A REFINED STRESS-STRAIN ANALYSIS IN THE LOAD TRANSFER ZONE OF FLAT SPECIMENS OF HIGH-STRENGTH UNIDIRECTIONAL COMPOSITES IN UNIAXIAL TENSION

1. THEORETICAL ANALYSIS

G. G. Portnov, V. L. Kulakov, and A. K. Arnautov

Keywords: uniaxial tension, unidirectional composite, stress concentration

With the use of an analytical approach developed, the influence of distribution of a tangential load on the stress concentration in uniaxially tensioned flat specimens of high-strength unidirectional composites near the grips of a testing machine is evaluated. In view of singularity of the analytical solution derived at the points of discontinuity of boundary conditions, for estimating the stress concentration, it is suggested to employ the averaged value of longitudinal stresses, which is calculated by means of an improper integral across the thickness of a near-surface layer.

Introduction

A reliable determination of mechanical properties, especially the strength, of structural materials is of primary importance for designing force elements of critical constructions. The static uniaxial tension tests on unidirectional composites with highly anisotropic elastic and strength properties have always been associated with considerable complications [1]. In the last years, the development of more perfect reinforcing fibers and binders, as well as the methods for their processing, such as pultrusion, promoted the creation of high-strength unidirectional composites, in particular, carbon-fiber-reinforced plastics (CFRP), which makes such tests even more complicated than before.

The tensile tests on a GRAFIL 34-700/EPON 9310 unidirectional epoxy CFRP, which was chosen for use in pilot models of flexible deep-water risers [2], gave quite unexpected results for its longitudinal tensile strength $\sigma_{xtu}$. In uniaxial tension along the stacking of fibers of nonstandard CFRP specimens in the form of round rods 1.88 mm in diameter, at a distance of 130 mm between the grips of a testing machine, it was found that $\sigma_{xtu (rd)} = 2977.0 \pm 80$ MPa [2]. However, in the structure of a flexible riser designed, the axial loads are taken up by a layer of flat tapes made of a unidirectional CFRP stacked at an angle to the longitudinal axis of the riser. Therefore, standard flat specimens were also tested in uniaxial tension along the fibers (according to the ASTM standard [3]). Their strength proved to be $\sigma_{xtu (fl)} = 2177.0 \pm 188$ MPa [4]. As a statistical estimation shows, at the relatively small coefficients of variation (5.0 and 8.6%, respectively), the 33% difference is undoubtedly signifi-
cant. We should note that the CFRPs of plane and cylindrical configurations were made in the same way — by pultrusion. Thus, in specimens of both the types, the fibers were straightened and tensioned, and their volume content was practically identical. The photos of destroyed specimens are shown in Fig. 1.

Such a great difference in the strength of specimens made of one and the same composite, but of considerably different geometrical forms, first of all, might be explained by the “scale effect”, since the stressed volume of the flat standard specimen 2.9 times exceeded that of the round rod. However, the calculations performed according to the procedure described in [5] showed that, at the variation in measured parameters mentioned and the distinction in the stressed volumes, a possible difference in the strength must not exceed 6-10%, which is much less than the 33% obtained.

The basic problem in uniaxial tension of unidirectional composites is connected with the way the external load is transferred to the test specimen. The mechanical or hydraulic wedge grips of a testing machine clamping the ends of a specimen, through friction, create shear forces on the specimen surface, which produce a tensile load in the working zone of the specimen. The tests on a high-strength unidirectional composite require the application of very high transverse compression forces to hold a specimen in grips and to achieve the ultimate longitudinal breaking stress in the working zone of the specimen, but the relatively low strength of unidirectional composites in transverse compression restricts their allowable value. To exclude the possibility of squashing or splitting the specimen in grips, its ends are protected by cover plates pasted with a structural adhesive. However, as numerical finite-element calculations have shown, this inevitably leads to a high concentration of all stresses operating near the forward edges of the cover plates [6-8].

For the flat standard specimens, 1.5-mm-thick cover plates made of a glass-fabric-based plastic were used, which were pasted with a structural polyurethane adhesive. The ends of the round specimens were strengthened with a woven glass tape impregnated with an epoxy compound, which was wound on them with a small tension up to a diameter of 5 mm. In addition, in testing the flat and round specimens, different wedge inserts (plane and prismatic, respectively) with notches for wedge