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STRESS-STRAIN STATE OF REINFORCED CONCRETE BEAMS STRENGTHENED WITH A NEW EXTERNAL STEEL STRUCTURE

The study presents a new structure for strengthening of one-span reinforced concrete beams in rectangular cross-section using external steel bars. The specific feature of the proposed strengthening is the unloading of the compressed upper zone of a beam with simultaneous compression of its lower stretched zone. The article considers some variants of making the strengthening structure with rigid and flexible reinforcement elements for faster tension of external bars, and the variant including only flexible elements. It provides a design scheme and method for such reinforced beams. The study provides experimental research data on the series of beams with different parameters of the strengthening structure in the form of «bending moment – deflection» and «bending moment - deformation of concrete» dependencies.

***Keywords:** strengthening, reinforced concrete beam, external steel bars, stress-strain state, deflection, deformation, bending moment.*

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НАПРУЖЕНО-ДЕФОРМОВАНИЙ СТАН ЗАЛІЗОБЕТОННИХ БАЛОК, ПІДСИЛЕНИХ НОВОЮ ЗОВНІШНЬОЮ СТАЛЕВОЮ КОНСТРУКЦІЄЮ

Представлено нову конструкцію підсилення однопрольотних залізобетонних балок прямокутного перерізу за допомогою зовнішньої сталевої арматури. З'ясовано, що особливістю запропонованого підсилення є розвантаження верхньої стиснутої зони балки при одночасному стисканні її нижньої розтягнутої зони. Розглянуто варіанти виконання конструкції підсилення балок з жорсткими й гнучкими елементами підсилення для прискореного натягу зовнішньої арматури і варіант лише з гнучкими елементами. Запропоновано розрахункову схему для такої підсиленої балки та методику розрахунку. Наведено експериментальні дані дослідження серій балок з різними параметрами конструкції підсилення, що наведені у вигляді залежностей «згинальний момент – прогин» і «згинальний момент – деформації бетону».

***Ключові слова:** підсилення, залізобетонна балка, зовнішня сталева арматура, напружено-деформований стан, прогин, деформації, згинальний момент.*

Introduction. In recent years, the majority of long-maintained construction objects of the Ukrainian building complex require upgrading, reconstruction and strengthening of existing structures. Concrete beam elements are among the most used in such buildings, and their carrying capacity should be restored or increased.

Analysis of the latest research findings and publications. In order to increase the carrying capacity and reduce deformability of bent elements, the cross-section of a structure is increased, using ties or sprengels in the strained zone, arranging duplicating elements. There are many ways of strengthening bent elements, reflected in the works of outstanding Ukrainian and foreign scientists [3-9, 12-15]. The most effective and conventionally used ways of strengthening include ties and especially sprengels.

Specifying the unsolved aspects of the general problem. Thus, the application of a sprengel-type structure is accompanied by additional compressive forces that load additionally the beam's compressed zone, thereby accelerating the time of its failure. Therefore, the question of simultaneous unloading of both the stressed and compressed zones is currently unresolved. In addition, the evaluation of the work of the external strengthening system is quite a challenge because beam-strengthening system is statically indeterminated and requires additional experimental and theoretical researches.

Problem statement. The aim is to propose, make and research an effective structure of strengthening reinforced concrete beams that regulate forces in the beam element and compensate the negative impact of external load, while using the strength properties of concrete and steel.

Basic material and results. A new design solution for the system of strengthening one-span reinforced concrete beams performed by external steel bars and protected by patent [10] is shown in Fig.1.

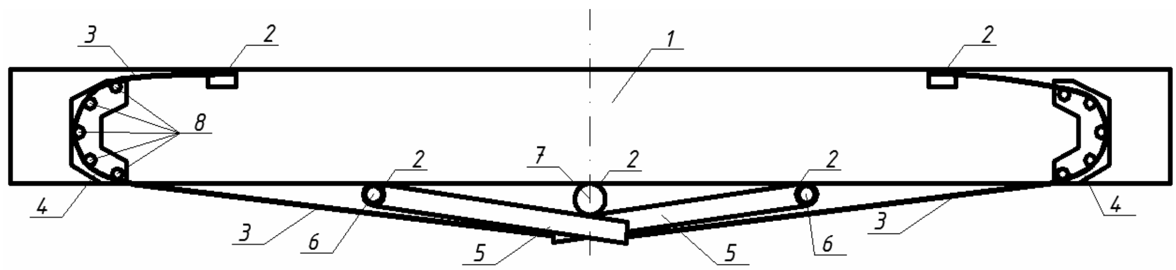

Figure 1 – Scheme of the beam with the proposed regulated structure of strengthening with external bars with levers, БП-І - БП-VІ series:
1 – reinforced concrete beam; 2 – steel plates fixed on the surface of the beam;
3 – external bars; 4 – guiding element; 5 – stressing structure in the form of two levers;
6 – hinge; 7 – roller; 8 – guiding rollers for elements 4

The specific feature of this structure is the ability to unload the compressed zone of the beam, in contrast to conventional sprengel ties that have an additional load on it. In addition, the system can work effectively under symmetrical load.

In order to test the proposed structure of strengthening reinforced concrete beams, there has been developed an experimental research program that included testing of samples of concrete cubes, prisms, steel bars. The measurements of beam samples were the following: length – 2100 mm, cross-section – 100×200 mm. Concrete class was the same for all experimental beams and was accepted C35/45.

The study accepted the reinforcement of beams with spatial frames of bars with a diameter of 6.5 mm. The working bars were of class A-240C. Reinforcement bars of the external strengthening system were of steel wire Ø5 mm for all samples of experimental beams. Seven series of reinforced concrete beams strengthened with external bars with different parameters of the strengthening system, and a series of conventional reinforced concrete beams were experimentally investigated.

The following beam marking was accepted: the first letters show whether the beam is strengthened (БП) or not (БО), the second number indicates the number of series, the third - the number of beams in each series. Geometric characteristics and number of external wires of experimental beams are given in Table 1.

Table 1 – Geometric characteristics of strengthened beams

№	Beam series	Roller diameter ***d***, mm	The number of external wires, ***N***	Characteristics of the guiding element **c**, mm	Type of strengthenin g	***k***, mm
1	БО	-	-	-	-	-
2	БП-I	35	1 Ø5 mm	100	Rigid levers	620
3	БП-II	55	1 Ø5 mm	70		620
4	БП-III	55	1 Ø5 mm	40		620
5	БП-IV	55	2 Ø5 mm	70		620
6	БП-V	55	3 Ø5 mm	70		620
7	БП-VI	55	2 Ø5 mm	70	Without levers	620
8	БП-VII	55	2 Ø5 mm	70		185

In Table 1 it is marked: ***n*** - number of external steel wires in each branch of the strengthening system; ***c*** - distance from the bottom ends of the beam to the point of maximum curvature of the external bar near the ends of the beam; ***k*** - distance from the beam support to the point where the flexible external bars are fixed to the bottom of the beam.

а) б)

Figure 2 – Testing of reinforced concrete beams strengthened with external steel wires of БП-V series including rigid levers – *a*, and of БП-VI series without levers - *b*

The testing of beams was conducted according to the given deformations in the certified building materials and structures laboratory (LBMK). Special mechanical jack was used. Control of the deformations of tested beams was performed using clock type indicators with a point value of 0.001 mm on the base that was 200 mm and the row of tensoresisters.

According to the experimental data the dependences «load - relative fiber deformation of concrete» and «load – deflection» were obtained. The results of the experimental data are presented in Table 2 and are shown in the dependency «carrying capacity *M* - deflection *w* in the middle and in the thirds of beam span» for conventional and strengthened beams in Fig. 3. In diagrams load is presented as a bending moment.

Table 2 shows the maximum values of deflections and bending moments achieved in the experiment and their values under the fixed parameter. In the first case the moment is shown under fixed deflections and in the second case the value of deflection is shown under fixed bending moment for beams.

Table 2 – The results of testing of beams

The name of the beam series	Bending moment, *M*, kNm		Deflection in the middle of the beam span *W*, mm	
	while w_{max}	while $W = \frac{1}{200} L_0$	while M_{max}	while $M=4.79$ *кНм*
БО	4.79	4.772	14.29	14.29
БП-I	11.39	10.423	14.41	1.429
БП-II	11.96	11.878	9.22	0.718
БП-III	12.90	11.033	16.33	0.975
БП-IV	16.57	16.570	10.02	0.714
БП-V	18.41	18.377	10.28	0.896
БП-VI	15.69	14.407	15.04	0.897
БП-VII	21.193	16.086	19.85	0.621

а) б)

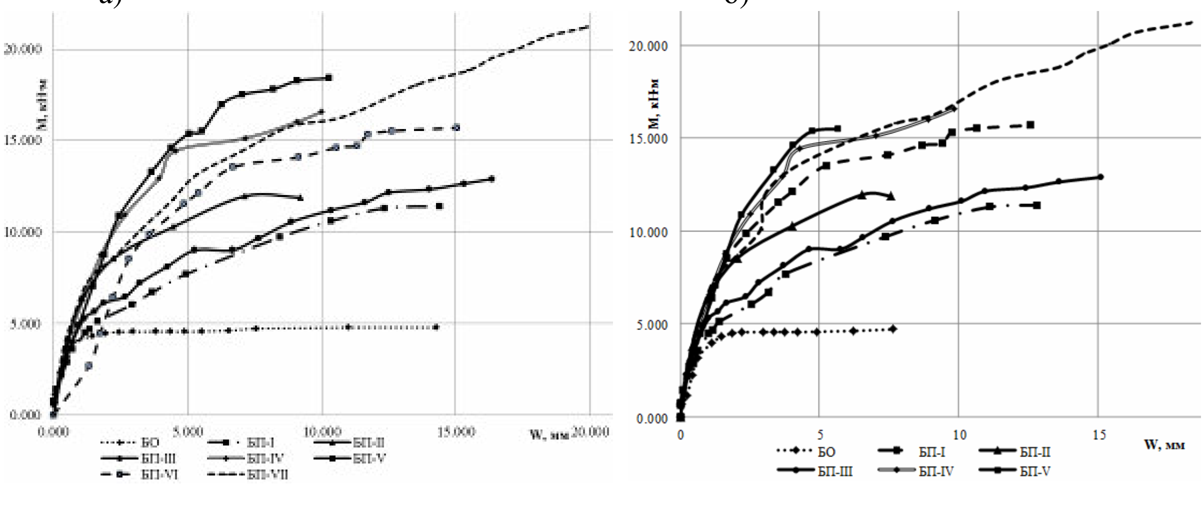

Figure 3 – Dependence «M-w» in the middle of the span - *a*
and in the thirds of the span - *b* of strengthened and conventional beams

Comparative analysis of the carrying capacity and deformability of strengthened beams compared with the conventional beams is presented in Table 3.

It is proved, the carrying capacity of strengthened beams was higher than of the conventional ones. According to the results of experimental studies the carrying capacity of reinforced beams was significantly higher than the control one. Thus, while strengthening beams with the system including rigid levers and one external wire element with a diameter of

5 mm in each branch the carrying capacity of beams increased up to 2.7 times; when two external wire elements were used in each branch, the carrying capacity increased up to 3.5 times; when three wire elements were used, carrying capacity increased up to 3.85 times. But this variant required additional costs on making rigid steel levers. Therefore, beams without levers with two wire elements in one branch were developed, manufactured and tested. An increase in carrying capacity amounted to 3.3 times (БП-VI) when the branches were fixed in the places where rigid levers were fixed. After determining an efficient place for fastening the strengthening branch, carrying capacity increases up to 4.42 times (БП-VII). The strengthened beams have much greater rigidity than the regular ones; a beam with rigid levers and three wire elements in one branch showed the greatest rigidity among the strengthened beams.

Dependence «load M - relative fiber deformations of concrete ε» on the central cross-section is presented in Table 4 and diagrams in Fig. 5.

Table 3 – The strengthening effect

The name of the beam series	$\frac{M_{БП}}{M_{БО}}$		$\frac{W_{БП}}{W_{БО}}$	
	while w_{max}	while $W = \frac{1}{200} L_0$	while M_{max}	while $M=4.79$ *кНм*
БО	1	1	1	1
БП-I	2.378	2.184	1.008	0.100
БП-II	2.497	2.489	0.645	0.050
БП-III	2.693	2.312	1.143	0.068
БП-IV	3.472	3.472	0.701	0.050
БП-V	3.843	3.851	0.719	0.063
БП-VI	3.276	3.019	1.052	0.0628
БП-VII	4.424	3.371	1.389	0.043

Table 4 - Relative fiber concrete deformations of the beam central cross-sections

The name of beam series	Relative concrete deformations according to the bending moment that is equal to			
	carrying capacity, M_{max}, kNm		carrying capacity of the conventional beam $M=4.79$ kNm	
	ε_{c1} x10^{-5}	ε_{c2} x10^{-5}	ε_{c1} x10^{-5}	ε_{c2} x10^{-5}
БО	320.7	-489.3	320.7	-489.3
БП-I	68.7	-135.1	28.7	-49.3
БП-II	46.3	-55.5	13.79	-21.1
БП-III	77.3	-870.1	17.4	-16.3
БП-IV	46.7	-49.6	15.5	-16.1
БП-V	125.0	-90.0	46.1	-25.1
БП-VI	106.3	-133.7	21.6	-16.1
БП-VII	125.0	-119.1	16.4	-16.5

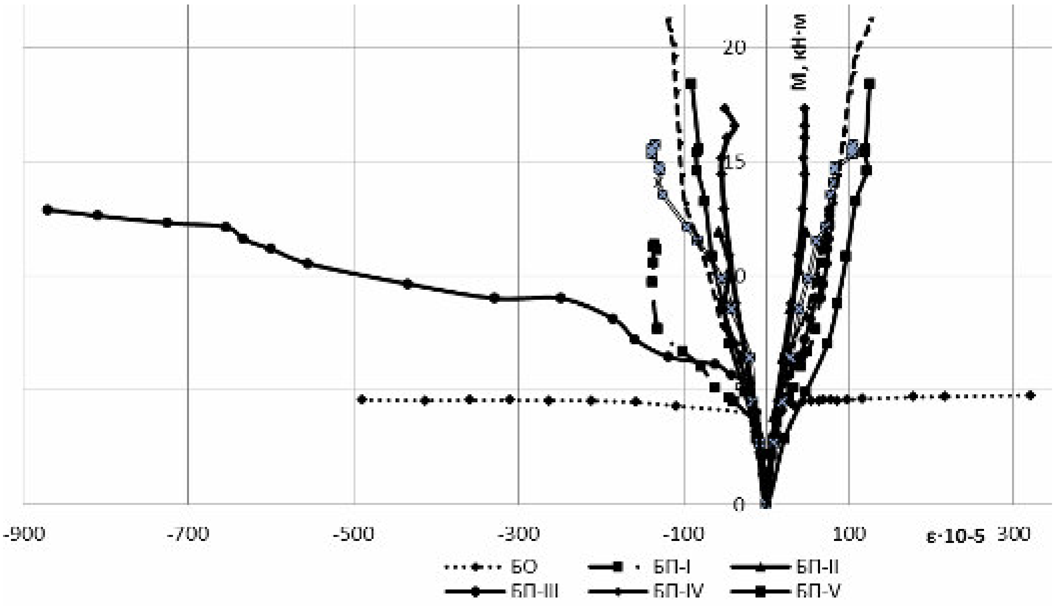

Figure 5 – Dependence «*M* - *ε*» on the beam central cross-sections

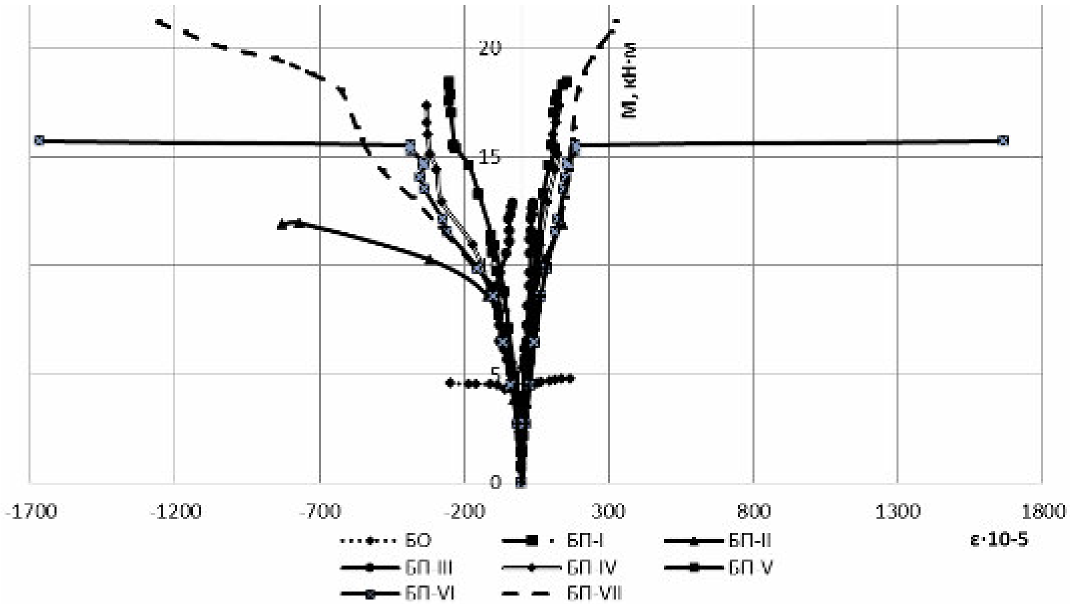

Figure 6 – Dependence «M - ε» on the beam cross-sections located in the thirds of their spans

It has been established that significant reduction in deformations of concrete is observed in strengthened beams in comparison with conventional beam series under the same load levels.

The character of crack formation and failure of the series of strengthened БП-I - VI and conventional control beams БО is shown in Fig. 7.

The study proposes a calculation method of such strengthened beams. It is considered the algorithm of calculation by the example of strengthened beam БП-VI without rigid levers. The method consideres the loss of tension because of friction under contact of external wire with rollers. The scheme of determining the forces in the branch of external wire is shown in Fig. 8.

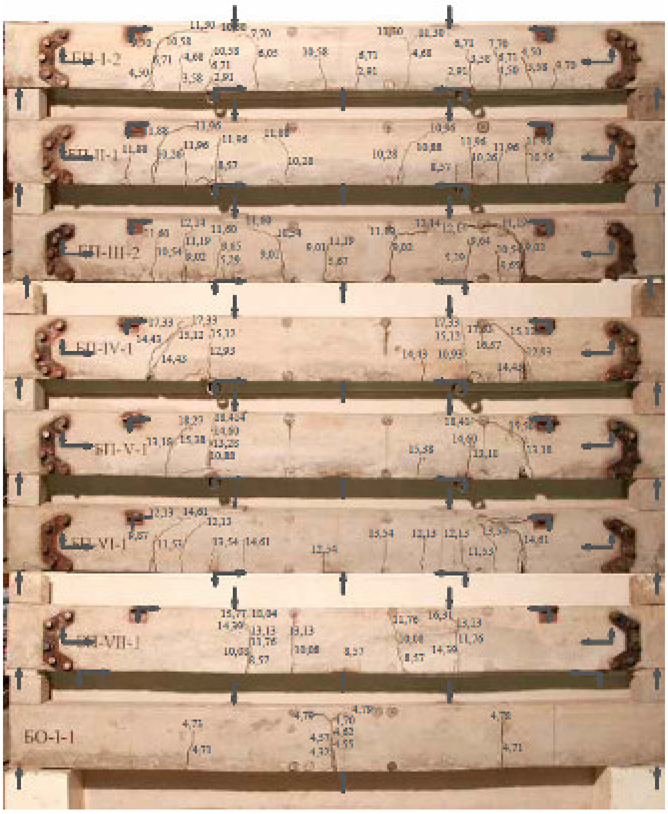

Figure 7 – Characteristic crack formation and failure of experimental beams

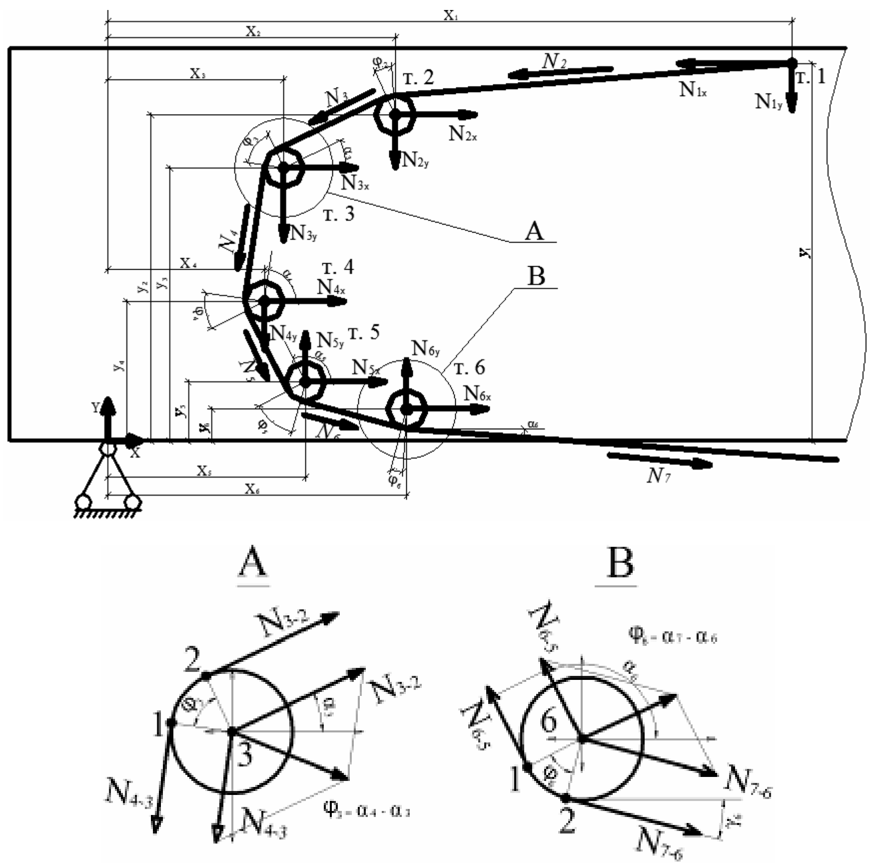

Figure 8 – Scheme of distribution of forces due to the action of the strengthening structure

According to the above scheme (Fig. 8) the resulting force on the lateral guiding element from the external reinforcement was obtained. The loss of the stress force in strengthening wire because of friction on rollers was considered. The calculation was conducted for the strengthening force of 19.796 kN in each branch of the reinforcement system for БП-VI beams. The value of the strengthening force was found in the experiment. The forces in the external wire in each part, from point 7 to point 1, is determined by the formula [5]:

$$N_{i-1} = \frac{N_i}{e^{f \cdot \varphi_{i-1}}} \tag{1}$$

where N_i – force in the leading branch;
N_{i-1} – force in the passive branch;
f – friction coefficient "steel on steel";
φ – angle of the contact between the branch and the roller.

After determining the resulting horizontal and vertical force the main calculation scheme of the strengthened beam has the form shown in Fig. 9.

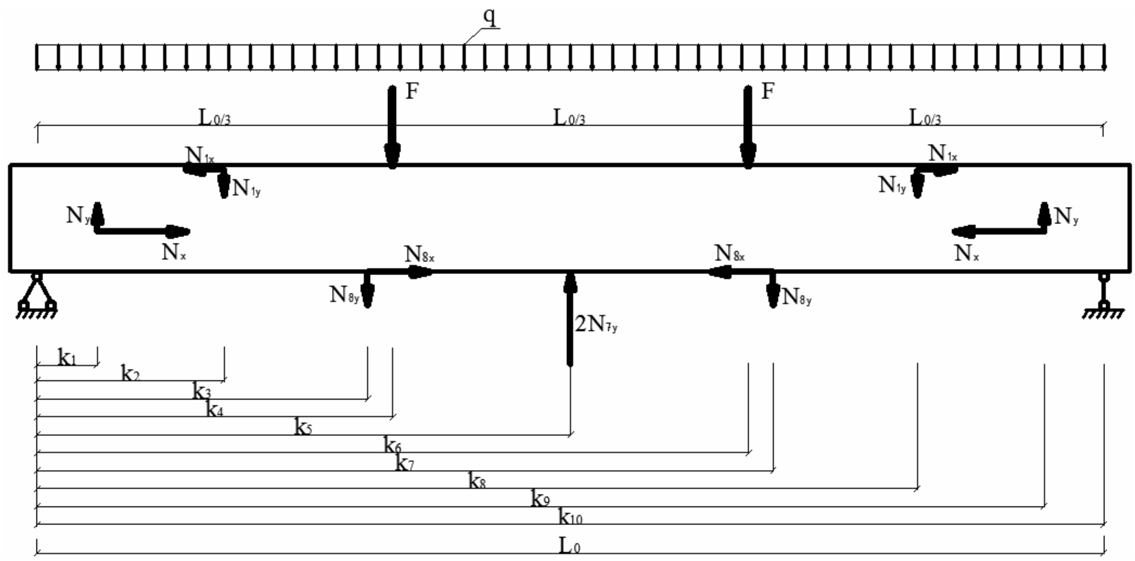

Figure 9 – The calculation scheme of the strengthened beam under the load of two concentrated forces F and live weight q

The diagram of total bending moment of the beam series БП- VI, strengthened with external bars, is shown in Figure 10.

The solid line shows total bending moment of the beam of БП- VI series (from unloading forces of the strengthening system and external load and live weight); the dotted line schematically shows the value of the bending moment without strengthening. In the calculations, the bending moment of the horizontal forces of the strengthening system was determined against the neutral line in each cross-section along the length of the beam, with the consideration of the variable eccentricity of beam deflections [1, 2, 11].

For the БП-VI series of reinforced beams the calculated bending moment was 15.508 kNm, and the corresponding experimental bending moment was 15.523 kNm. For this series of beam the discrepancy was insignificant, which confirms the adequacy of the calculation model БП-VI.

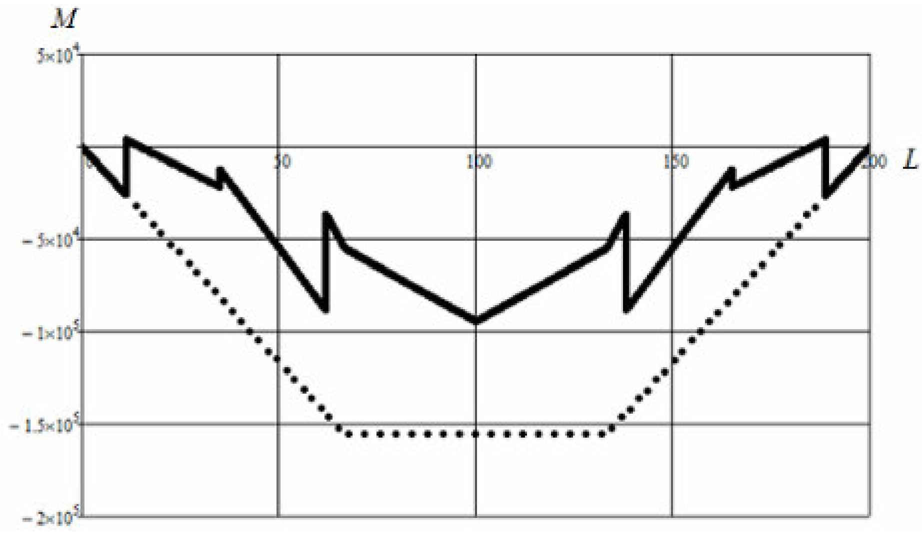

Figure 10 – Diagrams of the total bending moment of strengthened beams of БП- VI series

Conclusions. New strengthening system with external reinforcement for one-span reinforced concrete beams of a rectangular cross-section is presented. According to the results of experimental studies, carrying capacity increased up to 2.7 times in the beams strengthened with the system including rigid levers and one external wire element with a diameter of 5 mm in each branch; when two external wire elements were used in each branch, carrying capacity increased up to 3.5 times; when three wire elements were used. carrying capacity increased up to 3.85 times. Increase in the carrying capacity of the beams strengthened without levers amounted to 3.3 times (БП-VI) when the branches included two wire elements. After determining an efficient place for fastening the strengthening branch carrying capacity increases up to 4.42 times (БП-VII). Here, the strengthened beams had much greater rigidity than the regular ones. The beam with rigid levers and three wire elements in one branch showed the greatest rigidity. Convergence between the theoretical and experimental data by the example of БП-VI beams meets the requirements of calculation accuracy.

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