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IMPROVEMENT OF THE REPAIR METHOD OF THE AIRCRAFT COMPONENTS MADE OF POLYMER COMPOSITE MATERIALS WITH OPERATIONAL DAMAGE

The subject of study in this article is the repair method of the aircraft (A/C) components made of polymer composite materials (PCM) with operational damage. This article improves the repair method of the A/C PCM components with cracks and holes. Objectives: to improve the repair method of operational damage of the A/C PCM components by layer-by-layer removal of the defective area using a milling tool; propose dependencies to determine the serviceability period of the damaged area, considering the safety factor and geometric parameters of the defect. The following methods are used: analysis of existing and common repair methods of the A/C PCM components, mathematical approaches for their evaluation based on solving systems of equations. According to the analysis, the shortcomings of existing and common repair methods of the A/C PCM components with cracks and holes are identified. A proposal is made to improve the adhesive repair method of the A/C PCM components by using a milling tool with a curved cutting edge with a radius of curvature from 3 mm to 5 mm. The main stages of such repair are updated by filling the repair area with isotropic polymer paste. The dependencies of the geometrical parameters of layer-by-layer milling on the strength of the A/C PCM components are shown, considering the operating loads, calculated loads, and safety factors. The scientific novelties of the obtained results are as follows: the repair method of the A/C PCM components with operational damage using layer-by-layer milling with shaped radial mill to remove PCM layers in the defective area followed by filling the repair area with isotropic polymer paste is improved; the dependencies of geometric and strength parameters of the defective area of the A/C PCM components are established, which allow to easily determine the time of defect development before the destruction of the structure and the temporary period of serviceability of the A/C PCM components. The proposed improvement of the repair method will increase the period of operation of the A/C PCM components in general, which may be the next study.

Keywords: *aircraft; polymer composite material; repair; operational damage; layer-by-layer milling; strength.*

Introduction

Modern aviation world is characterized by the use of different materials. Among metal materials, steel, titanium, aluminum, and others are in the greatest demand.

Aluminum has a high-quality ratio of strength and weight, good molding ability, corrosion resistance and the ability to recycle it for reuse. These properties allow to change heavier copper and steel in some aircraft.

Nowadays in the aviation industry the use of non-metallic materials, such as PCM, is rapidly developing. PCM can be both stand-alone materials and in combination with metal, which allows to combine several properties that are not usually found in one material. For example, aluminum has a relative lightness and satisfactory strength, which is sometimes insufficient for the use of this material in critical structures of the A/C. Therefore, aluminum is additionally reinforced with boron fibers from refractory compounds (carbides, nitrides, borides and oxides), which have high strength [1].

Non-metal reinforcement is also used in aircraft structures with PCM, for example, to increase the load-bearing capacity of the A/C elements by transverse reinforcement [2].

The use of metallic and non-metallic materials both together and separately allowed to divide them into metal matrix composites (MMC), ceramic matrix composites (CMC) and polymer matrix composites (PMC) [3].

The competitiveness of PMC or PCM in relation to metals largely depends on the stability of their physical and mechanical properties, ease of control and repair of damage occurring during the A/C operation.

Repair of external damage of the A/C PCM components is caried out in accordance with the A/C operation and repair requirements, provided by the A/C designer.

The repair methodology depends on the defect and the damaged component type and must ensure the restoration of the structure to the state of A/C airworthiness.

Materials that can be used for repair are described in detail by the A/C designer in the relevant sections of the operating documentation.

The repair quality of PCM aviation parts and PCM multilayer adhesive structures should be confirmed by non-destructive testing (NDT) [4]. Modern NDT methods include reengineering technology, which can be used to control geometry of the unit surfaces based on a three-dimensional model according to analytical standard at all stages of the A/C lifecycle [5].

The most common defects of PCM structural elements are holes and cracks, which account for 60 % of total number of the defects' types [6, 7]. Similar A/C defects can occur at the production stage of the A/C PCM structures [8]. Among the NDT methods for such defects, the most common is the acoustic testing method [9].

Repair of the A/C PCM components with holes and cracks is usually based on the installation of repair inserts [10]. Today, popular methods of repair with inserts for such defects are:

– with the use of autonomous repair systems, the effectiveness of which is given in [11];

– mechanical – setting a temporary patch (metal or made of PCM) using bolted joints [12];

– adhesive – layer-by-layer removal of the components' damaged areas followed by the layup of pre-preg layers (Fig. 1) or installation of repair material [13].

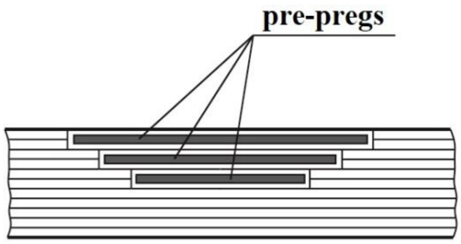

Fig. 1. Pre-preg layup in the repair area during the layer-by-layer removal of defective layers

The use of autonomous repair systems is a promising area, but is currently expansive and their use should be economically justified.

Installation of temporary metal or PCM patch with bolted joints has a significant disadvantage – the protrusion of the mounting heads on the outer aerodynamic surface, which degrades the A/C aerodynamic characteristics, as well as inability to ensure uniform load distribution in the structure from the repaired area.

The adhesive repair method with gluing of the composite patch, in comparison with a mechanical method, has no such shortcomings and provides effective loading redistribution from a defective area on a patch that essentially reduces the stresses concentration in the structure.

The only disadvantage of the adhesive method is that the layer-by-layer removal of the damaged area in the perpendicular direction of the fibers creates stress concentrators (Fig. 2), which reduces the fatigue strength of the A/C PCM components repaired area.

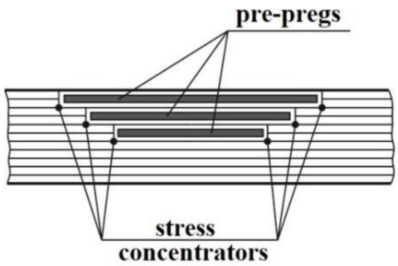

Fig. 2. Scheme of stress concentrators placement during the layer-by-layer removal of defective layers

Despite the shortcoming of the adhesive method of the A/C PCM components repair, today it is the most common among the methods of repairing multilayer structures and structures with honeycomb or tubular fillers [14], so research to improve the method of repairing the A/C PCM components with holes and cracks while maintaining the strength of the repaired area, as well as the possibility of establishing a temporary period of serviceability of the damaged area is an urgent task.

1. Statement of research tasks

To improve the method of repairing the A/C PCM components operational damage, the following tasks should be solved:

– improve the repair method of the A/C PCM components operational damage by layer-by-layer removal of the defective area using a milling tool with radius R;

– suggest dependencies to determine the temporary period of serviceability of the damaged area, taking into account the safety factor and geometric parameters of the defect to ensure operational strength.

2. Improving the method of repairing the A/C PCM components operational damage

In this paragraph the improvement of the repair method of the A/C PCM components operational damage by layer-by-layer removal of the defective area using a milling tool is suggested. The mill has a curved cutting edge with a curvature radius R from 3 mm to 5 mm, where the size of the mill radius depends on the depth of the repaired component's defective area (Fig. 3).

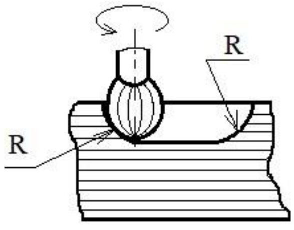

Fig. 3. Milling scheme of the defective area of the A/C PCM component, where R is the mill radius

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Repair of operational physical damages of the A/C PCM components consists of the main stages:

– layer-by-layer milling of the component's repaired area;

– treatment of milled surface with means that increase the adhesive properties of the surface, such as ВК-25 glue [15] and reduce the risk of cracks between the layers [16];

– filling the obtained recess with a composition of isotropic paste, with its subsequent treatment by vibration (sound or ultrasonic frequencies) to reduce internal voids, which is further proposed by the authors;

– polymerization, application of protective coatings on the component according to the component's manufacture and repair technological process.

Isotropic paste is a material that consists of two components: a matrix (binder) and a filler (reinforcement). Components from short-dimensional segments (2 … 7 mm) of a certain type of fiber are used for reinforcement [17]. In such pastes, high-strength fibers carry the main stress that arises in it under the action of external loads, and provide rigidity and strength of the repaired element in all directions of load.

The matrix that fills the interfiber space ensures the joint work of individual fibers due to its own rigidity and interaction that exists on the matrix and fiber boundary.

It should be noted that when milling of the repair recess, an area with rough surface is formed, which promotes a more stable adhesive bond of the isotropic paste with the material of the component being repaired.

Advantages of this repair type, compared to the typical adhesive method, are:

– reduction of the material volume removed by milling and increase of the repaired components strength due to use of the mill with radius R;

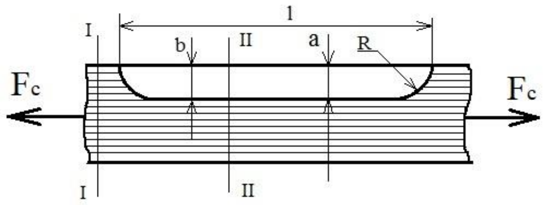
– reduction of the stress concentrators impact on the fatigue strength due to the smooth transition between the intersection of the created planes during milling;

– increase of the repaired area fatigue strength by applying a layer of glue;

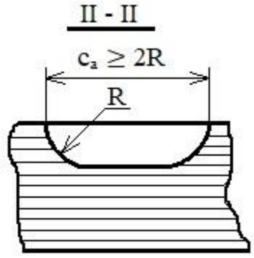
– reduction of the internal cavities due to vibration treatment (sound or ultrasonic frequencies).

3. Analysis of the layer-by-layer milling geometrical parameters influence on the A/C PCM components strength

For the analysis of the layer-by-layer milling geometrical parameters influence on the strength of the A/C PCM components to be repaired by the proposed method, the experimental parameters that schematically shown in Fig. 4 are determined: F_p is the calculated tensile force acting on the PCM structural element during operation; a is the A/C PCM component thickness at the place of repair; b is the depth of single-layer milling; c_a is the width of single-layer milling; R is the connection radius determined by the mill radius; $I-I$ is the cross-section of the product with the defect being repaired in the place of a solid array; $II-II$ is the cross-section of the product with the defect being repaired in the place of material removal for further isotropic paste application.



a



b

Fig. 4. Calculation scheme of the repair area of the A/C PCM component:
a – longitudinal section; b – cross-section

It is known that all structural elements (including the A/C skin) carry certain types of loads and alternate loads, such as stretching, compression, bending, torsion [18]. The most critical are tensions from tensile forces (stretching) [19].

In practice, the strength requirements are determined by operating loads (maximum actual loads F_a that are possible during operation) and the calculated loads F_c (operational actual loads F_a multiplied by the established safety factors f) [20].

When designing a specific structure of the A/C PCM component, the calculated loads are used

$$F_c = F_a f . \quad (1)$$

The coefficient f is assumed to be equal to 1.5. Under this condition, the tensile stress σ_1, which arises and acts in the element of the A/C PCM component (cross-section $I-I$, Fig. 4, a) is equal to

$$\sigma_1 = \frac{F_c}{S_1}, \qquad (2)$$

where $S_1 = ac_a$ is the undamaged part of the A/C PCM component element plain (cross-section $I - I$).

The actual operating stress σ_2 that arises and stretches the structure of the A/C PCM component from the remote defective area (cross-section $II - II$, Fig. 4, b) is equal to

$$\sigma_2 = \frac{F_c}{S_2}, \qquad (3)$$

where $S_2 = (a - b)c_a$.

It is known from the failure theory that the failure of a structure does not occur until the acting internal stress arising in the structure does not exceed the region of ultimate tensile strength σ_{tu} of the material from which it is made [21]

$$\sigma_1 < \sigma_{tu} / f. \qquad (4)$$

During the A/C flight operation, there may be case when the malfunction of the A/C PCM component is formed during post- or pre-flight service at the airport, where there are no conditions to remove the detected defect.

In this case, it is necessary to determine how much the detected defect has reduced the life of the A/C PCM component and predict the time to complete breaking, i.e., it is necessary to establish the ability to fly to the main base (base airport). For this purpose, it is necessary to measure the defective area and determine the maximum depth of, for example, crack, or depth of the local deformation area.

In the case of partial destruction of the structural element of the A/C PCM component, the operation continues due to the built-in safety factor f of the element (4).

With the increase of the initial defect of the structure of the A/C PCM component, the actual tensile stress σ_2 will increase until the moment of its destruction, when $\sigma_2 \geq \sigma_{tu}$.

To simplify the definition of equations, formula (3), taking into account S_2, can be turned to the following:

$$\sigma_2 = \frac{F_c}{\left[ac_a\left(1 - \frac{b}{a}\right)\right]}. \qquad (5)$$

Taking into account formulas (5) and (2), it is possible to obtain a simplified formula for calculating the allowable stresses of the A/C PCM components:

$$\sigma_2 = \sigma_1\left[\frac{1}{1 - \frac{b}{a}}\right]. \qquad (6)$$

Based on equation (6), it is possible to build the graph of dependencies of the actual tensile stresses σ_2 on the geometric parameters of the defect b/a as a function of different values of the safety factors f : 1.3, 1.5, 1.7, 2.0, where b/a_a is the actual value of the geometric parameter as a result of the defective area of the structural element of the A/C PCM component; σ_{2a} is the actual tensile stress (point B) in the weakened cross-section of the defective area of the structural element of the A/C PCM component; $(b/a)_{cr}$ is the critical value (point A) of the geometric parameter b/a of the defective area of the structure of the A/C PCM component, which will cause its destruction without repair (Fig. 5).

Assuming that at the last structure diagnosis of the A/C PCM component no physical defect was detected, and at the next diagnosis after time t_1 the actual defect with parameters b/a_a was detected, then according to the graph (Fig. 5): $f = 1.5$, $b/a_a = 0.15$, $\sigma_{2a} = 0.79\sigma_{tu}$.

Assuming that the gradient of defect development (increase of geometric parameter b/a) remains constant, it is easy to determine the time t_2 of defect development in the structure of the A/C PCM component until its complete destruction

$$t_2 = t_1\left[\frac{\left(\frac{b}{a}\right)_{cr}}{\left(\frac{b}{a}\right)_a}\right]. \qquad (7)$$

The temporary period Δt of the structure serviceability of the A/C PCM component with an operational defect is determined by the formula:

$$\Delta t = t_2 - t_1 = t_1\left\{\left[\frac{\left(\frac{b}{a}\right)_{cr}}{\left(\frac{b}{a}\right)_a}\right] - 1\right\}. \qquad (8)$$

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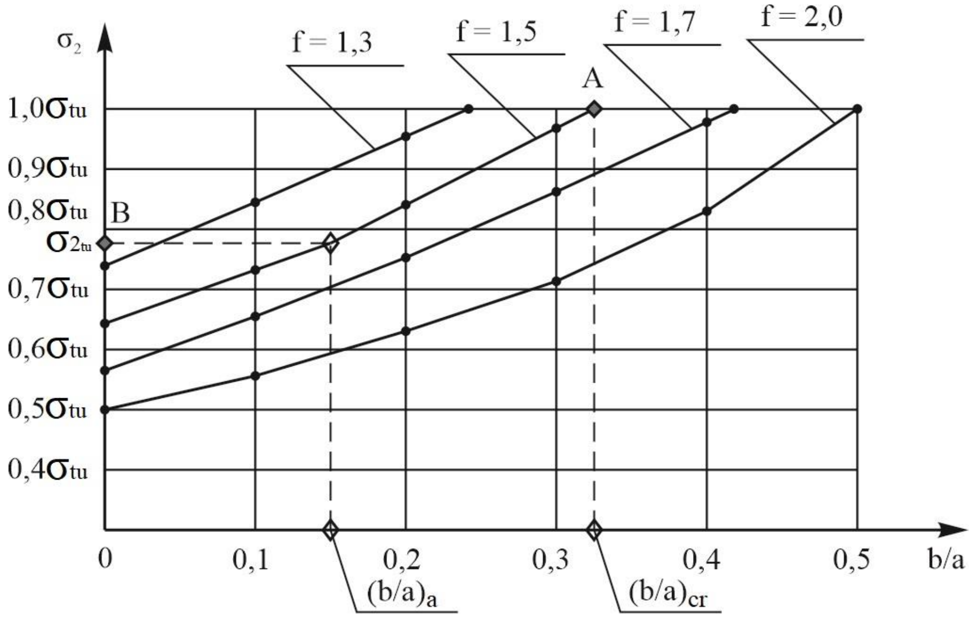

Fig. 5. Graph of dependencies of the actual tensile stress σ_2 from geometric parameter b/a of the defective area of the A/C PCM component at different values of the safety factor f

By the value of t, a decision is made on the sufficiency of time to move the A/C to the repair base or the need for its immediate repair at the parking area with the call of the appropriate crew with the equipment.

Conclusion

1. The analysis of the existing repair methods of the A/C PCM components showed the advantages of the adhesive repair method of such structures with operational damage – holes or cracks.

2. The relevance of research on the adhesive repair method improvement of the A/C PCM components with operational damage, which allows to maintain the strength of the repaired are, is confirmed.

3. The repair method of the A/C PCM components with operational damage is improved by using layer-by-layer smooth milling with the help of shaped radial mill to remove the PCM layers in the defective area, followed by filling the repair area with isotropic polymer paste.

4. The analysis of the geometric parameters influence on the strength properties of the A/C PCM components is given, which allows to establish the dependencies of the actual tensile stress σ_2 on the geometric parameter b/a of the defective area of the A/C PCM component at different values of safety factor f.

5. Dependencies for determination of temporary period Δt of repair area serviceability taking into account safety factor and geometric parameters of defect are offered and justified. The value of Δt allows to established the time of possible operation or its absence and the impossibility of operation of the A/C PCM component with operational damage.

References (GOST 7.1 2006)

1. Fayomi, O. S. I. Mechanical behavior of composite materials in metal [Text] / O. S. I. Fayomi, K. O. Babaremu, I. G. Akande // International Journal of Mechanical Engineering and Technology (IJMET). – 2019. – Vol. 10, Iss. 3. – P. 19–30.

2. Нитка, С. М. Підвищення несучої здатності елементів конструкції із полімерних композиційних матеріалів шляхом поперечного армування [Текст] / С. М. Нитка, О. А. Шевченко // Матеріали XV міжнародної науково-технічної конференції «АВІА-2021». – К. : НАУ, 20-22 квітня, 2021. – С. 36–40.

3. Fayomi, O. S. I. Impact of Al-Composites in the Manufacturing Industry: A Neccessity [Text] / O. S. I. Fayomi, K. O. Babaremu, I. G. Akande // International Journal of Civil Engineering and Technology. – 2019. – Vol. 10, Iss. 3. – P. 92–102.

4. Мурашов, В. В. Контроль качества авиационных деталей из полимерных композиционных материалов и многослойных клееных конструкций [Текст] / В. В. Мурашов, Е. И. Косарина, А. С. Генералов // Авиационные материалы и технологии. – 2013. – Вып. 3. – С. 65–70.

5. Implementation of reengineering technology to ensure the predefined geometric accuracy of a light aircraft keel [Text] / K. Maiorova, Iu. Vorobiov, M. Boiko, V. Suponina, O. Komisarov // Eastern-European Journal of Enterprise Technologies. – 2021. – Vol. 6, No. 1 (114). – P. 6–12. DOI: 10.15587/1729-4061.2021.246414.

6. Астанін, В. В. Експлуатаційні пошкодження елементів конструкцій літальних апаратів із композиційних матеріалів і методи їх ремонту [Текст] / В. В. Астанін, О. В. Глоба, О. А. Шевченко // Технологические системы: материалы первой технической конференции украинского отделения международного общества по продвижению материалов и технологий (SAMPE). – К. : УкрНІАТ, 2011. – № 4(57). – С. 64–68.

7. Андреев, А. В. Эксплуатационная несущая способность конструкций отечественных и зарубежных воздушных судов транспортной категории из полимерных композиционных материалов. Часть 2. Анализ видов, характера и частоты эксплуатационных повреждений [Текст] / А. В. Андреев, С. А. Бычков, А. В. Кондратьев // Вісник ОНМУ : зб. наук. пр. – О. : ОНМУ, 2016. – № 2(48). – С. 180–194.

8. Гайдачук, А. В. Анализ технологических дефектов, возникающих в серийном производстве интегральных авиаконструкций из полимерных композиционных материалов [Текст] / А. В. Гайдачук, А. В. Кондратьев, Е. В. Омельченко // Авиационно-космическая техника и технология. – 2010. – № 3(70). – С. 11–20.

9. Булах, І. О. Аналіз методів неруйнуючої дефектоскопії виробів з композиційних матеріалів [Текст] / І. О. Булах, О. В. Глоба // Вісник Чернігівського державного технологічного університету. Серія : Технічні науки. – 2013. – № 2(65). – С. 36–42.

10. Глоба, О. В. Ремонт пошкоджень елементів конструкцій із композиційних матеріалів з використанням комп'ютеризованої системи та комплексу інструментальних засобів [Текст] / О. В. Глоба, О. А. Шевченко // Вісник Національного технічного університету України «Київський політехнічний інститут». Серія Машинобудування. – 2011. – № 62. – С. 76–80.

11. Андреев, А. В. Особенности ремонта деталей из полимерных композиционных материалов при помощи автономного ремонтного оборудования [Текст] / А. В. Андреев // Mechanics and Advanced Technologies : сб. науч. тр. Национального технического университета «КПИ». – Киев, 2018. – Вып. 3(84). – С. 69–74.

12. Hanser, S. New technology for new aircraft [Text] / S. Hanser, G. Ferrer, S. Dupouv // JEC Composites, May – June, 2019. – No. 128. – P. 44 – 46.

13. Proof of a composite repair concept for aeronautical structures: a simplified method [Text] / F. Collombe, Y. Davila, S. Avila, A. Morales, L. Crouzeix, Y.-H. Grunevald, H. Hernandez, N. Rocher & F. Cénac // Mechanics & Industry. – 2019. – Vol. 20, No. 8. – P. 1–14. DOI: 10.1051/meca/2020056.

14. Лупкин, Б. В. Метод ремонта агрегатов из композиционных материалов с трубчатым (сотовым) заполнителем в полевых условиях [Текст] / Б. В. Лупкин, В.С. Нитка // Открытые информационные и компьютерные интегрированные технологии : сб. науч. тр. – Х. : НАКУ, 2014. – № 63. – С. 33-41.

15. Клей ВК-25 [Електронний ресурс]. – Режим доступу: http://alfa-sintez.com/klei_VK-25.html – 12.01.2021.

16. Characterization of Adhesives Bonding in Aircraft Structures [Text] / M. G. Romano, M. Guida, F. Marulo, M. G. Auriccio, S. Russo // Materials. – 2020. – Vol. 13, Iss. 21. Article No. 4816. – P. 1-13. DOI: 10.3390/ma13214816.

17. Волокна для армирования композиционных материалов [Електронний ресурс]. – Режим доступу: https://poznayka.org/s77441t1.html – 12.01.2021.

18. Limonin, M. V. Numerical estimation of in-service damages' effect on the loadbearing capacity of composite aircraft structures elements [Text] / M. V. Limonin, Y. I. Dudarkov, E. A. Levchenko // Advances in Composites Science and Technologies 2020 (ACST 2020). – 2020. – Vol. 1990. – P. 1–5. DOI: 10.1088/1742-6596/1990/1/012013.

19. A generalized framework towards structural mechanics of three-layered composite structures [Text] / M. Aßmus, K. Naumenko, A. Öchsner, H. Altenbach // Technische Mechanik. – 2019. – Vol. 39, No. 2. – P. 202–219. DOI: 10.24352/UB.OVGU-2019-019.

20. Авиационные правила. Часть 25. Нормы летной годности самолетов транспортной категории. – ОАО «АВИАИЗДАТ», 2009. – 274 с. [Електронний ресурс]. – Режим доступу: http://www.gostrf.com/normadata/1/4293795/4293795750.pdf – 12.01.2021.

21. Aßmus, M. Structural Mechanics of Anti-Sandwiches. An Introduction [Text] / M. Aßmus. – SpringerBriefs in Continuum Mechanics. Springer, Cham, 2019. – 128 p. DOI: 10.1007/978-3-030-04354-4.

References (BSI)

1. Fayomi O. S., Babaremu K. O., Akande G. Mechanical behavior of composite materials in metal. *International Journal of Mechanical Engineering and Technology (IJMET)*, 2019, vol. 10, iss. 3, pp. 19-30.

2. Nytka, S. M. Pidvyshchennya nesuchoyi zdatnosti elementiv konstruktsiyi iz polimernykh kompozytsiynykh materialiv shlyakhom poperechnoho armuvannya [Increasing the bearing capacity of structural elements made of polymer composite materials by transverse reinforcement]. *Materialy XV mizhnarodnoyi naukovo-tekhnichnoyi konferentsiyi «AVIA-2021»*, 2021, pp. 36-40. (In Ukrainian).

3. Fayomi, O. S. I., Babaremu, K. O., Akande, I. G. Impact of Al-Composites in the Manufacturing Industry: A Neccessity. *International Journal of Civil Engineering and Technology*, 2019, vol. 10, no. 3, pp. 92–102.

4. Murashov, V. V. Kontrol' kachestva aviatsionnykh detalei iz polimernykh kompozitsionnykh materialov i mnogosloinykh kleenykh konstruktsii [Quality control of aviation parts made of polymer composite materials and multilayer glued structures]. *Aviatsionnye materialy i tekhnologii*, 2013, no. 3, pp. 65-70. (In Russian).

ISSN 1727-7337 (print)
ISSN 2663-2217 (online)

5. Maiorova, K., Vorobiov, Iu., Boiko, M., Suponina, V., Komisarov, O. Implementation of reengineering technology to ensure the predefined geometric accuracy of a light aircraft keel. *Eastern-European Journal of Enterprise Technologies*, 2021, vol. 6, no. 1(114), pp. 6-12. DOI: 10.15587/1729-4061.2021.246414.

6. Astanin, V. V., Hloba, O. V., Shevchenko, O. A. Ekspluatatsiyni poshkodzhennya elementiv konstruktsiy lital'nykh aparativ iz kompozytsiynykh materialiv i metody yikh remontu [Operational damage of aircraft composite structural elements and methods of their repair]. *Tekhnologicheskie sistemy: materialy pervoi tekhnicheskoi konferentsii ukrainskogo otdeleniya mezhdunarodnogo obshchestva po prodvizheniyu materialov i tekhnologii* (SAMPE), 2011, no. 4(57), pp. 64-68. (In Ukrainian).

7. Andreev, A. V., Bychkov, S. A., Kondrat'ev, A. V. Ekspluatatsionnaya nesushchaya sposobnost' konstruktsii otechestvennykh i zarubezhnykh vozdushnykh sudov transportnoi kategorii iz polimernykh kompozitsionnykh materialov. Chast' 2. Analiz vidov, kharaktera i chastoty ekspluatatsionnykh povrezhdenii [Operational bearing capacity of structures of domestic and foreign aircraft of the transport category from polymer composite materials. Part 2. Analysis of the types, nature and frequency of operational damage]. *Visnyk ONMU: zb. nauk. pr*, 2016, no. 2(48), pp. 180-194. (In Ukrainian).

8. Gaidachuk, A. V., Kondrat'ev, A. V., Omel'chenko, E. V. Analiz tekhnologicheskikh defektov, voznikayushchikh v seriinom proizvodstve integral'nykh aviakonstruktsii iz polimernykh kompozitsionnykh materialov [Analysis of technological defects arising in the serial production of integral aircraft structures from polymer composite materials]. *Aviacijno-kosmicna tehnika i tehnologia* [Aerospace technic and technology], 2010, no. 3(70), pp. 11-20. (In Russian).

9. Bulakh, I. O., Hloba, O. V. Analiz metodiv neruynuyuchoyi defektoskopiyi vyrobiv z kompozytsiynykh materialiv [Analysis of methods of non-destructive testing of products made of composite materials] *Visnyk Chernihivs'koho derzhavnoho tekhnolohichnoho universytetu. Seriya : Tekhnichni nauky*, 2013, no. 2, pp. 36-42. (In Ukrainian).

10. Hloba, O. V., Shevchenko, O. A. Remont poshkodzhen' elementiv konstruktsiy iz kompozytsiynykh materialiv z vykorystannyam komp''yuteryzovanoyi systemy ta kompleksu instrumental'nykh zasobiv [Damage repair of structural elements made of composite materials using a computerized system and a set of tools]. *Visnyk Natsional'noho tekhnichnoho universytetu Ukrayiny «Kyyivs'kyy politekhnichnyy instytut». Seriya Mashynobuduvannya*, 2011, no. 62, pp. 76-80. (In Ukrainian).

11. Andreev, A. V. Osobennosti remonta detalei iz polimernykh kompozitsionnykh materialov pri pomoshchi avtonomnogo remontnogo oborudovaniya [Repair features of parts made of polymer composite materials using autonomous repair equipment]. *Mechanics and Advanced Technologies: sb. nauch. tr. Natsional'nogo tekhnicheskogo universiteta «KPI»*, 2018, no. 3(84), pp. 69-74. (In Russian).

12. Sebastien Hanser, Guillaume Ferrer, Sebastien Dupouv. *New technology for new aircraft. JEC Composites*, May – June, 2019, no. 128, pp. 44-46.

13. Collombe, F., Davila, Y. et al. Proof of a composite repair concept for aeronautical structures: a simplified method. *Mechanics & Industry*, 2019, vol. 20, no. 8, pp. 1-14. DOI: 10.1051/meca/2020056.

14. Lupkin, B. V., Nitka, V. S. Metod remonta agregatov iz kompozitsionnykh materialov s trubchatym (sotovym) zapolnitelem v polevykh usloviyakh [Repair method of composite materials units with tubular (honeycomb) filler in the field]. *Otkrytye informatsionnye i komp'yuternye integrirovannye tekhnologii*, 2014, no. 63, pp. 33-41. (In Russian).

15. *Kley VK-25* [Glue VK-25]. Available at: http://alfa-sintez.com/klei_VK-25.html (accessed 12.01.2021) (In Russian).

16. Romano, M. G., Guida, M., Marulo, F., Auricchio, M. G. & Russo, S. Characterization of Adhesives Bonding in Aircraft Structures. *Materials*, 2020, vol. 13, iss. 21, article no. 4816, pp. 1-13. DOI: 10.3390/ma13214816.

17. *Volokna dlya armirovaniya kompozitsionnykh materialov* [Fibers for reinforcing composite materials]. Available at: https://poznayka.org/s77441t1.html (accessed 12.01.2021) (In Russian).

18. Limonin, M. V., Dudarkov, Y. I., Levchenko, E. A. Numerical estimation of in-service damages' effect on the loadbearing capacity of composite aircraft structures elements. *Advances in Composites Science and Technologies (ACST 2020)*, 2020, vol. 1990, pp. 1-5. DOI: 10.3390/ma13214816.

19. Aßmus, M., Naumenko, K., Öchsner, A. & Altenbach, H. A generalized framework towards structural mechanics of three-layered composite structures. *Technische Mechanik*, 2019, vol. 39, no. 2, pp. 202-219. DOI: 10.24352/UB.OVGU-2019-019.

20. *Aviatsionnye pravila. Chast' 25. Normy letnoi godnosti samoletov transportnoi kategorii* [Aviation rules. Part 25. Airworthiness standards for transport category aircraft]. OAO «AVIAIZDAT» Publ., 2009. 274 p. Available at: http://www.gostrf.com/normadata/1/4293795/4293795750.pdf (accessed 12.01.2021). (In Russian).

21. Aßmus, M. *Structural Mechanics of Anti-Sandwiches. An Introduction*. SpringerBriefs in Continuum Mechanics. Springer, Cham, 2019. 128 p. DOI: 10.1007/978-3-030-04354-4.

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УСОВЕРШЕНСТВОВАНИЕ МЕТОДА РЕМОНТА СОСТАВНЫХ ЧАСТЕЙ АВИАЦИОННОЙ ТЕХНИКИ ИЗ ПОЛИМЕРНЫХ КОМПОЗИЦИОННЫХ МАТЕРИАЛОВ С ЭКСПЛУАТАЦИОННЫМИ ПОВРЕЖДЕНИЯМИ

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Предметом изучения статьи является метод ремонта составных частей (СЧ) авиационной техники (АТ) из полимерных композиционных материалов (ПКМ) с эксплуатационными повреждениями. Целью является усовершенствование метода ремонта СЧ АТ из ПКМ с трещинами и пробоинами. Задачи: усовершенствовать метод ремонта эксплуатационных повреждений СЧ АТ из ПКМ путем послойного удаления дефектной зоны с применением фрезерного инструмента; предложить зависимости определения временного периода работоспособности поврежденной зоны с учетом коэффициента безопасности и геометрических параметров дефекта. Используемые методы: анализ существующих и распространенных методов ремонтов СЧ АТ из ПКМ, математические подходы для их оценки на основе решения систем уравнений. Согласно проведенного анализа установлены недостатки распространенных и существующих методов ремонтов СЧ АТ из ПКМ с трещинами и пробоинами. Предложено усовершенствование клеевого метода ремонта СЧ АТ из ПКМ путем применения фрезерного инструмента с криволинейной режущей кромкой с радиусом кривизны от 3 мм до 5 мм. Обновлены основные этапы такого ремонта путем заполнения ремонтной зоны полимерной изотропной пастой. Показаны зависимости геометрических параметров послойного фрезерования и прочности СЧ АТ из ПКМ с учетом эксплуатационных нагрузок, расчетных нагрузок и коэффициента безопасности. Научная новизна полученных результатов заключается в следующем: усовершенствован метод ремонта СЧ АТ из ПКМ с эксплуатационными повреждениями использованием послойного фрезерования с помощью фасонной радиусной фрезы для удаления слоев ПКМ в зоне дефекта с последующим заполнением зоны ремонта изотропной полимерной пастой; установлены зависимости геометрических и прочностных параметров дефектной зоны СЧ АТ из ПКМ, позволяющие легко определить время развития дефекта до полного разрушения конструкции и временный период работоспособности СЧ АТ из ПКМ с повреждением. Предлагаемое усовершенствование метода ремонта позволит увеличить период эксплуатации СЧ АТ из ПКМ и АТ в целом, что может стать следующими исследованиями.

Ключевые слова: авиационная техника; полимерный композиционный материал; ремонт; эксплуатационное повреждение; послойное фрезерование; прочность.

УДОСКОНАЛЕННЯ МЕТОДУ РЕМОНТУ СКЛАДОВИХ ЧАСТИН АВІАЦІЙНОЇ ТЕХНІКИ З ПОЛІМЕРНИХ КОМПОЗИЦІЙНИХ МАТЕРІАЛІВ ІЗ ЕКСПЛУАТАЦІЙНИМИ ПОШКОДЖЕННЯМИ

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Предметом вивчення в статті є метод ремонту складових частин (СЧ) авіаційної техніки (АТ) з полімерних композиційних матеріалів (ПКМ) із експлуатаційними пошкодженнями. Метою є удосконалення методу ремонту СЧ АТ із ПКМ з тріщинами та пробоїнами. Завдання: удосконалити метод ремонту експлуатаційних пошкоджень СЧ АТ із ПКМ шляхом пошарового видалення дефектної зони із застосуванням фрезерного інструменту; запропонувати залежності для визначення тимчасового періоду працездатності пошкодженої зони з урахуванням коефіцієнта безпеки та геометричних параметрів дефекту. Використовуваними методами є: аналіз існуючих і розповсюджених методів ремонтів СЧ АТ із ПКМ, математичні підходи для їх оцінювання на основі розв’язання систем рівнянь. Отримані такі результати. Згідно проведеного аналізу встановлено недоліки розповсюджених і існуючих методів ремонтів СЧ АТ із ПКМ з тріщинами та пробоїнами. Надано пропозицію з удосконалення клейового методу ремонту СЧ АТ із ПКМ шляхом застосування фрезерного інструменту, що має криволінійну ріжучу кромку з радіусом кривизни від 3 мм до 5 мм. Оновлені основні етапи такого ремонту шляхом заповнення ремонтної зони ізотропною полімерною пастою. Показані залежності геометричних параметрів пошарового фрезерування на міцність СЧ АТ із ПКМ з урахуванням експлуатаційних навантажень, розрахункових навантажень та коефіцієнта безпеки. Висновки. Наукова новизна отриманих результатів полягає в наступному: удосконалено метод ремонту СЧ АТ із ПКМ з експлуатаційними пошкодженнями використанням пошарового фрезерування за допомогою фасонної радіусної фрези для видалення шарів ПКМ у зоні дефекту з наступним заповненням зони ремонту ізотропною полімерною пастою; встановлені залежності геометричних та міцнісних параметрів дефектної зони СЧ АТ із ПКМ, які дозволяють легко визначити час розвитку дефекту до повного руйнування конструкції та тимчасовий період працездатності СЧ АТ із ПКМ з пошкодженням. Запропоноване удосконалення методу ремонту дозволить збільшити період експлуатації СЧ АТ із ПКМ та АТ в цілому, що може стати наступними дослідженнями.

Ключові слова: авіаційна техніка; полімерний композиційний матеріал; ремонт; експлуатаційне пошкодження; пошарове фрезерування; міцність.

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