Research of the carbon/epoxy laminated curved beams strength in four-point bending test

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Abstract. The experimental study results of the of the carbon/epoxy laminated curved beams strength of samples based on laminated carbon fiber and laminated carbon fiber reinforced in the transverse direction by Tufting firmware with four-point bending are presented. We obtained loading diagrams and diagrams of the dependence of the cumulative energy values of acoustic emission signals for layered samples and layered samples reinforced with transverse piercing. The tests were carried out according to the procedure agreed upon with the international standard ASTM D6415 with using the electromechanical system Instron 5965 and the acoustic emission signal recording system AMSY-6.

1. Introduction
Currently, composite laminate is widely used in various industries, such as aerospace, building, energy, etc. The widespread use of this class of materials in critical structures necessitates to experimentally study the processes of damage and destruction accumulation. One of the typical fracture types in laminated composites is delamination, resulting in a partial loss of load-bearing capacity. In addition, the importance and relevance of this area of research are due to the fact that modern engineering structures include various geometric bends, which in turn lead to stress concentration and the formation of lamination. That is why there is a need for an experimental study of the lamination processes in composite samples having different angles and radii in their geometry [1].

One of the experimental methods for strength test of a curved beam at four-point bending is presented within ASTM. This method has various advantages over other existing methods: the stress does not depend on the angular position and the bending moment in the working part of the sample is constant. In addition, this is the most realistic attitude to determining the interlayer tension strength for many composite structures with curved geometry. The authors in their studies confirm the effectiveness of the curved beam method in four-point bending [2]. Many modern scientific studies use the acoustic emission method to study the strength of laminated composites [3-7]. In this paper, the AE method is used to control the process of accumulation of damage to composite laminate with different manufacturing processes. Analysis of AE signals will allow comparing the mechanics of samples during mechanical loading. The purpose of the paper is to assess the effect of the transverse sewing (with Tufting) on the mechanics and strength of carbon laminate at four-point bending of the curved beam.

2. Materials and methods
2.1. Materials
The materials studied were carbon laminate fibre-based AKSA F49 12K and epoxy binder T26 consisting of 12 layers and 12 layers with transverse reinforcement by Tufting. A total of 20 samples were tested, 10 of each type. Tufting technique is one of the practical methods to strengthen the material throughout the thickness [10]. This technique requires one-sided access to the workpiece, passing the thread through the thickness of the layered workpiece and returning it along the same way, the workpiece is sewed without any nodes between the threads (figure 1).

![Figure 1](image1.png)

**Figure 1.** Scheme of manufacturing samples of layered preforms reinforced in the transverse direction by the Tufting method.

2.2. Experimental procedure
On the basis of the collective use centre "Center for Experimental Mechanics" of the Perm National Research Polytechnic University (CUC CEM PNRPU), a series of tests were carried out on samples of a curved beam made of carbon laminate for four-point bending. The tests were carried out on the Electromechanical system Instron 5965 according to ASTM D 6415. The speed of the movable gripper 2 mm/min. The load was measured by a force gauge with a capacity of up to 5kN. The accuracy of the load measurement is 0.5% of the measured value in the range of 0.2% -1% of the rated power of the force gauge. The sample was installed in the attachment for four-point bending (figure 2, a). The centre distance of the lower and upper supports is 100 mm and 75 mm, respectively, the diameters of the pressure shafts are 9.5 mm. Destruction control of samples was carried out by recording acoustic emission signals.

Tests for the four-point bending of the beam were carried out together with acoustic emission signals recording. The recording was carried out throughout the test until the destruction of the sample using the system Vallen Amsy-6 (Germany). One broadband sensor (frequency range 450-1150 kHz) and a preamplifier with a gain of 34 dB were used. The sensor was attached to the samples with the help of a rubber device (figure 2, b).

![Figure 2](image2.png)

**Figure 2.** Test scheme (a) and a sample installed in a snap with an attached AE sensor (b).

The following parameters were determined from ASTM D6415 tests: the resulting force applied to the four-point bending device (P, N); the strength of the curved beam (CBS, N) and the corresponding
angle between the horizontal and the sample leg ($\varphi$, deg.). The characteristics of CBS is calculated as in equation (1).

$$CBS = \left( \frac{P}{2w \cos(\varphi)} \right) \left( \frac{d_x}{\cos(\varphi)} + (D + t) \tan(\varphi) \right)$$

Where D is the diameter of the cylindrical power shaft (mm); t is the average thickness of the sample (mm); w is the average width of the sample (mm); $\varphi$ is the angle between the horizontal axis and the leg of the sample (deg.); $d_x$, $d_y$ — horizontal and vertical distance between the power supports (mm); $P$ — the resulting force applied to the four-point bending device (N); $\Delta$ - the relative movement between the upper and lower part of the attachments (mm).

3. Results and discussion

The test results are shown in Table 1. Figure 3, a. shows typical loading diagrams for samples with and without sewing in the transverse direction.

| № | Material                          | P, N  | $u$, mm | $\varphi$, ° | CBS, N  |
|---|----------------------------------|-------|---------|--------------|---------|
| 1 | Laminated samples without Tufting | 598±168 | 2.77±0.67 | 41.67±0.92 | 455±111  |
| 2 | Laminated samples with Tufting   | 331±44 | 4.13±0.32 | 39.50±0.53 | 234±29   |

Analyzing the loading diagrams, the obtained characteristics and fracture appearance of CFRP samples after testing four-point bending it may be noted that the cross sewing (with Tufting) in this type of loading is an additional stress concentrator that leads to a decrease in the bearing capacity of the curved beam (CBS) of 47% at almost the same angles $\varphi$ and 49% increase of the relative movement values between the upper and lower part of the attachments. Loading diagrams are qualitatively different for samples without Tufting and with Tufting. According to the given loading diagrams (figure 3) it can be seen that the sample without Tufting is elastically loaded to the maximum values of the load-bearing capacity, then there is a dynamic breakdown by 80-85% after which there is an equilibrium most critical deformation of the damaged material to the full extension of the curved beam [11-12]. The sample with Tufting is loaded to the maximum values of the bearing capacity, then there is a dynamic breakdown of 30-35%, the redistribution of stresses in the damaged region of the sample occurs and the sewing starts to work by limiting the further lamination development which leads to higher values of the bearing capacity of the damaged material relative to the undamaged material.

The energy parameter ($E$, $V^2s$) was chosen as an informative parameter of AE signals [5, 6]. By summing the values of the energy parameter for the entire sample loading time, the value of the cumulative energy of AE signals ($CE$, $V^2s$) is obtained. Typical dependency diagrams of cumulative energy and displacement for laminated samples and laminated samples reinforced in the transverse direction by Tufting are presented in figure 3, b. Analyzing the values dependency diagrams of cumulative energy of AE signals for the laminated samples and laminated samples reinforced by cross-stitching, it can be noted that the graphs are similar in nature, however, limit values for laminated samples are 16% lower when the displacement is equal to 12 mm. Higher values of the AE signals cumulative energy for samples reinforced with Tufting, as opposed to samples without Tufting, are associated with the destruction of fibre bundles of this sewing. Similar dependencies were recorded during tensile tests of these materials [8, 9].

Figure 4 shows the initial loading portion (until the first failure in the diagram) for of CFRP laminated samples (figure 4, a) and laminated stitched carbon fibre (with Tufting) (figure 4, b), combined with graphs of the AE signals energy parameter distribution. It is noted that despite the similarity of the graphs of the cumulative energy dependence of AE signals for the two types of samples (figure 3, b), the graphs of the distribution of energy parameters differ. So, for the laminated samples the increase in energy parameter starts at the moment before the first breakdown on the diagram of loading, and for
stitched laminated samples (with Tufting) happens at all stages of loading up to the first breakdown. This may be due to the fact that in this type of testing, the laminated samples lose their bearing capacity from interlayer cracking, and the values of the energy parameter of AE signals at the moment of the breakdown in the loading diagram are associated with the growth of the defect between the layers of the composite. For samples with sewing, the growth of this type of defect is prevented by fibres in the longitudinal direction, and the values of the energy parameter are associated with the destruction of such fibres of the sewing.

Typical types of CFRP samples destruction are shown in figure 5.

**Figure 3.** Typical loading diagrams (a) and dependences of the cumulative energy of AE signals on the displacement of a mobile capture (b) for a layered sample (dashed line) and a layered sample by cross-stitching (solid line).

**Figure 4.** The initial loading sections (up to the moment of the first breakdown in the diagram) for samples of laminated carbon plastics (a) and layered stitched carbon plastics (b).

**Figure 5.** Typical types of fracture of samples of layered carbon fiber (a) and layered carbon fiber with cross-stitching (b).

4. Conclusions
Thus, the series of four-point bend tests of curved beam samples made of laminated CFRP and laminated CFRP with transverse sewing (with Tufting) was carried out. The influence of laminated CFRP transverse sewing on the mechanical behaviour and strength at four-point bending of the curved beam was experimentally established. It is noted that the laminated CFRP samples of without sewing have greater rigidity and load-bearing capacity before the first breakdown on the loading curves, while the composite with transverse sewing has a greater residual load-bearing capacity. In addition, the composite with transverse sewing has higher values of cumulative energy of AE signals, which is associated with the accumulation of damage between the layers (matrix destruction) and the rupture of fibre bundles in the transverse sewing.

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