Service life testing of composite material

A A Sturov, N S Chashhin, Y N Ivanov
Irkutsk National Research Technical University, 83, Lermontov St., Irkutsk, 664074, Russia
E-mail: hero124@yandex.ru; rufle54007@mail.ru; iv_yuriy@istu.edu

Abstract. The study aims to determine the effect of a "delamination" defect on the service life of carbon fiber reinforced polymer (CFRP) specimens and specimens that have been repaired. The tests were performed using an EHF-EV101K2-04N-1E universal testing machine, and ultrasonic flaw detection was carried out using the ELISA GMIUC002-14 complex. In the study, loading ranges were selected for cyclic tests performed for defect-free, defective and repaired specimens. The tests revealed the effect of the defect and its repair on durability of CFRP products.

1. Introduction
The share of composite materials in mechanical engineering increases. As a result, the issue of damaged composite product restoration is becoming urgent since the cost of composite materials is much higher compared to that of conventional ones [1–5]. CFRP is the most promising material. It combines high strength and flexiblity not inherent in metallic materials. If necessary, bolted connections or riveted joints are used to connect CFRP with metallic materials [6–10]. Formation of holes for fastening connection is a time-consuming operation since the requirements for processing modes of the materials included in the package are opposite, and this can result in a defect inside the hole in case of emergency situation [11–16].

The experimental study aims to determine the effect of a defect in the hole of CFRP products on their service life, and to investigate the feasibility of their repair for its extension.
To achieve this aim it is required:
- to test the application of a defect on a CFRP specimen using special equipment that ensures the desired repeatability of the damage zone on the specimen;
- to perform repeated static loading to determine the service life of specimens before their destruction, to identify the difference between the defect-free specimen and the repaired one [17–20].

2. Experimental work
The object of the study is a CFRP specimen (PRISM EP2400 RS AK-00-RE-013-032-2012 binder; 24K IMS-1/4 AK-00-RE-013-032-2012 filler; G120 AK-00RE-013-018-2012 fiberglass).

These specimens are structurally similar to the wing panels of the MS-21 aircraft and contain holes like those in the junction of the "console wing-center wing". The dimensions of the specimen for testing are 320x45x16 mm with a Ø14H9 hole in the center. The specimen size was chosen in accordance with GOST R 56810-201, taking into account the features of the testing machine. Figure 1 shows a sketch of the specimen indicating its size.
The universal EHF-EV101K2-04N-1E testing machine (Japan) was chosen as the main technological equipment. It is used for input testing of the mechanical properties of materials under tension/compression/bending. It is also used to conduct cyclic tests to determine the fatigue characteristics of materials and the conformity of the manufacturing process of parts to industry standards.

The occurrence of internal defects was tested with the complex GMI AERO (France) ELISA GMIUC002-14 used for ultrasonic non-destructive testing.

3. Specimen preparation
   A) Defect formation
   A defect was created in specimens using a special tool. It allows similar damages at a given depth. After defect formation, the specimen is subject to flaw detection to indicate the damage zone. Figure 2 shows a sketch of the specimen with the tool installed in it for defect formation.

   B) Defect repair
   Defect repair technique:
   1) preparation of the repair zone (cleaning the defect zone, dusting, degreasing);
   2) applying a repair resin to the defect zone; a syringe with a needle was used to inject resin;
   3) installation of special tool "thermal bolt";
   4) controlled heating and holding with respect to the curing cycle of repair resin

4. Experiment
   As part of the tests for repeated load test of the holes, it is planned to investigate "delamination" according to the following stages:
   Stage 1 – finding the maximum load at which the specimen is failed;
   Stage 2 – cyclic loading of the defect-free specimen until its failure;
   Stage 3 – cyclic loading of the defective specimen until its failure;
   Stage 4 – cyclic loading of the repaired specimen until its failure.
   Specimens are loaded according to the four-point bending scheme, since the scheme simulates
aircraft loads. A three-point loading scheme is not suitable since the entire load is transmitted through the roller to the hole in the center.

A) Static loading
After preparation, specimens are subjected to static loading to determine the failure stress and to cyclic loading on a four-point tool to estimate fatigue failure. Figure 3 shows the experimental scheme for four-point bending.

![Figure 3. Loading scheme](image)

The static test aims to determine the failure stress $\sigma_{\text{fail}}$ required to determine the maximum operating load ($N_y$), which is calculated using the equation:

$$\sigma_{\text{fail}} = f \times N_y$$

where $f$ is a safety factor of 1.5. [21]

B) Cyclic loading
The tests imply loading of specimens with an asymmetric cycle at a stress level of 0.1 $\sigma_{\text{fail}}$ to 0.70 $\sigma_{\text{fail}}$, where the upper voltage level corresponds to the maximum operating load, and the lower one excludes vibrations and specimen movement during the test.

Specimens are subjected to periodic flaw detection of the hole area every 60000 cycles. The results are recorded in the measurement protocol. Tests are completed after specimen failure. The number of cycles that causes specimen failure is registered in the test protocol.

5. Results
A) Static loading
Failure stress of the specimen under static loading on a four-point tool is 10,407 kN. Figure 4 presents a graph of specimen failure during static testing.

![Figure 4. Graph of destruction under static loading](image)

B) Cyclic loading of a defect-free specimen
Based on data obtained from static tests, the parameters of the machine for cyclic tests were determined. Figure 5 shows the test pattern for four-point bending.
The specimen withstood 204487 cycles and subsequently failed. The specimen was triply subjected to ultrasound testing to detect the growth of defects (after 60000, 120000 and 180000 cycles). The defects were detected after 120000 cycles using ultrasound testing. Figures 6 and 7 show the defect zones after ultrasound testing.

C) Cyclic loading of a specimen with “delamination” defects
The specimen began to fail after 9000 cycles, similar defects without a defective specimen appear after 100000–120000 cycles. Figure 8 shows the initial defect zone on the specimen prior to testing.
After 19000 cycles, the defect reached the edges of the specimen. After 21991 cycles, the specimen failed. Figure 9 shows the destroyed specimen.

Figure 9. Specimen after 21991 cycles

D) Cyclic loading of a specimen with repaired defects
After 32000 cycles, "delamination" was visually recorded on the edges of the specimen.
After 35631 cycles, the specimen failed.
Table I and Figure 10 present the comparison of different specimens.

Table 1. Comparison of specimens

| Type of specimen | Number of cycles | %  |
|------------------|------------------|----|
| Defect-free      | 204487           | 100|
| Defective        | 21991            | 10,75|
| Repaired         | 35631            | 17,42|

Figure 10. Histogram of service life of specimens

6. Conclusions
1. Analysis of the test results showed that a "delamination" type defect significantly reduces service life of the specimen.
2. Analysis of the measurement protocols revealed that injection of resin with a syringe did not ensure...
complete filling of the defective zone. Therefore, the defect boundaries before and after repairing changed insignificantly, but even an incomplete filling of the defect zone increased service life of the specimen by 62% compared to the defective specimen. Further studies will focus on improvement of the technology of resin injection into the defective zone. The method of vacuum infusion and special equipment are planned to be used in the studies.

References
[1] Stepanov A A 1987 Obrabotka rezaniem vysokoprochnyh kompozicionnyh polimernyh materialov. Cutting of high-tensile composite polymeric materials (Leningrad: Mashinostroenie) 176 p
[2] Tsao C C 2008 Investigation into the effects of drilling parameters on delamination by various stepcore drills J. of materials processing technology 206 405–11
[3] Drozhzhin V I 1983 Fizicheskie osobennosti i zakonomernosti processa rezanija sloistyh plastmass. Physical properties and trends of the cutting of layer plastic: Thesis’ abstract 05.03.01 (Kiev) 39 p
[4] Shyha I, Leung S S, Aspinwall D K, Bradley S, Dawson S and Pretorius C J 2010 Drilling of Titanium/CFRP/Aluminium Stacks Key Engineer-ing Materials 447–448 624–33
[5] Islam M N, Rafi N H and Charoon P 2009 An Investigation into Effect of Canned Cycles on Drilled Hole Quality Proceedings of the World Congress on Engineering (WCE–2009 vol I) 1–3 July (London U.K.)
[6] Stepanov A A 1980 Some issues of cutting of high durable composite materials Potential of cutting structure materials (Moscow: CN NTO mashproma) pp 254–5
[7] Kuo C L, Soo S, Aspinwall D, Thomas W, Carr C, Pearson D, M'Saoubi R and Leahy W 2015 Performance of multimargin coated tools in one-shot drilling of metallic composite stack materials under varying feed rate and pecking conditions Proceedings of the 38th International Matador Conference, vol 7–4, 28–30 March pp 231–8 (Huwei, Taiwan, Province of China)
[8] Lomaev V I and Dudarev A S 2006 Potential of hole machining during the production of CFRP civil aviation products Machine building technology vol 7 18–22
[9] Garrick R 2007 Drilling Advanced Aircraft Structures with PCD (Poly–Crystalline Di-amond) Drills SAE Technical, paper 2007–01–3893
[10] Atarsia A, Mueller–Hummel P and Hollenbaugh S 2013 High efficiency in machining carbon fiber composites and metal stacks for aerospace application Finer Points pp 18–28
[11] Pikalov A A 2012 Peculiarities of hole making in hybrid KM–Ti–Al stacks Mechanics and machine building 669–79
[12] Ivanov Y N, Kaverzin E Y and Chapyshev A P 2013 Experimental studies of thermal material expansion effects during the dry drilling of holes in CFRP/Ti stacks Bull. of Irkutsk State Technical Univer. 10(81)
[13] Spiridonov A A 1981 Experiment planning when studying engineering processes (Moscow: Machine building) 184 p
[14] Kolesnik V A, Kolesnik V A, Krivoruchko D V and Mital D 2015 Cutting temperature during the drilling of CFRP/Ti stacks Cutting and tool in engineering systems Int. (Scientific and Engineering Proceedings vol 85) pp 126–36 (Kharkov: NTU KhPI)
[15] Chashin N S and Ivanov Yu N 2015 Processing holes in mixed bags by the method of orbital drilling Vestnik Irkutsk State Technical University 11(106) 44–9
[16] Chashin N S 2016 Evaluation of the accuracy of hole machining in carbon plastic on the industrial robot KUKA KR210 R2700 Extra Aeromachinery and transport of Siberia: collection of reports from All–Russia Youth research and scientific conf. pp 308–13
[17] Paulo R G and Loić B 2018 Comparison between three-point and four-point flexural tests to determine wood strength of Eucalyptus specimens Maderas: Ciencia y Tecnología 20(3) 333–42
[18] Theotokoglou E E and Sideridis E 2011 Study of composite beams in asymmetric four-point bending J. of Reinforced Plastics and Composites 30(13) 1125–37
[19] Michel G 1993 Four-point bending tests on off-axis composites Composite Structures 24(2) 89–98
[20] Murat K, Fazil S, Nuri E and Kenan C 2016 Failure behavior of composite laminates under four-point bending J. of Composite Materials vol 50 iss. 26 3679–97
[21] Aviatsionnyye pravila. Normy letnoy godnosti ochen legkich samoletov 2006 (Mezhgosudarstvennyy aviatsionnyy komitet) 100 p