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ANALYSIS OF THE STRAIN-STRESS STATE OF THE BENDING CONTINUOUS RC-BEAMS WITH HYBRID REINFORCEMENT IN THE TENSILE ZONE UNDER INTERMEDIATE SUPPORT

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Abstract

The article considers the proposed model describing the stress-strain state of bent statically indeterminate reinforced concrete beams with combined reinforcement (the joint arrangement of metal and composite rods) of the stretched zone of the central support section, based on the positions of the general deformation model of cross-sections with normal separation cracks between concrete subelements formed by two adjacent cracks and the block model of the resistance of the bent element. The prerequisites and assumptions for applying the proposed model are presented. The stress-strain state of the central reference section of the considered elements is analyzed according to the proposed model. The criterion of destruction of statically indeterminate reinforced concrete beams with hybrid reinforcement of the stretched zone of the central support section is revealed, which fully allows taking into account the redistribution of internal forces between the support and span sections of the element.

Keywords: statically indeterminate beams, reinforced concrete, composite reinforcement, block model, combined reinforcement, bending.

АНАЛИЗ НАПРЯЖЕННО-ДЕФОРМИРОВАННОГО СОСТОЯНИЯ ИЗГИБАЕМЫХ СТАТИЧЕСКИ НЕОПРЕДЕЛИМЫХ ЖЕЛЕЗОБЕТОННЫХ БАЛОК С КОМБИНИРОВАННЫМ АРМИРОВАНИЕМ НАД ЦЕНТРАЛЬНОЙ ОПОРНОЙ РАСТЯНУТОЙ ЗОНОЙ

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Реферат

В статье рассматривается модель, описывающая напряженно-деформированное состояние изгибаемых статически-неопределимых железобетонных балок с комбинированным армированием (совместное расположение металлических и композитных стержней) растянутой зоны центрального опорного сечения, основанная на положениях общей деформационной модели поперечных сечений с трещинами нормального отрыва между бетонными подэлементами, образованными двумя соседними трещинами и блочной модели сопротивления изгибаемого элемента. Представлены предпосылки и допущения при применении предлагаемой модели. Выполнен анализ напряженно-деформированного состояния центрального опорного сечения рассматриваемых элементов по предлагаемой модели. Выявлен критерий разрушения статически неопределимых железобетонных балок с комбинированным армированием растянутой зоны центрального опорного сечения, который в полной мере позволяет учитывать перераспределение внутренних усилий между опорными и пролетными сечениями элемента.

Ключевые слова: статически неопределимые балки, железобетон, композитная арматура, блочная модель, комбинированное армирование, изгиб.

Introduction

To date, there is an increase in the use of composite reinforcement in construction (in international practice, FRP – fiber reinforced polymer composite), which is a polymer element reinforced with high-strength fibers (glass, carbon, basalt or aramid) [1–3]. The main application of this type of reinforcement is found in the production of reinforced concrete structures, the exploitation of which takes place in highly aggressive environments, where it is difficult to provide reliable corrosion protection to metal fittings, or in structures in which it is necessary to ensure neutral magnetic and dielectric properties.

The main factor that does not allow directly replacing all tension steel reinforcement with FRP is its low modulus of elasticity. Numerous studies [4-6] show that it is the modulus of elasticity of the composite reinforcement used that is the dominant factor in the operation of flexure reinforced concrete elements reinforced with composite bars without prestressing.

One of the possible solutions to expand the scope of application of composite reinforcement without prestressing will be the introduction of a reinforced concrete element reinforced with composite reinforcement into the tension zone of a certain percentage of metal reinforcement (combined or hybrid reinforcement), thereby achieving a more rational and safe operation of the structure as a whole [7]. The greatest effect from the use of combined reinforcement is expected from its application in statically indeterminate bending elements, primarily due to the rational redistribution of actions effects (mainly moments) between the support sections with combined reinforcement and span sections with tension indeterminate steel reinforcement.

To describe the stress-strain state of statically undetectable bent reinforced concrete beams with combined reinforcement, a model is proposed based on the provisions of the general deformation model for cross sections with cracks of normal separation between concrete sub elements and a block model of the resistance of the bending element.

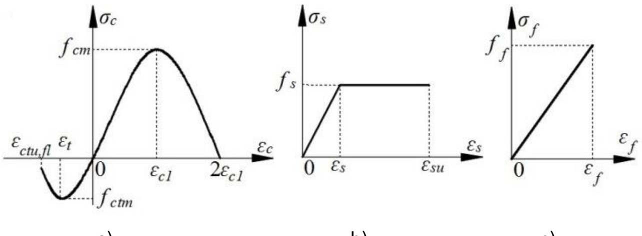
Assumptions of the general deformation model

The general deformation model of a reinforced concrete element [8, 9] makes it possible to take into account the nonlinear properties of materials in the cross section under consideration, using nonlinear relationships «stress-strain» of concrete and reinforcement deformation.

In accordance with the provisions of the general deformation model, the cross-section of the bending reinforced concrete element is represented as a set of elementary areas (layers) and longitudinal reinforcing tars. Within these sites, normal stresses are considered to be uniformly distributed and equal to their average values.

Relative deformations along the section height are distributed according to the hypothesis of plain sections [10, 11], i.e. for relative strains averaged along the length of the element section with cracks of normal separation. The distribution of normal stresses over the height of the element, which correspond to the averaged strains, correspond to the cross section with a crack of normal separation.

Each elementary area of concrete beams, bars of steel reinforcement and composite reinforcement under the influence of forces from the applied load experience uniaxial tension or compression in accordance with the «stress-strain» diagrams used $\sigma = f(\varepsilon)$ (Fig. 1).



a) b) c)

Figure 1 – Relationship «$\sigma - \varepsilon$» for concrete (a), steel reinforcement (b) and composite reinforcement (c)

As an approximation of the diagrams of concrete «$\sigma_c - \varepsilon_c$» under compression (1) and tension on the ascending (3a) and descending (3b) branches, a nonlinear relationships according to Model Code 2010 and [12] with a descending branch are used:

$$\sigma_c = \frac{k\eta - \eta^2}{1+(k-2)\eta} f_{cm} , \qquad (1)$$

where $k = \frac{1{,}1E_{cm,n}/\varepsilon_{c1}/}{f_{cm}}$; $\eta = \frac{\varepsilon_{c0}}{\varepsilon_{c1}}$; (2)

$$\sigma_{c_t} = 1{,}2\left(\frac{\varepsilon_{ct}}{\varepsilon_{ct1}}\right) - 0{,}2\left(\frac{\varepsilon_{ct}}{\varepsilon_{ct1}}\right)^6 ; \qquad (3a)$$

$$\sigma_{c_t} = \frac{\left(\frac{\varepsilon_{ct}}{\varepsilon_{ct1}}\right)}{\alpha_{ct}\left[\left(\frac{\varepsilon_{ct}}{\varepsilon_{ct1}}\right) - 1\right]^{1,7} + \left(\frac{\varepsilon_{ct}}{\varepsilon_{ct1}}\right)} f_{ctm}; \qquad (3b)$$

Where ε_{ct1} – strains corresponding to the peak point of the deformation diagram (Fig. 1 a), equal to $\varepsilon_{ct1} = (44 f_{cm}) \cdot 10^{-6}$ MPa;

$\alpha_{ct} = 0{,}312(f_{ctm})^2$ – correction factor depending on the tensile strength of concrete $f_{ctm} = 0{,}3 f_{cm}^{2/3}$ (calculated based on the average compressive strength of concrete f_{cm} [13].

The ultimate strains of concrete, which according to [15] are equal to:

$$\varepsilon_{ctu,fl} = \frac{K \cdot \varepsilon_{ct1}}{2} ; \qquad (4)$$

where $K = 6{,}4 + 0{,}1223 f_{cm}$.

The maximum strains of concrete under compression, in accordance with the current code [15], are accepted depending on the concrete class within $\varepsilon_{cu1} = (-3{,}5 \ldots -2{,}8) \cdot 10^{-3}$. Based on the fact that in the sections of statically indeterminate reinforced concrete elements at the stage close to the ultimate (the appearance of plastic hinges with the opening of cracks of normal separation), there is a redistribution of forces along the section with the achievement of significant strains exceeding the ultimate values, a diagram of concrete deformation under compression without limiting the length of the descending branch is adopted in the general deformation model.

To approximate the deformation diagrams of the longitudinal steel and composite reinforcement of the tensile zone under the support section of the beams under tension/compression uses piecewise linear functions passing through the base points(f_{ym}; $\varepsilon_{ym} = f_{ym}/E_s$),ultimate yield strength yield strains respectively and corresponding strains (E_s – the initial modulus of elasticity of the steel reinforcement) and f_{fm}; $\varepsilon_{fm} = f_{fm}/E_f$ – the ultimate strength of composite reinforcement and its corresponding value of the strains (E_f – modulus of elasticity of composite reinforcement).

Assumptions of the proposed model

To analyze the stress-strain state of flexural reinforced concrete elements with combined reinforcement, a model for continuous beams with metal reinforcement by G.Manfredi was used as a base [16].

The proposed model, which describes the stress-strain state of statically indeterminate reinforced concrete beams with combined reinforcement of the tensile zone under the support section, is based on the following assumptions of the basic block model [16], taking into account their design features: - a statically indeterminate flexural reinforced concrete element is an element with a length of L, divided into subelements of finite length ΔL (Fig. 2) formed by two adjacent cracks of normal separation, which occur in sections where tensile stresses in concrete reach the limit values. The sub-elements are interconnected by tensioned steel and composite reinforcement and compressed concrete;

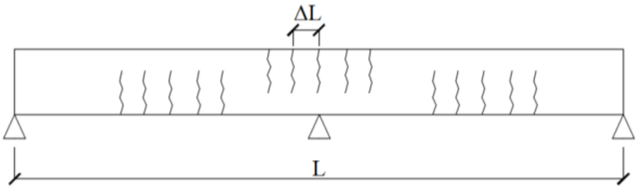
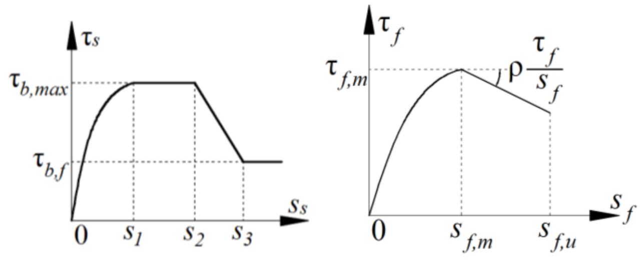


Figure 2 – Diagram of the division of a reinforced concrete element into subelements according to [16]

– concrete, composite and metal fittings work together in accordance with the accepted laws of adhesion according to ModelCode 2010 (MC2010). The laws of adhesion relate tangential stresses over the contact area of reinforcing bars with concrete and their mutual displacement $\tau_b = f(s)$, $\tau_{fb} = f_f(s_f)$ (Fig.3 a,b);



a) b)

Figure 3 – Graph of the dependence of tangential stresses of stretched metal reinforcement (a) and composite reinforcement (b) with concrete depending on the amount of slippage s in accordance with MC2010

Graph of tangential stress dependence τ_b according to the contract of stretched metal reinforcement with concrete, depending on the amount of slippage s according to MC2010 it includes the following parametric points:

$\tau_b = \tau_{bmax}(s / s_1)^{\alpha}$ for $0 \le s \le s_1$;
$\tau_b = \tau_{bmax}$ for $s_1 \le s \le s_2$; (4a)
$\tau_b = \tau_{bmax}(\tau_{bmax} - \tau_{b,f})(s - s_2)(s_3 - s_2)$ for $s_2 \le s \le s_3$;
$\tau_b = \tau_{b,f}$ for $s_3 < s$,

where, τ_{bmax} – the maximum coupling voltage, which, depending on the coupling conditions and is equal to $2{,}5\sqrt{f_{cm}}$ or $1{,}25\sqrt{f_{cm}}$;

α – the coefficient that models the shape of the coupling law curve is from 0 to 1;

$\tau_{b,f} = 0{,}4\tau_{b,max}$ – resistance to slippage on the last horizontal section of the curve.

Resistance to slippage on the last horizontal section of the curve.

$$\tau_{fb} = \tau_{fm}\left(\frac{s_f}{s_{fm}}\right)^{\alpha} \qquad \text{for } 0 \le s_f \le s_{fm} \qquad (46)$$

$$\tau_{fb} = \tau_{fm} - \frac{\tau_{fm}\rho(s_f - s_{fm})}{s_{fm}} \qquad \text{for } s_{fm} \le s_f \le s_{fu}$$

τ_{fm} – maximum clutch tension;

α – a coefficient that models the shape of the coupling law curve.

The values of parametric points are determined empirically for a specific type of composite reinforcement:

- tensile stresses in concrete are distributed evenly from steel and composite reinforcement over the effective area around the tars. The depth of the effective area of concrete is taken according to BR 5.03.01-2020 and is equal to the lesser of the values $2{,}5(h-d)$, $(h-x)/3$, $h/3$ (where h – full beam cross-section height; d – working height of the beam section; x – the height of the compressed concrete zone in cross-section with a crack of normal separation) (Fig. 4). According to studies of concrete strains under tension [10, 11], it is assumed that concrete strains under tension are assumed to be constant over the entire area;

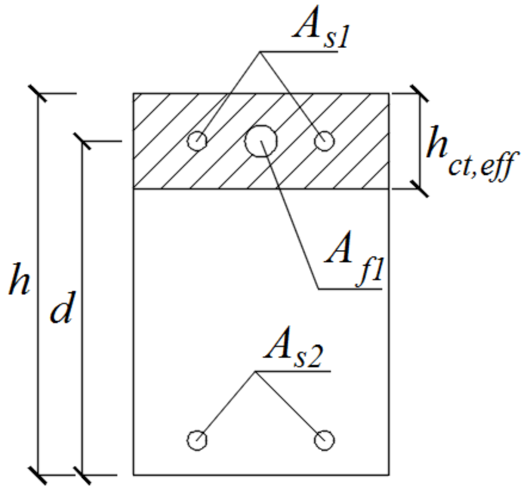


Figure 4 – Effective height $h_{ct,eff}$ stretched concrete of the support section of beams with combined reinforcement

- cracking the normal margin of the tensile zone of the reference section with a combined reinforcement occurs at a strains of concrete at the level of the centre of gravity tensile combination of rebar values that match the value of the limit of elasticity of the concrete cross-section in bending [18];
- in the process of deformation under applied load there are two stages of cracking: cracking transient, i.e., the appearance of new cracks might and established the emergence of new cracks is impossible, i.e., the number of cracks does not change;
- at the first stage of cracking, characteristic zones are identified in each concrete sub element: length $l_{f,j}$ at the edges of cracks, where there is a redistribution of tensile stresses between metal and composite reinforcement and concrete $(\varepsilon_s > \varepsilon_{ct})$,$(\varepsilon_f > \varepsilon_{ct})$ and length $\left(L_{m,i} - l_{f,j} - l_{f,j+1}\right)$ in the middle of the subelement where concrete and reinforcement are deformed together $(\varepsilon_s = \varepsilon_{ct})$, $(\varepsilon_f = \varepsilon_{ct})$.
- at the second stage of cracking along the entire length of the beam sub element, there is a redistribution of tensile forces between concrete, steel and composite reinforcement $(\varepsilon_s > \varepsilon_{ct})$,$(\varepsilon_f > \varepsilon_{ct})$;
- the opening width of cracks of normal separation in the tensile zone of the central support section of a statically indeterminate beam is due to the mutual displacement of reinforcing metal and composite rods relative to concrete at the level of its center of gravity on both sides of the crack edges along the length of the stretch stress redistribution section $l_{f,j}$.

Analysis of the stress-strain state of the sections under central support

The stress-deformable state of the central support section of a statically indeterminate reinforced concrete beam with a combined reinforcement of the tensile zone is described by the equilibrium equations of bending moments and longitudinal forces, equilibrium equations for individual steel and composite bar «bond-slip»s, equations of individual rods, the condition for the distribution of relative deformations along the cross-section height in accordance with the hypothesis of flat sections of Bernoulli and diagrams for materials of individual elementary areas, which are formed by dividing the beam section into elementary platforms-layers, while each longitudinal bar of the working steel and composite reinforcement is considered as a separate elementary area. The equations of the stress-strain state:

$$\begin{cases} \sum_{i=1}^{k}\sigma_{c,i}A_{c,i}(y_0 - y_{c,i}) - \sum_{i=k+1}^{m}\sigma_{s,i}A_{s,i}(y_0 - y_{s,i}) - \\ -\sum_{i=k+1}^{m}\sigma_{f,i}A_{f,i}(y_0 - y_{f,i}) - \sum_{j=1}^{n}\sigma_{ct,j}A_{ct,j}(y_0 - y_{ct,j}) - M = 0 \\ \sum_{i=1}^{k}\sigma_{c,i}A_{c,i} - \sum_{i=k+1}^{m}\sigma_{s,i}A_{s,i} - \sum_{i=k+1}^{m}\sigma_{f,i}A_{f,i} - \sum_{j=1}^{n}\sigma_{ct,j}A_{ct,j} = 0 \\ \frac{d\sigma_s(x)}{dx} - \frac{4}{\emptyset}\tau_s(x) = 0; \qquad \frac{d\sigma_f(x)}{dx} - \frac{4}{\emptyset}\tau_f(x) = 0; \\ \frac{ds_s(x)}{dx} - \varepsilon_s(x) + \varepsilon_{ct}(x) = 0; \qquad \frac{ds_f(x)}{dx} - \varepsilon_f(x) + \varepsilon_{ct}(x) = 0; \\ \varepsilon_{c,i} = \frac{1}{r_c}\left(y_0 - y_{c,i}\right); \quad \varepsilon_{s,i} = \frac{1}{r_c}\left(y_0 - y_{s,i}\right); \quad \varepsilon_{f,i} = \frac{1}{r_c}(y_0 - y_{f,i}); \\ \sigma_{c,i} = f(\varepsilon_{c,i}); \quad \sigma_{s,i} = f(\varepsilon_{s,i}); \quad \sigma_{f,i} = f(\varepsilon_{f,i}); \end{cases} \qquad (5)$$

where $\sigma_{c,i}, \varepsilon_{c,i}$ – accordingly, normal stresses and strains in the i-th elementary site of compressed concrete;

$\sigma_{ct,j}, \varepsilon_{ct,j}$ – accordingly, normal stresses and strains in the j-th elementary site of stretched concrete;

$\sigma_{s,i}, \varepsilon_{s,i}$ – accordingly, normal stresses and strains in the i-th elementary area of tensil steel reinforcement;

$\sigma_{f,i}, \varepsilon_{f,i}$ – accordingly, normal stresses and strains in the i-th elementary area of tensile composite reinforcement;

$A_{c,i}, y_{c,i}$ – accordingly, the cross-sectional area and the distance from the selected axis to the center of gravity of the i-th elementary area of compressed concrete;

$A_{ct,j}, y_{ct,j}$ – accordingly, the cross-sectional area and the distance from the selected axis to the center of gravity of the j-th elementary area of tensile concrete;

$A_{s,i}, y_{s,i}$ – accordingly, the cross-sectional area and the distance from the selected axis to the center of gravity of the i-th elementary area of the tensile steel reinforcement;

$A_{f,i}, y_{f,i}$ – accordingly, the cross-sectional area and the distance from the selected axis to the center of gravity of the i-th elementary area of the tensile composite reinforcement;

$\frac{1}{r_c}$ – the curvature of the beam in the section under the bending moment;

τ_s, τ_f – accordingly, the bond stresses of the longitudinal steel and composite bars.

In the first iteration in the zone under the central support with combined reinforcement under the bending moment $\Delta M = M_{sup}$, equal to the moment of cracking separation M_{crc}, the position of a subelement (or two subelements) formed on the left or right at a distance l is considered from the central crack. The value of the bending moment in the cross section along the central crack on the support from the action of load is determined by known methods of structural mechanics.

From the solution of the system of equations (5) at each stage of loading, implementing an iterative process of sequentially calculating the position of the center of gravity of the reference section under consideration y_0, the curvature of the element in this section $\frac{1}{r_c}$, strains in the reinforcement, normal stresses, secant deformation modules in elementary concrete and reinforcement pads, we obtain the parameters of the stress-strain state of the bending elements with combined reinforcement. The end of the process of successive approximations at each stage of loading is determined by the specified accuracy of solving the initial equations.

If the tensile strains in the elementary area of the concrete beam $\varepsilon_{ct,i}$ tensile of the beam exceed the ultimate values $\varepsilon_{ctu,fl}$, then this indicates the formation of a new crack of normal separation and, consequently, in further calculations, the axial stiffness of this elementary area will be zero, i.e. $E_{c,i}A_{ct,i} = 0$, and the bending moment, at which the strains reach values $\varepsilon_{ctu,fl}$, corresponds to the moment of cracking M_{crc}.

As a result of the calculation, at a given bending moment, we obtain the stress-strain state of the reference section under consideration by combined reinforcement of the tensile zone: stresses in steel and composite reinforcement in the section with a crack, the height of the compressed zone *x*, bending stiffness *EI* and the curvature of the beam $\frac{1}{r_c}$, which are used in further calculations.

For example, deflection of a beam by a span l_{eff} in a cross section with the *x* coordinate under the action of an external bending moment *M(x)* can be defined by the equation:

$$a = \int_0^{l_{eff}} \overline{M}(x)\frac{1}{r_c}(x)\, dx \qquad (6)$$

where $\overline{M}(x)$ – the moment in the cross section from the point force applied in the direction of the determined displacement;

$\frac{1}{r_c}(x)$ – the curvature of the beam with combined reinforcement from the action of the bending moment from the external load.

Substituting into equation (6), instead of the total curvature of the beam with combined reinforcement, the curvature of the beam $\frac{1}{r_c}(x)$ under load, we get an additional deflection of the beam from the increment of the load.

The failure of statically indeterminate reinforced concrete beams with combined reinforcement along the normal cross-section is applied to the longitudinal axis, at which the conditions of equilibrium of internal forces of the system of equations (5) will be observed. This failure criterion allows to fully taking into account the redistribution of internal forces in statically indeterminate reinforced concrete beams with combined reinforcement of the tensile zone under central support section.

Conclusion

To analyze the stress-strain state of bent statically indeterminate reinforced concrete beams with combined reinforcement of the tensile zone of the central support, a model is proposed based on the positions of the general deformation model of cross-sections with cracks of normal separation between concrete subelements formed by two adjacent cracks and a block model of the resistance of the flexural element. The analysis of the stress-strain state of the central support section of the elements under consideration according to the proposed model fully allows us to take into account the redistribution of internal forces between the support and span sections of the element, taking into account the influence of the difference in the characteristics of steel and composite reinforcement.

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