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Quasi-Static Penetration Properties of Hybrid Composites with Aramid, Carbon and Flax Fibers as Reinforcement

Joanna Pach[1*], Alona Pawłowska[2]

[1] Department of Lightweight Elements Engineering, Foundry and Automation, Faculty of Mechanical Engineering, Wroclaw University of Science and Technology, Wyb. Wyspiańskiego 27, 50-370 Wrocław, Poland

[2] Department of Polymer Materials Engineering, Faculty of Materials Engineering, Kazimierz Wielki University, JK Chodkiewicza 30 Street, 85-064 Bydgoszcz, Poland

* Corresponding author's e-mail: joanna.pach@pwr.edu.pl

ABSTRACT

This work presents the experimental results of a quasi-static penetration test of laminates on a polyurea-polyurethane matrix, reinforced with aramid, carbon and flax fibers. A total of 15 series of samples with different reinforcement configurations were prepared. A quasi-static penetration test was performed for coefficient SPR = 5. The SPR = Ds/Dp was calculated as the ratio of the support hole diameter (Ds) to the punch diameter (Dp). A punch with a rounded 9-mm diameter tip was used to penetrate the material. Percentage changes of penetration energy (%E) and maximum load (%P) compared to a non-hybrid laminate were calculated in order to estimate the impact of hybridization on the properties of laminates. The energy absorbed during the quasi-static penetration test was used to calculate the PSS (punch shear strength) of the laminates. Damage analysis was performed after the puncture test. It was observed that both the type of reinforcement and the configuration of the reinforcement layers have a potential impact on the obtained results and the laminate damage mechanism.

Keywords: hybrid composites, hybridization, laminates, polymer-matrix composites, quasi-static penetration test.

INTRODUCTION

Fiber-reinforced polymer composites are widely used in the automotive, aeronautical, construction and military industries. The appropriate choice of a composite is preceded by numerous strength tests, both quasi-static and dynamic [1, 2]. Based on the test results, it is possible to design composites with optimized properties for the selected application. The properties of polymer composites reinforced with glass fibers [3, 4], carbon fibers [5, 6], aramid fibers [7, 8] and, in recent years, natural fibers [9, 10] are extensively described in the literature.

The pursuit of achieving the best possible material properties while minimizing manufacturing costs makes hybrid composites (containing a minimum of two types of reinforcement in a single matrix) a popular choice. Hybrid composites were used for the first time in the 1960s and 1970s [11], which resulted from the growing popularity of carbon fibers. Due to their high price, new solutions that would reduce the cost of producing carbon-containing composites were searched. In addition to carbon fibers, glass fibers (which are cheaper than the least) started to be introduced into the polymer matrix. A study conducted in 1972 by Hayashi concluded, that the failure strain of a carbon/glass hybrid composite was 40% greater compared to a reference carbon fiber composite [11].

Despite the passage of time, research on carbon/glass hybrid composites is still relevant. Due to various fiber types and hybrid effects, the relationship between hybrid structures and their behavior under static and dynamic loading is not completely understood yet. Wu's study [12] investigated the tensile behaviors of various interlayer and intralayer C/G (carbon/glass) hybrid composites. It was shown that the tensile strength of interlayer and intralayer hybrid composites depends on the C/G hybrid ratio and increases with the carbon fiber content.

Reducing manufacturing costs, as is the case with carbon-glass composites, is not the only benefit of hybridization. The purpose of combining two types of fibers in a single composite is to preserve the desirable mechanical properties and to mitigate some of their shortcomings. Combining lower-modulus fibers, such as aramid fibers with carbon fibers, in a single matrix is used to obtain high strength and stiffness compared to composites with a single type of reinforcement. Lower-modulus fibers such as aramid fibers make hybrid composites more resistant to damage while high-modulus fibers provide load-bearing capacity and stiffness of the composite [13].

Despite the advantages offered by hybrid composites, it is important to note the likelihood of side-effects resulting from using reinforcements made of different materials. Technologically, it might result in difficulties caused by different adhesive properties of the fibers to the polymer matrix, which can cause undesirable phenomena such as delamination between the reinforcement and the polymer matrix. Hence, the hybridization effect on individual properties of composite is subject to verification, among other things, in quasi-static tests.

Bulut et al. [14] compared glass/aramid/carbon hybrid laminates in an epoxy matrix in a quasi-static penetration test. They observed that in addition to the type of reinforcement used, the stacking sequence within the matrix is important and can improve the damage resistance of the composite.

Pach et al. compiled comparative data from quasi-static penetration tests for laminates with different stacking configurations of aramid/carbon reinforcement in a polypropylene [15] and polyurethane-polyurea matrix [16]. In both works, higher values of absorbed energy and puncture resistance (PSS) were registered when carbon fibers were present in the outer layers and aramid fibers inside the laminate. Similar conclusions in regard to energy absorption and different conclusions on the PSS were drawn by authors who tested laminates with similar stacking sequences of aramid and carbon fabrics in an epoxy matrix [14]. Due to a number of additional variables, such as the number and stacking sequence of reinforcement layers and the influence of the matrix on different types of reinforcements, understanding the failure mechanisms of hybrid laminates requires further research.

So far, the hybridization effects have been described for composites reinforced with glass fibers [17, 18], carbon fibers [19, 20] and aramid fibers [21]. In recent years the advantages of hybridization with natural fibers have also been considered [22, 23, 24].

Hybrid composites are tested in ballistic tests, among others [25, 26]. Epoxy matrix laminates reinforced with aramid, carbon and glass fibers were compared due to their efficiency in energy absorption. The research shows that a positive hybridization effect was obtained for aramid-carbon laminates [25]. In recent years, natural/aramid hybrid composites have also been tested for military helmets [26].

P. Wambua et al. [27] compared the ballistic properties of polypropylene composites reinforced with flax, hemp and jute fabric. The flax composites were best at absorbing the ballistic impact energy. The front and rear surfaces of the natural composites were reinforced with mild steel, which improved the ballistic properties of the analyzed composites.

Despite the relatively good mechanical properties of natural fibers, their characteristics are variable and depend on: the origin of the plant, weather conditions, the type of soil they grew on and the maturity of the plant; which is a significant disadvantage. The effective reinforcement of the laminate with natural fiber also depends on the surface treatment of the fiber, the manufacturing method, the length of the fiber, the mass/volume ratio of the fiber and its orientation [23].

This paper proposes a comparison of hybrid laminates with the most commonly used reinforcement types, i.e. carbon and aramid fibers. Flax fibers were chosen as the third type of reinforcement.

As for the polymer matrix, currently, the most commonly researched group of laminates with aramid or carbon fibers are epoxy matrix composites [28]. In this study, polyurethane-polyurea resin was used as the polymer matrix, which deviates from the standard for this type of composites and is a relatively new solution. Its use in combination with reinforcing fabrics opens up new application possibilities in instances, where short fabrication time or vertical application is necessary. This study aims to analyze the hybridization and stacking sequence effects on the energy absorption capacity and puncture resistance in a quasi-static penetration test.

EXPERIMENTAL PROCEDURE

Materials and samples preparation

Laminates described in this study were made using three types of plain weave fabrics: aramid fabric (173 g/m^2; dist. Havel Composites, Cieszyn, Poland), carbon fabric (200 g/m^2; dist. Havel Composites, Cieszyn, Poland) and linen fabric (550 g/m^2; Technotex, Bielawa, Poland). Figure 1 shows the fabrics used to manufacture the laminates. Fiber properties are summarized in Table 1.

A two-component polyurethane-polyurea resin (Almacoat Floor SL, Alma-Color, Gniew, Poland) of 1.10 g/cm^3 density was used as the matrix of the polymer laminates. The resin components were mixed in a 100:13 mass ratio

The samples were manufactured using the hand lay-up method. Each of the laminates consisted of 16 layers of reinforcement. The fabrics were infused with resin layer by layer. Afterwards, the samples were left under load for 24 h. Figure 2 shows the stacking sequence of the reinforcement layers. Table 2 summarizes the specimen designations and reinforcement configuration.

The A, N, C denoted samples were made entirely of one type of reinforcement fabric – aramid (A), natural (N) and carbon (C) respectively. Hybrid specimens are a combination of two types of

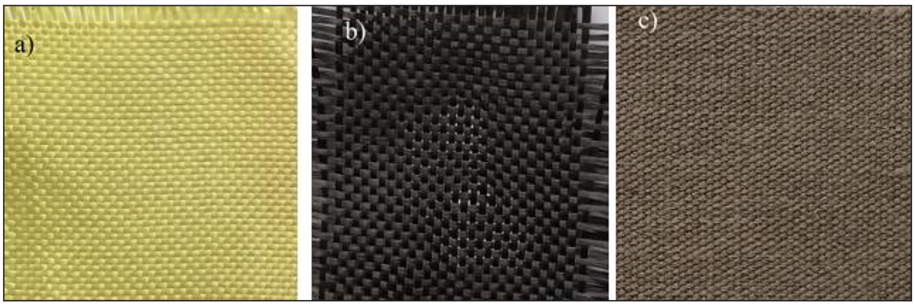


Figure 1. Fabrics used as reinforcement of laminates: a) aramid, b) carbon, c) natural (flax)

Table 1. Physical and mechanical properties of fibers

Fibers	Density (g/cm^3)	Tensile strength (MPa)	Young's modulus (GPa)	Areal Density [g/m^2]
Aramid	1.44	2700–3600	60–145	173
Carbon	1.75	3000–6000	200–300	200
Flax	1.4–1.5	600–1100	45–100	550

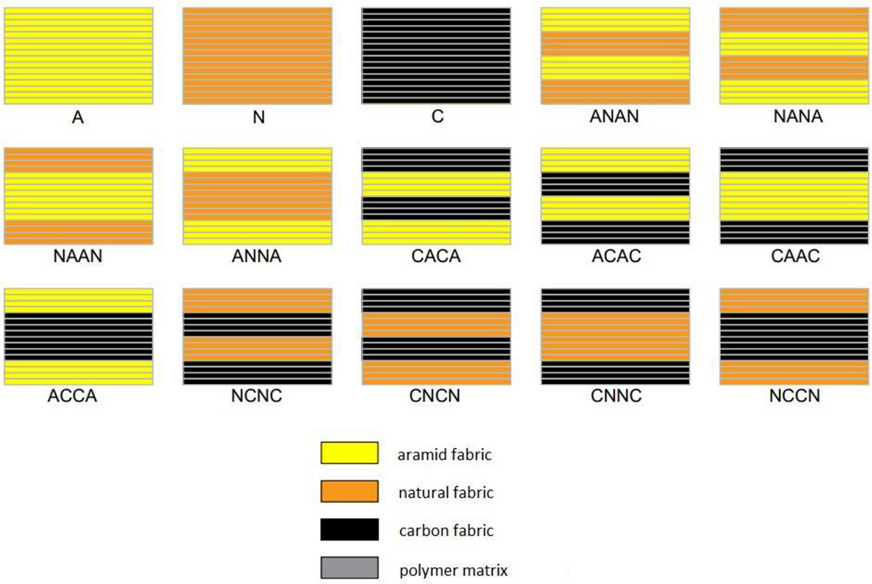


Figure 2. Reinforcement layer configuration in laminates

Table 2. Sequences of fabric arrangement and content of reinforcement layers in laminates

Sample	Fiber sequence arrangement	M_A [%]	M_N [%]	M_C [%]
A	$(0^\circ_A/90^\circ_A)_8$	43.79	0.00	0.00
N	$(0^\circ_N/90^\circ_N)_8$	0.00	0.00	57.71
C	$(0^\circ_C/90^\circ_C)_8$	0.00	50.80	0.00
ANNA	$[(0^\circ_A/90^\circ_A)_2(0^\circ_N/90^\circ_N)_2]_S$	12.02	0.00	38.30
NAAN	$[(0^\circ_N/90^\circ_N)_2(0^\circ_A/90^\circ_A)_2]_S$	13.24	0.00	42.17
NANA	$(0^\circ_N/90^\circ_N)_2(0^\circ_A/90^\circ_A)_2(0^\circ_N/90^\circ_N)_2(0^\circ_A/90^\circ_A)_2$	12.68	0.00	40.40
ANAN	$(0^\circ_A/90^\circ_A)_2(0^\circ_N/90^\circ_N)_2(0^\circ_A/90^\circ_A)_2(0^\circ_N/90^\circ_N)_2$	13.00	0.00	41.41
ACCA	$[(0^\circ_A/90^\circ_A)_2(0^\circ_C/90^\circ_C)_2]_S$	19.28	22.29	0.00
CACA	$(0^\circ_C/90^\circ_C)_2(0^\circ_A/90^\circ_A)_2(0^\circ_C/90^\circ_C)_2(0^\circ_A/90^\circ_A)_2$	21.34	24.67	0.00
CAAC	$[(0^\circ_C/90^\circ_C)_2(0^\circ_A/90^\circ_A)_2]_S$	19.98	23.10	0.00
ACAC	$(0^\circ_A/90^\circ_A)_2(0^\circ_C/90^\circ_C)_2(0^\circ_A/90^\circ_A)_2(0^\circ_C/90^\circ_C)_2$	22.76	26.31	0.00
NCCN	$[(0^\circ_N/90^\circ_N)_2(0^\circ_C/90^\circ_C)_2]_S$	0.00	14.21	39.15
CNNC	$[(0^\circ_C/90^\circ_C)_2(0^\circ_N/90^\circ_N)_2]_S$	0.00	13.13	36.18
CNCN	$(0^\circ_C/90^\circ_C)_2(0^\circ_N/90^\circ_N)_2(0^\circ_C/90^\circ_C)_2(0^\circ_N/90^\circ_N)_2$	0.00	14.52	40.00
NCNC	$(0^\circ_N/90^\circ_N)_2(0^\circ_C/90^\circ_C)_2(0^\circ_N/90^\circ_N)_2(0^\circ_C/90^\circ_C)_2$	0.00	14.68	40.43

reinforcement and were labeled according to the designations assigned to the used reinforcement types. A total of 15 series of samples were made.

Quasi-static penetration test (QSPT)

The quasi-static penetration test was carried out using a TINIUS OLSEN H25KT testing machine, in accordance with the ASTM D-732 norm. A rounded cylindrical punch of 9 mm diameter was mounted in the upper jaw of the machine. The samples measuring 100 × 100 mm were placed between two metal plates with centrally located holes. The diameter of the hole in the support plate was 45 mm. The ratio of the support plate hole diameter Ds to the punch diameter Dp for the carried out tests was equal to 5. Since the aim of this study was to analyze the effect of the composition and stacking sequence of the composite layers rather than the effect of the SPR factor, all tests were performed with SPR = 5. The QSPT was carried out with a constant displacement rate of 1.25 mm/min

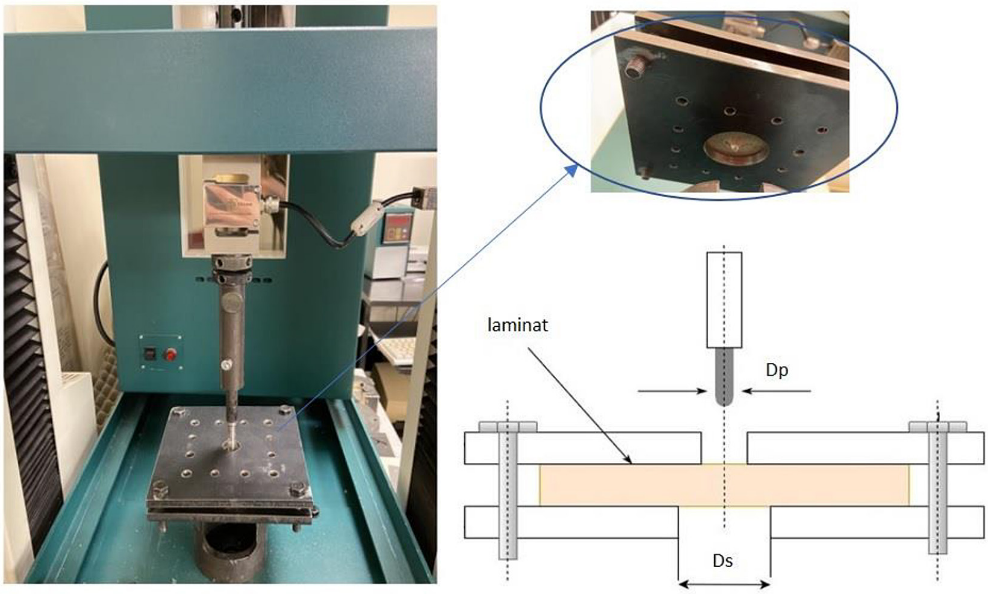


Figure 3. Schematic of the quasi-static punch shear test fixture. Dp – punch diameter, Ds – support diameter

and a total displacement of 30 mm. The schematic and test stand are shown in Figure 3.

The QSPT tests were conducted to determine the maximum force (P) and to calculate the punch shear strength (PSS) of the analyzed laminates. The PSS value corresponds to the maximum force counteracting the deformation of the material due to penetrator pressure, and thus its failure resistance, and is calculated using formula (1) [14].

$$PSS = \frac{P}{\pi \cdot D_p \cdot H_c} \quad (1)$$

where: P – maximum punching force, D_p – punch diameter, H_c – sample thickness.

Recording the force-displacement relationship during the penetration test made it possible to calculate the energy absorbed (E_a) during laminate destruction and to evaluate the hybridization effect of the analyzed laminates. The total absorbed energy was determined using the trapezium integration method and was calculated as the surface area under the force-displacement curve.

Hybridization effect

The effect of introducing additional reinforcement into the composite can be evaluated using the hybridization effect. It can be defined as a positive or a negative deviation of mechanical properties from the rule-of-mixture behavior [14]. Using this definition presents some challenges, as it is difficult to determine the composition parameter experimentally. Examples of such parameters are relative volume ratios of low and high-elasticity fibers.

Another method used by researchers is to evaluate hybridization using the percentage change in mechanical properties of composites with multiple types of reinforcement relative to a non-hybrid composite [16, 17, 29]. Equations 2, 3 and 4 were used to evaluate the hybridization effect on particular values referred to in this paper.

$$\%E = (E_h - E_n)/E_n \times 100\% \quad (2)$$

$$\%P = (P_h - P_n)/P_n \times 100\% \quad (3)$$

$$\%PSS = (PSS_h - PSS_n)/PSS_n \times 100\% \quad (4)$$

where: E_h, E_n – energy absorbed by the laminates: hybrid and non-hybrid laminates, P_h, P_n – maximum force for the hybrid (P_h) and the non-hybrid (P_n) laminates, PSS_h, PSS_n – punch shear strength (PSS) for the hybrid and the non-hybrid laminates.

Due to the difference in thickness of the compared laminates, a full evaluation of the hybridization effects was performed by calculating the hybridization influence on the PSS value, which accounts for the value of the thickness of the samples.

RESULTS AND DISCUSSION

QSPT

The destruction process of the laminate in the quasi-static penetration test can be divided into stages, which correspond to the three areas in the force-displacement curves obtained during the tests. The areas are: elastic, damage and friction. The explanation of the course and stages of this process have been the subject of earlier studies and were described in detail in the work of Bulut et al. [14], as well as in other publications [16, 29]. Figures 4 and 5 summarize the shapes of the

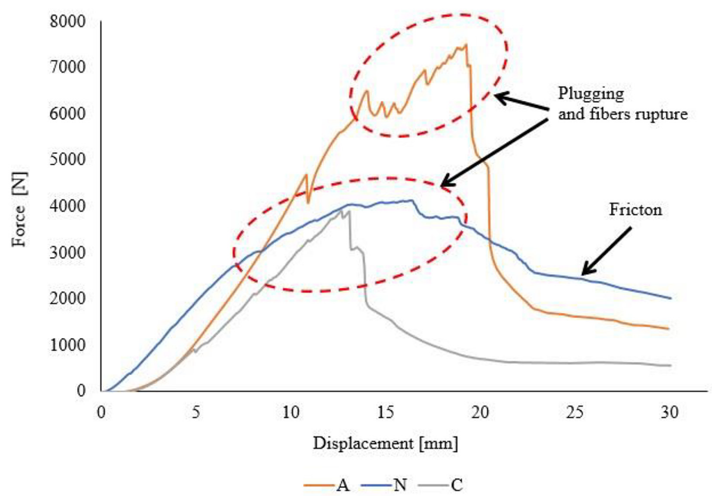


Figure 4. Force as a function of displacement for non-hybrid laminates

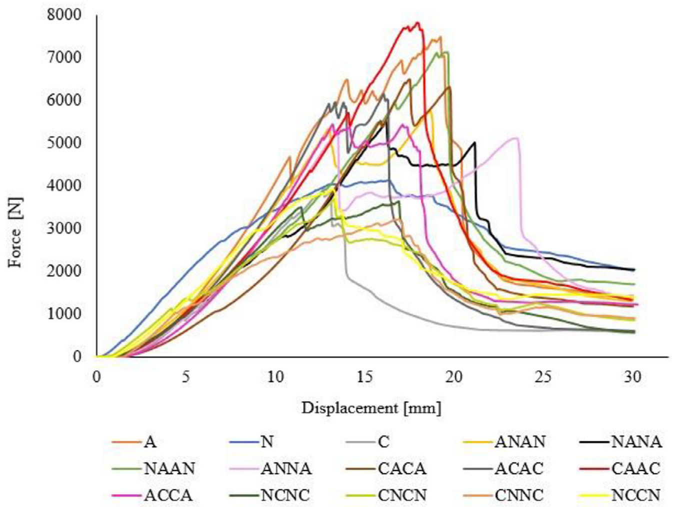


Figure 5. Penetration force-displacement curves of hybrid and non-hybrid laminates

force-displacement curves for the tested laminates. Figure 4 summarizes laminates with a single type of reinforcement, while Figure 5 compares the shapes of all 15 types of analyzed laminates.

In the first stage of the laminate destruction process, the force increases linearly in the elastic region and the laminate is subject to elastic bending. Further, the curve peaks multiple times, which can correspond to the destruction of subsequent reinforcement or matrix layers, or delamination. The maximum peak marks the destruction of fibers and is usually followed by a sudden drop in force value. This region of the graph corresponds to the loss of load-bearing capacity of the composite. The next part of each of the presented curves is a flattening stage corresponding to the friction between the laminate and the punch at the puncture site. Despite having the same 3 stages of laminate destruction, differences in the shapes of the force-displacement curves can be observed, which characterizes the tested laminates.

The comparison of the curves for single-type reinforcement laminates (with one type of reinforcement) shows, that the highest force value of about 7.5 kN was recorded for laminates with aramid fiber reinforcement (Fig. 4). For carbon fiber and natural fiber reinforced laminates the force values were similar at about 4 kN.

For laminates with natural fiber reinforcement, a flatter curve is noticeable, lacking a clear maximum peak, which can be seen for the other laminates. Using natural fiber as reinforcement does not significantly increase the maximum force value, hence the lack of a pronounced peak, which is seen for other types of reinforcement.

The highest maximum force value among all the analyzed laminates was recorded for CAAC samples and amounted to 7.8 kN. Considering the ACCA sample with a reverse stacking sequence of reinforcement layers, the maximum force value was lower by more than 2 kN. Similar observations were made for NAAN and ANNA laminates with natural and aramid fiber reinforcement. The maximum force value for the NAAN laminate was about 7.0 kN and is also about 2 kN higher than the ANNA laminate.

When performing calculations and analyzing test results, it should be noted that the tested laminates differed in thickness due to the use of different types of fabric. This is common when comparing hybrid laminates. In such cases, the number of reinforcement layers, which is constant for all compared laminates, is used as a reference point instead of the sample thickness.

In order to fully interpret the results taking into account the thickness of the tested laminates, the PSS (punch shear strength) was calculated. The obtained values are shown in Figure 6.

The highest puncture resistance value of 45 MPa was recorded for the CAAC laminate, which is significantly higher than that of the ACCA laminate. It was noted that placing the carbon fabric in the outer layers and the aramid fabric inside the laminate had a positive effect on the test result. On the other hand, the alternate arrangement of carbon and aramid fibers allowed us to improve the PSS values in comparison to the carbon laminate and obtain values similar to the aramid laminate. These results demonstrate a significant influence not only of the type of reinforcement used, but

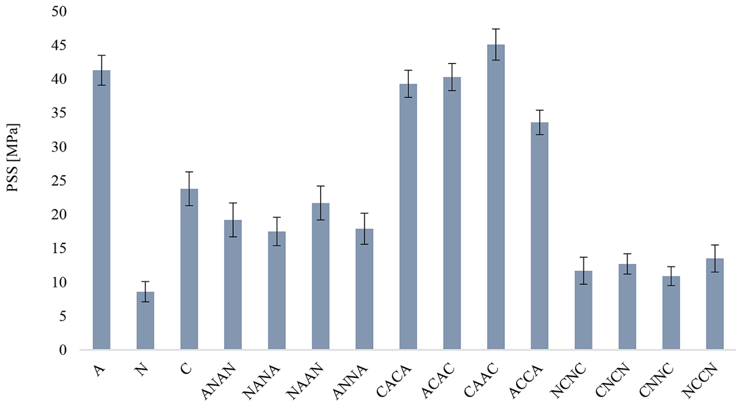


Figure 6. PSS comparison of hybrid and non-hybrid laminates

also of the stacking sequence of reinforcement layers on the achieved test results.

The differences in obtained results can be explained by looking at the characteristics of the reinforcing fibers. Carbon fiber is more brittle compared to the ductile aramid fiber, which undergoes tension before breaking. The results obtained, i.e. the highest PSS value for the CAAC laminate, are consistent with previous studies on polypropylene matrix [15] and polyurethane-polyurea matrix [16] but different than the results obtained using an epoxy resin matrix [14]. The discrepancy in results depending on the type of matrix used prompts further consideration of the failure mechanism. Different failure mechanisms are probably dominant depending on the type of matrix. In carbon fiber-reinforced composites, fiber destruction is usually the dominant mechanism. In epoxy composites reinforced with aramid fibers, delamination also plays an important role. This is related to the characteristics of the fibers themselves and differences in elastic strain. During impact loading, brittle fibers are destroyed faster than the polymer matrix, so in laminates with carbon fibers, the mechanism associated with fiber destruction is dominant. Aramid fibers, on the other hand, exhibit high reversible strain and can be stretched before failure, therefore delamination can occur before fiber breakage.

In this study, the used matrix is much more flexible than the epoxy matrix, therefore delamination can be slightly less significant here than in the case of composites with a stiffer epoxy matrix since the impact energy can be partially absorbed due to the reversible strain of the matrix. For composites with reinforcement layers arranged alternately, e.g. CACA and ACAC or NANA and ANAN, the PSS results are similar. Larger differences can be observed for laminates in which one type of reinforcement created the outer layer and 8 layers of the same reinforcement were inside the laminate. For aramid-natural laminates, the best results were observed for the NAAN internal arrangement of the aramid fabrics. CAAC laminates yielded similar results. The NAAN fabric configuration is 40% more puncture resistant than a specimen reinforced solely with natural fibers (N).

Figure 7 summarizes the results of calculating the total energy absorbed during the puncture

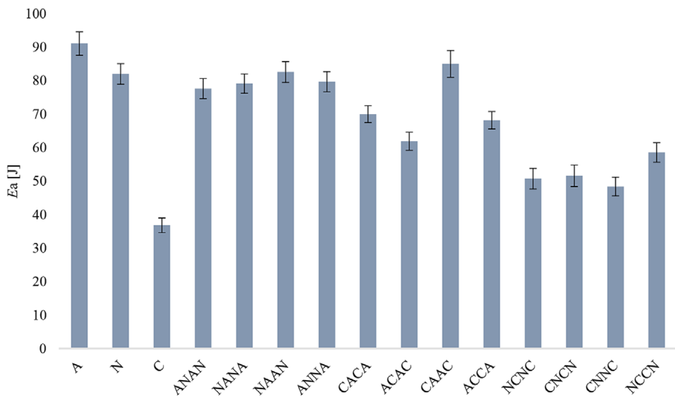


Figure 7. Comparison of absorbed energy (Ea) values for hybrid and non-hybrid laminates

test. The highest energy value (91 J) was registered for aramid laminates (A), which is about 6% higher than for the CAAC hybrid composite. A high value of absorbed energy was also observed for natural fiber laminates (N), although they exhibited the lowest puncture resistance. The lowest values of energy absorbed during puncture were achieved by laminates with carbon reinforcement.

Due to the thickness differences of the analyzed laminates, Figure 8 shows the relationship between the absorbed energy and sample thickness

The thickest laminates were samples containing flax fibers. The value of absorbed energy of the N laminate was one of the highest recorded, but lower than that of the aramid laminate and the CAAC and NAAN hybrid laminates. The NAAN hybrid composites were about 60% thinner than the N laminate while the difference in absorbed energy was about 0.5 J. The carbon fabric-reinforced laminates (C) exhibited the lowest value of absorbed energy. This value could be improved by adding natural fibers, which involves increasing the thickness of the laminate. However, the best results in the absorbed energy value were achieved by hybridization of carbon laminates with aramid fabric. In conclusion, as demonstrated on Figure 8, the type of reinforcement used rather than the thickness of the laminate had the greatest impact on the absorbed energy values.

Visual analysis of damage

Due to the complexity of the laminate structure, the destruction process occurs in stages, and both intra-layer damage as well as defects between individual laminate layers are distinguished. The purpose of the visual analysis of laminates after puncture was the identification and evaluation of the damage that had occurred. Table 3 shows images of the samples after puncture.

The laminate's efficiency in absorbing energy is closely tied to the properties of the reinforcing fibers, which can be destroyed by exceeding their tensile strength or being sheared. Phenomena resulting from exceeding the tensile strength during the puncture test also include delamination and matrix cracking. Damage can also occur as a result of friction between the punching pin and the specimen [30].

In non-hybrid aramid laminates and hybrid laminates containing aramid fabric in the outer layers, a characteristic cross formed by virgin fibers can be seen on the front and/or back sides of some laminates. This phenomenon is tied to the transfer of the greatest loads by the fibers in direct contact with the penetrator and has been described by Jamroziak [31], among others. In the case of aramid fibers, which exhibit higher ductility than carbon or natural fibers, stretching of fibers in contact with the penetrator is observed, which is visible in the form of a characteristic cross on the surface of the laminate. In most analyzed laminates, deformation of the laminate surface in the form of a convex cone on the side opposite to the applied load was also observed.

In laminates where carbon fibers made up the outer layers, fiber shearing was observed. In the rear layer of the laminate, the push-out of the plug was formed without pulling out the fibers, which is due to the brittleness of carbon fibers. In composites reinforced with natural fabric, longitudinal cones,

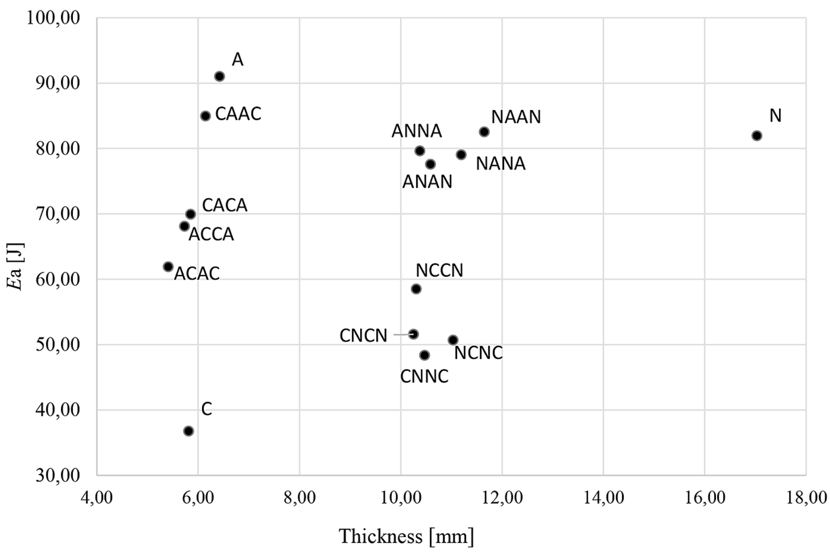
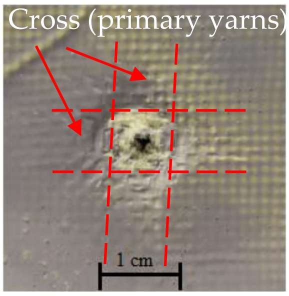
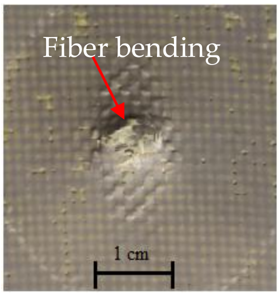
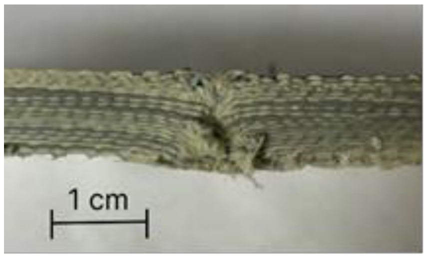
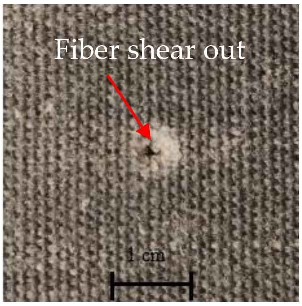
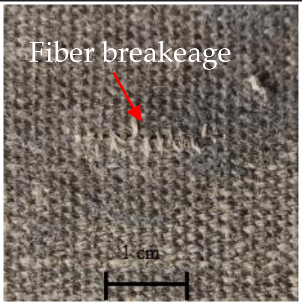
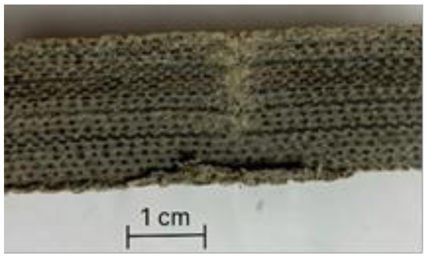
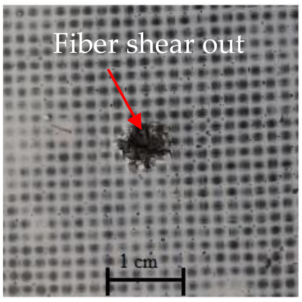
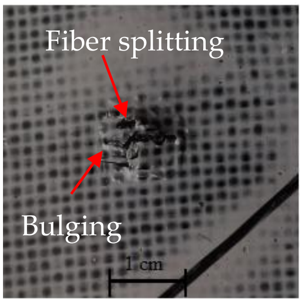
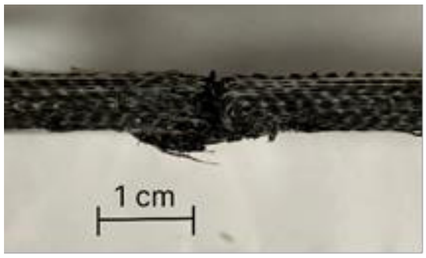
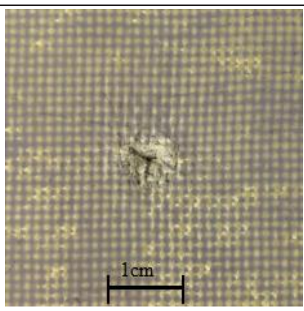
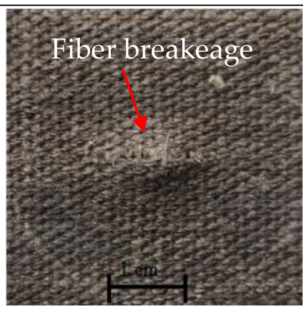
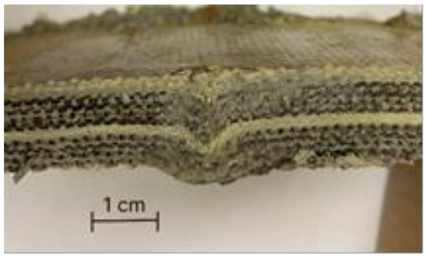
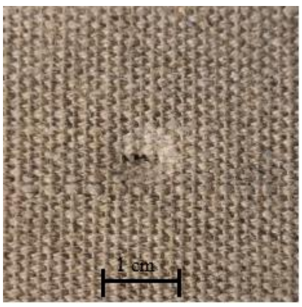
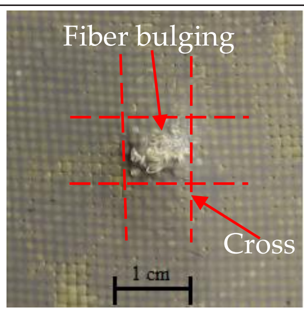
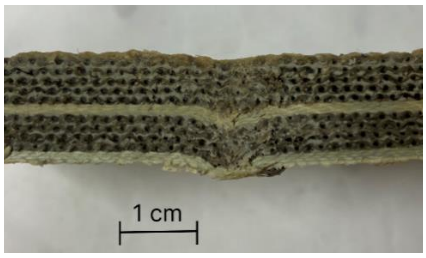


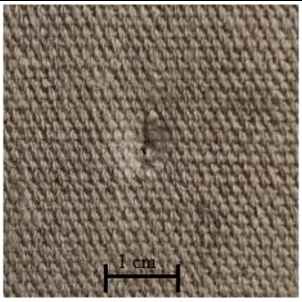
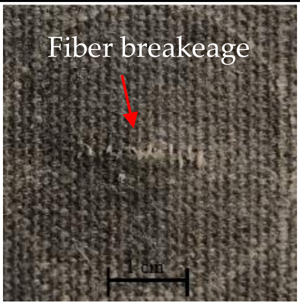
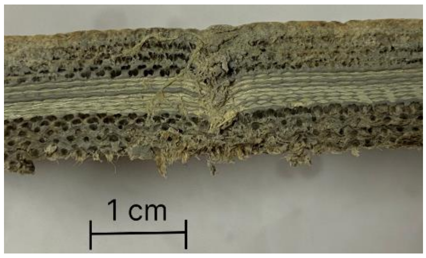
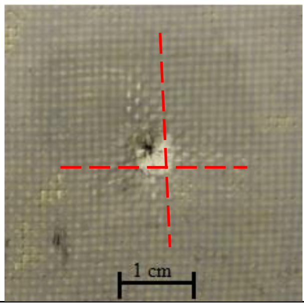
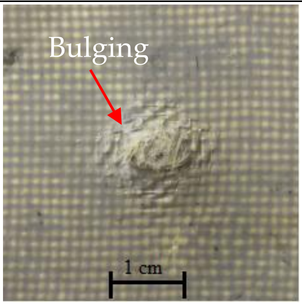
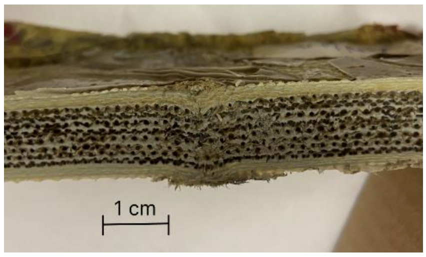
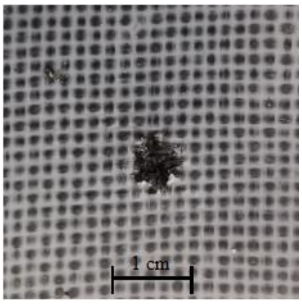
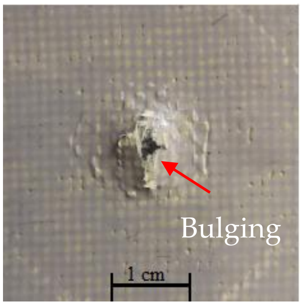
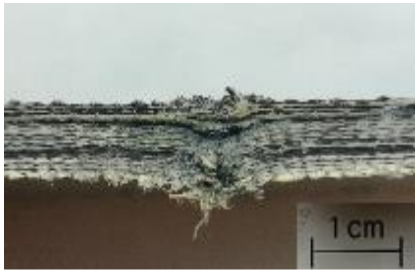
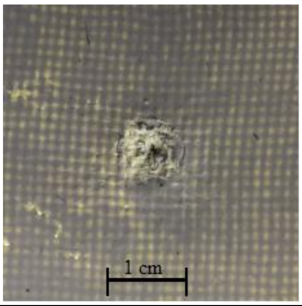
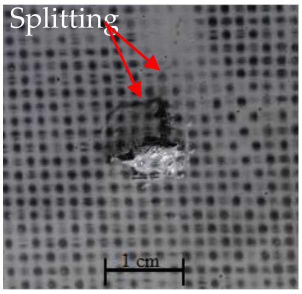
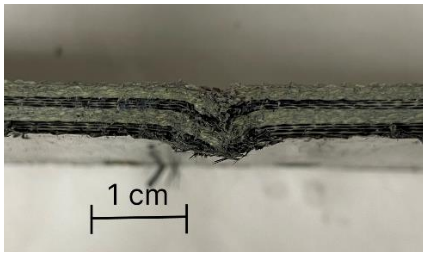
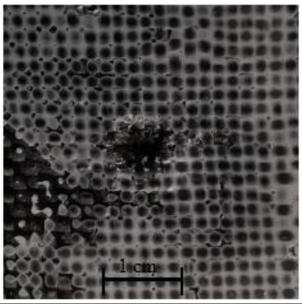
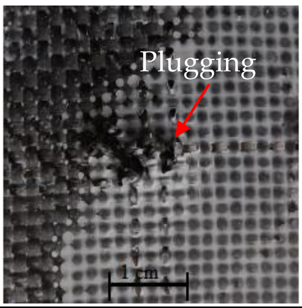
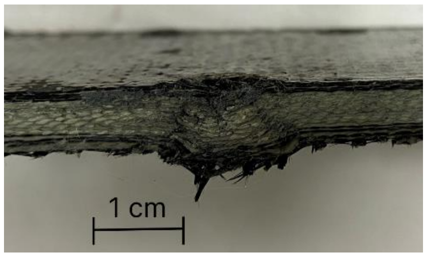
Figure 8. Effect of laminate thickness on energy absorption

Table 3. Laminate samples after quasi-static penetration tests

Sample	Front	Back	Cross-sectional views of the samples
A			
N			
C			
ANAN			
NANA			

resulting from the propagation of longitudinal damage to the fabric, can be seen in the back layers. The failure mechanism of the laminates was also affected by the polymer matrix. Due to the flexible polyurethane-polyurea matrix, a certain amount of energy could be absorbed by the reversible strain of the composite without causing permanent damage. This is mainly due to the greater resistance of the flexible matrix to damage initiation and propagation [32].

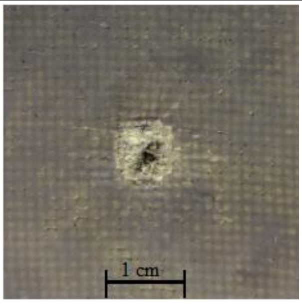
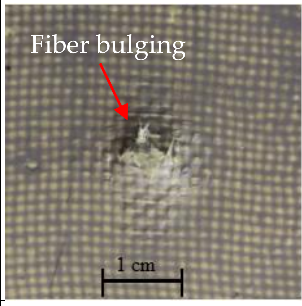
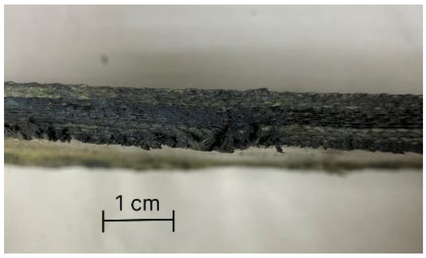
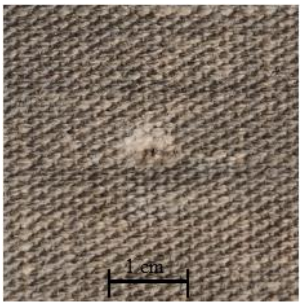
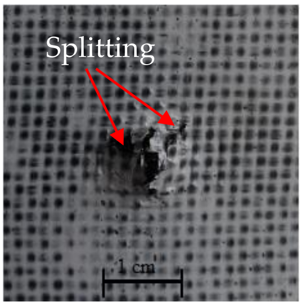
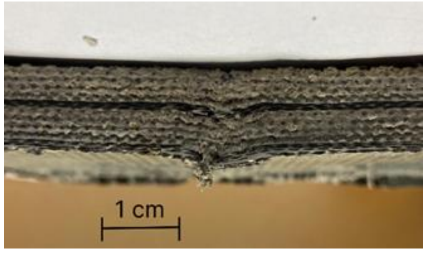
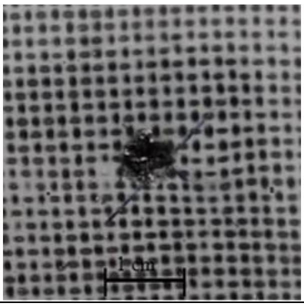
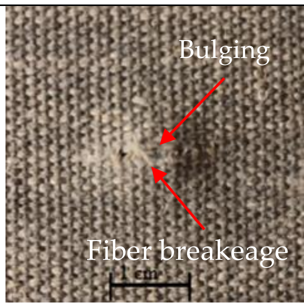
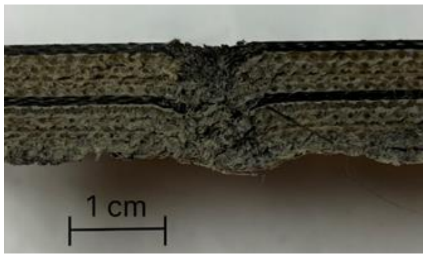
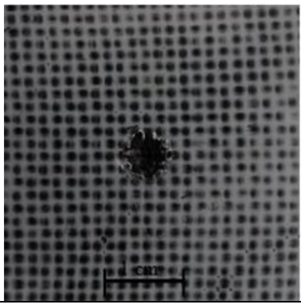
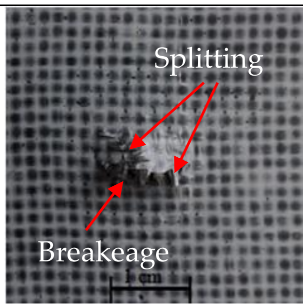
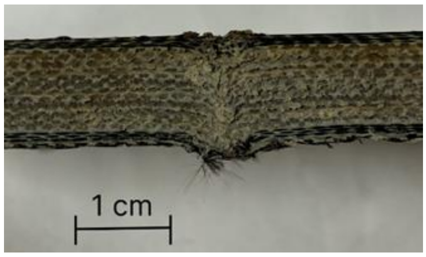
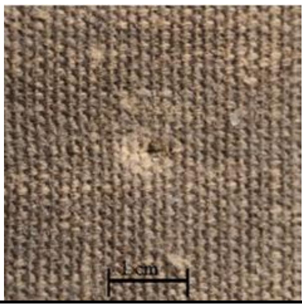
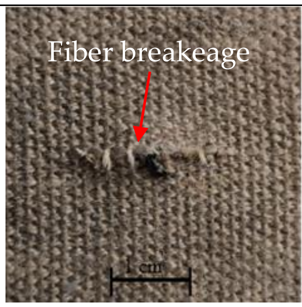
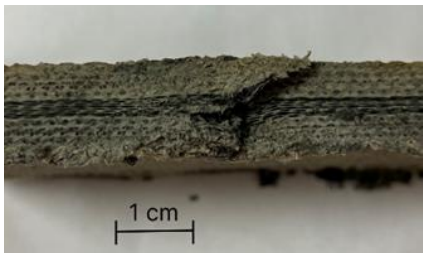
Cont. Table 3

NAAN			
ANNA			
CACA			
ACAC			
CAAC			

Hybridization effect

The effect of hybridization of laminates was evaluated in terms of maximum punching force (P), energy absorbed during punching (E) and puncture resistance (PSS). Depending on the type of non-hybrid laminate chosen as a reference point, different results of the hybridization effect can be presented. In this study, the hybridization effects were determined in reference to three groups of specimens containing aramid, carbon and natural reinforcement. This approach makes

Cont. Table 3

ACCA			
NCNC			
CNCN			
CNNC			
NCCN			

it possible to better evaluate what reinforcement configuration of the hybrid laminate improves or worsens the properties relative to the selected non-hybrid laminate. Figures 9, 10 and 11 show the results of the hybridization effect depending on the choice of non-hybrid laminate taken as a reference.

In the case of hybrid laminates compared to aramid laminates, a positive hybridization effect was obtained only for CAAC laminates for the value of maximum force. In other cases, the hybridization of aramid laminates does not have a positive effect on both the value of absorbed

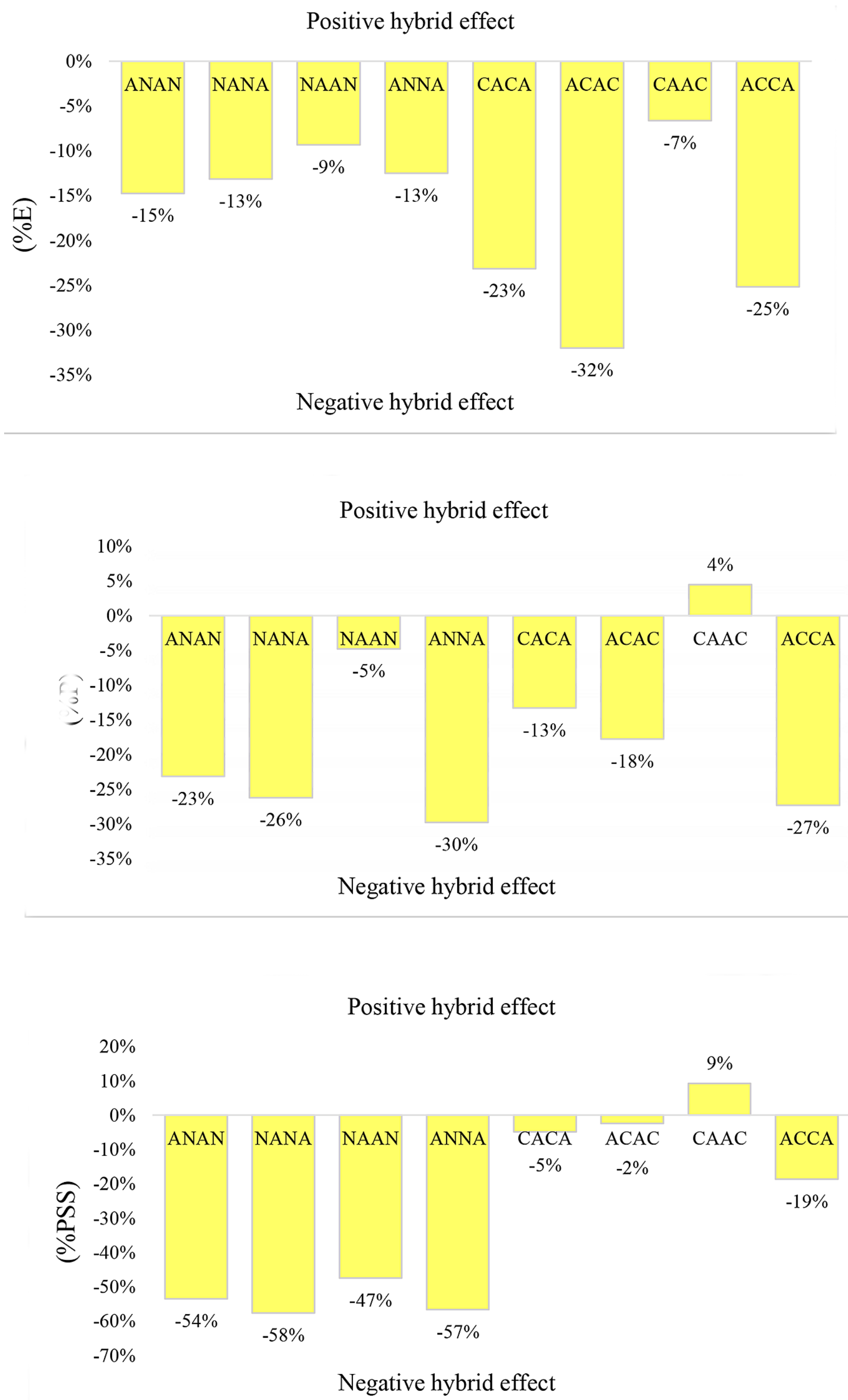


Figure 9. The effect of hybridization compared to aramid laminates, (calculations based on averaged values)

energy and maximum force. In the following figures, the hybridization effect was calculated in comparison with natural fiber laminates.

The hybridization of natural fiber laminates with both aramid and carbon fibers had mostly a negative effect on the value of absorbed energy. The value of the maximum force was higher for aramid-flax fiber hybrid laminates. It can be noted that the best results were obtained for the NAAN configuration. This is consistent with previous observations on the favorable results of aramid fiber arrangement inside the analyzed laminates. Regarding the PSS values, the hybridization effects are favorable regardless of

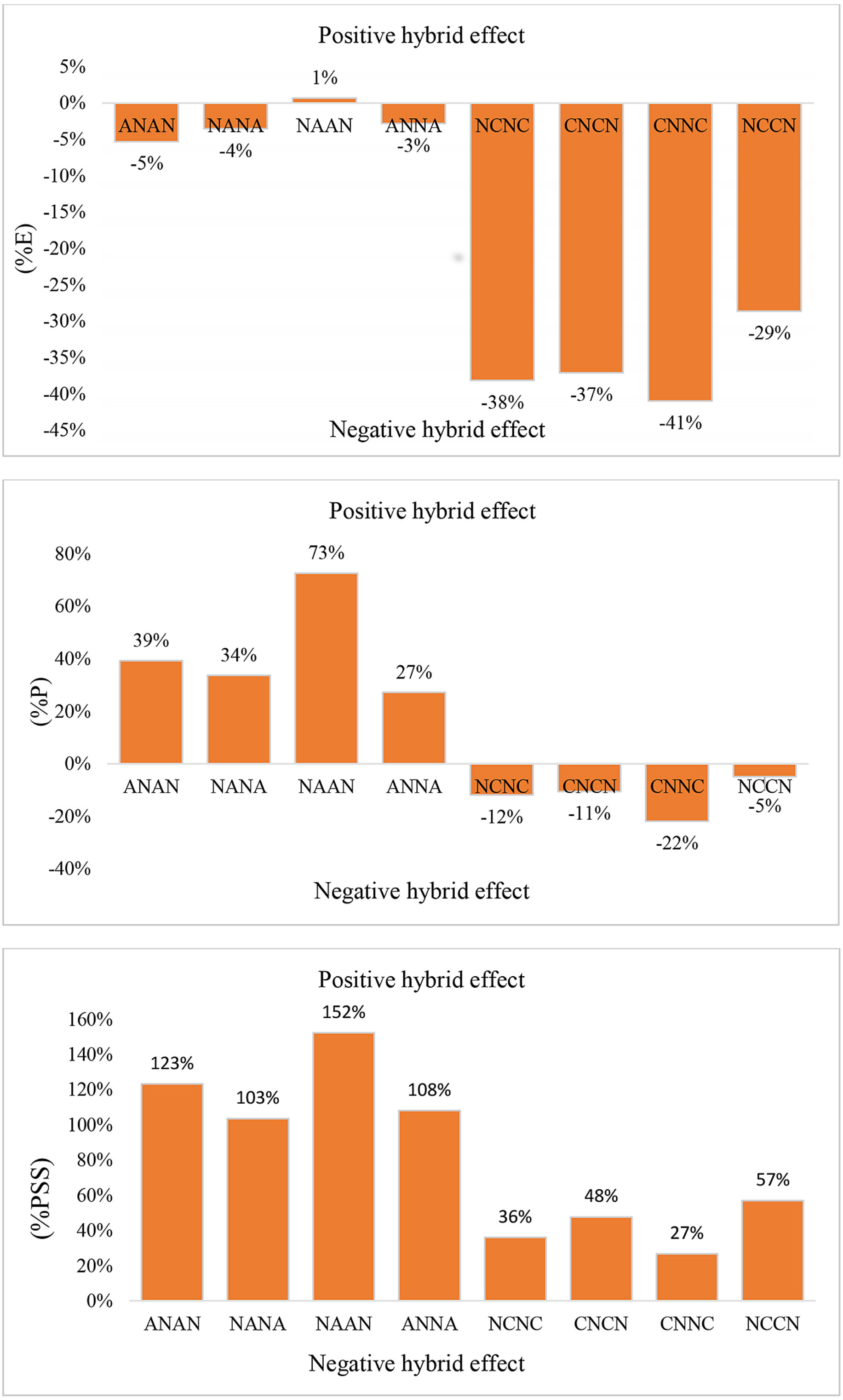


Figure 10. The effect of hybridization compared to natural laminates (calculations based on averaged values)

the layer configuration of the laminates. This has to do with the reduced thickness of the hybrid laminates, compared to flax laminates, which is taken into account when calculating PSS values. Figure 11 summarizes the effects of hybridizing carbon laminates with aramid and linen fabrics. Hybridization of the carbon fabric for each of the tested samples positively influenced the value of absorbed energy. An increase in the value of maximum force and puncture resistance was observed due to the introduction of aramid fabric into the carbon laminate. Positive effects of hybridization with aramid fabric were obtained for each analyzed configuration.

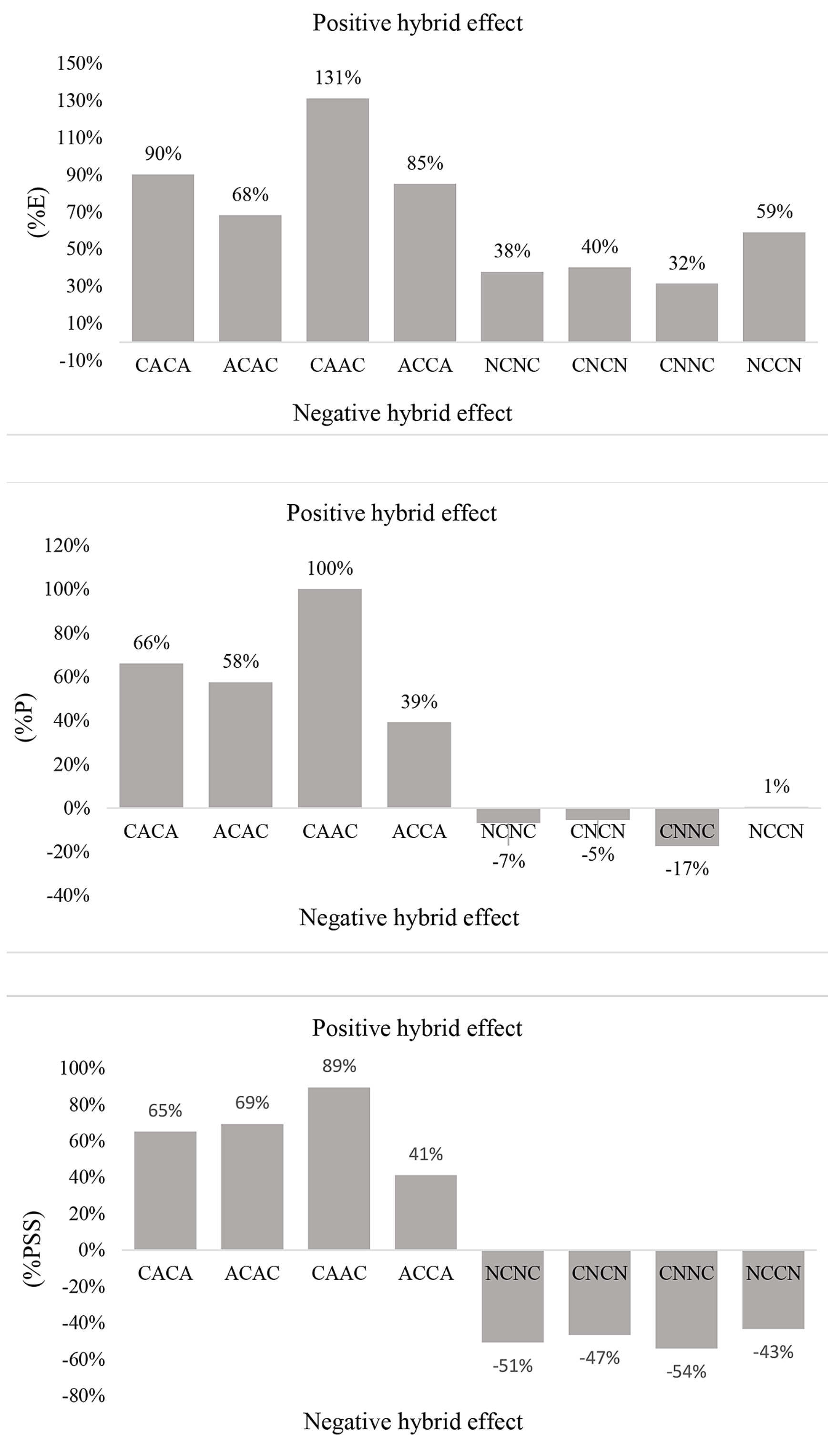


Figure 11. The effect of hybridization compared to carbon laminates (calculations based on averaged values)

CONCLUSIONS

After analyzing the obtained results, the following conclusions were formulated:

1. Among the single-type reinforcement laminates, the highest value of puncture force, puncture resistance and the highest value of absorbed energy were registered for aramid laminates (A). The results obtained are connected with the high ductility of aramid fibers, which undergo stretching before failure. In the puncture test, this property plays an important

role and allows us to achieve higher values in the conducted experiment. The lowest value of energy was absorbed by laminates with carbon fibers (C), due to their brittleness.

2. The stacking sequence of reinforcement in the laminate affects the results of the quasi-static puncture test. In both aramid-carbon and aramid-natural hybrid laminates, better results were achieved with the location of the 8 layers of aramid fabrics inside the laminate. Considering all the hybrid laminates analyzed, the highest value of maximum force, absorbed energy and puncture resistance was registered for CAAC hybrid laminates.
3. The thickness of the laminate does not have a decisive influence on the results of the quasi-static puncture test. The properties of the composite defined by the puncture test are determined primarily by the type of reinforcement and its stacking configuration. The thickness of the laminates and the values of absorbed energy were compared. Natural fiber (N) laminates were the thickest among the tested samples. The NAAN hybrid composite was about 60% thinner (7 mm) and absorbed only 0.5 J less energy. This means that a significant reduction in material thickness has little effect on the value of energy absorbed by the composite, while the type of reinforcement used is important. The highest value of absorbed energy was registered for aramid laminate (A), which was more than 2.5 times thinner than natural laminate (N).
4. The choice of a single-type reinforcement laminate, which serves as the reference point is important for evaluating the effect of hybridization. Relating the results of hybrid laminates to the carbon laminate, it was concluded that hybridization with both aramid and natural fabric has a positive effect. CAAC laminates absorbed the most energy and for them, the greatest positive hybridization effect was shown. All of the carbon composites with the addition of aramid fabric achieved a positive hybridization result. Hybridization of carbon laminates with natural fabric increased the value of absorbed energy, but negatively affected the results of maximum force measurements.
5. After visual analysis, the presence of a characteristic cross effect was noted in the front layers of A, ANNA and ACCA samples. This effect is related to the pulling out of the virgin fibers and was visible in laminates in which the aramid fabrics were located in the outer layers. With other kinds of reinforcement, this type of effect was not observed. A post-impact cone was observed on the underside of the laminate, and its appearance varied depending on the type of laminate. In composites with aramid fabric in the rear layers of the laminate, the cone was taller compared to samples with carbon or linen fabric. This is due to the high elasticity of aramid fibers, which are stretched during the test before they are broken.

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