THE EFFECT OF PATTERN WIDTH ON THE PROPERTIES AND BEHAVIOR OF INTERFACIALLY ENGINEERED COMPOSITES WITH DESIGNED FAILURE

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Abstract

Without increasing the reliability of composites, their broader use in safety-critical components might be limited by their unfavorable failure process, which is mainly based on the interaction of different damage mechanisms from different sources and often occurs at random locations and without any particular sign. In our research, we developed and investigated a method that can be suitable for controlling and designing the failure process of composites in terms of pre-determined location and mode of failure. For this purpose, we manufactured UD carbon-fiber/epoxy composite plates, which contained a locally weakened adhesion zone formed by polycaprolactone (PCL) thermoplastic interlayer material. The failure mode and location of the composite specimens were evaluated under uniaxial tensile loading. The results show that the application of PCL interlayer material enables the design of the failure process of polymer composites, and it does not influence their mechanical properties significantly.

1. Introduction

Polymer composites, due to their complex microstructure and manufacturing technologies, are fundamentally affected by a wide variety of damage modes from different sources, such as defects in the raw material, manufacturing induced and in-service flaws, which differ significantly in their typical sizes, from nano to macro, and in their effect on the composite structure. The initiation and propagation of damage and the mode of failure that may occur, are essentially determined by the loading conditions and the structure of the composite [1, 2].

Damage in composites, especially delamination, is often difficult to detect and localize. However, its presence usually leads to a reduction in the effective strength and stiffness of the composite, and its propagation can lead to failure. Detecting these damages and investigating the residual mechanical properties of the composite are essential to ensure proper structural health monitoring, which is best achieved by using non-destructive testing methods [3].

Besides other NDT methods such as computed tomography, acoustic emission testing, and ultrasound testing, which are often used for the investigation of composite materials, the digital image correlation (DIC) technique is a cost-effective, relatively simple method - optical analysis of the mechanical response to mechanical excitation - that can be used to detect damage at the meso- and macro-levels of a composite and to detect the propagation of damage. This information is provided by the high local strain values and the changes in the strain field observed during DIC-based full-field strain measurements [4, 5].

Another problem is that the failure of composites is challenging to predict and often occurs catastrophically. Therefore, to increase the reliability of composites, it is essential to influence their failure processes and make them more controllable. Failure can be partially localized by creating artificial damage, but this usually results in a significant loss of strength and cannot determine the mode of damage [6]. The failure process can be controlled by methods that aim to achieve pseudo-ductile behavior, where one possible method is the modification of interfacial adhesion, e.g., with nanofiber mats [7] or polymer films [8]. Applying polycaprolactone (PCL) thermoplastic interlayer material also seems successful in achieving pseudo-ductile behavior. PCL can be solved in the epoxy matrix. Thus, it does not create a new phase and applying it as interlayer material enables the influence of the failure process by the formation of locally weakened adhesion zones and the local modification of the matrix material [9, 10].

In the present research, we manufactured locally interfacially engineered composite plates containing PCL interlayer material. Our aim was to predefine the failure mode and location. The composite specimens were investigated under uniaxial tensile loading. Based on the measured data, the influence of the local modification of interfacial adhesion and the width of the weakened adhesion zone on the mechanical properties as well as the failure mode and position were evaluated.

2. Materials and methods

2.1. Materials

We applied IPOX MR 3010 (IPOX Chemicals Kft., Budapest, Hungary) DGEBA-based epoxy resin (EP) as matrix material of the composites, which was mixed with IPOX MH 3124 amine type curing agent in a weight ratio of 100:35. The reinforcement material was PX35FBUD0300 (Zoltek Zrt., Nyergesújfalu, Hungary) stitch-bonded unidirectional carbon fabric (309 g/m^2 surface weight), consisting of Panex35 50k rovings. As interlayer material, we used eMorph175N05 (Shenzhen Esun Industrial Co. Ltd., Shenzhen, China) poly (ϵ-caprolactone) (PCL) filament (1.75 mm diameter, 60°C melting temperature, 180°C printing temperature).

2.2. Sample production

Composite plates with [$0°_6$] layup sequence were manufactured by vacuum-assisted resin transfer molding (VARTM). For interfacially engineered composites, the PCL filament was printed directly on the surface of the carbon fabric by fused filament fabrication (FFF) method (Figure 1) using a CraftBot Plus 3D printer (CraftUnique Kft., Budapest, Hungary). Interlayer material was applied perpendicular to the fiber direction and placed only between the two middle plies.

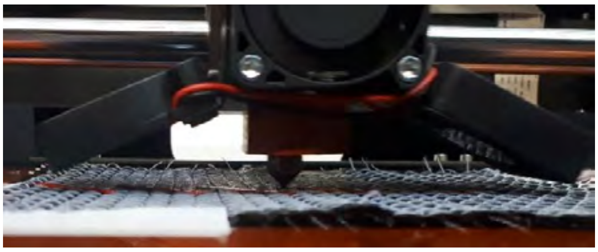


Figure 1. 3D printing of PCL interlayer material on the reinforcement fabric using FFF method

The thickness of the interlayer material, thus the weakened adhesion zone, was constantly 0.4 mm, only width differed in each plate. Plates containing 1, 2 and 3 mm wide interlayer material were produced.

Besides interfacially engineered composites, reference samples containing no interlayer material were also manufactured. Specimens prepared for the material testing were cut from the composite plates with a Mutronic Diadisc (Mutronic, Rieden am Forggensee, Germany) diamond disc cutter.

2.3. Methods

Initially, the fiber volume fractions of the composite plates were determined through density measurements conducted with a Sartorius Quintix 125D weighing scale (Sartorius Lab Instruments GmbH, Göttingen, Germany) following the rule of mixtures principle.

Tensile tests were performed according to ISO 527-4 standard using a Zwick Z250 (Zwick GmbH, Ulm, Germany) universal testing machine with a 250 kN load cell. During the tensile tests, 15 mm wide and 250 mm long specimens were investigated. The specimens were protected with bonded end-tabs, resulting in a free length of 150 mm. The test speed was set at 5 mm/min. Displacements were measured using a Mercury Monet (Sobriety, Kurim, Czech Republic) optical strain measuring system based on digital image correlation (DIC) featuring a 5 MPixel resolution IDS U3-3080CP-P-GL (Imaging Development Systems Inc., Obersulm, Germany) camera and two LED lights. Data acquisition was carried out with a frame rate of 10 Hz. The results were processed with Mercury RT-v2.9 software.

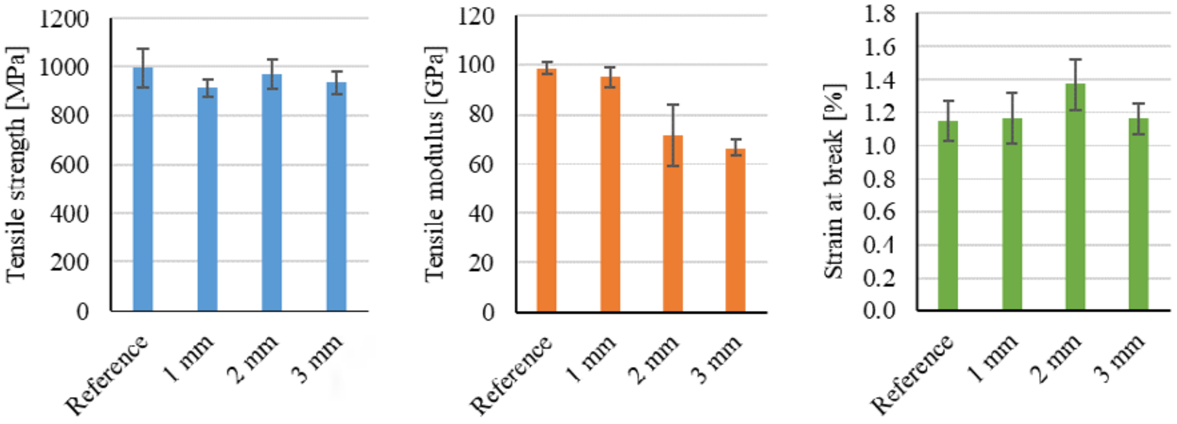
Before testing, the optical strain measurement system was calibrated in order to mitigate lens distortion and establish a correlation between the specimen's actual size and its representation in the recorded images. A gauge length of 75 mm was used for global strain measurement, applying a line probe within the software. Two additional line probes were used: one for further global strain measurement with a length of 50 mm, and another for local strain measurement in the region of the PCL interlayer material, covering 15 mm in length. DIC technique was used to generate a full-field strain map, where the calculated points were spaced at 20-pixel intervals, using a facet window size of 40 pixels × 40 pixels. For the DIC measurements, a high-contrast pattern was painted on the surface of the specimens.

3. Results and discussion

The results of the fiber volume fraction estimation based on density measurement showed that the average fiber volume fraction of the manufactured composite plates was 39.45±1.07 V/V%. The experienced differences do not affect the mechanical properties significantly, which enables the comparison of the different plates.

3.1. Tensile properties

Firstly, the tensile properties – tensile strength and modulus – of the different composite specimens were determined, and the effect of the PCL pattern width on them was evaluated (Figure 2).



a) b) c)

Figure 2. The effect of the width of PCL interlayer material on the tensile properties a) tensile strength, b) tensile modulus, c) strain at break

The results indicate that using PCL interlayer material does not significantly affect the tensile strength and the strain at break. On the other hand, using PCL causes a decrease in the tensile modulus, which is more significant with the increasing width of the interlayer material. This effect might be caused by the locally weakened adhesion, the fiber waviness and the resin-rich areas formed by the PCL interlayer material. During the tensile tests, we experienced that the interfacially engineered composites tend to fail in the region of the PCL interlayer material, and the frequency of the localized failure increases with the width of the PCL pattern.

3.2. Line probe tests

Following that, data obtained from Line Probe (LP) measurements, carried out by DIC during the tensile tests were analyzed to detect potential damage, particularly the formation of delamination. In the line probe test, elongation along three lines of varying lengths was measured. Line probes A2 and A3 provided insights into the global strain, while A1 specifically indicated local strain within the region of the interlayer material (Figure 3). The measured data was evaluated for the reference specimens as well.

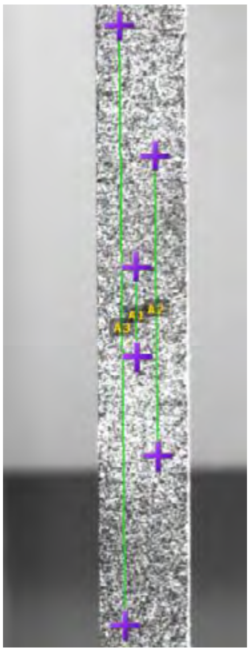
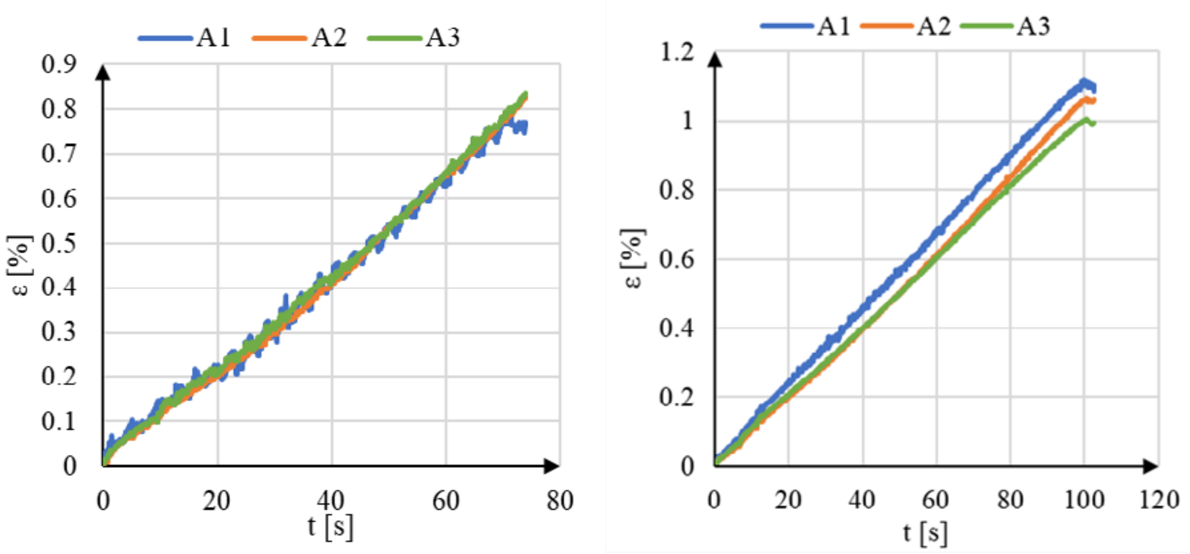


Figure 3. Arrangement of the line probes on the surface of the composite specimen: A1= 15 mm for local strain measurement, A2=50 mm and A3=75 mm for global strain measurement

The measured data indicate that the presence of the PCL interlayer material results in a deviation between the local and global strain values by locally increasing strain in the modified region. Higher strain values in the interfacially engineered region might lead to localized failure by reaching the failure strain earlier. In contrast, in the case of the reference sample, there is no significant difference in the elongations measured by the line probes. The only noticeable difference is that the line probe measuring local strain is affected by higher levels of noise (Figure 4).

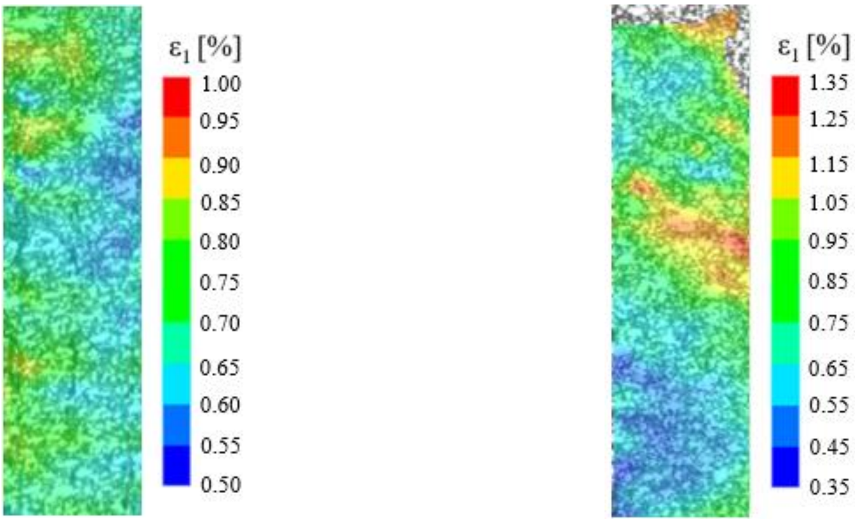


a) b)

Figure 4. The results of the line probe test for a) a reference specimen, b) a specimen containing 3 mm wide, 0.4 mm thick PCL interlayer material

3.3. Full-field strain measurement

Then, strain fields were determined using the DIC technique, and the strain fields of the different composite specimens were compared at an identical global strain value of 0.7%. The results suggest that, while relatively homogenous strain fields belong to the reference composites, the presence of PCL interlayer material causes local high-strain values. These zones indicate the localization of damage and failure as well as the occurrence of local delamination. This effect was observed to become more significant with the increase in the PCL pattern's width. A characteristic strain field for a reference specimen and a specimen containing 3 mm wide and 0.4 mm thick PCL interlayer material can be seen in Figure 5.



a) b)

Figure 5. The results of the full-field strain measurement at 0.7% global strain for a) a reference specimen, b) a specimen with 3 mm wide and 0.4 mm thick PCL interlayer material

4. Conclusions

In our research, we manufactured locally interfacially engineered composites by applying 3D-printed PCL interlayer material in order to design their failure. We carried out tensile tests supported by DIC to investigate the effect of the pattern width of PCL on the mechanical properties and the failure process. The results show that the application of PCL interlayer material enables the design of the failure process of polymer composites, and it does not influence their mechanical properties significantly. The mechanism of the method can be explained with several effects of PCL: local modification of interfacial adhesion and the matrix material, as well as the formation of fiber waviness and resin-rich areas.

Acknowledgments

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