Calculating the stress-strain state of connecting nodes in pre-fabricated structures from composite materials

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Annotation. The paper numerically studies adhesive-mechanical composite joints with metal and composite connecting elements (rivets and fasteners). The results of comparative experimental tests of metal and composite connectors are presented. The stress-strain state in various layers of composite plates reinforcing composite fibers and in an epoxy matrix is investigated.

1. Introduction

Composite materials (KM) are increasingly used in various fields of technology. One of the most common are polymer composite materials (PCMs), which are actively introduced into highly loaded structural parts [1, 2]. As a rule, highly loaded structural elements from PCMs form metal-composite contact pairs at attachment points, which require the solution of design, strength and technological problems. The calculation of the stress-strain state (SSS) in the metal-composite joint zone causes significant difficulties associated with the lack of a developed theory, the presence of a volumetric stress state in the contact zone and the need to experimentally determine a significant number of PCM characteristics [3, 4].

Currently, mechanical fasteners, metal bolts, rivets and small fasteners are actively used [5, 6].

Making and machining of holes for metal bolts and rivets causes the PCM fibers to be cut and requires precise and expensive tools; the technological process for installing such fasteners is associated with the occurrence of significant stresses due to tightening and increased stress concentration in the region of the hole.

One of the drawbacks of metal fasteners is that when two or several parts made of PCMs are connected at the moment of formation of the closing head, micro-cracking (destruction of the binder) of the connected parts occurs due to a shock or other mechanical stresses that occur during their formulation, due to the small relative elongation of a number of composites (for carbon plastics it is 0.5–0.15%). It should also be borne in mind that when exposed to moisture, such compounds are subject to corrosion, and this decreases the strength properties of the compound.

Analyzing the area of lap-connected plates using mechanical fasteners, it can be noted that when transferring forces from one element to another through riveting or a bolt, a complex VAT is formed in the composite around the bolt [5, 7, 8].

The part of the material located between adjacent holes is stretched; the zone located behind the fastener body is loaded with contact pressure, which causes compression and shear stresses in the PCM.

The destruction of the mechanical connection of composite elements can occur in a weakened section, as a result of shear, crushing of the composite, separation of heads and a cut of fasteners. A combination of these forms of destruction is also possible. Therefore, the strength of mechanical joints is affected by such physicomechanical characteristics of the composite material as the tensile, shear and collapse strengths determined experimentally.

Unlike metal rivets, a more complex SSS arises in a composite fastener, which is determined by the
The behavior of the PCM fastening mechanical element under the action of external loads is determined by the properties of the reinforcing fibers and the matrix, as well as the structure of the fiber-matrix boundary layer.

In composites, high-strength fibers are known to absorb the main stresses arising in the composition under the action of external loads and provide rigidity and strength in the direction of fiber orientation. The mechanical properties of the matrix should ensure the effective joint work of reinforcing fibers under various types of loads. Strength characteristics of the matrix material are determinative for shear loads, structural loading in directions different from fiber orientation, and also for cyclic loading [2, 4, 9, 10].

As a result of the analysis of the available fasteners, a composite rivet was developed [11] (Fig. 1).

**Figure 1** – PCM-based fastener: a) composite rivet; b) photo of the rivet; c) positioning; d) fixation; e) polymerization; f) finished product

The setting head (1) and the shank (2) are made of polymerized fiber composite. The length of the shank (2) is equal to the thickness of the connected package of PCMs. The length of unpolymerized fibers (3) is determined from the conditions for the formation of the height and diameter of the setting head, the ends of the fibers are polymerized into the secondary head (4) with a diameter equal to the diameter of the rod.

In the center of the shank (2) along its axis, there is a hole in which the polymer mandrel (5) freely moves, one end of which is polymerized in the center of the secondary head (4). Before the rivet is inserted into the mounting hole, unpolymerized fibers (3) are impregnated with an epoxy composition. After the rivet mandrel is inserted into the mounting hole, the mandrel (5) is pulled towards the shank, and a locking head is formed due to the bending of unpolymerized fibers (3) in the radial direction. The rod is fixed in an extended position due to a groove on its body (6) and a split washer (7). After polymerization of the locking head, the mandrel is broken off along the groove.

In [12], with the participation of one of the authors, comparative experimental studies were carried out to determine the strength properties of metal and composite rivets. Two pre-glued carbon fiber plates KMU-4l were connected with rivets, with simultaneous making of an adhesive-mechanical joint. For testing, 5 samples of joints with standard rivets were prepared: with a plunger (aluminum body and steel core); rivnuts (high-strength aluminum alloy V-65); small fasteners of two types (d = 1 mm, aluminum alloy AMg-5 and steel 1Cr18Ni9Ti), as well as with the developed composite rivets. The riveting by metal rivets was carried out at the Irkutsk Aviation Plant. Experimental studies were carried out in the Central Plant Laboratory of the plant using the R-5 rupture machine.

The following mechanical characteristics of the materials were accepted:

- for the **KMU-4l monolayer**: $E_1 = 135000$ MPa; $E_2 = 5000$ MPa; $G_{12} = 4500$ MPa; $\sigma_{t1} = 850$ MPa; $\sigma_{t2} = 95$ MPa; $\tau_{12} = 600$ MPa; $\mu_{12} = 0.2$; $\mu_{21} = 0.0155$;
• for the **KMU-4l package** with a thickness of 3 mm and with layer laying $[0; \pm 45; 90]_3$: $E_1 = 34856 \text{ MPa}$;
  $E_2 = 30219 \text{ MPa}; E_3 = 43846 \text{ MPa}; \mu_{12} = 0.273; \mu_{13} = 0.237; G_{12} = 11921 \text{ MPa}; G_{13} = 4500 \text{ MPa};$
  $\sigma_v = 400 \text{ MPa}; \tau_{12} = 80 \text{ MPa}; \mu_{31} = 0.343; \mu_{12} = 0.343;$
• for rivets with a plunger: aluminum body, $E = 70000 \text{ MPa};$
  $\sigma_v = 400 \text{ MPa}; \mu = 0.32; \text{ steel core, } E = 200000 \text{ MPa}; \sigma_v = 500 \text{ MPa}; \mu = 0.26;$
• for **rivnuts** (aluminum alloy B-65): $E = 72000 \text{ MPa}; \sigma_v = 400 \text{ MPa}; \sigma_t = 280 \text{ MPa};$
  $\mu = 0.32;$
• for small-diameter fasteners (steel 1Cr18Ni9Ti): $E = 212000 \text{ MPa}; \sigma_v = 655 \text{ MPa}; \sigma_t = 355 \text{ MPa}; \mu = 0.26;$
• for **composite rivets**: $E = 34856 \text{ MPa}; \sigma_v = 400 \text{ MPa}; \mu = 0.373.$

Composite rivets were tested with three patterns of reinforcing fiber winding along the mandrel.

**Type A (longitudinal arrangement).** The fibers are located along the rivet mandrel; shear and shearing forces are suffered by the matrix and, to a lesser extent, by fibers; the force of head separation is made by fibers in interaction with the matrix (Fig. 2a).

**Type B (transverse arrangement).** The fibers on the shank are arranged transversely, and in the central part along the rivet mandrel. The shearing and crushing forces are experienced mainly by the matrix and part of the fibers on the outer side of the mandrel, the forces of rivet head tear off are experienced by longitudinal fibers in the central part of the rod (Fig. 2b).

**Type C (cross arrangement at an angle).** The outer layers of fibers are located at an angle $\phi$ along the rivet mandrel. Angle $\phi$ equals 45 degrees or so. The shearing and crushing forces are perceived by the matrix and, for the most part, of fibers located at an angle $\phi$ to the axis of the rod, the riveting heads are torn off by longitudinal fibers located in the central part (Fig. 2c).

In winding types B and C in the central part of the mandrel, there is a small part of the fibers (about 15...20%) arranged along the longitudinal axis.

![Figure 2](image-url) **Figure 2** Layout of the fibers in the rivet

The material used for rivets was “Grapan-27”, which has the following characteristics (TU 1916–204–51385208–2001):
• density - 1.75;
• linear density - 724 tex,
• ultimate compressive strength $\sigma_c = 1100 \text{ MPa};$
• ultimate tensile strength $\sigma_t = 1300 \text{ MPa};$
• modulus of elasticity on bending $E_b = 183 \text{ GPa}.$

As a binder, high-strength epoxy adhesive, $\sigma_v = 400 \text{ MPa},$ was used.

In technology, about 90% of all fasteners work in shear, while one of the main types of rivet fracture is a cut along the plane of connection of the plates [1, 2]. Based on this, samples with rivets were subjected to tensile strength tests on a bar shear using KMU-4l material as the basis for the joint (Fig. 3).
Figure 3  Samples of the studied joints: a) with a rivnut; b) with a rivet with a plunger; c) with PCM rivet; d) with small-diameter fasteners

The test results for some fasteners are summarized in Table 1. Figure 4 shows the results for rivets made from PCM. The average values for five trials are presented.

Table 1  Test results for all types of rivets

| Sample type                                              | $F_t$ [N] | $\tau_{av}$ [MPa] |
|----------------------------------------------------------|-----------|--------------------|
| PCM rivet, longitudinal reinforcing of fibers in mandrel (type A) | 16110     | 410.4              |
| PCM rivet, lateral reinforcing of fibers in mandrel (type B) | 18500     | 471                |
| PCM rivet, cross reinforcing of fibers in mandrel (type C)  | 19060     | 485.4              |
| Rivet with plunger                                       | 4000      | 203.8              |
| Rivnut                                                   | 4660      | 237.5              |
| Small-diameter fasteners                                 | 19450     | 497                |

Figure 4  Test results for PCM rivets of A, B and C types

According to the experimental results, the best result was shown by the winding pattern of reinforcing fibers of type C with a cross arrangement. In addition, there was a high strength of the adhesive-mechanical connection with small diameter fasteners made of 1Cr18Ni9Ti steel. Connections with metal rivets turned out to be the least durable due to the fact that riveting creates a high level of interference. In contrast to the tightening along the axis of the rivet, the interference in the transverse direction relative to the axis of the rivet in a composite package can lead to cracking of the walls of the holes for the rivets and reduce the strength of the connection.

Next, numerical modeling was carried out using the FEM of loading composite rivets of types A, B
and C in order to confirm the experimental results for these patterns of winding reinforcing fibers.

At the first stage, the elastic characteristics of the composite were determined by the technique presented in [13, 14]. For this, a typical scheme of a representative element of a composite material with the dimensions is selected shown in Fig. 5a. Then a quarter of the representative element is modeled (due to the symmetry of the problem) by the finite-element method (FEM) (Fig. 5b). With a representative element, numerical experiments were carried out, consisting in a sequential predetermined movement of the faces of the representative element along the coordinate axes while fixing the remaining faces. As a result of the FEM solution, average stresses on the faces of the element were obtained, and using the generalized Hooke's law in elastic form, the elastic characteristics of the composite were determined.

**Figure 5** a) finite element model of the representative element of the composite; b) modeling the connection of composite plates and composite fasteners

**Figure 6** Models of composite fasteners of types A, B and C (matrices not shown)

**Figure 7** FEM model of fibers and matrix of composite fasteners of type C (a, b) and fiber model for composite fasteners of type B (c)
This technique has been widely used recently, because it gives more accurate results in determining the elastic characteristics of the composite than the calculation according to the mix rule or other analytical formulas.

At the second stage, finite element modeling of composite rivets (Figs. 6 and 7) and general loading of the adhesive bond with such rivets (Fig. 5c) was carried out.

The calculation results—the acting stresses in MPa and strains—are presented in Tables 2 and 3.

Table 2 shows the von Mises contact stresses between the layers of reinforcing fibers and the composite connection plates for type B composite fastener. Table 2 in each column shows the interaction of the corresponding layer (1st, 3rd, and 4th) from top to bottom reinforcing fiber with composite plate material. The first row of the table shows the deformed state of the corresponding fiber layer; in the second line, the deformation of this layer in the plane of contact of composite plates; in the third row, contact stresses in composite plates. The right column of the table shows the magnitude of the acting contact stresses according to von Mises in MPa.

**Table 2** Contact von Mises stresses in the layers of composite plates for composite rivet type C (MPa)

| 1st composite layer (+45°) | 3rd composite layer (90°) | 4th composite layer (0°) | MPa |
|----------------------------|---------------------------|--------------------------|-----|
| Section view of layers     |                           |                          |     |
| Stresses in fibers of layers|                           |                          |     |
| Stresses in composite plates|                           |                          |     |

Table 3 illustrates the stresses in the layers of reinforcing fibers for a composite type C fastener (cross reinforcement). Von Mises stresses in 1...4 fiber layers are shown from top to bottom in each column. For the 1st and 2nd fiber layers, the first row of the table shows the stresses in opposite diametrical sides. The second row of the table shows the stresses at the section of the corresponding layers of fibers, while the epoxy matrix is not shown. The right column of the table shows the magnitude of the acting von Mises stresses in MPa.

Layers of fibers are numbered from 1st inner to 4th outer.
At the next stage, we compared the maximum von Mises stresses that occur in the outer layers of composite fastener fibers of types A, B, and C with the same external load on the simulated adhesive-mechanical joint. In addition, sections with maximum shear stresses (at the junction of composite plates) were selected in composite rivets. Stresses were averaged over finite elements located in this section along the outer rows of fibers (Fig. 8).

Figure 8 Von Mises stresses on the external fibers of composite fasteners: a) type A, b) type B, c) type C.

The average values of maximum von Mises stresses were as follows:

- type A – 4017 MPa,
- type B – 2820 MPa,
- type C – 1132 MPa.

The stress distribution by types of composite fasteners is shown in Fig. 9.
Figure 9 Von Mises stress dependence in composite rivet fibers

Evidently, type C composite rivets (with cross-fiber reinforcement) provide the lowest level of stress, and, therefore, are the most durable of the considered types of rivets.

Conclusions
1. The strength of composite fasteners is largely due to the angle of winding of fibers along the rivet core. The destruction of the connection with the type C fastener (cross-reinforcement of fibers in the rivet mandrel) occurs at a force level of 15...25% more than for metal rivets and with type A fasteners (longitudinal reinforcement of fibers in the rivet mandrel).

2. The margin of static strength for adhesive-mechanical joints with metal rivets is lower than for adhesive-mechanical joints with PCM fasteners with cross-fiber reinforcement, the effectiveness of which reaches 100...120% of the initial strength. Samples with metal rivets withstand a load of 70...90% of the initial strength.

3. The comparative tests of composite rivets of three types showed that rivets of type C, with cross-reinforcement of fibers, have the highest strength characteristics. Taking into account numerous studies [15], confirming the higher resistance of composites to the effects of adverse environmental factors compared with various types of metal rivets, type C composite rivets can be recommended for use as fasteners of structures.

4. Comparison of theoretical and experimental values of the research results shows that for 90% of the experiments, the error did not exceed 15...20%. This allows speaking about the adequateness of the FEM model used to determine the strength properties of the developed types of composite fasteners, as well as to calculate the SSS in the region of the rivet hole in composite plates.

References
[1] Vorobei V V, Sirotkin O S 1985 Connection of structures from composite materials (Leningrad: Mashinostroenie) p. 168
[2] Karpov Ya S 2006 Joints of composite parts and assemblies (Kharkov: Kharkiv Aviation Institute) p. 359
[3] Tsarakhov Yu S 1980 Design of joints of composite aircraft elements: Teaching guide (Moscow: MIPT) p. 82
[4] Karpov Ya S 2001 Principles of designing joints of highly loaded parts of aircraft from composite materials Questions of design and production of aircraft: Coll. Sci. Papers 122
[5] Vashukov Yu A, Peresypkin V P, Peresypkin K V, Nikonorov N N 2005 Finite element stress
state modeling when reinforcing holes in structural elements from polymer composite materials.  

[6] Pykhalov A A, Pashkov V P 2010 Application of the finite element method and the contact problem of a solid deformable body in modeling of fractured bone fixation. Modern technologies. System analysis. Modeling 3 (27) 27-33

[7] Pykhalov A A, Pashkov V P, Zotov I N 2014 Modeling of mechanical systems with vague material properties using the finite element method and computed tomography. Modern technologies. System analysis. Modeling 2 (42) 44-50

[8] Korzhenevsky A V, Veselsky S I, Makarenko V A 1985 et al. Studying crushing strength of composite materials. Problems of design and production of aircraft structures: Coll. Sci. Papers. – Kharkov: Kharkiv. Aviation Institute 112-116.

[9] Karpov Ya S, Makarenko V A, Marchenko V G 1989 Studying the anisotropy of the crushing strength of composite materials under fasteners. Calculation and design of structures of aircraft: Coll. Sci. Papers 82-91.

[10] Pykhalov A A, Fedotov P K 2013 Numerical modeling of boundary conditions and load in the analysis of the stress strain state of a rock during its crushing between rolls in a roller press. Modern technologies. System analysis. Modeling 1 (37) 27-32

[11] Aleskovsky S L, Vlasov S V, Kuznetsov S N, Natubidze S A, Shevchik A P RF Patent No. 2219390 (20 December 2003)

[12] Tanis C, Poullos M 1980 Composite Fasteners – A Compatible Joining Technique for Fibrous Composites in Structural Design. Fibrous Composites in Structural Design 645–657.

[13] Kuznetsov S N 2004 Technique for repair of airframe design units for military aircraft with composite fasteners, taking into account the influence of operating conditions. Dissertation of Cand. Sci. (Engineering) Irkutsk Higher Military Aviation School 189

[14] Andrianov I V, Danisheshvky V V, Guillet A, Pareige P 2005 Effective properties and micromechanical response of filamentary composite wires under longitudinal shear // European Journal of Mechanics 24 2 196–206.

[15] S. Dariya Zade. 2013 Numerical technique for determining the effective characteristics of unidirectional composites. Bulletin of NTU “KhPI”. – Series: Dynamics and Strength of Machines, 58 (1031) 71-77.