the interfacial interaction between the matrix and defects, the loss of tensile strength of CFRPs varies with the types of defects. The tendency of tensile strength loss is almost the same for Cu and PTFE, which is due to the planar solid state of Cu and PTFE. However, PTFE is an almost inert component in contact with epoxy resin, while the metal surface can form strong mechanical or even chemical-in-nature bonds with the epoxy resin. Probably because of the very small size of defects compared to CFRPs, the comparative tensile strength loss is almost similar to that of CFRPs with Cu and PTFE. It is also observed that the thickness difference between Cu and PTFE has very little influence on the results observed since the thickness difference between them is very small compared to CFRPs as well as to the length and width of Cu and PTFE.

It can be seen that the application of a separating agent has a much greater influence on the tensile strength of CFRP. Not only is the strength for the applied area size much more reduced than for the other two defects, due to the liquid state of the separating agent, it also penetrates into the UD-NCF layers and prevents the resin from bonding these layers. Therefore it generates a much bigger defect volume.

Based on these discussions, it can be concluded that the separating agent and defect with a size of 6×6 mm^2 harm the ten-

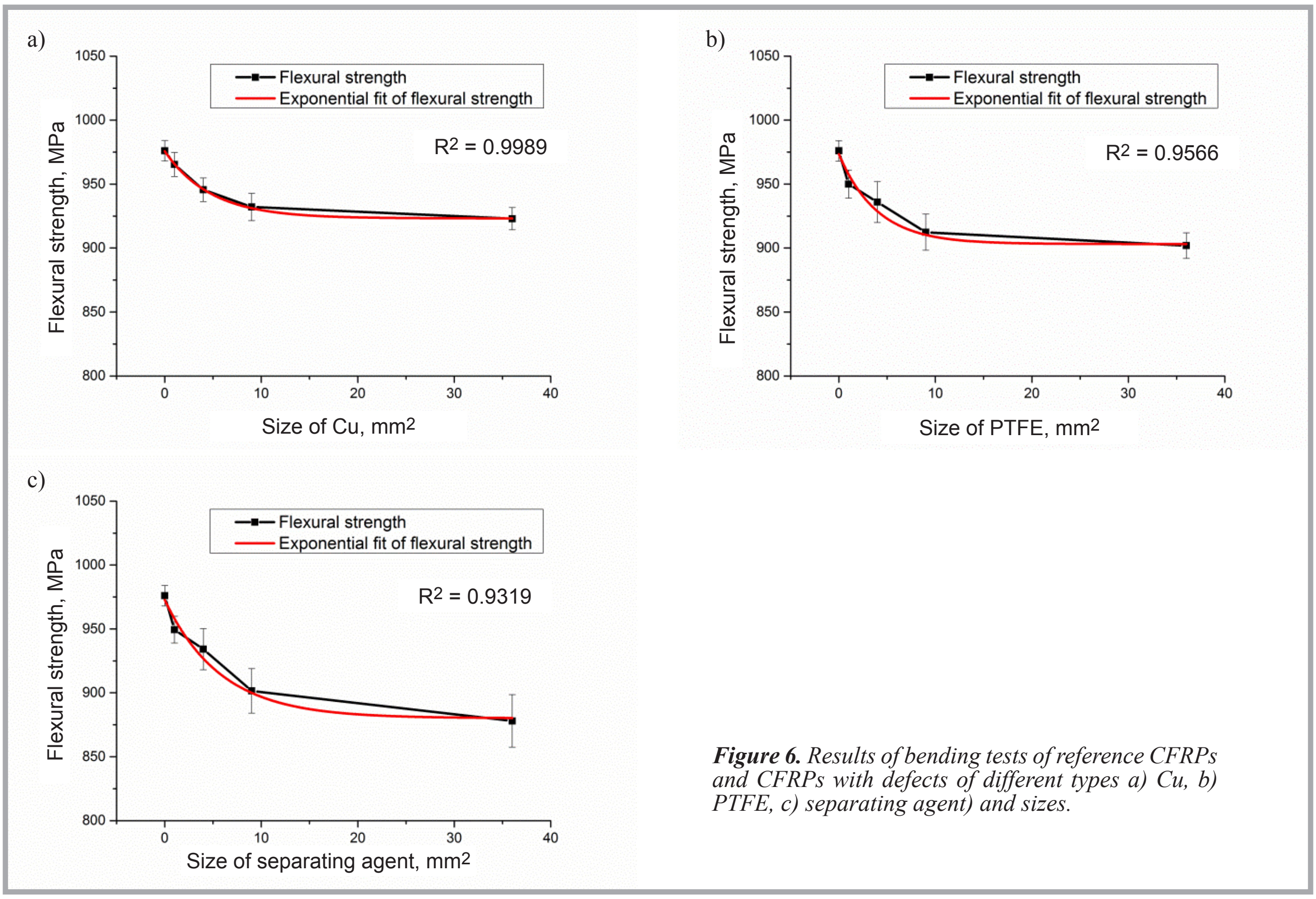

Figure 6. *Results of bending tests of reference CFRPs and CFRPs with defects of different types a) Cu, b) PTFE, c) separating agent) and sizes.*

Figure 7. *Rupture of a CFRP with copper after the bending test.*

sile strength of CFRP the most. Here the tensile strength of reference CFRPs and CFRPs with defects of all types were fitted exponentially.

The tensile tests performed revealed in the case of defects of all sizes and types (Cu, PTFE and separating agent) that rupture occurred at the place of the inserted defects in the test specimen. The defects – situated between the fabric layers in CFRPs – interrupted the adhesion between the matrix and reinforcing fibres. Thus rupture occurred at the place of the defects in CFRPs. As an example of these types of defects, the breakage of Cu after the tensile test is shown in ***Figure 5***.

Bending tests

Results of the bending tests of CFRPs performed in terms of flexural strength are shown in ***Figure 6***. The flexural strength of CFRPs with a defect showed the same tendency as the tensile tests. In this case, the flexural strength of CFRPs with integrated Cu, PTFE and separating agent decreased in an exponential manner. However, some deviations in the case of CFRPs with defects are presented in ***Figure 6***. This can be attributed to the displacement of the defects during impregnation on one hand, and a lack of precision during the tailoring of the CFRPs on the other.

The results for the flexural strength remain in the range of 870 to 970 MPa, and the size and type of the defect had a significant impact on the bending behavior of CFRPs. After completion of the bending tests, the sample broke completely. As an example, a CFRP with integrated copper after a bending test is shown in ***Figure 7***.

Impact strength

Results regarding the impact strength of reference CFRPs and CFRPs with defects are demonstrated in ***Figure 8***. The impact strength exhibited the same tendency as the tensile and flexural strength.

Figure 8 reveals that the impact strength of CFRPs decreased in an exponential manner by increasing the size of defects. This indicates that by do so, CFRP becomes prone to brittleness. Variations were presumably caused by manual production.

Full, partial and no-breakage – these are the three types of sample breakage occurring in impact tests according to DIN EN ISO 179-1. All samples evaluated within this research project exhibited a complete rupture after the impact test. As an example, a sample of Cu after an impact test is shown in ***Figure 9***.

Conclusions

The aim of this research project was to conduct a mechanical characterization of CFRPs. In order to achieve this goal, CFRPs were fabricated with different defects associated with their different sizes.

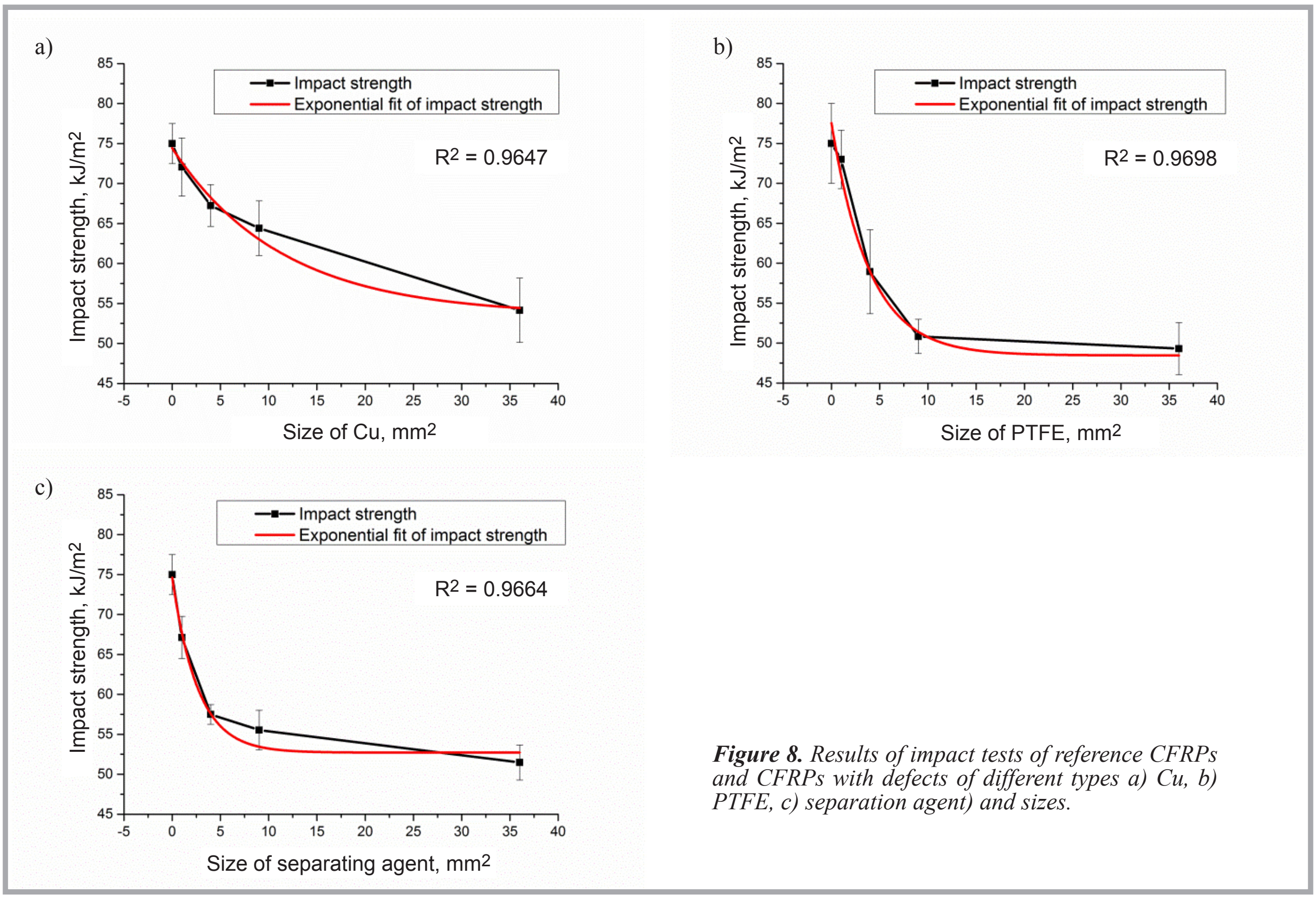

Figure 8. *Results of impact tests of reference CFRPs and CFRPs with defects of different types a) Cu, b) PTFE, c) separation agent) and sizes.*

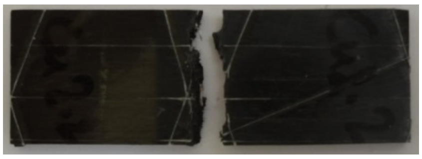

Figure 9. *Rupture of a CFRP with integrated copper after the impact test.*

In order to reveal the effect of the type and size of defect on the strength, stiffness and brittleness of the CFRPs, tensile, bending and flexural tests were performed, and results were compared to those of reference CFRPs. Essentially we can conclude that the qualitative effects of defects on the mechanical properties of CFRPs were determined. The next step will be to use this knowledge for a simulation model of defects in CFRPs.

Acknowledgements

The results are compiled in the cooperation projects KF2048951WM4 (Technische Universität Dresden) within the scope of a ZIM initiative promoted by the Federal Ministry for Economy and Energy. Financial support is gratefully acknowledged.

References

1. Lässig R, Eisenhut M, Mathias A, et al. Series production of high-strength composites. Perspectives for the German engineering industry. Roland Berger Strategy Consultants; 2012.
2. Petrulis D, Petravičius A, Petrulyte S. Effects of the Functional Compound on the Properties of Composite Tape Yarns. *FIBERS AND TEXTILES in Eastern Europe* 2016; 3(117): 44-50. DOI: 10.5604/12303666.1196611.
3. Pinho LV, Carou D, Davim JP. Comparative study of the performance of diamond-coated drills on the delamination in drilling of carbon fiber reinforced plastics: Assessing the influence of the temperature of the drill. *Journal of Composite Materials* 2016; 50: 179-189.
4. Jahn B. Der globale CFK-Markt. In: Industrievereinigung Verstärkte Kunststoffe e.V. (AVK) und Carbon Composites e.V (CCeV). Composites-Marktbericht; 2013 (in German).
5. Holmes M. Carbon fibre reinforced plastics market continues growth path. *Reinforced Plastics* 2013; 57: 24-29.
6. Freitag M. Carbon – BMW hat Nachschubprobleme beim Bau des i3. Available at: http://www.manager-magazin.de/unternehmen/autoindustrie/carbon-bmw-hat-nachschubprobleme-beim-bau-des-i3-a-954274.html (accessed 21.06.2017).
7. Erb T, Schürmann H. Fibre-reinforced plastics: A new method for defect assessment. *Auto Technology* 2005; 5: 68-71.
8. Smith RA. Composite defects and their detection.pdf. Band 3, EOLSS. Available at: http://www.eolss.net/sample-chapters/c05/e6-36-04-03.pdf (accessed 31.07.2017).
9. Heslehurst RB. Defects and damage in composite materials and structures. CRC press; 2014. ISBN 978-1-1380-7369-2.
10. Poudel A, Shrestha SS, Sandhu JS, et al. Comparison and analysis of Acoustography with other NDE techniques for foreign object inclusion detection in graphite epoxy composites. *Composites Part B: Engineering* 2015; 78: 86-94.
11. Barry TJ, Kesharaju M, Nagarajah C. Defect characterisation in laminar composite structures using ultrasonic techniques and artificial neural networks. *Journal of Composite Materials* 2016; 50: 861-871.
12. Liu B, Zhang H, Fernandes H. Quantitative Evaluation of Pulsed Thermography, Lock-in Thermography and Vibrothermography on Foreign Object Defect (FOD) in CFRP. *Sensors* 2016; 16(5): 743. DOI:10.3390/s16050743.
13. Tartare M, Rebuffel V, Ducros N, et al. Dual and Multi-energy Radiography for CFRP Composites inspection. 11th European Conference on Non-Destructive Testing (ECNDT 2014), October 6-10, 2014, Prague, Czech Republic.
14. Xu Y, Chen R, Liu Z. An acoustic-optical fiber NDE technique for interfacial debonding detection in FRP-retrofitted

structures. *NDT & E International* 2015; 72: 50-57.
15. Zöcke C, Langmeier A, Stössel R, et al. Quantitative Auswertung von Fehlstellen an Bauteilen aus Faserverbundwerkstoff mit Lock-In Thermographie. Thermografie-Kolloquium 2007 – Vortrag 17 (in German).
16. Cheng L, Tian GY. Comparison of Nondestructive Testing Methods on Detection of Delaminations in Composites. Available at: http://www.hindawi.com/journals/js/2012/408437/, (accessed 04.11.2017).
17. Kochan A. Untersuchungen zur zerstörungsfreien Prüfung von CFK-Bauteilen für die fertigungsbegleitende Qualitätssicherung im Automobilbau. PhD dissertation: Technische Universität Dresden, Germany; 2011 (in German).
18. Pekbey Y, Sayman O. A numerical and experimental investigation of critical buckling load of rectangular laminated composite plates with strip delamination. *Journal of Reinforced Plastics and Composites* 2006; 25: 685-697.
19. Ashir M, Nocke A, Cherif C. Effect of the position of defined local defect on the mechanical performance of carbon fiber-reinforced plastics. *AUTEX Research Journal* Epub ahead of print 16 October 2018. DOI: 10.1515/aut-2018-0034.
20. Ashir M, Nocke A, Bulavinov A, et al. Influence of defined amount of voids on the mechanical properties of carbon fiber-reinforced plastics. *Polymer Composites* Epub ahead of print 7 March 2018. DOI:10.1002/pc.24820.
21. Heuer H, Schulze M, Pooch M, et al. Review on quality assurance along the CFRP value chain – Non-destructive testing of fabrics, preforms and CFRP by HF radio wave techniques. *Composites Part B: Engineering* 2015; 77: 494-501.
22. Cherif C. Textile Materials for Lightweight Constructions: Technologies-Methods-Materials-Properties. Berlin, Heidelberg: Springer-Verlag GmbH; 2016. ISBN 978-3-662-46340.
23. http://www.faa.gov/regulations_policies/handbooks_manuals/aircraft/amt_airframe_han dbook/media/ama_ch07.pdf (accessed 12.04.2016).
24. SGL. Specification sheet. Available at: http://www.sglgroup.com/cms/_common/downloads/products/productgroups/cm/textile-products/SIGRATEX_Textile_materials_made_from_Carbon_Glass_Aramid_Fibers_e.pdf (accessed 15.05.2017).
25. Hexion. Specification sheet. Available at: https://www.hexion.com/Products/TechnicalDataSheet.aspx?id=8246 (accessed 21.06.2017).
26. Prockat J. Developing large structural parts for railway application using a fiber reinforced polymer design. Universitätsverlag der TU Berlin; 2005. ISBN: 978-3798319554.

Received 13.10.2017 Reviewed 31.08.2018