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METHODS OF CREATING PRESTRESS IN SPAN STRUCTURES AND FEATURES OF THEIR CALCULATION

І. Прокопович, А. Ткачьов, С. Мироненко, О. Ткачьов. **Способи створення попередньої напруги в пролітних конструкціях та особливості їх розрахунку.** Тема роботи пов ‘язана з можливістю дослідити вплив кривизни попередньо напруженого кранового моста на його несучу здатність. В роботі автори пропонують нове конструктивно–технологічне рішення попереднього напруження кранового моста, яке дозволяє уникнути головних недоліків, які притаманні у нині використовуваних конструкціях. Запропонована конструкція дозволяє також уникнути постійного напружено–деформованого стану балки, де величина розвантажувального моменту залежить від величини діючого робочого навантаження. Для позитивного розгляду поставленої задачі виникає необхідність отримання точного рівняння кривої прогинів кранового мосту. Таке завдання вимагає розробки нової математичної моделі, а також розвиток та уточнення вже існуючих математичних моделей преформованих балкових систем. Що і є метою цієї роботи. В роботі запропонована нова математична модель базується на загальній теорії стійкості пружних систем, при розробки якої були враховані реальні умови конструктивного виконання кранового моста. Отримані універсальні рівняння кривої прогинів балки з початковою кривизною, які дають можливість дослідити її напружено-деформовану поведінку при сумісної дії на балку навантажень в площині підвісу вантажу одночасно з осьовим ексцентричним навантаженням. Отримані в даній роботі результати можуть бути прийняті до уваги при визначенні геометричних характеристик перерізів балки, а також для вдосконалення методів розрахунку проектування пролітних балкових систем на стадіях їх проектування, а також в умовах реальної експлуатації. Крім того, наведені авторами рекомендації можуть бути застосовані при ремонті кранових мостів, їх модернізації з метою підвищення вантажопідйомності, а також збільшення терміну служби вантажопідйомної машини без демонтажу.
Ключові слова: попереднє напруження, початкова кривизна, несуча здатність, крановий міст, статична жорсткість, деформаційний стан

I. Prokopovych, A. Tkachev, S. Myronenko, O. Tkachev. **Methods of creating prestress in span structures and features of their calculation.** The topic of the work is related to the possibility of investigating the influence of the curvature of a prestressed crane bridge on its bearing capacity. In the work, the authors propose a new structural-technological solution for prestressing the crane bridge, which allows avoiding the main shortcomings inherent in the currently used structures. The proposed design also avoids the constant stress-deformed state of the beam, where the magnitude of the unloading moment depends on the magnitude of the working load. For a positive consideration of the given task, there is a need to obtain an exact equation of the crane bridge deflection curve. Such a task requires the development of a new mathematical model, as well as the development and refinement of already existing mathematical models of preformed beam systems. This is the purpose of this work. The paper proposes a new mathematical model based on the general theory of stability of elastic systems. During its development, the real conditions of the construction of the crane bridge were taken into account. The universal equations of the deflection curve of the beam with the initial curvature are obtained, which make it possible to investigate its stress-strain behavior under the simultaneous action of loads on the beam in the plane of the suspension of the load simultaneously with an axial eccentric load. The results obtained in this work can be taken into account when determining the geometric characteristics of beam sections, as well as for improving the calculation methods for the design of span beam systems at the stages of their design, as well as in real operation conditions. In addition, the recommendations given by the authors can be applied in the repair of crane bridges, their modernization in order to increase the load capacity, as well as increase the service life of the lifting machine without dismantling.
Keywords: prestress, initial curvature, bearing capacity, crane bridge, static stiffness, deformation state

Introduction

In modern production, special attention is paid to issues that are directly related to the improvement of the technical parameters of lifting machines. Among the main issues mentioned are those related to the development, manufacture and operation of overhead cranes with prestressed main beams [1]. Thus, in order to create prestress in the span system of the crane, it is necessary to bend the main beams (Fig. 1), namely, to artificially create the initial curvature [2]. The metal constructions of such cranes have increased bearing capacity. They are economical, easy to manufacture and have high operational reliability [3]. Despite the great bearing capacity, such structures have serious drawbacks that limit their use. The main of these disadvantages is the low rigidity of the span structure due to the reduced moment of inertia of the section. Therefore, the deflection arrow of the main beam significantly deviates from the straight shape [4]. This deficiency may be the result of the fact that the span beams, firstly, are constantly in a deformed state. In addition, the deformed state of the beam remains even when the beam is not loaded. And secondly, the moment that unloads the span structure does not de-

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pend on the size of the load on the hook.

It should be noted that the elastic line of real structures of prestressed main beams also has some initial curvature [5]. On the one hand, these may be minor deflections of the beam due to its own weight, which do not significantly affect the bearing capacity of the structure. And which, as a rule, are neglected, based on the initial straight shape of the beam [6]. On the other hand, it is related to the structural features of the beam. For example, giving them a construction lift, where the initial curvature of the axis of the beam is created artificially during manufacturing [7]. In other cases, as a result of the relaxation of residual welding stresses [8], as well as in case of systematic bridge overloads associated with intensive work of the beam in the elastic-plastic stage [9].

Fig. 1. Bridge crane with prestressed main beams

Thus, it is obvious that the issues related to the search for new constructively – technological ways of creating prestressing in span systems are very relevant at the present time.

Analysis of research publications

An analysis of the publications in this field has shown that a large number of studies have been carried out for pre formable span beams. Among them, numerical [10] and experimental [11] modeling of bending beam structures was considered and analyzed. A number of publications were devoted to determining the static [12] and dynamic [13] stiffnesses of a prestressed beam depending on the position of the moving load along the length of the span [14]. In [15], the stress-deformed behavior of a stressed beam in the plane of the load suspension under the influence of a moving vertical temporary load was modeled and analyzed. The deformed behavior of the beam at different ratios of transverse and longitudinal loads was subjected to deep research and analysis, where the optimal deflections and bends of the beam in the vertical and horizontal planes were determined [16]. A new mathematical model of the prestressed span structure was proposed, which makes it possible to maximally take into account the approximation of the calculation scheme of the beam to its real structural form. As a result, research and analysis of the stress-deformed state of this structure with variable moments of inertia of the section along the span were carried out [17]. A further review of beam system publications revealed that structural elements of beam tensioning devices, such as tightening and anchor stops, have unreasonably overestimated safety margins and do not reflect the real behavior of the structure under load [18].

Thus, the analysis of the conducted studies shows that almost all prestressed beam systems are constantly in a deformed state. This deformed state has a positive effect on the beam at the moment when it experiences a moving vertical load. And it negatively affects the crane bridge when the beam is not loaded. These shortcomings can be accompanied by a violation of the nodes and mechanisms connected to the metal structure [19], skewing of the end beams [20], which sometimes leads to emergency situations of the load lifting machine. In addition, there is a possibility of skidding of the running wheels of the cargo trolley when it moves uphill from the support in the direction of the span [21]. As a result, the energy costs of the movement mechanism also increase [22]. In all the considered works, the mathematical modeling of span systems is based on the assumption of the initial straightness of the elastic line, and in the expressions used for engineering calculations, the curvature of the beam is also not taken into account [23]. This leads to a significant discrepancy between the calculation results and the experimental values [24]. In this case, it should be noted that transverse and eccentric compressive loads act on the span beams of the prestressed bridge in the plane of the load suspension. Small deviations of the beam from the straight shape of its bending line, as well as eccentricity, in the case of applying a transverse force, significantly affect the deflections of the beam and the stresses caused in it, which are not proportional to the magnitude of the vertical force. Therefore, the influence of the initial curvature of the beam must be taken into account with regard to the geometrical characteristics of the beam cross-sections. In connection with this, to study the stress-strain behavior

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of a crane bridge, there is a need to obtain an accurate expression of the deflection curve of a deformed beam having an initial radius of curvature. The analysis of the reviewed publications revealed one more drawback of the applied unloading method – the moment that unloads the span structure does not depend on the magnitude of the temporary load, which also does not facilitate the operation of the deformed span system.

The purpose and objectives of the research

Thus, the purpose of this work is to propose a new structural-technological method of increasing the load-bearing capacity of the span structure, where the magnitude of the unloading moment depends on the weight of the cargo. And in the absence of it, that is, in the absence of a working load on the beam, it will not automatically be subjected to preliminary deformation. To achieve positive results of the set goal, it is necessary to solve the following tasks: analyze the already known mathematical models, where the previous tension is most fully realized; develop a new mathematical model for the proposed method of unloading the bridge, which allows you to take into account the curvature of the beam both before and during the action of the working load on it; analyze the obtained results and give appropriate recommendations.

Presentation of the main material

In mechanical engineering, devices are widely used in which the prestressing of the span structure is formed by the method shown in Fig. 2. Where in the process of manufacturing or installation, with the help of anchors *1*, the necessary force is created in the fasteners *2* [25]. Since the line of action of force N is at a distance e from the neutral bending axis of beam *3*, an unloading moment opposite in sign to the working one is created in it.

The calculation scheme of the described unloading method is shown in Fig. 3, where the following designations are adopted: l – crane bridge span; c – the distance from the right support to the load F acting on the beam in the vertical plane; q – the intensity of the distributed tension from the weight Q of the beam; e – the distance from the neutral axis of the bridge bend to the longitudinal force S; x is the current f coordinate of the location of the bridge deflection determination; EI – stiffness of the beam in the plane of the load suspension.

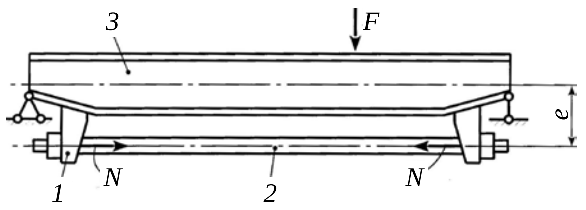

Fig. 2. Structural diagram of the main beam with prestressing

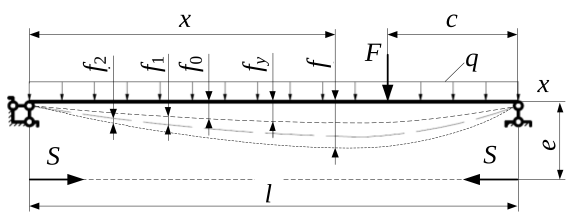

Fig. 3. Calculation diagram of the main beam with prestressing

When developing the calculation scheme, the following assumptions were made – the beam rests on ideal hinges, its material works in the elastic region. In addition, for this method of unloading the span system, we will consider the calculation scheme of the beam, based on the assumption of the initial curvature of the elastic line. The curvature of the beam can be created in the following ways: the first is artificial, during its manufacture. And the second – in the process of its operation with systematic overloads and other cases that were given above.

In the first case, the amount of deflection of the beam can be determined by calculation when the weight of the beam Q is known, or the intensity q of the distributed load from its weight. When drawing up the differential equations of the deflection curves of the beam, it should be taken into account that the prestress of the span can be created either when the vertical load F acts on the beam, or without it, that is, F=0. For simplification, let's denote:

$$\frac{S}{EI} = k^2. \tag{1}$$

Then the differential equations of the deflection curve for the left and right parts of the beam will be:

– for the area $0 \le x \le (l - c)$,

$$\frac{d^2 f_0}{dx^2} + k^2 f_0 = -\frac{x}{2lEI}(2Fc + ql(l - x)) + k^2 e, \tag{2}$$

– for the area $x \geq (l - c)$,

$$\frac{d^2 f_0}{dx^2} + k^2 f_0 = -\frac{l-x}{2lEI}(qlx + 2F(l-c)) + k^2 e. \tag{3}$$

The complete integral of these equations will be, respectively:

$$f_0 = C_1 \cos kx + C_2 \sin kx + \left[e - \frac{Fcx}{lS} - \frac{q}{S}\left(\frac{2 + k^2 x(l-x)}{2k^2} \right) \right], \tag{4}$$

$$f_0 = C_3 \cos kx + C_4 \sin kx + \left[e - \frac{F(l-c)(l-x)}{lS} - \frac{q}{S}\left(\frac{2 + k^2 x(l-x)}{2k^2} \right) \right]. \tag{5}$$

After determining the constants of integration and simple transformations, we present the equation of the ordinate of the initial curvature of the beam in its final form, with F=0:

$$f_0 = \left(\cos kx + \sin kx \operatorname{tg}\frac{kl}{2} - 1 \right)\left(\frac{q}{k^2 S} - e \right) - \frac{qx}{2S}(l-x). \tag{6}$$

The maximum ordinate "y" in the middle of the span will be at x=c=0.5l, namely:

$$y = \frac{\left(1 - \cos\frac{kl}{2}\right)\left(\frac{q}{k^2 S} - e\right)}{\cos\frac{kl}{2}} - \frac{ql^2}{8S}. \tag{7}$$

With further loading of the pre-stressed span structure with a vertical force (i.e. $F \neq 0$), the final form of the equation of the deflection curve of the beam will have the following form:

– for the area $0 \leq x \leq (l - c)$,

$$f = f_0 + \left(\cos kx + \sin kx \operatorname{tg}\frac{kl}{2} - 1 \right)\left(\frac{q}{k^2 S} - e \right) + \frac{F}{S}\left(\frac{\sin kc \sin kx}{k \sin kl} - \frac{cx}{l} \right) - \frac{qx}{2S}(l-x), \tag{8}$$

– for the area $x \geq (l - c)$,

$$f = f_0 + \left(\cos kx + \sin kx \operatorname{tg}\frac{kl}{2} - 1 \right)\left(\frac{q}{k^2 S} - e \right) + \frac{F}{S}\left(\frac{\sin k(l-c) \sin k(l-x)}{k \sin kl} - \frac{(l-c)(l-x)}{l} \right) - \frac{qx}{2S}(l-x). \tag{9}$$

In the second case, when the span system has finite deformations, we assume that the axis of the beam has the form of a sinusoidal curve with the maximum ordinate in the middle of the span and is given by the equation:

$$f_0 = y \sin\frac{\pi x}{l}. \tag{10}$$

When the beam is loaded, in working condition, it will experience the joint action of eccentric - longitudinal force and transverse forces S from the temporary load F and its own weight Q. At the same time, from these forces, the axis of the beam receives additional deflections f_1 and f_2, respectively. The ordinates of the deflection curve can be obtained by superimposing the deflections from each individual transverse force acting together with the longitudinal force S.

The final ordinates of the deflection curve will be:

$$f = f_0 + f_1 + f_2. \tag{11}$$

Deflections f_1 and f_2 will be considered as one total deflection:

$$f_{12} = f_1 + f_2. \tag{12}$$

Then, we will rewrite the equation for the final ordinates of the beam deflection curve in the form:

$$f = y\sin\frac{\pi x}{l} + f_{12}. \tag{13}$$

Deflections are found in the usual way, using the differential equations of longitudinal transverse bending known from the theory of stability of elastic systems:

– for the area $0 \le x \le (l-c)$,

$$\frac{d^2 f_{12}}{dx^2} + k^2 f_{12} = k^2\left(\left(-\frac{Fcx}{lS} - \frac{qx(l-x)}{2S}\right) + e - y\sin\frac{\pi x}{l}\right), \tag{14}$$

– for the area $x \ge (l-c)$,

$$\frac{d^2 f_{12}}{dx^2} + k^2 f_{12} = k^2\left(\left(-\frac{F(l-c)(l-x)}{lS} - \frac{qx(l-x)}{2S}\right) + e - y\sin\frac{\pi x}{l}\right). \tag{15}$$

The general solutions for these equations will be respectively:

$$f_{12} = C_1\cos kx + C_1\sin kx - \frac{Fcx}{l} - \frac{q}{2S}\left(\frac{2}{k^2} + x(l-x)\right) + e + \frac{k^2l^2}{\pi^2 - k^2l^2}y\sin\frac{\pi x}{l}, \tag{16}$$

$$f_{12} = C_3\cos kx + C_4\sin kx - \frac{F(l-c)(l-x)}{l} - \frac{q}{2S}\left(\frac{2}{k^2} + x(l-x)\right) + e + \frac{k^2l^2}{\pi^2 - k^2l^2}y\sin\frac{\pi x}{l}. \tag{17}$$

We proceed in the same way as in the above expressions. After determining the constants of integration and the necessary transformations, we present the equation of the ordinates of the beam deflection curve, in its final form:

– for the area $0 \le x \le (l-c)$,

$$f = \frac{(\pm y)\pi^2\sin\frac{\pi x}{l}}{\pi^2 - k^2l^2} + \left(\cos kx + \sin kx\,\mathrm{tg}\frac{kl}{2} - 1\right)\left(\frac{q}{k^2S} - e\right) - \frac{qx}{2S}(l-x) + \frac{F}{S}\left(\frac{\sin kc\sin x}{k\sin kl} - \frac{cx}{l}\right), \tag{18}$$

– for the area $x \ge (l-c)$,

$$f = \frac{(\pm y)\pi^2\sin\frac{\pi x}{l}}{\pi^2 - k^2l^2} + \left(\cos kx + \sin kx\,\mathrm{tg}\frac{kl}{2} - 1\right)\left(\frac{q}{k^2S} - e\right) - \\ - \frac{qx}{2S}(l-x) + \frac{F}{S}\left(\frac{\sin k(l-c)\sin(l-x)}{k\sin kl} - \frac{(l-c)(l-x)}{l}\right). \tag{19}$$

In the equations, the ordinate y should be recognized as negative (–*y*) if the curvature of the beam will bend upwards. In other cases, the curvature of the beam is directed downward, and the ordinate is taken as positive (+*y*). In cases where the initial curvature of the beam can be neglected, the ordinate is set to zero – *y*=0.

The above equations are also convenient in that the deflection curve of a prestressing bridge can be obtained taking into account its curvature both under the joint action of forces *F* and *Q* and under the separate influence of these loads. If it is necessary to estimate the amount of deflection only from the temporary load *F*, it is necessary to zero the intensity of the distributed load from the weight of the beam, taking *q*=0 Otherwise, if it is necessary to determine the deflection of the beam only from its weight, it is necessary to reset the moving load to zero *F*=0.

Values of bending moments can be obtained by double differentiation of the above deflection equations:

$$M = -EI(f)''. \tag{20}$$

In this way, expressions were obtained, with the help of which it is possible to conduct an analysis of the stress-deformed behavior of the crane bridge, as well as to conduct calculations on the main performance criteria – static and fatigue strength, static and dynamic stiffness and general stability.

Figure 4 suggests another, new way of creating a prestressed state of a span structure. Where the magnitude of the unloading moment in the span structure *1* depends on the weight of the load and the resulting forces in the rope. One end of this rope is attached to the drum *3*, then it goes around the blocks of the cargo trolley *2*, the blocks of the hoist *4*, where it is attached, where it is attached with the other end. The forces from the rope are transmitted to the anchor devices *5*, and since the line of action of the compressive forces is applied below the neutral axis of the bending of the span structure *1*, an unloading moment of the opposite sign to the working moment is created at the locations of the anchor devices.

That is, such a constructive and technological solution allows to neutralize the main disadvantages of the previously applied method of creating the prestressing of the crane bridge, namely: it unloads the span structure with a moment, the magnitude of which depends on the magnitude of the moving load acting on the main beam in the plane of the load suspension, namely, by the weight of the load hanging on the hook. And, secondly, the main beams of the bridge are subjected to deformation only during the action of the working load on them. That is, the beam is automatically in a stressed-deformed state only when a load hangs on the hook. In the absence of a load, the beam is in a non-stressed state, namely, there is no action of the moment that unloads the bridge.

In Fig. 5 shows the calculation scheme of this crane bridge. It is developed on the assumption of the initial straightness of the elastic line, since the beam does not deform before the action of the working load. For this case, the stressed-strained behavior of the bridge can be analyzed using well-known mathematical models of pre-stressed beams proposed by the authors of the above works [26].

The deflection curve of a prestressed beam can be obtained using the following equations:

– for the area $0 \le x \le (l-c)$,

$$f = \left(\cos kx + \sin kx \, \mathrm{tg}\frac{kl}{2} - 1\right)\left(\frac{q}{k^2 S} - e\right) + \frac{F}{S}\left(\frac{\sin kc \sin kx}{k \sin kl}\right) - \frac{qx}{2S}(l-x), \qquad (21)$$

– for the area $x \ge (l-c)$,

$$f = \left(\cos kx + \sin kx \, \mathrm{tg}\frac{kl}{2} - 1\right)\left(\frac{q}{k^2 S} - e\right) + \frac{F}{S}\left(\frac{\sin k(l-c) \sin k(l-x)}{k \sin kl}\right) - \frac{(l-c)(l-x)}{l} - \frac{qx}{2S}(l-x). \qquad (22)$$

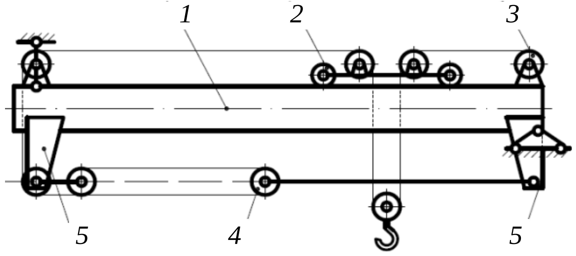

Fig. 4. Structural scheme of the main beam with automatic prestressing

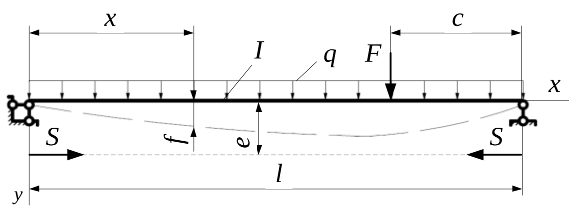

Fig. 5. Calculation diagram of the main beam with automatic prestressing

Research results

The obtained expressions made it possible to carry out the deformation calculation of span beams for load combinations II*a*, II*b* for a bridge crane with a load capacity of 12.5 t and a span of 16.5 m. Part of the calculation results is presented in the table in the form of conditional deflections of the main beam for the 4*K* operating mode group with the permissible value of the conditional deflection – $[f/l]=2\cdot10^{-3}$. Curves of bridge deflections were obtained with the ratio of longitudinal S and transverse F forces acting on the beam in the range:

$$\frac{S}{F} = 1; 1.5; 1.75; 2.0.$$

The analysis of the deformed state of the beam was carried out taking into account the most unfavorable cases: when a temporary load F is found in the middle of the span (c=x=0.5l) and above the support (c=0, x=0.5l).

The results of the analysis (see Table 1) indicate a significant difference in the deflections of a beam with an initial rectilinear axis and a beam with an initial radius of curvature. It can be seen that the initial or acquired curvature of the beam negatively affects the condition of the bridge, increasing its deflections at the middle position of the temporary load. Moreover, the determining criterion is the increase in force *S* during tightening. This is explained by the fact that the self-tension of the tightening, which occurs as a result of loading the beam with the working load *F*, is small compared to the force created in the pre-tension stage and is usually about one third of it.

Table 1

Conditional deflections of the main beam

y, mm	Conditional deflections of the main beam at *S*/*F*							
	1.0		1.5		1.75		2.0	
	c=*l*/2	*c*=0	*c*=*l*/2	*c*=0	*c*=*l*/2	*c*=0	*c*=*l*/2	*c*=0
0.0	0.88	–0.22	0.78	–0.33	0.71	–0.38	0.67	–0.45
0.3	0.90	–0.21	0.79	–0.32	0.77	–0.35	0.75	–0.37
0.5	0.91	–0.20	0.80	–0.31	0.78	–0.34	0.76	–0.36
0.7	0.92	–0.19	0.81	–0.30	0.79	–0.32	0.77	–0.35
0.8	0.93	–0.18	0.84	–0.29	0.80	–0.30	0.77	–0.34
1.0	0.94	–0.17	0.86	–0.27	0.81	–0.29	0.78	–0.33
1.3	0.99	–0.15	0.91	–0.20	0.83	–0.27	0.81	–0.28
1.5	1.1	–0.13	1.08	–0.15	1.00	–0.24	0.96	–0.26
1.8	–1.2	–0.12	1.15	–0.13	1.09	–0.20	1.05	–0.22
2.0	1.28	–0.10	1.19	–0.11	1.16	–0.19	1.09	–0.20
2.5	1.41	–0.08	1.39	–0.17	1.26	–0.18	1.21	–0.19
Beam without prestressing (*y*=0) deflection only								0.91

We also note that at the same time, the calculated bends of the bridge decrease when *c*=0 and *c*=*l*. This greatly facilitates the state of the metal structure when working with loads above or near the supports, and also prevents a number of known disadvantages. At the same time, an increase in the eccentricity of the force *S*, as well as the length of the spans, leads to an increase in the bending and deflection of the beam.

Conclusions

The work developed a universal mathematical model of a prestressed crane bridge with an available initial radius of curvature. The presented model makes it possible to study the stressed-strained state of the bridge both with and without the initial radius of curvature. And also with joint or separate action on the bridge of working mobile *F* and stationary *Q* loads with simultaneous action on the beam of eccentric transverse force *S*.

The equations obtained by the authors of the deflection curves (bends) of the main beam of the bridge crane made it possible to analyze its deformed behavior with the ratio of longitudinal and transverse forces acting on the beam in the range:

$$\frac{S}{F} = 1; 1.5; 1.75; 2.0.$$

In the work, the authors propose a new structural-technological solution for prestressing the crane bridge, which allows avoiding the main shortcomings inherent in the currently used structures. The proposed design also allows to avoid a permanent stressed-deformed state of the beam, where the magnitude of the unloading moment depends on the magnitude of the working load.

The results obtained in this work should be taken into account in the future when determining the geometric characteristics of the beam sections, as well as for improving the calculation methods for the design of span beam systems. In addition, the recommendations given by the authors can be applied in the repair of crane bridges, their modernization in order to increase the load capacity, as well as increase the service life of the lifting machine without dismantling.

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