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Effect of Hybrid Structure on Flexural Strength of Fiber Reinforced Curved Composites

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Abstract

Research on composite materials includes studies of both single types of fiber fabrics and hybrid structures containing more than one type of fiber. In addition, not only the materials used but also the various geometrical properties of composites are included in the literature. This study encompasses the production of epoxy-based composites reinforced with glass and carbon fibers employing various stacking sequence combinations in a hybrid manner by taking the diameter value (760 mm) as a coreference from the corresponding existing literature. For this purpose, four distinct groups of specimens were fabricated: unidirectional glass fiber only, unidirectional carbon fiber only, and their hybrid configurations. Flexural tests were carried out on curved specimens at a fixed span to length ratio (1/32). The findings indicate significant strength variations across the specimen types, with the carbon fiber only specimens exhibiting the highest peak load value. Furthermore, the incorporation of hybrid structures demonstrated a beneficial enhancement in performance outcomes by reducing the production cost as an asset. Specifically, the $[C3G]_s$ specimens were found to yield favorable results in terms of both peak force and cost efficiency, thus affirming the advantages of the hybrid composite structure. In addition, the effect of different production parameters including the type of composite processing, namely vacuum infusion and hand layup, in addition to the curing temperature and time on the flexural strength of the resulting composites were investigated using flat specimens. The obtained experimental results were evaluated and discussed with emphasis placed on the peak strength.

Keywords: composite materials, curved composite, flexural strength, hybrid composite.

1. Introduction

Engineering materials are generally classified under different headings. In line with the developing industry and technology, the need for a combination of various properties has arisen. Composite materials are the subject of ongoing research in this class. Fiber reinforced composite structures are widely discussed by researchers from different perspectives, ranging from theoretical and experimental studies evaluating fiber orientations, fiber types, matrix material and additives to the matrix material like in [1].

In research, materials are evaluated by means of mechanical tests. These include tensile [2], compression [3], flexure, impact and fatigue tests such as [4], [5] and [6]. Experiments performed on flat specimens are compared with theoretical calculations and numerical solutions made in computer environments are also

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reported on. Moreover, academic studies on tests of curved composite specimens are published. In addition to testing, damage characterization is a separate research topic in curved structures like in [7].

How changes in the orientation of fiber structures and the use of different fiber materials affect the mechanical properties has been investigated in recent papers. Biricik et al. [8] examined thermal and mechanical properties of flax char/carbonfiber reinforced polyamide 66 hybrid specimens. Selver et al. [9] investigated the mechanical properties of jute/glass and flax/glass hybrid structures. In another study, Campos Pais Coelho et al. [10] considered cylindrical composite specimens by combining carbon, Kevlar and glass fiber layers in sequences. Similarly, multiple, repeated or single low velocity impacts on semi-cylindrical specimens and impact studies involving sandwich structures are available in the literature such as Ferreira et al. [11,12,15] and Reis et al. [13,14]. In this context, Dong and Davies [16] published a study in which carbon and glass fiber fabrics were researched. The flexural strength of composites having a hybrid structure was investigated. Glass and carbon fibers were present on the tensile surface and the effect on the mechanical test results was interpreted. Another flexural load study was presented by Kalantari et al. [17]. The effect of the use of a hybrid structure (carbon/glass fiber) on the flexural strength was examined by the researchers. The investigation was based on two different methods, namely classical lamination theory and finite element analysis. Four different damage theories were considered in the study. Yanen et al. [18] conducted a study on the critical buckling loads of different test specimens, among which curved composite plates were considered.

Another widely studied topic related to curved composite structures is low speed impact tests. In studies involving this type of analysis, different radii, test bearings, fiber orientations and impactor designs are used as the parameters in the experiments. In addition, the experimental results are analyzed from various perspectives. Kaboglu et al. [19] performed weight drop impact tests of curved structures of various dimensions and stacking sequences. Three different radii were used in the investigation. In addition, a flat structure was also included among the specimens. Two different stacking sequences ($[0/0/-45/+45/90/90]_s$ and $[90/90/-45/+45/0/0]_s$) were employed for each geometry. Avazpoor et al. [20] studied the effect of the radius of curvature on low speed impact strength. The radii of curvature were selected as 10, 15, 20 cm. Samples produced with glass fiber were subjected to the test. According to the results, an increase in peak force values was observed in all the specimen types with an increase in impact energy. In parallel with this, a rise in the peak load value was observed with a decrease in curvature diameter. As a result of the investigation, it was stated that the energy absorption capacity of curved specimens is higher than that of flat specimens. Gebhardt et al. [21] states that existing studies are on flat and cylindrical samples, but curved structures with varying properties are found in engineering applications. For this reason, they carried out a study on elliptic composite structures. Within the scope of the study, low speed impact was considered. On the other hand, an analytical solution for doubly curved structures was discussed by Sharma et al [22]. Sahoo et al. [23] considered flat and curved composite structures in their research. Static and free vibration properties were evaluated and three-point bend test results were also interpreted in the study.

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Apart from low speed impact tests, there are also examinations in the literature where higher speeds are considered. Phadnis et al. [24] conducted such a study. Composite panels having different radii of curvature were investigated during shock loading. Flat, 304.8 mm and 111.8 mm radii of curvatures were evaluated as the geometric dimensions. The problem was also analyzed in a computer environment by numerical analysis. The damage modes, numerical solutions and experimental results were interpreted.

Bending tests are a widely used analysis method among mechanical tests by researchers. Experimental results on flat specimens are frequently published in the literature, however, it is seen that experimental studies in the case of curved systems are rather limited. Kaboglu et al. [25] carried out an experimental study on flexural strength different from their previous study [19]. Specimens of three different diameters (760, 380, 304 mm) were subjected to three-point bending tests. A punch speed of 1 mm/min was applied in the experiment. Specimens of each size were produced for two different stacking sequences. As a result of the research, force-displacement result graphs were generated.

In this study, the hybridization effect on curved composite structures was systematically analyzed. A diameter of 760 mm, as referenced in existing literature like in Kaboglu et al. [25], was utilized. The flexural load capacity of the specimens was evaluated, encompassing both hybrid and single type fabric configurations. The resultant data were compared to assess performance differences. The primary focus of this experimental investigation is to determine the influence of hybrid structural compositions on the flexural strength of curved composites. Glass and carbon fabrics were considered to obtain the hybrid structures. The hybrid structures consisted of carbon fabric face layers such as one carbon face layer and two carbon fabric face layers. Peak force measurements of the specimens were systematically recorded and analyzed. The findings pertaining to both pure and hybrid structures were discussed in relation to their mechanical properties. Additionally, the cost implications of the materials were addressed in the conclusions of the study. The cost and peak force values were observed together. The aim is to ascertain whether more cost-effective hybrid structures could be obtained compared to samples made of only carbon fabrics. In the second section of the study, flat samples were produced employing different methods, namely hand lay-up and vacuum infusion (with/without curing). The effects of the processes were examined and discussed with the results. The test results of the flat specimens were examined in order to improve the peak force values.

2. Materials and methods

Within the scope of the research, a hybrid layer structure in a curved composite structure was considered. The effect of the hybrid layer structure on bending strength was the focus of the research. The hybrid structures consisted of unidirectional glass fiber textile (G) and unidirectional carbon fiber textile (C). The density of the fabrics was 300 g/m^2. HEXION®-LR635 epoxy and HEXION®-LH637 hardener were utilized to fabricate the composites. For the production of the curved samples, priority was given to the type of mold production. In this case a metal mold was preferred as the mold must remain stiff during the production of the composites.

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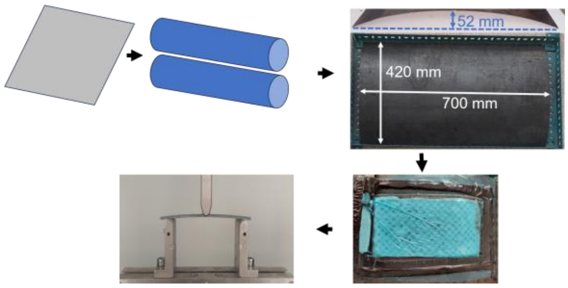

Figure 1. Mold (with dimensions) and sample production process

The sheet was first bent to the radius value to be used in the scope of the research in a pipe bending machine (Figure 1). The mold was 420 mm in width and 700 mm in length. In addition, the height of the mold relative to the flat floor was 52 mm (Figure 1).

Carbon glass fiber fabrics were employed in the production of the samples. In order to create the hybrid structure, the number of fibers of different materials was varied. Thus, the ratio of fiber materials in each type of structure was changed. Hence, a change in the results can be observed. Diagrams of the different arrays examined within the scope of the research are given in Figure 2. The samples used this study are curved and have a certain radius of curvature; however, the diagrams in Figure 2 are only representative for easy understanding of the arrays.

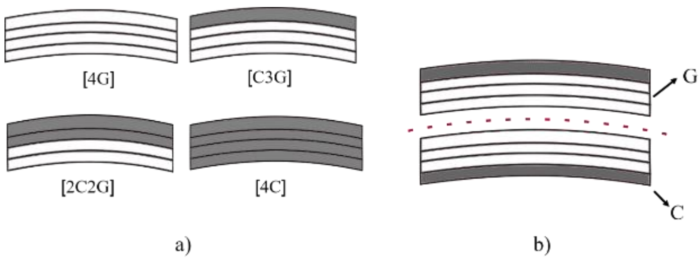

Figure 2. a) Sequences of fiber layers applied in the study, b) illustration of symmetry plane

In Figure 2, the carbon layers are shown in dark color. The sample consisting of a single carbon fiber layer (C) and 3 glass fiber layers (G) is denoted by [C3G]. There is a symmetry plane here. For this reason, the bottom and top layers of the sample consist of carbon fiber and the layers between the two layers consist of glass fiber. There are 8 layers of fibers in the samples.

The mold cleaning process was performed with acetone. The mold surface was cleaned several times and left to dry. After the mold surface cleaning process, a mold release agent was applied to the mold surface. The epoxy and hardener used in production were mixed in a ratio of 100/28 (epoxy/hardener) by weight, which was cured for a week at room temperature. The fabrics were laid on the mold in $[0/0/0/0/0]_s$ orientation. The direction of orientation of the fibers is the same as the axis of symmetry shown in Figure 2b. The specified order was followed in the production of the hybrid structures. Figure 2b shows the laying order of one of the

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hybrid structures. The sequence was repeated according to the symmetry axis. After the hand lay-up process, vacuum tape was applied on the mold. A -760 mmHg vacuum level was employed during the production.

Peel ply fabric was placed on the fibers and covered with release film. A blanket was laid on top of the film to absorb the excess resin as given in Figure 1. The wall thickness of the prepared samples was checked at several different points and the average wall thickness was determined from the measurements. From this wall thickness, the dimensions of the three-point bending specimen were determined according to standard ASTM D 7264 (2021) [26], which concerns flat specimens. A span/thickness ratio of 1/32 was selected. Accordingly, a span width of 96 mm was used in the tests (Figure 3a).

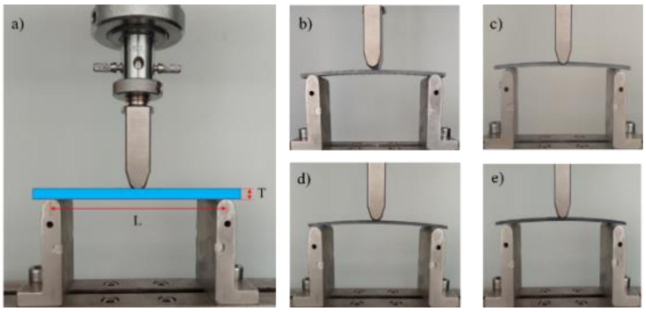

Figure 3. Three-point flexure test a) [4G]$_s$, b) [C3G]$_s$, c) [2C2G]$_s$, d) [4C]$_s$).

In the test setup used, the support diameter is 10 mm. Accordingly, the specimen length was selected as 125 mm (Figure 3). The depth of the specimens is 13 mm. After production, the specimens were sectioned from the produced samples using a diamond disc. Cooling with water was applied during the cutting process; thus, damage that may occur due to heating during the cutting process was avoided. The three-point bending tests were conducted with a universal tensile test setup. During the test, a feed rate of 1 mm min^{-1} was considered as given in the standard.

In the next part of the research, flat test specimens were produced and the effect of the production method and curing process on the mechanical strength was investigated. The vacuum infusion method (Figure 4) was employed to investigate the effect of the production process. Samples were produced by both hand lay-up and vacuum infusion methods, and the results were compared. To unveil the effect of the post curing cycle applied to the samples produced by vacuum infusion, they were exposed to 5 hours of curing at 70°C in an oven. Deformation was prevented by using metal plates during the curing process.

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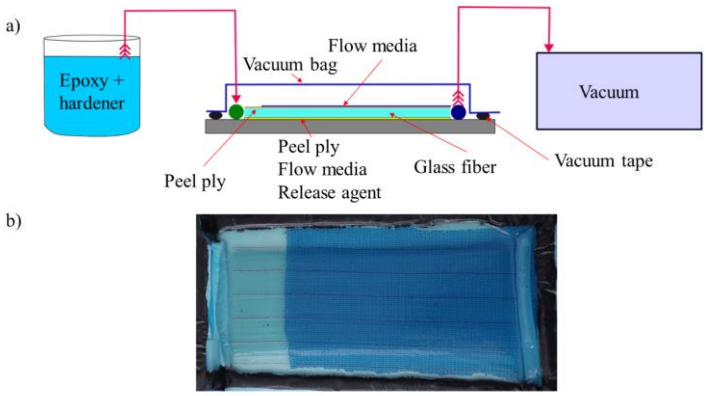

Figure 4. a) Diagram of vacuum infusion process, b) top view of sample

Results

The obtained results show that hybridization is has a significant influence on the curve characteristics of the force-displacement graphs (Figure 5). Table 1 gives the stacking sequence of the hybrid composites produced by hand lay-up.

Table 1. Hybrid composite types

$[4G]_s$	Type 1
$[C3G]_s$	Type 2
$[2C2G]_s$	Type 3
$[4C]_s$	Type 4

Firstly, the samples in which all the layers consisted of glass fiber were tested. The maximum force values of the specimens during the test were recorded as 183.88 N, 171.21 N and 168.32 N, respectively (Figure 5 a). The displacement values corresponding to the forces are 7.37 mm, 5.9 mm and 5.59 mm. When the results are compared, they are consistent with each other. The maximum force values achieved by the Type 1 specimens are in the range of 168-184 N.

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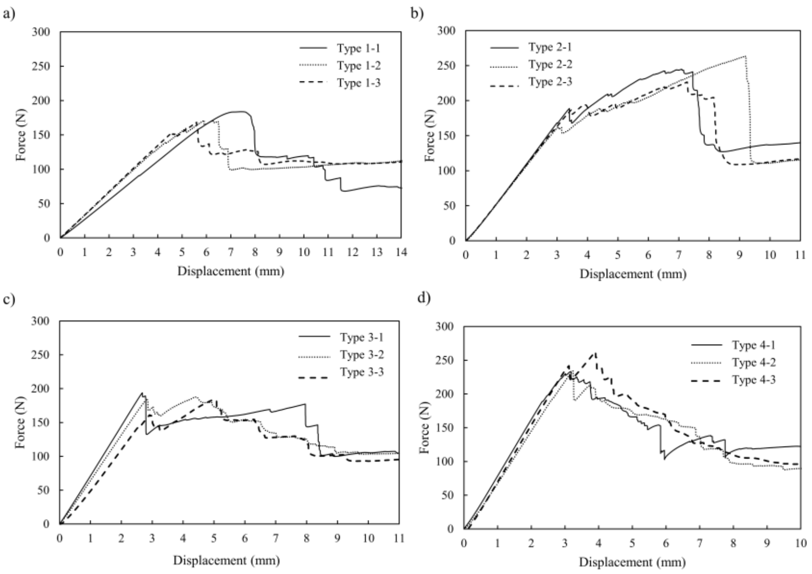

Figure 5. Force displacement graph of a) Type 1, b) Type 2, c) Type 3 and d) Type 4

The Type 2 sample group has a hybrid structure. A carbon fiber layer is placed in the top and bottom surfaces of the samples. The maximum force values observed in three repetitions are 244.93 N, 263.42 N and 226.55 N (Figure 5b). The corresponding displacement values are 7.09 mm, 9.2 mm and 7.27 mm, respectively. The maximum force values reached by the test specimens in the Type 2 hybrid structure are in the range of 226-245 N, which is an increase compared to the Type 1 group.

The three test results of the specimens in the Type 3 group are given in Figure 5c. The maximum force values attained by the specimens during the test are 193.8 N, 187.6 N and 182.94 N, respectively. The corresponding displacement values are 2.67 mm, 4.39 mm and 4.93 mm. The maximum force value is in the range of 182-194 N but compared to the Type 2 hybrid structures, the maximum force range is lower. However, when evaluated in terms of displacement, they gave better results than the specimens in both the Type 1 and Type 2 groups.

Finally, the force-displacement graph of the Type 4 group is given in Figure 5d. The specimens in this group consist entirely of carbon fiber fabric. Regarding the maximum forces, values of 233.36 N, 262.50 N and 234.10 N were determined respectively. The displacement values corresponding to these forces are 3.17 mm, 3.90 mm and 3.23 mm. The maximum force range is between 233-263 N. The peak force values of the specimens with carbon on the face were higher than the glass fabric faced samples. These results are consistent with the literature. Dong and Davies state that [16] carbon/epoxy laminas should be the skin and glass/epoxy laminas should be the core. In the current research, the curved specimens with a face layer composed of carbon fabric exhibited better peak force values than those with two face layers of carbon fabrics.

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Table 2. Mass measurement and cost calculation results of each specimen

Sample type	Specimen No.	Peak force (N)	Mass (g)	Cost ($)
1 [4G]s	Specimen 1	183.88	6.35	0.10
	Specimen 2	171.21	6.07	0.09
	Specimen 3	168.33	5.94	0.09
2 [C3G]s	Specimen 1	244.93	5.80	0.17
	Specimen 2	263.42	5.74	0.16
	Specimen 3	226.55	5.94	0.17
3 [2C2G]s	Specimen 1	193.84	5.45	0.24
	Specimen 2	187.63	5.43	0.24
	Specimen 3	182.94	5.55	0.24
4 [4C]s	Specimen 1	233.36	5.53	0.39
	Specimen 2	262.50	5.40	0.39
	Specimen 3	234.10	5.50	0.39

The mass and costs of each specimen type are given in Table 2. The total fabric cost was obtained from the fabric sizes used in the specimens and the prices. The matrix material cost was determined by considering the mixture ratio of the epoxy and hardener costs. Total cost calculation consists in combining the determined costs together. Thus, observations could be made in terms of both the peak force and cost. The measured and calculated properties of the samples are given in Table 2 and Figure 6. When the peak force values are observed for the samples produced with only carbon fabric, the peak force value is the highest. The peak force is compared with the cost calculation because the peak force value can only be approximated in samples using a hybrid structure at a lower cost. The answer to this question is being investigated.

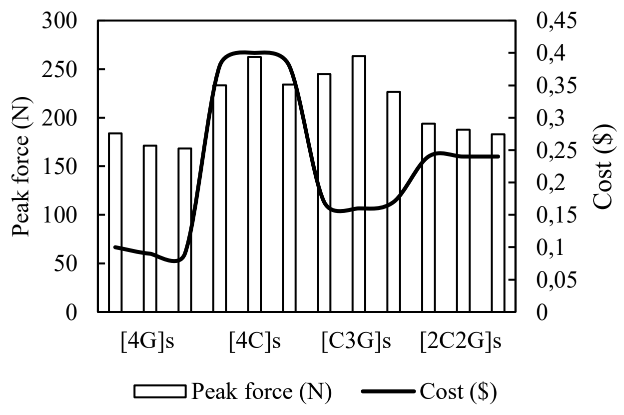

Figure 6. Graphical representation of Table 2

In addition to the conducted studies, effective parameters were examined with flat samples to further improve the results. The results obtained from the same tests are compared to each other with a particular emphasis on the type of the processing methods. Each test was repeated 3 times for the sake of statistical

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assessment. Hand lay-up is abbreviated as “HL” in Figure 7 while vacuum infusion only is indicated by “V” in Figure 7. Samples that were also post cured are referred to as “VPC” in Figure 7 and Figure 9.

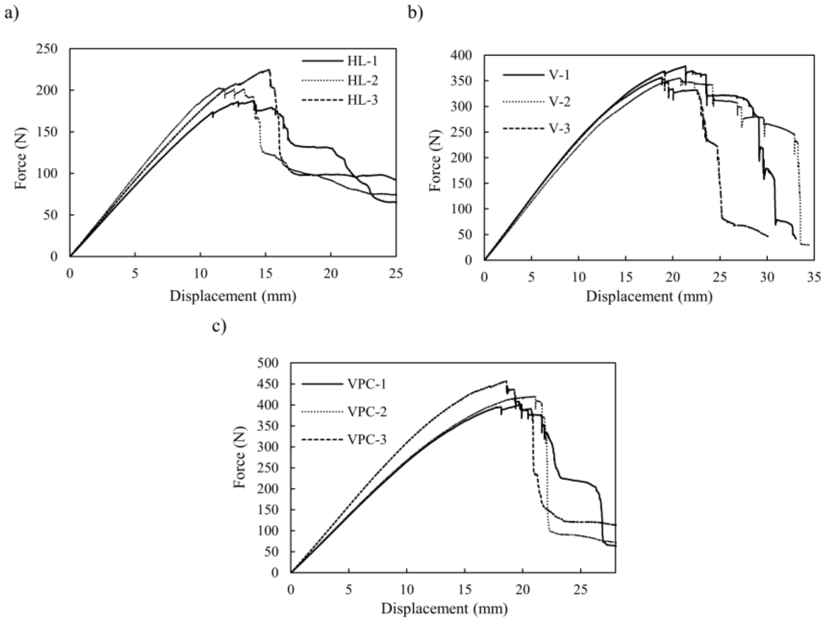

Figure 7. Results ([4G]$_s$) of hand lay-up (HL), vacuum infusion (V), cured flat samples (VPC).

When the peak force values obtained as a result of the two different production methods are compared, the effect of the production method on the strength of the specimens is evident. It is also evident from the graphs that the curing process is also effective in terms of effective strength values.

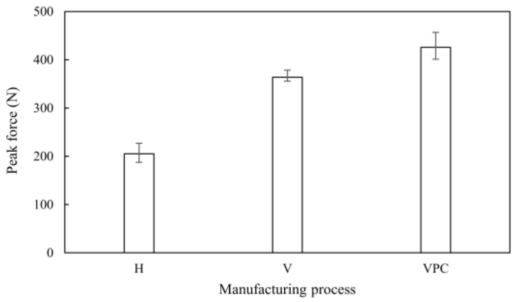

Figure 8. Nominal values of peak forces according to manufacturing process

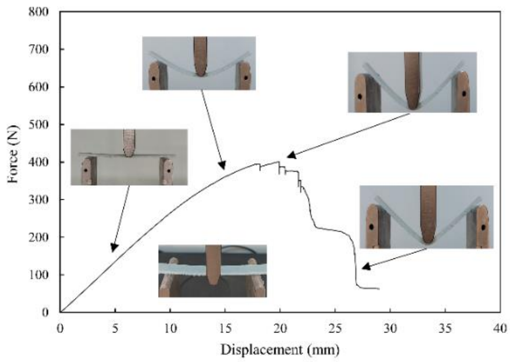

Figure 9. Specimen VPC-1 during flexure test

Not only the peak strengths of the specimens were examined, but also visual inspection was performed of the cured and noncured vacuum infused specimens after the test. Photographs of the fractures are given in Figure 10. As can be seen in the figure, the noncured specimens appear to be more damaged and the fibers separated. In the cured samples, delamination is observed, but damage to the outer layer is not visible.

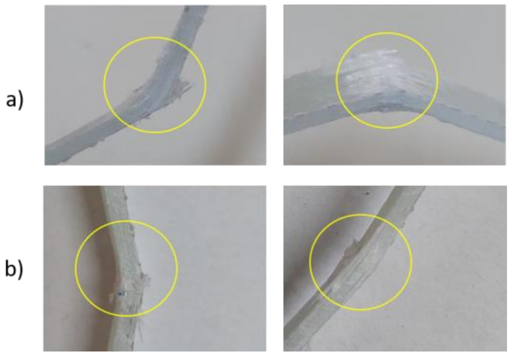

Figure 10. Sample photographs of a) V and b) VPC after flexural test

Conclusions

The obtained results seem to be correspond with one other. When the graphs of the different composites are compared, specific differences are observed.

- When Type 1 is analyzed, a peak force occurred and afterwards a certain decrease in the force value was observed. After that, the displacement value increased horizontally while the force value remained stable.
- Damage occurred first in the specimens in the Type 2 group. Then the force value grew with the increase in the displacement value. After the force value reached a maximum point (as shown in Figure 5 b), a decline was observed. After that, there was a stable trend in the graph.
- In Type 3, a peak force value was observed, followed by a fall in the force level. Afterwards, an approximately stable trend was observed in the force value.
- In the Type 4 specimens, after the peak force value there was a significant drop in the force value with a stable slope. The decrease continued in accordance with the displacement. The decline took place together with large displacement.

Different results were obtained for each type, which was an expected observation. Not only the test results but also the production should be taken into consideration in order to select the appropriate composite. In production, the priority is the cost. Glass and carbon fabrics are different in terms of cost. Looking at the results of the Type 4 samples, high values were obtained in terms of peak force. The aim of this study was to investigate the effect of hybrid structures on the peak force values. Looking at the hybrid structures, the Type 2 group specimens have a better peak force values than Type 1. In addition, although the Type 2 composite is lower than Type 4 in terms of cost, the peak force values are close to Type 4. When the peak force and cost are considered together, Type 2 is seen as the logical choice.

The effect of the production method was also analyzed. It should also be taken into consideration that higher strength values can be achieved by producing the composite using vacuum infusion and applying the curing process, which promotes crosslinking, with strength values going up by roughly around 20% (in comparison to the V specimens) when the maximum strength value is taken into account.

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