Estimation of the residual strength of supporting composite structural elements

R A Kayumov¹,², D E Strakhov¹, A M Sulejmanov¹ and E B Tuysina¹

¹Kazan State University of Architecture and Engineering, 1 Zelenaya st., Kazan, 420043, Russia
²Kazan National Research Technical University named after A.N.Tupolev, 68 K.Marks str., Kazan, 420015 Russia

E-mail: strachovde@mail.ru (D E Strakhov)

Abstract. The proposed study will allow us to develop a calculation method to predict the service life of fiberglass structures providing reliability and resistance; a design method for polymer composite structures taking into account damage accumulation and aggressive factors that affect the decrease in the strength of the studied material. The method of aging and failure of polymer composite materials was developed. The significance of the results for the construction industry lies in the development of a methodology for assessing the service life of fiberglass structures of the investigated building structures.

1. Introduction
Currently, the need for the use of load-bearing structural elements made of polymer composite materials has significantly increased. This necessitates studying the mechanisms of damage and its development that affect the load bearing capacity and durability of elements and compounds. The disadvantage of the methods for calculating such elements and compounds is the lack of accurate experimental data, as well as the variety of compositions of modified composites with different operational properties. The calculation of polymer composite materials for resistance and durability, a description of their rheological properties, assessment of the characteristics of long-term creep-rupture is an undeniable task today.

Pultrusion process is the most versatile and technological in production of various fiberglass elements of load-bearing structures. The manufactured products have fiberglass reinforcement in one direction in which the mass is pulled. The full range of effects on the polymer composite material during operation is temperature, aqueous, alkaline or acidic environment, the influence of the atmosphere, various biodeteriorations leading to climatic and natural aging [1-10].

The working capacity of the material is characterized by three qualitative characteristics - heat resistance, strength and durability, each of which is determined by a set of physical constants, where a change in one working parameter can be achieved by changing the other two [11]. Thus, experimentally determining the values of physical constants, it is possible to predict the durability of the material.
2. The study of flat elements reinforced with fiberglass

In this work, we investigate a polymer composite material in the form of flat extended elements reinforced with fiberglass. Research media were selected: air, distilled water and aqueous alkali solutions. It is known that when moisture penetrates PCM, weakening of bonds at the fiber-binder boundary occurs, microcracks appear [12-15], which leads to a decrease in strength. The first aqueous solution of alkali, modeling the liquid phase of concrete, adopted of NaOH – 8 g. and KOH – 22.4 g. per 1 liter of distilled water (GOST 31938-2012), the pH of the alkaline solution was in the range from 12.6 to 13. To exclude interaction of air with CO2 and evaporation, the alkaline solution was in a closed container. The concentration of the second aqueous solution was doubled. With the penetration of moisture into the PCM, weakening of bonds at the fiber-binder boundary occurs, microcracks appear [4–7], which leads to a decrease in strength.

The studied samples were deformed in the form of a three-hinged fastening (Figure 1), mechanical deformation was assumed to be 20, 30, and 60% of the destructive deformation. When conducting intermediate measurements the equipment was disassembled. After control measurements the equipment was reassembled. Test temperature accepted 18 ± 3 degrees. Samples were aged in selected media for 540 days with intermediate measurements. Measurements were carried out with KM-8 cathetometers with an accuracy of 0.001 mm.

The dependences of residual deformations on time are obtained (Figs. 2-5).

Figure 1. General view of the studied samples, the magnitude of the deflection of 30 mm, 25 mm and 15 mm (authors' illustration). General view of the studied samples, the magnitude of the deflection
Figure 2. Air environment, deformation height 30 mm, 25 mm and 15 mm, 538 days (authors’ illustration).

Figure 3. Aquatic environment, deformation height 30 mm, 25 mm and 15 mm, 538 days (authors’ illustration).

Figure 4. Alkaline composition, deformation height 30 mm, 25 mm and 15 mm, 538 days (authors’ illustration).

Figure 5. Doubled alkaline composition, deformation height 30 mm, 25 mm and 15 mm, 538 days. A sample 25 mm high collapsed during the test after 61 days (authors’ illustration).

3. Prediction of long-term strength of composite depending on temperature and stress level.
This section presents the results of studies of round rods. The tests were carried out at various levels of long-term static load and without it. The load was applied by the method of longitudinal bending [16-22]. The temperature was also used as a factor that naturally accelerates the aging of the material. In total, two types of tests were carried out:
Type 1: samples were kept in an alkali solution (GOST 31938-2012) at various temperatures of 20 °C, 40 °C, 50 °C, 60 °C, excluding Stress-Strain state (SSS).
Type 2: the samples were aged in an alkali solution (GOST 31938-2012) at a temperature of 50 °C, the tests were carried out in SSS at three levels of deformation, equivalent to 0,2, 0,4, 0,6 of the strength of the PCA with longitudinal bending (hereinafter R).

The dependences of changes in residual strength at different stages of exposure of the samples in unstressed (Figure 6) and stressed (Figure 7) states were obtained.

As can be seen from the analysis of the test results, the pattern of strength change with a high level of correlation is described by linear functions. Therefore, in the time interval corresponding to the time of accelerated testing, the residual strength $\sigma_{res}$ can be determined by a function of the form:

$$\sigma_{res} = R \left(1 - K_{con} \cdot K_T \cdot \tau\right)$$  \hspace{1cm} (1)

where $R$ is the initial strength of the material, $m_{con} = \sigma / R$ is the level of long-term load in fractions of the initial strength; $K_{con} = f (m_{con})$ is a function of the level of continuous load $m_{con}$, which determines the effect of a given SSS on the change in the initial strength of the material; $K_T = g (T)$ is a function of the exposure temperature $T$, which determines the effect of temperature on the change in the initial strength of the material; $T$ is the exposure temperature of the samples, °C; $\tau$ is the exposure time of the samples.

**Figure 6.** Experiment results for type 1 (conditions: different temperature levels and alkali solution) with approximation by linear functions (authors’ illustration).

**Figure 7.** Experiment results of type 2 (conditions: various levels of mechanical load, temperature 50°C, alkali solution) with approximation by linear functions (authors’ illustration).
Thus, the task of determining the law of change in residual strength is reduced to determining the functions $K_{\text{con}}$ and $K_T$. We assume that at the level of continuous load $m_{\text{con}} = 0$, the function $K_{\text{con}} = 1$. Then, to determine the function $K_T$, we consider its values obtained during the type 1 test:

$K_T (T = 20 \, ^\circ \text{C}) = 1.4802$; $K_T (T = 50 \, ^\circ \text{C}) = 15.132$; $K_T (T = 40 \, ^\circ \text{C}) = 6.5234$; $K_T (T = 60 \, ^\circ \text{C}) = 22.226$.

Approximating the obtained experimental values of $K_T$, we determine the general form function for the test material (Figure 8 a) in the temperature range at which studies were carried out. The scope can be expanded without additional research only if there are appropriate justifications.

![Figure 8](image)

**Figure 8.** a) Definition of $K_T$ function; b) Definition of the $K_{\text{con}}$ function.

The dots indicate the values of the coefficients obtained by approximating the experimental strength values (authors’ illustration).

For a test of type 1, carried out at a temperature of $T = 50 \, ^\circ \text{C}$, the coefficient $K_T = 15,132$. Then, according to the values $(K_{\text{con}} \cdot K_T)$ obtained by approximating the test data of type 2, for various load levels we find:

$K_{\text{con}} (m_{\text{con}} = 0) = 1$;

$K_{\text{con}} (m_{\text{con}} = 0.2) = 2$;

$K_{\text{con}} (m_{\text{con}} = 0.4) = 4.01$;

$K_{\text{con}} (m_{\text{con}} = 0.6) = 10.02$.

Using the same approach as in determining the function for the coefficient $K_T$, the empirical values of the coefficient $K_{\text{con}} (m_{\text{con}})$ are approximated (Figure 8 b).

Thus, the prediction of the residual strength of PCR samples, tests that are carried out under conditions of an alkaline environment exposure at temperatures from 20 °C to 60 °C at loads from 0 to 0.6R, can be carried out according to the formula (1), where:

$K_T = 0.0008 \cdot T^{2.4831}; K_{\text{con}} = 0.9517 \cdot e^{3.835 \cdot m_{\text{con}}}$.

It should be noted that for a relatively small interval, the coefficients $K_T$ and $K_{\text{con}}$ can be considered as functions of one variable: temperature or continuous level respectively.

However, the possibility of applying the described approach for a time interval in which the law of change in residual strength for different types or test conditions occurs according to different laws and differs from a linear one should be determined individually.

4. **Assessment of continuous strength by the level of deformation.**

The maximum elastic deformation on the surface of a flat sample is calculated by the formula:

$$
\varepsilon_{\text{max}} = \frac{(w_{\text{max}} - w_{\text{res}})h}{4L^2}
$$

(2)

Here $w_{\text{max}}$ is the deflection of the central point of the sample, $w_{\text{res}}$ is the residual deflection of this point, $h$ is the thickness of the sample, $L$ is its length. We denote by $R0$ the initial tensile strength, and
F0 the value of the breaking load obtained in the experiment under "instant" loading. For each variant of the aggressive environment, one can obtain the dependence of the tensile strength on deformation after holding for a time t* from the condition:

$$\frac{R}{R_0} = \frac{F}{F_0}$$  \hspace{1cm} (3)

The expression for R can be approximated by a function in the form:

$$R = R_0(1 + \varepsilon \cdot k_1 + \varepsilon(\varepsilon - \varepsilon_1) \cdot k_2 + \varepsilon(\varepsilon - \varepsilon_2)(\varepsilon - \varepsilon_3) \cdot k_3)$$  \hspace{1cm} (4)

The coefficients k1, k2, k3 can be obtained from condition (3) for different values of F. This gives a system of equations, the solution of which can be written as:

$$k_1 = \frac{F_1 - F_0}{F_0 \varepsilon_1}, \quad k_2 = \frac{F_2 - F_0(1 + \varepsilon_k k_1)}{F_0 \varepsilon_2(\varepsilon_2 - \varepsilon_1)}, \quad k_3 = \frac{F_3 - F_0(1 + \varepsilon_k k_1 + \varepsilon(\varepsilon_3 - \varepsilon_1) k_2)}{F_0 \varepsilon_3(\varepsilon_3 - \varepsilon_1)(\varepsilon_3 - \varepsilon_2)}$$  \hspace{1cm} (5)

Here, F1, F2, F3 are the values of the breaking load obtained in the first, second and third experiments, ε1, ε2, ε3 are the deformations corresponding to these loads, found by formula (2). Instead of deformation ε, we can approximately substitute stresses, expressing them in terms of ε according to Hooke's law. By calculating k1, k2, k3 for various sample exposure times, which were then brought to failure, we can obtain their dependence on time. Then we obtain relation (4), which allows predicting the residual strength at any operating time of composite structural elements.

5. Conclusion

A study of a polymer composite material in the form of flat and round elongated fiberglass reinforced elements in various environments and at different temperatures was made. Relations are proposed that can be obtained on the basis of data from a number of experimental studies on transverse or longitudinal bending. They allow to predict the level of permissible continuous load at a given structure life cycle. The advantage of this approach is that the number of test types is significantly reduced, as a result, the number of samples is reduced, less time and equipment are required to obtain the necessary data on the material.

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