INFLUENCE OF INTERMITTENT CYCLIC LOAD ON THE MODEL OF PROTECTION OF REINFORCED CONCRETE BEAMS

Vasyl Karpiuk
Odesa State Academy of Building and Architecture, Department of Reinforced Concrete and Stone Structures, Ukraine, ScD
Anatoliy Kostiuk
Odesa State Academy of Building and Architecture, Department of Building Structures, Ukraine, PhD
Oksana Maistrenko
Odesa State Academy of Building and Architecture, Department of Reinforced Concrete and Stone Structures, Ukraine, PhD
Yulia Somina
Odesa State Academy of Building and Architecture, Department of Reinforced Concrete and Stone Structures, Ukraine
Corresponding author: syomina3091@ukr.net

Abstract: This article is devoted to the study of the work of reinforced concrete summer beam structures under conditions of action of cyclic loads with high levels. The authors found that studies on the development of physical models of atomic resistance of bending reinforced concrete elements, cyclic effect of lateral forces and the methods of calculation on their basis are important and appropriate due to certain features and essential specificity of the mentioned type of load. These primarily include nonlinearity of deformation, damage accumulation in the form of fatigue micro- and macro-cracks, fatigue construction materials destruction and so on. At work key expressions determining the limits of endurance of concrete, longitudinal reinforcement, anchoring longitudinal reinforcement, which create the endurance throughout the whole construction, are mentioned. Equally important, as noted in the present article is to establish the link between tensions and deformations element in these conditions because there is a presence of cyclic stress-induced creeps' deformations.

Keywords: endurance, cyclic load, exhausting destruction, cyclic stress-induced creeps, bay of shear fracture, reinforced concrete beam

1 INTRODUCTION

First of all, the article considers the peculiarities of changing the tension-deformed state of structures depending on the size of relative bay of shear (zero, small, middle and large), which in turn affects the scheme of destruction and distribution of existing efforts to force flow of concrete and reinforcement of member. In addition, the authors cite the physical models and proof expressions to determine the endurance limit (of objective fatigue strength) of composite materials in structure that take into account the real tension-deformed state of by-support sections of these members on conditions of the repeated loads depending on varying bay of shear.

In the current design rules, calculation of endurance of reinforced concrete structures is carried out in the assumption of elastic concrete work. Calculation of inclined sections is performed on condition that the main tensile stresses that occur at the center of gravity of the mentioned section shall be fully perceived by transverse reinforcement at stress in it, equal to the calculated resistance of transverse reinforcement $f_{sw,}$ multiplied by the coefficient of the conditions of work $\gamma_{sw,}$ and in elements without transverse reinforcement - concrete in tensions in it, which are equal to calculated resistance of concrete in tension $f_{ctd,}$ multiplied by the appropriate coefficient of the conditions of work γ_c.

This approach to the calculations is in contradiction with the real nature of inelastic work of reinforced concrete elements and does not reflect fracturing behaviors of reinforced concrete structures in the area of transverse forces actions during cyclic load, does not reflect the real stress-strain state, does not take into account ambiguity of perception of transverse forces of different elements with different bays of shear fracture and nature of formation and development of exhausting destruction cracks is not adjusted to reflect or indirectly takes into account the impact of a number of structural factors and external action factors that ultimately leads to significant differences between the calculated and experimental data.

Accordingly, the ***novelty*** is that the authors define the limit of endurance (objective strength) of structure's materials by determining real physical and geometric data of sections that are considered, appropriate relationships to distribution of stresses and deformations in the conditions of cyclic fatigue, taking into account the availability of cyclic strain-induced creep deformations, accumulation of residual strain, stress, micro and macro-cracks.

Theoretical studies on the development of physical models of fatigue resistance of bending reinforced concrete elements, cyclic effects of transverse forces and methods of calculation on their basis are practically absent. Therefore, in the present, development of physical models of fatigue resistance and fracture of by-beam sections of reinforced concrete beam elements that would correctly reflect their real work with real concrete and steel deformation elements at different spans of cut and at the same time also appropriate methods of calculation have just started.

In this context, ***the main contribution of*** this work is that it accumulates good preconditions for new engineering methods of calculating strength of by-support beam sections in reinforced concrete structures, which will consider a change in their tension-deformed state and changing strength properties of concrete, fittings and their adhesion and can be applied to the whole range of strength characteristics of materials, ranging from low-cycle repeated to frequent cyclical loading.

In *paragraph 2* of the Article, the authors make analysis of existing literary sources within the framework of this item. *Paragraph 3* is dedicated to the description of the work of reinforced concrete members with a zero bay of shear, which emphasizes the fact that the work of reinforced concrete member under such conditions is similar to the work of concrete member, where local compression takes place. *Paragraph 4* illuminates the models of resistance to structures with small, medium and large bays of shear. It is found that there are some features of the tension-deformed state of the members, depending on change of this factor. Namely, the feature of reinforced concrete elements with a small bay of shear is formation of local stress bars associated with load points of concentrated external forces, within which there is exhausting destruction. Exhausting destruction of by-support plot of members with large bays of shear occurs with formation of critical inclined crack, position of which is associated not only with load points of external force and support reaction, but also with internal force factors arising in a bay of shear (moments and transverse forces). In members with an average bay of shear destruction of by-support plots under cyclic loading has some signs of destruction as members with small bays of shear and members with long bays of shear. In this case, the nature of formation and development of cracks as well as exhausting destruction in this area during the specified loading exercise influence from as internal power factors, and local stress concentration in the relevant areas near the points of concentrated external forces. In *paragraph 5* of the work, conclusions are drawn that summarize the reviewed information discussed in relation to the selected research topics.

2 ANALYSIS OF LITERARY SOURCES ON THE CHOSEN TOPIC OF RESEARCH

Taking into account the relevance of the chosen topic and the need to replenish the research data within the framework of these studies, large number of scientists paid attention to this issue. The literature, based on the results of the experiments [1-10] indicates that repeated cyclic loading uniquely affect operating characters of reinforced concrete structures, namely when exposed to the mentioned type of loading deflections values and width of opening normal and inclined cracks of members, increase, on average, by 15-20%, and values of deformations of reinforcement and concrete − by 10-15%, bearing capacity of reinforced concrete structures decreases, approximately, by 20%. Also, researchers in [2, 3, 5, 6] workings found that conventional stabilization of strains and stresses in the members at operating load levels occur at 5-7 cycles. However, with the levels of stress that exceed operational, there is no such prediction.

Despite the rather large volume of research carried out and the establishment of predictions for the performance of reinforced concrete structures under the influence of cyclic repeated loads, the researchers have not yet reached the common view on taking into account this influence in practical engineering calculations of strength of normal and inclined sections of the members. Most researchers [2, 4, 11] continue to take into account the cyclic component of the load at the expense of the coefficient of working conditions, which does not reflect the real mechanics of work and destruction of reinforced concrete structures by actions of the specified type of load.

3 MODEL OF RESISTANCE OF REINFORCED CONCRETE MEMBERS WITH A ZERO BAY OF SHEAR FRACTURE

O.S. Zalesov, Y.A. Klimov, I.T. Mirsayapov [1], and others depending on the relative bay of shear fracture c_0 / h_0 identifies the main forms of exhausting destruction of reinforced concrete structures: items with a zero bay of shear fracture ($c_0 / h_0 = 0$), with low ($c_0 / h_0 \le 1,2$), with middle (1,2 $c_0 / h_0 \le 2$) and with a large bay of shear fracture ($c_0 / h_0 > 2$). His research using thermal imaging showed that in cells with $c_0 / h_0 \le 1{,}2$ there are local stress strakes between the points of application of concentrated force and the reference reaction of the beam, within which there is an exhausting destruction. With further decreasing relative bay of shear fracture limiting case occurs where $c_0 / h_0 = 0$ and $M_{max} = Q_{max} = 0$, i.e. lines of force and the reactions of the same match together, and there is a local compression, which can also be put into the overall system of protection of protection of reinforced concrete elements to action of transverse forces.

Relying on the research carried out by V.G. Donchenko, O.S. Zalesov, V.G. Kvasha, M.M. Kholmyanskiy, I.T. Mirsayapov [1] and others, physical model of fatigue resistance of concrete in this exercise can be presented as follows. By the local concrete compressive element between the loading platforms directional tracking compressive force flow, limited by sizes of load boards, is formed. Inside this flow stress state is dissimilar, since load is applied again to the flat element under the load boards with limited width friction force between these boards and the surface of concrete appear, because of which in concrete body compacted volumes are produced in the form of a wedge (fig. 1, a) with sides inclined to transferring load area with angle equal to the angle φ of concrete internal displacement (fig. 1, b), and inside of the wedge state of stress "compression-compression" is formed ($\sigma_{1c}^{max}(t),\ \sigma_{2c}^{max}(t)$). Moving the wedge as solid and its "jamming" in the surrounding concrete causes appearance of resistance and, consequently, splitting (tensile) stresses $\sigma_{2ct}^{max}(t)$ between the peaks of the impaction wedges, and along the sides of the wedge - the condition of pure shear is realized and there are tangential stresses $\tau_{12}^{max}(t)$. As a result of the pressure of these impaction sides as a solid on the surrounding concrete, there are also compressive stresses $\sigma_{1c}^{max}(t)$ (fig. 1, c). Therefore, in the middle zone between the peaks of the impaction wedges in sealing elements with dimensions $H \le 1{,}5\ L$ and $l_{loc} / H > 0{,}2$ on research of B.S. Sokolov [12] the compression core with width of l_{ef}, less than the width of the loading platform $l_{loc.}$ is formed.

Consequently, the criterion of exhausting destruction of concrete with local repeated compression can be represented as $\sigma_{1c}^{max}(t) > f_{cd,rep}(t)$, where $f_{cd,rep}(t)$ is objective (residual) strength of concrete in compressive stress force flow during cyclic loading at time *t;* $\sigma_{1c}^{max}(t)$ is the maximum compressive stress of the cycle from the outer load at time *t.*

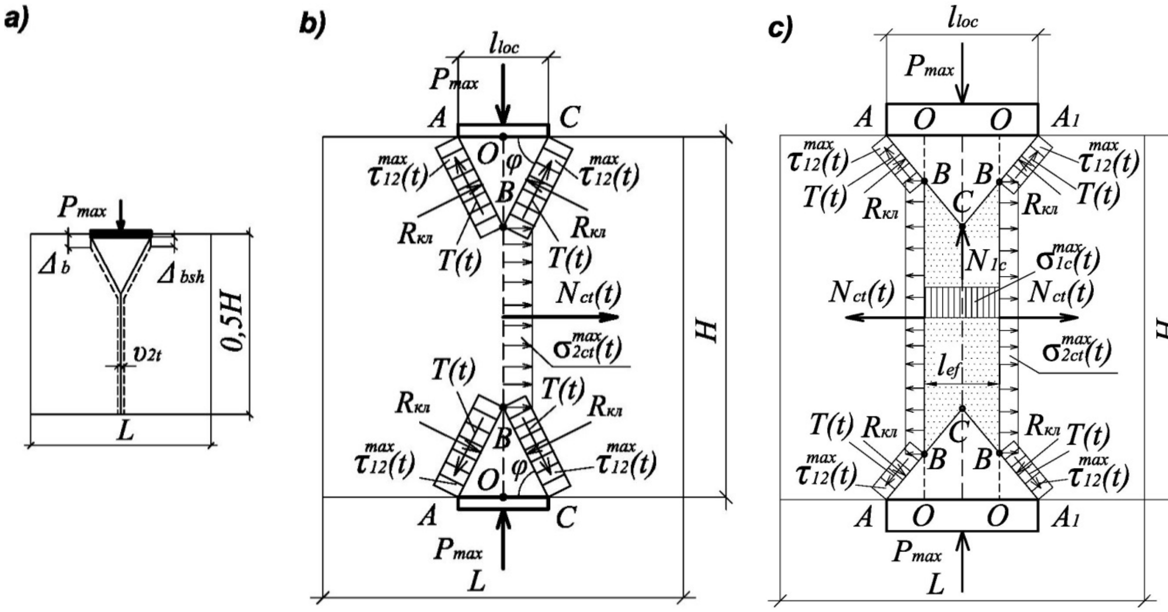

Figure 1 Model of concrete deformation in local compression re-load (*a*), distributions of stresses and efforts in cramped elements with zero bay of shear fracture during cyclic loading at l_{loc} / *H* < *0,2* (*b*) and at *l* $_{oc}$ / *H* > 0,2 (*c*)

A model of fatigue resistance of a reinforced concrete element serves as the basis of the fatigue resistance of a concrete element with local compression. Their geometric parameters and construction principles are the same. Distribution of stresses in concrete of reinforced concrete element with the first load and during cyclic loading, as well as concrete deformation schemes are accepted the same as in concrete elements (fig. 1, *a, b, c*). Vertical displacement of sealing wedges in concrete elements is resisted by surrounding concrete and the impact of horizontal and vertical reinforcement in the above mentioned equilibrium conditions for ABO semi-wedge and OO vertical section (fig. *1, b, c)* is taken into account as efforts in fixture $N_{sc}^{\max}(t)$; $Q_{s}^{\max}(t)$; $N_{s}^{\max}(t)$. Hence we get the analytical expression about objectively strength of concrete in compressive force flow during cyclic loading at time *t*:

$$f_{cd,rep}(t)=\frac{h_t ctg\varphi}{l_{loc}\sqrt{\pi l(t)}\cdot Y(l)}\times\left\{ k_{scf}(t)+\sum_{i=1}^{h}\frac{\sigma_{si}^{\max}(t)A_s}{b\cdot\sqrt{\pi\cdot l}(t)}\left\langle\begin{array}{c}\sqrt{\dfrac{l(t)+(i-0,5)\cdot s}{l(t)-(i-0,5)s}}+\\+\sqrt{\dfrac{l(t)-(i-0,5)\cdot s}{l(t)-(i+0,5)\cdot s}}\end{array}\right\rangle\right\}\times \quad (1)$$

$$\times\left\langle A-\left\{ G_c L_\varepsilon B+\frac{6E_s I_s L_\varepsilon\cdot n}{b\cdot\left(d_s\cdot\sqrt[4]{\dfrac{E_s}{E_c}}\cdot\left(1,4+1,25\sqrt[4]{\dfrac{a_s}{d_s}}\right)\right)^3}+C\right\}\times\left\{\frac{1}{E_c}+C_e\prod_{k=1}^{k=n}K_k a\cdot\psi_\upsilon+\int_{t_o}^{t}\frac{\partial}{\partial\tau}\left[\frac{1}{E_c(\tau)}+C(t,\tau)\right]dt\right\}\right\rangle^{-1}$$

where $h_t = H - l_{loc}cos\varphi sin\varphi$; φ − an angle of inclination of compaction wedge faces at loading areas, before rupture crack appearance: $\varphi = arctg\left[0,48(l_{loc}/h)^{2/3}\right]$, after appearance and development of this crack: $\varphi = arctg(0,25 f_{cd}/f_{cdt} - 1,56)$; l_{loc} − the width of the support area, $l_{loc} = l_{sup}\cdot sin\alpha$; l_{sup} − the width of the loading area; $l(t)$ − length of fatigue crack; $Y(l)=\left\{Y_1(l)+\frac{\sigma_{1c}}{\sigma_{2t}}\cdot\frac{2\sqrt{1+\delta\sqrt{1-(1-\delta)^{-4}}}}{(1+(1+\delta)^2)^2}\right\}$, $Y_1(l)$ − dimensionless factor, σ_{1c} − concentration of main compressive stresses, σ_{2t} − concentration of main tensile stresses, $\delta = l_{loc}/H$ − the relative length of the load plates; k_{scf} − is critical stress intensity factor of fittings by repeated loads at time *t*; A_s − cross-section area of longitudinal reinforcement; *b* – cross-section width; *i* - the quantity of transverse reinforcement rods that crosses the half-length of the fracture; *s* - distance between the bars of transverse reinforcement; $A=1$ and $B=1/\sin^2\varphi$ − for concrete elements with dimensions $H \le 1,5L$ and $l_{loc}/H < 0,2$, and also − for concrete elements with dimensions $H > 1,5L$, $A=\cos^2\varphi$ and $B = ctg^2\varphi$ − for concrete elements with dimensions $H \le 1,5L$ and $l_{loc}/H > 0,2$;

$L_{\varepsilon} = \frac{1}{\pi}\left(\left(2\theta_{\kappa}-\pi\right)\cdot tg\theta_{\kappa}-\left(2\theta_{н}-\pi\right)\cdot tg\theta_{н}\right)$, $\theta_{\text{н}} = arctg\sin\varphi\cos\varphi$, $\theta_{\kappa} = arctg\frac{H}{l_{loc}}$; G_c – shear modulus of concrete; E_s – modulus of elasticity of longitudinal reinforcement; I_s – moment of inertia of cross section; *n* – quantity of transverse rods in shear span; d_s – diameter of the working reinforcement; E_c – modulus of elasticity of concrete; a_s – protective layer of the working reinforcement of concrete; *C* – measure of cyclic creep of concrete; C_e – limit measure of sample creep; K_k – correction factor for determining the limit creep measure; a – function that taking into account the strength properties of concrete and its age; ψ_{υ} – ratio that taking into account the influence of the loading speed.

4 MODELS OF REINFORCED CONCRETE ELEMENTS RESISTANCE WITH SMALL, MEDIUM AND LARGE BAYS OF SHEAR FRACTURE

Further study of author, I.T. Mirsayapov [1] and others showed that with $c_0 / h_0 > 2$ exhausting destruction of bending by-bay elements section occurs with forming a critical inclined crack, position of which is associated not only with the points of application of external force and support reaction, but also with the internal force factors arising in the bay of shear fracture (in moments and with transverse forces). If $1{,}2 < c_0 / h_0 \leq 2$ destruction of by-bay sections of beam elements under cyclic loading has ill-similar destruction characteristics both of elements with small bays of shear fracture and elements with long bays of shear fracture. In this case, the nature of the formation and development of cracks and exhausting destruction in this area during the specified exercise influence as internal power factors, and local stress concentration in the relevant areas near the points of application of concentrated external forces influence.

The peculiarity of "long" bending reinforced concrete elements with small spans *($a_0 < 1{,}2\ h_0$)* is the formation of local bands of stresses associated with the point of application of external forces concentrated within which exhausting destruction happens. This feature of ordinary reinforced concrete beams with small bays of shear fracture unites them with the "short" (high) elements. In both cases, this feature manifests itself at small values of the relative distance between the forces acting on the element.

T.I. Baranova, O.S. Zalesov [13], B.S. Sokolov [12] and others believe that for practical calculations of "short" elements the easiest solution of the problem is creation of computational model in the form of skeletonized bar system (SBS), which consists of sloping compressed bands and stretched lower and compressed upper reinforcing belts which are closed in areas of application like to focus concentrated forces and support reactions (fig. 2).

The principle of building a computational model is in determining compressive stresses in the inclined power flows and tensile stresses in the horizontal flow, the intersection of which forms a system that can be called skeletonized-bar model of short elements. The main parameters defining the calculated inclined strips are the dimensions of the cargo l_{sup}^{top} and supporting l_{loc}^{bot} boards, under which flows of compressive stresses are formed. The smaller are the sizes of the boards, the higher is the density of trajectories. Consequently, the supporting and load boards form a slope and its width both from above and from below. The inclination angle of the main compressive stress flow is close to the inclining angle of the line connecting the centers of the application of the reference reaction and the external concentrated force.

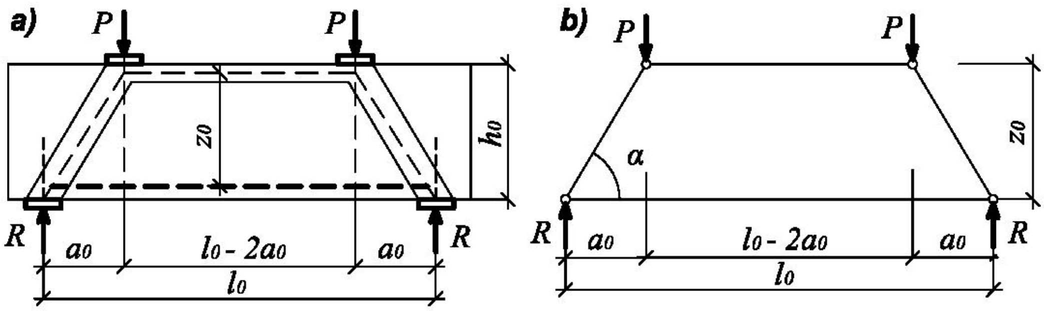

Figure 2 Generation of power flows in ordinary ("long") beams with small bays of shear fracture at reload (*a*) and its skeletonized bar analogue (*b*)

Obviously, when modeling the work of by-beam section of concrete elements for small bays of shear fracture with skeletonized bar analogue, we can assume that its fatigue strength is determined by endurance of each element of SBS, sloping compressed strips and strength of stretched reinforcement. Fatigue destruction of stretched zone element is the result of fatigue rupture of longitudinal reinforcement in the intersection of the inclined crack or a breach of fittings anchoring on the inclined crack. Therefore, the emerging stresses need to be limited to the values of objective strength during the cyclic loading (endurance) of concrete, fittings and their grip between themselves, that is, to ensure the durability of such reinforced concrete elements, it is necessary to adhere to the conditions of endurance:

$$\sigma_{1c}^{\max}(t) \le f_{cd,rep}(t),\ \sigma_{s,в}^{\max}(t) \le f_{ydq,rep}(t),\ \sigma_{s}^{\max}(t) \le f_{yd,an}(t) \tag{2}$$

where $\sigma_{1c}^{\max}(t)$ is compressive stress in a compressed power flow; $\sigma_{s,в}^{\max}(t)$ is current tensile stress in the most loaded fibers of longitudinal reinforcement at the intersection with inclined crack; $\sigma_{s}^{\max}(t)$ is current (maximum) axial tensile stress in the longitudinal reinforcement at the intersection with inclined crack; $f_{cd,rep}(t)$ is the limit of endurance of concrete with local compression; $f_{ydq,rep}(t)$ is the limit of endurance of the longitudinal fittings for tension; $f_{yd,an}(t)$ is the limit of endurance of longitudinal reinforcement anchoring.

The experimental studies [1, 12, 13] showed that the stress-strain state inside the old compressive force flow is the same as in planar stressed elements for the actions of local load. Therefore, to estimate the fatigue strength of an inclined compressed strip, a model of exhausting destruction at compression and equation of objective (residual) strength of concrete and reinforced concrete with cyclic loading can be applied. At the same time, if the axis "1" (fig. 3) is directed along the longitudinal axis of oblique compression force stream, and the axis "2" is in the orthogonal direction and accept the same designations, as in the elements with zero bays of shear fracture, then the stressed state within an oblique compressed power stream can be presented by fig. 3.

Since development of cyclic stress-induced creeps $\varepsilon_{1c,\ pl}$ in compressed concrete towards stress

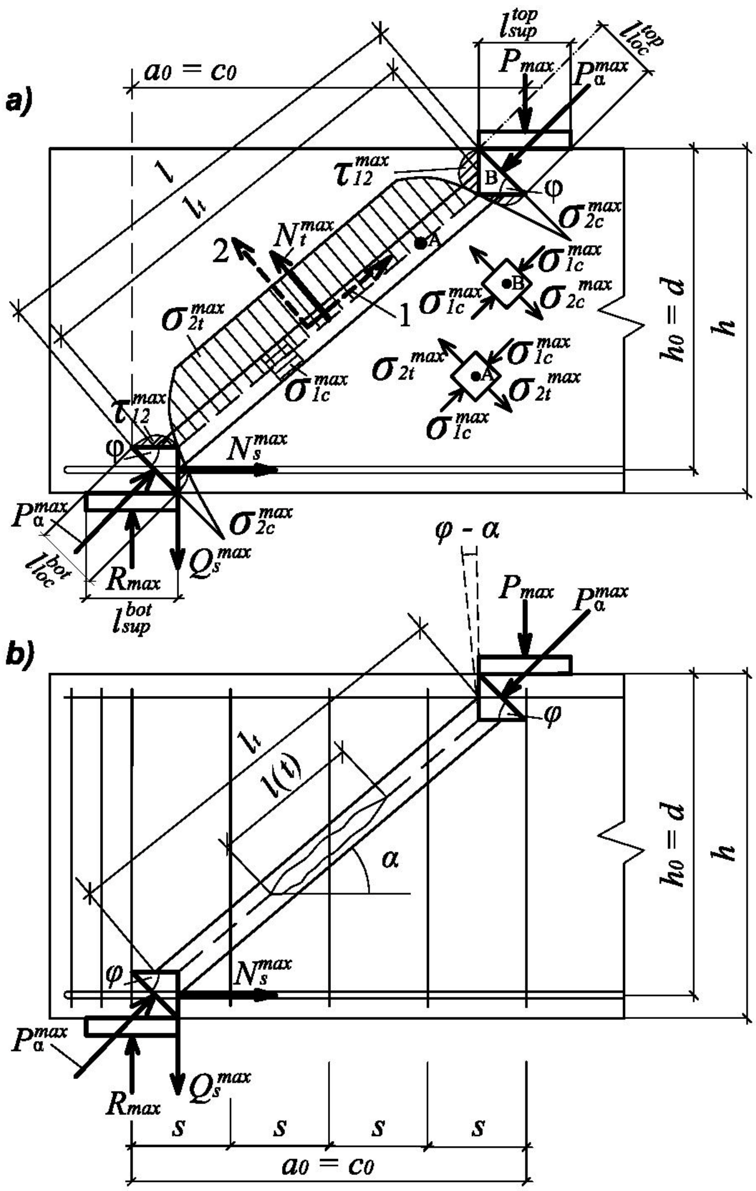

Figure 3 Physical model (*a*) and calculation scheme (*b*) of bending reinforced concrete element resistance, with a small bay of shear fracture of the joint action of transverse force and bending moment

$\sigma_{1c}^{\max}\left(t_0\right)$, as in local compression, occurs in free conditions, and nothing prevents its development, it can also be assumed that $\sigma_{1c}^{add}\left(t\right)=0;\ \sigma_{s}^{add}\left(t\right)\approx 0;\ \sigma_{1c}^{\max}\left(t\right)=\sigma_{1c}^{\max}\left(t_0\right);$ $\sigma_{s}^{\max}\left(t\right)\approx\sigma_{s}^{\max}\left(t_0\right),\ \sigma_{1c}^{\max}\left(t_0\right)$ and $\sigma_{s}^{\max}\left(t_0\right)$ are quite simply determined at the first load from equilibrium conditions based on the model of fatigue resistance.

Due to the fact that the stress-strain state within inclined compressed band and nature of its exhausting destruction and nature of exhausting destruction of flat-stressed members for actions of local stress, expression to determine the objective fatigue strength (endurance limit) of compressed oblique stripes on time *t* on the analogy of (1) takes the form:

$$f_{cd,rep}(t) = \frac{\left(k_{scf}\left(t\right) + K_{isw}\left(t\right)\cos\alpha\right)\cdot l(t)\, ctg\varphi}{l_{\sup}\sin\alpha\sqrt{\pi\, l\left(t\right)}\; Y\left(l\right)} \times$$

$$\times\left\langle A_{нп} - \left\{ G_c L_\varepsilon B_{нп} + \frac{6E_s I_s L_\varepsilon \cdot n\cdot\cos\left(\varphi-\alpha\right)\sin\alpha}{b\left(d_s\sqrt[4]{\frac{E_s}{E_c}}\left(1{,}4+1{,}25\sqrt[4]{\frac{a_s}{d_s}}\right)\right)^3 \sin\varphi} \right\} \times \right. \tag{3}$$

$$\left. \times\left\{ \frac{1}{E_c} + C_e \prod_{k=1}^{k=n} K_k a\psi_\upsilon + \int_{t_o}^{t} \frac{\partial}{\partial\tau}\left[\frac{1}{E_c\left(\tau\right)} + C\left(t,\tau\right)\right]dt \right\} \right\rangle^{-1}$$

where k_{scf}, $l(t)$, φ, $l_{\sup}$, $Y\left(l\right)$, G_c, L_ε, E_s, I_s, n, b, d_s, E_c, C_e, K_k, a, ψ_υ, C are according to (1); $K_{isw}\left(t\right)$ is stress intensity factor characterizing transverse reinforcement effect on the development of cracks in older compressive flow; α is angle of inclination of the compressed strip; $A_{нп}$ = 1, $B_{нп} = 1/\sin^2\varphi$ – for concrete elements with dimensions of cargo platforms l_{sup}/h <0,2; $A_{нп}$ = $cos^2\varphi$, $B_{нп}$ = $ctg^2\varphi$ – for concrete elements with dimensions of cargo platforms $l_{sup}/h \geq 0{,}2$; in elements without transverse reinforcement $K_{isw} = 0$.

Multi-cycle fatigue of fixtures is characterized by formation and development of fatigue cracks in it. Origination of fatigue cracks is the result of intensive plastic deformation of reinforcing steel in local volumes of stress concentration in the fixtures, which is the main source of periodic reinforcement profile. It results in significant hysteresis loops closed with an area equal to the energy that is spent far during one cycle of load. After exhausting plastic deformation in these local volumes cracks are formed, one of which could turn into the main crack. With further increase in the number of load cycles, development of the main crack is critical to the size. In respect to this for analytical description of exhausting destruction processes and changes in fatigue strength of steel reinforcement in reinforced concrete member by repeated stress methods of fracture mechanics are applied. The limit of endurance (objective strength) of longitudinal reinforcement at time *t* in place of its intersection with oblique crack under conditions of plane stress takes the form:

$$f_{sd,в}(t)=\sigma_{sc}\cdot k_{scf}(t)\Big/\sqrt{(Y(l)\cdot\sigma_{sc})^2\cdot l_s(t)+k_{scf}^2(t)} \tag{4}$$

$$\sigma_{sc}=\sigma_u\Bigg/\left\langle 1+\exp\left(-2E_s\cdot\varepsilon_{pl}^{pec}\big/\sigma_{su}\right)\sqrt{1+3\left(\tau_{si}^{max}\big/\sigma_{sвi}^{max}\right)^2}\right\rangle \tag{5}$$

where σ_{sbi}^{max} , τ_{si}^{max} are normal stresses in the most loaded (stretched) fibers and tangential stresses in the longitudinal reinforcement in the place of its intersection with a sloping crack; $l_s(t)$ is the length of the fatigue cracks in the fixture at time *t; k*$_{scf}$, $Y(l)$, E_s − are according to (1)*;* σ_{su} is temporary resistance of steel rupture; ε_{pl}^{pec} is residual plastic resource of steel.

The process of multi-cycle fatigue anchoring of fixtures is characterized by the formation and development of fatigue cracks in the contact zone between reinforcement and concrete. If level of stress of grip of reinforcement with concrete τ_g is high, and these tensions are greater than endurance limit of grip, that is the condition of τ_g / τ_{rep} > 1 is performed, it is emergence and development of cross-cutting (internal) fatigue cracks in the contact zone between reinforcement and concrete. As studies of B. Broms, I. Goto [14], M.I. Karpenko [15], M.M. Kholmyanskiy [16] show, these cross-cutting internal cracks form cone-shaped volumes. The above cracks are primarily developed under jetties of fittings and penetrate into the thickness of the concrete, which is smashed under these jetties. Therefore, the objective fatigue strength of concrete under jetties, and therefore adhesion forces of fixtures jetties with concrete must be determined as a function of the length of cone-shaped crack *l (t),* which continuously increases with the number of loading cycles. Therefore, the analytical characteristics of the exhausting destruction process in the contact zone, as well as changes in fatigue strength of longitudinal reinforcement anchoring by repeated stress the methods of fracture mechanics are also advisable to be applied. Then the limit of endurance (objective strength) of longitudinal reinforcement anchoring at time *t* is defined by:

$$\begin{aligned}
& f_{yd\ an,rep}(t) = k_{scf}(t)\, ctg\varphi \left(\frac{1,5a}{\cos\varphi_k} - \frac{c_r}{\sin\varphi_k}\sin\varphi\cos\varphi \right) \times \\
& \times \left(d + 2c_r + \left(0,75a - 0,5c_r ctg\varphi_k \sin\varphi\cos\varphi \right) \right) \times \\
& \times \left(1,5\left(1+\sin\alpha_r\right) - \sqrt{\sin\alpha_r} \right) \cdot \frac{2\tau_g\left(d+2c_r\right)\left(L+L_{pl}\right)}{d^2} \times \\
& \times \left(\sqrt{\pi\, l(t,\tau)} \cdot Y(l)\, s_r\left(d+2c_r\right)\sin 2\varphi_k \sin\alpha_r \right)^{-1} \times \\
& \times \left\langle 1 - \frac{G_c\left(3atg\varphi_k - 2c_r\sin\varphi\cos\varphi\right)}{c_r\cos\varphi\sin^2\varphi} \cdot \frac{A_{sh}}{A_c} \left\{ \begin{array}{l} \dfrac{1}{E_c} + C_e \displaystyle\prod_{k=1}^{k=n} K_k a\psi_\upsilon + \\ + \displaystyle\int_{t_o}^{t} \frac{\partial}{\partial\tau}\left[\frac{1}{E_c(\tau)} + C(t,\tau) \right] dt \end{array} \right\} \right\rangle^{-1}
\end{aligned} \tag{6}$$

where $\frac{A_{sh}}{A_c} = \frac{0,5\cos\varphi}{(d+c_r)}\left\{ d + 2c_r + \frac{0,5c_r\sin(\varphi-\varphi_k)}{\sin\varphi_k\cos\varphi} \right\}$; τ_g − adhesion stresses; k_{scf}, φ, $Y(l)$, G_c, E_c, C_e, K_k, ψ_υ, C, *a* – are according to (1); d - rod diameter; c_r, s_r, α_r − accordingly, height, step and tilt angle of fixtures jetties; *a* – a protective layer of concrete; L, L_{pl} − length of fixing reinforcement in concrete and plastic areas of this fixing; φ_k − angle of wedge under fixtures jetties; $l(t,\tau)$ − the length of fatigue crack in the concrete under fixtures jetties at time t.

During the cyclic loading under influence of great stress of concrete smashing under jetties of reinforcement deformations of cyclic stress-induced creep rapidly develop. As number of loading cycles *N* due to cyclic stress-induced creep of concrete reinforcement under jetties of reinforcement that surrounds them is an increase in movements growth $g_0^{max}(t)$ on the loaded end and inside the fastening $g_x^{\max}(t)$, which, in turn, leads to a redistribution of efforts of grip $P_{i,r}$ from more loaded jetties at the end of fixing to the jetties located at the bottom of the fixation, that is, there is a redistribution of adhesion stresses τ_g by the length of fastening. In this case, an increase in the number of load cycles leads to a continuous increase in the length of the plastic section and to increase of the completeness of the circuit of stresses of the clutch.

In elements with large bays of shear fracture ($a_0 / h_0 > 2$) (fig. 4), objective exhaustive strength of a sloping compressed strip at a brief moment of time *t* is defined by an analogy (1):

$$f_{cd,rep}(t) = \frac{\left(k_{scf}(t) + K_{1sw}(t)\right) \cdot l(t) \cos\gamma \, ctg\varphi}{x_{pl}\sqrt{\pi\, l(t)} \cdot Y(l)} \times$$

$$\times \left\langle 1 - \left[\frac{G_c L_\varepsilon}{\sin^2\varphi} + \frac{6 E_s I_s L_\varepsilon \cdot n \cdot \cos(\varphi - \gamma)\sin\gamma}{\left(d_s \cdot \sqrt[4]{\frac{E_s}{E_c}} \cdot \left(1,4 + 1,25\sqrt[4]{\frac{a_s}{d_s}}\right)\right)^3 \sin\varphi} \right] \times \right.$$

$$\left. \times \left\{ \frac{1}{E_c} + C_e \prod_{k=1}^{k=n} K_k a \psi_\upsilon + \int_{t_o}^{t} H_\sigma \frac{\partial}{\partial\tau}\left[\frac{1}{E_c(\tau)} + C(t,\tau) \right] dt \right\} \right\rangle^{-1} \qquad (7)$$

where k_{scf}, $l(t)$, φ, $Y(l)$, G_c, L_ε, E_s, I_s, n, d_s, E_c, a_s, C_e, K_k, a, ψ_υ, C are according to (1); K_{1sw} is according to (3); γ – an angle of inclination of straight line segment that models end part of danger inclined crack, $\gamma = arctg V_{c1}^{max} / N_{c1}^{max}$; H_σ – function of stress accumulations, for concrete $H_{\sigma_c} = 1 + \sigma_1^{add}(t) / \sigma_{1c}^{max}(t_0)$, for reinforcement $H_{\sigma_s} = 1 + \frac{E_s \cdot A_s \cdot L_\varepsilon \cdot H_\varepsilon}{b \cdot l_s \cdot \omega_s \cdot sin^2\varphi}$, for transverse reinforcement $H_{\sigma_w} = 1 + \frac{0,5 \cdot E_s \cdot m \cdot A_{sw} \cdot L_\varepsilon \cdot H_\varepsilon}{b \cdot l_{sw} \cdot \varpi_{sw} \cdot cosa \times sin^2\varphi}$, ω_s, ω_{sw} – stress distribution completeness coefficients respectively in longitudinal and transverse reinforcement, in the first approximation $\omega_s = \omega_{sw} = 0,8$; x_{pl} – is determined according to fig. 4.

The limit of endurance (objective strength) $f_{sd,в}(t)$ of longitudinal reinforcement at time *t* in place of its intersection with the critical inclined crack in plane stress conditions determined by (4) and (5). The endurance limit (objective strength) of anchoring longitudinal reinforcement $f_{yd,an}(t)$ on critical inclined crack is determined by (6). The endurance limit under axial load $f_{ydw,rep}(t)$ is determined by (4) and (5) taking into account that $\tau_{sw}^{\max} = 0$.

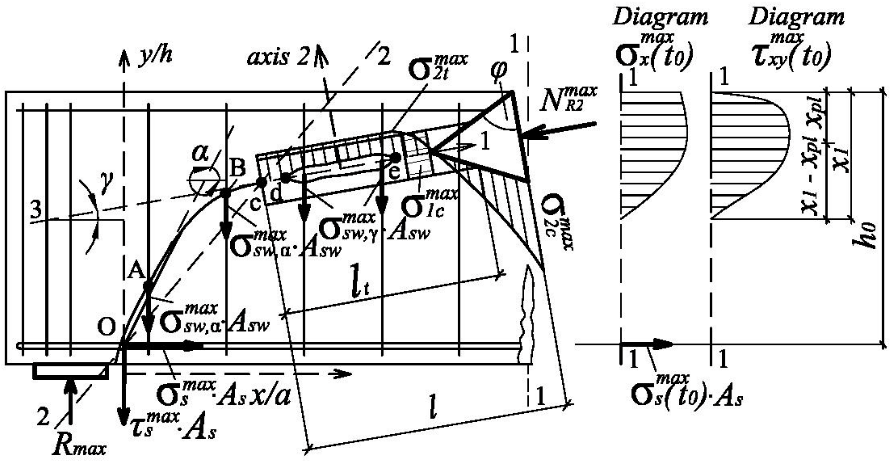

Figure 4 Physical and analytical models of fatigue resistance at by-support area of non-over-reinforced concrete members with large bay of shear fracture

Tests [1] of reinforced concrete beams of rectangular section with bay of shear fracture $a_0 = c_0 = (1{,}51 - 1{,}67)h_0$ revealed the following picture of formation and development of cracks and nature of exhausting destruction in area of transverse forces and bending moments. Since members with an average bay of shear fracture $1{,}2\ h_0 < c_0 = a_0 < 2\ h_0$ located on the borders of members with small bays of shear fracture bays and members with large bays of shear fracture, the work and the mechanism of fatigue at medium bays of shear fracture are the features of both the first and second, that the nature of the formation and development of cracks in the area of transverse forces and bending moments and fatigue following elements influencing factors both internal power and local stress state disturbance and stress concentration in the relevant areas in the field of application of external forces are concentrated. Therefore, by the middle bay of shear fracture fatigue occurs with formation of critical inclined crack, but destruction is affecting also the local stress state disturbance and stress concentration in these areas. The critical inclined crack may form in the distance (0,2 ... 0,3)*h* on the verge stretched and grow in directions both to support and to concentrated external force. In the stretched zone it develops along lines 2-2 (fig. 5), which connects the inside edges of the support plate with the outer face of the loading plate and completely crosses (to the inside edges of the supporting plate).

With the development from the support to the focused strength the critical inclined crack, after it is closer to the point *O,* i.e. to the intersection of lines 2-2 and 3-3, its direction changes and continues to develop along line 3-3 in the axis of inclined compressed flow. Meanwhile, inside the compressed flow of power through the action of tensile stress $\sigma_{2t}^{\max}$ is formed and develops a crack separation *d–e* along the axis 3-3, which then merges with the original plot OO_2 of critical crack. Obviously, the creation, development and disclosure of critical cracks in the tensile zone (area OO_2) are connected with flat turn and shearing action of inclined section 2-2, and its development and disclosure in the compressed area (*ed*) are caused by formation and development of section micro-cracks behind the line of action of tensile stress (fig. 5) in the area of "tension-compression" within the old compressed power flow formed by the force $P_{\beta}^{\max}$, and then merging them into macro-crack with the further development and opening of macro-crack separation. The distribution of stresses inside the inclined compressed power flow is the same as with smashing.

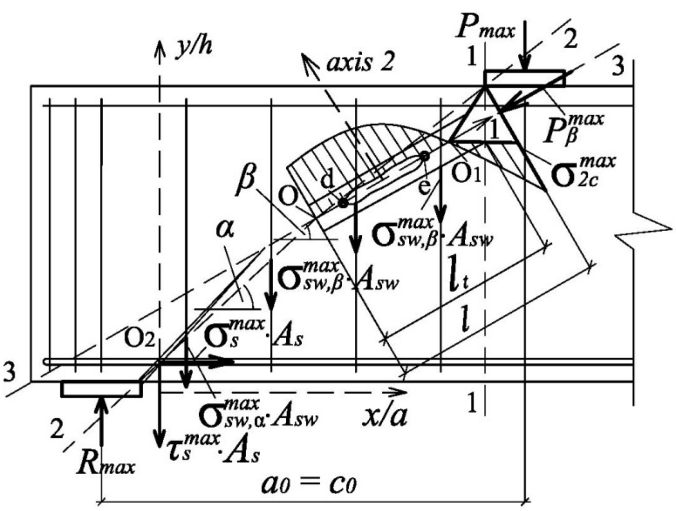

Figure 5 Physical and analytical models of fatigue resistance of non-over-reinforced concrete members with medium bay of shear fracture

For this case of stress-deformation state and fracturing nature objective fatigue strength (the endurance limit) of inclined compressed strip of concrete over critically inclined crack takes its form:

$$f_{cd,rep}(t)=\frac{\left[k_{scf}(t)+K_{1sw}(t)\right]l(t)ctg\varphi}{l_{sup}sin\beta\sqrt{\pi l(t)}Y(l)}\times\left\langle\begin{array}{l}1-\left\{\dfrac{G_cL_\varepsilon}{sin^2\varphi}+\dfrac{6E_sI_sL_\varepsilon n\cdot cos(\varphi-\beta)sin\beta}{\left[d_s\sqrt[4]{\dfrac{E_s}{E_c}\left(1,4+1,25\sqrt[4]{\dfrac{a_s}{d_s}}\right)}\right]^3 sin\varphi}\right\}\times\\ \times\left\{\dfrac{1}{E_c}+C_e\prod_{k=1}^{k=n}K_ka\psi_\upsilon+\int_{t_0}^{t}\dfrac{\partial}{\partial\tau}\left[\dfrac{1}{E_c(\tau)}+C(t,\tau)\right]dt\right\}\end{array}\right\rangle^{-1} \quad (8)$$

where k_{scf}, $l(t)$, φ, $Y(l)$, l_{sup}, G_c, L_ε, E_s, I_s, n, d_s, E_c, a_s, C_e, K_k, a, ψ_υ, C are according to (1); K_{1sw} is according to (3); β – an angle of inclination of straight line segment that models end part of danger inclined crack, $\beta=arctg\frac{h_0}{c_0}$.

The limits of endurance of transverse and longitudinal reinforcement and the endurance limit of anchoring it are determined according to (4), (5) and (6).

5 CONCLUSSIONS

Therefore, the analysis of existing methods of calculating the endurance of reinforced concrete structures with joint action of transverse forces and bending moments, based on the studies [1, 12, 15, 17, 18, 19] shows that in most cases they are performed assuming elastic of concrete without its physical nonlinearity and material deformation regimes change in the composition of structures under cyclic loading.

The considered physical and analytical models of resistance of by-support areas of non-over-reinforced concrete structures repeated transverse load of high levels involve different types of exhausting destruction of materials taking into account deformations of cyclic strain-induced creep, accumulation of damage in the form of atomic micro- and macro-cracks.

REFERENCES

[1] Mirsayapov I. 2009: Endurance of Reinforced Concrete Structures under the Action of Shear Forces: *Abstract of Doctor of Technical Sciences Thesis*: Specialty 05.23.01 – «Building Constructions, Buildings and Structures», Kazan.

[2] Babich, E.; Gomon, P.; Filipchuk, S. 2012: Work and Calculation of the Bearing Capacity of Bending T-sections Reinforced Concrete Elements under the Influence of Repeated Loads, Edition of NUWNM, Rovno.

[3] Zinchuk, N. 2004: Experimental Study of Stress-Strain State of Reinforced Concrete Bent Elements under the Single and Low-Cycle Loading at Elevated Temperatures, Economical Resource Materials, Constructions, Buildings and Structures, 11 (1), pp. 164-166.

[4] Melnik, S.; Borisjuk, O.; Kononchuk, O.; Petrishin, V. 2008: The Research of Reinforced Concrete Beams Work under the Action of Low-Cycle Loading, Economical Resource Materials, Constructions, Buildings and Structures, 17 (1), pp. 404-410.

[5] Kovalchik, Ja.; Koval, P. 2014: Investigation of Crack Resistance of Prestressed Reinforced Concrete Beams under the Influence of Low-Cycle Loading, Scientific and Practical Aspects of the Automobile and Transport Industries of the Road, 45 (1), pp. 282-287.

[6] Babich, V. 2003: Features of Continuous Reinforced Concrete Beams Work under the Repeated Loads, Building Constructions, 58 (1), pp. 8-13.

[7] Drobyshinec, S.; Babich, E. 2004: Work of Fiber Concrete and Fiber Reinforced Concrete Beams under the Action of Monotonic and Repeated Loadings, Composite Structures. Research, Design, Construction, Operation, 6 (1), pp 65-71.

[8] Valovoj, M. 2008: The Strength, Crack Resistance and Deformability of Concrete Beams under the Influence of Repeated Loads, Composite Structures. Research, Design, Construction, Operation, 8 (1), pp. 45-48.

[9] Karpiuk, V.; Albu, K.; Danilenko, D.; Somina Yu. 2014: Experimental Investigations of Reinforced Concrete Beams Performance under the Influence of Cyclic Loading, Papers and Commentaries of the 2nd International Academic Congress “Fundamental and Applied Studies in America, Europe, Asia and Africa”, 2 (1), pp. 682-696.

[10] Dorofeev, V.; Karpiuk, V.; Albu, K; Somina, Yu. 2016: Strength and Crack Resistance of Reinforced Concrete Beam Structures under the Action of Low-Cycle Loads of Constant Sign and Cyclic Alternating Loadings of High Levels, Bridges and Tunnels. Theory, Research, Practice, 10 (1), pp. 13-26.

[11] Kornejchuk, A.; Masjuk, G. 2008: Experimental Study of Bearing Capacity of Inclined Cross Sections of Bending Reinforced Concrete Elements under the Action of Low-Cycle Alternating Loads, Economical Resource Materials, Constructions, Buildings and Structures,16 (2), pp. 217-222.

[12] Sokolov, B. 1992: A New Approach to Calculating the Strength of Concrete Elements under Local Load Action, Concrete and Reinforced Concrete, 10 (1), pp. 22-24.

[13] Baranova, T.; Zalesov, A. 2003: Frame-Rod Calculating Models and Engineering Calculating Methods of Reinforced Concrete Structures, Association of Construction Universities Edition, Moscow.

[14] Goto, I. 1971: Cracks Formed in Concrete Around Deformed Tension Bars, ACI Journal, 68 (4), pp. 73-79.

[15] Karpenko, N. 1996: General Models of Reinforced Concrete Mechanics, Building Edition, Moscow.

[16] Kholmyanskiy, M. 1997: Concrete and Reinforced Concrete: Deformability and Strength, Building Edition, Moscow.

[17] Aslani, F.; Jowkarmeimandi, R. 2012: Stress-Strain Model for Concrete under Cyclic Loading, Magazine of Concrete Research, 64 (8), pp. 673-685.

[18] Trapko, W. ; Trapko, T. 2012 : The Bearing Capacity of Reinforced Concrete Elements under repeated compressive load reinforced by CFRP, Civil Engineer and Management, 57 (4), pp. 590-597.

[19] Papakonstantinou, C.; Balaguru, P.; Petrou, M. 2005 : Investigation of Reinforced Concrete Beams Reinforced with Composite Materials under Fatigue Loads, ACI Materials, 86 (4), pp. 41-60.