EFFECT OF THE POSITION OF DEFINED LOCAL DEFECT ON THE MECHANICAL PERFORMANCE OF CARBON-FIBER-REINFORCED PLASTICS

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Abstract:

Considering their energy and resource efficiency, fiber-reinforced plastics (FRPs) have been displacing metals and metal alloys for lightweight constructions. During the semiautomated manufacturing process of FRPs, and in particular during the laying of reinforced fabric layers, foreign bodies are enclosed within them, which in turn reduce the mechanical performance of FRPs. The research project presented in this article investigated if the loss in mechanical properties, such as tensile, flexural, and impact strengths, depends on the position of defined local defects, polytetrafluorethylene (PTFE) in this case, in the thickness direction of FRPs. In order to achieve this aim, PTFE was placed in different layers of reinforcing fabric before infusion. Subsequently, the mechanical performance of the fabricated FRPs was tested and evaluated. On the basis of the experiment, it can be concluded that the loss in mechanical properties was maximal if PTFE was laid in the middle position of FRPs in the thickness direction.

Keywords:

Fiber-reinforced plastics, defined local defects, mechanical characterization

1. Introduction

Fiber-reinforced plastics (FRPs) are a new class of materials, which is characterized by low density, corrosion resistance, and superior mechanical properties, such as higher specific strength (strength-to-density ratio) and specific rigidity (E-module-to-density ratio). Thus, they increasingly displace conventional constructional materials in the automotive, aerospace, and plant engineering industries [1-3]. For example, FRPs are used for Italian supercars; the BMW i3; Boeing 757, 767, 777, 787; and Airbus A310, A320, A330, A340, A350 and in even more exotic applications, for example, unmanned aerial vehicles (UAV), space launchers, or satellites with a weight reduction of around 70%, wherein per kg weight reduction saves more than 2,900 l of fuel per year [4,5]. Consequently, the application of FRPs leads to resource efficiency, on the one hand, and to environmental sustainability, on the other hand.

For the highly stressed and critical parts of FRPs, depending on their end application, the quality control of the manufactured FRPs is crucial. Owing to the internal quality issues, only about half of the produced FRP components are actually used [6]. Nondestructive testing (NDT) and destructive testing (DT) are the common methods for the quality control of FRP parts. Visual, ultrasonic, thermography, radiographic, electromagnetic, acousto-ultrasonic, and shearography testing are some common NDT methods [7]. The major advantage of NDT is more accurate and reliable inspection data. By means of the color code, the location and size of any defect in FRPs can be detected. This testing method is, however, costly compared to DT methods because it requires advanced equipment, which in turn necessitates a higher level of training and additional

certification [8]. The main drawback of DT is that the tested FRPs cannot be further used. Nevertheless, to derive the effect of size and position of defined local defects on the mechanical performance of FRPs, DT is unavoidable. Tensile, bending, and impact testing are some examples of DT.

Defects are caused mostly during the production stage of FRPs. Defects in FRPs occur as, for example, voids, foreign bodies, incorrect fiber volume because of insufficient or excess resin, bonding defects, fiber misalignment, wavy fibers, ply cracking, delamination, and fractures or buckling [9-11].

In the recent years, the fabrication of defined local defects inserted FRPs has received considerable attention from the composite community [12-22]. In [12-14], defined local defect inserted FRPs were fabricated by blind holes of varying diameters in different layers of FRPs and defined local defects of polytetrafluorethylene (PTFE). Also, carbon-fiber-reinforced plastics (CFRPs) with defined local defects containing aluminum oxide hollow balls and polystyrol balls were generated. Ray [15] used different types of materials, such as copper, zinc, gold, and aluminum foil, with different thicknesses to introduce artificial defects into the laminated composites during fabrication. The manufactured defined local defect incorporated FRPs are used for NDT, such as the quantitative evaluation of optical lock-in thermography or ultrasonic measurements of CFRPs, for the comparison of different NDTs, or for ultrasonic and thermographic NDT. To date, very little literature can be found on the DT of defined local defect inserted FRPs. In [16,14], experimental and numerical experiments of the critical buckling load of laminated glass-fiber-reinforced plastics with strip delamination were investigated, and the development of

the delamination of CFRPs made from unidirectional (UD) non-crimp carbon fabrics by the pendulum impact tester had been reported. Importantly, the influence of defined local defect in different layers on the mechanical performance of FRPs has not yet been reported.

The aim of this work is to evaluate the mechanical performance of FRPs by introducing defined local defect into the different layers of FRPs. In order to reach this goal, FRPs with defined local defect in different positions in the thickness direction were fabricated. Then, the mechanical characterization of fabricated FRPs, such as tensile, bending, and impact testing, was determined.

2. Materials and methods

2.1. Materials

Carbon fiber exhibits a lower density, higher tensile strength, and reduced elongation at break compared to other reinforcing fibers [12]. UD non-crimp fabrics (NCFs) possess excellent mechanical properties in warp direction compared to other fabric types [23]. For this reason, in this research, UD-NCFs made of carbon rovings (SGL Group, Germany) were chosen as reinforcing fabrics. The areal weight, density, thickness, and fineness of an individual roving of the UD-NCFs used were 300 g/m², 1.77 g/cm³, 0.33 mm, and 800 tex, respectively. Different types of defined local defect can be enclosed within CFRPs during the processing stage. In this research, a PTFE sheet (Rump Folien GmbH, Germany) with a thickness of 0.05 mm was chosen as a sample foreign material.

The epoxy matrix, being a class of thermosetting matrix systems, shows superior adhesion properties to fibers compared to other matrix systems [5]. Consequently, the epoxy matrix was adopted for the infusion of UD-NCFs in the development of CFRPs with PTFE in this research. The resin system used for the infusion comprised the infusion resin MGS RIMR 135 and the hardener RIMH 137 (Hexion, Sokolov, Czech Republic) at a mixing ratio of 10:3. The density as well as the flexural, tensile, compressive, and impact strengths of the applied resin-hardener mixture were 1.18 g/cm³, 90 N/mm², 60 N/mm², 80 N/mm², and 70 KJ/m², respectively [24].

2.2. Fabrication of CFRPs

For the fabrication of CFRPs with PTFE, a type of vacuum-assisted resin infusion molding process named Seemann Composites Resin Infusion Molding Process (SCRIMP) was used because of its low-cost manufacturing process [25]. During the preparatory process, UD-NCF was cut into 300 * 600 mm² from the as-received roll. The sample thickness during the mechanical testing of the composite was 2 mm, and for this reason, six layers of UD-NCFs were laid during infiltration. Owing to the experimental aim, which focuses on the effect of the position of PTFE, the dimension of PTFE was fixed at 3 * 3 mm². According to the mechanical test layout, PTFEs were laid exactly in the center between layers 1 and 2, 2 and 3, as well as 3 and 4. A representative laying of PTFE in

the center between layers 1 and 2 is shown schematically in Figure 1. CFRPs without PTFE were also infused by SCRIMP in order to compare the loss in mechanical strength to CFRPs with PTFE. Subsequently, CFRPs without PTFE were termed reference CFRPs. After infusion, the system is cured for 15 h at 50°C in a laboratory oven.

Figure 1. PTFE in the center between UD-NCF layers 1 and 2

After curing, CFRPs were tailored to a size of 250 * 15, 100 * 15, and 40 * 15 mm² by means of a laboratory wet saw for the tensile, bending, and impact testing, respectively.

2.3. Microscopic analysis

In order to characterize the position of PTFE in CFRPs with PTFE, an optical microscopic analysis was used. An AXIOImager.M1m microscope (Carl Zeiss AG, Germany) was used for this purpose. The sample for microscopic analysis is prepared by tailoring CFRPs to a size of 20 * 10 mm², embedding these in an epoxy matrix followed by polishing to achieve clarity when viewed under the microscope. Specimens are photographed at a microscopic magnification of 1,000×

2.4. Mechanical characterization

The mechanical characterization of reference CFRPs and CFRPs with PTFE, including tensile, bending, and impact tests, was performed to investigate the effect of the position of PTFE on their mechanical performance. A tensile testing machine (Zwick Z 100 Zwick GmbH & Co. KG, Germany) was used for the tensile and bending tests of both types of CFRPs. The stiffness of both types of CFRPs was characterized by means of the 4-point loading test method. The tensile and bending test setups on the tensile testing machine are shown in Figure 2. A Charpy pendulum impact tester (CEAST 9050, Instron GmbH, Germany) with a pendulum of 15 J and a fall speed of 3.8 m/s was used for the impact testing of CFRPs. The test setup for the impact testing is shown in Figure 3. The tensile, bending, and impact tests were carried out according to DIN EN ISO 13934-1, DIN EN ISO 14125, and DIN EN ISO 179-1, respectively. Each test was performed at 23°C and 50% relative humidity and repeated seven times to attain statistically meaningful results. The stress-strain behavior by tensile as well as bending and impact strength-stress behavior were evaluated using testXpert® and instron® softwares, respectively.

Figure 2. Testing machine Zwick Z100 for tensile (left) and bending (right) testing

Figure 3. Charpy impact testing machine

Figure 4. Optical microscopic analysis of a sample CFRP with PTFE

3. Results and discussion

The results of the microscopic analysis and mechanical testing of both reference CFRPs and CFRPs with PTFE are described in this section. A statistical relationship between the distance of PTFE from the top surface and the tensile, bending, and impact test results of the CFRPs was derived. The evaluation of the external structure after the mechanical characterization is also discussed.

3.1. Optical microscopic analysis

A sample photomicrographic image of CFRPs with PTFE is shown in Figure 4. The PTFE is marked by the red box. The

black spots in the figure are the binding yarn of individual rovings in UD-NCF. The gray areas surrounding these black spots are the matrix. The thickness of the reference CFRP is 2.193 mm. The PTFE lies at a distance of 0.366, 0.756, and 1.097 mm from the top surface of CFRPs with PTFE. The optical microscopic analysis is the basis for the derivation of a statistical fit for the mechanical performance of CFRPs with the distance of PTFE from the top surface of CFRPs with PTFE.

3.2. Tensile testing

The results of the tensile testing of reference CFRPs and CFRPs with PTFE are shown in Figure 5.

Figure 5. Results of the tensile test of reference CFRPs and CFRPs with PTFE

In Figure 5, it can be observed that the maximum tensile strength was obtained from reference CFRPs instead of CFRPs with PTFE. This is due to the superposition of carbon fibers caused by the PTFE in CFRPs.

The position of PTFE influenced the result of the tensile testing for CFRPs with PTFE. The tensile strength tended to reduce by increasing the distance of PTFE from the top surface of CFRPs with PTFE, which is presented in Figure 5. The reduction in tensile strength at an increasing distance of PTFE from the top surface behaved in an exponential manner. CFRP with PTFE at a distance of 1.097 mm from the top surface showed the least tensile strength among all variations. At a distance of 1.097 mm, PTFE was approximately in the neutral axis of the CFRPs in the thickness direction, where the superposition effect was higher compared to the other variations. The superposition effect in the neutral axis reduced the tensile strength, mostly because the load transmission was deflected from the neutral axis during the tensile testing. Another reason for the reduction of tensile strength of CFRPs with PTFE is the delamination between fibers and matrix. The presence of PTFE in CFRP interrupts the adhesion between the fiber and matrix. As the load transmission from matrix to fiber during the tensile testing occurs along the neutral axis of CFRP, the delamination in the neutral line reduces the tensile strength of CFRP more than that of delamination in other places. Variations caused by manual processing could be the reason for these deviations shown in Figure 5.

3.3. Bending testing

The bending test results of reference CFRPs and CFRPs with PTFE are shown in Figure 6. The flexural strength of CFRPs

Figure 6. Results of the flexural test of reference CFRPs and CFRPs with PTFE

with PTFE exhibited the same tendency as the tensile testing. In this case, the reference CFRPs possessed maximum flexural strength. By increasing the distance of PTFE from the top surface of CFRPs with PTFE, their bending strength reduced. The flexural strength of all variations was fitted exponentially. The results of the flexural testing of CFRPs varied between 850 and 720 MPa. Some deviations appeared as presented in Figure 6, which can be attributed to the displacement of PTFE occurring either during the infusion of carbon UD-NCF or during the tailoring of reference CFRPs and CFRPs with PTFE. Similar to the tensile testing, the superimposition effect of carbon fibers and the delamination between the fiber and matrix affect the bending properties of CFRPs with PTFE.

After the flexural test, all samples broke completely. An example of completely broken CFRPs with PTFE is provided in Figure 7.

3.4. Impact strength testing

The impact strength results of reference CFRPs and CFRPs with PTFE are demonstrated in Figure 8. The impact strengths of both types of CFRPs were comparable to the tensile and flexural strengths. The impact strength was found to be significantly lower when the distance of PTFE from the top surface was increased. The reduction in impact strength amounted to 25.73% by increasing the distance of PTFE from 0.366 to 1.097 mm in CFRPs with PTFE. The impact strength of CFRPs with PTFE reduced in an exponential manner by increasing the distance of PTFE from the top surface, which is shown in Figure 8.

Figure 7. Complete rupture of CFRPs after the flexural test

Figure 8. Results of the impact test of reference CFRPs and CFRPs with PTFE

On the basis of the impact characterization, it can be concluded that in case of all CFRPs with PTFE, the rupture ran through the position of the inserted PTFE in the test specimen. The PTFE in between the fabric layers in CFRPs interrupted the adhesion of matrix and reinforcing fibers. Thus, the rupture of CFRPs during the impact testing occurred along the position of PTFE in CFRPs. A typical breakage of CFRPs with PTFE after the impact test, where the PTFE was inserted at a distance of 0.366 mm from the top surface, is shown in Figure 9.

Figure 9. Rupture of CFRPs after the impact test. PTFE in CFRP is marked by yellow arrow.

4. Conclusion

The aim of this research project was the mechanical characterization of CFRPs with defined local defect inserted in different positions, especially in the thickness direction. For this reason, a sample defined local defect, PTFE in this case, was inserted in between different layers of carbon UD-NCFs during their laying in the fabrication process of CFRPs. Reference CFRPs (CFRPs without PTFE) were also fabricated to compare their mechanical test values too. Tensile, flexural, and impact tests were performed for both reference CFRPs and CFRPs with PTFE. By increasing the distance of PTFE from the top surface, the tensile, flexural, and impact strengths of both types of CFRPs were reduced in an exponential manner. The mechanical performance of CFRPs with PTFE, where the PTFE was laid along the neutral axis of CFRPs, was the lowest. The result of the research project described in this article presents how and in which position the defined local defect mostly affect the mechanical performance of CFRPs. Furthermore, the developed reference CFRPs and CFRPs with PTFE can be used as reference materials for the NDT of

composite materials, for instance, for eddy-current testing or the sampling array technology.

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