DEPENDÊNCIA DOS MECANISMOS DE DESTRUIÇÃO “GLARE” DA EXTENSÃO DE AMOSTRAS EM TESTES DE FLEXÃO DE TRÊS PONTOS**DEPENDENCE OF GLARE DESTRUCTION MECHANISMS ON THE ELONGATION OF SAMPLES IN TESTS TO THREE-POINT FLEXURAL****ЗАВИСИМОСТЬ МЕХАНИЗМОВ РАЗРУШЕНИЯ GLARE ОТ УДЛИНЕНИЯ ОБРАЗЦОВ В ИСПЫТАНИЯХ НА ТРЕХТОЧЕЧНЫЙ ИЗГИБ**SHA, Minggong^{1*}; PROKUDIN, Oleg A.^{2*}; SOLYAEV, Yury O.^{3,4}; VAKHNEEV, Sergey N.⁵¹ Northwestern Polytechnical University (NPU), School of Civil Aviation, 127 West Youyi Road, zip code 710072, Beilin District, Xi'an Shaanxi – People's Republic of China^{2,3} Moscow Aviation Institute (National Research University), Institute of General Engineering Training, 4 Volokolamskoe highway, zip code 125993, Moscow – Russian Federation⁴ Institute of Applied Mechanics of Russian Academy of Sciences, 7 Leningradsky Ave., zip code 125040, Moscow – Russian Federation⁵ Moscow Aviation Institute (National Research University), Department of Engineering Graphics, 4 Volokolamskoe highway, zip code 125993, Moscow – Russian Federation

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Received 15 April 2020; received in revised form 10 June 2020; accepted 16 June 2020

RESUMO

Os testes de flexão são uma das maneiras eficazes de determinar experimentalmente os módulos de elasticidade e cisalhamento. Uma tarefa importante na implementação dos materiais compósitos em estruturas aeroespaciais é o desenvolvimento de métodos para determinar as características físico-mecânicas dos materiais. O artigo apresenta os resultados de testes de flexão de três pontos de amostras do material compósito metal-polímero GLARE. Foram estudadas as amostras constituídas por 17 camadas para as quais a dureza aparente entre camadas foi determinada de acordo com os resultados dos testes de flexão de três pontos. Foi estabelecido que, para as amostras estudadas, mecanismos de cisalhamento entre camadas são realizados quando a relação entre comprimento e espessura é menor que 10. A destruição está localizada na zona da camada central, que atende aos requisitos dos padrões de teste de feixe curto. No entanto, esses testes de GLARE são sempre acompanhados pela ocorrência de deformações plásticas significativas associadas à presença de camadas de alumínio na estrutura do material. Com o alongamento de amostras acima de 10, realiza-se um mecanismo de destruição, no qual ocorrem a separação de camadas e perda de estabilidade das camadas externas no lado comprimido da amostra. Quando o alongamento das amostras é menor que 4, nas amostras realiza-se o mecanismo de destruição de acordo com o tipo de indentação com grandes deformações não lineares. De acordo com os resultados do teste, foi determinada a dependência dos mecanismos de destruição realizados no alongamento das amostras.

Palavras-chave: GLARE, flexão de três pontos, feixe curto, mecanismos de destruição, dureza entre camadas.

ABSTRACT

Tests on bending are one of the effective ways to experimentally determine the elasticity and shear moduli. An important task in the implementation of composite materials in aerospace structures is the development of methods for determining the physical and mechanical characteristics of materials. The paper presents of tests for three-point bending of samples of metal-polymer composite material "GLASS-REinforced" Fibre Metal Laminate (GLARE) are presented. Examined samples, consisting of 17 layers, for which apparent interlayer strength of the results of tests on three-point bending was established by the method of "short beam". It was established that for the studied samples, interlayer shear mechanisms were realized at the ratio of dimensions of length to thickness of at least 10. Localization of fracture occurs in the area of the central layer,

which corresponds to the requirements of standards for conducting tests of the method of short beams. Nonetheless, such GLARE tests are always accompanied by the occurrence of significant plastic deformations associated with the presence of aluminum layers in the structure of the material. With the elongation of samples of more than 10, a fracture mechanism is realized in them, during which delamination and loss of stability of the outer layers on the compressed side of the sample occur. When the elongation of samples of less than 4 is implemented in samples takes place, the mechanism of destruction of indentation type with large nonlinear deformations. According to the test results, the dependence of the realised fracture mechanisms on the elongation of the samples is determined.

Keywords: *GLARE, three-point bending, short beam, fracture mechanisms, interlayer strength.*

АННОТАЦИЯ

Испытания на изгиб являются одним из эффективных способов экспериментального определения модулей упругости и сдвига. Важной задачей при внедрении композиционных материалов в авиакосмических конструкциях является разработка методов определения физико-механических характеристик материалов. В работе представлены результаты испытаний на трехточечный изгиб образцов металлополимерного композиционного материала GLARE. Исследованы образцы, состоящие из 17 слоев, для которых определена кажущая межслоевая прочность по результатам испытаний на трехточечный изгиб. Установлено, что для исследованных образцов реализуется механизмы межслоевого сдвига при соотношении размеров длины к толщине менее 10. Локализация разрушения происходит в зоне центрального слоя, что соответствует требованиям стандартов на проведение испытаний по методу короткой балки. Однако, такие испытания GLARE всегда сопровождаются возникновением значительных пластических деформаций, связанных с присутствием алюминиевых слоев в структуре материала. При удлинении образцов более 10 в них реализуется механизм разрушения, при котором происходит отслоение и потеря устойчивости внешних слоев на сжатой стороне образца. При удлинении образцов менее 4 в образцах реализуется механизм разрушения по типу индентирования с большими нелинейными деформациями. По результатам испытаний определена зависимость реализующихся механизмов разрушения от удлинения образцов.

Ключевые слова: *GLARE, трехточечный изгиб, короткая балка, механизмы разрушения, межслоевая прочность.*

1. INTRODUCTION:

Composite metal-polymer materials of GLARE type are promising structural materials for use in the construction of aviation vehicles (Kablov *et al.*, 2016; Podzhivotov *et al.*, 2016; Antipov *et al.*, 2018; Serebrennikova *et al.*, 2016; Topchiy *et al.*, 2019). These composite materials are laminated panels, formed by alternating thin layers of fiberglass and aluminum alloys. By comparison with metals, GLARE has increased specific strength, long-term durability, fire resistance. Examination of dependency on mechanical properties of GLARE from the parameters of the reinforcement is an important task, the solution of which is necessary for conducting the strength calculations and optimal design structures. One of the important characteristics determining the structural properties of GLARE, as well as other composite materials, is the interlayer strength.

Testing samples in three-point bending by the method of "short beam" (ASTM D2344...; Babaytsev *et al.*, 2017; GOST R 57745-2017...

2018) is one of the simplest methods for determining the interlayer strength of composite material (Vasiliev and Morozov, 2018). This method is widely used at research and development of composite structures since it does not require the use of complex experimental equipment and strain measurement. At the same time, the interlayer strength is an important parameter from the point of view of design, so it is used when formulating criteria for the strength of composite materials (Jones, 2014; Dmitriev *et al.*, 2011; Vasiliev and Morozov, 2018), and, in particular, when assessing the strength of the structures of GLARE. The occurrence of interlaminar cracks can lead to a reduction in carrier capacity element designs and, subsequently, to their degradation, e.g., by the mechanism of local loss resistance (Remmers and De Borst, 2011; Alekseev *et al.*, 2019; Kachanov, 2012; Sevryukova *et al.*, 2012; Lapidus and Abramov, 2018).

Though, such a simple method as a test to three-point bending contains certain deficiencies associated, in the first place, with the fact that

when these tests in samples are implemented in a complex stress state, there arise not only the tensions of the interlayer shift but also tensile/compressive stress, leading to errors in determining characteristics of material (Vasiliev and Morozov, 2018). The complexity that arises when testing samples for interlayer shear, in addition to the indicated errors associated with the inhomogeneous stress state of the samples, also lies in the fact that interlayer strength determined in the tests is not a material constant, but depends on the distance between supports. This problem is known and for ordinary composite materials (Wisnom, 1991; Xie, and Adams, 1995; Li *et al.*, 1999; Ossipyan *et al.*, 2004; Privalko *et al.*, 2005; Abali *et al.*, 2013) and for metal-polymer composites (Hinz *et al.*, 2005; Hinz *et al.*, 2009; Polilov and Tatus, 2012; Lin *et al.*, 2018; Li *et al.*, 2018; Jakubczak *et al.*, 2018; Lin *et al.*, 2019), and it is explained by the decrease of tangential stresses for working short samples (by the standards relative elongation of the samples should be 6 – 11), in comparison with the classical models of beams, which assume a constant value of the shear force and, accordingly, constant values of shear stresses (accurate to the sign) along the length of the sample. Therefore, the use of the usual ratio for estimating the shear stresses acting in a beam using the Equation 1 (ASTM D2344...) leads to an increase in the seeming interlayer strength of the material. Moreover, the effect of the length of sample on the results of tests of the interlayer strength is explained by 1) concentration of stress near the poles, for the exclusion of which special tooling is applied (Podzhivotov *et al.*, 2016; Antipov *et al.*, 2018;) 2) a statistical dependence of durability on sizes of the sample (Wisnom, 1991), 3) the occurrence of interlayer cracks outside of the neutral axis of the sample (Li *et al.*, 1999) and 4) specific dependence of the interlayer strength on parameters of mechanics of fracture (Polilov and Tatus, 2012).

In recent years there was a large amount of work, in which ways of finding the interlayer strength of metal-polymer composites were examined, according to the method of "short beam" (Lin *et al.*, 2018; Hinz *et al.*, 2005; Lin *et al.*, 2019; Hinz *et al.*, 2009; Li *et al.*, 2018; Jakubczak *et al.*, 2018; Polilov and Tatus, 2012). In GLARE, the destruction of the interlayer shear can occur both at the boundary of the contact metal and within the composite layers. In the first case, in fact, according to the results of tests defined by adhesive strength of the contact metal/composite with shear, and in the second – interlayer strength inside the composite layer. Consequently, in tests,

it is possible to determine only the characteristic that is of less value. An additional feature, which arises when testing GLARE samples by "short beam" method, is the plasticity of aluminum layers, which leads to a substantially nonlinear diagram of load-displacement, which, however, is not a hindrance to use estimates of tangential stresses in classical Equation 1, which is valid for any type of material, both elastic and plastic (Vladimirov, 2016; Antipov *et al.*, 2017). Thus, the main object of studies using GLARE is determining the degree of the error, which is realized when using the method of "short beams" by relation to more accurate, but, and more labor-intensive methods of testing. In particular, in this study, the effect of dimensions (elongation) of samples on the fracture mechanisms realized in the GLARE tests was examined.

2. MATERIALS AND METHODS:

For test samples with GLARE structure, 9/8 with unidirectional circuit reinforcing composite layers were made (Figure 1, Figure 2 a). The thickness of the samples was 5.5 mm, the width was 7 mm, and the length was 20-170 mm. The thicknesses of layers of fiberglass and aluminum alloy were ~ 0.32 mm. As a substitute for fiberglass, basalt fiber can be used in the manufacture of the test sample. According to its mechanical characteristics, continuous basalt fiber occupies an intermediate position between fiberglass and carbon fibers at a relatively low price. This makes this product extremely attractive for consumers for whom there are restrictions on the entry price, but at the same time, high mechanical properties are important. Selection of said structure samples is due, firstly, to the available equipment and diameter poles in the test machine, which does not allow testing too short samples and using 17 – layered GLARE, with thickness 5.5 mm, enables testing of samples of length 25-55 mm (i.e., there is an extension of 5-10, which corresponds to standard requirements) on existing supports.

Secondly, the selection of unidirectional structure of reinforcement allows to reduce the likelihood of formation of the bundles within the composite layers and, therefore, allows to evaluate the interlayer strength of the contact aluminum/composite. Using any other reinforcement schemes would lead to primary delamination at the most weakened internal boundaries between the layers of fiberglass with different directions of reinforcement. With this in process operation, it was assumed that the initial interlayer strength of the composite layers is

known, or can be determined by standard methods.

The third factor influencing the selection of the scheme of reinforcement in samples is the need to localize interlaminar cracks on boundaries by maximally closely spaced to the neutral axis of the sample. It is important to note that multilayer cracks in GLARE, even if they pass through the center of the sample, always turn out to be shifted by half the thickness of the metal layer located on the neutral line. Thus, the use of samples of large thickness allows to reduce the relative displacement of cracks from the neutral axis, and, therefore, to reduce the calculation errors of the standard Equation 1, which gives accurate values only in case of the central location of an interlayer crack (Equation 2).

Where P is the effective load, b , h are the width and thickness of the sample.

Tests were carried out on the set Instron 5969 (Figure 2b) with lower supports of 5 mm diameter and a top support diameter of 10 mm. The test speed was 1 mm/min. Tests stopped at the decrease of the load more than 50% of the maximum. The test results were processed on the basis of Equation 1 in accordance with which the apparent (conditional) interlayer strength was determined.

Three-point bending tests were conducted in accordance with ASTM D2344. In the test the specimens were placed symmetrically on the supports and loaded by the loading nose of testing machine at the center. Deflections in the center of specimens for the prescribed loading level were registered in the tests. Corresponding load-deflection curves were plotted and used for the evaluation of the load-bearing capacity and interlaminar shear strength of specimens with different length.

3. RESULTS AND DISCUSSION:

According to the test results, it was established that the interlayer shift could be realized in samples with elongation of not more than eight and not less than 4.5. A typical mechanism of destruction can be well observed in the course of the test on lateral ends of all the samples (Figure 3a), but after removing the load, interlayer cracks were well distinguishable only in samples with elongation over 6 (Figure 3b). For samples with elongation of more than 10, the fracture mechanism changed. For such samples, detachment and loss of stability of the metal layer were realized in the compressed area of the sample near the support (Figure 4). For a very

short sample with elongation, less than 4 took place wrinkling of the samples, i.e., took place the failure mechanism with large transverse strains – "indentation" (Figure 5).

The characteristic diagrams of load-displacement for GLARE samples are presented in Figure 6. We can see that the given sample at a load above 1000 N chart becomes nonlinear, which can be explained by appearance plastic deformations in the layers of aluminum. With the destruction and start of an interlayer crack, a sharp drop in load occurs, which can be explained by a decrease in bending stiffness of the sample (Xie and Adams, 1995).

The dependence of breaking load on the distance between the supports obtained in the tests is presented in Figure 7. These points indicate the experimental data and the lines show theoretical approximation by the relations given below. Firstly, it follows from the obtained results that the bearing capacity of the sample decreases with increasing distance between the supports, which qualitatively corresponds to classical solutions from the theory of resistance of materials. In particular, reduction of the breaking load may be attributed to the assumption that there is a certain critical value of compressive stress, leading to detachment of the upper metal layer (as in Figure 4). The level of stress in this layer due to its small thickness can be considered as constant, and it can be found by classical beam theory. Hence, at the time of destruction, there is the Equation 3.

From this follows the estimate for maximum load (Equation 4). Where all values are known, except for critical stresses, the value of which was selected to describe the available experimental data $\bar{\sigma} = 1020 \text{ MPa}$. The recorded estimate (Equation 4) is qualitative and approximate, though, it shows that the maximum load in the three-point bend is inversely proportional to the elongation of the sample Equation 5 for elongations greater than 10, and this dependence is confirmed by experiment. For smaller values of elongation, this law does not work, and the dependence becomes different – the mechanism of destruction is changed to interlayer shift at the center of the sample (Figure 3). The implementation of such a mechanism is an objective of the tests. Nonetheless, it can be seen from Figure 7 that the maximum load during the interlayer shear is also dependent on the distance between the supports. This effect is known for composite materials (as it was noted above), but it is involved in contradiction with the classical solution of theory resistance materials with a

three-point bending shearing force constant on the right and left of the applied load and, consequently, are tangent strains change in an analogous manner along the length of the sample and are not dependent on this length. Apparently, in the experiment, this was not observed.

To describe the resulting dependence and for the evaluation of true interlayer strength, it is proposed to use a modified solution of the problem of three-point bending, which may be obtained in the framework model beams, built under gradient theory of elasticity (Babaytsev and Zotov, 2019; Lurie and Solyaev, 2018; Lurie *et al.*, 2018; Berezovskii *et al.*, 2015). This dependence is determined by the following relationship (Equation 6). Where – τ_0 is true interlayer strength, and the parameter d is the scale parameter of the problem, it has the dimension of length and, generally speaking, its value should be correlated with the diameter of bearings, which are used in the tests, in particular for very thin supports ($d \sim 0$) is the solution (Equation 6) goes to the classical solution (Equation 2). To describe the experimental data, values of the indicated solution parameters (Equation 5) were selected, and they amounted to:

– True interlayer strength $\tau_0 = 60.4$ MPa,

– Scale parameter – $d = 2.7$ mm (that is, approximately, the radius of the lower supports in the area where the destruction takes place).

The obtained dependence is presented in Figure 7 by a solid line. It can be seen that in case of the small extension of samples and with the mechanism of destruction of interlayer shear, the solution (Equation 6) better describes the experimental data in comparison with the solution (Equation 4), as well as, obviously, and by comparison with classic solution, which requires independence of carrier load from a distance between the supports during the interlayer shear. The load corresponding to the constant (true) interlayer strength of 60.4 MPa is presented by the horizontal dashed line in Figure 7. The dependence of the apparent interlayer strength on the distance between the supports can be found via a combination of Equation 2 and Equation 6 in the following form (Equation 7).

This dependence is presented in Figure 8 (solid line). The points on this figure represent the experimental data obtained by processing the results of the tests (Figure 7) with the use of Equation 2. The horizontal dotted line is the calculated true interlayer strength. The deviation of relation (Equation 7) from the experiment for the shortest samples may be caused by the change in

the mechanism of their destruction. As it was said, large transverse inelastic deformations occur in such samples upon destruction.

The results of tests of GLARE samples of various elongations for three-point bending were demonstrated.

4. CONCLUSIONS:

In the work, the “short beam” method was analyzed in order to determine the elasticity characteristics of composite materials, which allow to implement a program for determining the complex of elasticity characteristics of composite materials necessary for structural analysis according to the technical theory, and can be used in the development and improvement of standards. In these tests, the samples with a large number of layers and with unidirectional reinforcement schemes were used, which allowed reducing the experimental error when using standard equipment. According to the test results, the dependence of the realized fracture mechanisms on the elongation of the samples was established.

Obtained estimation of interlayer strength for GLARE ~ 60 MPa, which corresponds to a typical level of interlayer strength of polymer composite materials, but in the tests, destruction took place on the border of the contact metal and composite layers, which allows us to state that the found value of interlayer strength is the characteristic of metal/composite contact, as it is realized in GLARE.

5. ACKNOWLEDGMENTS:

This work was supported by the grant of the Russian Science Foundation (project No. 17-79-20105) in Moscow Aviation Institute.

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$$\bar{\tau} = \frac{3P}{4bh} \quad (\text{Eq. 1})$$

$$\bar{\tau} = \frac{3P}{4bh} \quad (\text{Eq. 2})$$

$$\frac{3LP_{\max}}{2bh^2} = \bar{\sigma} \quad (\text{Eq. 3})$$

$$P_{\max} = \bar{\sigma} \frac{2bh^2}{3L} \quad (\text{Eq. 4})$$

$$P_{\max} \sim (L/h)^{-1} \quad (\text{Eq. 5})$$

$$P_{\max} = \frac{4}{3}bh \frac{\tau_0}{1 - 1/\text{ch}(L/(4d))} \quad (\text{Eq. 6})$$

$$\bar{\tau} = \frac{\tau_0}{1 - 1/\text{ch}(L/(4d))} \quad (\text{Eq. 7})$$

Figure 1. Structure of 17-layer GLARE laminate

Figure 2. Samples of 17-layer GLARE (a) for tests on the three-point bending (b)

a)

b)

Figure 3. The interlayer shifts in samples of GLARE, a: displacement of layers in the end zone of the sample, b: sample after conducting the test.

Figure 4. Destruction of samples of large elongation (> 8)

Figure 5. The nature of fracture and permanent deformations in samples of small elongation (< 4.5)

Figure 6. Load-displacement diagram, obtained when testing GLARE sample on the three-point flexural

Figure 7. The dependence of the breaking load during bending on the relative distance between the supports, normalized to the thickness of the sample.

Figure 8. The dependence of the apparent interlayer strength on the relative distance between supports in the tests using the short-beam method. The points are experiment data, and the solid line is data from formula (5).