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Residual deformations in obliquely reinforced fibrous composites: experiments on cyclic stretching

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Abstract. Experimental studies of test samples from a obliquely reinforced composite based on carbon tape on cyclic stretching were carried out. It is established that the loading and unloading branches do not coincide, forming a hysteresis loop, and the axial deformation at each subsequent cycle at the same stress level in the cycle gains an increment that decreases in the initial cycles and tends to a constant value with a further increase in the number of cycles. This process is called the process of adaptability of the composite material. On the basis of tests on multi-cycle stretching of a composite with an aging after unloading, a viscoelastic component was distinguished from accumulated strain at each loading cycle. It is shown that at the initial cycles, the total strain accumulated in the sample by the end of the unloading process can be represented as a sum consisting of residual strain formed due to structural changes in the composite and creep deformation that disappears in the sample after unloading and holding during a long time.

1. Formulation of the problem
The special purpose space engineering products are currently widely used structural elements made of fibrous composite materials [1-8], in particular, carbon fiber, which, during operation with multiple (multi-cycle) loading (in particular, thermal), must maintain the stability of geometric dimensions and forms. It was found that during ground tests of such products and during their operation, distortions of measured parameters are always recorded, apparently due to the formation of residual deformations in the structure. All mechanisms for the formation of such residual deformations in fibrous composites during the operation of structural elements made from them have not yet been fully identified, which raises an actual problem in world science in the field of mechanics and mechanical engineering.

2. Cyclic deformation experiments
Extensive scientific literature is devoted to the study of the nonlinear deformation of unidirectional fibrous composites [9–20]. In particular, in [9], such a study is carried out for a unidirectional composite based on glass fibers under shear conditions under repeated cyclic loading of test samples with a stacking scheme \([+45^\circ,-45^\circ]_s\) \((s \) is the number of monolayers). Based on the obtained experimental data, the secant shear modulus \(G_{12}\) is calculated and a conclusion is made about its fall after loading the sample with ten cycles. The authors explain the fall in the shear modulus by the
degradation of the composite under the conditions of the shear deformations that are formed in the composite.

Studies shear test samples of fibrous composites with polymeric matrix show [11, 21] that the relationships between the tangential stresses and corresponding shear deformations are substantially non-linear in terms of loading and subsequent unloading significantly differ among themselves, thus they are always fixed permanent deformation. In particular, such studies were carried out on the nonlinear deformation of a unidirectional fiber composite based on ELUR-P carbon tape and HT-118 [22, 23] binder under shear conditions under repeated loading by tensile and compression tests of test samples with a stacking pattern \([+45^\circ,-45^\circ]\)\(_{2s}\). For tensile tests, test samples \([+45^\circ,-45^\circ]\)\(_{2s}\), \(s = 2\), with an average thickness of \(h = 0.56\) mm, a width of \(b = 24.60\) mm, and a length of the working part of \(l = 110\) mm were used. For compression tests, samples were made with an average thickness \(h = 4.12\) of mm, a width of \(b = 24.91\) mm and a length of the working part of \(l = 25\) mm.

When stretching a package of layers with the above laying pattern, both the fiber and the binder in the axes of orthotropy are under tension in the direction of the fibers and shear by tangential stresses, and when compressing a package of layers, they are under compression and shear by tangential stresses. The experiment was carried out under the conditions of the same maximum normal stresses \(\sigma_x\) in each “load-unload” cycle. This type of loading is quite accurately equivalent to the operation of the composite in a real design, where the stresses should not exceed their certain predetermined (operational) values.

With the previously found value of the limiting (destructive) stress \(\sigma_x^B\) in the case of tensile testing by multiple loading, the samples were brought to stresses \(\sigma_{x\max} = 0.7\sigma_x^B\) whose magnitude was \(\sigma_{x\max} = 65\) MPa. Measurement of axial deformations was carried out using a contact extensometer with a base of measurement 50mm.

The deformation diagrams obtained under the conditions of stretching by “load-unloading” cycles with the traverse speed of movement 0.5mm / min are shown in Figure 1 for samples \([+45^\circ,-45^\circ]\)\(_{2s}\), \(s = 2\), aged eight months after their manufacture. It can be seen that the loading and unloading branches do not coincide, forming a hysteresis loop, and the axial deformation \(\varepsilon_x\) at each subsequent cycle with the same \(\sigma_x\) in cycle increases by the value \(\Delta\varepsilon_x^{(i)}\), where \(i\) is the cycle number. With an increase in the number of cycles, the value of \(\Delta\varepsilon_x^{(i)}\) decreases, which indicates the process of hardening the fiber composite at each loading cycle. Such a process is called the process of adaptability of the composite material. It should be noted that for a given \(\sigma_{x\max} < 0.7\sigma_x^B\) there exists a limit number of cycles \(i = N\) for which \(\Delta\varepsilon_x^{(N)} \rightarrow 0\), where \(\Delta\varepsilon_x\) does not depend on the number of cycles, but depends on the loading rate.

![Figure 1](image-url)
3. Residual deformations of the adaptability of the hereditary viscoelastic composite

Extensive scientific literature is devoted to the studies of the viscoelastic behavior of fibrous composite materials with a polymer matrix. It is known that, in the loaded state, viscoelastic creep deformations form in the polymer matrix, which are reversible to certain stress levels. In order to isolate them from the dependences shown in Figure 1, special experimental studies of the test samples described above, aged eighteen months after manufacturing, were carried out for cyclic stretching. For all cycles of loading and unloading, the dependences of the strain on time were obtained for the kinematic loading of a sample at a speed of 0.5 mm / min, and the dependences of stress on time corresponding to such loading. In order to exclude possible bending deformations and the appearance of noise on the readings of the strain gauge after loading up to $\sigma_x^+ = 45$ MPa, the sample was unloaded by the kinematic method up to $\sigma_x^- = 1.5$ MPa. It has been established that from the moment of time $t = 120$ sec and further, the reversible part of the deformation is clearly fixed, due to the viscoelastic behavior of the material. The “machine” deformation diagram corresponding to the above dependences is shown in Figure 2, and in Figure 3 it is shown on a different scale for clarity. In these figures, the “●” marker and the point $B_1$ correspond to the time $t = 120$ sec, and the “△” marker and the point $B'_1$ dot to the time $t = 24$ hour, when the process of reverse recovery of the sample due to viscous creep deformations can be considered complete. Obviously, it is permissible to assume that without the viscous properties of the binder on the dependency $\sigma_x = \sigma_x(\varepsilon_x)$, after 60 seconds instead of point $A_1$, we would have to get the point $A'_1$, and after unloading the sample after 60 sec to get point $B'_1$ instead of point $B_1$. After extrapolating the curve $AB$ on the axis $O\varepsilon_x$, we find point $\varepsilon_x^{(1)} = \Delta\varepsilon_x^{(1)}$ and, having drawn a line through the points $A', B'$, we find the point $\Delta\varepsilon_x^{(r)}$.

Thus, the total deformation $\varepsilon_x^{(1)}$ accumulated by a time of $t = 120$ sec can be represented as $\varepsilon_x^{(1)} = \varepsilon_{\text{rec}}^{(1)} + \varepsilon_{\text{cre}}^{(1)}$, considering it to consist of residual deformation $\varepsilon_{\text{rec}}^{(1)}$ formed due to structural changes in the composite, and creep deformation $\varepsilon_{\text{cre}}^{(1)}$ that disappears in the sample after its unloading and aging in for a long time.

The equations of straight lines of the first cycle passing through points $O, A'_1$ and points $A'_1, B'_1$, we write in the form $\sigma_x^{(1)} = E_x^{(1)} \varepsilon_x^{(1)}$, $E_x^{(1)} = \tan \phi_x^{(1)}$, introducing into consideration the secant modulus of elasticity $E_x^{(1)}$ at the loading stage, and in the form $\sigma_x^{(1)} = E_x^{(1)} \varepsilon_x^{(1)}$, $E_x^{(1)} = \tan \phi_x^{(1)}$, introducing into consideration the positive characteristic $p_x^{(1)}$ and secant modulus of elasticity $E_x^{(1)}$ at the unloading stage. Note that the dependences are the physical relations that connect the stresses and strains in the process of loading and unloading the sample without taking into account the viscoelastic properties of
the material. Under the condition $\sigma_+^{(i)} = 0$ (after complete unloading of the sample), the second relation is followed by the formula $\varepsilon_{\text{res}}^{(i)} = p_i^{(i)} / E_i^{(i)}$, which allows determining the residual deformation during the first cycle of loading and unloading after prolonged aging and removal of the external load.

Repeating multiple cycles kinematic loading and unloading of the sample with the same velocity, after aging for 24 hours after each cycle fix the results of experiments in the form of parameters $p_i^{(i)}, p_i^{(i)}, E_i^{(i)}, E_i^{(i)}, \Delta \varepsilon_{\text{res}}^{(i)}, \Delta \varepsilon_{\text{cre}}^{(i)}$ shown in the table 1.

| $i$ | $E_i^{(i)}$, GPa | $p_i^{(i)}$, MPa | $E_i^{(i)}$, GPa | $p_i^{(i)}$, MPa | $\Delta \varepsilon_{\text{res}}^{(i)} \cdot 10^4$ | $\Delta \varepsilon_{\text{cre}}^{(i)} \cdot 10^4$ |
|-----|----------------|-----------------|----------------|----------------|----------------------------|----------------------------|
| 1   | 10,103         | 0               | 10,416         | -1,392         | 1.3                       | 1.1                       |
| 2   | 10,297         | -1,446          | 10,412         | -1,965         | 1.9                       | 1.4                       |
| 3   | 10,390         | -2,068          | 10,445         | -2,319         | 2.2                       | 1.6                       |
| 4   | 10,496         | -2,375          | 10,483         | -2,315         | 2.2                       | 1.8                       |
| 5   | 10,429         | -2,342          | 10,457         | -2,466         | 2.4                       | 1.7                       |
| 6   | 10,452         | -2,464          | 10,502         | -2,688         | 2.6                       | 1.6                       |
| 7   | 10,486         | -2,729          | 10,483         | -2,712         | 2.6                       | 1.7                       |

Analyzing the obtained results, it can be seen that the changes of parameters $E_i^{(i)}$ and $E_i^{(i)}$ from cycle to cycle are insignificant, and the almost complete stabilization of parameters $p_i^{(i)}, p_i^{(i)}, E_i^{(i)}, E_i^{(i)}, \Delta \varepsilon_{\text{res}}^{(i)}, \Delta \varepsilon_{\text{cre}}^{(i)}$ occurs in the fifth to seventh loading cycles. Significant changes in creep deformation $\Delta \varepsilon_{\text{cre}}^{(i)}$ are observed in the first and second loading-unloading cycles, corresponding to the unsteady creep stage, the formation of creep deformations with parameter $\Delta \varepsilon_{\text{cre}}^{(i)} \approx 1.7 \cdot 10^{-4}$, apparently, occurs at the steady-state creep stage of the binder material. As a result, within a certain $i$-th cycle of loading and unloading, the dependencies between stresses $\sigma_i^{(i)}, \sigma_i^{(i)}$ and strains $\varepsilon_i^{(i)}$ formed in the composite without creep deformations and accompanied by structural changes can be written in the linear approximation as $\sigma_i^{(i)} = -p_i^{(i)} + E_i^{(i)} \varepsilon_i^{(i)}, \sigma_i^{(i)} = -p_i^{(i)} + E_i^{(i)} \varepsilon_i^{(i)}$.

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