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STRESS-STRAIN STATE OF CRANE SECONDARY TRUSSES WITH HORIZONTAL BENDING

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Abstract: Crane secondary trusses perform the functions of crane and secondary structures. The lower chord of the truss is designed to resist torsion, vertical and horizontal bending forces. The aim of the study was to investigate the stress–strain state of the truss under horizontal bending conditions. The influence of geometric parameters on the horizontal flexibility and internal forces within the beam during horizontal bending was analyzed. Various techniques were employed to determine horizontal displacements, internal forces, and stresses in the beam due to the one-sided location of the crane and the braking of the crane trolley. Contributions from horizontal bending stresses to the overall stress state of the chord were demonstrated. Factors affecting the accuracy of calculations for horizontal bending were identified. The validity of the research findings was confirmed by comparing numerical calculation results with those from a field survey. The differences between the stress-strain states of the truss chord and the equivalent beam have been analyzed. It has been justified that a more accurate method for the preliminary calculation of the riding chord for horizontal bending needs to be developed. For verification calculations of the crane secondary truss, a spatial finite element shell calculation scheme should be used in specialized software systems. The stiffness of the truss chord during horizontal bending greatly exceeds that of the crane beam. When checking crane structures for deflections in the horizontal plane, deflections should be determined based on the braking forces from the trolley of a single crane acting across the path, as per the requirements of SP 20.13330.2016. When torsion occurs, the ride chord of the crane secondary truss undergoes a horizontal bending, therefore, when checking for horizontal maximum deflections, it is necessary to also take into account asymmetric vertical loads due to the one-sided arrangement of the crane.

Keywords: crane structures, crane secondary truss, stiffness of nodes, braking load, horizontal bending, torsion, malleability

НАПРЯЖЕННО-ДЕФОРМИРОВАННОЕ СОСТОЯНИЕ ПОДКРАНОВО-ПОДСТРОПИЛЬНЫХ ФЕРМ ПРИ ГОРИЗОНТАЛЬНОМ ИЗГИБЕ

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Аннотация: Подкраново-подстропильные фермы выполняют функции подкрановых и подстропильных ферм. Ездовой нижний пояс фермы предназначен для работы на кручение, вертикальный и горизонтальный изгиб. Цель работы – изучение напряженно-деформированного состояния фермы при горизонтальном изгибе. Проанализировано влияние геометрических параметров ферм на горизонтальную податливость и внутренние усилия в её ездовом поясе при горизонтальном изгибе. Различными методами определены горизонтальные перемещения, внутренние усилия и напряжения в поясе от нагрузок, вызванных односторонним расположением крана и торможением крановой тележки. Показан вклад напряжений от горизонтального изгиба в общее напряженное состояние пояса. Приведены факторы, оказывающие влияние на точность расчёта при горизонтальном изгибе. Достоверность результатов исследования подтверждается сопоставимостью результатов численного расчета с результатами натурного обследования. Проанализированы отличий напряженно-деформированного состояния пояса фермы от напряженно-деформированного состояния эквивалентной балки. Обоснована необходимость разработки более точного метода предварительного расчёта ездового пояса на горизонтальный изгиб. Для поверочного расчёта подкраново-подстропильной фермы в специализированных программных комплексах следует использовать пространственную расчётную схему из оболочечных конечных элементов. Жесткость пояса фермы при горизонтальном изгибе значительно превышает жесткость подкрановой балки. В соответствии с СП

20.13330.2016 при проверке подкрановых конструкций по деформациям в горизонтальной плоскости, прогиб следует определять от сил торможения тележки одного крана, направленных поперек пути. При кручении ездовой пояс подкраново-подстропильной фермы испытывает горизонтальный изгиб, поэтому при его проверке по горизонтальным предельным прогибам в расчёте также необходимо учитывать несимметричные вертикальные нагрузки от одностороннего расположения кран.

Ключевые слова: подкрановые конструкции, подкраново-подстропильная ферма, жесткость узлов, тормозная нагрузка, горизонтальный изгиб, кручение, податливость

INTRODUCTION

Crane secondary trusses (CST) are unique large-span structures that combine the functions of crane and secondary trusses [1]. The riding lower chord is designed not only to work on vertical bending, but also on torsion caused by the one-sided arrangement of the crane [2, 3], as well as on horizontal bending caused by braking the crane trolley [4]. The riding chord is a prismatic folded system, which was studied on the basis of the theory of thin-walled rods by V.Z. Vlasov and A.A. Umansky [5-7] by B.B. Lampsi, E.A. Beilin and others [8, 9]. The stress-strain state (SSS) of thin-walled beams of a closed profile and methods of its analysis are considered in [10-15]. According to the recommendations [16], with horizontal bending and torsion, the forces in the CST riding chord should be determined both in a single-span beam, with a span and a section corresponding to an equivalent chord. The inclusion of lattice elements in the operation of the CST for horizontal bending is not taken into account. The disadvantages of the calculation method used are noted in [17-21]. The purpose of this research are to identify the differences between the SSS of the truss chord and the SSS of an equivalent beam, to analyze the contribution of stresses from horizontal bending to the overall stress state of the chord and to consider factors affecting the accuracy of calculating the horizontal bending rate. To achieve the set goals, the following tasks were solved:

1) Study of the influence of the geometric parameters of the CST on the horizontal compliance and internal forces in its lower riding chord under horizontal load;
2) Determination by various methods of internal forces and stresses in the CST chord from an asymmetric vertical load caused by the one-sided position of the crane and a horizontal load caused by the braking of the crane. Analysis of the results obtained;
3) Determination of the maximum horizontal movements of the riding chord when the crane is positioned one-way and the trolley is braking. Calculation of the CST for the second group of limit states for horizontal limit deflections in accordance with SP 16.13330.2017 and SP 20.13330.2016.

METHODS

The first stage of the research is to analyze the influence of the geometric parameters of CST on the horizontal compliance and internal forces within its lower riding chord during horizontal bending. Four types of CST with different geometric characteristics are considered:

- Three-panel CST No. 1 with a span of 36 meters and a height of 6.5 meters;
- Three-panel CST No. 2 with a span of 36 meters and a height of 15.44 meters;
- Four-panel CST No. 3 with a span of 48 meters and a height of 13 meters;
- A three-panel experimental model CST No. 4 with a span of 9 meters and a height of 3.3 meters [17].

The change in the stiffness ratio of the lower chord and the entire CST, as well as the ratio of the height of the prefab to its span, is considered [22].

To obtain statistical data in order to assess the impact of the geometric characteristics of the CST on the horizontal flexibility of the chord, we constructed 52 flat computational schemes. To analyze the influence of the height-to-span ratio of the CST, we sequentially changed the height of each of the four CST's in six stages, so that the ratio of CST height to span length was consistently reduced from 0.5 to 0.1. To analyze the effect of stiffness ratio for each CST, we also sequentially changed the stiffness of lattice elements in six stages. In each case, we determined bending moment in horizontal plane, torque, malleability of junction between lattice and lower chord, and stiffness of lattice [23] using formula (1):

$$\mathrm{C} = \frac{1}{\delta_{CST}} - \frac{1}{\delta_b} \left[\frac{kN}{m}\right]; \tag{1}$$

where $\delta_{CST} -$ liability of the CST, determined by the formula:

$$\delta_{CST} = \frac{f_{CST}}{F} \left[\frac{m}{kN}\right]; \tag{2}$$

where $f_{CST} -$ deflection of the CST at the point where force F is applied.

$\delta_b -$ compliance of an equivalent beam with a section corresponding to the CST driving chord, determined by the formula:

$$\delta_b = \frac{f_b}{F} \left[\frac{m}{kN}\right]; \tag{3}$$

where $f_b -$ deflection of an equivalent beam at the point of application of force F.

The decrease in maximum displacements in the driving chord of the CTS relative to the equivalent beam is determined by the formula:

$$\Delta\delta = \left(1 - \frac{\delta_{CST}}{\delta_b}\right) \cdot 100\ [\%]; \tag{4}$$

The decrease in the ratio of span and height of the CST is determined by the formula:

$$\Delta\frac{h}{l} = \left(1 - \frac{h}{l}\right) \cdot 100\ [\%]; \tag{5}$$

where $h -$ height of CST, m;

$l -$ CST span, m.

The relative increase in lattice stiffness is determined by the formula:

$$\Delta C = \left(1 - \frac{\mathrm{C}_1}{\mathrm{C}_i}\right) \cdot 100\ [\%]; \tag{6}$$

where $\mathrm{C}_1 -$ lattice stiffness of the first (highest) CST from a number of studied;

$\mathrm{C}_i -$ stiffness of the elastic supports of the investigated CST.

The ratio of the stiffness of the lattice and the riding chord from the CST plane is defined as the ratio of the shear stiffness of the lattice section to the bending stiffness of the section of the riding chord. A concentrated force F = 100 *kN* is applied to the node in question from the CST plane.

The second stage of the study is to determine displacements, internal forces and stresses caused by the unilateral location of the crane and braking of the crane trolley. The object of research is CST No. 3, with an uncut lower chord. The calculation is performed using the following calculation schemes (CS):

- CS No. 1 – equivalent beam according to the recommendations [16];
- CS No. 2 – single-span flat rod CST considering misalignment of nodes [24] and rigid connections at supports [25];
- CS No. 3 – single-span CST flat rod considering alignment of nodes and supports;
- CS No. 4 – continuous flat CST core;
- CS No. 5 – uncut spatial CST using shell finite elements (Fig. 1).

Loading was carried out by a single crane with a lifting capacity of 450 tons. The weight of the cargo is 396 tons. Two of the most dangerous positions of the crane are considered [26, 27] – in the middle of the span and on the support. The value of the horizontal load from braking of the trolley is determined by [28] in accordance with SP 20.13330.2016. For CS No. 1-4, equivalent stresses were calculated analytically according to SP 16.13330.2017, the geometric characteristics of the section of the riding chord were determined by [28].

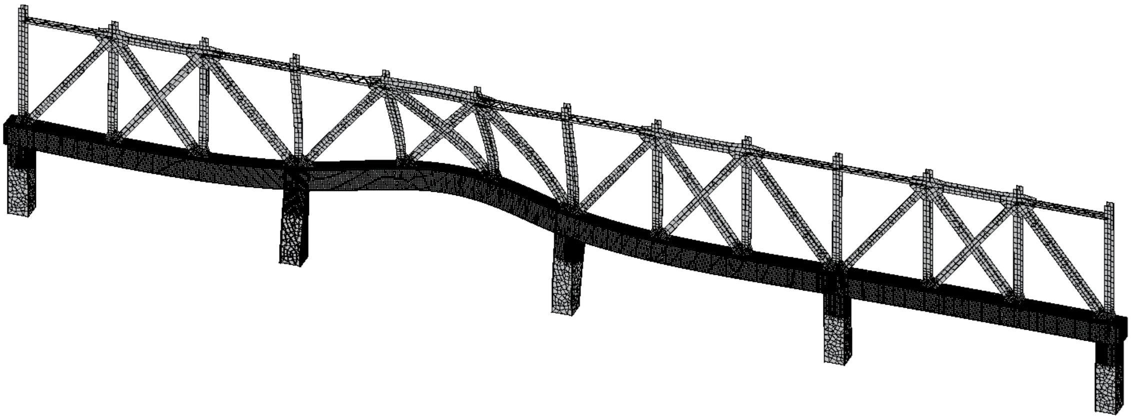


Figure 1. Deformations of CS No. 5 under horizontal load from crane braking in the middle of the span

The horizontal movements of the CST driving chord were calculated and the calculation was performed for the second group of limit states in accordance with SP 16.13330.2017 and SP 20.13330.2016.

In accordance with the appendix. D SP 20.13330.2016 horizontal maximum deflection of crane track beams for a group of crane operating modes 7K-8K:

$$f_u = \frac{l}{2000}; \tag{7}$$

where l – calculated span of the structural element.

The deflection is determined from the braking forces of the trolley of one crane directed across the track, at the mark of the head of the crane rails.

RESULTS AND DISCUSSION

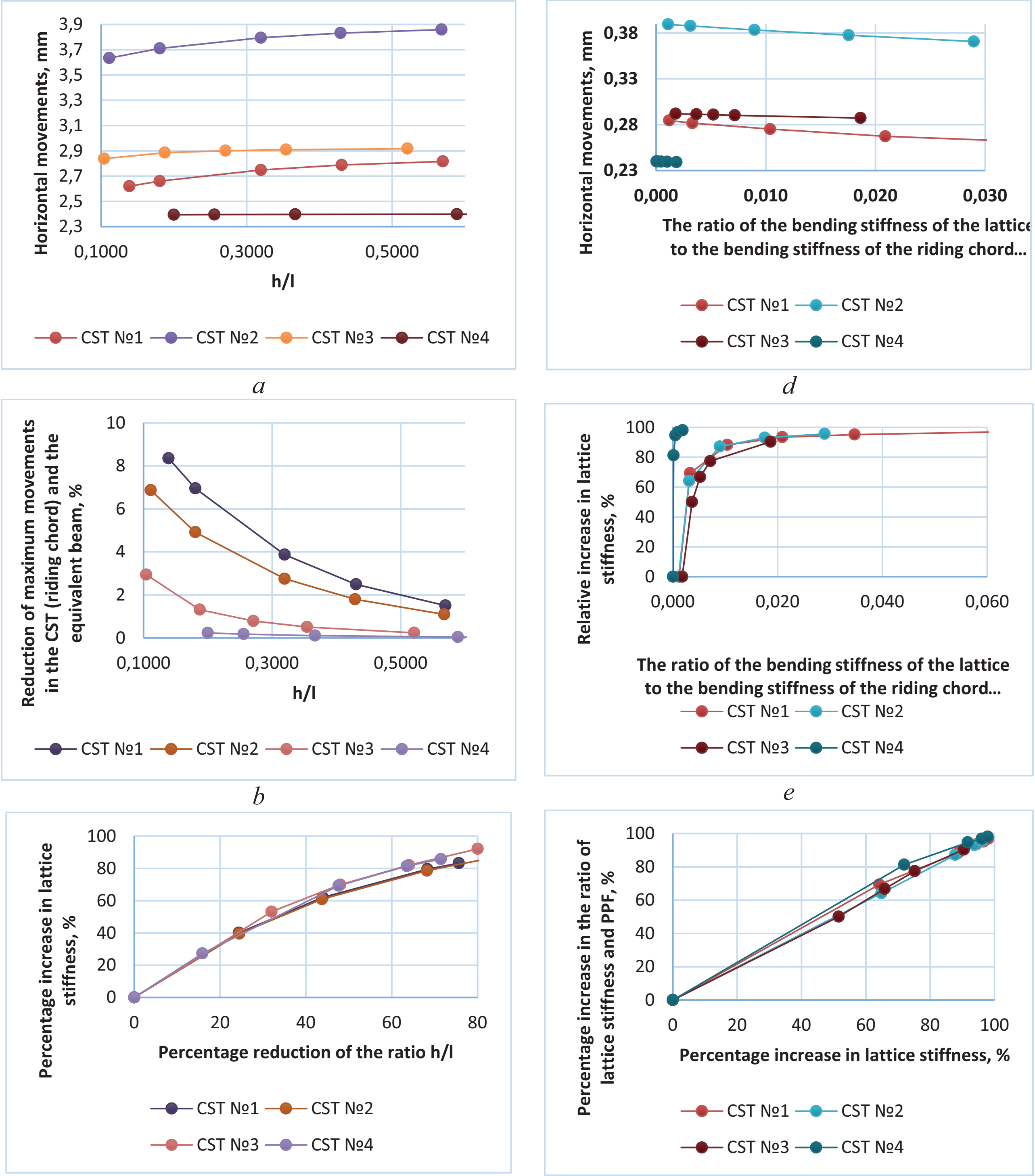
The results of the study of the influence of the geometric parameters of the CST on the horizontal compliance and internal forces in its lower riding chord are shown in Fig. 2 and 3.

When changing the ratio of height and span of the CST, the ratio of horizontal movements in the riding chord and the equivalent beam does not exceed 8.5%. When the stiffness ratio changes, the ratio of horizontal movements in the riding chord and the equivalent beam does not exceed 12.7%.

With an increase in the height and span ratio of the CST, horizontal compliance increases and the rigidity of the lattice decreases from the CST plane. The ratio of maximum movement in the CST riding chord and equivalent beam also decreases. When the stiffness of the grating and CST driving chord increase, the horizontal compliance decreases and the stiffness of the grating increases from the CST plane in a linearly proportional manner.

The graphs of percentage increase in lattice stiffness for all CSTs coincide when considering the dependence on percentage ratio of height, span, and stiffness. This confirms the reliability of the numerical experiment results.

Considering the calculation of the lower beam for horizontal bending of lattice elements leads to a reduction in the bending moment from the CST plane. When designing the core of the entire CST structure, the bending moments in the horizontal plane are at most 11% less than when calculated according to the equivalent girder beam design scheme. At the same time, using the beam design scheme does not allow us to obtain the torque values that occur in the drive chord during horizontal bending. As the ratio of CST height and span increases, the bending moment from the CST plane decreases. As the stiffness ratio of the grating and drive chord of the CST increases, so do the torque and bending moments from the CST plane.



a

d

b

e

c

f

Figure 2. Effect of geometric parameters of CST on horizontal compliance of riding chord: a) effect of ratio of height and span on horizontal compliance; b) reduction in maximum horizontal movement in CST riding chord compared to equivalent beam; c) effect of ratio of height and span on rigidity of lattice; d) effect of stiffness of CST elements on horizontal pliability; e) effect of CST element stiffness on lattice stiffness; f) effect of CST element stiffness on lattice stiffness

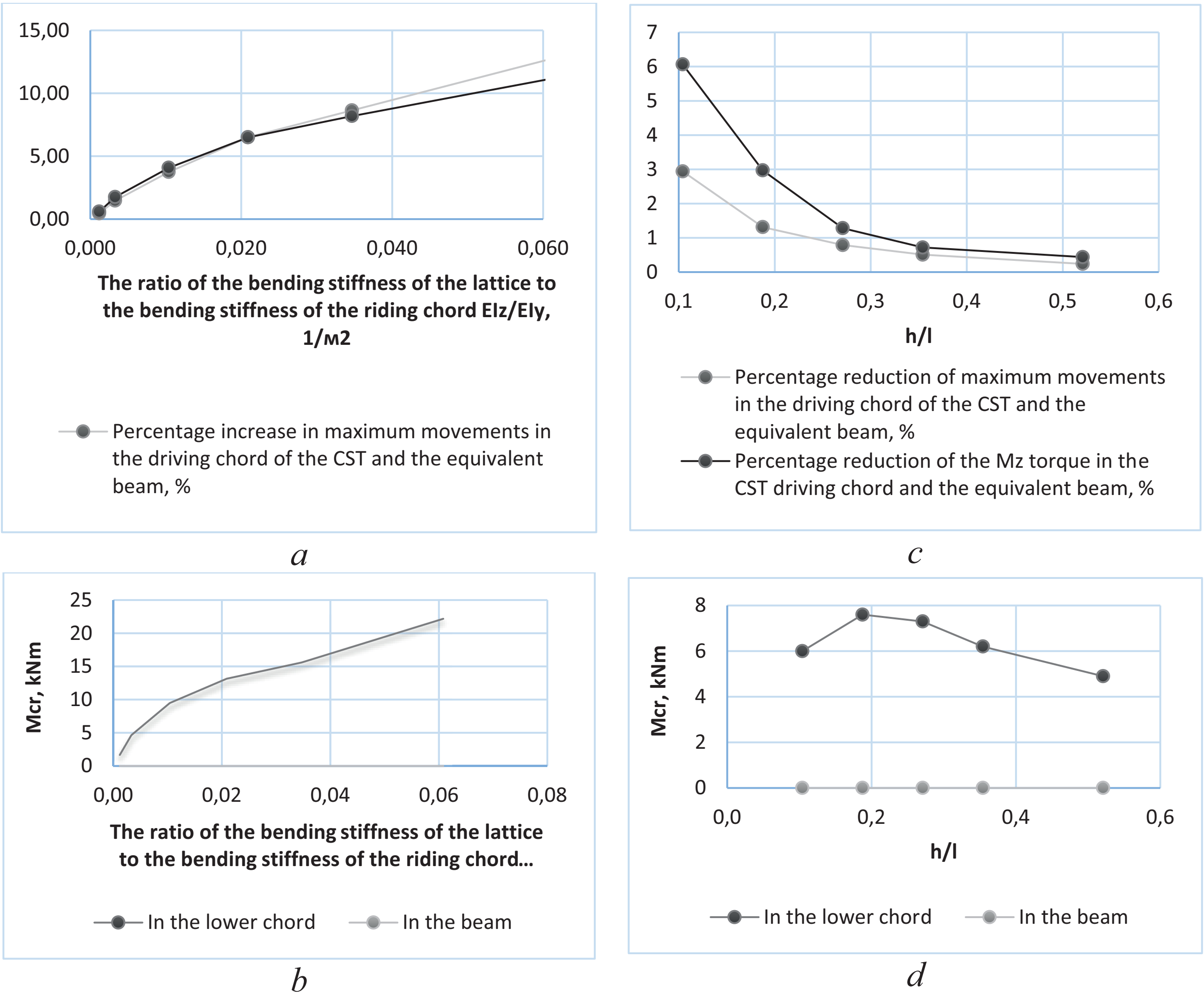


Figure 3. Effect of geometric parameters of CST on internal forces and movements of riding chord: a) effect of stiffness ratio on horizontal movement and horizontal plane moment of CST No. 1 riding chord; b) effect of stiffness ratio on torque of CST No. 1; c) effect of height and span ratio on horizontal movement and horizontal plane moment for CST No. 2; d) effect of height and span ratio on torque for CST No.2

The operation of the riding chord under a horizontal load caused by crane braking is more challenging than under an asymmetric vertical load resulting from a one-sided arrangement of the crane [29, 30]. With an asymmetric vertical load, the operating scheme of the CST can be divided into vertical bending and twisting of the riding chord, along with bending and twisting of lattice elements. Under a horizontal load, bending of the chord away from the CST plane occurs along with its twisting, and twisting is accompanied by horizontal bending. Simultaneously, both linear and angular displacements have opposing signs when dividing the effect into components, reducing the bending moment of the chord relative to the plane of the CST compared to the bending moment in the horizontal plane of an equivalent beam.

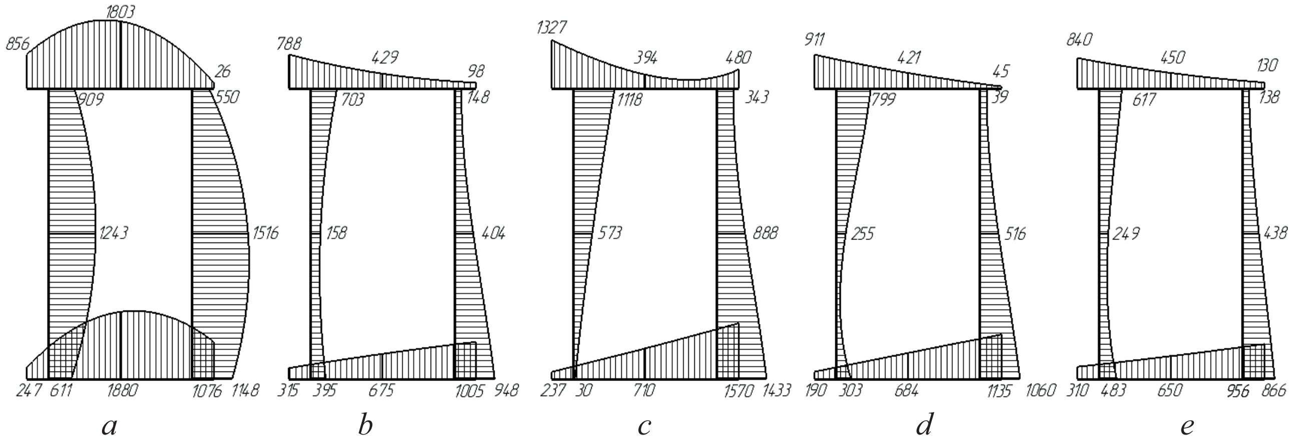
The results of the analysis of displacements, internal forces, and stresses caused by an asymmetric vertical load due to the one-sided positioning of the crane, as well as a horizontal load resulting from the braking of the crane, are presented in Table 1 and Fig. 4 and 5.

Due to braking with a one-way crane, the maximum torque in the driving chord increased by

16%, the bending moment from the CST plane increased by 39%, the transverse force increased by 35%, and the maximum horizontal movement increased by 43%. The maximum horizontal movement determined by CS No. 1, according to the recommendations [16], is more than three times higher than the movement determined by spatial CS No. 5. The maximum horizontal movements determined by the flat rod CS No. 1-4 are at least 1.6 times higher than the movement determined by the spatial CS No. 5 of the shell elements. The forces and stresses determined by CS No. 1 for the beam differ significantly from the results of numerical calculations for the riding chord as part of CST.

Table 1. Forces and movements of the CST driving chord

No. CS	Horiz. mov., mm	N_{max} in the outermost panels, t	N in the middle panel, t	$N_{k,max}$ in the outermost panels, tm	M_k in the middle panel, tm	$M_{y,max}$ in the middle panel, tm	$M_{z,max}$ in the middle panel, tm	$Q_{y,max}$ in the outermost panels, t	$Q_{z,max}$ in the middle panel, t
The load from the crane on one side and the braking									
1	26,8	0	0	-1563	-768	8198,0	344,3	26,3	-315,1
2	13,2	29,2	-55,5	420,9	7,53	1048,9	286,3	51,2	-311
3	58,3	43,0	-82,5	371,4	8,39	901,0	744,6	50,0	-311
4	14,9	314,6	207,8*	400,9	14,88	1047,4*	391,9	54,1	-309
5	8,5	-	-	-	-	-	-	-	-
Crane load on one side without braking									
4	14,3	314,6	207,8	333,3	12,44	1047,4	238,3	34,9	-309
Breaking load									
1	26,8	-	-	-	-	-	344,3	26,3	-
2	5,3	-	-	24,1	-	-	111,9	24,2	-
3	19,9	-	-	40,6	-	-	253,1	22,0	-
4	5,7	-	-	41,1	-	-	153,6	24,7	-
5	3,5	-	-	-	-	-	-	-	-
Note: forces with * were used to plot the stresses of CS No. 1-4									



a b c d e

Figure 4. Diagrams of equivalent stresses [kgf/cm²] of the driving chord in the middle of the span, obtained by analytical calculation: a – according to CS No. 1; b – according to CS No. 2; c – according to CS No. 3; d – according to CS No. 4; numerical calculation; d – according to CS No. 5. The load from the crane on one side and the braking of the trolley

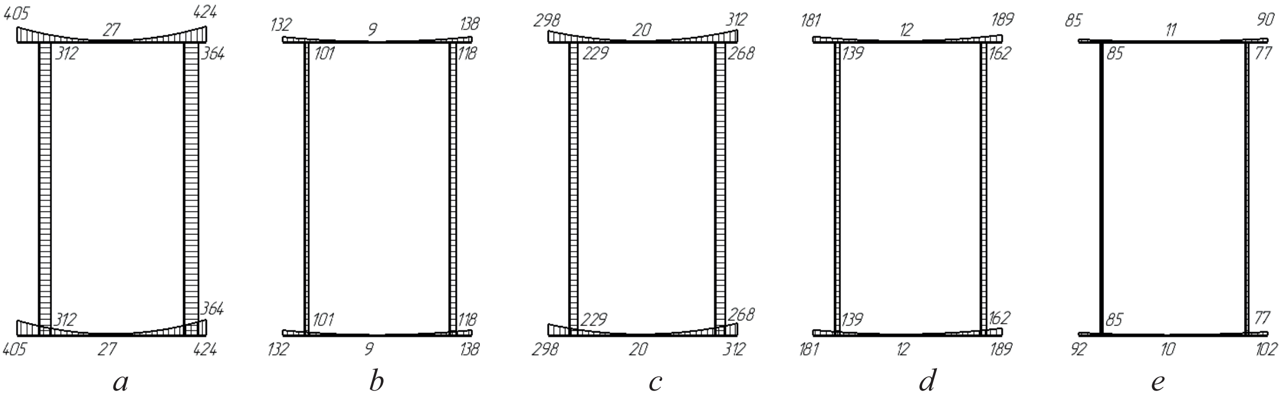


Figure 5. Diagrams of equivalent stresses [kgf/cm^2] of the driving chord in the middle of the span, obtained by analytical calculation: a – according to CS No. 1; b – according to CS No. 2; c – according to CS No. 3; d – according to CS No. 4; numerical calculation; d – according to CS No. 5. Braking load of the crane trolley

From a one-way crane load with braking, the torque according to CS No. 1 was four times higher than according to CS No. 2, and the bending moment from the CST plane was almost eight times higher. When braking without considering the vertical load from the crane, the bending moment on the CST plane, according to CS No. 1, is three times greater than according to CS No. 2. When switching from rigid connections on the supports, according to CS No. 2, to articulated ones, according to CS No. 3, under braking loads, the maximum torque increases by a factor of 1.7, the bending moment in the horizontal plane increases by a factor of 2.3, and the horizontal movement increases almost fourfold.

In the split CST according to CS No. 2, relatively uncut according to CS No. 4, under braking load, the torque is 1.7 times lower, the bending moment in the horizontal plane is 1.4 times lower. At the same time, the first typical single-span CSTs have a minimum zero survivability [31, 32]. Later CSTs [33, 34], to ensure the smoothness of the axis of the riding chord during deformations and increase its rigidity, are made continuous [35].

Due to braking with a one-way crane, the maximum torque in the driving chord increased by 16%, the bending moment from the CST plane increased by 39%, the transverse force increased by 35%, and the maximum horizontal movement increased by 43%. The maximum horizontal movement determined by CS No. 1, according to the recommendations [16], is more than three times higher than the movement determined by spatial CS No. 5. The maximum horizontal movements determined by the flat rod CS No. 1-4 are at least 1.6 times higher than the movement determined by the spatial CS No. 5 of the shell elements. The forces and stresses determined by CS No. 1 for the beam differ significantly from the results of numerical calculations for the riding chord as part of CST.

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The deflection from the braking forces of the trolley of one crane, directed across the path, is 3.5 mm (Table 1). Checking for the second group of limit states along the horizontal limit deflection is performed with a large margin:

$$f_b = 3{,}5\,mm < f_u = \frac{36000}{2000} = 18\,mm.$$

For an equivalent beam at a given load, the maximum horizontal displacement is 26.8 mm (Table 1), the rigidity condition is not met. The stiffness of the CST chord for horizontal bending is 7.7 times higher than the stiffness of the beam.

Since the CST riding chord undergoes horizontal bending during torsion [30], the horizontal deflection limit should include a component of horizontal displacement caused by an asymmetric vertical load due to the one-sided location of the crane. The maximum horizontal displacement resulting from the combined effects of the loads caused by the single-sided position of the crane and the braking of the crane trolley is 8.5 mm (Table 1). The contribution to the overall horizontal movement from the asymmetric vertical load component is 1.4 times greater than that from braking, and should not be ignored when checking for stiffness.

$$f_{b+c} = 8{,}5\,mm < f_u = \frac{36000}{2000} = 18\,mm.$$

The check is in progress. Taking into account the component of the asymmetric vertical load, the stiffness of the chord is more than 3 times higher than the stiffness of the equivalent beam.

As part of the author's supervision, specialists from TSNIIproektstalkonstruction and Chelyabproektstalkonstruction carried out an inspection of the converter shop of the Magnitogorsk Metallurgical Combine [36-39], commissioned in 1990, which uses longitudinal CSTs. A series of full-scale tests was carried out with the measurement of SSS in the most frequently damaged nodes of CST No. 3 using the strain gauge method. In [29, 30], the results of numerical calculation of CS No. 5 are compared with the results of a field survey. They have a relatively small discrepancy, presumably caused by the influence of welding stresses and the accumulation of crack-like defects in the near-seam zones [40, 41].

CONCLUSIONS

1. The CS of the beam [16] does not display the operation of the CST riding chord for horizontal bending. The horizontal displacements determined by the CS of the beam greatly exceed the displacements determined by the spatial CS of the shell finite elements. The forces and stresses determined by the CS of the beam differ significantly from the results of numerical calculations of the riding chord as part of the CST. The use of a CS beam does not allow to obtain the values of the torque that occurs in the driving chord during horizontal bending. It is necessary to develop a more accurate method of preliminary calculation of the CST driving chord for horizontal bending.
2. With horizontal bending of the riding chord caused by braking of the crane trolley, flat rod CS give a significant error in determining displacements and stresses (analytically calculated from internal forces) relative to the spatial CS. For the verification calculation of the CST, it is recommended to use spatial CS from shell finite elements. The entire frame or part of the structure should be included in the CS [42].
3. Verification of the second group of limit states is carried out in accordance with SP 20.13330.2016, which does not distinguish CST from other crane structures. It is recommended to determine the deflection from the braking forces of the trolley of one crane directed across the path. During torsion, the CST riding chord experiences horizontal bending, the contribution to the total horizontal movement of the component from the asymmetric vertical load caused by the one-sided

arrangement of the crane may exceed the contribution from the horizontal load caused by the braking of the trolley. When checking the CST for the second group of limit states for horizontal limit deflections, it is necessary to take into account not only the horizontal forces from braking the crane trolley, but also the asymmetric vertical loads from its one-sided location. The rigidity of the CST riding chord for horizontal bending significantly exceeds the rigidity of the crane beam.

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