Stack fabric felting to get PCM $G_{IIC}$ improvement and LVI tolerance

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Abstract. In this work, there was developed a three-axis CNC felting machine with one barbed needle. Felting is a kind of needle-punch technology for joining fabric stack by broken and pulled fibres. The density of needle hits is a valuable factor to make the required shear strength of polymeric composite materials in the specified places. Using the glass-fibre reinforced plastic (GFRP) with plain weave felted fabric, a noticeable decrease in strength with an increase in the needle hits density from 0 to 90 cm$^{-2}$ is shown. For a laminated GFRP made from a stack of fabrics, it has been shown that the shear strength of the single-lap joint and the interlaminar shear fracture toughness $G_{IIC}$ significantly increase with an increase in the needle hits density. This is important for modern aircraft shells exposed to random low-velocity impacts during ground or flight operations.

1. Introduction

Nowadays, the creation of new aircraft structures cannot be imagined without composite materials, which have high specific strength and stiffness, and are also capable of operating under conditions where traditional structural materials are inapplicable. Laminated fabric reinforced plastics (FRP) operate effectively under a load in X- or Y-direction of the fabric reinforcement. However, due to the absence of fibres in the Z-direction in these materials, they are highly susceptible to delamination, have a low resistance to transverse shear or impact loads. The strength of laminated FRPs in the transverse direction is close to the strength of the matrix or matrix adhesion to the fibrous reinforcing filler, which is about 3-4% of the strength of the composite in the XY plane of the reinforcement [1, 2].

To eliminate this drawback, methods of introducing the third direction of reinforcement are used, which leads to an increase in impact strength, reduces the probability of delamination. It becomes possible to create a polymer composite material (PCM) with a given spatial anisotropy of physical and mechanical properties, or vice versa, approaching its structure to be isotropic [3-7].

Methods for obtaining 3D-reinforcing preforms can be classified as follows [8-13]: 3D-weaving, braiding, knitting, stitching, tufting. However, these methods of 3D-reinforcement have several disadvantages: the high cost of creating a 3D-fabric, the curvature of the fibres during knitting, required access to the material from both sides when stitching the material. Therefore, the issues related to obtaining polymeric composite materials (PCM) reinforced in Z-direction and possessing increased crack resistance are incredibly relevant for the new generation of aircraft structures.

2. Felting technology

The main problem in the aerostructural use of laminated PCMs is delamination. Felting of dry fabric preform before matrix impregnating will avoid delamination at low-velocity impact during service of PCM structures.
For felting, the standard triangular needle with three barbs on each edge is used. During the felting process, the needle pierces the threads of the dry fabric, the barbs cling to the fibres and pull it to the other side of the material (Figure 1). As a result, after impregnation/curing, PCM is strengthened in the Z-direction, and its transverse shear cracks toughness increases. Felting technology requires access to only one side of the material, while the needed area with the desired needle hits density can be pierced. The disadvantages of felting are weakening of fabrics in the XY plane of reinforcement and thickening of PCM in the Z-direction.

3. Felting machine
In this work, a three-axis felting machine has been manufactured. It provides programmable movement of steel frame with fabric in the XY plane using stepping motors to pierce the desired area by the needle. In the upper part, a vertical drive of an industrial sewing machine is used, in which a triangular barbed needle is attached instead of a regular needle. Needle stroke is 16 mm, with a frequency of five strokes per second. The front view of the specimen after felting is shown in Figures 3-4. The mean length of the pulled glass fibres is about 1 mm to join the stack of dry fabrics with at least 1 mm thickness.
4. Tensile testing
Mechanical tests were carried out on a universal testing machine INSTRON 5882 to determine the tensile strength of glass fabric after felting. Felted glass fabric was impregnated with a compound of ETAL370 epoxy resin and ETAL45 hardener (100/45 weight ratio). The impregnated fabric was kept under pressure of 2-3 bar at 80°C for 5 hours. The post-cure mode was 1 hour at 100°C, 2 hours at 150°C, 3 hours at 170°C. Felted area on specimens was 25x25 mm, hits density $Z=10, 30, 50, 70$ and 90 cm$^{-2}$. The failure of the specimens occurred mostly at the edge of the felted area, Fig.5 (white cross).

The dependence of the failure load on the hits density is shown in Figure 6. With an increase in the hits density, the failure load decreases significantly: with $Z= 90$ cm$^{-2}$, the load is reduced by 50%.
The dispersion of the felted fabric’s strength is connected with the stochastic nature of the needle hit process: some hits are in the middle of the thread, but other ones are near the edge or even in the space between warp/weft threads.

5. Single-lap joint shear test
For single lap-joint shear testing, the specimens were prepared using the following technology. Two layers of dry fabric were felted on the machine with a density $Z=10, 30, 50, 70$ or $90$ cm$^{-2}$. After felting of area 25x25 mm, the specimens were impregnated with the same compound (see par.4), and 2 mm thick ready GFRP plates were glued on both sides. The schematic of the specimens is shown in Figure 7. All specimens were tensiled in the wedge grips of the universal testing machine with shear in the felting region (Figure 8). Specimens were broken in the $Z$-reinforced area (Figure 9). The shear strength increases with an increase in hits density by about 50% (Figure 10).

![Figure 6. Dependence of tensile failure load on felting density $Z$.](image)

![Figure 7. Schematic of a shear test specimen.](image)

![Figure 8. A specimen in the grips of the INSTRON universal testing machine.](image)  
![Figure 9. Specimen after failure in the felted area.](image)
6. End-notched flexure (ENF) test

One of the most important characteristics of polymer composite materials is the interlaminar shear fracture toughness. The importance of this feature lies in the peculiarities of applying a load to the specimen: especially weak points are loaded - the matrix and the interphase zone [14]. Currently, there are many approaches to assessing interlayer shear fracture toughness [15, 16]. The most commonly used standards are ASTM D5528, ASTM D7905, ASTM D6671, ASTM D15114. The ENF method (ASTM D7905 standard) was used in this work and allowed determining the interlayer shear fracture toughness $G_{IIc}$ according to the three-point bending scheme (Figure 11). Shear stresses arise at the crack tip, resulting in pure transverse shear.

![Figure 11. The specimen and loading diagram for ENF testing:](image)

$a$ – initial crack, $2t$ and $B$ – specimen thickness and width, $L$ – specimen length, $P$ – load.

Interlaminar shear fracture toughness $G_{IIc}$ is calculated according to ASTM D7905:

$$G_{IIc} = \frac{3mP_{\text{max}}a^3}{2B}$$

(1)

where $m$ – compliance calibration coefficient, $P_{\text{max}}$ – the maximum load, $a$ – the crack length under load $P_{\text{max}}$, $B$ – specimen width.

Five tests were carried out (crack lengths $a = 10, 20, 25, 30$ and $40$ mm) for each felting density $Z$ to determine the calibration coefficients of compliance denoted $m$, Eq. 1. Specimens had $2t = 5$ mm and $B=16$ mm. The distance between the supports (bending span $L$) is 100 mm. Loading speed 10 mm/min. For each high density, the dependences of the compliance $C$ on the cube of the crack length $a^3$ were plotted, and the compliance coefficient $m$ was determined from this dependence. An example of this dependence for a high density $Z = 10$ cm$^2$ is shown in Figure 12.
Figure 12. Dependence of the specimen compliance $C$ on the cube of the crack length $a^3$ to determine the compliance calibration coefficient $m$.

After determining the calibration coefficient $m$, tests were carried out until the failure of specimens with an initial crack length $a = 25$ mm. Figure 13 shows the "load-displacement" diagram of the specimen after felting with hits density $Z = 10$ cm$^{-2}$. The maximum load for each specimen is determined using this diagram.

Figure 13. Load-displacement diagram (hits density $Z = 10$ cm$^{-2}$). Circle shows a zone of the maximum applied load.

The crack length was invariable up to $P_{\text{max}}$ and then fast developed. In this case, we can use the initial crack length $a$ in Eq. (1). Figure 14 depicts the dependence of the interlaminar shear fracture toughness $G_{\text{IIc}}$ on the hits density. Interlaminar shear fracture toughness increases with an increase in hits density by about 40%. Table 1 shows the average value and range of values of interlaminar fracture toughness for each hits density.
Figure 14. Dependence of the interlaminar shear fracture toughness $G_{IIc}$ on the hits density $Z$.

Table 1. Interlaminar shear fracture toughness $G_{IIc}$.

| Hits density $Z$, cm$^{-2}$ | Average interlaminar fracture toughness $G_{IIc}$, J/m$^2$ | Min/Max interlaminar fracture toughness $G_{IIc}$, J/m$^2$ |
|-----------------------------|----------------------------------------------------------|--------------------------------------------------------|
| 0                           | 2011                                                     | 1779/2465                                              |
| 10                          | 2444                                                     | 2280/2736                                              |
| 30                          | 2488                                                     | 2363/2664                                              |
| 50                          | 2510                                                     | 2310/2971                                              |
| 70                          | 2710                                                     | 2518/2941                                              |
| 90                          | 2835                                                     | 2373/3272                                              |

7. Conclusions
- There was developed a three-axis CNC felting machine for joining a stack of dry fabrics with pulled fibres with various hits densities with arbitrary trajectory and required area.
- Tensile tests have shown weakening of the composite material depending on the hits density down to 50%.
- Lap-shear strength increases up to 50% with increasing hits density from zero to 90 cm$^{-2}$.
- Interlaminar shear fracture toughness $G_{IIc}$ of specimens at a hits density of 90 cm$^{-2}$ is 40% higher than for the original specimens.

For future works, we plan to continue an investigation of felting technology for aramid and carbon fibres’ preforms and composites utilising in the new aircraft grid structures as the outer shell.

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