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THE EFFECT OF THE LOADING ORDER ON THE FORMATION OF THE STRESS-STRAIN STATE OF THE REINFORCED CONCRETE FRAME STRUCTURE

UTJECAJ PORETKA OPTEREĆENJA NA FORMIRANJE STANJA NAPREZANJA I ISTEZANJA OKVIRNE STRUKTURE KONSTRUKCIJE OD ARMIRANOG BETONA

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Abstract: *The paper considers the influence of the physical and geometric nonlinearity of reinforced concrete frame structures on the formation of the stress-strain state in the phased construction of a building. The basic principles of a statically indeterminate reinforced concrete frame structure analysis with a consideration of the design scheme creation order and load application, as well as the cracking processes, are proposed. An example of the two steps of the analysis of the transversal frame of a three-storey and three-span building for administrative and production purposes in accordance with the proposed principles of the analysis is shown. The method of the analysis is based on the study of the fundamental technological scheme of the building construction with the partition of the analysis which is accomplished on the corresponding enlarged steps. With a consideration of the construction and loading order and processes of cracking in the elements, a comparison of the results of the implemented analysis in the elastic stage is done.*

Keywords: *cracking, numerical-analytical boundary element method, reinforced concrete frame structure, order of loading*

Prethodno priopćenje

Sažetak: *U radu se razmatra utjecaj fizičke i geometrijske nelinearnosti armiranobetonskih okvirnih konstrukcija na formiranje stanja naprezanja i istezanja u faznoj izgradnji zgrade. Predlažu se osnovna načela analize okvirne strukture statički neodređene armiranobetonske konstrukcije s obzirom na redoslijed oblikovanja i primjenu opterećenja, kao i proces pucanja. Primjer dva koraka analize poprečnog okvira iskazan je na zgradi trorasponske konstrukcije s tri kata za administrativne i proizvodne svrhe, u skladu s predloženim načelima analize. Metoda analize temelji se na proučavanju temeljne tehnološke sheme građevne konstrukcije s podjelom analize koja se postiže kroz odgovarajuće uvećane korake. Imajući u vidu izgradnju, redoslijed opterećenja i proces pucanja elemenata, uspoređeni su rezultati provedene analize u elastičnoj fazi.*

Ključne riječi: *pucanje, numeričko-analitička metoda graničnih elemenata, okvirna struktura armirano betonske konstrukcije, redoslijed opterećenja*

1. INTRODUCTION

It is known [4, 7] that cracking has a significant effect on the stress-strain state of reinforced concrete structures. It causes the development of displacements, falling of pre-stressing forces, change and redistribution of the internal forces.

In statically indeterminate reinforced concrete structures, due to their physical and geometric nonlinearity, the sequence of the creation of the design scheme and the application of the load affect the distribution of internal forces [9, 10, 11].

The simultaneous impact of the above-mentioned factors on the stress-strain state of statically indeterminate reinforced concrete frame structures has still not been sufficiently studied.

Thus, the development of the methods for determining the stress-strain state of reinforced concrete frame structures is based on the numerical-analytical boundary element method, which allows the inspection of the functioning of systems up to the limit state; and the respective physical nature of their work is the actual and necessary task for the subsequent development of the analysis theory of statically indeterminate reinforced concrete structures.

The aim is to study the effect of the construction and loading order, as well as the processes of cracking on the stress-strain state of reinforced concrete frame structures with the use of the numerically-analytical boundary element method [1, 2, 3].

2. THE PRINCIPLE OF THE MODELING OF THE DESIGN SCHEME WITH A CONSIDERATION OF THE LOADING ORDER

In design practice, including the frame structure, static analysis is made on the full design loads (a combination of permanent and temporary loads). Strength calculation and construction are made on the design forces, which were acquired as a result of this calculation.

In real terms, the construction of buildings is carried out in stages. The loading of the constructed parts is carried out in the respective stages. By the time of the subsequent stages of the erection of the building, the stiffness of the constructed parts can differ from the stiffness in the elastic phase.

Thus, a redistribution of the internal stresses in the real circumstances also occurs in stages, depending on the technology of the building construction.

Before performing the calculations, it is necessary to examine the fundamental technology of the building scheme erection and divide the analysis in the corresponding enlarged steps. The analysis results at each stage are the initial data for the realization of the following analysis.

The analysis method of reinforced concrete frame structures with a consideration of the cracking processes by using the numerically analytical method of boundary elements is proposed in the paper [4].

The partition of the rods of the frame structure (columns and beams) onto the elements with piecewise constant stiffness is carried out in determining the stress-strain state of reinforced concrete frame structures with a consideration of the cracking processes by using the numerical and analytical boundary element method.

The stiffness of elements is determined by using a practical method based on a simplified "bending moment - curvature" diagram, proposed in [5, 6].

The analysis is carried out with the assumption of the structure functioning in the elastic stage, which is why the bending stiffness is defined as the product $E_b I_{red}$ in the first stage.

Further, stiffness is determined by curvatures that are obtained on the basis of the bending moments.

Stiffness does not change in the elements where the bending moments do not exceed the cracking value. In reinforced concrete elements, cracking is taken into account in accordance with [5...7]. In the areas where the bending moments exceed the cracking value, the element stiffness is determined by a formula that is proposed by I. E. Prokopovich in [7]:

$$B_g = E_b A_b h_0^2 \sqrt{\mu n_1}\, b_1, \tag{1}$$

where, A_b – the cross-sectional area of the beam;

h_0 – the working height of the section;

$\mu = A_s / A_b$ – the sectional ratio of reinforcement;

A_s – the sectional area of the valve;

$n_1 = E_s / E_b$ – the ratio of the elastic modulus reinforcement and concrete.

Coefficient b_1 is defined as follows:

$$b_1 = \beta_1 + \beta_2 \left(\frac{M_{crc}}{M} \right)^2, \tag{2}$$

An element with a rectangular cross-section has the following values of coefficients: β_1 = 0,159, β_2 = 0,074.

At the limit value of the bending moment ($M=M_u$), the curvature may increase indefinitely at the constant bending moment (i.e. under the assumption that a plastic hinge formed in the cross-section).

An analysis of the frame structure with the new values of stiffness is accomplished after the determining of the stiffness of each element.

These operations are repeated until convergence is reached.

It is necessary to divide the analysis process on enlarged steps in order to reflect the real order of the application of loads on the building frame.

An analysis of a one-story frame of the first floor is accomplished only through a constant load. As a result, in some elements, the process of cracking is observed, which sharply reduces their stiffness.

When considering the design scheme that represents a two-storey frame, the initial stiffness of the first floor elements is taken from the results of the first stage analysis, and the stiffness of the second floor elements is taken from the assumption of the work in the elastic stage.

At the subsequent stages of the analysis, the stiffness of the already erected elements is similarly received from the results of the previous stage.

3. AN ANALYSIS OF THE REINFORCED CONCRETE STRUCTURE WITH A CONSIDERATION OF THE LOADING ORDER

Consider the example of the first two stages of the analysis of the transversal reinforced concrete frame of a three-storey and three-span building for administrative and production purposes with a consideration of the load application order. The analysis was performed by using the program developed in the system of computer mathematics MATLAB, which allows the consideration of the processes of cracking [4].

The distance between transverse frames is assumed to be 6.0 m. The collection of permanent and temporary loads on each floor of the building and the analysis of the frame structure in the elastic stage are made with a consideration of the current regulations [8].

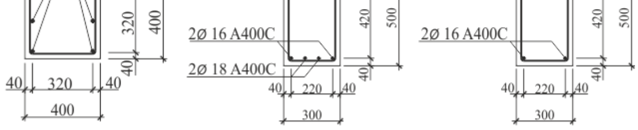

Figure 1. Cross-sections of the frame elements
a) columns; b) span sections of beams; c) support sections of beams.

The reinforcement of elements and the construction of the reinforced concrete frame are made according to the results of the frame structure analysis in relation to the action of the design loads (Fig. 1).

The design scheme of the building framework at the first step is applied as a one-storey frame loaded by a constant load (Fig. 2).

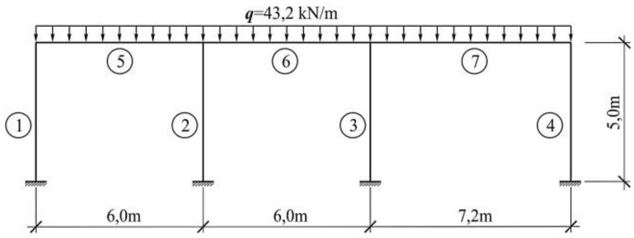

Figure 2. Estimated carcass scheme building on the first stage of the calculation

4. RESULTS OF THE ANALYSIS

The diagrams of the bending moments that occur in the structure at the first step of the analysis in the elastic stage and with a consideration of the cracking processes are shown in Fig. 3.

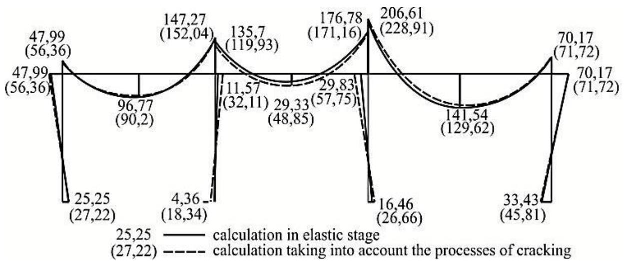

Figure 3. The diagram of the bending moments at the first stage of the calculation

Table 1. Comparison of the results at the first stage

№ of elements	№ of sections	Values of the bending moments *M*, kNm		Change of forces *Δ*, %
		analysis in the elastic stage	analysis with a consideration of cracking	
1	1	25.25	27.22	7.80
	3	-47.99	-56.36	17.44
4	1	-33.43	-45.81	37.03
	3	70.17	71.72	2.21
5	1	-47.99	-56.36	17.44
	2	96.77	90.2	-6.79
	3	-147.27	-152.04	3.24
6	1	-135.69	-119.93	-11.61
	2	29.33	48.85	66.55
	3	-176.78	-171.16	-3.18
7	1	-206.61	-228.91	10.79
	2	141.54	129.62	-8.42
	3	-70.17	-71.72	2.21

Note: Section 1 taken at the left end of the element;
Section 2 taken in the middle of the element;
Section 3 taken at the right end of the element.

Table 1 shows a comparison of the bending moment values that occur in some elements of the structure at the first stage of the construction obtained in the results of the analysis in the elastic stage and with a consideration of the cracking processes.

Table 1 shows that the moments occurring in the outside columns increase. In the support sections of the outside beams the moments increase and decrease in the span sections. In the mid-span beam, moments decrease in the support sections and increase in the span at almost 67%.

The design scheme at the second step is applied as a two-storey frame (Fig. 4).

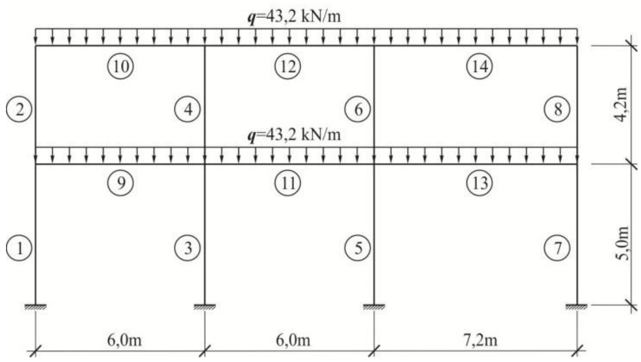

Figure 4. The estimated building framework scheme at the second stage of the calculation

The diagrams of the bending moments that occur in the structure at the second step of the analysis in the elastic stage and with a consideration of the cracking processes are shown in Fig. 5.

Table 2 shows a comparison of the bending moment values that occur in some elements of the structure at the first stage of the construction obtained in the results of the analysis in the elastic stage and with a consideration of the loading order and cracking processes.

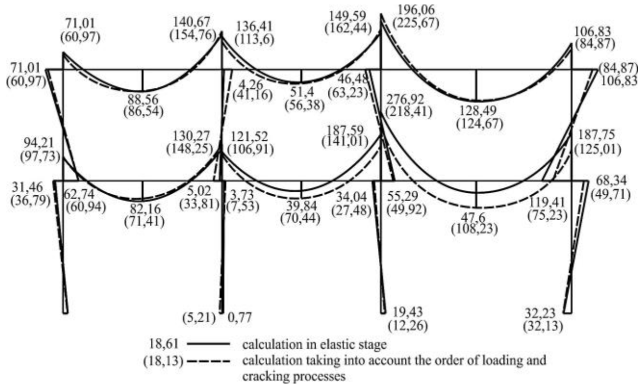

Figure 5. The diagram of the bending moments at the second stage of the calculation

As shown in Table 2, bending moments are the most reduced, in comparison with the elastic analysis in the columns of the right outside span. The largest redistribution, in comparison with the elastic analysis, occurred in the span sections of the middle and right span beams. Thus, in the mid-span the value of the bending moment increased by about 77%, and in the outside it increased by 127%.

Table 2. Comparison of the results of the calculation at the second step

№ of elements	№ of sections	Values of the bending moments *M*, kNm: analysis in the elastic stage	Values of the bending moments *M*, kNm: analysis with a consideration of the cracking and loading order	Change of forces *Δ*, %
1	1	18.61	18.13	-2.58
	3	-31.46	-36.79	16.94
2	1	62.74	60.94	-2.87
	3	-71.01	-60.97	-14.14
7	1	-32.23	-32.13	-0.31
	3	68.34	49.79	-27.14
8	1	-119.41	-75.22	-37.01
	3	106.83	84.87	-20.56
9	1	-94.21	-97.73	3.74
	2	82.16	71.41	-13.08
	3	-130.27	-148.25	13.80
10	1	-71.01	-60.97	-14.14
	2	88.56	86.54	-2.28
	3	-140.67	-154.76	10.02
11	1	-121.52	-106.91	-12.02
	2	39.84	70.44	76.81
	3	-187.59	-141.003	-24.83
12	1	-136.41	-113.6	-16.72
	2	51.4	56.38	9.69
	3	-149.59	-162.44	8.59
13	1	-276.92	-218.41	-21.13
	2	47.6	108.23	127.37
	3	-187.75	-125.01	-33.42
14	1	-196.06	-225.67	15.10
	2	128.49	124.67	-2.97
	3	-106.83	-84.87	-20.56

Note: Section 1 taken at the left end of the element;
Section 2 taken in the middle of the element;
Section 3 taken at the right end of the element

5. CONCLUSION

The results of the example of the first two stages of the analysis of the transversal frame of a three-storey and three-span building indicate that the consideration of the phasing of the construction (of the order of the application of loads) and cracking has a significant impact on the redistribution of internal forces.

The continuation of various investigations should be done for a detailed study of the examined effects.

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