

DETERMINATION OF THE DURABILITY OF FERROCONCRETE BRIDGE BEAMS REINFORCED BY COMPOSITE STRIPS

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We propose a procedure for the evaluation of the service life of ferroconcrete beams reinforced by composite strips based on the energy approach and develop technical tools for measuring displacements over the height of the beam with the use of the method of digital image correlation. An algorithm of image processing for the determination of local strains is proposed. We performed experimental investigations of a reinforced ferroconcrete beam under cyclic loading and established the number of cycles to its fracture.

Keywords: reinforced ferroconcrete beam, stress-strain state, elastoplastic strain energy, digital image correlation.

In the course of long-term operation of bridge structures under cyclic loads, defects are gradually accumulated in their elements. To guarantee the reliable operation of bridges and prolong their service life, it is customary to reinforce ferroconcrete beams by gluing of composite strips reinforced with carbon fibers on their bottom surface [1, 2]. In this case, it is necessary to determine the stress-strain state (SSS) of beams and substantiate the duration of their safe service life.

To determine the SSS and deflections of reinforced ferroconcrete beams, it is customary to use the same approach as in the case of beams without reinforcement. It is based on finding their strength in normal sections according to the design fracture resistances of concrete and reinforcement [1].

The initiation of fatigue cracks in the stretched region of the concrete of ferroconcrete beams affects the position of the neutral line. Hence, it is difficult to determine the SSS by the method of plane sections. In this case, to estimate the fatigue strength of these beams, we propose to use an approach that takes into account the changes in the SSS for all components of reinforced ferroconcrete beams.

The accumulation of defects in concrete, reinforcement, and composite strips affects the strain and fracture resistances of beam and the duration of its service life.

Determination of the Stress-Strain State

The determination of the residual life of ferroconcrete beams is based on finding the unit characterized by the most intense accumulation of defects leading to the formation of cracks and the loss of their load-bearing

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capacity. Therefore, it is important to regularly detect these sites by monitoring the strain state of the beam and perform the required recovery and/or repair works. If the cracks appear in the investigated beam, then its load-bearing capacity is restored by gluing special composite strips [1, 2]. On the basis of the data of experimental investigations and recommendations made in [2], it is proposed to design ferroconcrete beams reinforced with composite strips. At the same time, there are no approaches to the analysis of their operation and evaluation of the number of cycles to fracture of reinforced ferroconcrete beams. To predict their durability, it is necessary to formulate a model of fracture with regard for the accumulation of defects under cycling loads.

We assert that the load-bearing capacity of the reinforced beam is lost if the yield point [1] of the material is attained in stretched reinforcement with simultaneous fracture of the composite strip and the zone of compression of concrete.

To estimate the degree of damage to a ferroconcrete beam under cyclic deformation, it is customary to use a hypothesis based on the energy approach and setting of the ultimate degree of damage in the most loaded site. In other words, the ferroconcrete beam reinforced with a strip is destroyed when the elastoplastic strain energy becomes equal to the fracture energy of the composite strip. This is confirmed by the data of testing of reinforced beams and also by the fact that the composite strip is subjected to the largest deflections and highest strains, as follows from the theory of normal sections [2].

The initial local energy content of the material of the strip is determined by the specific fracture energy under static loading W_c from the true stress-strain curve $\sigma(\varepsilon)$:

$$W_c = \int_0^{\varepsilon_c} \sigma(\varepsilon) d\varepsilon. \tag{1}$$

Here, ε_c is the critical level of strains.

The energy losses in an elementary volume of the material for a certain period of operation measured by the number of loading cycles n ($1 \leq n \leq N$) can be found as follows:

$$W_s(\varepsilon_{\max}, \sigma_{\max}) + W_f(\Delta\varepsilon, \Delta\sigma, m_f, n), \tag{2}$$

where

$W_s(\varepsilon_{\max}, \sigma_{\max})$ is the static component of the energy losses,

$\Delta\varepsilon = \varepsilon_{\max} - \varepsilon_{\min}$ and $\Delta\sigma = \sigma_{\max} - \sigma_{\min}$ are, respectively, the strain and stress ranges in the first loading cycle,

ε_{\min} and ε_{\max} are the minimal and maximal values of strains,

$\sigma_{\min} = \sigma(\varepsilon_{\min})$, $\sigma_{\max} = \sigma(\varepsilon_{\max})$,

$$W_s(\varepsilon_{\max}, \sigma_{\max}) = \int_0^{\varepsilon_{\max}} \sigma(\varepsilon) d\varepsilon, \tag{3}$$

$W_f(\Delta\varepsilon, \Delta\sigma, m_f, n)$ is the cyclic component of the energy losses for n loading cycles:

$$W_f(\Delta\varepsilon, \Delta\sigma, m_f, n) = \sum_{i=1}^n w_i(\Delta\varepsilon, \Delta\sigma, m_f) = w_1(\Delta\varepsilon, \Delta\sigma) \sum_{i=1}^n m_f(i). \quad (4)$$

Here,

$$w_i = m_f(i)(1-R) \int_{\varepsilon_{\min}}^{\varepsilon_{\max}} \sigma(\varepsilon) d\varepsilon = m_f(i) w_1(\Delta\varepsilon, \Delta\sigma)$$

are the energy losses in the i th loading cycle for the stress ratio R , $m_f(i)$ is the index of cyclic hardening-and-softening, which reflects the cyclic changes in size of the initial hysteresis loop $W_1(\Delta\varepsilon, \Delta\sigma)$, and, in addition, $m_f(1) = 1$.

We determine the total relative energy losses for n loading cycles by the parameter $\lambda(n)$:

$$\lambda(n) = \frac{W_s(\varepsilon_{\max}, \sigma_{\max}) + W_f(\Delta\varepsilon, \Delta\sigma, m_f, n)}{W_c}. \quad (5)$$

In the accepted notation, we can now write the following criterion equation of fracture:

$$\lambda(N) = 1$$

or, in a more detailed form,

$$\frac{W_s(\varepsilon_{\max}, \sigma_{\max}) + W_f(\Delta\varepsilon, \Delta\sigma, m_f, N)}{W_c} = 1. \quad (6)$$

To determine these characteristics, we carried out special experimental investigations according to the corresponding procedure.

The fracture energy of a composite strip was determined under the conditions of tension of a plane specimen 120 mm in width and 1.2 mm in thickness from the corresponding diagram and the fracture energy of reinforcement was found under the conditions of tension of a standard specimen with \varnothing 10 mm according to the constructed true stress-strain diagram.

The fracture energy of concrete was found as a result of compression tests of cubic specimens $100 \times 100 \times 100$ mm in size with recording the corresponding complete stress-strain diagram in a special device [3]. In this case, the values of strains are recorded on the lateral surface of the specimen by the method of digital image correlation (DIC) [4].

The results of these tests were used to determine the characteristics of strength of the composite strip σ_f and ε_f under static loading. Thus, we get the following transcendental equation and solve it numerically to determine the number of loading cycles up to the fracture of the ferroconcrete beam with glued composite strip:

$$\sigma_{\max} \frac{\Delta\varepsilon}{2} = \frac{\sigma_f^2}{E} (2N)^{2b}, \quad (7)$$

where σ_{\max} is the maximal stress in a cycle and b is an experimentally determined coefficient.

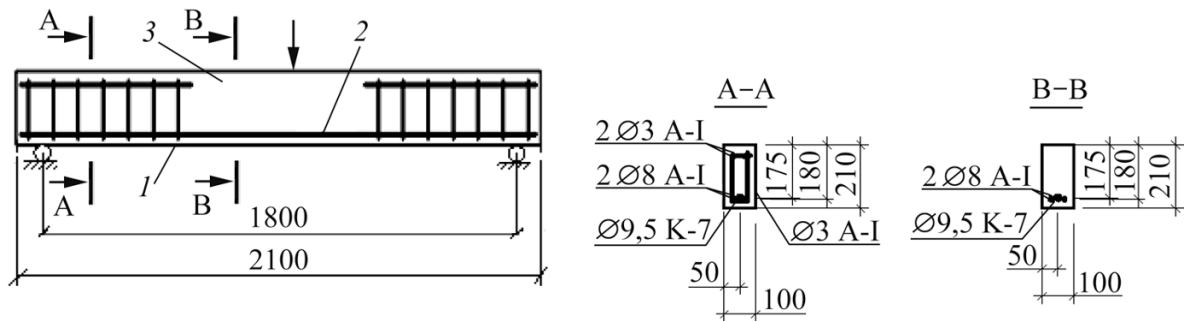


Fig. 1. Design of tested specimens: (1) composite strip, (2) steel reinforcement, (3) compression zone of concrete.

Evaluation of the Durability of Ferroconcrete Beams Reinforced by Composite Strips

We analyzed the process of cyclic loading and deformation of a ferroconcrete beam reinforced with a CFRP strip (Fig. 1) according to the following scheme: The length and the scheme of anchorage of the strip at the sites of gluing were determined according to the procedure developed in [6]. The beam was loaded by static forces level by level, and the field of displacements on the lateral surface was recorded with the help of the DIC. The accumulated data enabled us to determine the levels of strains in the strip, in concrete, and in the reinforcement located at different heights of the beam. After this, we determined the strain distribution in each component of the reinforced beam by the formulas

$$\varepsilon_{xx_i} = \frac{\partial u_i}{\partial x_i} + \frac{1}{2} \left[\left(\frac{\partial u_i}{\partial x_i} \right)^2 + \left(\frac{\partial v_i}{\partial x_i} \right)^2 \right],$$

$$\varepsilon_{yy_i} = \frac{\partial v_i}{\partial y_i} + \frac{1}{2} \left[\left(\frac{\partial u_i}{\partial y_i} \right)^2 + \left(\frac{\partial v_i}{\partial y_i} \right)^2 \right].$$
(8)

The strain distribution obtained by the DIC was compared with the numerical results obtained by the finite-element method (FEM). The body of the beam (with strip and reinforcement) was split into 70,000 eight-nodal elements in the form of parallelepipeds for the loads

$$P_1 = 4 \text{ kN}, \quad P_2 = 8 \text{ kN}, \quad P_3 = 12 \text{ kN}, \quad \text{and} \quad P_4 = 24 \text{ kN}.$$

Under loading, we measured the deflection of the beam at its center relative to the line of force action. The comparison of the results obtained by the DIC and FEM methods for strains and deflections reveals their good agreement, which confirms the possibility of finding the true strains in the beam under the conditions of its bending at the most loaded site. By using the values of strains, the stresses were found from true stress-strain diagrams for the components of the beam. The results of static investigations and relations (2) were used to determine the fracture energy of reinforced ferroconcrete beams.

The fatigue strength of a ferroconcrete beam with glued composite strip was studied by the force scheme of three-point bending with asymmetric loading cycles in an EUS-20 universal hydraulic machine. In the course of cyclic loading, we recorded the maximal P_{\max} and minimal P_{\min} forces in a cycle and, with the help of the DIC, established the displacements and deflections of the beam. The experimental investigations were carried

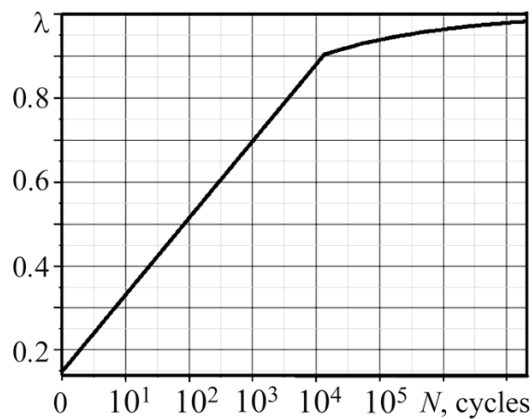


Fig. 2. Accumulation of damage in a concrete beam.

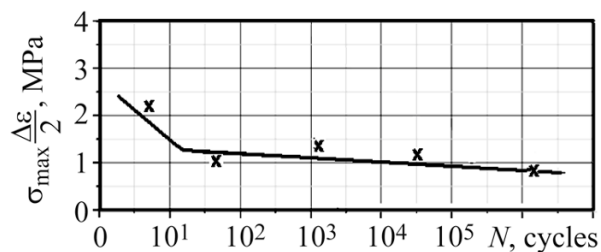


Fig. 3. Dependence of the fracture energy on the number of loading cycles.

out for the load ratio $R = P_{\min}/P_{\max} = 0.3$. Finally, we determined the strain range in the composite strip

$$\Delta \varepsilon = \varepsilon_{\max} - \varepsilon_{\min}$$

according to the values of displacements and found the stresses from the fracture diagrams of the strip according to the known levels of strains.

The tests were performed for different strain ranges $\Delta \varepsilon$ and the corresponding numbers of cycles to fracture N were determined.

For the ferroconcrete beam reinforced with a GFRP composite strip $100 \times 210 \times 2100$ mm in size, we plotted the graphical dependence of the degree of damage λ on the number of loading cycles (Fig. 2). The mechanical characteristics of the strip are as follows:

$$\sigma_f = 2400 \text{ MPa}, \quad \varepsilon_f = 0.045, \quad \text{and} \quad b = 0.06.$$

The results of evaluation of the durability of the reinforced beam computed by the formula (solid line) and determined experimentally (symbols) are shown in Fig. 3.

As a result of reinforcement by a composite strip, the durability of the beam increases by about 30–40%.

The proposed approach can be used for the evaluation of the durability of ferroconcrete beams and their optimal reinforcement by composite strips. This type of reinforcement is extensively used in the course of repairs of bridge structures with an aim of prolongation of the period of their safe operation.

CONCLUSIONS

We propose a procedure for the evaluation of the durability of ferroconcrete beams reinforced by composite strips and show that their durability increases by 30–40% as compared with the unreinforced beam.

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