Introduction. One of the directions of the development of engineer durability calculations of structural elements theory is consideration of their rheonomous properties in order to describe the processes of long-term deformation and destruction. From the one hand, for calculating creep and long-term durability of structural elements it is necessary to use the equation of mechanical states which describes complicated deformation processes. From the other hand, kinematic equation of damages should be used in deformation type. The materials show rheonomous and hereditary features in deformation processes as well as in long-term destruction. Despite of the fact that there are a lot of theoretical and experimental researches, the question of choosing adequate description method of deformational processes for different classes of polymer materials under non-stationary loading and complex stress cannot be finally solved.
especially in the most complex thermomechanical loadings [1–7]. The requirements of practical applicability for the resulting mechanical state equation in some cases of cyclic loading makes us to make a compromise in accuracy while describing complex deformation processes. The task is to reduce this compromise to the logical minimum.

The development of cyclic creep model provides new opportunities for experimental research task formulation, makes experiment purposeful and allows to choose test program for checking the theory.

**Research targets.** Studies of creep of partially crystal polymer and composite materials on polymer base remain topical. The influence of complex static and cyclic stress state and non-stationary loading conditions on deformation process mostly remains unclear.

Research targets are:
1. According to the short-term monotonic loading tests data, to make up an equation of mechanical states in terms of real stresses and deformations under complex stress state for direct and reverse creep for three modifications of tetrafluoroethylene.
2. To research and to describe creep of the same materials under non-stationary static and cyclic stationary and non-stationary loading.
3. To make a conclusion about the possibility of formalization of destruction deformation criteria for studied materials.

**Materials and testing method with predetermined intensity of real stresses.** The samples were made of pipe blanks of polytetrafluoroethylene F-4, F-4D by turning on the lathe tool and part of F-4D blanks were annealed; F-4D blanks were heated until 80 °C with the following cooling in the heating stove. The degree of materials’ crystallinity was detected by German – Weidinger’s method and it is: 30% for F-4, 45% for F-4D, 38% for inner surface of F-4D, 25% for outer surface of F-4D.

The thickness of the wall was measured from the condition of constant value. The ratio between main stress values is close to equiaxial tension and the lowest – tangential stresses (\( n = \sigma_{x}/\sigma_{0} \)) were measured with considering current values of outer diameter (\( D \)) and thickness of the wall (t). The thickness of the wall was measured from the condition of constant value.

The intensity of real (logarithmic) stresses were obtained by formula:

\[
\sigma_{l} = \frac{1}{\sqrt{2}} \sqrt{(\sigma_{x} - \sigma_{0})^{2} + (\sigma_{y} - \sigma_{0})^{2} + (\sigma_{z} - \sigma_{0})^{2}}. \tag{1}
\]

Real stress components (axial \( \sigma_{x} \) and tangential \( \sigma_{0} \)) were measured with considering current values of outer diameter (\( D \)) and thickness of the wall (t). The thickness of the wall was measured from the condition of constant value. The ratio between main stress components \( n = \sigma_{x}/\sigma_{0} \) was established by choice of equipment plunger pair [25]. The delay time of equipment adjustment was not exceed 2 minutes, besides the fluctuations of stress intensity were not exceed 5% from set value of stress intensity \( \sigma_{l} \) and fluctuations \( n \) were not exceed 6%.

Obtained experimental data under short time loading and creep with static loading are presented in the form of deformation curves in coordinates \( \varepsilon_{l} - \varepsilon_{0} \) and creep curves in coordinates \( \varepsilon_{l}^{\max} - \tau \). The intensity of real (logarithmic) stresses were obtained by formula:

\[
\varepsilon_{l} = \frac{1}{2} \sqrt{(\varepsilon_{x} - \varepsilon_{0})^{2} + (\varepsilon_{y} - \varepsilon_{0})^{2} + (\varepsilon_{z} - \varepsilon_{0})^{2}}. \tag{3}
\]

Real deformation components \( \varepsilon_{x}, \varepsilon_{y}, \varepsilon_{z} \) were obtained by following dependences, considering current sample dimensions \( D, t \) and current base \( l \) (the sample length):

\[
\varepsilon_{x} = \ln \frac{l}{l_{0}}; \quad \varepsilon_{y} = \ln \frac{D - r}{D_{0} - r}; \quad \varepsilon_{z} = \ln \frac{D}{D_{0}}. \tag{4}
\]

Lode’s parameter for stresses is calculating:

\[
\mu_{s} = 2 \frac{\sigma_{z}}{\sigma_{0}} - 1 \mu_{s} = 2 \frac{\sigma_{z}}{\sigma_{l}} - 1, \tag{5}
\]

where \( \sigma_{l} \) and \( \sigma_{0} \) – the main stresses.

**Tests results.** Polytetrafluoroethylene deformation under short time loading. Short time loading PTFE deformation tests were held under linear and flat stress states with various ratios of axial and tangential stresses \( n = \sigma_{x}/\sigma_{0} \) in conditions of proportional loading. For PTFE there is an influence of stress state type on deformation curve, besides the material shows the highest rigidity when the ratio \( \sigma_{x}/\sigma_{0} \) is close to equiaxial tension and the lowest – when it is under linear stress state. The variation of
the loading speed from 0.03 MPa/sec. to 0.3 MPa/sec. influences on the deformation curves insignificantly.

The law of immediate deformation was studied by tests on the fast sample unloading from the fixed level of stress intensity under various types of stress state. Non-linear dependences of instantly elastic deformation from stress intensities for studied fluoroplastics are presented in an article [26]. According to the results of the measurements, the transverse deformation coefficient values under axial tension are vary from 0.3 to 0.48.

For the selection of the law of instant plastic deformation (the term is conditional) the data of the tests on the multiple loading with the speed \( d\sigma_i/dt = 0.1–0.3 \) MPa/sec., with the registration of the \( \sigma_i \) and \( \varepsilon_i \) levels and further instant sample unloading was used. After exposure of at least one hour, permanent (instant elastic) deformations were measured. The dependence of instant plastic fluoroplastics deformations from the stress intensity is presented in the article [27]. Instant plastic deformations of fluoroplastics depend on the type of the stress state.

**Direct and reverse creep under static loading.** Direct creep is the increase of deformations in time under permanent real stresses (i.e. under constantly decreasing loads) (fig. 1–3). Complete deformation is the sum of four components: instant elastic, instant plastic, viscoplastic, viscoelastic [7–13]. To study viscoelastic creep deformation the tests on reverse creep (fig. 4–6) were held (returning after loading).
As a result, the complete equation of mechanical states in stress and deformation intensities ($\sigma_i$, $\varepsilon_i$) under stationary loading was obtained, besides the condition of deformation speeds and stress deviators similarity is observed [27]:

$$
\varepsilon_i = \frac{2(1+\nu)\sigma_i}{3E_0(1-2\nu)} + \gamma \left[ (\alpha - \beta \mu) e^{m(\sigma_i)} - 1 \right] + \\
+ \int_0^\gamma (\nu - \mu_5) e^{\frac{\sigma_i}{\sigma}} \left[ A_1 e^{-t \gamma} + A_2 e^{-\frac{t}{\mu_5}} \right] d\theta + \\
+ \int_0^\gamma (d - \mu_5) k \left( \frac{\sigma_i}{\sigma} - \delta \right) \left[ A_3 e^{\frac{\gamma}{\sigma}} \right] d\tau. \tag{6}
$$

Table 1

| Parameters | Studied materials |
|------------|-------------------|
| $E_0$, MPa | F-4 | F-4D | F-4D_0 |
| 800        | 900 | 615  |
| $\sigma_{\infty}$, MPa | 27.5 | 28.5 | 22.5 |
| $\nu$ | 0.48/0.50 | 0.48/0.50 | 0.48/0.50 |
| $\gamma$ | 1·10^{-2} | 1·10^{-2} | 1·10^{-2} |
| $\alpha$ | 0.05 | 0.20 | 0.25 |
| $\beta$ | 0.03 | 0.06 | 0.08 |
| $m$ | 2.80 | 1.65 | 2.20 |
| $\sigma_{\infty}$, MPa | 10 | 10 | 10 |
| $a$ | 1 | 1 | 1 |
| $b$ | 0.1 | 0.1 | 0.6 |
| $c$ | 0.30 | 0.08 | 0.26 |
| $n$ | 3.2 | 3.7 | 2.8 |
| $A_1$ | 5.5·10^{-2} | 11·10^{-4} | 9.5·10^{-4} |
| $A_2$ | 1.7·10^{-2} | 1.8·10^{-4} | 1.8·10^{-4} |
| $\mu_1$, sec. | 110 | 110 | 85 |
| $\mu_2$, sec. | 2475 | 3200 | 3000 |
| $A_3$ | 7·10^{-6} | 14·10^{-6} | 26·10^{-6} |
| $\delta$ | 1.05 | 1.18 | 1.17 |
| $A_4$ | 14.0·10^{-3} | 14.1·10^{-3} | 1.5·10^{-3} |

**Non-stationary static loading modes of studying materials.** Non-stationary static loading modes are presented on the fig. 7–10. Here also the dependences of real deformations from time are shown. According to the comparison of experimental and calculated data, generally, the calculation reproduces the creep process under complex loading mode with satisfactory accuracy. The experiment showed, that the differences are mostly connected with insufficient accuracy in approximation of functions $A_1 e^{-t \gamma} + A_2 e^{-\frac{t}{\mu_5}}$. To describe viscoelastic component of the complete deformation in this function, it is necessary to take more than two exponents. One of the additional exponents has to have the relaxation time in the following interval: $10^{-10}$ sec. $\leq \mu \leq 15·10^3$ sec.
Creep under cyclic loading with various frequencies. Fluoroplastics F-4, F-4D, F-4D₀ creep under cyclic loading with the frequencies 2.4 Hz, 5.0 Hz and 10.0 Hz were tested in the conditions of maximum per cycle intensity constancy with the cycle asymmetric coefficient \( \tau = \frac{\sigma_{i}^{\min} - \sigma_{i}^{\max}}{\sigma_{i}^{\max} - \sigma_{i}^{\min}} = 0.5 \) and temperature 22 ± 1 °C (fig. 14–16). The form of the cycle is sinusoidal. To compare creep complete deformations under static and cyclic loadings, isochronous dependences were made \( \sigma - \varepsilon \) and \( \sigma_{\max}^{\max} - \varepsilon_{\max}^{\max} \) while obtaining the creep time \( t = 5 \cdot 10^3 \text{ sec.} \) (fig. 11–13).
Огородов Л.И., Николаева И.П., Яковлева Е.Л., Фоминых О.В. Строительная механика инженерных конструкций и сооружений. 2018. Т. 14. № 3. С. 216–225

**Строительная механика инженерных конструкций и сооружений. 2018. Т. 14. № 3. С. 216–225**

ЭКСПЕРИМЕНТАЛЬНЫЕ ИССЛЕДОВАНИЯ

Fig. 16. The maximum stress intensity dependence from the maximum deformation intensity F-4D with $\tau_1 = 5000$ sec. ($n = \infty$):
- $f = 0$; $\bullet$ - $f = 0$ Hz; $\circ$ - $f = 1.2$ Hz; $\Delta$ - $f = 10$ Hz; $\nabla$ - $f = 5$ Hz with $n = 2.8$

Thus, experimental points of the same material and type of stress state under frequencies of 2.5 and 5.0 Hz do not completely match to the experimental ones under stationary static loading. It is also noticeable that the material rigidity tends to increase under cyclic loading in comparison with static one, if the maximum variable stress intensity during the cycle equals to the intensity of permanent stresses under stationary loading. Besides, in comparison with static loading and frequencies of 2.5 Hz and 5.0 Hz, under frequencies of 10 Hz there is a significant rigidity increase. The most valuable increase of the material rigidity is when $n = \sigma_\infty / \sigma_0$ is close to $n = \infty$ (linear tension), i.e. under conditions, when under static loading there is the most intensive development of viscoplastic deformations.

The examples of the creep curves under cyclic loading are presented on the fig. 11–13, 17, 18. The nature of the curves differs from one for the static loading. Let us apply for cyclic loading the same equation as for various cases of static loading from the previous section. The instant elastic and instant plastic intensity deformation components are calculated from the maximum stresses per cycle and viscoelastic component is calculated directly by substitution of a variable $\sigma_\infty$ values in the equation:

$$\varepsilon_t^{VE} = (a - b\mu_\infty) \int_0^\tau C \left( \frac{\sigma_{max}}{\sigma_c} \right)^n k(\tau - \Delta) d\theta. \quad (7)$$

The calculation of the first three complete deformation components does not occur logical issues, but the calculation of viscoplastic component is not so obvious. After drafting series of attempts, the following empirical dependence for that component under cyclic loading was suggested:

$$\varepsilon_t^{max} = \frac{2(1+\psi)\sigma_{max}}{3E_1(1-2\nu_2)} + \gamma[(\alpha - \beta\mu_\infty)\alpha^m(\sigma_{max} - \sigma_\infty) - 1] +$$
$$+ (a - b\mu_\infty)\lambda_\infty C \left( \frac{\sigma_{max}}{\sigma_c} \right)^n \int_0^\tau A_1 e^{-\frac{\tau}{\tau_2}} + A_2 e^{-\frac{\tau}{\tau_4}} d\theta +$$
$$+ (a - b\mu_\infty)\lambda_\infty C \left( \frac{\sigma_{max}}{\sigma_c} \right)^n \int_0^\tau A_2 e^{-\frac{\tau}{\tau_6}} + A_4 e^{-\frac{\tau}{\tau_8}} d\tau,$$  \quad (8)

where $\lambda_\infty$ – is an empirical coefficient (for F-4 $\lambda_\infty = 0.58$, for F-4D $\lambda_\infty = 0.65$, for F-4D $\lambda_\infty = 0.5$).

The calculated according to this equation creep curves are presented on the fig. 20, 21.

Moreover, there was made an attempt to use that empirical dependency also for creep deformation presentation under non-stationary modes of cyclic loading as a several cycle blocks with variable values of $\sigma_{max}^{\infty}[30]$.

**Discussions. Ultimate deformation of fluoro-plastics under static and cyclic loading.** First of all, studying of ultimate deformation is important from an opportunity of formulation some deformation destruction criteria for polymer materials [7]. Experimental data about ultimate material deformation al-
allows to estimate objectively admissible creep deformation of structural elements. For the fluoroplastics in wide range of $n$ there is no ultimate deformation constancy [30]. In whole series of non-stationary loading cases the current deformations $\varepsilon_i (\varepsilon_{i,\text{max}})$ already reach the ultimate value zone on the first loading steps (fig. 19). That also attests against deformation destruction criteria.

![Fig. 19. Creep curves and loading mode ($n = 1.25$) of cyclic loading with the frequency of 5 Hz](image)

The study of PTFE F-4 sample failure mode is interesting. Under static loading with mostly tensile axial stress the destruction occurs along the transversal section of the tubular sample without visible localization of viscoplastic deformation (with the maintaining the assigned real stress considering the deformation changes). Under biaxial stress state, when $n = 1.25$, in the destruction place pores occurs, which means that the material is strongly loosened. Sometimes pores occurs in samples under axial tension. Probably, the loosening precedes the sample disruption along the plane of transverse section. Under cyclic loading the same material loosening occurs and only in some cases when $n = 1.25$ the failure mode differs from described. Under that conditions before the pores appearance a small bubble occurs on the surface of the damaged sample.

Experimental results can be used for estimation of structural elements rigidity.

**Conclusion.** Creep deformation of fluoroplastics (F-4, F-4D, F-4D$_0$) under stationary and non-stationary loading is satisfactory described by the equation of mechanical states, which considers instant elastic, viscoelastic, instant plastic and viscoplastic deformation components with the use of the volume constancy condition and the condition of stress and deformation deviators similarity. Also that deformations can be described with addition of special parameters, which are functions of the stress deviator form.

The speed of creep under cyclic loading with the constant sign of real stress intensities is lower, than the one under the same static loading when the intensity of permanent stresses $\sigma_i$ equals to the intensity of the maximum variable stresses $\sigma_{i,\text{max}}$. Frequency changing from 2.5 to 10 Hz does not cause any significant changing of polytetrafluoroethylene deformation properties, except the case of uniaxial tension with the frequency of 10 Hz, when the increase of the material rigidity occurs, in comparison with other frequencies and $n = \sigma_i / \sigma_0$ values during the experiment.

An application of the mechanical states equation, based on results of statistical test results, to the cyclic loading mode gives quite lower results of designed deformation creep values. Thus, an empirical amendment was suggested to that equation of mechanical states.

For fluoroplastics in quite wide range $n$ there is no constancy in ultimate deformations. The current deformations already reach the ultimate value zone on the first stages of loading, however, destruction does not occur. That also attests against deformation criteria of failure.

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**For citation**

Ogorodov L.I., Nickolaeva I.P., Yakovleva E.L., Fominykh O.V. (2018). Creep of polytetrafluoroethylene under various loading conditions. Structural Mechanics of Engineering Constructions and Buildings, 14(3), 216–225. DOI: 10.22363/1815-5235-2018-14-3-216-225.

**Для цитирования**

Ogorodov L.I., Nickolaeva I.P., Yakovleva E.L., Fominykh O.V. Creep of polytetrafluoroethylene under various loading conditions // Строительная механика инженерных конструкций и сооружений. 2018. Т. 14. № 3. С. 216–225. DOI: 10.22363/1815-5235-2018-14-3-216-225.