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# METHODS FOR REDUCING NOTCH SENSITIVITY OF HYBRID PSEUDO-DUCTILE POLYMER COMPOSITES WITH FABRIC REINFORCEMENT: EXPERIMENTAL STUDY

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ABSTRACT

Composite materials reinforced with synthetic fibres have been used in aviation and space technology for more than half a century. Fibre-reinforced composites with high specific strength and corrosion resistance are an attractive alternative to traditional structural materials, including steels, aluminium and titanium alloys. At the same time, composites based on carbon and glass fibres are inherently brittle structural materials with high strength sensitivity to stress concentrations due to the design features of the structures or defects that occur in operation. One way to solve this problem is hybridisation which makes it possible to increase the nonlinearity of the composite stress-strain diagram and reduce sensitivity to notches. Hybrid composites combine several types of reinforcing filler with different fracture strains and exhibit a pronounced pseudo-ductile plateau in tension. Such material behaviour ensures the redistribution of stresses near the concentrator and potentially reduce notch sensitivity. When designing hybrids, it is necessary to take into account the influence of different factors including the ratio between the components and their lay-up, using various technological methods, and the specific strength of the finished material. This paper presents the results of an experimental study on the strength of hybrid composites based on glass and carbon fabrics in the open hole tests. It was found that hybrids with an extended hardening area after the pseudo-yield plateau are were more notch sensitive. A low elongation component layers rotation on angles up to 10°, as well as the use of thin polymer veils, also reduce the sensitivity of the composite strength to the presence of the defects.



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## Introduction

The stress concentration has a significant effect on the performance of composite structures due to the brittle mechanical behaviour of traditional layered polymer composite materials (PCM). The increased sensitivity to local stresses leads to the necessity of large normative safety factors and reduces the overall weight efficiency. One of the possible solutions to this problem is to expand the area of nonlinear deformation of the material, which ensures the redistribution of stresses in the defect zone and increases the allowed loads. Traditional composite materials often do not have a pronounced nonlinearity of deformation and, in most cases, are considered linearly elastic up to failure.

Researchers and engineers proposed several ways to obtain a pronounced non-linear behaviour on traditional composites, for example, using reinforcement with metal [1–4] or high-strength polymer fibres [5–7]. Despite significant inelastic deformations for composite materials (up to 15 %), these methods are not applied in modern critical highly loaded structures, since they do not allow to meet high requirements for mass efficiency, specific strength and/or stiffness.

Hybridisation is one of the promising methods for expanding the region of nonlinear deformation (up to pseudo-ductility) by combining at least two types of reinforcing fillers with low and high elongation in failure (LE and HE) in one composite material.

There are interlayer, intralayer and intrayarn hybridisation [8–13] (Fig. 1, *a*).

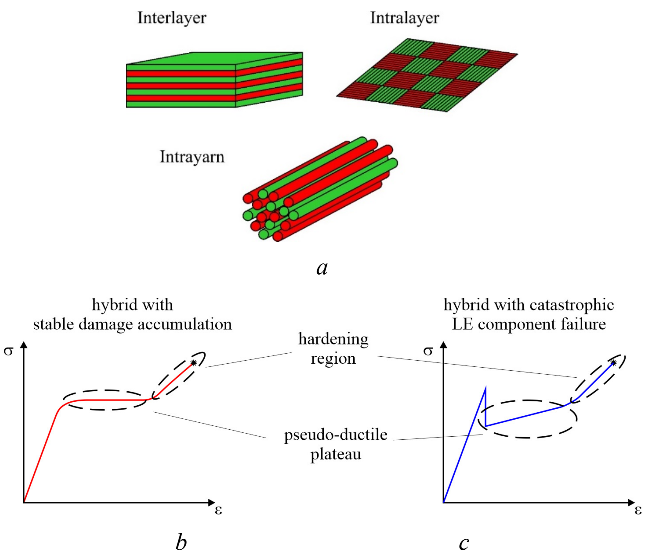


Fig. 1. Types of hybridisation (*a*); Stress-strain diagram of pseudo-ductile composite with the stable damage accumulation in LE component (*b*); Stress-strain diagram of pseudo-ductile composite with the catastrophic failure of LE component (*c*)

Interlayer hybridisation seems to be the most technologically advanced, as it focuses on the use of known materials and technologies like contact or autoclave moulding of packages from LE and HE prepregs. The LE component fails earlier, while HE component continues to bear the applied load. In [14–16], emphasis is placed on ensuring a stable accumulation of damage in LE component which avoids a sharp drop in the stresses level on the stress-strain diagram and reduces the risk of sudden failure (Fig. 1, *b*). The sharp stresses drop is associated with a single fragmentation of the LE component and its subsequent delamination (Fig. 1, *c*). In this case, LE layers are unloaded which can lead to an overload of HE component layers and a general decrease in the strength. It should be noted that in most studies the authors considered hybridisation of unidirectional composites, whereas only a few works are devoted to hybridisation using fabrics with plain, twill, or satin weave structures [17].

The topic of pseudo-ductility as a way to reduce the sensitivity of composite materials to the presence of holes and notches is poorly covered in literature [18–21]. The published studies are different in methods of assessing the influence of stress concentrators on the material strength, and there is no comparison of the hybrids strength with the strength of the hybrid components. This allows to speak only about the effectiveness of a definite hybrid composite within a series of comparative tests of a number of hybrid PCMs. The comparison is strongly necessary if the possibility of replacing a non-hybrid composite material with a hybrid one is assessed. In most cases, the strength of the hybrid under uniform stress (rectangular specimens) is lower than that of the composite based on LE component only. For this reason, the resulting benefit of reducing the concentrator effect on the strength of the overall structure by hybridisation might be negligible. In [22] to assess the strength of the specimens with stress concentrators, it was proposed to use notch sensitivity factor

$$k_F = \mathrm{Fn}/\mathrm{F}_0,$$

where Fn is nominal failure stress in a weakened section of a specimen with a concentrator, a $F_0$ – ultimate tensile strength of the rectangular specimen. The value of the notch sensitivity factor typically is within the range of $0 < k_F < 1$, whereas in critical aerospace structures it is important to create conditions for obtaining insensitivity to holes and notches ($k_F \to 1$).

The article considers the effect of lay-up engineering of a layered hybrid composite on the sensitivity to stress concentrators. Hybrid composites were composed of LE and HE components based on carbon and glassfabrics, respectively. The authors studied such technological methods as influence of LE and HE layers ratio, the change in the stacking sequence and the angle of LE layers in the package, and the modification of the interface between LE and HE layers with thin polymer veils as well. To assess the effectiveness of the above mentioned methods, notch sensitivity factor and the final weight efficiency of hybrid composites were used.

## 1. Materials and methods

### 1.1. Materials

In the present study, plain weave glass fabric with the areal density of 200 g/m$^2$ was used as the HE component, and twill weave carbon fabric with the similar areal density of 200 g/m$^2$ was used as the LE one. [23–24]. In addition, non-woven veils with the areal density of 15 g/m$^2$ made of polypropylene fibres were placed between LE and HE layers in several composites. A mixture of epoxy resin, diethylene glycol, and triethanoltetramine ED-20/DEG/TETA (82/8/10 by weight) was used as a matrix. Composite materials were made by hand lay-up followed by pressing for 12 hours at a temperature of 25 °C. To ensure the desire plate thickness and fibre volume fraction, spacers with pre-defined thickness were installed between the press plates. Post-curing was carried out at the temperature of 80 °C for 5 hours. The thickness of the one layer was 0.20 mm for both fabrics.

At the first stage of the research, an influence of the stress-strain diagram on the notch sensitivity factor was assessed. The hybrid, that showed the greatest strength increase for the specimens with defects, was chosen as the basis for evaluating the effectiveness of changing the orientation and position of the LE layers in the package.

### 1.2. Hybrid composites design

To implement the pseudo-ductility effect, a certain ratio between HE and LE components is required. The ratio depends on their mechanical characteristics (modulus of elasticity, tensile strength) and the orientation of the fibres to the loading direction. The previously developed FARGR-2 software module [17] was used to calculate nonlinear stress-strain diagrams for layered composites consisting of fabric layers with arbitrary fibre orientations. To obtain the calculated stress-strain diagram, it is required to set the elastic characteristics of the fabric layer ($E_1$, $E_2$, $G_{12}$, $\mu_{12}$), as well as the warp/weft strength limits $F_{1t}/F_{2t}$, shear strength $F_{12}$.

The calculation algorithm implemented into the program is a combination of the classical laminated plate theory (constant deformations over the thickness, absence of delamination, monotonic increase in loads) supplemented by the mechanism of scattered microdamages accumulation [25]. For this purpose, the idea of Daniels [26] about the dry bundle of fibres, which work in parallel and are independently fractured, was used. The normal distribution law describes the strength properties scattering.

### 1.3. Experiments

Several types of specimens were prepared for the experimental research (Fig. 2). To obtaining stress-strain diagram of the hybrid and non-hybrid composites, rectangular specimens with end tabs were used for tensile tests. Specimens with open holes were tested without end tabs. For shear tests, V-notched specimens were cut with CNC milling machine.

Three specimens were tested on each material type and test method. The tests were carried out on a universal testing machine INSTRON 5900R. Digital image correlation (DIC) system Vic-3D [27] was used to obtain strain fields during the tests. The strain gauge mode made it possible to determine the average longitudinal and transverse strains for the subsequent calculation of elastic moduli and Poisson's ratios.

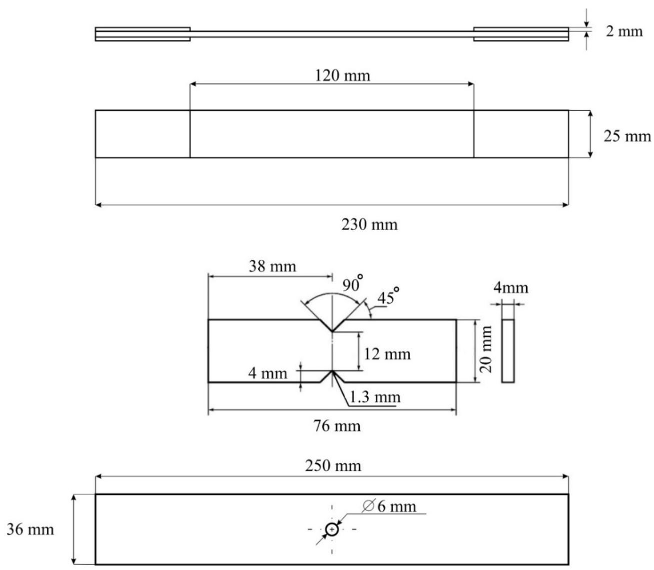


Fig. 2. Sketches of the specimens for tensile, shear, and open hole tests

## 2. Results and discussion

Experimental elastic and strength properties of fabric glass-reinforced plastics and carbon-reinforced plastics are shown in Table 1 (the ± sign denote the standard deviation of experimental results).

Table 1

Elastic and strength properties of the GFRP and CFRP

| Material | $E_1$, GPa | $E_2$, GPa | $F_{1t}$, MPa | $F_{2t}$, MPa | $G_{12}$, GPa | $F_{12}$, MPa | $\mu_{12}$ |
|---|---|---|---|---|---|---|---|
| CFRP [$^y0_{20}$] (twill) | 58,7 ± 3,3 | 58,0 ± 3,1 | 764 ± 12 | 760 ± 11 | 4,1 ± 0,2 | 116 ± 3 | 0,07 |
| GFRP [$^c0_{20}$] (plain weave) | 26,8 ± 0,9 | 26,8 ± 0,9 | 509 ± 15 | 509 ± 15 | 4,5 ± 0,3 | 80 ± 2,6 | 0,15 |

Open hole test results (tensile strength and notch sensitivity factor) are shown in Table 2. The last column in Table 2 shows the produced hybrids rating of in comparison to GFRP (taken as 100 %).

Open hole test results showed that for the original composites (fabric carbon and fibreglass), the hole presence led to average specimens strength decrease by 1.5–1.7 times (№ 1, 2 in Table 2).

Table 2

Notch sensitivity factor (highlighted) and other data of the GFRP, CFRP and hybrids

| № | Material | $\rho$, g/sm$^3$ | $E_X$, GPa | $F_X$, MPa | $F_{Xn}$, MPa | $k_F = F_{Xn}/F_X$ | $F_{Xn}/\rho$, $m^4/s^2$ | *Rating, %* |
|---|---|---|---|---|---|---|---|---|
| 1 | CFRP [$^y0_{20}$] (twill) | 1,480 | 58,7 ± 3,3 | 764 ± 12 | 449 ± 9 | 0,575 | 30,3 | — |
| 2 | GFRP [$^c0_{20}$] (plain weave) | 1,760 | 26,8 ± 0,9 | 509 ± 15 | 343 ± 8 | 0,662 | 19,5 | 100 |
| 3 | Hybrid №1 [$^c0_{10}/^y0_4/^c0_{10}$] | 1,713 | 35,1 ± 0,1 | 491 ± 11 | 386 ± 4 | 0,787 | 22,5 | 115 |
| 4 | Hybrid №2 [$^c0_9/^y0_2/^c0_9$] | 1,732 | 30,6 ± 0,6 | 486 ± 2 | 335 ± 2 | 0,690 | 19,3 | 99 |
| 5 | Hybrid №3 [$^c0_{10}/\pm^y10_2/^c0_{10}$] | 1,713 | 36,2 ± 0,8 | 474 ± 12 | 376 ± 7 | 0,793 | 21,9 | 112 |
| 6 | Hybrid №4 [$^c0_{10}/\pm^y20_{2s}/^c0_{10}$] | 1,732 | 31,9 ± 0,2 | 434 ± 10 | 375 ± 2 | 0,862 | 21,6 | 111 |
| 7 | Hybrid №5 [$^c0_4/^y0_1/^c0_4/^y0_1/^c0_2$]$_S$ | 1,713 | 35,3 ± 0,4 | 450 ± 7 | 343 ± 3 | 0,763 | 20,0 | 103 |
| 8 | Hybrid №6 [$^c0_{10}$/v/ $^y0_4$/v/ $^c0_{10}$] | 1,713 | 36,2 ± 0,8 | 486 ± 7 | 384 ± 6 | 0,790 | 22,4 | 115 |

## 2.1. Influence of hybrid composites design

Components ratio control in the hybrid composites allows to change the shape of the pseudo-ductile hybrid stress-strain diagram (change of Yung modulus, pseudo-ductile plateau and hardening region length). To assess the influence of the stress-strain diagram shape, stress-strain diagrams of hybrid composites reinforced by glass and carbon fibre were calculated (№ 3 and № 4 in Table 2). The diagrams had different hardening region lengths after pseudo-ductile plateau (Fig. 3). The ratio of GFRP and CFRP thicknesses for short hardening region was 5/1, for an extended hardening region it was 9/1.

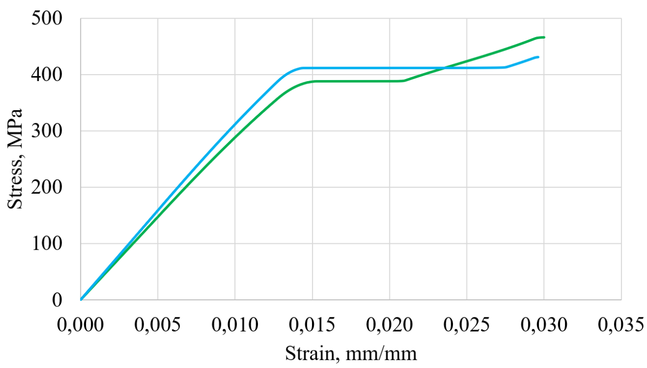


Fig. 3. Calculated stress-strain diagrams of hybrid PCMs with different hardening region length

Experimental and calculated stress-strain diagrams are shown in Fig.4 and Fig.5.

It is important to note that Hybrid № 1 had maximum stresses at the moment of the carbon layers failure (strain is about 1.5 %). The maximum stresses at the moment of LE component failure were taken as strength of rectangular specimens with end tabs, as subsequent deformation of the package could no longer be considered stable.

Both hybrid PCMs showed a slight decrease of strength relatively to GFRP (less than 5 %). However, the hybrid with a short hardening region showed more than 12 % strength increase in open hole tests and 18.9 % rise of notch sensitivity factor. The hybrid with a glass/carbon fibre ratio of 9/1 did not show a significant change in the notch sensitivity factor.

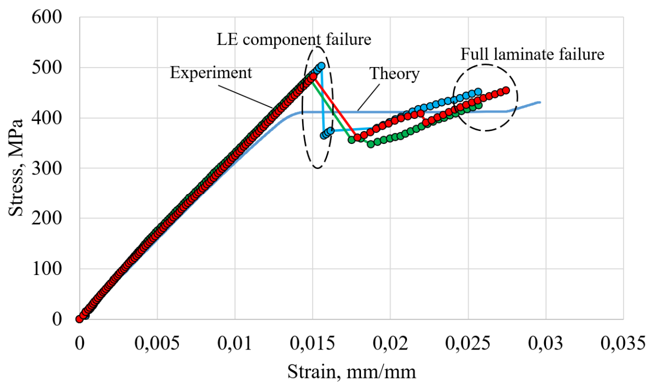


Fig. 4. Experimental and calculated stress-strain diagrams of Hybrid №1 (ratio of GFRP and CFRP thicknesses was 5/1)

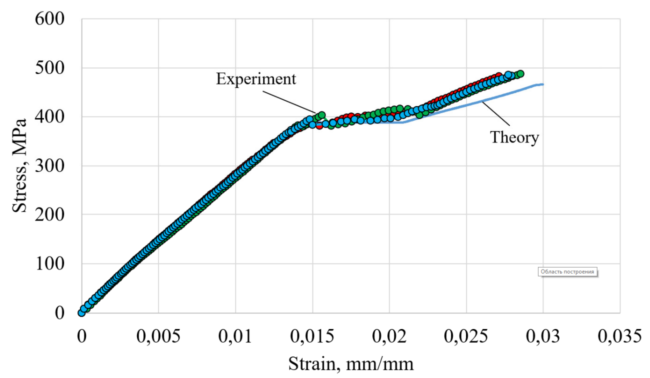


Fig. 5. Experimental and calculated stress-strain diagrams of Hybrid № 2 (ratio of GFRP and CFRP thicknesses was 9/1)

This confirms that for the efficient hybridization it is necessary to ensure the reinforcing components failure at the same stress level. According to the test results, Hybrid №1 was chosen as the basis for assessing the effectiveness of other technological methods.

## 2.2. Influence of fibre rotation and stacking sequence

In [28–30], it was shown that it is possible to ensure stable deformation and damage accumulation in the composite by rotating the layers through small angles ± φ to the load axes. The presented results are proposed to be extended to hybrid PCM reinforced with fabrics. In this case, there is still no significant decrease in the elastic modulus along the loading axis. At the same time, the rotation of the fibres makes it possible to expand the region of nonlinear deformation significantly. It is assumed that LE component layers rotation will ensure gradual and stable damage accumulation of the composite.

Hybrid № 1, which had less notch sensitivity, was taken as the basis to determine the efficiency of LE component layers rotation and separation. Glass-carbon hybrid composites were fabricated with the carbon layers rotation by ± 10° and ± 20° to load axes (Table 2, № 5 and 6, Fig. 6, left).

Also, based on Hybrid 1, the composite with carbon layers spaced apart from the stacking center was made (Table 2, No. 7, Fig. 6, right). It is assumed that this way of LE layers spacing will help to avoid its single fragmentation and provide dispersed damage accumulation to achieve better stress redistribution around hole.

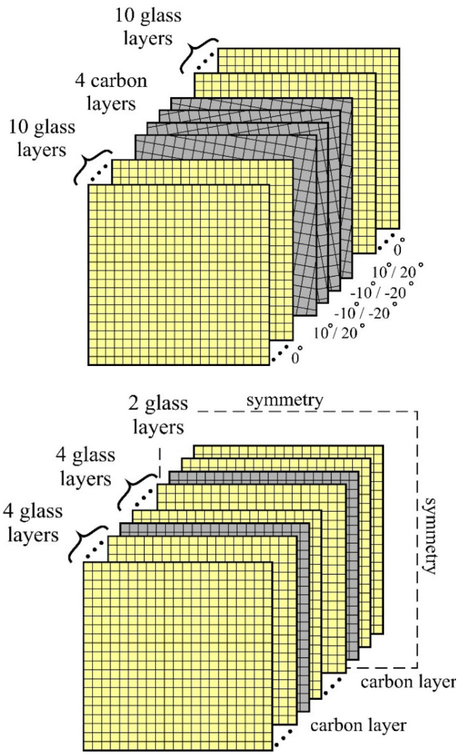


Fig. 6. Lay-up for composites with LE layers rotation (left) and LE layers spacing

The rectangular and open hole specimens tensile test results are shown in Table 2 (№ 5–7).

The highest notch sensitivity factor was observed in the hybrid PCM with fabric layers rotation by ± 20°. However, this result was achieved because this hybrid had the lowest rectangular specimens strength among the considered composites (Fig. 7).

The rotation of LE component layers by ± 10° also led to the decrease of rectangular and open hole specimens strength. However, the decrease did not exceed 5 %. At the same time, there were significant changes in composite deformation and failure process. (Fig. 8). The maximum stresses in this case were not observed during the CFRP layers fragmentation (strain about 1.3 %), as it was during Hybrid №1 loading. Maximum strength was achieved at full lay-up failure. In this case the probability of catastrophic failure during elastic deformation was reduced. For this reason, Hybrid № 3 failure pattern is considered to be more preferable than Hybrid № 1.

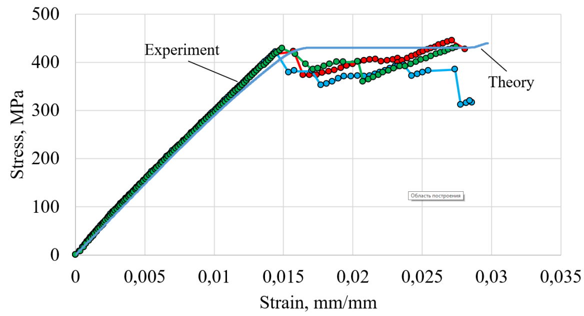


Fig. 7. Experimental and calculated stress-strain diagrams of Hybrid № 4 (LE component rotation by ± 20°)

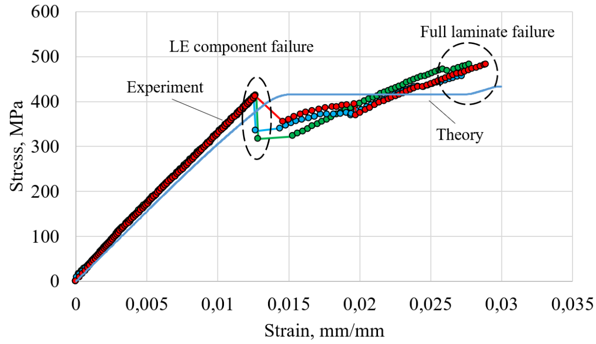


Fig. 8. Experimental and calculated stress-strain diagrams of Hybrid № 3 (LE component rotation by ± 10°)

LE component spacing from stacking center had a negative impact on the material strength. Strength of specimens with round holes was at the same level with GFRP, while the failure stress of rectangular specimens decreased by more than 10 %. This is probably due to the occurrence of eccentric tension during the failure of LE layers lying near one of the composite outer surface. It leads to additional bending moment and as a result to local overload of the composite.

Thus, to maximize the hybridization potential, it is recommended to place the layers of the LE component in the lay-up center and rotate them at a small angle.

## 2.3. Influence of thin polymer veils

Modification of the interface between the hybrid PCM components in case of interlayer hybridization is aimed at changing the mechanical properties that characterize the behaviour of the composite in the transverse shear aspect (planes 1–3 and 2–3). Felting [31; 32], the introduction of short fibres into the interlayer space [33], and the use of thin polymer veils [34] can serve as examples of such modification. The first two methods can significantly increase the interlaminar shear strength. However, delamination of component interface occurs due to the LE component unloading after its failure. As a result, the presence of LE component fragments on the HE component surface can be cause for stress concentration and HE component premature failure. Thus, thin polymer veils at the component interface can expand the region of nonlinear shear deformation and reduce the risk of HE component damage accumulation during LE component fragmentation. In the present study, a number of comparative tests were carried out with classic hybrid PCM (Hybrid № 3, Table 2) and hybrid PCM modified with veils (Hybrid № 6 Table 2).

One layer of veil (non-woven polypropylene mat) was placed at the interfaces between the LE and HE components (Fig. 9). The thickness of the nonwoven layer in the hybrid lay-up was ~20 μm. For this reason, veils influence on the lay-up thickness, the reinforcement volume fraction, and the density of the composite were considered negligible.

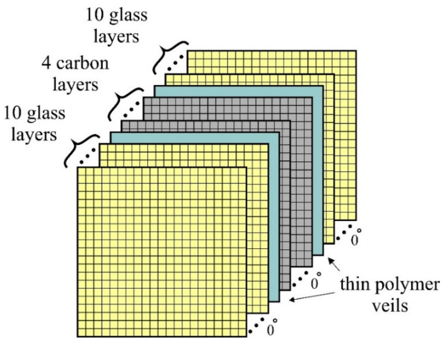


Fig. 9. Lay-up for composites with thin polymer veils between LE and HE layers

To assess the notch sensitivity of hybrid with veils, the specimens considered in the previous sections were used. The test results are shown in Table 2 (№ 8, veil marked with 'v') and Figure 10.

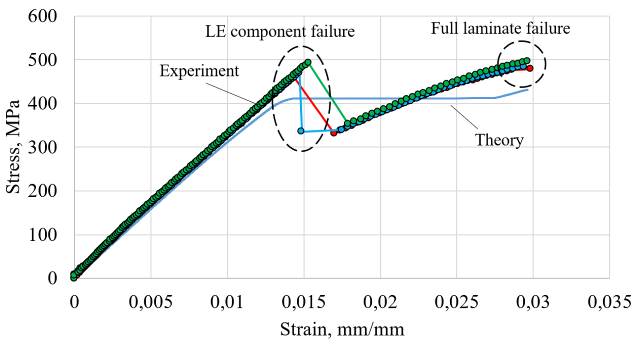


Fig. 10. Experimental and calculated stress-strain diagrams of Hybrid №6 (with thin polymer veils)

The addition of polymer veils at the interface also made it possible to achieve the maximum composite strength at the strain about 3 %. Stress-strain diagram had no peaks or falls after carbon layers fragmentation (stress drop at the strain of 1.5 %) (Fig. 10). GFRP layers showed stable damage accumulation up to the full lay-up failure. This might be due to the fact that LE component fragmentation did not cause damage to HE component layers. Thus, the usage of thin polymer veils can reduce the damage of the HE component and reveal its strength resource as part of a hybrid package.

## 2.4. Developed composites weight efficiency assessment

The main goal of hybridization is the increase of the material weight efficiency, that is, the specific strength in the presence of a concentrator. For developed hybrids (№ 3–8, Table 2), the weight efficiency of developed hybrids (№ 3–8, Table 2) was assessed in comparison with GFRP. The specific strength of GFRP in open hole tests was taken as 100 % (№ 3, Table 2).

The highest value of the specific strength in open hole tests was observed in Hybrid № 1 without additional modifications. However, as mentioned above, the highest strength of rectangular specimen was not achieved at the full laminate failure (Fig. 6). Hybrid № 6, which contains thin polymer veils at the interface between HE and LE components, is proved to be the most rational (in terms of practical use) among the considered hybrids.

## Conclusion

The article considers hybrid pseudo-ductile PCMs with carbon fabric (LE component) and glass fabric (HE component). The influence of the LE/HE ratio, LE layers position and orientation, the use of thin polymer veils at the interface between LE and HE components were experimentally studied.

It was found that composite materials have a lower sensitivity to stress concentrators if they do not have an extended hardening area after the pseudo-ductile plateau. The use of thin polymer veils at the interface between the LE and HE layers, as well as the rotation of LE layers by an angle of ± 10° also reduce notch sensitivity factor. The most rational hybrid lay-up with 5/1 glass/carbon ratio and polymer veils between HE and LE components had 15 % greater specific strength than the non-hybrid GFRP.

At the next stage of the research, it is planned to study the effect of thin polymer veils and small rotations of LE layers on the mechanical behaviour and sensitivity to stress concentration of all-carbon hybrid composites with small hardening area after the pseudo-ductile plateau.

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