



# Influence of Horizontal Inertial Loads on the Operation of Overhead Crane Girders

Anatoliy Tkachev , Aleksey Tkachev , Oleksandr Fomin , Oleksandr Bondar ,  
and Elena Naidenko 

Odessa Polytechnic National University, 1, Shevchenko Avenue, Odessa 65044, Ukraine  
a.lena2808@ukr.net

**Abstract.** Crane spans with prestressed girders operate under the same conditions, modes, and load capacities as conventional cranes. The load-carrying capacity of their spans must be provided with high strength and stiffness in two planes - in the main vertical plane and the horizontal plane. However, studies of the stress-strain state of a crane with a prestressed bridge operating in the horizontal plane have not been conducted. A mathematical model of the pre-stressed main beam has been developed in the paper. An analysis of its deformed state from the plane of cargo suspension and under the simultaneous influence of vertical and horizontal forces has been carried out, which allowed establishing. The obtained results can be further used to design bridge-type cranes with prestressed span beams to increase their lifting capacity and extend their service life without disassembly. As well as improving the existing structures and engineering methods of calculation, both at the design stages and under real operating conditions.

**Keywords:** Industrial growth · Bridge crane · Stress-strain state · Prestressed beams · Beam deflections

## 1 Introduction

The paper deals with the issues related to bridge-type cranes with prestressed spans. Such cranes are used to a limited extent in the industry [1]. It should be noted that cranes with prestressed span girders have considerably less weight, owing to less moment of inertia of beam section that positively influences on many other parameters improving operating conditions of the machine and is a significant advantage [2]. At the same time, such span beams are more deformable, which can lead to structural failure or malfunction [3].

This is because the metal structures of such cranes are more deformable than conventional cranes [4], which may be one of the causes of performance failure and unnecessary energy consumption to overcome the track gradient [5]. These factors are among those that limit the use of these cranes.

At the same time, cranes with prestressed span girders have significantly less weight and smaller dimensions than conventional cranes and a lower cost of the crane's metal structure, which can be 75–80% of the cost of the crane.

Note that the operation of cranes with pre-stressed beams occurs under the same conditions, operating modes, and the same lifting capacities as usual, for which the calculation in the design of the crane bridge is carried out following the established design combinations of loads - "a" (IIa, Ia) and "B" (II<sub>B</sub>, I<sub>B</sub>) [6]. The combination of loads "a" corresponds to the mode of lifting the load or its braking when lowering (with the other mechanisms turned off). In this case, the crane bridge is loaded in the plane of the suspension of the load with vertical loads [7]. Prevention of the destruction of the crane bridge and the occurrence of permanent deformations with a given probability is guaranteed if the conditions are met [8].

$$\sigma_a = \frac{(-EJ_1)y''}{W_1} \leq Rm, \quad y \leq [y] \quad (1)$$

The combination of load "B" corresponds to the mechanism of the crane's movement when the load is suspended. Thus, the crane bridge experiences an oblique bend, as it is loaded in two planes: in the plane of the suspension of the load ( $xoy$ ) by vertical loads, and from the plane of the suspension ( $xoz$ ) - by the horizontal inertial load  $Fu$ . Then the condition for preventing its destruction will have the form

$$\sigma_{II_B(I_B)} = \frac{(-EJ_1)y''_1}{W_1} + \frac{(-EJ_2)z''}{W_2} \leq Rm, \quad (y + z) \leq [y], \quad (2)$$

where  $EJ_1$ ,  $EJ_2$  - is the rigidity of the crane bridge when bending in the plane of the suspension and from the plane of the suspension of the load, respectively;  $W_1$ ,  $W_2$  - moments of inertia of the section in the same planes, respectively;  $R$  - design steel resistance;  $m$  - coefficient of working conditions;  $y$ ,  $z$  [ $y$ ] - the deflections of the span beam, in the planes  $xoy$ ,  $xoz$  and the allowable deflection, respectively.

Thus, during the operation of a pre-stressed crane bridge in conditions of oblique bending, the bridge must be provided with high strength and rigidity in two planes - in the main vertical plane  $xoy$  and the horizontal -  $xoz$ . This condition must be considered in matters related to the calculation and design of cranes with prestressed bridges. It requires additional research in relation to the real operating conditions of the crane. In this connection, the issues related to the calculation and design of such structures require special attention and study and are very relevant.

## 2 Literature Review

The analysis of the publications shows that the mathematical models of span beams were subjected to separate studies [9], numerical modeling of prestressed beams was carried out [10]. But at the same time, studies related to oblique bending of beams were carried out only for conventional crane bridges [11] exposed to transverse [12] and horizontal inertial loads [13, 14]. Such mathematical models cannot be used in our case. Since the beams are also exposed to longitudinal compressive forces, which in turn requires the development and consideration of a different mathematical model.

In addition, studies were carried out for prestressed beams on the issues of their static stiffness [15]. However, the work of the bridge superstructure was considered only in the vertical plane [16, 17].

It should be noted the works where the preformation of the bridge was determined as the difference between the deflections from the action of transverse forces and the deflection of the beam from the action of the longitudinal forces of the preliminary stress and self-tension in the tightening [18, 19]. This also cannot be considered by us, since prestressed beams refer to systems that do not obey the principle of superposition. And this approach will not always be correct and gives only approximate results.

It follows from all that there have been no publications related to the operation of a prestressed beam for load combinations “B”.

This, in turn, requires the development and consideration of a new mathematical model, where the maximum approximation of the design scheme to the real operating conditions of the crane is put forward in the first place.

The purpose of this study. Thus, the purpose of this work is to study further the stress-strain state of a pre-stressed main beam operating simultaneously in two planes. The issues considered in it are those in which the nature of the action of loads on the beam is put forward in the first place with the maximum approximation of the design scheme to the real constructive form.

To achieve this goal, it is necessary to solve the following tasks to develop a mathematical model of a pre-stressed crane bridge, taking into account the work of the main beams in the horizontal and vertical planes; investigate to analyze the results obtained.

### 3 Research Methodology

When developing the mathematical model, following the requirements put forward for the crane bridge operation, we notice that it is necessary to consider two types of bridge design diagrams: the first for the load combination “a” and the second for the load combination “B”. When compiling design diagrams, we assume that all elements of the crane are solid, the beam operates in the elastic stage, and rests on ideal hinges.

Let us introduce the notation

$$U = \cos k_1 x + \sin k_1 x \operatorname{tg}(0,5 k_1 l) - 1, \quad (3)$$

$$k_1^2 = \frac{S}{EJ_1} \quad (4)$$

Then the expression of the curve of the crane bridge deflections and bending moments in the  $xoy$  plane will be (Fig. 1)

$$y = -hU + \frac{F}{S} \left( \frac{\sin k_1 a \sin k_1 x}{k_1 \sin k_1 l} - \frac{ax}{l} \right), \quad (5)$$

$$M = -hS(U - 1) + \frac{F \sin k_1 a \sin k_1 x}{k_1 \sin k_1 l}, \text{ if } 0 \leq x \leq (l - a) \quad (6)$$

$$y = -hU + \frac{F}{S} \left( \frac{\sin k_1(l - a) \sin k_1(l - x)}{k_1 \sin k_1 l} - \frac{(l - a)(l - x)}{l} \right), \quad (7)$$

$$M = -hS(U - 1) + \frac{F \sin k(l - a) \sin k(l - x)}{k \sin kl}, \text{ if } l \geq x \geq (l - a) \quad (8)$$

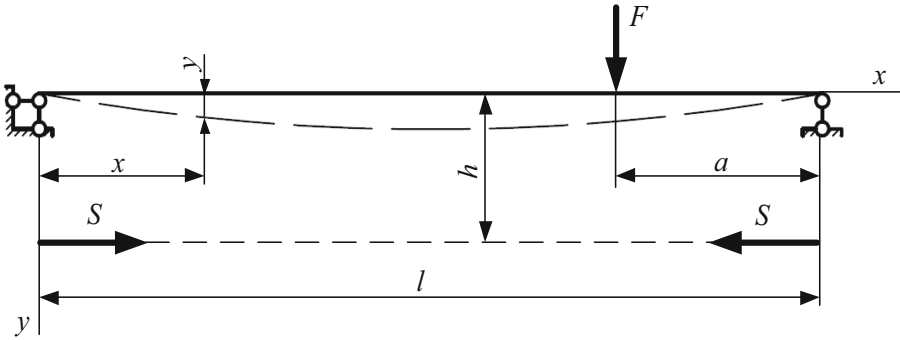


Fig. 1. Calculation scheme of the bridge for the load combination “a”.

### 4 Results

With the combination of loads “B” on the prestressed crane bridge acts (in the plane  $xoz$ ) horizontal inertial load  $F_u$  determined by the masses of the bridge  $m_m$ , cart  $m_t$ , cargo  $m$ , and acceleration  $\gamma$

$$F_u = (m_m + m_t + m) \cdot \gamma \tag{9}$$

The design diagram of the span beam, when it works in the horizontal plane, is shown in Fig. 2.

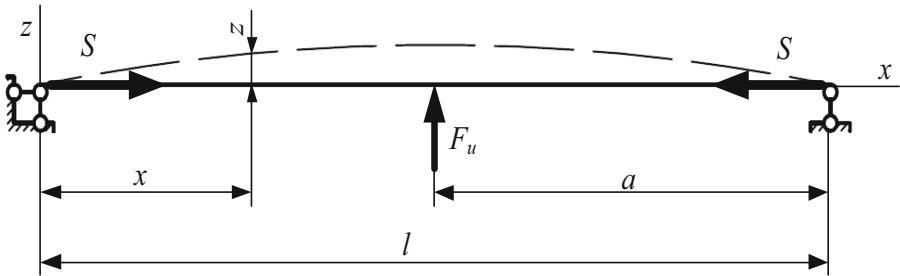


Fig. 2. Calculation scheme of the bridge for the load combination “B”.

Let's point

$$z^2 = \frac{S}{EJ_2} \tag{10}$$

Then, the differential equations of the deflection arrows for the left and right parts of the prestressed crane bridge, at  $a = 0,5l$ , will be, respectively

$$\frac{d^2z}{dx^2} + k^2z = -\frac{0,5 F_u x}{EJ_2}, \text{ if } 0 \leq x \leq (l - a) \tag{11}$$

$$\frac{d^2z}{dx^2} + k^2z = -\frac{0,5 F_u(l-x)}{EJ_2}, \text{ if } x \geq (l-a) \quad (12)$$

The total integral of this equation is

$$\begin{aligned} z &= C_1 \cos kx + C_2 \sin kx - \frac{0,5F_Hx}{S} \\ z &= C_1 \cos kx + C_2 \sin kx - \frac{0,5F_u x}{S} \\ z &= C_3 \cos kx + C_4 \sin kx - \frac{0,5F_u(l-x)}{S}, \end{aligned} \quad (13)$$

The integration constants  $C_1, C_3$  are determined from the conditions at the ends of the beam, where the deflections are zero, and  $C_2, C_4$  - at the point of force  $F_u$ , where both sections of the beam deformation curve have the same deflection and common tangent

$$C_1 = 0, \quad (14)$$

$$C_2 = \frac{F_u \sin 0,5kl}{Nk \sin kl}, \quad (15)$$

$$C_3 = \frac{F_u \sin 0,5kl}{Nk}, \quad (16)$$

$$C_4 = -\frac{F_u \sin 0,5kl}{Nk \operatorname{tg} kl} \quad (17)$$

In our case, the force  $F_u$  is applied in the middle of the beam, so the deformation curve is symmetrical. Thus, we can consider one of the two sections of the beam. After simple transformations, we obtain the corresponding expression for the beam deflection arrow

$$z = \frac{F_u}{S} \left( \frac{\sin 0,5kl \sin kx}{k \sin kl} - 0,5x \right) \quad (18)$$

We get the bending moment by differentiating the last expression twice

$$M = -EJ_2 \left( \frac{d^2z}{dx^2} \right) = \frac{F_u}{S} \left( \frac{\sin 0,5kl \sin kx}{k \sin kl} - 0,5x \right) \quad (19)$$

According to the obtained expressions, for combinations of loads “a” and “B”, mathematical research of the deformed state of the beam with the span of  $l = 10$ . Deformations of the bridge are presented in the form of beam deflections.

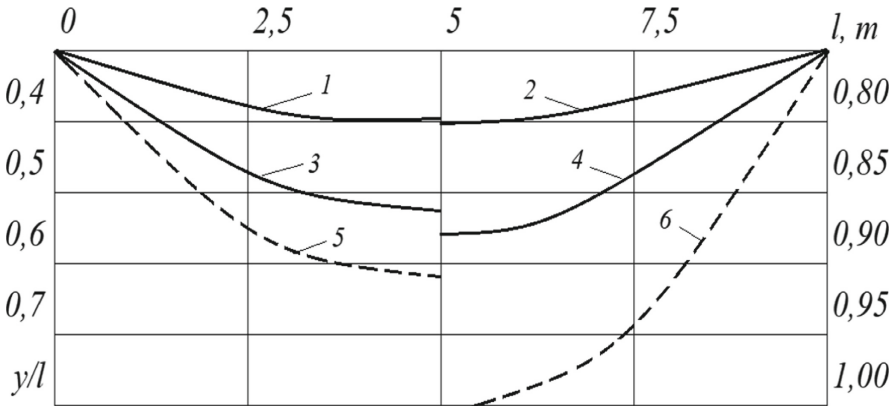
$$\frac{y/l}{[y/l]}; \quad \frac{z/l}{[y/l]}; \quad \frac{(z+y)/l}{[y/l]} \quad (20)$$

The analysis of the results obtained with the combination of loads “a” has researched that, with the ratio of forces acting on the beam  $F/1, 5$ , the use of prestressing gives a possibility to minimize the deflection of the span.

**Table 1.** Conditional deflections of the main beam.

$\frac{F_i}{S_i}$	Sectional location	Load capacity, $F_i, m$								
		$F_1 = 0,5$			$F_2 = 0,63$			$F_3 = 1,0$		
		$\frac{F_a}{S_i}$	$\frac{F_b}{S_i}$	$\frac{F_c}{S_i}$	$\frac{F_a}{S_i}$	$\frac{F_b}{S_i}$	$\frac{F_c}{S_i}$	$\frac{F_a}{S_i}$	$\frac{F_b}{S_i}$	$\frac{F_c}{S_i}$
$\frac{F_i}{0,75}$	$0,5 l$	0,49	0,5	0,69	0,64	0,66	0,92	0,97	0,81	1,26
	$l$	-0,08		-0,51	-0,08		-0,66	-0,08		-0,81
$\frac{F_i}{1,0}$	$0,5 l$	0,42	0,6	0,73	0,6	0,73	0,94	0,94	0,86	1,62
	$l$	-0,11		-0,61	-0,11		-0,74	-0,11		-0,86
$\frac{F_i}{1,25}$	$0,5 l$	0,37	0,65	0,75	0,56	0,8	0,97	0,9	0,9	1,3
	$l$	-0,16		-0,67	-0,16		-0,69	-0,16		-0,91
$\frac{F_i}{1,5}$	$0,5 l$	0,35	0,68	0,76	0,54	0,84	0,99	0,89	0,94	1,67
	$l$	-0,18		-0,7	-0,18		-0,86	-0,18		-0,95
$\frac{F_i}{1,75}$	$0,5 l$	0,29	0,74	0,79	0,46	0,92	1,03	0,8	1,0	1,3
	$l$	-0,25		-0,78	-0,25		-0,95	-0,25		-1,03
$\frac{F_i}{2,0}$	$0,5 l$	0,27	0,82	0,86	0,40	1,0	1,1	0,75	1,2	1,4
	$l$	-0,3		-0,87	-0,3		-1,04	-0,3		-1,3

The Conditional deflections of the main beam, are shown in Table 1. Deformations of the bridge in the plane  $xoy$ , is shown in Fig. 3; deformations of the bridge in the planes  $xoy, xoz$ , is shown in Fig. 4.



**Fig. 3.** Deformations of the bridge in the plane  $xoy$ .

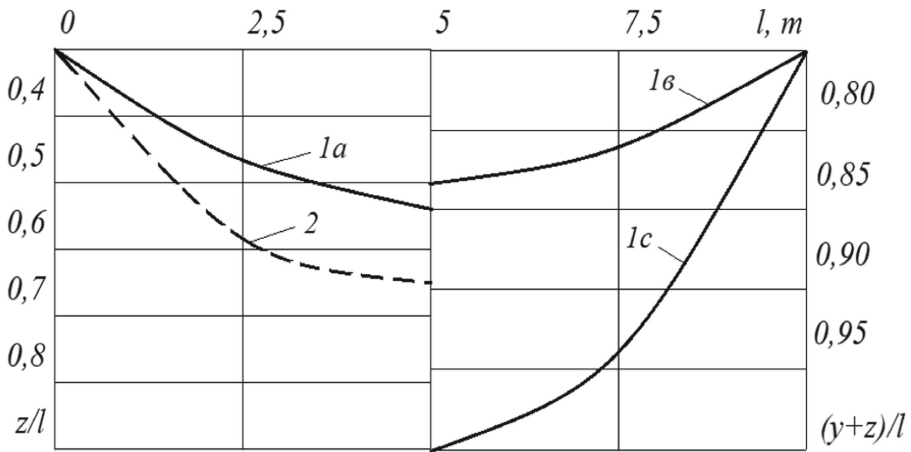


Fig. 4. Deformations of the bridge in the planes  $xoy$ ,  $xoz$ .

## 5 Conclusions

Thus, Table 1 and Fig. 3 show that when the eccentric compressive force  $S$  is applied, the beam's deflections can be reduced by 50–70%, which has a positive effect on the deformed state of the span bridge.

Besides, Table 1 and Fig. 4 show that for the combination of “B” loads, an increase in the magnitude of compressive forces leads to a significant increase in deformations in the horizontal plane. The ratio of forces  $F/1.5$  (Fig. 4) can be acceptable for the crane bridge. At the same time, note that the beam deformations at oblique bending (curves  $1b$  and  $1c$ ) exceed the limits of deflections from temporary load  $F$  of the usual bridge without unloading devices. It requires special attention when designing prestressed crane bridges.

The results obtained in this work can also be used in the future for modernization to increase their carrying capacity, increase the service life without dismantling, and improve existing structures and engineering calculation methods during design and in real operation conditions.

## References

1. Bonopera, M., Chang, K., Lee, Zheng-Kuan.: State-of-the-Art Review on Determining Prestress Losses in Prestressed Concrete Girders. *Appl. Sci.* 10, 72–57 (2020).
2. Chebrovsky, A., Savva, Y.: Review of the state of prestressed metal beams and the study results of operating crane beams when operating on a moving load. *PNU Bull. Khabarovsk* 4(31), 383–402 (2013)
3. Tkachev, A., Tkachev, A., Predrag, D., Prokopovych, I., Kostina, M.: Static stiffness of the crane bridges under moving load distribution. In: Tonkonogyi, V., Ivanov, V., Trojanowska, J., Oborskyi, G., Pavlenko, I. (eds.) *Advanced Manufacturing Processes III. LNME*, pp. 43–52. Springer, Cham (2022). [https://doi.org/10.1007/978-3-030-91327-4\\_5](https://doi.org/10.1007/978-3-030-91327-4_5)

4. Yifei, T., Lijin, L., Guomin, S., Dongbo, L., Xiangdong, L.: Overhead crane camber deformation assessment and energy analysis. *Proc. Inst. Mech. Eng. Part B* **6**, 55–52 (2014)
5. Qu, X., Xu, G., Fan, X., Bi, X.: Intelligent optimization methods for the design of an overhead traveling crane. *Chinese J. Mech. Eng.* **28**(1), 187–196 (2015)
6. Zhegulsky, V., Mironov, I., Lukashuk, O.: *Design and Calculation of Crane Metal Structures*. Ural Publishing House University, Russia (2019)
7. Menzel, U.: Krane – Einsatzerfahrungen und Entwicklungstendenzen. *Kranfachtagung* **14**, 77–86 (2006)
8. Oguamanam, D., Hansen, J.: Dynamics of a three-dimensional overhead crane system. *J. Sound Vib.* **242**(3), 411–426 (2012)
9. Lou, T.J., Lopes, S.M.R., Lopes, A.V.: Numerical modeling of externally prestressed steel 436-concrete composite beams. *J. Constr. Steel Res.* **121**, 229–236 (2016)
10. Zou, J., Huang, Y., Feng, W., Chen, Y., Huang, Y.: Experimental study on flexural behavior of concrete T-beams strengthened with externally prestressed tendons. *Math. Biosci. Eng.* **16**(6), 6962–6974 (2019)
11. Cho, K., Kim, S.T., Cho, J.R., Park, Y.H.: Estimation of tendon force distribution in prestressed concrete girders using smart strand. *Appl. Sci.* **7**, 1319 (2017). <https://doi.org/10.3390/app7121319>
12. Kim, J., Kim, J.W., Park, S.: Investigation of applicability of an embedded EM sensor to measure the tension of a PSC girder. *J. Sens.* **2019**, 2469647 (2019). <https://doi.org/10.1155/2019/2469647>
13. Jianqun, W., Shenghua, T., Zheng, H., Zhou, C., Zhu, M.: Flexural behavior of a 30-meter full-scale simply supported prestressed concrete box girder. *Appl. Sci.* **10**(9), 30–76 (2020)
14. Yao, D.L., Jia, J.Q., Yu, F.: Analysis on shear ductility of prestressed ultra-high reinforced concrete beams. *J. Harbin Eng. Univ.* **34**(5), 593–598 (2013)
15. Iodchik, A.: Deflections of a steel beam, pre-stressed by bending of the I-beam. *Bull. VSSTU* **5**(44), 45–52 (2013)
16. Iodchik, A., Kravchuk, V.: Engineering calculation of steel prestressed beam. *TOGU Gazette* **2**(29), 64–72 (2013)
17. Zhang, K.X., Sun, Q.S.: Experimental study of reinforced concrete T-beams strengthened with a composite of prestressed steel wire ropes embedded in polyurethane cement (PSWR-PUC). *Int. J. Civil Eng.* **16**(9), 1109–1123 (2018)
18. Park, H., Jeong, S., Lee, S.C., Cho, J.Y.: Flexural behavior of post-tensioned prestressed concrete girders with high-strength strands. *Eng. Struct.* **112**, 90–99 (2016). <https://doi.org/10.1016/j.engstruct.2016.01.004>
19. Garcia, J.M., Bonett, R.L., Schultz, A.E., Carrillo, J., Ledezma, C.: Flexural behavior of ungrouted post-tensioned concrete masonry beams with unbonded bars. *Constr. Build. Mater.* **203**, 210–221 (2019). <https://doi.org/10.1016/j.conbuildmat.2018.12.101>
20. Tkachov, A., Tkachov, O., Sydorenko, I.: Improvement of the deformed state of flight beams of bridge cranes. In: Bovnegra, L. (eds) *Modern Technologies and Design Art: Series of Monographs Faculty of Architecture, Civil Engineering and Applied Arts: Monograph*, vol. 37, pp. 118–125. Katowice School of Technology, Katowice (2020)