Methods for experimental research of carbon fiber reinforced plastics with damages for fan blades

D S Palchikov¹

¹Composite materials strength department. Central Institute of Aviation Motors named after Baranov P.I. Baranov (CIAM), Moscow

E-mail: den1153@yandex.ru

Annotation. The paper is devoted to the methods of experimental studies of carbon fiber reinforced plastics strength with damage of various categories. The first part of the work is devoted to the analysis of the existing damage classification for aircraft parts made of polymer composite material, as well as the development of a quasi-static punching method for their application to carbon fiber samples. In the second part of the work, experimental studies of the residual tensile strength of carbon fiber T144 with damages of various categories are presented. The dependence of the residual tensile strength on the punching energy is obtained. Based on the obtained data and recommendations of the FAA, the permissible levels of tensile stresses for carbon fiber T144 were 529 MPa, which is two times higher than the calculated level of the CIAM fan blade model tensile stresses from this material in the operating mode. The reported study was funded by RFBR according to the research project № 18-29-18071/18.

1. Introduction

In modern engineering practice, there is no simple engineering method for designing polymer matrix composite material parts, considering the drop in their strength properties due to mechanical and, in particular, impact damage. This problem is especially relevant for such parts as carbon fiber (CFRP) fan blades, during the operation of which the ingress of foreign objects is a very likely event. Considering the fact that CFRP strength can be significantly reduced due to the presence of impact damage, the use of the strength characteristics of CFRP in the "initial" state for designing a fan blade is unacceptable. This thesis is consistent with the Federal Aviation Administration (FAA) guidelines [1] for the design of polymer composite aircraft parts (Figure 1).

Figure 1. Account defects and damages in the process of designing composite structures

According to FAA materials [1], it is recommended to use strength characteristics obtained taking into account damage for the design of PCM parts. According to AC 20-107B [2], the classification of damage is arbitrary and based on visual detection:

- Category 1 – allowable damage that may go undetected by scheduled or directed field inspection and allowable manufacturing defects. Some examples of Category 1 damage include barely visible impact damage (BVID) and allowable defects caused in manufacturing or service (e.g., small delamination, porosity;
• Category 2 - damage that can be reliably detected by scheduled or directed field inspections performed at specified intervals. Some examples of category 2 damage include visible impact damage (VID), VID (ranging in size from small to large), deep gouges or scratches, manufacturing mistakes not evident in the factory, detectable delamination or debonding;

• Category 3 – Damage that can be reliably detected within a few flights of occurrence by operations or ramp maintenance personnel without special skills in composite inspection. Such damage must be in a location such that it is obvious by clearly visible evidence or cause other indications of potential damage that becomes obvious in a short time interval because of loss of the part form, fit or function. Some examples of Category 3 damage include large VID or other obvious damage that will be caught during walk-around inspection or during the normal course of operations (e.g., fuel leaks, system malfunctions or cabin noise);

• Category 4 – Discrete source damage from a known incident such that flight maneuvers are limited. Some examples of Category 4 damage include rotor burst, birdstrikes, tire bursts, and severe in-flight hail;

• Category 5 - Severe damage created by anomalous ground or flight events, which is not covered by design criteria or structural substantiation procedures.

In the FAA concept, the residual strengths of CFRP with damage in these categories are related to the levels of ultimate loads realized during the operation of the part (Figure 2). The maximum permissible operating load on a part is estimated based on its residual strength after damage. According to the recommendations for ensuring the performance of parts from polymer matrix composite material, the levels of the design limit (Ultimate load), operational (Limit Load) and emergency loads (0.7·Limit Load) should be related to each other in a ratio of 1.5: 1: 0.7 [2].

![Figure 2. Schematic diagram of design load levels versus categories of damage severity](image)

From the diagram above, the Limit Load should be below the residual strength of a Category 2 damaged part. A part with damage of the third category must maintain operability at or close to Limit Load [2], and the residual strength of a part with damage category 1 (Ultimate load) must be at least 1.5 higher than the Limit Load. Summarizing the above, the system for assessing the permissible loads (stresses) of a part from polymer composite material is based on the residual strength of a part with various damage categories.

This paper is devoted to experimental studies of CFRP strength with damage in order to subsequently assess the permissible loads (stresses) of carbon fiber fan blade developed at CIAM. In this work, the FAA approach was taken as a basis, but with the presence of a number of additions. One of the major additions is refinement of damage classification. Since the classification of damage in FAA is very conditional and is based only on visual detection, the following damage classification is proposed, which is additionally related to CFRP destruction mechanisms, which are realized during impact.

Category 1 damage – microcracks in the matrix that do not go beyond the layer (not detectable visually);
Category 2 damage – internal delamination without fiber destruction;
Category 3 damage – damage with partial fibers destruction;
Category 4 damage – damage with significant fiber damage (penetration through).

The refined classification was obtained on the basis of CFRP plate damage diagram analysis by quasi-static indentation method by a hemispherical indenter [3]. This method is an alternative to the impact of a falling weight [4] and is used to damage of CFRP specimens. Figure 3 shows a diagram of CFRP plate complete punching with dimensions of 100x150x4.6 mm by a hemispherical indenter (indenter diameter Di = 16 mm, hole diameter under the sample ds = 76 mm). A CFRP plate was made from prepreg T144 (ITECMA UMT49/T191) with a reinforcement scheme corresponding to the fan blade reinforcement scheme [0°;+45°;0°;-45°].

![Figure 3. Load-displacement behavior of carbon fiber (T144) under quasi-static indentation loading](image)

Analysing this diagram, it is possible to trace the successively replacing mechanisms of CFRP destruction during indentation, which is an analogue of impact. The first stage of specimen indentation corresponds to period of initiation and microscopic cracks growth that do not extend beyond the layer. As a rule, there is a local adhesion disruption between fibres and matrix, as well as appearance of matrix cracks inside monolayers. Although at this stage the process of CFRP destruction takes place, this does not affect the overall specimen stiffness. The critical load for the first level of failure will be load at which first clear change of load curve occurs (point A). The second stage is associated with delamination growth in composite material. An increase in load is accompanied by an increase in delamination zone of material, where the epicentre is contact area with indenter (BC). But at a certain moment of indentation, the supporting fibers begin to collapse (point C). At peak load, growth of delamination area reaches a critical value. With the initial failure of fibers, the specimen can no longer take increasing bending load, and the load on indenter begins to drop. The load peak corresponds to destruction mechanisms change and separates the second and third categories of damage.

The third stage is associated with the course of fibers destruction process. Fibers are destroyed by contact with indenter, by tensile and compressive forces on the specimen surfaces, and by shear stresses along its thickness. The process ends with a through-penetration (fourth stage, point D). The indenter slides along the walls of the hole, almost without causing damage to the material. The punctured specimen has the maximum damage possible for an indenter of a given diameter. The critical points of indentation diagram will correspond to ultimate values of the residual strength of the material with the corresponding damage categories, and can be used in calculations as the ultimate strength of material with certain type damage: with microcracks, with delamination, with broken fibers.

The additions presented make the FAA classification more complete and valid. In addition, the proposed method of damaging (quasi-static indentation), in contrast to impact, makes it possible to implement any
of presented damage levels. The parameters measured in the process of indentation (load and displacement of indenter) make it possible to calculate impact energy on specimen at any moment of indentation, including at diagram critical points.

2. Experimental determination of various categories damage influence on CFRP tensile strength

Experimental studies of damage effect on strength were carried out on specimens from CFRP T144 with a "blade" reinforcement scheme \([0^\circ; +45^\circ; 0^\circ; -45^\circ]\). This material is used by «CIAM» for the development and creation of carbon fiber fan blades. The main methodological difficulties for solving the problem were the choice of the geometric dimensions of the specimens, as well as the boundary conditions for indentation (the diameter of the indenter \(D_i\), the diameter of the hole under the sample \(D_s\)). At the first studies stage of CFRP tensile strength with damage, specimens (T144) with a thickness \(h = 3.1\) mm, width \(b = 100\) mm, length \(L = 300\) mm were made (Figure 4).

To inflict damage of various categories by indentation, an indenter with a diameter of \(d_i = 16\) mm was chosen, and a hole in the lower plate under the sample \(d_s = 76\) mm (the ratio of the hole diameter in the lower support \(D_s\) to the indenter diameter \(D_i\) will be denoted as the coefficient \(\text{SPR} = D_s / D_i\)). The choice of these parameters was borrowed from the standardized method of causing damage to polymer composite materials by a falling weight \([4]\), where the diameter of the striker is \(D_i = 16\) mm, and the lower plate under the sample has a rectangular cutout with dimensions \(76 \times 125\) mm. The loading scheme of a specimen during punching is shown schematically in Figure 6 \([5, 6]\).

The first two samples (№ 1,2) were completely pushed through, that is, they were loaded until pierced through with an indenter (category 4). Sample № 3 was loaded with an indenter up to the load corresponding to the beginning of fiber rupture (category 3), samples № 4, 5 - up to the load corresponding to the internal damage stage and preceding the onset of fiber breakdown (category 2). Figure 6 shows diagrams of indentation of 5 samples of T144 CFRP.
The energy $E$ expended on damage was determined as the area under the indentation load curve. After indentation, fiberglass tabs were glued to the specimens for subsequent tensile tests. The results of testing samples 100 mm wide with damage of various categories are presented in the form of loading diagrams (Figure 8), as well as Table 1.

Determination of ultimate tensile strength was carried out according to the equation (1), regulated by the standard test method ASTM D3039 [7]:

$$\sigma = \frac{P}{b \cdot h}$$

(1)

Where

$P$ – maximum load, N
$b$ – specimen width, mm
$h$ – specimen thickness, mm

**Table 1.** Residual tensile strength values of T144 specimens with a width $b = 100$ mm

| Specimen label | Width [mm] | Thickness [mm] | Maximum Load [kN] | Tensile Strength [MPa] | Energy expended during indentation $E$, J |
|---------------|------------|----------------|-------------------|------------------------|------------------------------------------|
| №1 (4 category) | 98,50      | 3,10           | 153,02            | 501,14                 | 58,27                                    |
| №2 (4 category) | 99,30      | 3,10           | 148,49            | 482,37                 | 53,68                                    |
| №3 (3 category) | 101,10     | 3,20           | 171,46            | 529,99                 | 20,84                                    |
| №4 (2 category) | 98,20      | 3,20           | 235,36            | 748,98                 | 13,33                                    |
pecimen label & Width [mm] & Thickness [mm] & Maximum Load [kN] & Tensile Strength [MPa] & Energy expended during indentation Е, J
\hline
№5 (2 category) & 99,0 & 3,10 & >240 & - & 7,88 \\
\hline

These tests showed that specimens geometric dimensions for these studies are not optimal. High specimen width leads to high breaking loads values (specimen with the 2nd category of damage could not be destroyed). It is easy to conclude that use of specimens of such a width when testing CFRP with the 1st damage category is also excluded. Next stage of testing was the development of the same test program on smaller width specimens. For this, 6 samples of the same thickness (h = 3.1 mm) and width b = 50 mm were made. Due to change of specimen width, the diameter of indenter (Di = 8 mm) and diameter of the hole in the bottom plate (Ds = 38 mm) were also changed. Specimens №1,2 were also completely pushed through (4th category of damage). Samples №3,4 are pushed up to loads corresponding to the beginning of fiber damage (category 3), sample № 5 - up to loads corresponding to the 1st damage category, sample № 6 - to the load level corresponding to intermediate damage between the 1st and 2nd category (conventionally designated as category 1-2). Figure 9 shows the indentation diagrams for specimens № 1-6. After damaging the specimens, fiberglass tabs were glued. Photo of specimens with various damage categories also shown in Figure 9.

![Indentation diagrams for CFRP specimens № 1-6 (b=50 mm)](image1)

**Figure 8.** Indentation diagrams for CFRP specimens № 1-6 (b=50 mm)

Below, in Figure 11, the loading curves of these specimens in tension are shown.

![Loading curves of CFRP specimens with various damage categories](image2)

**Figure 9.** Loading curves of CFRP specimens with various damage categories

The results of residual tensile strength values of T144 specimens with a width b = 50 mm are presented in Table 2.
Table 2. Residual tensile strength values of T144 specimens with a width b = 50 mm

| Specimen label | Width [mm] | Thickness [mm] | Maximum Load [kN] | Tensile Strength [MPa] | Energy expended during indentation Е, J |
|----------------|------------|----------------|-------------------|------------------------|----------------------------------------|
| №1 (4 category)| 50,09      | 3,14           | 83,95             | 533,74                 | 25,95                                  |
| №2 (4 category)| 49,82      | 3,12           | 84,75             | 545,23                 | 25,4                                   |
| №3 (3 category)| 49,75      | 3,11           | 106,47            | 688,16                 | 7,24                                   |
| №4 (2 category)| 49,61      | 3,15           | 146,17            | 935,37                 | 6,18                                   |
| №5 (1 category)| 49,70      | 3,13           | 204,08            | 1311,91                | 0,48                                   |
| №6 (1-2 category)| 49,57   | 3,14           | 188,35            | 1210,08                | 2,78                                   |

As can be seen, the destruction of specimens № 1-4 occurred in location area of previously inflicted damage, and the destruction of specimens № 5,6 - outside the damage zone. This fact indicates the suitability of the selected specimen sizes for determining the residual tensile strength of CFRP with damage of 2 - 4 damage category. Obviously, to determine the effect of category 1 damage (matrix microcracks, BVID) on CFRP tensile strength, it is necessary to use specimens with a reduced width of working zone.

To solve the problem of determining the residual tensile strength of CFRP with the 1st category of damage, specimens with a reduced working area were used (Figure 12).

Figure 10. Plot of specimen with a reduced working area (in mm)

In this case, damage was done on plates (b = 46 mm wide and L = 146 mm long) before the procedure for reducing the working area. Damage was done with a hemispherical indenter with Di = 34 mm (Ds = 38 mm). The use of an indenter of this diameter is due to the need to obtain a wide damage zone, comparable to the full width of specimens working zone. The specimens loading diagrams by indenter are shown in Figure 13. As mentioned earlier, the appearance of category 1 damages during indentation corresponds to an obvious change of the loading curve slope.

Figure 11 - Indentation diagrams for CFRP specimens (category 1 damage)
Specimen №1 was atrial one, it was pushed to a clear peak, which corresponds to the 2nd category. The remaining 5 specimens were loaded by indentation to loads corresponding to the 1st category of damage. After the damage was done, the working area of the samples was mechanically reduced.

According to the results of tensile tests, the strength of specimens with 1st category damage (specimens № 2-6) varied from 1063 to 1198 MPa. The destruction of specimens № 2,3 occurred outside the working area, and therefore the results of these tests were not taken into account in the analysis. Specimens № 4 - 6 had destruction in the working area. The results of all the above tensile tests of T144 specimens with inflicted various categories damages are shown in Figure 14 as the dependence of the residual strength on the energy spent on damaging the indenter per 1 mm of specimen thickness (J / mm).

![Figure 12. Plot of residual strength versus damage severity](image)

Despite the fact that points of diagram were obtained by testing different geometry specimens, and damage was carried out by indenters of different diameters, the total dependence of the residual tensile strength on the indentation energy can be described by a power curve fit [8].

3. Evaluation of fan blade allowable stresses

Using the FAA recommendations and the results obtained, an evaluation of the permissible tensile operating stresses (LL) of fan blade can be made. Figure 15 shows the distribution of tensile (radial) stresses of a fan blade from carbon fiber T144 (CIAM).

![Figure 13. FEA plot showing radial stress contours (kgf/mm²)](image)

As can be seen, in the operating mode in the field of centrifugal forces (N = 4100 rpm), the calculated maximum tensile stresses of the fan blade are 26.975 kgf = 254.5 MPa. According to the FAA recommendations [2], the allowable stress level (LL) should not exceed the strength value of CFRP with
damage category 3. In the case of T144, the tensile strength with the 3rd damage category is 529 MPa. With these values, the margin of safety for static tensile stresses for a T144 carbon fiber fan blade can be estimated:

\[
n = \frac{LL^+}{LL_{\text{secn}}} = \frac{529}{264.5} = 2.0
\]  

(2)

Where \( LL^+ \) - allowable stress level according to FAA recommendations

\( LL_{\text{secn}} \) – level of maximum design tensile stresses of the fan blade.

The estimates obtained are graphically shown in Figure 16.

![Figure 16](image)

**Figure 14.** Plots of residual strength versus damage severity for carbon fiber T144

4. **Conclusion**

In this work, a method has been developed for determining of CFRP tensile strength with various damage categories. Also, a method of inflicting damages by the quasi-static indentation method has been tested. It is shown that the proposed method allows inflicting damage of a given category. Based on the data obtained, the level of permissible tensile stresses of the fan blade from considered carbon fiber T144 was determined, and the margin of safety was estimated. The obtained tensile strength margin of safety (\( n = 2 \)) is estimated and presented to demonstrate the application of obtained experimental data. Naturally, for a more accurate assessment of the performance of a damaged CFRP fan blade, similar estimates should be obtained not only for tension, but also for compression, interlayer shear, and in-plane shear, and the corresponding fracture criteria should be applied.

**References**

[1] Ilcewicz L 2009 Past Experiences and Future Trends for Composite Aircraft Structure *Montana State University Seminar* p 18

[2] Federal Aviation Administration. Advisory Circular AC 20-107B p 13 2010

[3] ASTM D6264/D6264M. Standard Test Method for Measuring Damage Resistance of Fiber-Reinforced Polymer-Matrix Composite to Concentrated Quasi-Static Indentation Force.

[4] ASTM D7137/D7137M – 12 Standard Test Method for Compressive Residual Properties of Damaged Polymer Matrix Composite Plates

[5] Gama B, Gillespie Jr. J 2008 Punch shear-based penetration model of ballistic impact of thick-section composites *Composite Structure* 89

[6] Xiao J, Gama B, Gillespie Jr. J 2007 Progressive damage and delamination in plain weave S-2 glass/SC-15 composites under quasi-static punch-shear loading *Composite Structure* 78

[7] ASTM D3039/D3039M Standard test method for tensile properties of polymer matrix composite Materials 2014
[8] Alan T 2011 Low Velocity Impact Damage to Carbon/Epoxy Laminates 2nd Innovative International Composites Summit Paris