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RESEARCH OF METHODS FOR DETERMINING DYNAMIC STRESS OF THE BARS IN THE MAIN STRUCTURE OF GANTRY CRANE INSTALLED ON THE CAP OF BRIDGE PIER TO SERVE INSTALLATION OF SUPER-T GIRDER

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Abstract

The article presents briefly findings in researching methods for determining dynamic stress of the bars in the main structure of gantry crane installed on the cap of bridge pier to install and launch SUPER-T girder. In order to study the dynamic stresses in the bars of the main truss structure of the gantry, the author first had to build a dynamic model, using Matlap software to solve the problem of dynamics with two cases cargo lowering combination combines braking and moving of gantry with cargo to find out the rules and values of dynamic cable tension, dynamic inertial force (time-varying force), then consider these forces is the external force acting on the main truss structure model of the gantry, from which the author calculates the value of internal force and stress of each bar corresponding to the value of dynamic cable tension and corresponding dynamic inertia force. with two adverse working cases of the gantry. Using Matlap software to calculate the author has obtained a graph of internal force, stress changes over time of each bar in the main truss steel structure of the gantry. The findings of the research provided methods for determining the dynamic stress of the bars in the main structure of gantry crane, pointed out values and rules of change of the dynamic stress of the bars in the main structure of gantry crane. The findings of the research may be used to calculate fatigue, life-span of the main steel structures as well as other parts of the gantry crane.

Keywords: dynamic stress, gantry crane, stress of steel structures, dynamic stress of the bars, dynamic cable tension.

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1. Introduction

The gantry crane installed on the cap of bridge pier to serve installation of Super-T girder is one of the specialized construction unit in the Bridge construction industry, the gantry crane is used to assemble the girder into the supporting positions on the cap. This gantry crane is featured by the fact that it carries a load (Super-T girder, weight 80 tons) and length is great and the braking process occurs continuously. In the process of calculating the steel structure design, let's usually make calculations using the static stress method. In practice, the structure is sometimes not destroyed by static stress but is destroyed by dynamic stress (stress appearing instantaneously), because stress values in bars will change continuously depending on the variation of dynamic cable tension value impact to main structure of gantry crane. Therefore, it is necessary to study the laws of variation as well as the dynamic stress values in bars of the steel structure. The findings of the research will be a premise for the research on fatigue strength problems for steel structures.

To determine the dynamic stress, the author first solves the dynamics problem from which to determine the value of the dynamic cable tension (the force changes with time and it is considered as the external force acting on the main structure), then proceeds to calculate the value of internal force and stress of each bar according to the dynamic cable tension. Currently, there have been many research works on the dynamics of gantry cranes, the researches on the stress in structures of the gantry crane have also been done, but no author has mentioned the problem of studying the dynamics and dynamic stress for specialized gantry cranes, used for the installation of super-T girder in the construction of assembled concrete bridges. Therefore, this issue has been studied by the author and will be introduced in the next section.

2. Materials and Methods

2. 1. Research object

The research object is a gantry crane serving the installation of Super-T girder with the overall structure shown in **Fig. 1**:

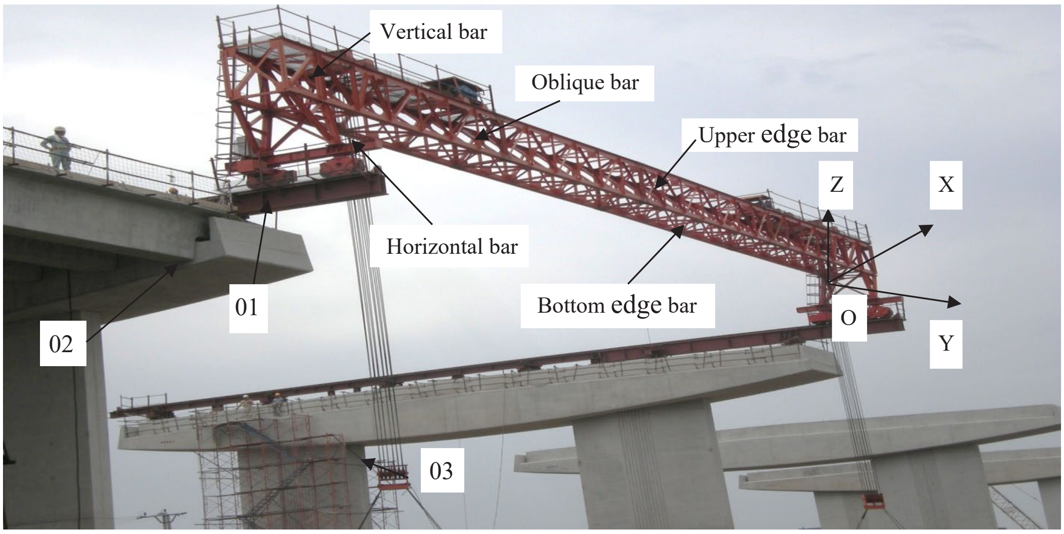

Fig. 1. Overall gantry crane installed on the cap

The working principle of a gantry crane is as follows: the gantry crane moves out of the console of the rail support girder (01) mounted on the bent cap (02) of pier columns, then lowers the two hooks of the electric winch (03) to lift the concrete bridge girders (Super-T girder, length 38 meter, weight 80 tons) from the vehicle carrying bridge girders on the ground, then gantry crane moves to inside the pier caps and lower the Super-T girder to the supporting in the bearing positions on each bridge pier. After installing all Super-T girder of a span, a crane is used to lift the entire gantry crane system to the ground and then move the whole device to another span to continue installing the girder of next span.

2. 2. Determination of dynamic cable tension (F_c) acting on the main truss steel structure of gantry crane

To determine the dynamic cable tension (F_c), it is possible to solve the dynamics problem for the gantry crane in case of danger (lower the goods in combination with braking). Many dynamic models have been mentioned by different authors [1–8]. However, the gantry crane researched by the author is a specialized type, so the dynamics model and equations of motion have been studied and presented by the author in the next section.

2. 2. 1. Building a dynamics model of the gantry crane when lowering goods in combination with braking

The dynamics model is shown in **Fig. 2**. Of which, XOY – the absolute coordinate system; θ_1, θ_4 – the referred moment of inertia of the coupling and lifting mechanism motor rotor, kgm^2; m_3 – the referred mass of the gantry crane, kg; m_2 – the referred mass of the lifted cargo (Super-T girder), kg; q_1, q_4 – angular displacement of lifting mechanism motor, rad; q_2 – displacement of mass m_2, m; q_3 – displacement of mass m_3, m; q_d – angular displacement of cable reel, rad; S_1 – converted stiffness of a lifting rope branch, N/m; S_2 – converted stiffness of the gantry crane system, N/m; K_1 – vibration quenching coefficient of cargo cable in hoist assembly Ns/m; $M(q_1)$, $M(q_4)$ – torque of lifting mechanism motor, Nm; M_f – braking torque, Nm.

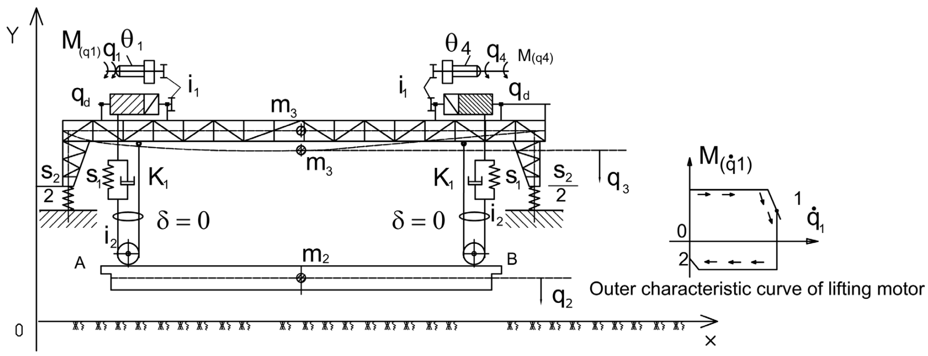

Fig. 2. Dynamics model of the gantry crane installed on the cap of bridge pier when lowering the Super-T girder combined with the brake

From the dynamics model shown in **Fig. 2**, it is possible to produce the equations of motion as follows:

$$\begin{cases} \theta_1\ddot{q}_1 - i_2^2K_1\left(-R^2\dot{q}_1 + R\dot{q}_2 - R\dot{q}_3\right) - i_2^2S_1\left(-R^2q_1 + Rq_2 - Rq_3\right) = M_f + \dfrac{m_2gR}{2}; \\ m_2\ddot{q}_2 + i_2^2K_1\left(-R\dot{q}_1 + 2\dot{q}_2 - 2\dot{q}_3 - R\dot{q}_4\right) + i_2^2S_1\left(-Rq_1 + 2q_2 - 2q_3 - Rq_4\right) = 0; \\ m_3\ddot{q}_3 - i_2^2K_1\left(-R\dot{q}_1 + 2\dot{q}_2 - 2\dot{q}_3 - R\dot{q}_4\right) + m_3g - i_2^2S_1\left(-Rq_1 - Rq_4 + q_2 - \left(2 + \dfrac{S_2 + S_3}{i_2^2S_1}\right)q_3\right) = 0; \\ \theta_4\ddot{q}_4 - i_2^2K_1\left(-R^2\dot{q}_4 + R\dot{q}_2 - R\dot{q}_3\right) - i_2^2S_1\left(-R^2q_4 + Rq_2 - Rq_3\right) = M_f + \dfrac{m_2gR}{2}. \end{cases} \quad (1)$$

Dynamic cable tension in a cable branch.
Left side:

$$F_{ct} = \frac{m_2g}{i_2} + i_2K_1(R\dot{q}_1 - \dot{q}_2 + \dot{q}_3) + i_2S_1(Rq_1 - q_2 + q_3). \quad (2)$$

Right side:

$$F_{cp} = \frac{m_2g}{2i_2} + i_2K_1(R\dot{q}_4 - \dot{q}_2 + \dot{q}_3) + i_2S_1(Rq_4 - q_2 + q_3).$$

2. 2. 2. Solving the system of equations of motion

The input parameters to solve the equations of motion (1), (2) corresponding to the specifications of the studied gantry crane are as follows: $m_2 = 25242$ (kg); $m_3 = 80.000$ (kg); $g = 9.8$ (m/s^2); $i_2 = 12$; $K_1 = 1200$ (Ns/m); $S_1 = 375000$ (N/m); $S_2 = 18120000$ (N/m) $S_3 = 75172857$ (N/m); $R = 0.00018$ (m), $\theta_1 = \theta_4 = 0.595$ (kgm^2); $M_f = 86.4$ (Nm).

Torque of lifting mechanism motor is calculation as:

$$M(\dot{q}_1) = M(\dot{q}_4) = 2592 - 25.8\dot{q}_1. \quad (3)$$

The results obtained are the dynamic cable tension (F_c) and acceleration $\ddot{q}_3$ as shown in **Fig. 3, 4**.

From **Fig. 3, 4** that when lowering the Super-T girder at a steady speed, the cable tension and oscillation of the steel structure are always in a sTable state, but when braking suddenly, both the cable tension and the amplitude of oscillations increase suddenly ($F_{cd} = 1.4F_c$). These changes happen in very short time of about five to ten seconds.

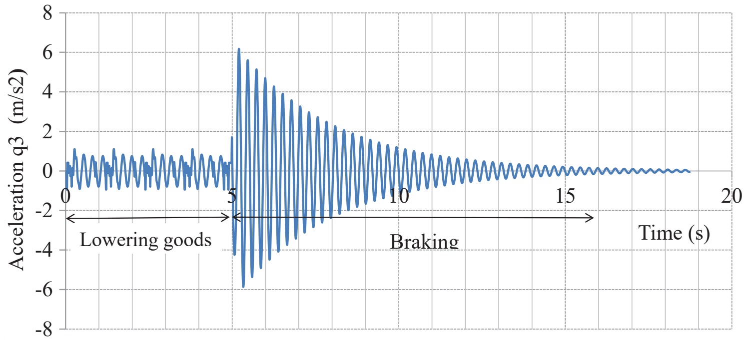

Fig. 3. Acceleration $\ddot{q}_3$

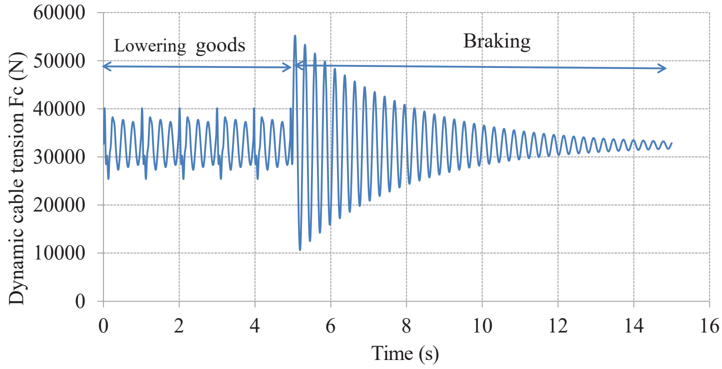

Fig. 4. Dynamic cable tension (F_c) for left side

2. 3. Determination of dynamic stress in bars of the main steel structure of gantry crane

Many authors have made researches on the stress in steel structures of gantry crane [9–13], but there are few works that have mentioned the problem of dynamic stress in bars of the main steel structure. To solve this problem, the author has built a calculation method according to the following steps.

2. 3. 1. Building a calculation diagram

Since the truss structure has a symmetrical shape, the author only considers the left half of the structure (from node 1 to node 14), the internal forces in right bars (from node 14 to node 28) will have the same value as the left side. The calculation diagram is shown as **Fig. 5, 6**:

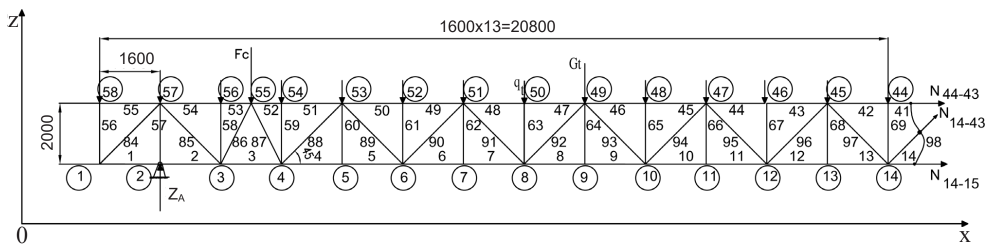

Fig. 5. Diagram of truss calculation in 1/2 of the *ZOX* plane

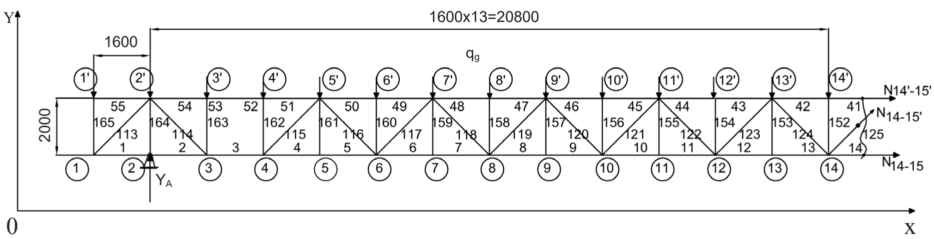

Fig. 6. Diagram of truss calculation in 1/2 of the *YOX* plane

2. 3. 2. Applied load

In the *ZOX* plane, loads acting on the truss vertically (in the *ZOX* plane) include: F_c – dynamic cable tension acting at node 55 (position of the pulley assembly of lifting and lowering winches); q_t – weight of the truss distributed at nodes; Z_A: the reaction force at the support position of the main truss on the left.

In the *YOX* plane, loads acting on the truss horizontally (in the *YOX* plane) include: q – total value of the inertia force and the wind resistance distributed at the nodes of the truss when the gantry crane is carrying cargo and moving; Y_A: reaction force at the support of the main truss on the left.

Force of inertia:

$$\vec{F} = m\vec{a}, \tag{4}$$

of which m – total mass of truss structure and lifting girder $m = m_3 + m_2$, (kg); a – horizontal oscillating acceleration as the gantry crane moves together with cargo and it will changes over time depending on the speed of gantry crane travelling.

The total force acting on each truss node will be:

$$q = q_{qt} + q_g = (3758.a + 420). \tag{5}$$

3. Results and discussion

3. 1. Determination of internal force in bars

In the *ZOX* plane, considering the most disadvantageous case of the structure (for bars in the *ZOX* plane) which is when the cargo is moving downwards and sudden braking is performed. The value of internal force in each bar of the main truss depends on the dynamic cable tension (F_c) as shown in **Table 1**:

Table 1
Internal force values of main truss bars in the *ZOX* plane depending on the value of dynamic cable tension F_c

No.	Bar No.	Element symbol	Internal force value (*N*)	No.	Bar No.	Element symbol	Internal force value (*N*)
1	2	3	4	5	6	7	8
Upper and Bottom edge bars							
1	N_{1-2}	1	7074	8	N_{8-9}	8	508981+1.2F_c
2	N_{2-3}	2	7074	9	N_{9-10}	9	508981+1.2F_c
3	N_{3-4}	3	131809+1.2F_c	10	N_{10-11}	10	579744+1.2F_c
4	N_{4-5}	4	276738+1.2F_c	11	N_{11-12}	11	572668+1.2F_c
5	N_{5-6}	5	256539+1.2F_c	12	N_{12-13}	12	608056+1.2F_c
6	N_{6-7}	6	296909+1.2F_c	13	N_{13-14}	13	623970+1.2F_c
7	N_{7-8}	7	296909+1.2F_c	14	N_{14-15}	14	640259+1.2F_c
41	N_{44-43}	41	–(615138+1.2F_c)	49	N_{52-51}	49	–(213600+1.2F_c)
42	N_{45-44}	42	–(615138+1.2F_c)	50	N_{53-52}	50	–(155543+1.2F_c)
43	N_{46-45}	43	–(625752+1.2F_c)	51	N_{54-53}	51	–(175742+1.2F_c)
44	N_{47-46}	44	–(546129+1.2F_c)	52	N_{55-54}	52	–(187773.6+1.2F_c)
45	N_{48-47}	45	–(544363+1.2F_c)	53	N_{56-55}	53	–(75852+1.2F_c)
46	N_{49-48}	46	–(562048+1.2F_c)	54	N_{57-56}	54	–(111606+F_c)
47	N_{50-49}	47	–(574604+1.2F_c)	55	N_{58-57}	55	–(96732+0.428F_c)
48	N_{51-50}	48	–(371375+1.2F_c)	–	–	–	–
Vertical bar							
56	N_{1-58}	56	–8843	63	N_{50-8}	63	–140090
57	N_{57-2}	57	–(100996+0.99F_c)	64	N_{49-9}	64	–122404
58	N_{56-3}	58	–18918	65	N_{48-10}	65	–88449
59	N_{54-4}	59	–210834	66	N_{47-11}	66	–17686
60	N_{53-5}	60	–210834	67	N_{46-12}	67	–44234

Continuation of Table 1

1	2	3	4	5	6	7	8
61	N_{52-6}	61	−184305	68	N_{45-13}	68	–17686
62	N_{51-7}	62	−166618	69	N_{44-14}	69	–8843
Oblique bar							
84	N_{57-1}	84	−12632	92	N_{49-8}	92	–93748
85	N_{57-3}	85	−(169542+1.48F_c)	93	N_{49-10}	93	–75811
86	N_{55-3}	86	−(123276+1.12F_c)	94	N_{47-10}	94	–50545
87	N_{55-4}	87	−123276	95	N_{47-12}	95	–37912
88	N_{53-4}	88	−144280	96	N_{45-12}	96	–25280
89	N_{53-6}	89	−131647	97	N_{45-14}	97	–12647
90	N_{51-6}	90	−119014	98	N_{43-14}	98	–14.28
91	N_{51-8}	91	−106381	–	–	–	–

(The value of internal force in Table 1 is only calculated for bars of the left half of the truss)

In the *YOX* plane, considering the most disadvantageous case of the structure (for bars in the *YOX* plane) which is when the cargo is fixed on hooks and the gantry crane performs the movement along the rail. The value of internal force in each bar of the main truss depends on the force of inertia as shown in **Table 2**.

Table 2

Internal force values of main truss bars in the *YOX* plane

No.	Bar No.	Internal force value	No.	Bar No.	Internal force value
1	N_{1-2}	(3006.a+336)	8	N_{8-9}	186447.a+20832
2	N_{2-3}	97512.a+8736	9	N_{9-10}	174631.a+19512
3	N_{3-4}	(33077.a+1536)	10	N_{10-11}	362336.a+40488
4	N_{4-5}	119853.a+13392	11	N_{11-12}	211264.a+23604
5	N_{5-6}	96226.a+10752	12	N_{12-13}	228565.a+25536
6	N_{6-7}	147350.a+16464	13	N_{13-14}	240912.a+26292
7	N_{7-8}	130809.a+14616	14	N_{14-15}	231586.a+25872
41	$N_{15'-14'}$	–(231586.a+25872)	48	$N_{8'-7'}$	–(168401.a+18816)
42	$N_{14'-13'}$	–(244683.a+25872)	49	$N_{7'-6'}$	–(117280.a+13104)
43	$N_{13'-12'}$	–(221040.a+24696)	50	$N_{6'-5'}$	–(144556.a+16152)
44	$N_{12'-11'}$	–(222546.a+24864)	51	$N_{5'-4'}$	–(66155.a+7392
45	$N_{11'-10'}$	–(347296.a+38808)	52	$N_{4'-3'}$	–(33077.a+1536)
46	$N_{10'-9'}$	–(201486.a+22512)	53	$N_{3'-2'}$	–(33077.a+3696)
47	$N_{9'-8'}$	–(183927.a+18312)	54	$N_{2'-1'}$	–(8375.a+936)
Vertical bar					
165	$N_{1-1'}$	–(3758.a+420)	158	$N_{8-8'}$	–(69816.a+7800)
164	$N_{2-2'}$	–(45282,7.a+5040)	157	$N_{9-9'}$	–(5369.a+600)
163	$N_{3'-3}$	–(45105.a+5040)	156	$N_{10-10'}$	–(40285.a+4500)
162	$N_{4-4'}$	–(37588.a+4200)	155	$N_{11-11'}$	–(30081.a+840)
161	$N_{5-5'}$	–(102028.a+1140)	154	$N_{12-12'}$	–(3757.a+420)
160	$N_{6-6'}$	–(91291.a+10200)	153	$N_{13-13'}$	–(3757.a+420)
159	$N_{7-7'}$	–(5369.a+600)	152	$N_{14-14'}$	–(3770.a+420)
Oblique bar					
113	$N_{1-2'}$	–(5366.a+599)	120	$N_{10-9'}$	–(26855.a+3000)
114	$N_{3-2'}$	–(64435.a+7200)	121	$N_{10-11'}$	–(21487.a+2400)
115	$N_{4-5'}$	–(53698.a+6000)	122	$N_{12-11'}$	–(16118.a+1800)
116	$N_{6-5'}$	–(48330.a+5400)	123	$N_{12-13'}$	–(10750.a+1200)
117	$N_{6-7'}$	–(42961.a+4800)	124	$N_{14-13'}$	–(5387.a+600)
118	$N_{8-7'}$	–(37592.a+4200)	125	$N_{14-15'}$	–(5387.a+600)
119	$N_{8-9'}$	–(32224.a+3600)	–	–	–

3. 2. Dynamic stress

Stress values in tension and compression bars are determined by the formula:

$$\sigma_k = \frac{N_z}{F} = \frac{A + B.F_c(t)}{F}, \text{ (N/mm}^2\text{)}; \ \sigma_n = \frac{N_z}{\varphi F} = \frac{A + B.F_c(t)}{\varphi F}, \text{ (N/mm}^2\text{)}. \quad (6)$$

Of which A, B – constants; N_z – tensile (compression) force appearing in each bar, (N); F – cross-sectional area of each bar, (mm^2); $F_c(t)$ – dynamic cable tension acting on the truss structure (as a time-based function), (N).

In case of lowering Super-T girder in combination with the brake (in the ZOX plane). After replacing, the value of the dynamic cable tension $F_c(t)$ is determined through the results of solving the dynamics problem corresponding to the working case: Lower Super-T girder in combination with the brake of the gantry crane type installed on the cap of bridge pier (This is the most dangerous working case of the gantry crane during the lifting-lowering process). Conduct programming on Matlab software to solve the expressions in **Table 1**, the author has determined dynamic stress values that change over time. Stress results for some bars with large values are shown **Fig. 7–11** follows:

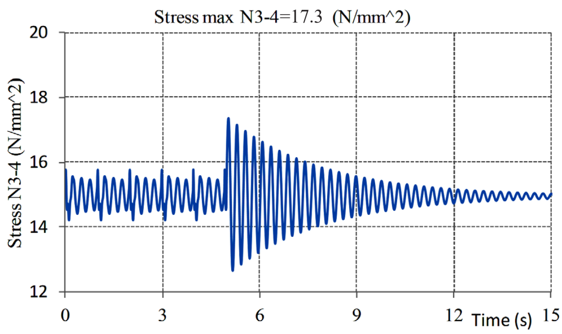

Fig. 7. Bar stress N_{3-4} of edge bar

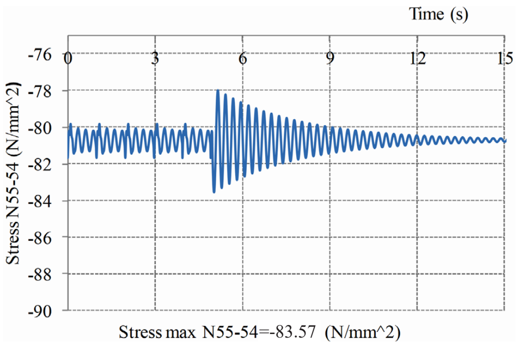

Fig. 8. Bar stress N_{55-54} of edge bar

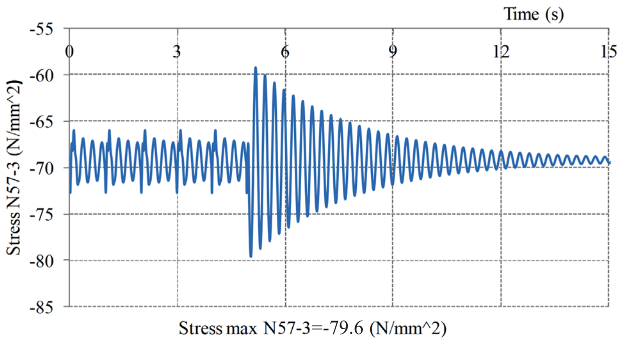

Fig. 9. Bar stress N_{57-3} of oblique bar

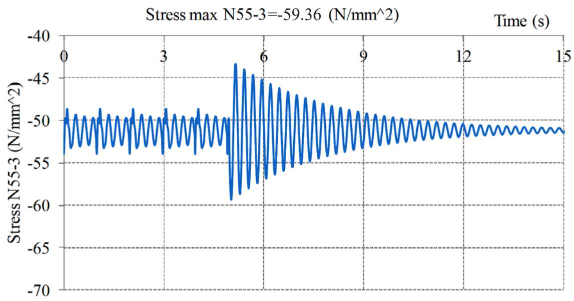

Fig. 10. Bar stress N_{55-3} of oblique bar

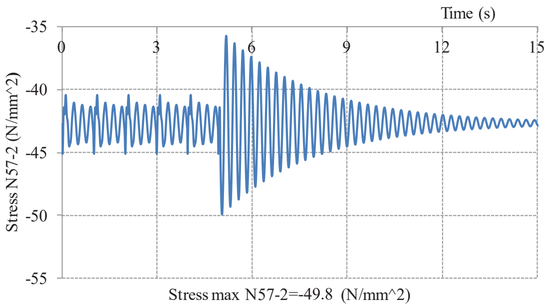

Fig. 11. Bar stress N_{57-2} of vertical bar

In **Fig. 7–11,** it is possible to see that the stress value in Edge bar, Oblique bar, Vertical bar changes greatly when dynamic cable tension force occurs. Stress values increase from 5 % to 25 % the initial static stress. The dynamic stresses in the bars will vary over a period of 5 to 10 seconds.

In case of hanging Super-T girder fixed and then let gantry crane travelling (in the *YOX* plane). After replacing, the value of acceleration $a(t)$ as expression (3) is determined through the problem of dynamics corresponding to the working case (Moving goods of the gantry crane type installed on the cap of bridge pier). Conduct programming on Matlab software to calculate, the author has determined the values of internal forces and stresses that change over time corresponding to the expressions in **Table 2** of all bars in the truss corresponding to 1/2 main truss of the *YOX* plane. The values of internal force, stress and maximum stress chart of bars are shown from **Fig. 12–19** follows:

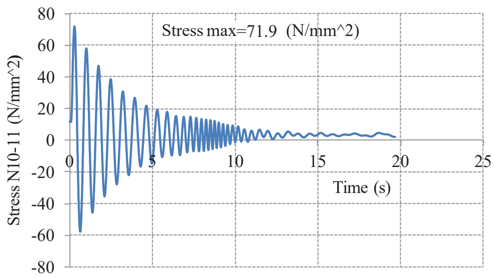

Fig. 12. Stress in bar N_{10-11} of left edge bar

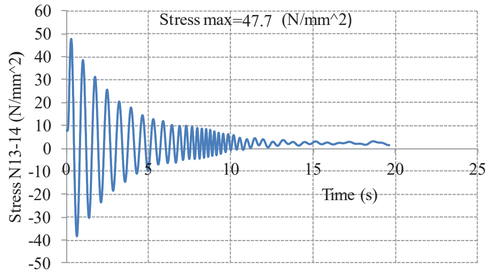

Fig. 13. Stress in bar N_{13-14} of left edge bar

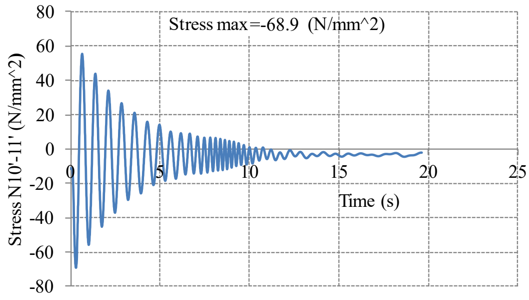

Fig. 14. Stress in bar $N_{10'-11'}$ of right edge bar

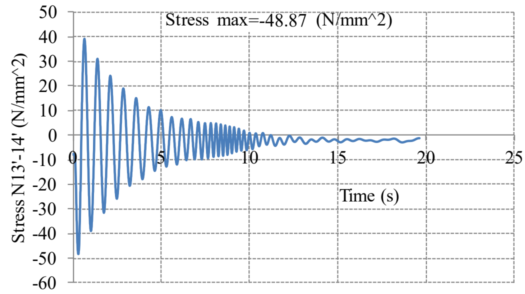

Fig. 15. Stress in bar $N_{13'-14'}$ of right edge bar

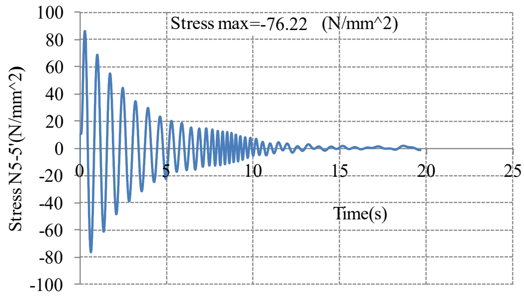

Fig. 16. Stress in bar $N_{5-5'}$ of horizontal bar

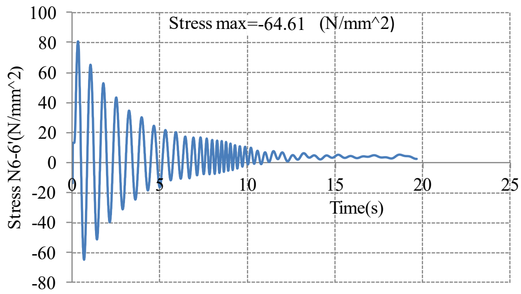

Fig. 17. Stress in bar $N_{6-6'}$ of horizontal bar

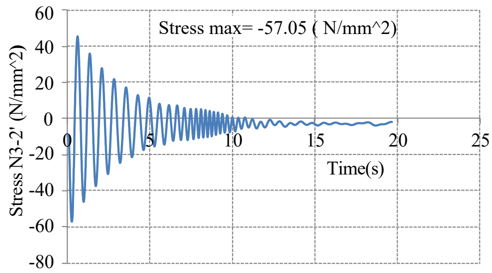

Fig. 18. Stress in bar $N_{3-2'}$ of oblique bar

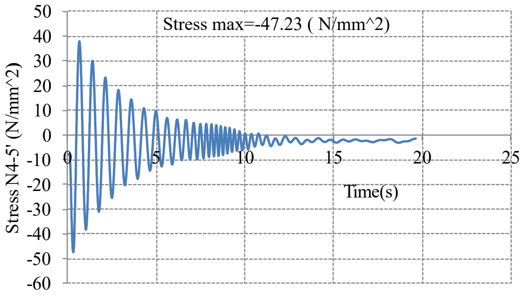

Fig. 19. Stress in bar $N_{4-5'}$ of oblique bar

In **Fig. 12–19**, it is possible to see that the values and rules of stress change in the left edge bar, right edge bar, horizontal bar, oblique bar depend greatly on the acceleration when the gantry moving. The stress value in the bars may be increased by 2 to 5 times the initial static application value. The stresses present in the bar will vary over a period of ten seconds. This is the most disadvantageous case when calculating the structural strength of the gantry crane.

4. Conclusions

The author has determined the time-varying laws of internal force and stress in all bars of the main truss, has determined the maximum stress values in bars of the main truss in the vertical plane (*ZOX* plane) corresponding to the case of lowering cargoes in combination with the brake of the gantry crane considered above, and at the same time determined the internal force and dynamic stress in all bars of the main truss (the *YOX* plane) corresponding to the case of fixed and movable suspension gantry cranes. Based on the internal force and dynamic stress charts of all bars, the author has determined the times of occurrence and quenching of stress in bars of the main structure.

The findings of the research may be used to calculate fatigue, life-span of the main gantry crane as well as other parts of the gantry crane.

Conflict of interest

The authors declare that there is no conflict of interest in relation to this paper, as well as the published research results, including the financial aspects of conducting the research, obtaining and using its results, as well as any non-financial personal relationships.

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Data availability

Manuscript has data included as electronic supplementary material.

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