Influence of adhesive bond line thickness on joint strength of composite aircraft structures

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Abstract. Methods for assessing the effect of the thickness of the adhesive layer in the adhesive joint of thin-walled composite structural elements on the strength of the entire joint are considered; a critical analysis of existing theoretical methods for predicting the strength of adhesive joints is given. The contradiction between the theoretical estimates of the effect of the adhesive thickness on the strength and the results of experiments and practical experience in the use of adhesive joints of composite panels is established. It is revealed that the most effective methods for predicting the load-bearing capacity of adhesive joints are energy models of fracture mechanics based on the intensity of the release of fracture energy and the formation of a pre-fracture zone in the adhesive layer. Assuming the determining role of changes in the size and shape of the initial fracture zone depending on the thickness of the adhesive layer, the results of the prediction of the strength of the adhesive joint are compared with experimental data.

1. Introduction

The widespread application of polymer composite materials (PCM) in the aerospace industry has become possible due to their inherent complex of structural and special properties that cannot be realized in traditional metal materials. An important structural and technological advantage of PCM over metals and alloys is the possibility of replacing mechanical connections (rivet, bolt, screw, etc.) connections with the help of adhesives, mainly on a polymer basis, which are similar in chemical and technological parameters and structure to the binders of polymer composites. However, effective replacement of fasteners with adhesive joints [1-4] can be achieved only if the levels of strength, durability and operational survivability are not lower than similar properties of mechanical joints.

Ensuring the required level of mechanical properties, adhesive joints of PCM parts is possible on the basis of taking into account the features of the mechanical behavior of composite structures and factors that affect the reliability and functionality of the connection. Experience in the operation of adhesive structures shows that almost all failures of the elements are associated with damage or complete destruction of the adhesive layer, which is objectively the weakest link of the node due to the low strength of the adhesive itself and the weakened contact zone of the adhesive with the connected surfaces. At the same time, the thickness of the adhesive layer, through which the force flows from one
part to another are transmitted, is the most important structural parameter of the joint, which determines the strength and durability of the entire joint.

Therefore, the purpose of this paper is to research the effect of the thickness of the adhesive layer on the load-bearing capacity and resource of structural carbon fiber joints. Also, to identify opportunities to reduce the specific weight of mechanical fasteners for aircraft components by expanding the introduction of high-strength adhesive joints.

A significant influence of the thickness of the adhesive layer on the strength of the entire joint is primarily due to the unevenness of the stress-strain state both along the length of the bonding section and along the thickness of the adhesive layer, which leads to a concentration of stresses at the edges and boundary areas of the joint. These circumstances increase the importance of experimental and theoretical studies of the stress-strain state and strength of the adhesive intermediate layer, depending on its geometric parameters, mainly thickness.

2. The objects and methods of research
The calculated methods for estimating the effect of the adhesive layer thickness on the load-bearing capacity of the entire joint are based on two different approaches. The first method is based on classical methods for determining the limit state of the adhesive layer according to the destruction criteria. It includes the calculation of the stress-strain state of the joint by various analytical or numerical methods. For example, by simplified elastic shear analysis [5], using the two-dimensional theory of first-order shear deformation (FSDT) [6], using elastic base models [7], nonlinear modeling of elastic-plastic deformation [8], two-dimensional geometrically nonlinear finite element model [9-15], etc. All analytical models show the stress singularity at the extreme points of the adhesive layer, which can be eliminated by various simplifications. Most often, these simplifications are reduced to the hypothesis of the invariance of the stress state over the thickness of the adhesive and ignoring the effect of transverse shear in the joint elements.

Another method is based on the methods of fracture mechanics. The fracture mechanics approach assumes a violation of the integrity of the adhesive joint in the form of crack development and uses mainly the energy criteria of failure, such as the intensity of the fracture energy or the critical $J$-integral. The assessment of the effect of the adhesive layer thickness on the strength of the entire joint in this case relies on knowledge of the stress-strain state in the process region adjacent to the crack tip, and micromechanical models of elastic-plastic deformation, which allow determining local criteria for crack resistance in connection with irreversible pre-fracture processes at the crack top.

Noteworthy are the models based on the critical size of the damage zone and the deformation criterion of destruction [16], the introduction of the cohesion zone for equivalent modeling of adhesive layers of different thicknesses [14], the implantation of the Barenblatt cohesive zone model in the finite element method, and the consideration of the nonlinear behavior of the adhesive during the propagation of damaged zones in the adhesive layer [15-17]. The main difficulties in predicting the strength of adhesive joints in this case are the complexity of the experimental determination of the characteristics of the crack resistance of the adhesive - the intensity of the fracture energy, the critical stress intensity coefficient, and the micromechanical parameters of the models – the size of the pre-fracture zone, crack opening, the length of the cohesive zone, and others.

From the experience of using adhesive joints in both metal and composite structural units, it is known that the greatest strength under short-term loading corresponds to thin adhesive layers with a thickness of $= 0.05...0.3$ mm for most joint configurations. Usually, the optimal thickness of the adhesive joint is about 0.2 mm, depending on the type of adhesive, the geometry and stiffness of the elements to be joined, and the type of load. Most researchers have experimentally established a tendency to increase the strength (figure 1) at low adhesive thicknesses to reach a maximum at the optimal bonding thickness, followed by a significant decrease in strength for thick ($> 0.3...0.4$ mm) adhesive joints.
Figure 1. The transformation in the shear strength of the VK-27 glue ($\tau_u$) from the thickness of the adhesive layer ($h$) [18], (triangle points are authors experiment).

Figure 2. Calculated values of the coefficient of concentration of tangential stresses in the glue VK-9 ($n$) depending on the thickness of the adhesive layer ($h$) and the length of the overlap.

However, traditional analytical methods used for the analysis of adhesive joints predict increased strength with an increase in the thickness of the adhesive layer. Figure 2 shows graphs of a sharp decrease in tangential stresses in the adhesive layer with an increase in the thickness of the adhesive layer for different sizes of the overlap length of the panels.

The stress concentration coefficient, which is the ratio of the maximum stress in the joint to the average, calculated by dividing the value of the tensile load by the area of the joint, is determined as follows:

$$n = \frac{\tau_{\text{max}}}{\tau_{cp}} = k \frac{l}{2} \text{cth} \frac{kl}{2} .$$  \hspace{1cm} (1)

Parameter depends on the thickness of the adhesive layer and the stiffness characteristics of the connection elements:

$$k = \frac{2G}{\sqrt{Eth}} ,$$  \hspace{1cm} (2)

where $G$ is the shear modulus of the adhesive, $E$ and $t$ is the elastic modulus of the material of the glued panels and their thickness, respectively.

A decrease in stress concentration means that the breaking load increases with increasing thickness of the adhesive joint. A similar trend follows from the calculation of normal stresses by both analytical and numerical methods. In all theories using the first approach, the limiting load increases with increasing thickness of the connection line (figure 3, curves 1-3). However, this forecast does not correspond to the trends found in the experiments (figure 3, curve 4), and the practical experience of using adhesives [19].

Researchers [13, 20] identify several main reasons for this discrepancy between the results of experiments and the theoretical forecast for assessing the effect of the thickness of the adhesive seam, which can be divided by the nature of their occurrence into mechanical-phenomenological and structural. From the point of view of the mechanics of the deformation and destruction process, the choice of inadequate criteria for the destruction of the adhesive layer and ignoring some important factors of the mechanical (deformation process) behavior of the adhesive can have a significant impact on the calculation results. Namely, the uneven distribution of stresses over the thickness, additional bending loads due to a violation of the loading symmetry, the influence of changes in the geometry of the sample with an increase in the thickness of the adhesive layer, changes in the mechanisms of energy
dissipation in the adhesive layer plasticity, the development of damage due to an increase in the distance between the surfaces that are glued. The degree of influence of the adhesive thickness in the joint may also be affected by the circumstances associated with structural changes in the adhesive layer as a polymer material. The most important of them are the presence of defects, damages and micro cracks in the glue, which do not take into account the analytical models. The reasons for the appearance of defects and damage in the adhesive are technological in nature; the formation of micro cracks can be caused by residual stresses during curing. Obviously, in thicker layers of adhesive, an increase in the number and size of defects and micro cracks is more likely. In addition, due to technological features, the structure of the adhesive may change with increasing thickness (for example, due to differences in curing conditions) and the properties of the adhesive / substrate interface (for example, due to interfacial stresses occurring at the interface or emission or stoichiometric processes in the contact zone).

Figure 3. Effect of the adhesive joint thickness (h) on the breaking load (Pc) in a single overlap joint: theoretical predictions and experimental results: 1 – Goland-Reissner model; 2 – Volkersen model; 3 – FEM; 4 – an experiment [13].

From the analysis of the literature, it follows that the most acceptable approach for practical strength estimates depending on the thickness of the adhesive layer is the approach of fracture mechanics, which demonstrates partial agreement with the practical results of the use of adhesive joints.

3. Bond thickness effect on the energy release rate of a crack
The main idea of the methods of fracture mechanics applied to adhesive joints is to model the limit state of the adhesive layer by the process of propagation of internal defects in the form of a longitudinal crack. For such a model, the adhesive polymer layer is destroyed with the manifestation of inelastic effects, which are associated with the blunting of the crack tip in the form of the formation of a pre-fracture zone in brittle adhesives or a zone of plastic deformation in elastic-plastic adhesives 2a sizes:

$$\sigma_{c, max} = \frac{EG_c}{\pi h_0} h_0 2a_p. \quad (3)$$

where $E$ and $G_c$ are the elastic modulus and the energy release rate of a crack, $\sigma_c$ – limit intensity.

It is assumed that the maximum strength of the adhesive joint is achieved when the size of the pre-fracture zone corresponds to the thickness of the adhesive layer:
The scheme of the influence of the thickness of the adhesive layer on the mechanism of destruction of the adhesive can be as follows (figure 4).

The global strength of the joint in this case increases with the increase in the thickness of the adhesive. At the $h = h_0 = 2a_p$, the size of the fictitious crack $(2l + 2a)$ is reduced to a minimum value, which corresponds to the limit strength of the adhesive layer $\sigma_{c,\text{max}}$. When the thickness of the adhesive layers increases to $h > h_0$, there are no geometric restrictions on the part of the substrates, and the size of the zone of intensive energy release (pre-fracture), in accordance with the fracture mechanics, is determined only by the characteristics of the crack resistance of the adhesive.

The presented model of changing the mechanisms of destruction depending on the geometric parameter of the adhesive layer is significantly simplified and does not take into account some important factors – the influence of the stiffness of the connected elements, the stress distribution over the layer thickness, the micro-damage of the polymer glue layer, etc.

4. Results and discussion

To assess the influence of the possibility of predicting the load-bearing capacity of the adhesive joints of composite elements depending on the thickness of the adhesive joint, tensile strength (tear-off) tests of the adhesive joint samples were carried out using the method of determining the tear-off strength characteristics of the composite panels of aircraft structures. To exclude the influence of the stiffness of the glued sheets, aluminum alloy plates were selected as substrates, the thickness of which is significantly greater than the thickness of the studied adhesive layers.

The results of testing the epoxy glue with dots are shown in figure 5, table 1, which also shows the calculated curve of the dependence of the strength of the adhesive joint on the thickness of the adhesive layer. The calculated values of the limiting stresses $\sigma_c$ are obtained in accordance with the information provided in paragraph 2 (figure 5) the model of destruction of the adhesive joint. The limiting stresses in the adhesive layer were calculated using the Orovan formula [21], in which the half-length of the fictitious crack is equal to the size of the pre-fracture zone $a_p$.

![Figure 5](image_url)

**Figure 5.** Effect of the thickness of the adhesive layer (h) on the strength ($\sigma_c$) of the joint during separation.
Table 1. Parameters of the calculated model of the strength of adhesive joints and the results of strength tests.

| Parameter                                      | Value   |
|------------------------------------------------|---------|
| Elastic modulus $E$, MPa                      | 1500    |
| Energy release rate of a crack $G_C$, J/m²     | 220     |
| Size of the zone of pre-fracture, mm          | 0.253   |
| Thickness of the adhesive layer, h, mm        | 0.10 0.25 0.253 0.50 0.75 1.00 |
| Limit strength, MPa                           |         |
| – experiment                                   | 9.4 19.5 20.4 14.5 10.6 10.9 |
| – numerical solution                           | 9.1 14.3 20.4 14.4 14.4 14.4 |

5. Conclusion

The results of the tensile tests of thin adhesive joints ($h < h_0$) are fully consistent with the forecast of the fracture mechanics and confirm the trend of increasing strength for thin joints to thicknesses of $\approx 0.2 \ldots 0.3$ mm. In this range of thicknesses, the influence of the connected elements (substrates) and the bluntness of the microcracks due to the tightness of the deformation affect.

The peak of the strength values according to the model falls on the thickness of the adhesive equal to the size of the cracking zone, but it is not possible to determine the strength characteristics at this point experimentally, since in practice it is difficult to realize the thickness of the adhesive layer with an accuracy of 0.01 mm. For the problems of designing adhesive joints, it is possible to positively evaluate the possibility of calculating the optimal thickness of the adhesive layer by the characteristics of the strength and crack resistance of the adhesive by the methods of fracture mechanics.

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