Modeling and Optimization of a Mechanical Point Connection with the Reinforcement of Structures Containing Polymer Composite Materials

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Abstract. The methodology of determination of geometric parameters of the reinforcing element in case of highly resourceful mechanical point joint formation in the products of anisotropic polymer composite material (PCM) is presented. Physical-mechanical properties and the safety factor of the composite material are also taken into account as well as the material of the reinforcing element. The developed methodology applying finite-element modelling allows to analyze the strained state of the reinforced element and to determine optimal parameters of its mounting.

1. Introduction
Most joints of large-size parts and units of polymer composite material (PCM) are made by a large amount of mechanical fastening elements such as bolts and rivets [1, 3, 4, 5, 6] requiring holes. At the same time, there are some major problems of maximum reduction of stress concentration along the hole contour, and the problem of defect formation in the join holes arising during part production, resulting in the reduction of their bearing capacity and durability of parts, units, and assemblies [2, 4, 7, 8, 13, 14, 16, 17, 18, 19, 20].

2. Formulation of the problem
One way to reduce stress concentration and to achieve their more even distribution is [5, 9, 10, 11, 12, 15] to install them with the primary expanding of the intermediate metal bushing between the composite material plate and the bolt transmit loads. The primary expanding of the reinforcing bushing is necessary to reduce operational tensile stress rate in the hole, and to develop compressive stress along the contour to keep the adhesive interlayer. The developed method [10, 11, 12] of bushing embedding (Figure 1) allows adjusting the field of radial compressive stresses along the hole contour with the reinforcement due to the size and the shape of the lugs. But it is necessary to know the geometric parameters of the reinforcing element. They depend on the physical-mechanical properties of the composite material, kind of the load, and the formed stress field.
Figure 1. The method of embedding of the reinforcing element: a, b) embedding process of the reinforcing element; c) fields of radial compressive stresses; d) reinforcing element; 1- reinforcing element; 2- sheet billet; 3- die; 4- matrix.

3. Theoretical and experimental research
The experimental research has been carried out in four stages. To get comparable results we used the same material of the plate for further calculations. The plate was made of fiberglass plastic, but the material of the bushing would vary. The plate thickness is 4.0 mm. The plate characteristics are given in Table 1.

Table 1. Mechanical properties of the fiberglass plastic plate.

| Parameter                     | Value | Unit of measurement |
|-------------------------------|-------|---------------------|
| Young modulus, axis X         | 121000| MPa                 |
| Young modulus, axis Y         | 8600  | MPa                 |
| Young modulus, axis Z         | 8600  | MPa                 |
| Poisson ratio, XY             | 0.27  | -                   |
| Poisson ratio, YZ             | 0.4   | -                   |
| Poisson ratio, XZ             | 0.27  | -                   |
| Shear modulus, XY             | 4700  | MPa                 |
| Shear modulus, YZ             | 3100  | MPa                 |
| Shear modulus, XZ             | 4700  | MPa                 |

At the first stage, applying the developed finite-element model [10] it was evaluated the stress field in the plate at the boundary of the hole with the reinforcing bushing and the inserted fastening element (bolt). Gluing in was used as a manufacturing process of reinforcing [9]. Figure 2 shows the stress fields of the plate with the hole reinforced by the bushing with the bolt under tension. Steel and aluminum and titanium alloys were used as bushing material.
Figure 2. Stressed state in the plate at the boundary of the reinforced hole under tension: a- steel bushing; b – titanium bushing; c – aluminum bushing.

Figure 3 shows diagrams of stress distribution on the tensioned plate made of PCM along the hole contour reinforced by the bushing (the bushing is made of various materials) and the fastening element inserted into it. It is clear from Figure 3 that the steel bushing provides the least stress concentration factor along the hole contour. However, the problem of stress concentration does not disappear.

At the second stage, it was evaluated the stress state of the reinforced holes under [10, 11] axial plastic compression and gluing in of reinforced bushing (Figure 1). Because of the specific properties of the composite material, radial expanding of the bushing is to be variable depending on the direction of the reinforcement of the composite material, direction of load action and the material of the reinforcing bushing.

The value of maximum radial expansion is to be determined individually applying strength criterion [11] for each part made of composite material, and in the general case is to be less 0.1 mm.

To determine the geometric parameters of the reinforcing bushing firstly it is necessary to determine the value and the compressive stress zone that is to be received in the embedding of the bushing.

Figure 3. The stresses at the boundary of the hole reinforced by the bushing made of various materials.

It is clear from Figure 3 that aluminum and titanium bushings give a qualitatively similar stress field. To even the field it is necessary to provide the compressive the stress field at the hole boundary within the
angle range from 0 to 60 degrees. Press-fitting of the steel bushing is not expedient, as it is required to provide stress field within the range from 70 to 90 degrees that is in the zone of minimum plate resistance. It may result in plate destruction. Besides, in this case, forces necessary for the plastic strain are much higher than for the aluminum and titanium alloys. In this case, the main advantage is a lightening of the products due to the substitution of steel bushings for aluminum and titanium ones.

Stresses arising under press-fitting of the bushing in the hole are not to destroy composite material. On the other hand, stresses arising under press-fitting of the bushing are to be sufficient to provide the plastic strain throughout the height of the bushing. This results in the necessity of complex solution of the task.

At the third stage, the shape and the size of lugs of the reinforcing elements were determined. Aluminum and titanium alloys were used as materials for bushings. They well suit for press-fitting because their yield strength is rather low in comparison with the steel. This provides the possibility of press-fitting without composite material destruction. Permissible operating stresses for most aluminum and titanium alloys are 250 – 300 MPa [9], and this meets permissible stresses for most products of composite material.

It should be taken into account that it is possible to provide compressive stresses only according to the certain law. Having analyzed the diagrams shown at Figure 3, it was determined that it was necessary to develop the preliminary field of compressive stresses within the angle range from 0 to 60 degrees. The level of these preliminary stresses can be determined based on the analysis of the same diagrams. During the experimental research, we used the reinforcing bushings with geometrical dimensions shown in Figure 4.

![Figure 4. Geometrical dimensions of the reinforcing bushings used in the experimental research.](image)

Analysis of the strained state of the press-fitted bushings shown in Figure 4, a, b has shown non-uniformity of the strain throughout the height of the plate (Figure 5a). It is inadmissible as it results in non-uniformity of the stress field throughout the height of the plate made of plastic composite material. Taking into account these disadvantages, we have tried the bushing type shown in Figure 4 c. Figure 5 shows the strains under the press-fitting of this bushing. Analysis of the strained state has shown that, on the whole, the situation is getting better, and yet the strain is not uniform.
Figure 5. The strained state under press-fitting [mm]:
   a) bushings shown in Figure 4 a, b;  b) bushing shown in Figure 4 c.

Research of the strained state of the embedded bushing with double-sided lugs (Figure 4d) has shown that in the zones of radial expansion the strains along the outer contour of the bushing are uniform throughout the height (Figure 6). This allows getting the uniform stress field throughout the height in the plate.

Figure 7 shows the diagrams of alterations of the equivalent stresses at the boundary of the hole under tension of the plate with the press-fitted bushing and the common one. It is clear from Figure 7 that under the tension of the plate with the press-fitted bushing stresses are being evened sufficiently and the stress concentration is reducing. It means that it is possible to apply aluminum bushings with preferred radial expansion.

Figure 6. The strained state of the reinforcing bushing with double-sided lugs [mm].
At the fourth stage, theoretical determination of the strained state of the reinforcing element along the outer contour was carried out and then it was compared with the strained state determined by the results of the experimental research received at the third stage. Besides, the mathematical model developed in [11] was used where the radial displacement along the outer contour of the reinforcing bushing was determined as

$$U_r = \frac{1}{2} aR \left( 1 - \frac{r^2}{R^2 \cos^2 \varphi} \right),$$

(1)

where $a$ - variable parameter determined according to the method from [11]; $r$ – radius of the current coordinate of the reinforcing bushing; $R$ – outer radius of the bushing.

From the equation (1) assigning maximum displacement value, it is possible to determine the value of the straining motion when embedding the bushing $\Delta h$. As a result of the comparison of the theoretical and experimental data, it has been revealed that the experimental data are higher than the calculations by 6 – 9%.

4. Research results and their practical significance
As a result of research, the methodology of determination of geometric parameters of the reinforcing element depending on the physical-mechanical properties of the composite material and its safety factor, and also on the material of the reinforcing element has been developed. Developed methodology applying finite-element modelling allows to analyze the strained state of the reinforced element and to get its uniform strain throughout the height of the plate. These researches were carried out according to the list of critical manufacturing technologies of the plants of United Aircraft Corporation developed by Decree № 340 of the Russian Government. It is connected with the research of the influence of design technology parameters of assembling on their strength and durability characteristics of the bolt and rivet joints “composite – metal”.

5. Conclusion
Experimental research of the formation process of the joint “reinforcing element – composite material” applying finite-element modelling has been carried out. The research has shown high the efficiency of the developed reinforcing process to increase the bearing capacity of mechanical point joints and to determine the strained state of the reinforcing element.
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