Assessment of Error of the Experimental Determination of Interlaminar Shear Strength

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Abstract. Owing to high strength and weight perfection of the polymeric composite materials, they are used in the manufacturing of various equipment. Laminated polymeric materials are the most studied and widespread composite varieties. These materials implement high elastic and strength characteristics in the reinforcement plane; however, they have minimal performance capabilities at interlaminar shear. Assessment of non-uniform distribution of shear stresses over the shear surface is carried out for the specimens intended for determination of the interlaminar strength according to the current standards. Based on the model of adhesive joint, the dependence is obtained which relates the error in assessment of the interlaminar shear strength to the elastic characteristics of the material and geometry of the specimen's working part. The dependence allows controlling the degree of underestimation of interlaminar shear strength of the material when planning the experiment. Modification of specimens recommended by normative documents for interlaminar shear tests is substantiated. The results of experimental study of unidirectional carbon fiber composite interlaminar strength using modified specimens are presented. The typical nature of failure of specimens with 90° and 0° layup patterns after tests is analyzed. According to results of the experiments, values of interlaminar strength are at the level of 53.5 MPa, with the variation coefficient of 3.5% and 5.7% underestimation of the result.

Keywords: Composite specimen · Non-uniform distribution · Strength reduction · Adhesive joint

1 Introduction

At present time, polymeric composite materials (PCM) have widespread application in various industries, successfully replacing metals, which are traditionally used in many branches of technology [1, 2]. Owing to the transition to designing and manufacture of load-bearing elements of structures made of PCM, in particular, in transport, aviation and

astronautics, the relevance of the problem of their joints increases [3, 4]. For many reasons, no determination of the interlaminar shear bearing capacity is given in the existing system for calculation of mechanical joints [5, 6]. Firstly, in the bearing-type mechanical joints of thin-walled structures, ratio of diameter of the fastening element to thickness of the package being fastened allows considering the problem as two-dimensional one (in the plane of a part). Secondly, shear characteristics of metals make shear failure in the plane of fastening element practically impossible. Thirdly, mechanical joint design and technology solutions are aimed at reducing the non-uniformity of stresses across the thickness of the package [7, 8]. In case of joining of parts made of PCM, their delamination in the mechanical joint is quite likely, since the interlaminar shear strength of the material is low [9, 10]. Therefore, correct setting of the permissible level of interlaminar shear stresses is essential in order to ensure the bearing capacity and resource of the joints.

2 Literature Review

To determine the interlaminar shear strength, the methods developed for determination of shear characteristics of the package in the laying plane are used [11]. Obtaining of the uniform field of stresses is the main difficulty in the performance of interlaminar shear tests [12]. It gave rise to the large number of test methods, of which there are more than a dozen today [13]. Detailed reviews of these tests are presented in [11, 14]. The features and performance potential of the available shear test methods are compared in the review [14] (Table 1). This paper also gives a conclusion that the Iosipescu method can be recognized the only accurate method, which requires the special equipment, use of strain gauges and specimens of the complex geometry.

Table 1. A comparison of the features and performance potential of available shear test methods [14]

Test method (with ASTM Sid. No., if applicable)	Uniform shear stress state	All three stress states practical	Shear strength obtained	Shear stiffness obtained
Short beam shear (D 2344)	–	–	+	–
Losipescu shear (D 5379)	+	+	+	+
± 45° tensile shear (D3518)	–	–	+	+
Two-rail shear (D 4255)	–	–	+	+
Three-rail shear (D4255)	–	–	+	+

(*continued*)

Table 1. (*continued*)

| Test method (with ASTM Sid. No., if applicable)	Uniform shear stress state	All three stress states practical	Shear strength obtained	Shear stiffness obtained
Double-notched shear (D 3846)	+	−	+	+
Torsion of a thin tube (D 5448)	+	−	+	+
Cross-beam sandwich	−	−	+	+
Torsion of a solid rod	−	−	+	+
Four-point shear	−	−	+	−
Picture frame shear	−	−	+	+
Plate twist	−	−	−	+
Off-Axis (Tensile)	−	−	+	+
V-notched rail shear (D 7078)	+	+	+	+

The methods of short beam (three-point bending), two-point plate twist and notched specimen tension are dealt with in [11, 13].

Short beam shear test [13] is the simplest method while giving a fairly good estimate of the ultimate interlaminar shear strength. Peculiar feature of such tests is the need to ensure the failure on shear stresses [15]. More detailed analysis of the features of the short beam failure is given in [16]. In particular, it is indicated that when the ratio of thickness of the sample δ to the distance between supports l is less than 4, there is a probability of collapsing and interlaminar shear (the smaller the ratio, the higher the probability of collapsing). With $4 \leq l/\delta \leq 8$ the failures resulting from the interlaminar shear and bending may occur. Furthermore, as moving closer to the lower limit of the range, probability of the shear increases. Therefore, scatter of results can be explained by the transition from one type of failure to another. The papers [12, 15] present the analysis of influence of the distance between the supports on the value of the ultimate strength. This parameter significantly affects the failure mode: at small distance between the supports the specimen collapses, while the impact of tensile and compressive stresses increases at large distance between supports.

The classical method of plate twist (three-point twist) [13] does not provide the determination of the ultimate interlaminar shear strength, but so-called method of two-point plate twist is described in [11, 16]. In accordance with this method, the specimen should be strictly flat, without initial deflections and curvatures, and its thickness δ should be constant. In plan, the plate should have the shape of a square with side l. The recommended side to thickness ratio is $25 \leq l/\delta \leq 100$, but the results of tests of

fiberglass, carbon fiber composite and boron-fiber reinforced plastic mentioned in [11, 16] indicate that already at $l/\delta \geq 15$ there is a good reproducibility of results.

One of the most accurate methods for determination of the interlaminar strength of PCM is the tension of notched specimens (Fig. 1) [13, 16, 17]. The method is quite simple in use, but it has significant drawbacks: in case of testing of specimens with asymmetrical notches (Fig. 1, a), the devices to prevent bending are required; besides, assessment of stress concentration is the laborious procedure, and there is high sensitivity to the quality of making notches. Since an undercut or overcut is unacceptable, it is advisable to generate the notches and hole (Fig. 1, b) in the process of the specimen molding.
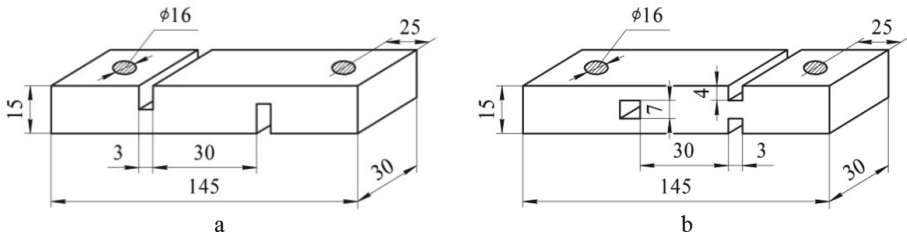
Fig. 1. Notched specimens: a – with asymmetrical notches; b – with symmetrical notches and a hole

There is an open question concerning the determination of distance between notches, where the shear occurs (length of the tested joint). According to the data of [13, 16], the recommended value of the distance is between 10 and 30 mm. The review of test methods [14] shows that at present time, along with tension of notched specimens, the uniform stressed state can be obtained with the use of V-Notched Rail Shear method, but it is also rather difficult to implement in practice.

With regard to mechanical joints, interlaminar shear strength in the system of the-oretical calculations has not been sufficiently investigated [18]. In a number of papers [19–21] the laminated composite is considered as a bonded structure. These papers out-line the idea (which undoubtedly deserves attention) that interlaminar stresses in the laminated composite are similar to those in the adhesive joint. In this case, the principle of "smearing" of the fastening element is used for its further calculation as the adhesive. This principle has proven itself well in the calculations of compounds with cross-link micro-elements [22] and sandwich structures [23]. The exact solution for analysis of the characteristics of the laminated structures' interlaminar shear is proposed in [24]. The paper [25] describes the function of interlaminar failure, on the basis of which the criteria for delamination failure are established, taking into account the effect of compression across the thickness at the interlaminar shear failure. However, the existing methods are applicable for the laminated structures with simple boundary conditions only. The limitations of the analytical theory and impossibility of its use in the analysis of the interlaminar mechanical properties of PCM are indicated in [26]. This paper proposes to study interlaminar properties of the composite laminates with the use of numerical methods.

Therefore, we can conclude that the problem of assessment of the interlaminar shear strength is multifaceted and controversial one. On the one hand, it is necessary to provide the most accurate description of the behavior of the material in the shear zone of the real joint. On the other hand, during interpretation of the results and their analysis it is necessary to remain within the framework of the engineering methodology for calculation of the joint. The latter requirement restricts the use of numerical methods for the interlaminar shear zones' calculation.

The purpose of the study is to assess non-uniformity of distribution of shear stresses over the shear surface for the specimens meant for determination of the interlaminar strength according to the current standards, and to obtain a dependence relating the error in the assessment of the interlaminar shear strength to elastic characteristics of the material and geometry of the specimen working part.

3   Research Methodology

The papers [11, 13] suggest that for the specimens intended for determination of the interlaminar strength according to the current standards, two approaches can be used when choosing the dimensions of their joints. The first approach assumes that the length of the joint is as small as possible. In this case, the magnitude of stress overshoots is the lowest and stress distribution can be considered uniform along the joint. The second approach consists in choosing the largest possible size of the joint. In this case, the stress peaks will be maximum, but the areas of their manifestation are negligible compared to dimensions of the joint. It allows neglecting the effect of stress non-uniformity in the analysis of results of the experiments. The papers [5, 10, 22] show that in case if the joint is too long, unloaded zone appears in its middle part. It makes the second approach proposed in [11, 13] completely inapplicable.

To resolve the issue of the permissible dimensions of the specimen working zone, we consider it as an adhesive joint of parts of the same stiffness (Fig. 2).
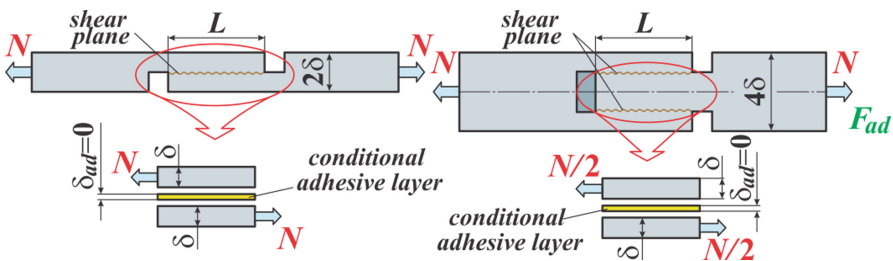
Fig. 2. Modeling of specimens for determination of interlaminar strength as an adhesive joint

The essence of the method is to assess the defect in the bearing capacity of the joint when comparing two one-dimensional models of the joint. The original model is used to calculate the ultimate strength of the package based on the test results.

$$F_{int} = \frac{\overline{N}}{L},$$

(1)

where $\overline{N}$ – ultimate linear load (load breaking a specimen and related to its width); L – control length of the joint (distance between notches in the specimen).

From (1) it follows that the first estimated value can be obtained as:

$$\overline{N}^{I} = F_{int}L. \tag{2}$$

The control model is more accurate one, since it takes into account non-uniform distribution of stresses in the connecting layer along the joint. The model, despite its simplicity, describes the adhesive layer stressed state rather accurately [19, 20]. The specimen itself is designed so that under loading the stress distribution curve has two practically identical peaks (see Fig. 3).
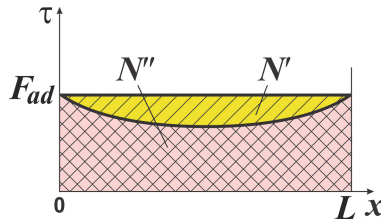
Fig. 3. Stress distribution curve in the connecting layer along the joint

So, it is possible to assess the ultimate load at which the values of stresses in the peaks reach the ultimate interlaminar shear strength and delamination of the specimen occurs

$$\overline{N}^{II} = F_{int}\delta\sqrt{\frac{2E_x}{G_{int}}}th\frac{kL}{2}, \tag{3}$$

where δ – thickness of specimen from its free side to the notch (see Fig. 2); E_x and G_{int} – modulus of elasticity of the material (package) of the specimen along the axis of loading and interlaminar shear module, respectively; k – coefficient of stress concentration along the adhesive joint (according to the Volkersen model [19, 20])

$$k = \frac{1}{\delta}\sqrt{\frac{2G_{int}}{E_x}}. \tag{4}$$

For the further assessment of error of the interlaminar shear, it is sufficient to substitute the load value (3) in (1) taking (4) into account and divide the left and right sides of the equation by the ultimate strength of the package F_{int}. In this case, we obtain the formula to assess the error of the package interlaminar shear strength

$$\Delta = \frac{1}{\overline{L}}\sqrt{2\overline{E}_x}th\left(\frac{\overline{L}}{2}\sqrt{\frac{2}{\overline{E}_x}}\right), \tag{5}$$

where $\overline{L} = L/\delta$; $\overline{E}_x = E_x/G_{int}$.

Now it is sufficient to set the permissible level of error in the assessment of strength, and it is possible to estimate the permissible ratios of the geometry of the specimen for the known ratios of the elastic parameters of the material. For example, when setting the permissible error of 5% we get $\Delta = 0.95$. The relevant solutions of Eq. (5) are given in Table 2.

Table 2. Maximum permissible values of the geometric parameters of the specimen working zone at $\Delta = 0.95$

Elastic properties of the package $\overline{E}_x$	3	50	113	350	546	750	900
Working zone relative length $\overline{L}$	1.0	4.0	6.0	10.56	13.19	15.46	16.94

Based on the data presented, we constructed an approximating dependence

$$\overline{L} \leq 0,5644\sqrt{E_x}, \tag{6}$$

Therefore, it is every reason to correct the dimensions of specimens recommended by the normative documents for interlaminar shear tests (Fig. 4).

The papers [11, 13] show the versions of specimens with the relative geometry of the working zone $\overline{L} = 4$ (see Fig. 1, a) and $\overline{L} = 7.5$ (see Fig. 1, b).
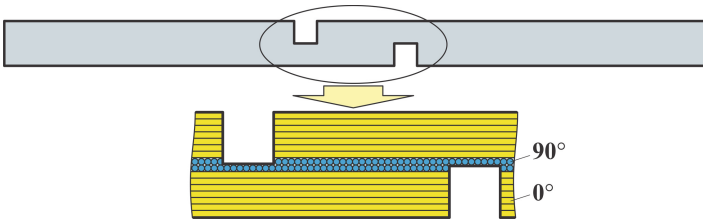

Fig. 4. Modified version of the specimen

Solution of the function inverse to (6) shows that in order to ensure underestimation of the interlaminar strength of up to 5%, the first version of the specimen (Fig. 1, a) is applicable for materials with $\overline{E}_x \geq 50.15$, while the second version (Fig. 1, b) is suitable for the materials with $\overline{E}_x \geq 177$ only. Thus, the first version is applicable for most composites with priority layup pattern of 0°, and the second one can be used only for unidirectional packages made of high-modulus carbon fiber composites and boron-fiber reinforced plastics.

4 Results

According to the recommendations of the standards, dimensions of the specimen should correspond to those indicated in Fig. 5 [11, 13].
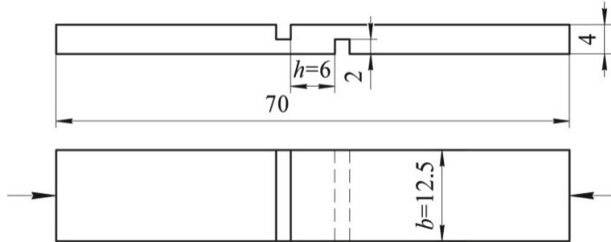

Fig. 5. Interlaminar shear test specimen

For the manufacture of modified specimens, we used unidirectional carbon fiber composite based on ELUR-0.08P tape and 5–211-BN binder with the properties given in Table 3. Two versions of the PCM package were tested with the layup patterns of 0° and 90° to the axis of loading. As shown by Fig. 5, the relative length of the working zone is equal to three. The check according to the proposed method showed that for the carbon fiber composite with 0° layup pattern $\overline{E}_x = 24.64$ (see Table 3). Therefore, according to (5), the ultimate strength estimate will be 0.943 of the real one. It means that underestimation of the strength assessment is 5.7%. For the package with 90° layup pattern $- \overline{E}_x = 1.274$, i.e. $\Delta = 0.507$, and underestimation of the estimate will reach 49.3%.

Tests of specimens with layup pattern of 90° to the axis of loading ended in combined failure in the weakened sections and working zone of Fig. 6, instead of pure shear.

Table 3. Properties of unidirectional carbon fiber composite based on ELUR-008 P/5–211-BN

| Parameter	Value	Parameter	Value
Monolayer thickness, mm	0.087	Ultimate tensile strength across the grain, MPa	21
Ultimate tensile strength along the grain, MPa	677	Ultimate compressive strength across the grain, MPa	210
Ultimate compressive strength along the grain, MPa	939	Modulus of elasticity across the grain, GPa	7
Modulus of elasticity along the grain, MPa	136	Ultimate shear strength in the laying plane, MPa	75
Poisson's ratio	0.32	Shear modulus in the laying plane, GPa	5.5
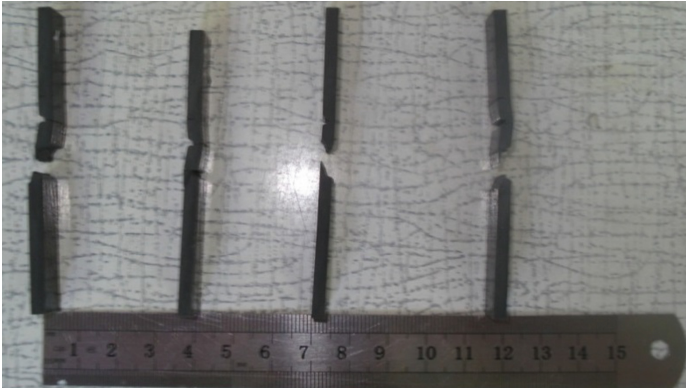
Fig. 6. Specimens with 90° layup pattern after tests

Most likely, the test recommended by the standards [11, 13] in the direction of 90° to the layup can be performed on woven fabrics or unidirectional materials with the dominating layup pattern of 0°, and within the median surface – 90° (Fig. 6).

Tests of specimens with layup pattern of 0° to the axis of loading gave positive results: interlaminar shear failure took place in the area limited by grooves (Fig. 7).
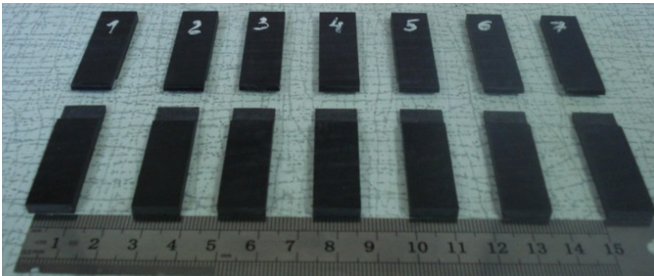
Fig. 7. Specimens with 0° layup pattern after tests

The results obtained are given in Table 4. Statistical processing of the results showed that the arithmetic mean value of the ultimate interlaminar shear strength is 53.5 MPa with the variation coefficient of 3.02%.

According to the obtained values of the ultimate interlaminar shear strength (Table 4), values of the minimum distance to the edge, at which delamination of the composite part is possible, were assessed. The results are shown in Table 5.

Table 4. Interlaminar shear test results for specimens with 0° layup pattern

Specimen number	Dimensions of the specimen working zone (average value)		Area, mm^2	Force, N	Stress, MPa
	Width b, mm	Length h, mm (distance between grooves)			
1	12.52	6.13	76.75	4200	54.72
2	12.61	6.04	76.16	4300	56.46
3	12.64	5.75	72.7	3850	52.96
4	12.55	6.06	76.05	3900	51.28
5	12.51	5.54	69.31	3900	56.27
6	12.58	6.04	75.98	3650	48.02
7	12.51	5.4	67.57	3700	54.76

The relative distance to the edge should be not less than 2.5 diameters in the real structures according to recommendations [5, 7, 9]. It follows from Table 5 that for the carbon fiber composite based on ELUR-008 P/5–211-BN no delamination should occur in almost all cases (except for the use of high-strength fastening elements).

Table 5. Relative distance to the edge at which the composite part may delaminate

Value of ultimate tensile strength of the fastening element, MPa	Relative width of the part per one load-bearing point	Required relative distance to the edge of the part
300	4	1.101
	5	0.881
600	4	2.202
	5	1.762
900	4	3.303
	5	2.642

5   Conclusions

Assessment of non-uniform distribution of shear stresses over the shear surface is carried out for the specimens intended for determination of the interlaminar strength according to the current standards. It is shown that the experimental value of the strength is hardly probable. It is a positive factor; however, underestimation of strength can be unacceptably significant.

Based on the unidirectional model of adhesive joint, the dependence is obtained which relates the error in assessment of the interlaminar shear strength to the elastic characteristics of the material and geometry of the specimen's working part. The dependence allows controlling the degree of underestimation of interlaminar shear strength of the material when planning the experiment.

The analytical dependence is obtained for determination of the limit value of the ratio of specimen dimensions depending on elastic characteristics of the material under condition of 5% error in the assessment of the interlaminar shear strength.

According to the results of the experiments for unidirectional carbon fiber composite based on ELUR-0.08P tape and 5–211-BN binder, the obtained values of interlaminar strength are at the level of 53.5 MPa, with the variation coefficient of 3.5% and 5.7% underestimation of the result.

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