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BEARING CAPACITY OF STEEL-CONCRETE BENT ELEMENTS REINFORCED WITH ADDITIONAL UNSTRAINED ARMATURE AT DIFFERENT LEVELS OF STRAINED STATE

In this article, there are given the results of studies on the strength of steel-concrete bent elements, in which additional reinforcement was introduced at various levels of initial reinforcement and loading, as well as after unloading, and the beams were brought to destruction. The need for overhead cover reinforcement during the process of its exploitation appears not only in the course of reconstruction but also due to its physical aging that is caused by various factors. Accomplished part of the research does not take into account the prehistory of the work of the bent element before reinforcement or takes it into account approximately. The objective of the study of bent elements, in which the reinforcement with additional unstrained reinforcement is performed under the current load of different levels, has practical and theoretical significance. Moreover, such study is urgent and the solution of the problem will contribute to the growth of the economic efficiency of reinforcing steel-concrete structures.

Key words: steel-concrete bent elements, sheet armature, additional armature, unloading, residual strain, firmness, deformation.

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НЕСУЧА ЗДАТНІСТЬ СТАЛЕБЕТОННИХ ЗГИНАНИХ ЕЛЕМЕНТІВ, ПОСИЛЕНИХ ЗА РІЗНИХ РІВНЕЙ НАПРУЖЕНОГО СТАНУ ДОДАТКОВОЮ НЕНАПРУЖЕНОЮ АРМАТУРОЮ

Проаналізовано результати експериментальних і теоретичних досліджень згинаних елементів, підсилених додатковою арматурою в розтягнутій зоні, в яких додаткову арматуру встановлювали для відновлення або збільшення несучої здатності. Оскільки ефективність використання додаткової арматури для збільшення міцності, жорсткості значною мірою визначається напруженим станом згинаного елемента до підсилення, то проаналізовано результати досліджень впливу різнорежимних навантажень та розвантажень на напружений стан згинаних елементів до підсилення. Для перевірки теоретичних положень і методики розрахунку напруженого стану згинаних сталебетонних елементів, які підсилюються розтягнутою додатковою ненапруженою арматурою під навантаженням різного рівня, досліджено балки на короткочасні та тривалі навантаження. Наведено теоретичні дослідження та методику розрахунку міцності та деформацій згинаних елементів із додатковою ненапруженою арматурою. Встановлено дві стадії роботи згинаного елемента із додатковою арматурою під час розрахунку міцності. Перший – коли в початковій арматурі напруження дорівнюють межі текучості, і балка стає непридатною для експлуатації. Другий – фізичне руйнування балки настає у разі досягнення в додатковій арматурі напружень межі текучості.

Необхідність у підсиленні перекрить у процесі їх експлуатації виникає не тільки під час реконструкції, але і з причини фізичного їх старіння, яке спричинене різними факторами. Змінні температурно-вологісні умови негативно впливають на несучу здатність та експлуатаційну придатність конструкцій. У частині виконаних досліджень не враховано передісторії роботи згинаного елемента до підсилення або враховано його приблизно. Також відсутні рекомендації з оцінювання залишкової міцності згинаного елемента при визначенні кількості додаткового армування, величину арматури підсилення часто приймають, не враховуючи напруженого стану згинаного елемента до підсилення. Завдання дослідження згинаних елементів, в яких підсилення додатковою ненапруженою арматурою виконується під діючим навантаженням різного рівня, є актуальним, вирішення його сприятиме зростанню економічної ефективності підсилення залізобетонних конструкцій.

Ключові слова: сталебетонні згинані елементи, листова арматура, додаткова арматура, розвантаження, залишкові напруження, міцність, деформації.

Introduction. In the country it could be observed the increasing number of overhead covers that need to be strengthened to increase the bearing capacity of the buildings which are under the process of reconstruction according to new technologies as well as restoring the bearing capacity at the physical aging of steel-concrete structures. Among the structural, technological and economic requirements, the most successful one is considered to be the increase of the armature in the stretched zone, since over time the level of tension in the compressed zone decreases due to the concrete creeping and the increase of concrete durability over time. This allows to load up the compressed zone with additional stretched armature, while the openness of the stretched zone ensures the technological convenience of the implementation of the reinforcement [2].

The purpose of experimental research is to reveal the peculiarities and rules of the development of deformations and the effect on the deflections and strength of the additional stretched armature and to verify the method of calculation of the stress state of the bent elements, which are reinforced under a load of different levels. For the first time in Ukraine, the norms for reinforcement DBN B.3.1.-1-2002 indicate the need to take into account the stress state of the reinforced structure when calculating the reinforcement [7].

Scientific sources and publications review. To implement the mentioned reinforcement tasks, the method of reinforcement is chosen. The works [2, 12, 13] show that one of the most economical methods of constructive-technological requirements is the reinforcement of the stretched zone by the method of augmentation, which is associated with the establishment of additional reinforcement. Moreover, even when the relative height of the compressed zone approaches the limit value $x = x_R$ at the initial reinforcement, it is possible to install additional reinforcement because the strength of the concrete increases in time, and the concrete creeping in the compressed zone contributes to lowering of the neutral axis, as well as to increasing of the height of the compressed zone and reducing the stresses in the concrete [3, 9, 14]. The method of reinforcement with augmentation (increasing the reinforcement of the stretched zone) allows to use effectively the main armature in the conditions of joint work with the armature of reinforcement [2].

The purpose and the objectives of the research. The gist of the experiment is the uninterrupted measurements of the deformations in the compressed and stretched zones, the deflections before and after the setting of the additional armature installed in the stretched zone of the bent elements, which were under the short-term and long-term load of different levels. Herewith, the deformation measurements were carried out uninterrupted from loading, long-term loading (for some beams unloading), setting additional armature, loading up with short-term or long-term loading and brought to destruction. During the research the parameters were changed: the value of the initial and additional armature, the level of initial long-term loading and unloading before installing additional armature. Twin beams were also studied for reinforcement and load levels at short-term loading. Steel concrete unstrained beams with a spam of 2 m, a crosscut of 0.12x0.24 m and with main sheet armature which has thickness of $\delta = 2$ and $\delta = 4$ mm and mounting armature in a compressed zone with 2Ø6 A240 were studied at the age of concrete 140 days with a prism strength $f_{ck,prism} = 19MPa$ and an average value of the initial modulus of elasticity $E_{cm} = 29.1 \times 10^3 MPa$.

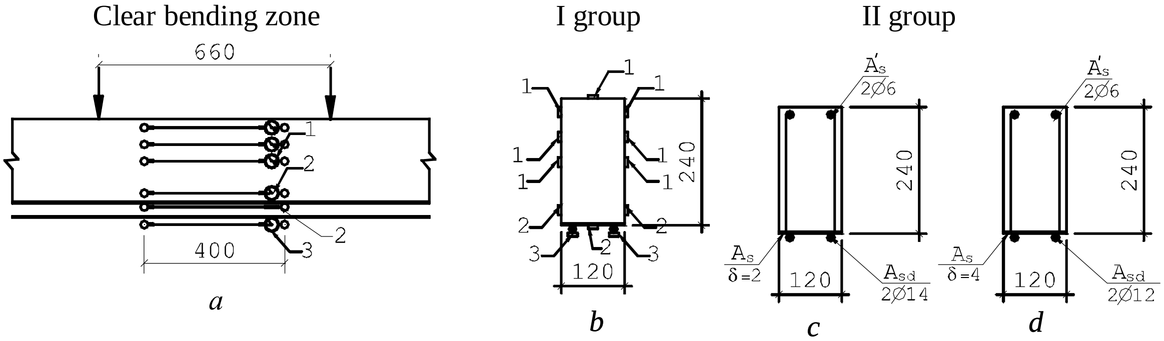

Fig. 1. Indicator on concrete (1). Micro-indicator on the main armature and concrete (2). Micro-indicator on additional armature (3).
Picture 1 a, b – a diagram of loading up and placement of measuring devices;
c, d – reinforcement of beams of I and II groups

Beams with different level of sheet armature reinforcement were loaded in steps 0,56 and 0,76 Mp from a destructive moment, were held under load, unloaded or not unloaded, additional armature was installed, and the beams were brought to destruction. Welding of additional armature and installment of micro indicators on it was carried out within one hour, while previously installed devices on the loaded beam were not removed, in order to record all deformations at the states of unloading and rest during one hour.

Theoretical and experimental research. All designations are accepted according to DBN V.2.6-98: 2009. For additional armature enter the index “d". For example, $\varepsilon_{ud}, \sigma_{scd}, d_{0d}, z_d$, – average deformations of additional armature, the tension of additional armature, working height and the arm of pair of internal forces during reinforcement $A_s + A_{sd}$.

Using the prerequisites and the methods of calculating of the strength of normal crosscuts according to DBN V.2.6-98: 2009 we will provide a calculation scheme of efforts to determine the strength of a bent element with the additional armature put at a certain strained state of the element (Fig. 2, *b*). The strained state at the intermediate stages of work until the installment of the additional armature, we will determine according to the methods presented in DBN V.2.6-98: 2009 with tension in a crosscut with a crack (Fig. 2, *a*).

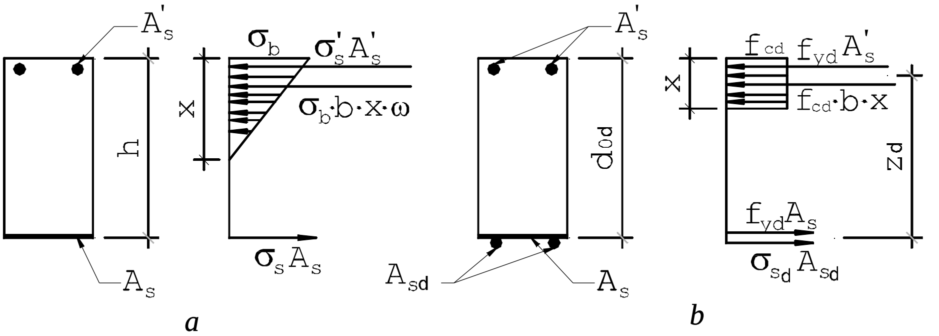

Fig. 2. Calculation schemes:
a – at calculation of tensions in the reinforcement before additional armature installation according to the methods of DBN V.2.6-98: 2009;
b – at calculation of the strength when $A_s + A_{sd}$

The strength of a bent element with additional armature according to figure 2b is determined by the formula:

$$M \le f_{cd} b x_d \left(d_{od} - 0.5x\right) + f_{yd}\left(d_{0d} - a^{'}\right), \tag{1}$$

while the height of the compressed zone is determined from the equation:

$$f_{yd} A_s + s_{sd} A_{sd} - f_{yd} A_s' = f_{cd} b x_d , \tag{2}$$

where A_s' – mounting armature, and the height of the compressed zone is $x_d \le x_R$ at $A_s + A_{sd}$. Taking into consideration that the main and additional armatures are fastened and work together in all stages of operation, as well as that bearing capacity and operational suit occur when the limit of fluidity is reached in the main armature, the tensions in the additional armature s_{sd} are:

$$s_{sd} = (f_{yd} - s_s)\frac{E_{sd}}{E_s}, \tag{3}$$

where s_{sd} – the tensions in the main armature at installment of additional armature, and f_{yd} – its calculated resistance (the limit of fluidity).

The average tensions and deformations of the main armature in the crack before the installing of the additional armature are determined:

$$s_{sm} = \frac{My_s}{A_s z}, e_{sm} = \frac{s_{sm}}{E_{sc}}. \tag{4}$$

The height of the compressed zone of concrete is determined by:

$$x = j_x (j_s + j_n) d . \tag{5}$$

The arm the force pair if the form of tensions in the concrete of the compressed zone is triangular (Fig. 2, a):

$$z = (d - \frac{x}{3}), \tag{6}$$

To compare, the height of the compressed zone and the arm of the force pair were also determined with the help of the square equation according to the procedure given in [1].

The long-term nature of the load for determining of $x(t)$, $z(t)$ was taken into account with the help of coefficients $y_s(t)$, $j_{b2}(t)$. As it can be seen from Picture 3 the values of deformations determined by two methods are close. However, the calculation x according to DBN B.2.6-98: 2009 is much simpler [6].

As it can be seen from Equation 3, the additional armature is used more effectively if the tensions are lower in the main armature before the installation of the additional one. Therefore, part of the beams was unloaded completely or partially before the installation of additional armature. While unloading, the bent element is situated under the influence of internal forces in a complex strained state. After full unloading, in the stretched armature, there are stretching tensions due to the impossibility to cover the cracks completely, the distortion of the concrete zones near the edges of the cracks and plastic deformations of the stretched concrete between the cracks. The return of the stretched armature to the initial position is also hindered by inelastic deformations of the compressed zone of concrete, resulting in a residual strained state. Stretching in the reinforcement should be balanced by compression of the concrete near the neutral axis, which in turn causes stretching in the edge fibers of concrete in the compressed zone. Using the research data presented in [3] as well as ours, a calculation scheme and formulas for the definition of residual strain (deformations) after full or partial unloading are established.

After full unloading from moment "M" the residual tensions in the stretched armature were determined:

$$s_s^0 = \frac{M(d - \frac{2}{3}x)}{4.5 A_s z^2},\quad s_{s(t)}^0 = \frac{M(t)\left[d - \frac{2}{3}x(t)\right]}{4.5 A_s z^2(t)} \tag{7}$$

If there were partial unloading from moment "M" till moment "$M_{роз}$", the residual tensions in the stretched armature were determined:

$$s_{sM_{роз}} = (s_{sM} - s_{s}^{0})\times\frac{M_{роз}}{M} + s_{s}^{0}, \quad s_{s(t)M_{роз}} = (s_{s(t)M} - s_{s(t)}^{0})\times\frac{M_{роз}}{M(t)} + s_{s(t)}^{0}, \qquad (8)$$

where s_{sM} is determined by the expression (4), and the transition to the average deformation is performed through the coefficient y_{s}.

After installation of the additional armature, the bent element works with new reinforcement $A_s + A_{sd}$ and new brought geometric characteristics. On the basis of the research data of bend elements on different-mode loadings, the change of strains (deformations) from additional external forces can be considered as growth (increase) of strains (deformations) under conditions of new reinforcement and new geometric characteristics.

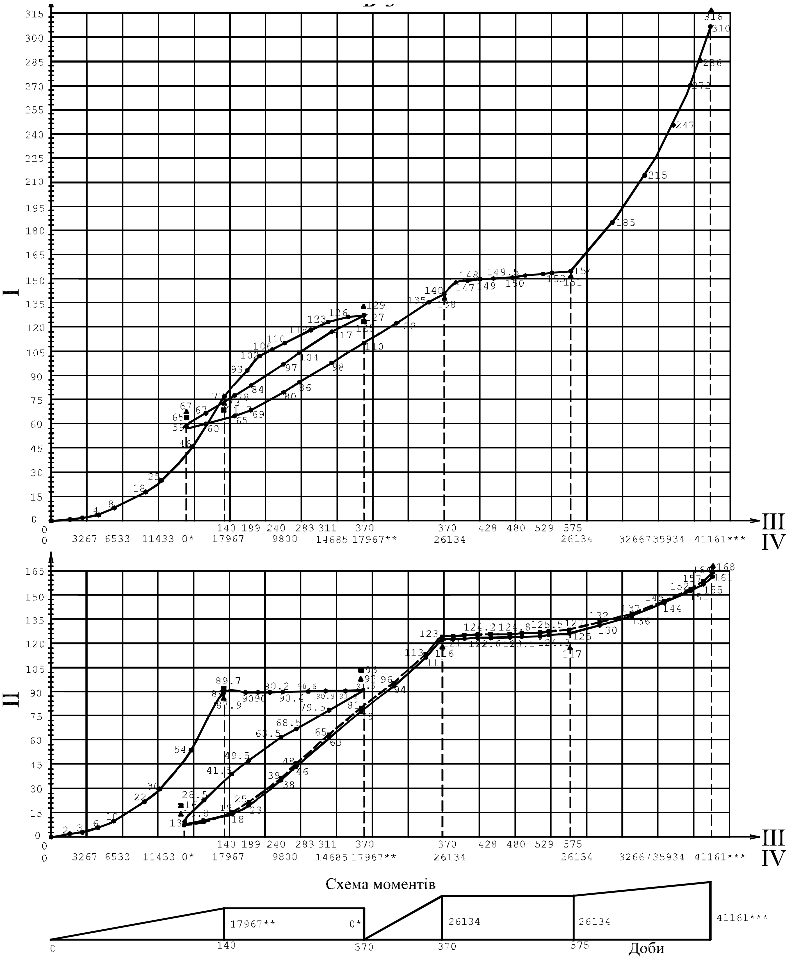

Fig. 3. Experimental and theoretical values of average edge deformations of concrete e_{cu}, armature e_{u}, beam B-3, μ = 0.0169, m_d = 0.008 at long-term loading

** The moment (unloading) of installation of additional armature* $k = \frac{M}{M_p} = 0$,

***The moment of loading up* $k = \frac{M}{M_p} = 0.56$, **The moment of destruction according to (*$A_s + A_{sd}$*)*

▲ *Theoretical values if x is according to DBN B.2.6-98: 2009,* ■ *Theoretical values if* x *is from equation*

I – average deformations of concrete $1*10^{-5}$, *II – average deformations of armature* $1*10^{-5}$, *III – days, IV – bent moment M, H*cm*

According to the expression 4 the tension and deformation of the reinforcement for the element with additional armature:

$$s_{smd} = \frac{My_{sd}}{z_{д}(A_s + A_{sd})};\ e_{smd} = \frac{s_{cmd}}{E_s} \tag{9}$$

The long-term nature of the loading is taken into account at determining $x_d(t)$, $z_d(t)$ through the coefficients $y_{sd}(t)$, $j_{b2}(t)$ determined for new reinforcement by $A_s + A_{sd}$.

Table 1

Experimental-theoretical and theoretical values of tensions in reinforcement and destructive moments

Group of beams coefficient of basic and additional armature	Number of beams	Loading level $\kappa = \frac{M}{M_p}$ Unloading level $\kappa = \frac{M_{pz}}{M_p}$	Tensions in the armature, s_s, s_{sd}, MPa				Theoretical destructive moment M_p^m Нхсм	Experimental destructive moment M_p^e Нхсм	$\frac{M_p^e}{M_p^m}$
			Experimental / *Theoretical*						
			During loading up s_{sm}; $s_{sm}(t)$	Residual during installation of additional armature s_{sm}^{0}; $s_{sm}^{M_{роз}}$	During destruction				
					In the initial armature s_{sm}	In the additional armature s_{smd}			
I m = 0.0084 $m_{д}$ = 0.0108	Б-1	$\frac{0.56}{0.31}$	$\frac{139.1}{161.5}$	$\frac{107.0}{103.4}$	$\frac{324.0}{314.6}$	$\frac{221.5}{211.2}$	28665	31360	1,09
	Б-2	$\frac{0.56}{0}$	$\frac{143.4}{161.5}$	$\frac{39.8}{31.1}$	$\frac{314.5}{318.0}$	$\frac{278.3}{286.9}$	32445	34627	1,07
II m = 0.0169 $m_{д}$ = 0.008	Б-3	$\frac{0.56}{0}$	$\frac{195.8}{196.8}$	$\frac{27.3}{33.2}$	$\frac{344.5}{359.0}$	$\frac{327.0}{308.6}$	43558	41160	0,95
	Б-4	$\frac{0.56}{0.31}$	$\frac{201.1}{196.8}$	$\frac{115.5}{120.5}$	$\frac{342.4}{345.8}$	$\frac{235.4}{225.3}$	40772	39854	0,98
	Б-5	$\frac{0.76}{0.31}$	$\frac{280.3}{268.9}$	$\frac{156.7}{135.9}$	$\frac{342.4}{344.5}$	$\frac{192.6}{208.6}$	40183	39201	0,98
	Б-6	$\frac{0.76}{0.76}$	$\frac{282.4}{268.9}$	$\frac{284.6}{268.9}$	$\frac{338.1}{329.6}$	$\frac{55.7}{60.5}$	34700	34620	0,99

Note: The experimental and theoretical values of the tensions are obtained from measured (on the basis of 400 mm) average deformations of the reinforcement e_{sc} *,* $e_{scд}$*, determined with* $s_{sc} = e_{sc} \times E_s$ *and* $s_{scд} = e_{scд} \times E_{sд}$ *, when the theoretical values are obtained according to the methods given in the article.*

The tension in the reinforcement in the element with the additional armature $s_{smд}$ for the moment "$\overline{M}$" is determined by:

$$s_{smd\,\overline{M}} = s_{sm_{зал}} + \Delta s_{smd}(\overline{M} - M_{роз}) \tag{10}$$

where $s_{sm_{зал}}$ – residual tensions in the reinforcement before the installation of additional armature at full unloading are determined according to the formula (7), and with partial unloading according to the formula (8).

Δs_{smd} – increase in tensions in the reinforcement from the moment of the installation of the additional armature at "M" till "$\overline{M}$" determined according to the formula 10.

Table 1 shows the tensions in stretched armature and the destructive moments for two groups of beams with different basic and additional armatures.

Before the installation of additional armature from picture 3 it is clear that the theoretical values of the average tensions of the reinforcement are smaller than the experimental ones in the beams of the second group by 3.5 – 8.6 %, while in the non-reinforced beams of the second group (B-1, B-2) the theoretical values are greater by 8.6 – 20 %, which is explained with not taken into account, in the theoretical values of tensions, the work of concrete over a crack, which is more substantial in little reinforced elements. With a long-term loading, this difference is only 8.6 % (B-1, B-2), which indicates an exception from the work of concrete over the crack. This pattern is observed with increasing level of loading, which also reduces the role of stretched concrete over the crack (Table 1). It has been experimentally proved that the residual tensions in the armature at full unloading depend on the size of the reinforcement and the level of loading from which the unloading is carried out. The larger loading to unloading contributes to the development of plastic deformations in compressed and stretched concrete, which restrains the regress of the armature to its original position. At the same coefficient of reinforcement, the residual tensions are greater in the beams, in which the loading level from which the unloading is carried out is larger (B-5, B-6)

The experimental values of tensions in stretched armature with partial unloading are more theoretical by 3.9 % in less reinforced beams of the first group, and larger by 4.7 % and 13 % in the beams of the second group with more initial reinforcement. This can be explained with the fact that with a larger reinforcement and a higher level of loading, the height of the cracks and their width of opening, and even their number, cause larger distortion of cross sections at the cracks, which holds back the deformations of the armature during unloading. The obtained experimental data correlate well with the results of special studies of bend elements at unloading [3].

On the stage of destruction, the theoretical values of tensions in the reinforcement differ from the experimental ones by -1.1 to 4.0 % in the beams of the first group (B-1, B-2) and in the beams of the second group the theoretical values are greater by 1.0 to 4.2 % and smaller by 2.5 %. As it can be seen, these differences do not contain a regular nature and can be explained only with the fact that the experimental value of the bearing capacity was determined at a certain degree of loading. The theoretical values of the tensions in the reinforcement are larger by 1.0 – 5.7 % of the values obtained from the research of the physical and mechanical characteristics of the reinforcement itself.

The tensions on the stage of destruction in the additional armature depend on the loading criterion (tension in the basic armature), in which additional armature was installed. The theoretical values of the tensions in the additional armature are larger than the experimental ones by 3.1 % and less by 0.5 to 4.9 %. So, these deviations are also not of a systemic nature. Attention is drawn to the small values of the tensions in the additional armature on the stage of destruction, when it is placed on the bent element which is close to the stage of the limit (B-6). This emphasizes the importance of unloading before the installation of additional armature (Fig. 3).

As it can be seen from Table 1, those elements are the strongest in which the additional armature was installed at its full unloading, since in this case the range of joint work of the initial and additional armature is the longest (B-2, B-3). Partial unloading of elements, before the installation of additional armature (B-1, B-4, B-5), also increases the strength of the elements in comparison with those in which the additional armature was installed without their unloading. The least strength have the beams in which additional armature is installed with larger load criteria without their unloading, because in this case the range of joint work of the armature before the stage of destruction is the smallest (B-6). Mentioned above features on the experimental values of the strength of the beams relate to both groups of beams, in which the different correlation of the initial and additional armature can be observed.

The nature of destruction of the beams with additional armature is very plastic, and not only because of $x < x_R$ at ($A_s + A_{sd}$), but when the tensions of fluidity in the initial armature are reached, the moment of external forces seems to be transferred onto additional armature. The beam continues to perceive a certain increase in the moment, but at the same time the deformation of the compressed and extended zones and the deflections grow intensively, up to the strength limit of the basic armature. Thus, with the joint work of the basic and additional armatures, installed in a steel concrete element at a certain strained state, additional armature is used to the limit of fluidity of the initial armature. In this case, the condition $x < x_R$ must be satisfied at $A_s + A_{sd}$.

Conclusions. 1. The researches have established that with the joint work of the basic and additional armature installed on the bent steel-concrete element in a strained state, the determining strength to increase the strength, firmness of the bent element and the efficiency of the use of additional armature is the residual strained state before the installation of additional armature. Therefore, the maximum unloading of the bent elements before the installation of additional armature is positive for the residual bearing capacity and increases the range of use of additional armature.

2. The strength of the bent element with the additional armature installed at a certain strained state of the element can be determined by the method of the limit state according to the DBN B.2.6-98: 2009, and the tensions in the additional armature on the stage of destruction are determined depending on the residual tensions in the basic armature before the installation of the additional one.

3. The tension in the reinforcement, before the installation of additional armature on the intermediate stage, is recommended to be determined with the DBN B.2.6-98: 2009 through determining of the height of the compressed zone in the section with a crack, when the coefficients y_s, j_{b2} should be determined by norms or by the level of loading and the characteristic of creep.

4. Unloading of any level (from full to partial) of the bent element before the installation of additional armature increases the range of joint work of the basic and additional armature and as a result the strength and firmness of the elements with additional armature and the efficiency of its use. The remaining tensions, deformations and deflections after unloading are recommended to be determined by the proposed methods based on other authors' and our experimental data.

5. The deformation of the reinforcement, deflection of the bent elements with additional armature is recommended to be determined as the sum of the remaining deformations of the armature, the deflections, got before the installation of additional armature and deformations obtained by the element after the installation of additional armature for an element with new geometric characteristics by ($A_s + A_{sd}$).

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