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Ability of Joining Composite Structures with Metal by Riveting

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Abstract. The technology of repairing the composite coverings of the MiG-29 airframe provides for the possibility of repairing with the use of metal battens, connected with the composite cover by riveting, with the use of metal washers protecting the composite against damage during rivet upsetting. Tests were carried out to check the possibility of replacing the composite covering repairs with solid rivets with blind rivets, which would eliminate the necessity for the troublesome disassembly and assembly of the damaged covering. The conducted research shows that the threaded blind titanium rivets meet the requirements to be substitutes for solid rivets. The performed numerical calculations show that in riveted joints, an important role in the load transfer is played by the friction forces between the joined elements, and the value of these forces depends on the pressure of the head and the tab. Titanium blind threaded rivets provide higher pressure than cold-headed ones.

Keywords: composites, mechanical fasteners, plain rivets, blind threaded rivets

1. INTRODUCTION

The development and implementation of composite materials created new possibilities in the field of innovative construction solutions for vehicles, aircraft, and other technical devices [1, 2] but it also requires the solution of maintenance and technological problems that arise with the use of these materials. The operational problem is, for example, low-energy impacts that do cause invisible damage that reduces the strength of fiber-reinforced polymer composites [3, 4]. Composite airframe structures cause maintenance problems, especially repair problems, which did not apply to metal structures. One of them is the limited possibility of using mechanical fasteners to connect composite materials with metal, which makes it difficult to repair mechanically damaged composite airframe structures. Even making holes for mechanical fasteners in composite materials creates specific problems [5, 6].

The technology of repairing composite coverings of the MiG-29 airframe provides for the possibility of repairing with the use of overlapping metal battens connected with the composite covering by riveting with the use of metal washers protecting the composite against damage during rivet upsetting. Such a repair requires the removal of the damaged covering in order to perform the repair and re-installation.

Tests were carried out to check the possibility of replacing the composite covering repairs with solid rivets with blind rivets, the use of which would eliminate the necessity for the troublesome disassembly and assembly of the damaged covering. The experimental tests compared the strength of the lap joints of the carbon composite with the AW2024T3 sheet, joined using the technique provided for in the repair technology (rivets 3560A-4) and with the use of 3.5-mm diameter countersunk head rivets, one-sided Huck, and MBF2110AB-05-15. The research took into account the influence of orthotropic properties of the tested composite on the strength of joints. Additionally, the concentration of stresses in the composite, caused by a hole with a diameter of 4 mm, was estimated by numerical calculations.

2. RESEARCH MATERIALS AND METHODOLOGY

The research was carried out using a commercial carbon composite manufactured by Carbon Center, made of five layers of carbon prepregs from canvas and roving fabrics by hot pressing (Fig. 1). Samples of various dimensions were cut from the composite sheet by the water jet method.

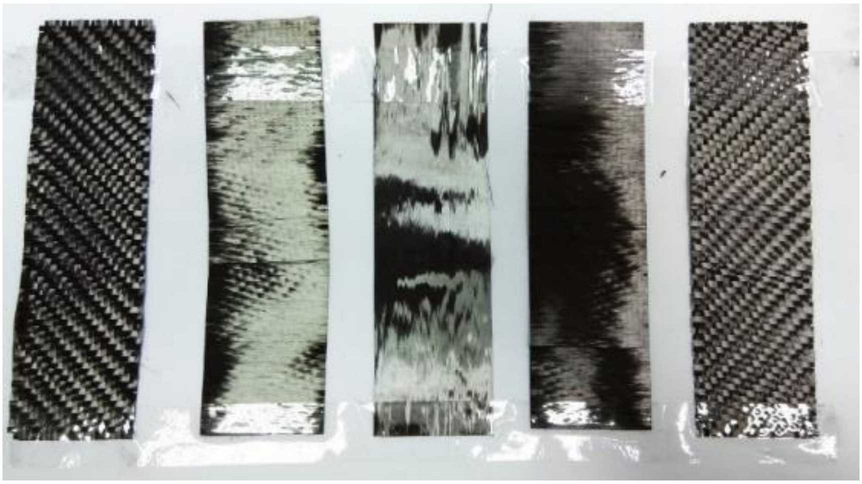

Fig. 1. Layout of carbon composite layers

The composite longitudinal elasticity modulus was determined in a direction of fibers of carbon fabrics and for the samples cut at an angle of 45°. Three-layer fabric glass handles were laminated at the end of the samples with the dimensions of 140 x 40 x 2 mm (Fig. 2). The handles made of three layers of E81 glass fabric saturated with Epidian 57/Z1 resin were wet laminated (Fig. 2). Curing of composite handles was carried out for 12 hours at ambient temperature with the pressures of 0.1 MPa and then for 5 hours at the temperature of 80°C. Similar holders were used in the lap samples on the composite elements.

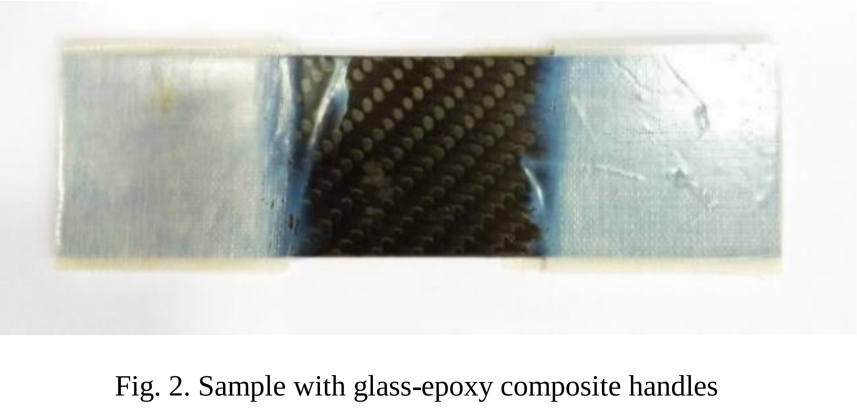

Fig. 2. Sample with glass-epoxy composite handles

Individual samples with different directivity were stretched in the HT-2402 universal testing machine using the 3542-025M-025-HT2 extensometer with a measuring base of 25 mm to determine Young's modulus of the tested composite.

The sensitivity of the tested composite to the effect of a notch in the form of a rivet hole with a diameter of 4 mm was also determined. In the samples with the dimensions of 140 x 25 x 2 mm, a hole was drilled centrally and their tensile strength was determined.

The tested joints of the composite with AW 2024T3 duralumin sheets, with a thickness of 2 mm, were made using standard rivets with a diameter of 4 mm with a lenticular head (3560A-4), Hock blind rivets with a diameter of 4.8 mm, blind titanium threaded rivets with a round head (MBF2110AB) -05-15), and rivets with a diameter of 3.5 mm with countersunk heads. Metal elements of the samples with the dimensions of 25 x 110 x 2 mm were cut with the laser method. One-lap and two-lap connections were tested.

Three 25-mm wide double-lap samples with different directivity of the composite were made (consisting of two 25 x 110 x 2-mm duralumin plates and one composite 25 x 140 x 2-mm placed between them) connected with two 4-mm standard rivets. The strength of the joints was determined by stretching the samples at a speed of 2 mm / min in the HT-2402 testing machine. In all the two-lap and one-lap riveted samples, the rivet spacing was used: 2*d* from the edge of the sheets and 3*d* between the rivets, where *d* - rivet diameter.

Three 25-mm wide double-lap samples with different directionality of the composite were made (consisted of two duralumin plates and one composite plate placed between them), connected with two standard rivets with a diameter of 4 mm. The strength of the joints was determined by stretching the samples at a speed of 2 mm / min in the HT-2402 testing machine.

Fig. 3. Double-lap samples

In single-lap samples with dimensions of joined elements, identical to those used in double-lap samples joined with plain rivets, metal washers were used to separate the composite from the upset formed rivet head.

When riveting with blind rivets, washers were not used. The strength of three-lap samples joined with different rivets was tested.

Fig. 4. View from two sides of a single-lap sample joined with solid rivets with the use of a spacer

3. RESEARCH RESULTS

Composite. The results of the composite Young's modulus tests are presented in Figs. 5 and 6.

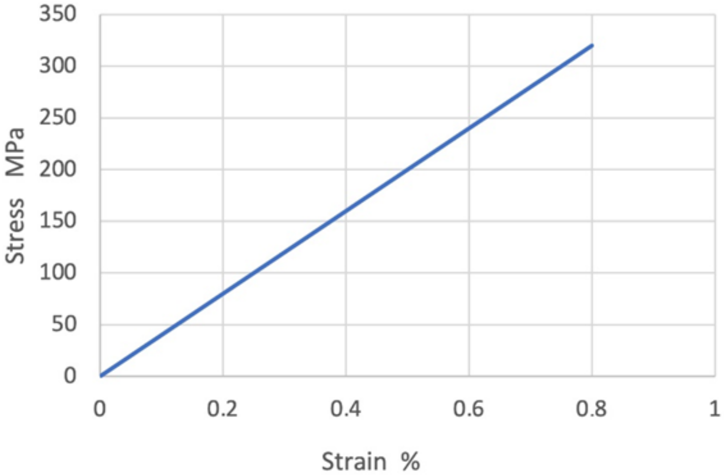

Fig. 5. The dependence of stresses on strain of a composite sample with multilayer reinforcement oriented parallel

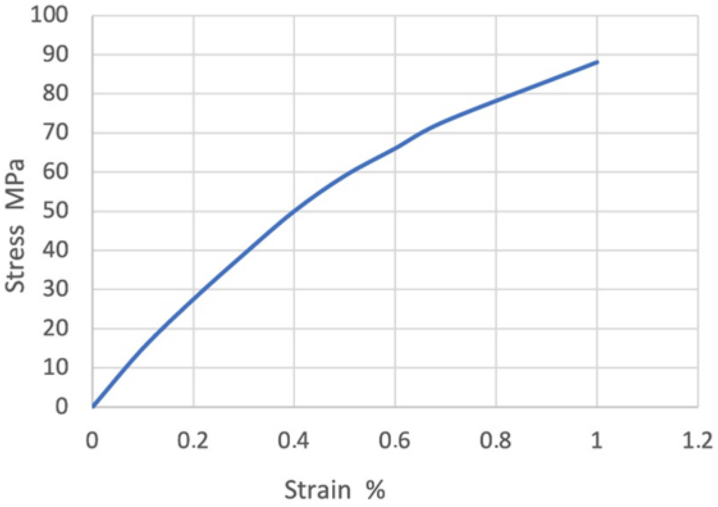

Fig. 6. The dependence of stresses on strain of a composite sample with multilayer reinforcement oriented at an angle of 45°

The Young's modulus of the tested composite in the direction parallel to the arrangement of the fibers of the plain fabrics was 40 GPa, the tested material showed linear properties and the tensile strength of 345 MPa. The composite sample, cut at an angle of 45°, was characterized by non-linear properties - along with deformation, the value of the elastic modulus decreased from the initial 13.57 GPa. The tensile strength of this composite was 160 MPa.

For the samples with 4-mm diameter holes, the average breaking stresses were 275 MPa for the sample with parallel orientation and 148.5 MPa for the sample cut at an angle of 45^o, respectively. It follows that the strength loss due, to the stress concentration, at the opening was 25% for the sample with a parallel orientation and 8% for the sample cut at an angle of 45°.

Double-lap samples. The results of the load capacity tests are given in Table 1. High repeatability of test results (range related to the average value from 5% to 11%) and a different mechanism of composite destruction were found - the cross-section with the hole crack perpendicular to the direction of the load (composite with parallel orientation) and shear at 45^o (composite cut at 45^o) - Figs. 7 and 8. The calculated stress values in the composite for medium destructive forces and calculated pressures show that in the case of composites with a parallel orientation the failure results from exceeding the permissible pressures of 526 MPa [the stress in the composite (200.5 MPa) was lower than the strength of the composite with the hole (275 MPa)]. In the case of the composite cut at an angle of 45^o, the damage was caused by exceeding the strength of the composite without the hole.

Table 1. The results of load capacity tests of double-lap samples joined with 4-mm standard rivets

	Sample No.	**Force or stresses**
Composite with parallel orientation	1	8127 N
	2	8580 N
	3	8560 N
	Average force	8422.3 N
	Stresses in the composite	200.5 MPa
	Pressure on the wall of the hole	526 MPa
Composite cut at an angle of 45^o	1	6723 N
	2	7490 N
	3	6827 N
	Average force	7013 N
	Stresses in the composite	167 MPa
	Pressure on the wall of the hole	438 MPa

Fig. 7. Damage to the composite with a parallel orientation

Fig. 8. Damage to the composite cut at an angle of 45^o

Single-lap samples. The results of the strength tests of single-lap samples are presented in Table 2.

Table 2. Load capacity test results for a single-lap

Composite orientation	Type of sample	Average destructive force (N) (range)	Destruction method
Composite with parallel orientation	Connected with 2 Huck rivets Φ =4.8 mm	8193 (8292-8034)	Composite destruction
Composite cut at an angle of 45^{o}		6845 (6981-6646)	Composite destruction
Composite with parallel orientation	Connected with 2 rivets blind titanium Φ = 4.1 mm (head on the composite side)	8650 (8770-8410)	Composite destruction
Composite cut at an angle of 45^{o}		5973 (6183-5762)	Composite destruction
Composite with parallel orientation	Connected with 2 rivets blind titanium Φ = 4.1 mm (formed rivet head on composite side)	7576 (7681-7423)	Composite destruction
Composite cut at an angle of 45^{o}		5793 (5853-5615)	Composite destruction
Composite with parallel orientation	Connected with 2 solid rivets with Φ = 4 mm (washer under formed rivet head)	5900 (5920-5880)	Cutting rivets (233 MPa)
Composite cut at an angle of 45^{o}		5800 (5920-5850)	Cutting rivets (229 MPa)
Composite with parallel orientation	Connected with 4 rivets with countersunk heads Φ = 3.5 mm (washer under formed rivet head)	10198 (10485-9854)	Cutting rivets (265 MPa)
Composite cut at an angle of 45^{o}		5630 (5690-5560)	Composite destruction

Solid rivets with a 3560A-4 lenticular head have a shear strength of 233 MPa and the rivets of Φ = 3.5 mm with a countersunk head have a shear strength of 265 MPa. Blind titanium rivets are characterized by higher shear strength than duralumin rivets. In most of the tested cases, when the composite with a parallel orientation was damaged, the average destructive stresses in the composite were lower than the stresses destroying the composite with the hole (275 MPa). It means that the impact of the connectors on the composite in form of pressures was significant. In the case of a connection with four rivets Φ = 3.5 mm, the failure occurred at the higher stress value than the strength of the composite with the hole. The reason for this may be high friction forces between the joined elements resulting from the use of 4 upset rivets.

Table 3. Stresses in the composite and stresses in the fasteners at the moment of failure of the joints

Composite orientation	Type of sample	Stress in composite (MPa)	Pressure on the wall of the hole (MPa)	Shear stress in fasteners (MPa)
Composite with parallel orientation	2 Huck rivets Φ = 4.8 mm	223	426.7	226.5
Composite cut at an angle of 45°		169	356.5	189.2
Composite with parallel orientation	2 rivets blind titanium Φ = 4.1 mm (head on the composite side)	207	527	327.8
Composite cut at an angle of 45°		143	364	226.3
Composite with parallel orientation	2 rivets blind titanium Φ = 4.1 mm (formed rivet head on composite side)	181	462	287.1
Composite cut at an angle of 45°		139	353	219.5
Composite with parallel orientation	2 solid with Φ = 4 mm (washer under formed rivet head)	140	369	233
Composite cut at an angle of 45°		138	363	229
Composite with parallel orientation	4 rivets with countersunk heads Φ = 3.5 mm (washer under formed rivet head)	283	364	265
Composite cut at an angle of 45°		156	171	146.3

4. NUMERICAL CALCULATIONS

The calculations were carried out in the ANSYS 16.2 system. The purpose of the calculations was to check the effect of the hole, made for a mechanical fastener with a diameter of 4 mm, on the stress concentration caused by a notch in the form of such a hole. The composite was given orthotropic properties listed in Table 3 on the basis of own research and publications [7]. The model of composite samples with parallel orientation and cut at an angle of 45°, 25-mm wide and 2-mm thick, was loaded with a force of 5,000 N. The results are shown in Figs. 10 and 11 with the calculated notch shape factor α:

$$\alpha = \frac{\sigma_{mak}}{\sigma_n} \tag{1}$$

where:
σ_{mak} - maximum stress at the hole,
σ_n - nominal stress (average in the cross section with the hole)

Table 4. Declared material constants of the composite

E_x [MPa]	E_y [MPa]	E_z [MPa]	ν_{xy}	ν_{xz}	ν_{yz}	G_{xy} [MPa]	G_{xz} [MPa]	G_{xz} [MPa]
40,000	40,000	3,000	0.2	0.53	0.53	4,000	6,000	6,000

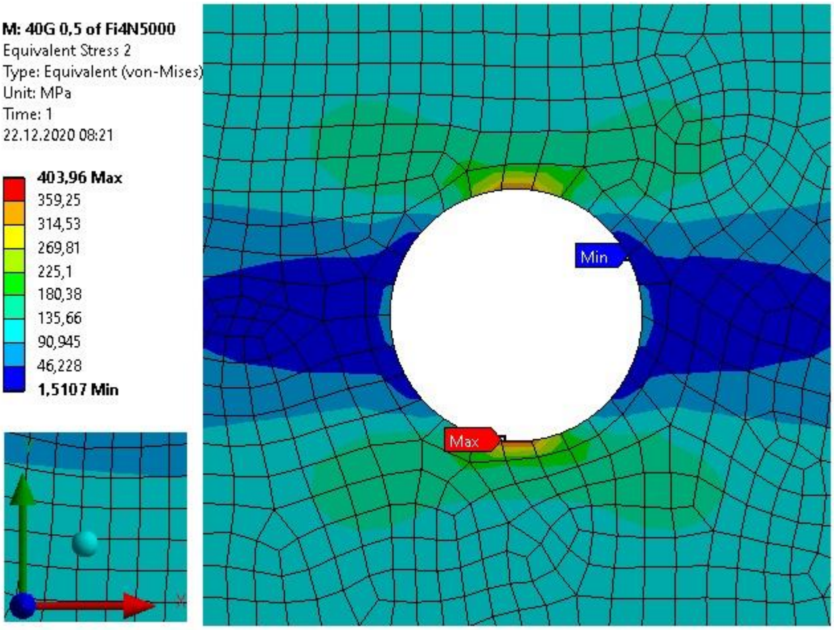

Fig. 10. Distribution of reduced stresses around a hole, with a diameter of 4 mm, made in a composite of parallel orientation (nominal stress 119 MPa), the shape factor $\alpha = 3.4$

The calculations show that a composite with a parallel orientation with a hole subjected to stretching has a greater concentration of stresses than in a composite cut at an angle of 45°. In the experimental tests of the strength of a sample with a parallel orientation, 25-mm wide with a hole of 4 mm, the force values were 9,750 N (nominal stress 235 MPa).

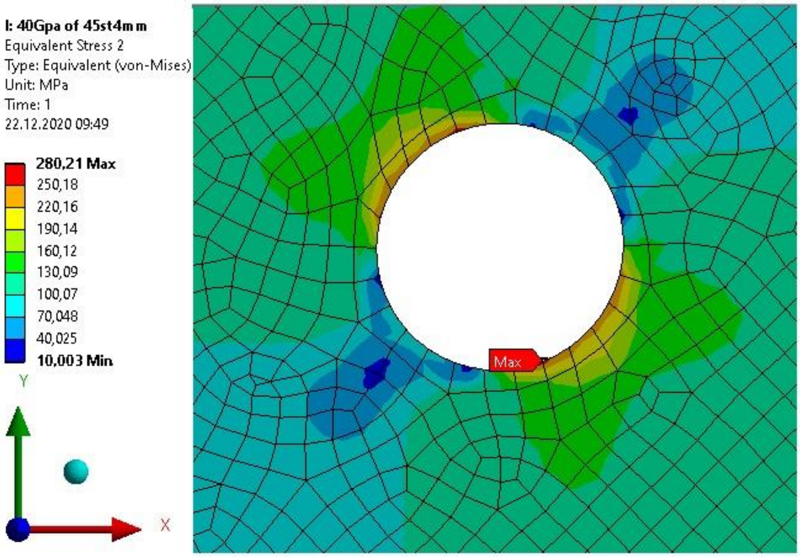

Fig. 11. Distribution of reduced stresses around a 4-mm diameter hole made in a composite, cut at an angle of 45^{o} (nominal stress 119 MPa), the shape factor $\alpha = 2.35$

If we divide the value of stresses destroying the composite without a hole by the value of the nominal stresses destroying the sample with the hole, we will calculate the value of the notch operation factor:

$$\beta_k = \frac{345}{235} = 1.47 \tag{2}$$

From dependence:

$$\beta_k = 1 + (\alpha_k - 1)\mu \tag{3}$$

we can calculate the composite sensitivity factor to notch action:

$$\mu = \frac{\beta_k - 1}{(\alpha_k - 1)} \tag{4}$$

$$\mu = \frac{1.468 - 1}{3.4 - 1} = 0.195$$

For a specimen, cut at an angle of 45^{o}, with a hole, the obtained force was 5,800 N (nominal stresses 138.1 MPa). In this case, the notch operation coefficient is:

$$\beta_k = \frac{235}{138.1} = 1.16$$

and the material sensitivity factor to notch action:

$$\mu = \frac{1.16 - 1}{2.35 - 1} = 0.12$$

Similar composite samples were loaded with a force of 2,500 N applied to the rivet placed in the hole (Fig. 12).

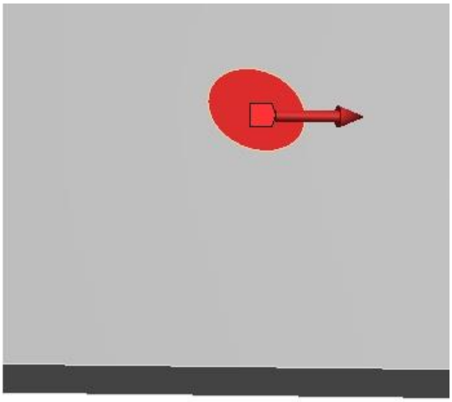

Fig. 12. The method of loading the composite with a rivet

The calculation results are presented in Figs. 13 and 14.

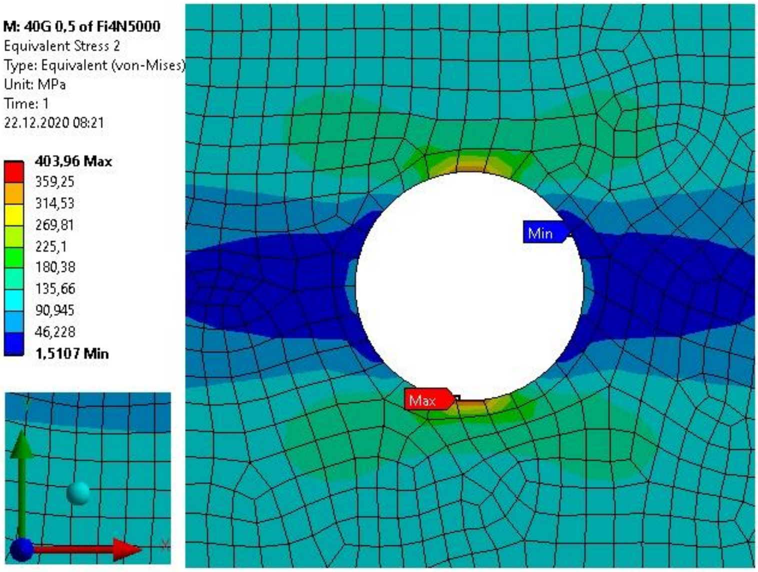

Fig. 13. Distribution of reduced stresses around a 4-mm diameter hole made in a composite with a parallel orientation loaded with a force of 2,500 N applied to the rivet

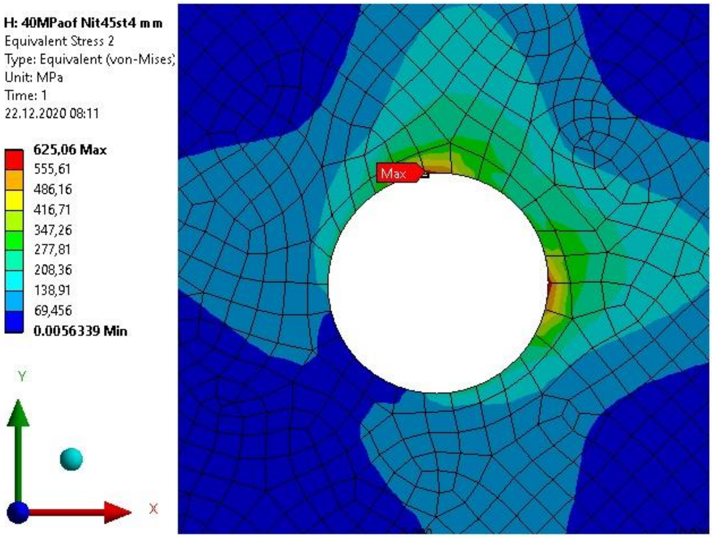

Fig. 14. Distribution of reduced stresses around a 4-mm diameter hole, made in a composite cut at an angle of 45°, loaded with a force of 2,500 N applied to the rivet

Loading composite by rivet causes local stress concentration. Greater stress concentration occurs in the composite cut at an angle of 45°. The high value of stresses, at the assumed load, proves that in riveted joints the load is transferred to a large extent by frictional forces what limits surface pressure of the rivet shank on the wall of the hole.

5. CONCLUSIONS

Orthotropic composites are characterized by different mechanical properties depending on the direction of the reinforcement arrangement. The strength of composites, as well as mechanical connections of composite parts, is also related to the direction of the reinforcement arrangement.

In general, it can be stated that the strength of the joints in the direction of fiber alignment is greater than in the direction of an angle of 45°. The nature of the composite destruction is also different - the load in the direction of fiber arrangement causes the material to break in the plane perpendicular to the load, and the load in the direction of 45° in relation to the arrangement of the fibers causes the material to be cut at the same angle.

The research shows that the tested blind rivets are able to withstand a higher shear load compared to standard 3560A-4 rivets made of D18P (PA24) aluminum alloy which results in greater strength of the connections made with these rivets.

The extremely low peel strength of the Huck rivet heads [8] virtually eliminates their use in the repair of responsible elements. On the other hand, threaded blind titanium rivets meet the requirements to be substitutes for solid rivets.

The use of blind threaded titanium rivets in the repair of composite coverings of the MiG-29 aircraft should significantly simplify the repair by eliminating the necessity to disassemble the cover being repaired.

Due to the possibility of repairing composite structures, it seems that the composites used for airframe coverings should be laminates with quasi-isotropic properties.

Based on the results of numerical calculations, it can be concluded that the sensitivity of the tested composite to the effect of the notch, in the form of a hole, is not high and it depends on the direction of the reinforcement arrangement.

In riveted joints, an important role in the transfer of loads is played by frictional forces between the joined elements. The value of these forces depends on the pressure of the head and the tab. Titanium blind threaded rivets provide higher pressure than cold-headed ones. [9]

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Możliwości łączenie struktur kompozytowych z metalowymi metodą nitowania

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Streszczenie. W artykulle przeprowadzono analizę możliwości zastąpienia nitów zwykłych wykonanych ze stopów aluminium nitami jednostronnymi wykonanymi z tytanu w naprawach kompozytowego pokrycia samolotu MiG-29. Kompozyty ortotropowe charakteryzują się różnymi właściwościami mechanicznymi w zależności od kierunku ułożenia zbrojenia. Wytrzymałość kompozytów oraz połączenia mechaniczne części kompozytowych są również związane z kierunkiem ułożenia zbrojenia. Z przeprowadzonych badań wynika, że testowane nity jednostronne są w stanie przenieść większe obciążenia ścinające w porównaniu do standardowych nitów 3560A-4 wykonanych ze stopu aluminium D18P (PA24), co skutkuje większą wytrzymałością połączeń wykonanych tymi nitami. Zastosowanie nitów jednostronnych powinno uprościć naprawę pokryć kompozytowych poprzez wyeliminowanie pracochłonnego demontażu naprawianego pokrycia. Na podstawie wyników obliczeń numerycznych można stwierdzić, że wrażliwość badanego kompozytu na działanie karbu w postaci otworu nie jest duża i zależy również od kierunku ułożenia zbrojenia.

Słowa kluczowe: łączniki mechaniczne, kompozyty, nity zwykłe, nity jednostronne nawlekane