- состав прав приводить в соответствие с составом обязанностей;
- выделять из состава обязанностей меру(ы) ответственности за ненадлежащее исполнение обязанностей;
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MODELING THE BEHAVIOUR OF STATICALLY INDETERMINATE REINFORCED CONCRETE STRUCTURES UNDER LOAD

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Abstract

One of the main differences of reinforced concrete is the possibility of cracking in concrete, which leads to a significant change in stiffness along the length of the element with cracks. The current state of the issue of the analysis of reinforced concrete elements is characterized by the widespread use of complex mathematical models and computational tools based largely on empirical and semi-empirical approaches to the analysis of the operation of reinforced concrete with cracks (deformation design model of the cross section based on concrete and reinforcement deformation diagrams, block model based on the dependences of the adhesion of reinforcement to concrete and the finite element method for calculating internal forces). So, the deformation design model of a flat section is used to calculate the moment of cracking and the strength of the element; block model of reinforced concrete between cracks - to calculate the opening width and crack pitch; structural mechanics methods (including the finite element method) for calculating internal forces and deflections. Using these approaches in the calculations of the stress-strain state of reinforced concrete elements (successively, moving from one method to another), the accumulation of calculation errors invariably occurs, since the parameters of the reinforced concrete structure calculated using different approaches have a mutual influence on each other. The purpose of this work is to attempt to combine these approaches for calculating the stress-strain state of reinforced concrete elements at all stages of work within the framework of a single calculation model, avoiding, if possible, the use of empirical relationships between them.

On the example of a continuous two-span reinforced concrete beam, the authors analyzed the proposed calculation model and obtained satisfactory results of convergence with experimental data.

Key words: reinforced concrete, modelling, continuous beam, deformational model, finite element model, block model.

МОДЕЛИРОВАНИЕ РАБОТЫ СТАТИЧЕСКИ НЕОПРЕДЕЛИМЫХ ЖЕЛЕЗОБЕТОННЫХ КОНСТРУКЦИЙ ПОД НАГРУЗКОЙ

Д.Н. Лазовский, Д.О. Глухов, Е.Д. Лазовский

Реферат

Одним из основных отличий железобетона является возможность образования трещин в бетоне, что приводит к значительному изменению жесткости по длине элемента с трещинами. Современное состояние проблемы анализа железобетонных элементов характеризуется широким использованием сложных математических моделей и вычислительных средств, основанных во многом на эмпирических и полуэмпирических подходах к анализу работы железобетона с трещинами. (деформационная расчетная модель поперечного сечения на основе диаграмм деформирования бетона и арматуры, блочная модель на основе зависимостей сцепления арматуры с бетоном и метода конечных элементов для расчета внутренних усилий). Так, расчетная модель деформации плоского сечения используется для расчета момента образования трещин и прочности элемента; блочная модель железобетона между трещинами – для расчета ширины раскрытия и шага трещины; методы строительной механики (в том числе метод конечных элементов) для расчета внутренних сил и прогибов. При использовании этих подходов при расчетах напряженно-деформированного состояния железобетонных элементов (последовательно, переходя от одного метода к другому) неизменно происходит накопление расчетных погрешностей, так как параметры железобетонной конструкции, рассчитанные по разным подходам, имеют взаимное влияние друг на друга. Целью данной работы является попытка объединить эти подходы к расчету напряженно-деформированного состояния железобетонных элементов на всех этапах работ в рамках единой расчетной модели, избегая, по возможности, использования эмпирических зависимостей между их. На примере неразрезной двухпролетной железобетонной балки авторы проанализировали предложенную расчетную модель и получили удовлетворительные результаты сходимости с экспериментальными данными.

Ключевые слова: Железобетон, моделирование, неразрезная балка, деформационная модель, метод конечных элементов, блочная модель.

Deformational design model of the element cross section. The distribution of deformations along the height of the cross section of a bent reinforced concrete element before the appearance of cracks obeys the hypothesis of flat section (Bernoulli). For reinforced concrete elements that have cracks in the tension zone, the flat section hypothesis is used as an assumption for the averaged longitudinal deformations of the tension and compression zones.

In the computational deformational model, the work of the tensile zone of concrete after the formation of cracks in the statement [4, 5] is taken into account by transforming the tensile diagram of free reinforcement (without concrete, in a section with a crack) into a diagram in which stresses σ_s are taken as free reinforcement, and relative deformations ε_s - for the averaged section in accordance with the hypothesis of flat sections, i.e. adjusted downwards taking into account the coefficient ψ_s [6, 7, 8].

For bending reinforced concrete element, the equations of the stress-strain state:

$$\sum_{i=1}^{k} \sigma_{ci}A_{ci}(y_0 - y_{ci}) + \sum_{i=k+1}^{n} \sigma_{si}A_{si}(y_{0}^{`} - y_{si}) - M = 0$$

$$\sum_{i=1}^{k} \sigma_{ci}A_{ci} + \sum_{i=k+1}^{n} \sigma_{si}A_{si} = 0, \tag{1}$$

$$\varepsilon_{(c,s)i} = \frac{1}{r}(y_0 - y_{(c,s)i}), \quad \sigma_{ci} = f(\varepsilon_{ci}), \ \sigma_{si} = f(\varepsilon_{si})$$

where $\sigma_{(c,s)i}$, $\varepsilon_{(c,s)i}$- normal stresses and longitudinal relative deformations in the i-th elementary area of concrete or reinforcement; $A_{(c,s)i}$and $y_{(c,s)i}$ - cross-sectional area and distance from the selected axis to the center of gravity of the i-th elementary area of concrete or reinforcement.

The criterion for the formation of cracks is the achievement by an elementary layer of concrete at the level of the center of gravity of the reinforcing bar the value of limiting relative deformations $\varepsilon_{ctm,u}$. The maximum value of the bending moment at which the equilibrium conditions (1) are met in the cross section with a crack corresponds to the strength of the reinforced concrete element.

Calculation of the stiffness of the section along the length of the reinforced concrete element with cracks is carried out taking into account the work of tensioned concrete as the average value of the sum of the stiffnesses of the elementary areas of concrete and reinforcement along the boundaries of the section:

$$(EI)_j = \frac{\left[\sum_{i=1}^{n} E_{(c,s)i}A_{(c,s)i}(y_0 - y_{(c,s)i})^2\right]_j + \left[\sum_{i=1}^{n} E_{(c,s)i}A_{(c,s)i}(y_0 - y_{(c,s)i})^2\right]_{j+1}}{2} . \tag{2}$$

Block design model of a reinforced concrete element. Describes the parameters of the stress-strain state of reinforced concrete between cracks [9-13]. The initial data, in addition to the characteristics of concrete and reinforcement, are stresses (relative deformations) in reinforcement in a cross section with a crack.

The main prerequisites for the model for a bending element are [14]: reinforced concrete element - a set of reinforced concrete blocks separated in the tension zone by normal cracks and interconnected by concrete of the compressed zone and tension reinforcement; reinforcement and concrete of the tensile zone work together in accordance with the relations of adhesion [1, 14], which establishes the dependence of shear stresses over the contact area of the diameter of Ø reinforcement with concrete on their mutual shear (s); stresses in the concrete of the tension zone are distributed uniformly over the effective area $A_{c,eff}$.

The distribution of relative strains of tensile concrete and reinforcement along the length of the block is described by the following system of equations (solved by successive approximations of the finite difference method (Figure 1)):

$$\{\frac{d}{dx}s = \varepsilon_s(\sigma_s) - \varepsilon_c\left(\frac{N - \sigma_s \cdot A_s}{A_{c,eff}}\right) \frac{d}{dx}\sigma_s = \frac{4}{\emptyset} \cdot \tau(s) \tag{3}$$

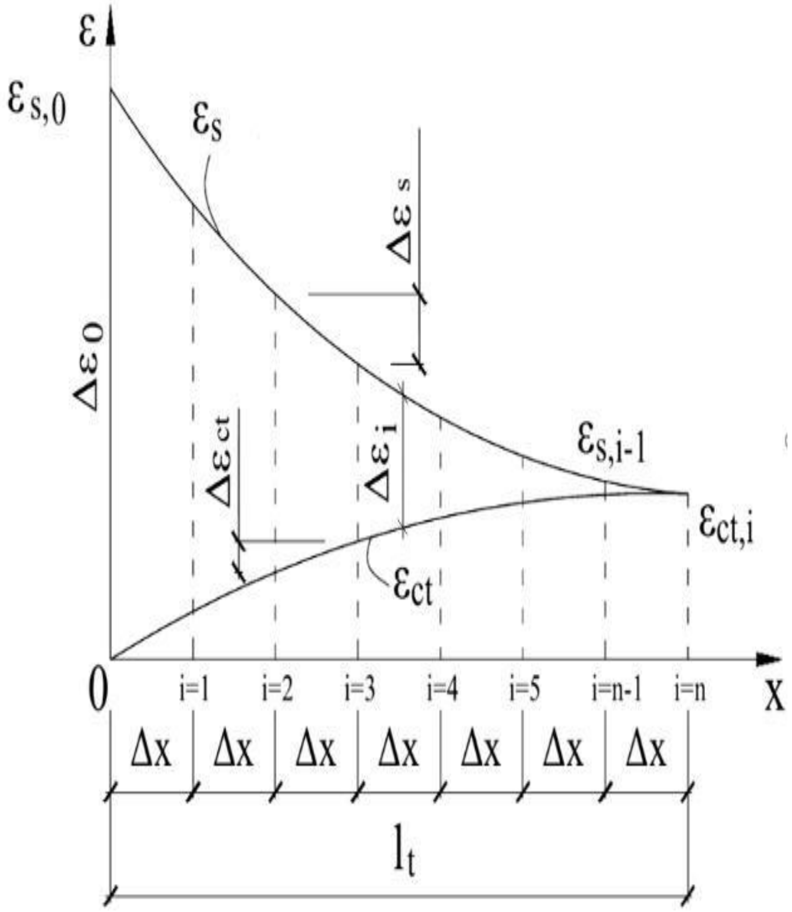


Figure 1. Distribution of relative deformations of concrete and reinforcement in a reinforced concrete block from the crack side

Two stages of cracking are considered in operation under the load of a bent reinforced concrete element [14]: the first stage is transient cracking, when, with an increase in the bending moment along the length of the reinforced concrete element, new cracks appear; the second is steady-state cracking, when the number of cracks practically does not increase (there is a redistribution of forces between reinforcement and concrete along the length of the reinforced concrete block in accordance with mutual shifts due to loss of adhesion.

At the first stage of cracking in a reinforced concrete block, the relative deformations of concrete do not exceed the values of the ultimate tensile strength of concrete, i.e. shear zones (redistribution) from the side of two adjacent fractures do not overlap (Fig. 2, a). With an increase in the bending moment, the relative deformations of concrete at the level of the center of gravity of the reinforcement in the zone of joint deformation reach the values $\varepsilon_{ctm,u}$, new cracks divided reinforced concrete block into smaller reinforced concrete blocks.

At the second stage of cracking along the entire length of the reinforced concrete block, the relative deformations of concrete at the level of the center of gravity of the reinforcement $\varepsilon_{ctm} \leq \varepsilon_{ctm,u}$, i.e. redistribution zones of two adjacent fractures overlap (Figure 2, b). With an increase in the bending moment from the external load, mutual shifts of the reinforcement and concrete occur (which manifests itself in the opening of cracks) and the redistribution of forces from concrete to reinforcement.

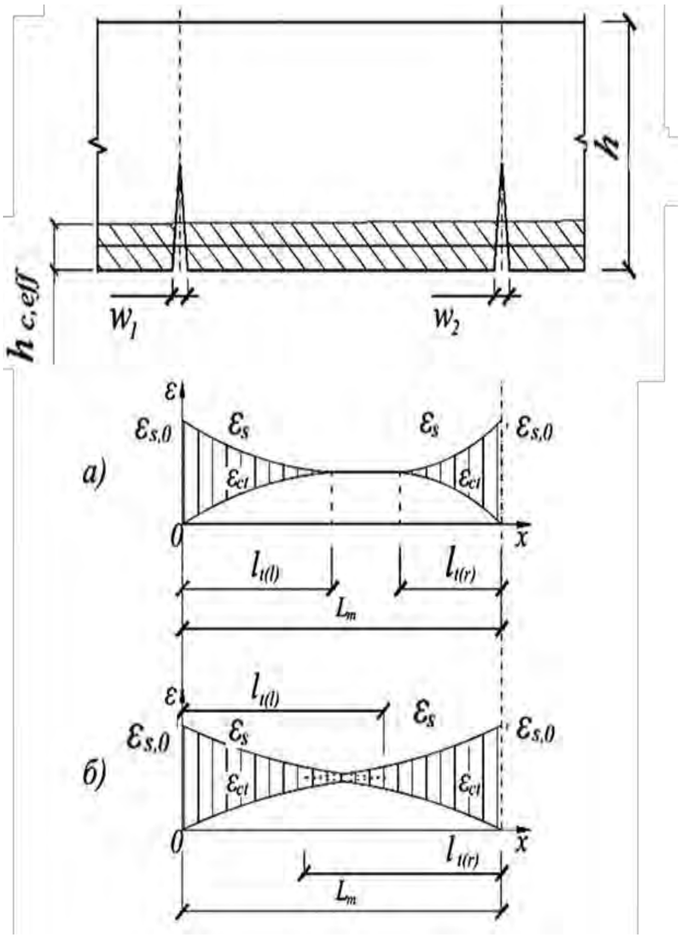


Figure 2. - Distribution of relative deformations of concrete and reinforcement along the length of the reinforced concrete block: a - at the first stage of cracking; b - at the second stage of cracking

The opening width of a crack is calculated as the sum of mutual displacements *s*(*x*) of reinforcement and tensile concrete in adjacent reinforced concrete blocks along the length of redistribution zones l_t to the left (*l*) and to the right (*r*) of the crack edges:

$$w = \int_{-l_{t(l)}}^{l_{t(r)}} s(x)dx = \int_{-l_{t(l)}}^{l_{t(r)}} [\varepsilon_s(x) - \varepsilon_{ct}(x)]dx \,. \tag{4}$$

Finite element method for analysis of internal forces. To calculate internal forces and deformations from the action of external loads in bending beam structures, bar finite elements are used. The stress-strain state of a reinforced concrete structure is determined by the equation of the finite element method for calculating displacements:

$$\{\delta\} = [K]^{-1}\{F\}, \tag{5}$$

where $\{\delta\}$ is the displacement vector; $\{F\}$ - external load vector; $[K]$ is the global stiffness matrix of the system.

The vector of internal forces of a single finite element is determined by the product of the local stiffness matrix and the displacement vector of the nodes of the finite element. The constructed finite element model is subjected to adaptive discretization. The elements of the model are adjusted to the analytical estimates of the reinforcement slip zones determined using the reinforced concrete block model. Based on the condition of smallness of the finite elements, the stiffness characteristics of the element (a section of a bent continuous beam) are considered as averaged over its length (2).

Having calculated, according to the block model, additional relative deformations (stresses) in the reinforcement along the length of its shear section in the concrete of the tension zone, taking into account, according to the deformation model, the new equilibrium state of any cross section (including the section with a crack), the correspondence of the distribution of relative deformations of concrete and reinforcement by the height of sections to the hypothesis of flat sections. Thus, the work of tensile reinforced concrete with cracks in the deformation model of the cross section with a crack is modeled without applying the coefficient ψs. Having determined, according to the deformation model, the distribution of stiffness along the length of a statically indeterminate (continuous) bending structure, by the methods of structural mechanics (finite element method), the distribution of internal forces (bending moments) and deformations (deflections) along its length is calculated. The algorithm for calculating the parameters of the stress-strain state of a continuous bending structure under the action of a load with the simulation of an equivalent equilibrium state of the cross section during the formation of a crack is shown in Figure 3.

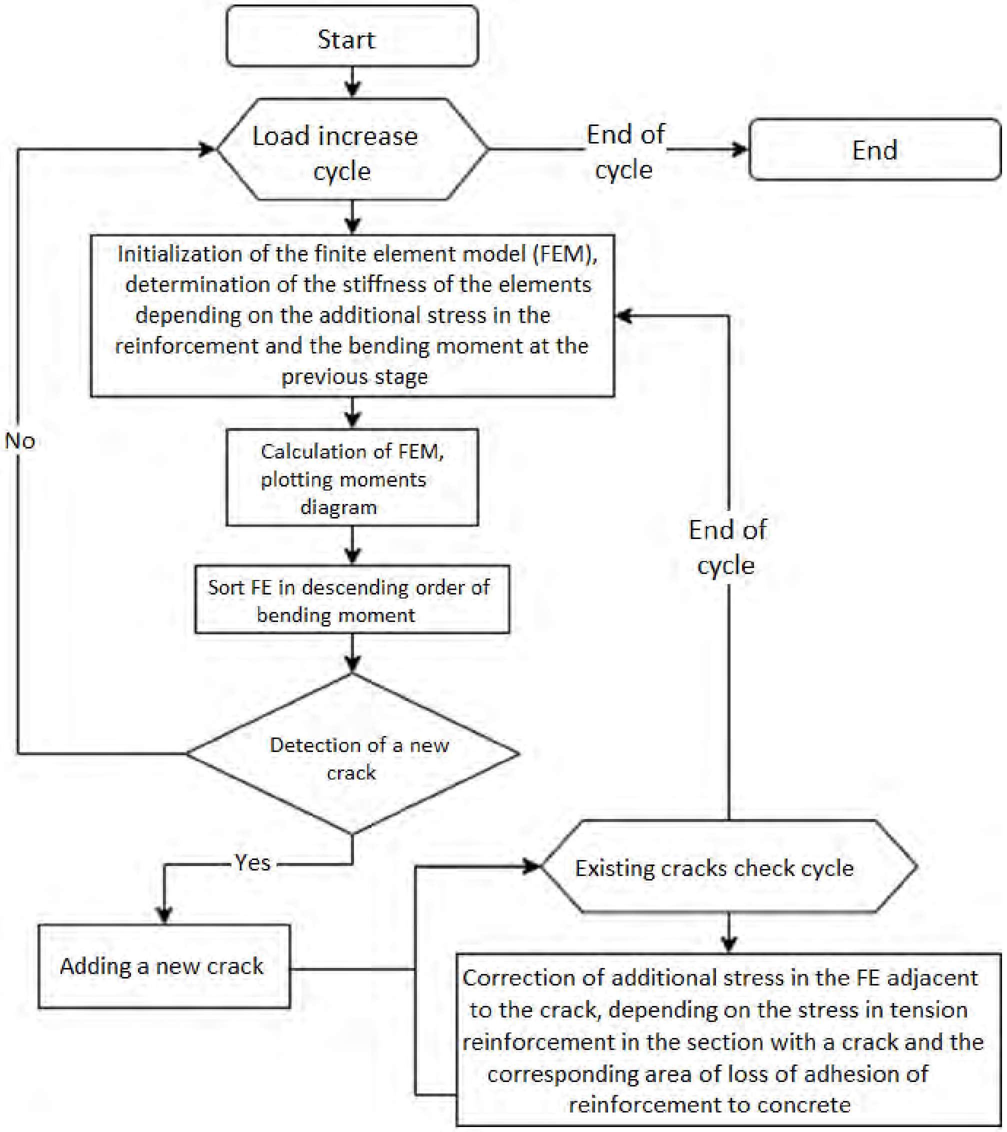


Figure 3. Algorithm for calculating the parameters of the stress-strain state of a continuous bending structure

Comparison of analysis results and experimental data. As experimental data for comparison with the analytical calculation results, a continuous two-span reinforced concrete beam hinged on the extreme supports with a distance between the axes of the supports of 1800 mm and a cross section of 120x190 mm, loaded with concentrated forces in thirds of the spans, was taken as experimental data [15]. The width of the steel plates of the beam supports is 100mm. The beam is symmetrically reinforced in the upper and lower zones with longitudinal bar reinforcement (2ø12 mm each, A_s=A_{s1}=226.19 mm^2 with a yield strength of 528.7 MPa, the ultimate strength of 592.8 MPa and an elongation at break of 7.6%. Distance from the upper and lower faces of beams to the center of gravity of the cross section of the reinforcement is 25mm.The compressive strength of concrete f_{cm} = 32.6MPa, the initial modulus of elasticity in compression is 31.38GPa, the tensile strength of concrete f_{ctm} = 2.53MPa. The concrete of the beam is made on portland cement without additives with granite crushed stone 5…20mm.

The diagram of deformation of the longitudinal bar reinforcement of the beam in tension and compression is assumed to be bilinear with the limitation of relative deformations by elongation at break.

The diagram of concrete deformation under compression is taken as a curved branch with a descending branch, without limiting its length in terms of deformations in order to obtain a complete redistribution of forces between the zones in the span and on the support of a statically indeterminate beam. To obtain a complete nonlinear diagram of concrete deformation of a bent structure in tension during bending, we calculate the tensile strength of concrete according to [3] in bending $f_{ctm,fl}$ and the initial modulus of elasticity in tension E_{ct} according to [16-18], relative deformations $\varepsilon_{ctm,1}$ at the peak point of the diagram deformation and ultimate tensile strength of concrete $\varepsilon_{ctm,u}$:

$$f_{ctm,fl} = f_{ctm} \cdot \left[1{,}6 - \frac{h}{1000}\right], \tag{6}$$

$$E_{ct} = \frac{10^7 \cdot f_{ctm}}{750 + 81{,}55 \cdot f_{ctm}}, \tag{7}$$

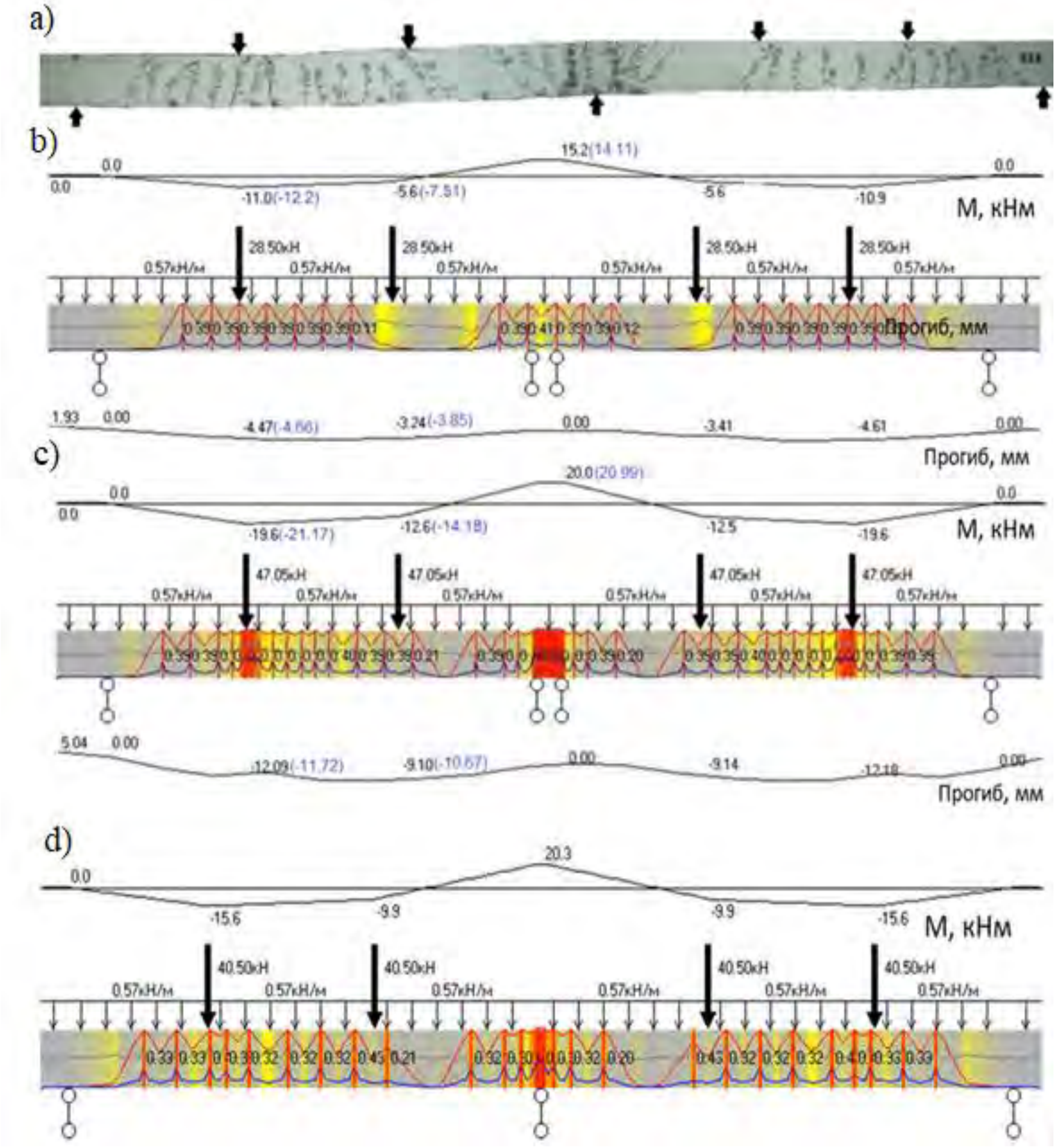
$$\varepsilon_{ctm,1} = \frac{2 \cdot f_{ctm}}{E_{ct}}, \tag{8}$$

$$\varepsilon_{ctm,u} = \frac{K \cdot \varepsilon_{ctm,1}}{2}, \tag{9}$$

$$K = 6{,}4 + 0{,}1223 \cdot f_{cm}. \tag{10}$$

The calculation results for the concrete of the considered continuous beam are as follows: $f_{ctm,fl}$=3,57МПа; E_{ct}=26,46ГПа; $\varepsilon_{ctm,1}$=19,1·10^{-5}; $\varepsilon_{ctm,u}$=1·10^{-3}.

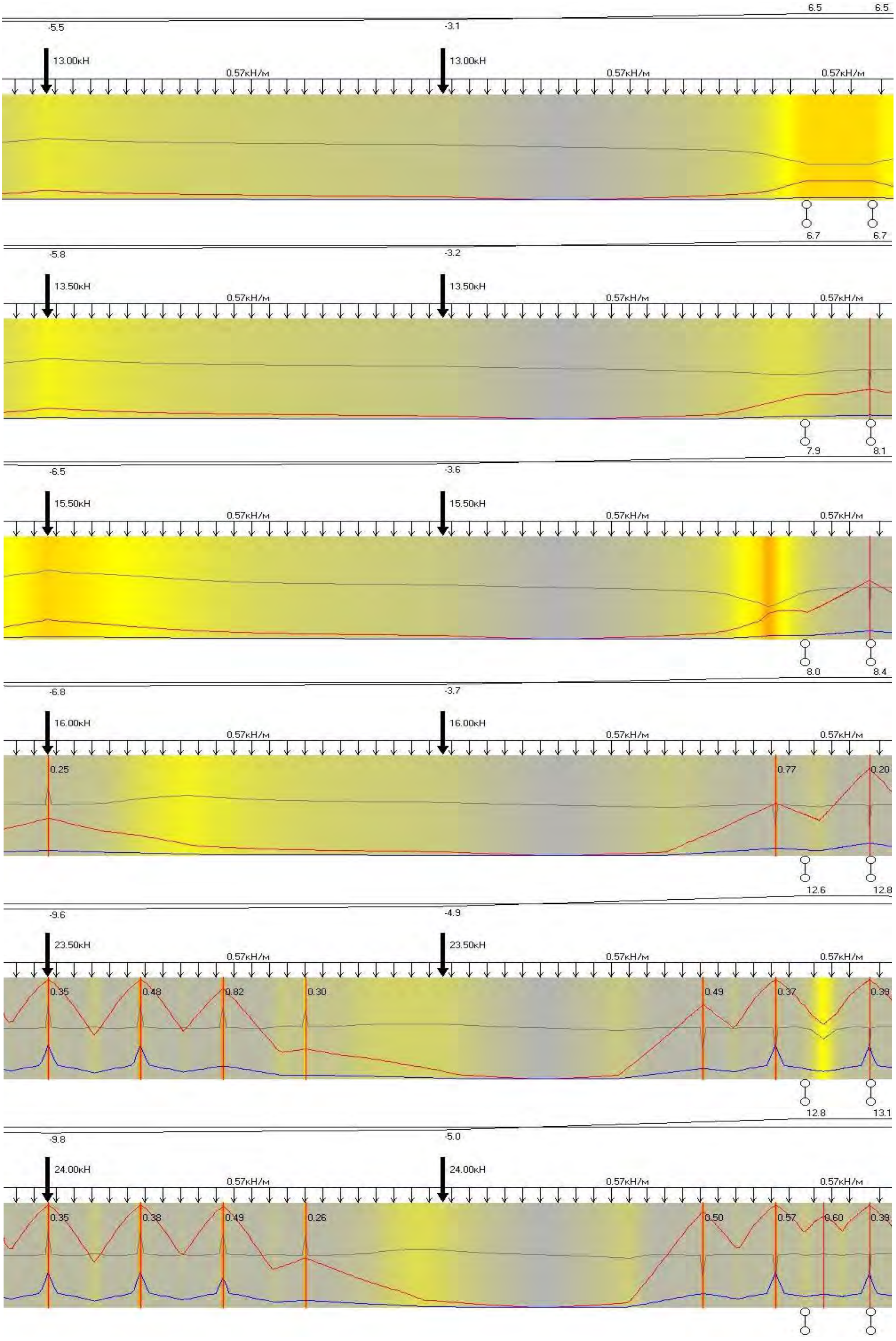
Figure 4 shows: a general view of the beam after destruction; diagrams of calculated and experimental bending moments under a load corresponding to the bearing capacity of the beam; calculation model of the beam before destruction.



a) general view after destruction; beam modeling result: b) and c) respectively at the characteristic value of the load (28.5 kN) and before failure (47.05 kN); d) before failure (40.5 kN) with point support on the middle support: plots of design (experimental) bending moments (numbers in kNm), calculation model of the beam with crack locations and width of their opening (vertical lines and numbers in mm), distribution of relative deformations (blue line) and stresses (red line) in the reinforcement, as well as the position of the neutral line (gray line), deflections of the reinforcement beam, as well as the position of the neutral line (gray line)

Figure 4. Experimental continuous reinforced concrete beam

The proposed model makes it possible to obtain the distribution of all parameters of the stress-strain state along the length of a continuous beam at any stage of loading (Figure 5).


6.5
6.5
-5.5
-3.1
13.00кН
0.57кН/м
13.00кН
0.57кН/м
0.57кН/м
6.7
6.7
-5.8
-3.2
13.50кН
0.57кН/м
13.50кН
0.57кН/м
0.57кН/м
7.9
8.1
-6.5
-3.6
15.50кН
0.57кН/м
15.50кН
0.57кН/м
0.57кН/м
8.0
8.4
-6.8
-3.7
16.00кН
0.57кН/м
16.00кН
0.57кН/м
0.57кН/м
0.25
0.77
0.20
12.6
12.8
-9.6
-4.9
23.50кН
0.57кН/м
23.50кН
0.57кН/м
0.57кН/м
0.35
0.48
0.82
0.30
0.49
0.37
0.39
12.8
13.1
-9.8
-5.0
24.00кН
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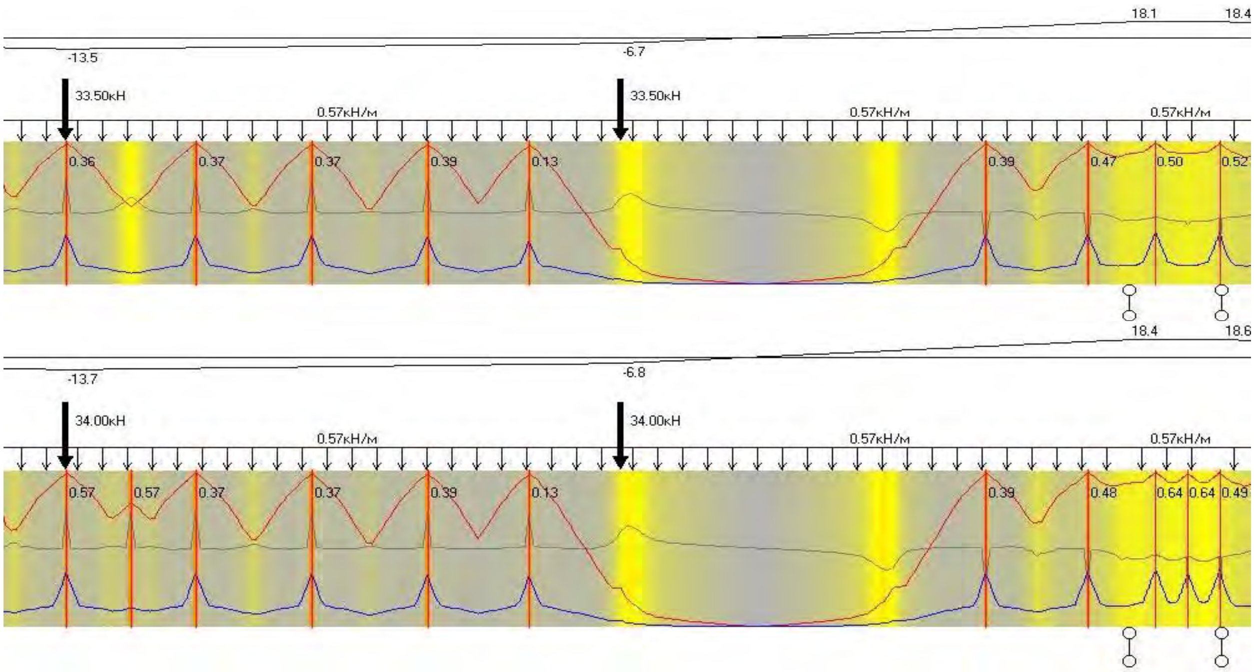

Figure 5. A fragment of the design model of a continuous reinforced concrete beam with critical cracks and their opening width (vertical lines and numbers in mm), plots of experimental and calculated bending moments (figures in kNm), distribution of relative deformations (blue line) and stresses (red line) , as well as the position of the neutral line (gray line)

Table 1 shows a comparison of the experimental and calculated (according to the proposed analytical model) parameters for a continuous reinforced concrete beam with the above-mentioned initial data. The maximum value of the experimental and calculated deflection, as well as the crack opening width of a continuous beam, was determined at a load of 28.5 kN, corresponding to its characteristic value.

Table 1. Comparison of experimental and calculated parameters of a continuous reinforced concrete beam.

Parameter	Exp. value	Calc. value	The ratio of the experimental value to the calculated
Bending moment at crack formation, kNm	5,92	6,6	0,89
Concentrated force at destruction, kN	46,95	47,05	0,99
The maximum value of the deflection in the span at 28.5 kN, mm	4,66	4,61	1,01
Maximum width of opening of cracks in the span at 28.5 kN, mm	0,33	0,39	0,82
Maximum width of opening of cracks on the support at 28.5 kN, mm	0,35	0,41	0,85

Comparison of the main parameters of a continuous reinforced concrete beam: bending moment of crack formation; opening of cracks after their appearance; deflections; concentrated efforts corresponding to the bearing capacity (strength) indicates their satisfactory convergence.

In the limit state (before failure) near the cross sections with critical cracks (with maximum bending moments on the continuous support and in the span), there is a sharp increase in the relative strains in the tensile reinforcement and a close to uniform distribution of stresses in the reinforcement along the length of the beam due to decoupling from concrete (Figure 6). This increase in deformations of tensile reinforcement in cross section with a critical crack increases the width of its opening. At the same time, in neighboring cross sections with cracks, there is a sharp decrease in the height of the compressed zone at almost the same stresses in the tensile reinforcement as in the critical crack.

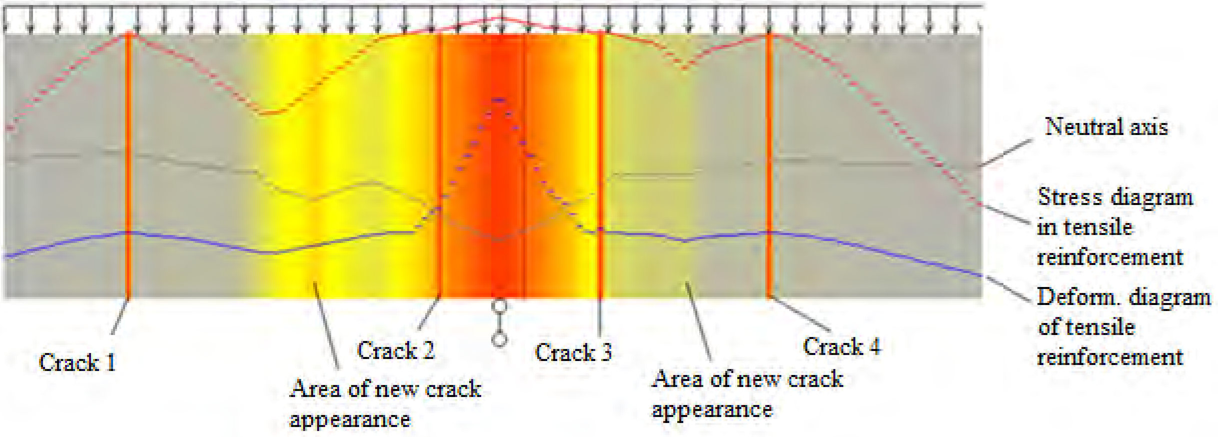

Figure 6. A fragment of the calculation model of the beam at the intermediate support in the limit state with cracks (vertical lines), the distribution of relative deformations (blue line) and stresses (red line) in the reinforcement, as well as the position of the neutral line (gray line)

Conclusion. Using the experimental example of a continuous two-span reinforced concrete beam, the possibility of methodically combining the deformational and block models together with the finite element method to calculate the parameters of a reinforced concrete structure at any stage of its operation is demonstrated.

A feature of the proposed model of a statically indeterminate reinforced concrete beam with an increase in external load is the asymmetric values of the calculated parameters in two spans due to a significant loading step. When a crack appears in one cross section in one of the spans of the beam, the stiffness and, accordingly, the forces are redistributed, which cease to be symmetrical at the next step of increasing the load.

In addition, the calculation scheme is sensitive to details (modeling of beam support areas, width of the concentrated load transfer zone, dimensional accuracy). For example, in the limit state for the same beam with a support model on the platform, 100 mm wide (Figure 4, c) and a model with an idealized point support (Figure 4, d), the limit value of the load differs by more than 10%.

Simulation of the work of a statically indeterminate structure shows that with an increase in the load in the beam, there is a constant process of redistribution of forces, while when a new crack appears at the support, the bending moment “creeps” into the span, when a crack appears in the span, the bending moment “flows” to the support. “Swings” occur, the more cracks, the more actively, but with smaller amplitudes, the buildup occurs. Each new crack unloads the adjacent areas due to the slippage of reinforcement in concrete and a decrease in stiffness and, as a result, due to the "leakage" of the bending moment. This leads to a decrease in the opening of cracks in the sections of the beam, unloaded by the bending moment. The redistribution of efforts goes in competing directions, this process is not directed in one direction (from support to span or vice versa).

Simulation of the process of cracking of a statically indeterminate structure showed that the area of cracking is much wider than a point hinge on a continuous support in models of statically indeterminate reinforced concrete structures.

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SIMULATION OF BENDING REINFORCED CONCRETE ELEMENTS WITH CRACKS

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Abstract

On the basis of deformational design analytical model of the cross section and block model of reinforced concrete element, a new analytical model is proposed by the authors. This model takes into account the work of tensioned concrete between cracks by applying additional stress in the reinforcement (steel bars) due to the difference in relative deformations between the tension reinforcement and concrete during the formation of a crack.

The developed model of analysis of reinforced concrete with cracks makes it possible to obtain the parameters of stress-strain state af the element in any cross-section along the length under the action of a bending moment and a longitudinal force.

Key words: reinforced concrete, crack, analytical model, deformational model, block model.

МОДЕЛИРОВАНИЕ РАБОТЫ ЖЕЛЕЗОБЕТОНА С ТРЕЩИНАМИ ПРИ ИЗГИБЕ

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Реферат

На основе расчетной деформационной аналитической модели поперечного сечения и блочной модели железобетонного элемента с трещиными авторами предложена новая расчетная модель. Эта модель учитывает работу растянутого бетона