

EVALUATION OF THE STRENGTH OF BOLTED JOINTS OF COMPOSITE PLATES

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We determine the bearing strength of many-row bolted joints of layered carbon fiber-reinforced plastic composites according to the level of strains in the vicinity of a single (isolated) hole subjected to contact loading through the bolt. According to results of the tests obtained by the method of digital correlation of images, we construct a fracture diagram on the stress–strain coordinates and establish admissible bearing stresses corresponding to an increase in the residual strains of the diameter of the hole by 2%.

Keywords: ovalization of holes, digital image correlation, bearing strength, bolted joint, strain field.

At present, the technologies of manufacturing of polymeric composite materials (PCM) are rapidly developed, which is explained by the need in new materials with improved physicomechanical properties. The contemporary composites are classified both according to their components and according to possible applications. In the present work, we study composite materials based on the epoxy polymeric matrix reinforced by long high-modulus carbon fibers with elevated strength and stiffness characteristics combined with a small weight. This is why they are now extensively introduced in the critical bearing elements of the space- and aircraft structures, in shipbuilding, and in transport and gradually replace traditional metal alloys. There are two main types of joints of composite structural elements with each other and with the metals, namely, adhesive (glued) and mechanical joints. The mechanical joints can be either bolted or riveted. The bolted joints are actually more technological and cost efficient, low-sensitive to the action of temperature and atmosphere, and are suitable for nondestructive demounting. As one of the main disadvantages of these joints, we can mention a significant brittleness of the polymeric matrix and a large anisotropy of the mechanical properties of composites, which should be taken into account in the design. Moreover, in this case, it is also necessary to increase the safety margins for joints, which complicates the application of PCM in the structures [1].

The standard experimental approaches to the evaluation of the strength of the bolted joints of PCM via the geometric parameters and loading modes give fairly contradictory results [2, 3]. This is why it is especially important to develop the numerical-experimental methods and engineering means aimed at the determination of the stress-strain state and permissible bearing stresses in bolted joints of the laminates by the methods of speckle metrology [4]. The required strength of composite–metal joints of this kind can be guaranteed if the working stresses acting in the contact zone do not exceed the permissible bearing stresses of the PCM.

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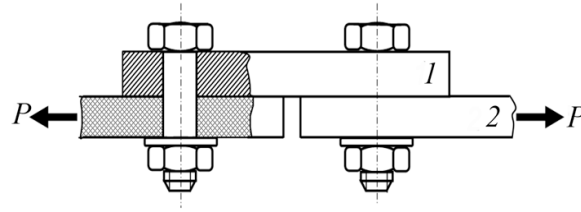


Fig. 1. Experimental model of loading of a composite specimen corresponding to a single-shear bolted joint: (1) metal; (2) composite.

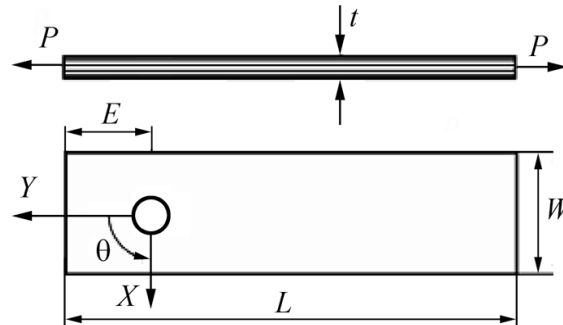


Fig. 2. Schematic diagram of the experimental specimen.

In what follows, by the method of digital image correlation (DIC), we obtain the distributions of stresses and strains in single and many-row bolted composite–metal joints and determine the bearing strength of these joints.

Formulation of the Problem

Actual bolted composite–metal joints most often contain from several bolts to several dozens of bolts located either in a single row or in several rows. Under the assumption that the distance between the bolts is sufficiently large, the maximum bearing capacity of these joints can be found, with a sufficiently high accuracy, according to the bearing strength of a specimen with single (isolated) hole and contact through the bolt (Fig. 1). This is why the indicated assumptions are basic for the evaluation of strength of the composite in a many-row joint [5]. In this case, the bolt is often simulated by a rod made either of alloyed steel or of titanium.

Specimens, Methods, and Results

We determine the bearing strength of a 12-layer ELUR–008P/BN-type carbon fiber-reinforced plastic composite with a $\pm 45^\circ$ scheme of arrangement of the reinforcement. Plane specimens of length $L = 135$ mm, width $W = 30$ mm, and thickness $t = 3.4$ mm with calibrated holes $d = 6$ mm in diameter in the working part of the specimen were produced according to the recommendations of the ASTM D 5961/5961M–01 [6]. Protective aluminum straps 1.5 mm in thickness were glued on both sides of the gripped part of the specimen (Fig. 2). For the unambiguous evaluation of permissible bearing stresses in the composite, it is necessary to establish the maximum permissible level of strains in the material. In the analyzed case, this is the degree of ovalization of the contact hole, which should not exceed 2% for the layered PCM [5, 6].

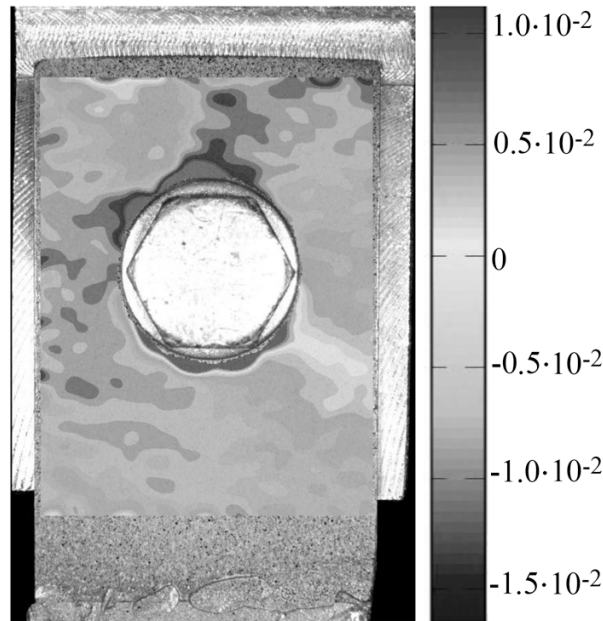


Fig. 3. Distribution of local strains ε_{yy} in the contact zone corresponding to a 2% ovalization of the hole.

Prior to testing, the edge of the specimen with protective straps was fixed by the bottom moving wedge grips of an FP-100 universal tensile-testing machine. To load the specimen, a contact element (CE) in the form of a steel bolt with a diameter $d = 6$ mm was placed in the hole. With the help of this element, the specimen was fixed in the plane of the top immobile grip (Fig. 3). In the course of stretching performed for a speed of motion of the cross-piece equal to 1 mm/min, the immobile CE deforms the hole. To determine the level of strains in the composite–metal contact zone, we used the DIC method, i.e., compared the speckle images of the specimen surface in the intact state and after loading [7]. The fields of displacements and local strains were found for all stages of loading according to the obtained digital images (Fig. 3).

The bearing stress in the bolted joint of the composite was found by using the well-known methods [7–9]. The fracture diagrams of the composite specimen were plotted on the "load–ovalization of the hole" (P – d) and stress–strain (σ – ε_{yy}) coordinates (Fig. 4). The permissible bearing stresses corresponding to the deformation of the contact hole by 2% are given by the following formula:

$$[\sigma_B] = \frac{P_{cr}}{d \cdot t},$$

where P_{cr} is the critical bearing force; d is the diameter of the hole, and t is the thickness of the composite specimen. The results of experimental investigations are presented in Table 1.

The developed procedure was used to determine permissible bearing stresses for a two-row bolted composite–metal joint. For this purpose, a series of specimens was made from the same material as the specimens with a single hole. These specimens were prepared in the form of two plates made of ELUR–008P/BN carbon fiber-reinforced plastic of length $L = 200$ mm, width $W = 100$ mm, and thickness $t = 3.4$ mm connected by two rows of M6 steel bolts with the help of a flat duralumin strap with a thickness of 5 mm (Fig. 5), which corresponds to the operating conditions of the actual structures.

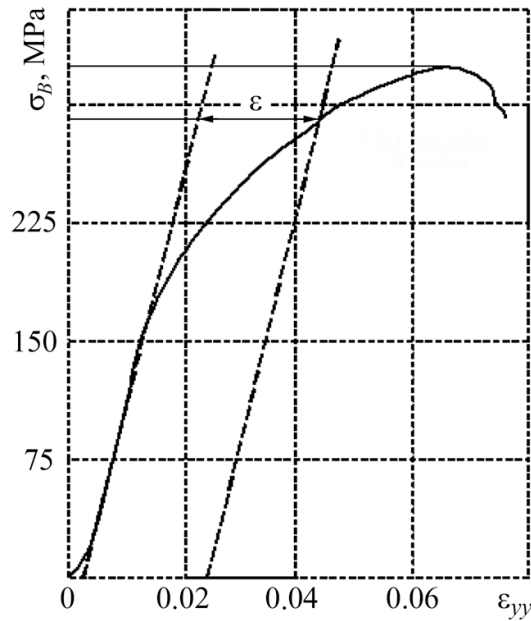


Fig. 4. Typical diagram of bearing for a single bolted composite-metal joint; ε is the deformation of the contact hole equal to 2%.

Table 1
Bearing Strains and Stresses for a Single Bolted Joint

No. of specimen	ε_{yy}	P_{cr} , N	$[\sigma_B]$, MPa
1	$2.01 \cdot 10^{-2}$	5100	250
2	$1.98 \cdot 10^{-2}$	5018	246
3	$2.02 \cdot 10^{-2}$	5385	264
4	$2.00 \cdot 10^{-2}$	5059	248
5	$2.03 \cdot 10^{-2}$	5610	275

The length of the working part of the specimen is $l = 160$ mm. To prevent fracture in the wedge grips of the tensile-testing machine, the protective fiberglass straps 120 mm in length were pasted to the edges of the specimen. To prevent the influence of bending moment at the joint of the laminate plates in the course of stretching of the specimen, we used protective straps of different thicknesses: 5 mm on the duralumin plate and 1.6 mm on the opposite side. During the tests, the specimen was fixed in the wedge grips of the EUS-20 tensile-testing machine and stretched at a rate of 1 mm/min. By using the DIC method, we obtained a general pattern of the distribution of strains in the vicinity of all bolts connecting two laminate plates under different loads (Fig. 6).

The strains ε_{yy} at the contact points of the specimen were determined according to the scale depicted in Fig. 3, which is identical to the scale in Fig. 6, whereas the bearing strength σ_u (Table 2) for a single bolted joint was found according to the σ - ε_{yy} diagram (see Fig. 4).



Fig. 5. General view of a composite specimen with two-row bolted joint.

Table 2
Bearing Strains and Stresses for a Two-Row Bolted Joint (Specimen No. 1)

Joint (see Fig. 6)	ε_{yy}	$[\sigma_B]$, MPa
1a	$0.61 \cdot 10^{-2}$	200
2a	$1.80 \cdot 10^{-2}$	225
3a	$0.51 \cdot 10^{-2}$	185
4a	$0.11 \cdot 10^{-2}$	105
5a	$0.50 \cdot 10^{-2}$	180
1b	$2.04 \cdot 10^{-2}$	246
2b	$2.10 \cdot 10^{-2}$	284
3b	$0.50 \cdot 10^{-2}$	190
4b	$2.00 \cdot 10^{-2}$	242
5b	$2.15 \cdot 10^{-2}$	290

It was established (Fig. 6) that the laminate in the zone of steel bolts connecting two parts of the composite specimen deforms in different way. This can be explained by the nonuniformity of tightening of the bolts and the misalignment of holes in the composite and duralumin plates. In the vicinities of the bolted joints 1b, 2b, 4b, 5b, and 2a, we recorded higher strains. This means that, in this case, the maximum permissible ovalization of holes can be attained faster. Comparing the distributions of strains near the contact points in the many-row bolted joint and in the specimen with single contact, we revealed an insignificant difference between these distributions caused by the mutual influence of strains in closely located bolts. These features should be taken into account in choosing the geometry of arrangement of bolts and the distance between the rows of bolts in designing the detachable many-row bolted joints.

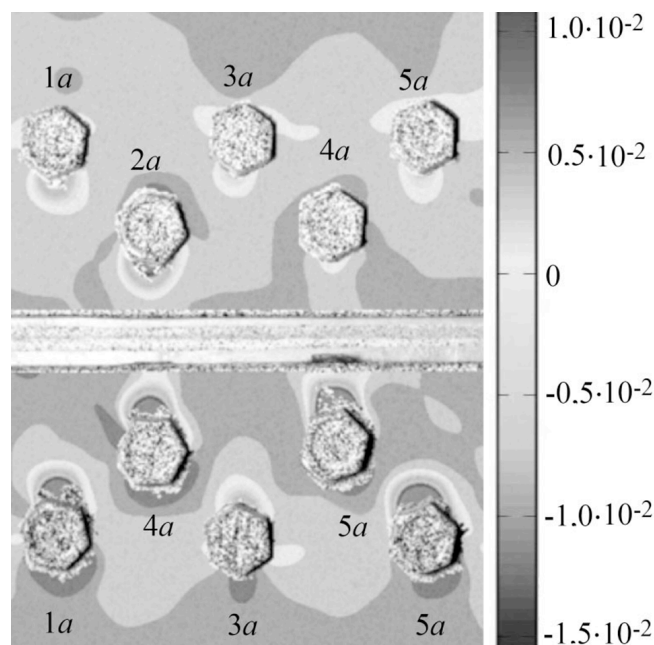


Fig. 6. Distribution of strains ε_{yy} over the surface of a composite specimen with $\pm 45^\circ$ scheme of reinforcement under the maximal load.

By comparing the distributions of local strains in the contact zones of two-row and single bolted joints, we determined the maximum permissible bearing stresses in the actual many-row joints of the identical PCM.

CONCLUSIONS

By comparing the bearing stresses obtained for a standard composite specimen with a single bolt, we determined their permissible values in many-row bolted composite-metal joints by the method of digital correlation processing of the images of the surfaces. The proposed method was experimentally checked by testing specimens made of ELUR-008P/BN layered carbon fiber-reinforced plastic composite materials with $\pm 45^\circ$ scheme of reinforcement.

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