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MODELING OF THE STRESS-STRAIN STATE OF BENT CONCRETE ELEMENTS WITH COMPOSITE ROD REINFORCEMENT

D. N. Lazovskiy [1], A. I. Hil [2], E. E. Genina [3]

Euphrosyne Polotskaya State University of Polotsk [1, 2]
Republic of Belarus, Novopolotsk
Ariel University [3]
Israel, Ariel

[1] *D. Sc. in Engineering, Prof., Prof. of the Dept. of Building Structures, e-mail: d.lazovski@psu.by*
[2] *PhD in Engineering, Assoc. Prof. of the Dept. of Building Structures, e-mail: a.hil@psu.by*
[3] *PhD in Engineering, Assoc. Prof. of the Dept. of Building Structures, e-mail: vgenyag@ariel.ac.il*

Statement of the problem. The use of composite core reinforcement in concrete structures is a promising direction in construction practice, however, to date, no single scientifically based approach has been developed for their calculation. The purpose of the work is to consider the possibility of using a deformation model to calculate the parameters of the stress-strain state of bent concrete elements with composite core reinforcement, including its prestressing.
Results. Based on the general deformation model, a method for calculating the parameters of the stress-strain state of bent reinforced concrete elements with composite reinforcement (including prestressed) was applied and verified against the background of experimental data, allowing for taking into account the strength and deformation characteristics of composite reinforcement, the amount of prestress taking into account the elastic compression of concrete, the stress-strain state at different stages of operation, including the stage of rebar release, the formation of cracks of normal separation, the limit stage. Satisfactory convergence of experimental and theoretical studies has been obtained.
Conclusions. Modeling the operation of a concrete element with composite reinforcement based on a deformation model allows you to obtain the parameters of its stress-strain state at any stage of work and further design structures with a choice of their most optimal reinforcement options. The results of experimental and theoretical studies can be used to verify the limiting conditions of load-bearing capacity and operational suitability for bent concrete structures consisting of concrete with different strength and deformation characteristics, reinforced with various types of composite core reinforcement.

Keywords: bendable concrete elements, composite core reinforcement, prestressing, deformation diagram, deformation model, stages of construction work.

Introduction. Despite their long history of development and application [4, 12, 25, 26], FRP Rebars — Fiber Reinforced Polymer Rebars are still cutting-edge in construction practice, and a unified approach to calculating such elements has not been developed yet.

Composite reinforcement is a heterogeneous system that is made up of a reinforcing high-strength fiber forming the foundation of the composite and is critical to its strength and rigidity, and a polymer matrix that performs the functions of connecting the fibers to each other, protecting the surface from external influences during transportation, installation and operation, and transferring forces to the fiber. Glass, basalt, aramid, and carbon are used as the starting material for the reinforcing fiber (foundation). Various types of thermosetting resins are used for polymer binders: organosilicon, phenolic aldehyde, epoxy, heat—resistant polyamide, polybenzimidazole polymers. Composite reinforcement is produced as rods of various types of profiles, plates, canvases [4, 19, 21, 25].

High tensile strength, low dead weight and high durability in an aggressive environment enable composite reinforcement to be used as the main reinforcing element in concrete structures [20, 23]. This is due to ensuring its reliable adhesion to concrete thanks to adhesion of materials, friction forces, and mechanical engagement of concrete with natural and artificially created irregularities on the surface of composite reinforcement. [10, 11, 18, 24]. Studies of joint work with concrete of composite reinforcement based on glass fibers [7, 8, 22, 27, 29] confirmed that composite reinforcement whose periodic profile was created by winding a fiberglass braid thread onto the body of the rod, does not slip in concrete, and when used in bent reinforced concrete elements, additional anchoring devices are not required including when it is pre-stressed. All of this makes it possible to seamlessly design concrete structures reinforced with composite reinforcement including prestressed ones.

The issue of calculating the structures under consideration is still critical. Most methods for calculating bendable reinforced concrete elements with composite reinforcement that accepts tensile forces elastically, with no plastic deformations and with a modulus of elasticity lower than that of steel, are based on the principles of plastic fracture in the limiting state [1, 13, 16]. The pre-stress of low-modulus composite reinforcement makes it possible to reduce the deflections and crack opening width of the bent elements, and to increase their strength with a higher degree of reinforcement. One of the promising methods for calculating bendable concrete elements with composite reinforcement is a deformation calculation model of cross-sections based on the use of material deformation diagrams, the principle of linear distribution of relative deformations over the height of the section (the hypothesis of flat sections) allowing one to account for the characteristics of materials, the stage of work of structures from their manufacture to the limiting state [6, 15].

The aim of the work is to apply a deformation model to calculate the parameters of the stress-strain state of bent concrete elements with composite core reinforcement including its prestress.

1. Initial data. Prestressed concrete beams [3] with a length of 2000 mm, a cross-sectional width of b = 120 mm, and a height of h = 200 mm, made of high-strength perlite-silicate concrete resistant to aggressive acid influences, were considered as samples for conducting experimental and theoretical studies. The concrete was autoclaved.

Table 1

Physical and mechanical characteristics of the beams

Beam brand	Compressive resistance of the concrete f_{cm}, MPa	Initial modulus of elasticity of concrete E_{cm}, MPa	Reinforcement A_f, мм^2	Tensile resistance of the reinforcement f_{fm}, MPa	Elasticity modulus of the reinforcement E_f, MPa	Pre-stress σ_p, MPa
БI-1	48.6	34400	8Ø6, 204	1340	57500	—
БI-3			2Ø6, 51		57500	446
БII-1	30.2	25200	6Ø6, 170	1320	50500	—
БII-3						418
БII-9			4Ø6, 113			367
БIII-1	39.2	30900	6Ø6, 170	1640	54500	224
БIII-3						412
БIII-5			4Ø6, 113	1360	5400	584

In the stretched area of the beams, grooves (b' = 60 mm, h' = 50 mm) were provided for installing prestressed composite reinforcement along the entire length of the beams, having extensions at the ends to ensure the joint work of the concretes not only due to the adhesion of precast concrete and sealing concrete, but also mechanical engagement. The grooves were sealed with naturally hardened polymer silicate concrete (axial compression resistance f_{cm} = 20 MPa), which eliminated the reduction in resistance and loss of prestress of the composite reinforcement during autoclave treatment and ensured the same acid resistance of the overall structure. Composite reinforcement based on glass fiber (brand Щ-15-ЖТ) was used as reinforcement. The resistance of concrete beams under axial tension and the corresponding relative deformations were calculated based on experimental values obtained during concrete compression testing. The physical and mechanical characteristics of the beams are shown in Table 1.

2. Diagrams of deformation of concrete and composite core reinforcement. The compression deformation diagram of concrete is assumed to be curved with a descending branch without limiting its length in terms of deformations in order to obtain a complete redistribution of forces between the compressed and stretched zones in the cross section of the bent element. The nonlinear dependence according to the *FIB Model Code for Concrete Structures 2010* and [5] is used as an approximation of the concrete deformation diagram under compression (1):

$$\sigma_c = \frac{k_c \eta_c - \eta_c^2}{1 + (k_c - 2)\eta_c} f_{cm}, \tag{1}$$

where $$k_c = \frac{1.1 E_{cm,n} \left|\varepsilon_{c1}\right|}{f_{cm}}; \quad \eta_c = \frac{\varepsilon_c}{\varepsilon_{c1}}; \quad E_{cm,n} = 22 \cdot \left(\frac{f_{cm}}{10}\right)^{0.3},$$

where f_{cm} — average strength of concrete under axial compression; $E_{cm,n}$ — average value of the modulus of elasticity of the concrete; ε_{c1} — relative deformation of concrete corresponding to the average strength of concrete f_{cm} under axial compression; ε_c — relative deformation of concrete under axial compression.

The approximation of the concrete deformation diagram with flexural tensile strength $f_{ctm,fl}$ [17], the initial tensile modulus E_{ct}, and relative deformations $\varepsilon_{ctm,1}$ at the peak point of the deformation diagram [17] is also assumed to be curved with the limitation of relative deformations by the ultimate extensibility of the concrete $\varepsilon_{ctm,u}$:

– the ascending branch: $$\sigma_{ct} = 1.2\left(\frac{\varepsilon_{ct}}{\varepsilon_{ct1}}\right) - 0.2\left(\frac{\varepsilon_{ct}}{\varepsilon_{ct1}}\right)^6; \tag{2a}$$

– the descending branch: $$\sigma_{ct} = \frac{\left(\frac{\varepsilon_{ct}}{\varepsilon_{ct1}}\right)}{\alpha_{ct}\left[\left(\frac{\varepsilon_{ct}}{\varepsilon_{ct1}}\right) - 1\right]^{1.7} + \left(\frac{\varepsilon_{ct}}{\varepsilon_{ct1}}\right)} f_{ctm,fl}, \tag{2b}$$

where

$$\alpha_{ct} = 0.312 \cdot (f_{ctm})^2; \quad f_{ctm,fl} = f_{ctm} \cdot \left[1.6 - 0.001h\right]; \quad E_{ct} = \frac{10^7 \cdot f_{ctm}}{750 + 81.55 \cdot f_{ctm}};$$

$$\varepsilon_{ctm,1} = \frac{2 \cdot f_{ctm}}{E_{ct}}; \quad \varepsilon_{ctm,u} = \frac{K \cdot \varepsilon_{ctm,1}}{2}; \quad K = 6.4 + 0.1223 \cdot f_{cm},$$

where f_{ctm} — average strength of concrete under axial tension, MPa; h — the height of the cross-section of the element.

In order to approximate the strain diagram of a longitudinal composite reinforcement under tension, a linear function passing through the point of ultimate tensile strength of the composite reinforcement f_{fm} and the corresponding marginal relative deformations $\varepsilon_{fum} = f_{fm} / E_{fm}$ where E_{fm} is the modulus of elasticity of the composite reinforcement.

3. Deformation calculation method. In the general case of calculating a bent element with prestressed reinforcement, two stages of its operation are considered: the first is at the moment of releasing the prestress of the reinforcement by compressing concrete when exposed to the bending moment M from the eigenweight of the concrete element; the second is when exposed to an additional bending moment M from an external load.

At the first stage, the relative deformations during compression in the elementary areas of concrete and reinforcement rods with no prestressing (with mixed reinforcement), as well as relative deformations at the level of the rods of prestressed reinforcement which characterize the loss of prestressing during compression are identified.

For concrete elements with prestressed composite reinforcement rods, the stress-strain state equations take the form:

$$\begin{cases} \sum_{i=1}^{k}\sigma_{c,i}A_{c,i}(y_0 - y_{c,i}) + \sum_{i=k+1}^{n}\sigma_{f,i}A_{f,i}(y_0 - y_{f,i}) - \sum_{i=k+1}^{m}\sigma_{fp,i}A_{fp,i}(y_0 - y_{fp,i}) - M_{own} = 0; \\ \sum_{i=1}^{k}\sigma_{c,i}A_{c,i} + \sum_{i=k+1}^{n}\sigma_{f,i}A_{f,i} - \sum_{i=k+1}^{m}\sigma_{f,i}A_{f,i} = 0; \\ \varepsilon_{(c,f)i} = \frac{1}{r_c}(y_0 - y_{(c,f)i}) + \varepsilon_{P,fp}; \ \varepsilon_{fp,i} = \frac{1}{r_c}(y_0 - y_{fp,i}) + \varepsilon_{fpk,i} + \varepsilon_{P,fp}; \\ \sigma_{c,i} = f(\varepsilon_{c,i}); \quad \sigma_{f,i} = f(\varepsilon_{f,i}); \quad \sigma_{fp,i} = f(\varepsilon_{fp,i}), \end{cases} \quad (3)$$

where $\sigma_{(c,f)i}$ — normal stresses in the i-th elementary site of concrete or reinforcement; $\sigma_{fp,i}$ — value of pre-voltage; $\varepsilon_{(c,f)i}$ — longitudinal relative deformations of an elementary concrete or reinforcement platform; $A_{c,i}$, $A_{f,i}$, $A_{fp,i}$ — cross-sectional area of the elementary site of concrete, reinforcement, prestressed reinforcement respectively; $y_{(c,f)i}$, $y_{fp,i}$ — distance from the selected axis to the center of gravity of the elementary platform of concrete, reinforcement and prestressed reinforcement respectively; $\varepsilon_{fpk,i}$ — relative deformation of the prestressed reinforcement rod corresponding to the initial controlled value of the prestress at the time of release; y_0 — distance from the accepted axis to the center of gravity of the section with no accountiing for the prestressed reinforcement, mm; $1/r_c$ — curvature of the element in the considered section; $\varepsilon_{P,fp}$ — relative deformation in the center of gravity of the cross section from the prestressing force is given by the formula:

$$\varepsilon_{P,fp} = \frac{\sum_{i=n+1}^{m}\sigma_{fp,i}A_{fp,i}}{\sum_{i=1}^{k}E_{cm,i}A_{ci} + \sum_{i=k+1}^{n}E_{f,i}A_{f,i}}, \quad (4)$$

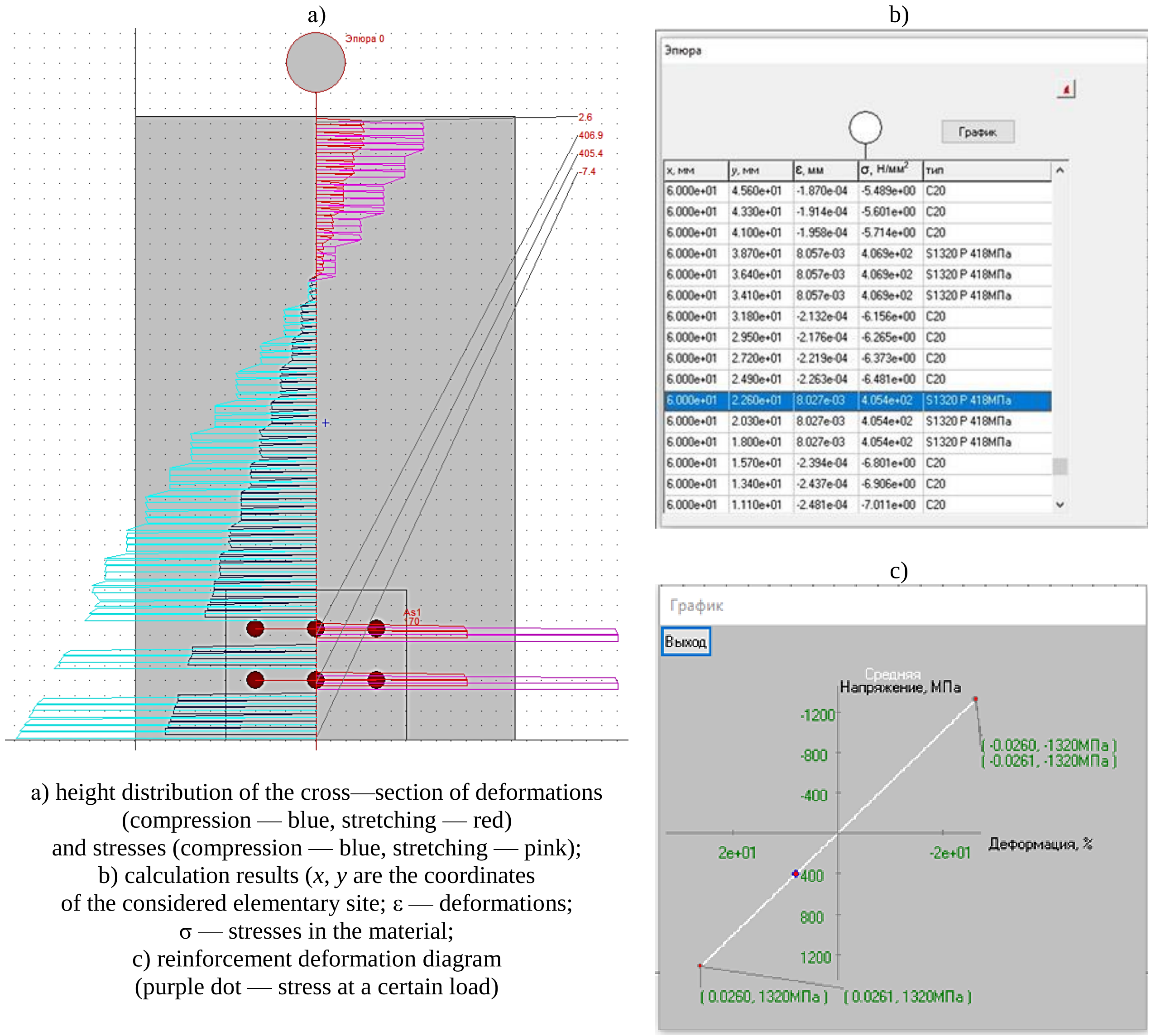
where $E_{cm,i}$ and $E_{f,i}$ — modulus of elasticity of the elementary platform of concrete and composite reinforcement respectively.

The relative deformations at the level of the rods of prestressed reinforcement characterizing the loss of prestress during compression are calculated using the formula:

$$\varepsilon_{1\,fp,i} = \frac{1}{r_c}(y_0 - y_{fp,i}) + \varepsilon_{P,\,fp}\,. \tag{5}$$

As a result of the calculation, the parameters of the stress-strain state of the normal section of the element are identified following the compression by prestressing, as well as prestressing $\sigma_{1fp,}$ aking into account the losses from elastic compression of concrete in the rods of prestressed reinforcement, which will be the initial ones at the second stage of the element operation. The presence of concretes of various classes in the cross section of the beam was taken into account according to the method [9]. During experimental studies, there was no shift in the contact of perlite silicate and polymer silicate concretes along the length of the beam.

The results of calculating the parameters of the stress-strain state of a concrete beam while releasing the prestress of composite reinforcement are shown in Fig. 1.



x, мм	y, мм	ε, мм	σ, Н/мм²	тип
6.000e+01	4.560e+01	-1.870e-04	-5.489e+00	C20
6.000e+01	4.330e+01	-1.914e-04	-5.601e+00	C20
6.000e+01	4.100e+01	-1.958e-04	-5.714e+00	C20
6.000e+01	3.870e+01	8.057e-03	4.069e+02	S1320 P 418МПа
6.000e+01	3.640e+01	8.057e-03	4.069e+02	S1320 P 418МПа
6.000e+01	3.410e+01	8.057e-03	4.069e+02	S1320 P 418МПа
6.000e+01	3.180e+01	-2.132e-04	-6.156e+00	C20
6.000e+01	2.950e+01	-2.176e-04	-6.265e+00	C20
6.000e+01	2.720e+01	-2.219e-04	-6.373e+00	C20
6.000e+01	2.490e+01	-2.263e-04	-6.481e+00	C20
6.000e+01	2.260e+01	8.027e-03	4.054e+02	S1320 P 418МПа
6.000e+01	2.030e+01	8.027e-03	4.054e+02	S1320 P 418МПа
6.000e+01	1.800e+01	8.027e-03	4.054e+02	S1320 P 418МПа
6.000e+01	1.570e+01	-2.394e-04	-6.801e+00	C20
6.000e+01	1.340e+01	-2.437e-04	-6.906e+00	C20
6.000e+01	1.110e+01	-2.481e-04	-7.011e+00	C20

a) height distribution of the cross—section of deformations (compression — blue, stretching — red) and stresses (compression — blue, stretching — pink);
b) calculation results (*x*, *y* are the coordinates of the considered elementary site; ε — deformations; σ — stresses in the material;
c) reinforcement deformation diagram (purple dot — stress at a certain load)

Fig. 1. Stress-strain state in the BII-3 beam at the first stage of calculation (release of prestressed fittings)

The equations of the stress-strain state of a bent concrete element with prestressing of individual rods of composite reinforcement at the second stage of calculation take the form:

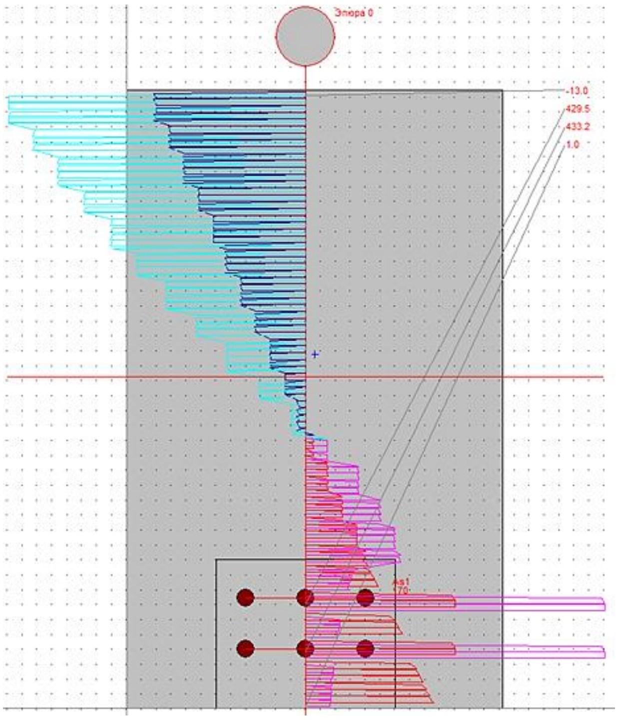
$$\begin{cases} \sum_{i=1}^{k} \sigma_{c,i} A_{c,i} (y_0 - y_{c,i}) + \sum_{i=k+1}^{n} \sigma_{f,i} A_{f,i} (y_0 - y_{f,i}) + \sum_{i=k+1}^{m} \sigma_{fp,i} A_{fp,i} (y_0 - y_{fp,i}) - (M_{own} + M) = 0; \\ \sum_{i=1}^{k} \sigma_{c,i} A_{c,i} + \sum_{i=k+1}^{n} \sigma_{f,i} A_{f,i} + \sum_{i=k+1}^{m} \sigma_{f,i} A_{f,i} = 0; \\ \varepsilon_{(c,f)i} = \dfrac{1}{r_c} (y_0 - y_{(c,f)i}) + \varepsilon_{1P,fp}; \;\; \varepsilon_{fp,i} = \dfrac{1}{r_c} (y_0 - y_{fp,i}) + \varepsilon_{fpk,i} + \varepsilon_{1P,fp}; \\ \sigma_{c,i} = f(\varepsilon_{c,i}); \;\; \sigma_{f,i} = f(\varepsilon_{f,i}); \;\; \sigma_{fp,i} = f(\varepsilon_{fp,i}), \end{cases} \tag{6}$$

where y_0 — distance from the accepted axis to the center of gravity of the section accounting for the prestressed reinforcement; $\varepsilon_{1P,fp}$ — relative deformation due to the action of the prestressing force.

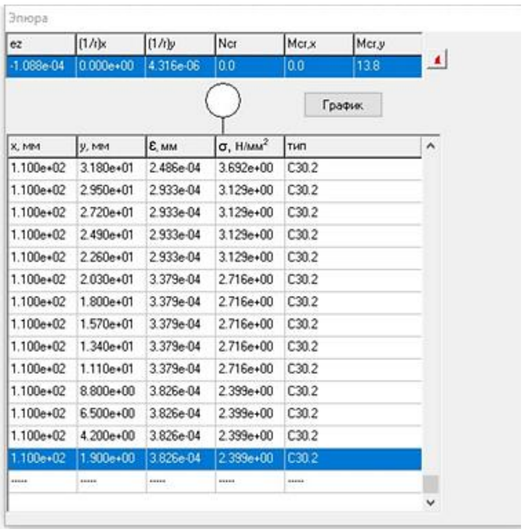
For elements with no prestressing, the system of equations (6) is applied with no accounting for the prestressed reinforcement. The criterion for the formation of cracks of normal separation is the achievement of maximum relative deformations by an elementary layer of concrete at the level of the center of gravity of the composite reinforcing rod $\varepsilon_{ctm,u}$.

The stress-strain state in the beam at the moment of formation of cracks of normal rupture isvin Fig. 2.

a)



b)



ez	(1/r)x	(1/r)y	Ncr	Mcr,x	Mcr,y
-1.088e-04	0.000e+00	4.316e-06	0.0	0.0	13.8

x, мм	y, мм	ε, мм	σ, Н/мм²	тип
1.100e+02	3.180e+01	2.486e-04	3.692e+00	C30.2
1.100e+02	2.950e+01	2.933e-04	3.129e+00	C30.2
1.100e+02	2.720e+01	2.933e-04	3.129e+00	C30.2
1.100e+02	2.490e+01	2.933e-04	3.129e+00	C30.2
1.100e+02	2.260e+01	2.933e-04	3.129e+00	C30.2
1.100e+02	2.030e+01	3.379e-04	2.716e+00	C30.2
1.100e+02	1.800e+01	3.379e-04	2.716e+00	C30.2
1.100e+02	1.570e+01	3.379e-04	2.716e+00	C30.2
1.100e+02	1.340e+01	3.379e-04	2.716e+00	C30.2
1.100e+02	1.110e+01	3.379e-04	2.716e+00	C30.2
1.100e+02	8.800e+00	3.826e-04	2.399e+00	C30.2
1.100e+02	6.500e+00	3.826e-04	2.399e+00	C30.2
1.100e+02	4.200e+00	3.826e-04	2.399e+00	C30.2
1.100e+02	1.900e+00	3.826e-04	2.399e+00	C30.2
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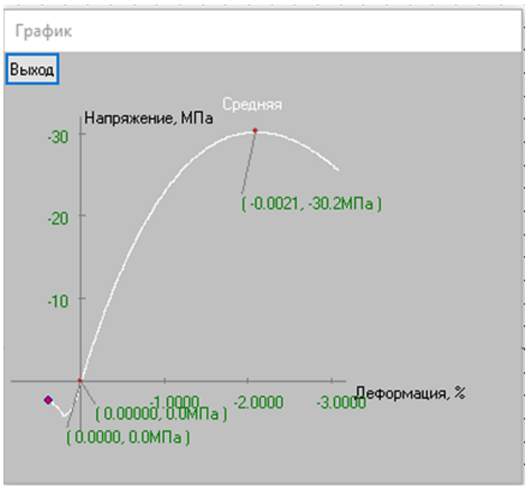
c)



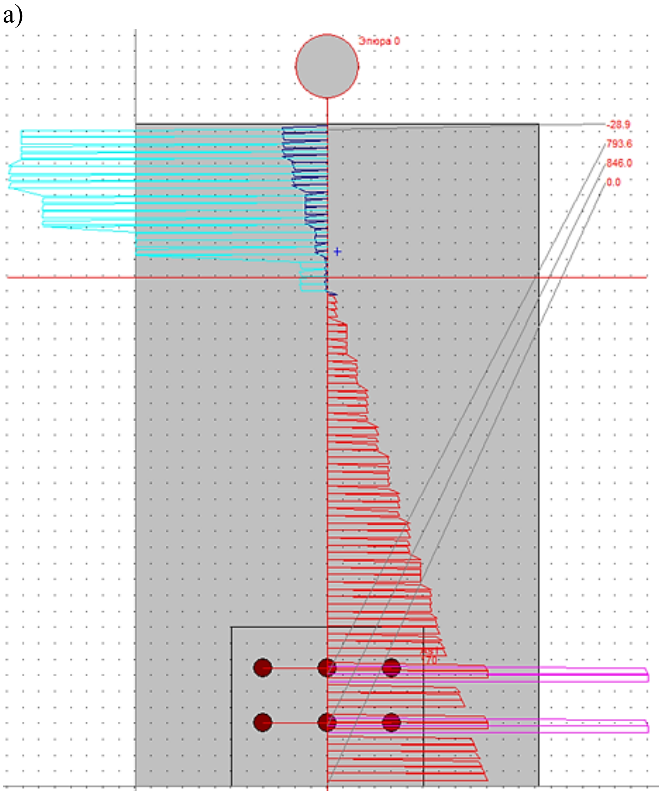
a) the height distribution of the cross—section of deformations (compression — blue, stretching — red) and stresses (compression — blue, stretching — pink);
b) calculation results (*x*, *y* are the coordinates of the considered elementary site; ε — deformations; σ — stresses in the material;
c) reinforcement deformation diagram (purple dot — stress at a certain load)

Fig. 2. Stress-strain state in the BII-3 beam during the formation of a normal separation crack

The maximum value of the external load at which the equilibrium conditions (6) are fulfilled corresponds to the strength of the concrete element with composite reinforcement.

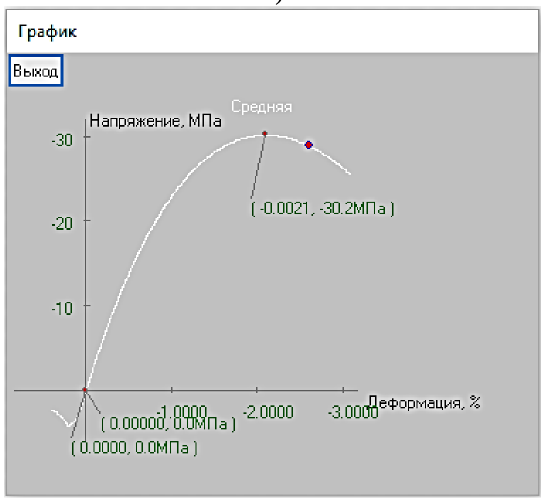
The stress-strain state in the beam at the second stage of the calculation (at the limit stage) is in Fig. 3.

a)



a) height distribution of the cross—section of deformations (compression — blue, stretching — red) and stresses (compression — blue, stretching — pink); b, c) deformation diagrams of the extreme fiber of the concrete of the compressed zone and composite reinforcement (purple dot — stress in the limiting stage)

b)



c)

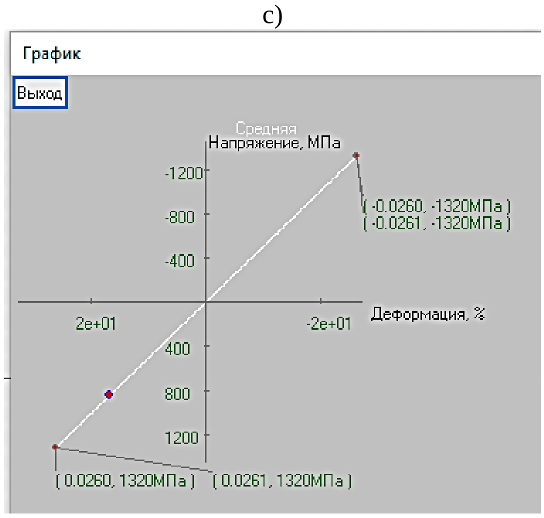


Fig. 3. Stress-strain state in the БII-3 beam at the second stage of calculation (limit stage)

The destruction of the beams took place along the compressed zone of concrete, while the normal stresses in the outermost rods of the reinforcement ranged from 64 to 81 % of the temporary resistance and depended on the degree of reinforcement.

The deflection of the bent structure by the design span l_d can be calculated based on the curvature of $1/r_c$ of the cross sections or by its maximum value at any stage of loading according to the formula:

$$a = \alpha \left(\frac{1}{r_c} \right) l_d^2, \tag{7}$$

where α — a coefficient that accounts for the loading scheme.

4. Results of the experimental and theoretical study. According to the suggested methodology, bendable concrete elements with composite reinforcement with the characteristics described in the initial data were analyzed. The calculation results are shown in Table 2.

Table 2

Results of experimental and theoretical study

Beam	Ultimate bending moment		Bending moment of cracking		Bending at 0,7M_u		$M_{cr,exp}$ / $M_{cr,calc}$	a_{exp} / a_{calc}	$M_{u,exp}$ / $M_{u,calc}$
	$M_{u,exp}$, kNm	$M_{u,calc}$, kNm	$M_{cr,exp}$, kNm	$M_{cr,calc}$, kNm	a_{exp}, mm	a_{calc}, mm			
БI-1	22.46	20.2	7.29	6.45	—	—	1.13	—	1.11
БI-3	10.2	9.6	8.36	7.5	—	—	1.11	—	1.06
БII-1	18.9	16.2	6.18	6	13.2	15.0	1.03	0.88	1.16
БII-3	23.94	22.1	14.48	13.8	6.84	7.5	1.05	0.91	1.08
БII-9	22.68	19.9	9.23	8.1	14.7	14.7	1.14	1	1.14
БIII-1	25.2	21.9	9.23	8.17	13.7	12.9	1.13	1.06	1.15
БIII-3	27.3	24.5	13.43	11.48	9.5	8.8	1.17	1.08	1.11
БIII-5	15.54	15.3	12.38	10.5	1.2	1.07	1.18	1.12	1.02

The suggested technique has also been tested in studies by other authors based on experimental data [2, 14, 28]. Beams with composite reinforcement based on glass [2, 14] and carbon [28] fibers with no prestressing were considered as investigated. A comparison of the calculation results using the suggested method with experimental data is shown in Table 3.

Table 3

Results of the beam calculation according to the suggested methodology.

Source	Parameters of the beam	$M_{u,exp}$, kNm	$M_{u,calc}$, kNm	$M_{cr,exp}$, kNm	$M_{cr,calc}$, kNm	a_{exp}, mm	a_{calc}, mm	a_{exp} / a_{calc}	$M_{cr,exp}$ / $M_{cr,calc}$	$M_{u,exp}$ / $M_{u,calc}$
[2]	$b×h×l$ (mm) 250×220×2980; f_{cm} = 25 MPa; A_{f1} 5Ø12 mm; f_f = 1200 MPa; A_{f2} 2Ø10 mm; f_f = 1200 MPa; E_f = 55000 MPa	50.97	51.5	6.6	7.8	40	35.2	1.13	0.84	0.99
[14]	$b×h×l$ (mm) 125×250×2000; f_{cm} = 25 MPa; A_{f1} 3Ø12 mm; f_f = 1200 MPa; A_{s2} 2Ø10 mm; f_{s2} = 500 MPa; E_f = 40000 MPa	30.5	32.4	7.9	6.92	14.5	13.3	1.09	1.14	0.94
[28]	$b×h×l$ (mm) 120×200×1750; concrete; f_{cm} = 46,5 MPa; A_{f1} 2Ø9,5 mm; f_f = 1670 MPa; A_{s2} 2Ø8 mm; f_{s2} = 500 MPa; E_f = 135900 MPa	28.28	31.5	2.63	2.24	6.92	7.47	0.92	1.17	0.89

The analysis of the research results shown in Table 2 and 3 displays satisfactory convergence of the experimental and calculated values.

Conclusions. Based on the general deformation model, a method for calculating the parameters of the stress-strain state of bent concrete elements with composite reinforcement (including prestressed ones) was applied and verified against the background of the experimental data, allowing for the strength and deformation characteristics of concrete and composite reinforcement, prestressing accounting for its loss from elastic compression of concrete during tempering, and the stage of operation. the bent element, including the stage of reinforcement tempering, crack formation, normal separation, and the limit stage.

The suggested criterion for the destruction of a bendable element with no restrictions of the limiting deformations of compressed concrete makes it possible to account for the nonlinear properties of concrete during compression and the redistribution of forces in the cross-section of the element.

Modeling the operation of a bent element based on a deformation model enable one to obtain the parameters of its stress-strain state for any cross-sectional shape, at any stage of operation, including those consisting of various concretes, and to rationally design structures with composite reinforcement.

The results of the experimental and theoretical study can be used in order to verify the ultimate strength and serviceability conditions for bendable concrete structures reinforced with various types of composite core reinforcement.

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