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REASONABLE DESIGN METHOD OF BOX CRANE GIRDER BY TAGUCHI METHOD

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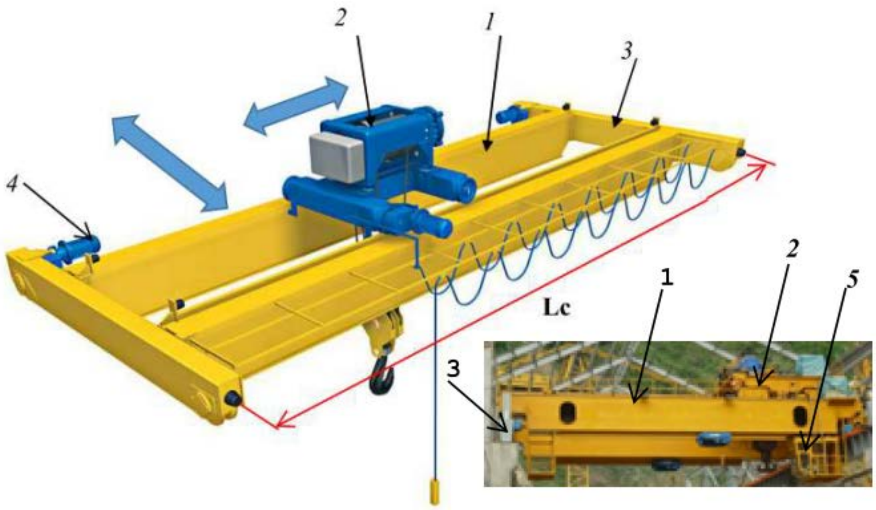
Overhead cranes are widely used in industrial systems. In this study, the research object is the main box girder of the overhead crane. The research objective is to find the parameters to obtain a lighter structure, which reduces the market price of the crane. The article studies the method of calculating crane girders and sets up the optimization algorithm. The study will use the Taguchi method, and ANOVA analysis to evaluate the influence of box girder parameters. The girder weight, stress, local stability, static displacement, and vibration frequency are response values. Constraint conditions are evaluated by examining each factor with response value according to the orthogonal matrix L16. Analysis of the Signal to Noise ratio and ANOVA by Minitab software will select the optimal parameters that satisfy the constraints, the goal is to reduce the volume compared to the original design. The test results of the crane with a lifting capacity of 250 tons, an aperture of 31 m, the girder weight reduced by 24.33 %, while the stress increased by only 6.16 %. The new design ensures suitable local stability conditions by making better use of the material's capabilities. With the new parameters, the technical criteria are guaranteed.

Keywords: box girder, optimal parameters, overhead cranes, static displacement, vibration frequency

1 INTRODUCTION

Overhead cranes are widely used in industrial systems. Fig.1 is a diagram depicting the general structure of a double girder overhead crane. Main girder 1 and side girder 3 form a rigid frame. Most commonly these griders have a rectangular box-shaped cross-section. The trolley 2 undertakes two basic movements, namely vertical and horizontal load transport. The whole crane is moved by the travel mechanism 4. The crane is controlled from the push-button box or the cabin 5. With the above structure, it is possible to transport loads to locations in space. The mass of main girder 1 accounts for the largest proportion of the total mass of the crane and that is why it is very important to reduce it to get a lighter structure, which also reduces the market price.

The designed crane box girder can be based on the recommendations in [1-3]. In which [1], and [2] give recommendations on the design, manufacture, and testing of lifting equipment in general, cranes in particular, especially basic calculations for cranes. Crane box girder structure, deflection, and vibration frequency of box girder structure are also indicated in [3].



1. Main girder, 2. Trolley, 3. Side girder, 4. Crane moving mechanism, 5. Cabin.

Fig. 1. Box-type double girder overhead crane

Calculating crane girders by analytics we often use simple calculation schemes and consider loads in different planes of action. This traditional calculation method simply does not depend on structural analysis software. Calculation by finite element method of crane girder in [4-6] is by different software such as CATIA V5, SAP2000, and ANSYS. The research and design of the crane [4] is for a fishing vessel maintenance workshop based on ASME B30.2-2005 standard. The stress is analyzed using a finite element program, resulting in a factor of safety of 1 .83. The study [5] performed the calculation and analysis of the crane double girder structure used in the laboratories. Calculation results are the bending stress and deflection of the main girder. The goal of model calculation and analysis is to develop a model crane and serve the test.

As mentioned above reducing the structural weight is very important, which also reduces the market price of the crane. Therefore, optimization techniques are constantly developing applications in engineering. Research in [7] has optimized the gear transmission, and the direct search algorithm and Matlab software are used to solve the problem. In the study in [8], the optimal variables are determined through the correction and interpolation coefficients. This paper used the finite element method to optimize the crane with a load capacity of 50 to 120 tons with an aperture from 10 to 32m, the objective function is the girder weight. In [9] is the review and comparison of different optimization algorithms that can be applied to the crane box girder design. The study in [10] presented a method to calculate the geometrical parameters of the crane steel structure with the objective function being the minimum mass, taking into account the local stability condition of the girder web. The geometrical parameters have been reasonably calculated including the cross-sectional dimensions of the box girders and the position of the stiffening walls.

Advanced optimization methods have many advantages, but the number of calculations is large and requires high computational hardware and software, application in the technique mentioned in [11]. In [12] using the program ANSYS has been paired with MATLAB software. The optimization method is the genetic algorithm. The optimization results for the box girder show that the total mass of the trapezoidal box girder has been reduced by about 38%. Research in [13] has considered the problem of optimizing the box section of the main girder of the crane. The optimization methods used advanced biology-inspired algorithms such as the Firefly Algorithm (FA), Bat Algorithm (BA), and Cuckoo Search algorithm (CS). The obtained optimization results are compared with several solutions of a single girder crane, which has verified the optimization method. Research on the optimal design of the main girder box cross-section of a double girder crane was mentioned in [14]. The moth-Flame Optimization (MFO) algorithm is used to solve this multi-criteria optimization problem [14]. In addition, [15] also studied the rational design of the crane structure to save energy. The article has proposed a green energy-saving design method based on artificial intelligence. The results show that compared with the original design, the machining waste after optimization is 63.43% lower and the cross-sectional area of the main girder is reduced by 27.03 % [15]. In the study [16], the subframe of the elevator was optimized. This study used the finite element method by SolidWorks software. The result of the study in [16] was a 20 % reduction in weight.

Taguchi method is mainly in the parameter design stage based on assessing the influence of factors on the objective function and at the same time determining the optimal parameters. Taguchi method has the advantages of simplicity and, small number of trials [17-21]. Using the Taguchi method for the fatigue analysis of the seat right angle mentioned in [18], this study presents a method to determine the critical design parameters to prolong the product life of components subjected to fatigue loads. In engineering technology, due to its advantages, the Taguchi method has been applied to many technical problems. Research in [19] applied the Taguchi method to optimally design a wheeled robot for transporting products to ensure higher adaptability and maximum stability during stair climbing. Taguchi method and Minitab software were used to determine the optimal parameters in [20], [21]. In [20], the research has built a problem to have the minimum pulling force of the crane. Experimental studies to determine the influence of working equipment parameters of small trench excavators on machine productivity are indicated in [21].

In this study, the research object is the main girder of the crane. The problem will be designed according to the cross-section between the girder. The main girder cross-section is a box. The research objective is to find the parameters to get a lighter structure and, reduce the market price of the crane. In this study, analytical methods with simple calculation diagrams are used to calculate internal forces. The study will the use Taguchi method, and ANOVA analysis to evaluate the influence of crane girder parameters. The crane box girder structure must satisfy the conditions of stress, local stability, static displacement, and vibration frequency. To apply the Taguchi method, the article researches the calculation method of crane girders and sets up the optimal algorithm. Crane's main girder weight, stress, local stability, static displacement, and vibration frequency are response values of the orthogonal matrix in the Taguchi method. Analysis of the Signal to Noise (S/N) ratio and ANOVA allows us to choose the optimal parameters that satisfy the constraints. The result will be a reduction in mass compared to the original design.

2 REASONABLE DESIGN METHOD OF CRANE MAIN GIRDER

2.1 Calculation model and effective load

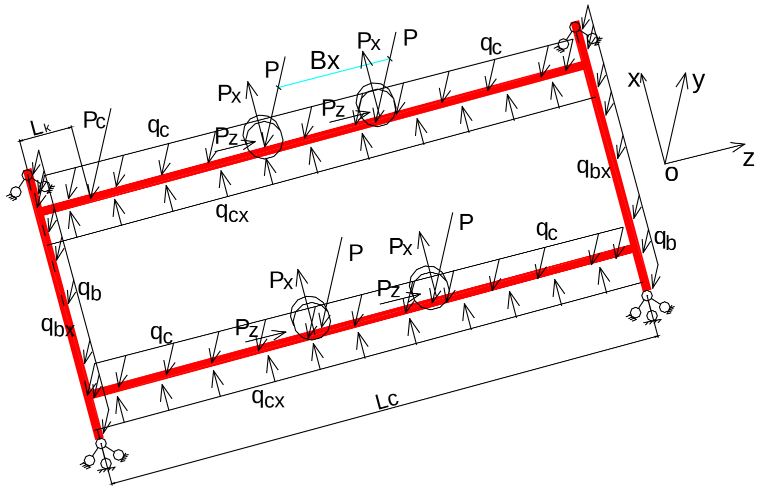
Crane box girders are subjected to many load components in different working states and conditions. Fig.2 is the calculation diagram of the crane girder steel structure. Loads include the self-weight of the crane girder structure, working loads, and special loads. This calculation method is applied according to [1-3].

In the self-weight of the crane girder includes the set,$S_G = \{q_c, q_b, P_c\}$. Where q_c, q_b and P_c are shown in Fig. 2. The working loads due to lifting or lowering loads ψQ and due to unstable horizontal movements areS_H. The dynamic coefficient is $\psi \geq 1.15$, $\psi = 1 + \xi v_n$. Whereξ is the coefficient for the crane [1], ξ = 0.6, $v_n$is the lifting speed (m/s).

Applying to the crane with the assumption that the compression forces on the wheels of the trolley are equal, we have:

$$P = \frac{\psi Q + G_x}{4} \tag{1}$$

Where Q is the load including the weight of the hanger (N), G_{xc} is the weight of the trolley (N).



q_c- distributed weight of main girder (N/mm), q_b- weight distribution side girder (N/mm), P - force from the wheel on the girder (N), P_c- cabin weight (N), P_x- load due to the inertia force when moving the crane due to the weight of the trolley and the load through the wheel acting on the girder (N), P_z-load due to the inertia force when moving the trolley over the wheel acting on the girder (N), q_{cx}- load due to inertia force when moving crane due to crane girder weight (N), L_c- crane aperture (mm),B_x- distance of two wheels (mm), L_K- distance from Cabin to girder end (mm)

Fig. 2. Diagram of forces acting on the crane girder

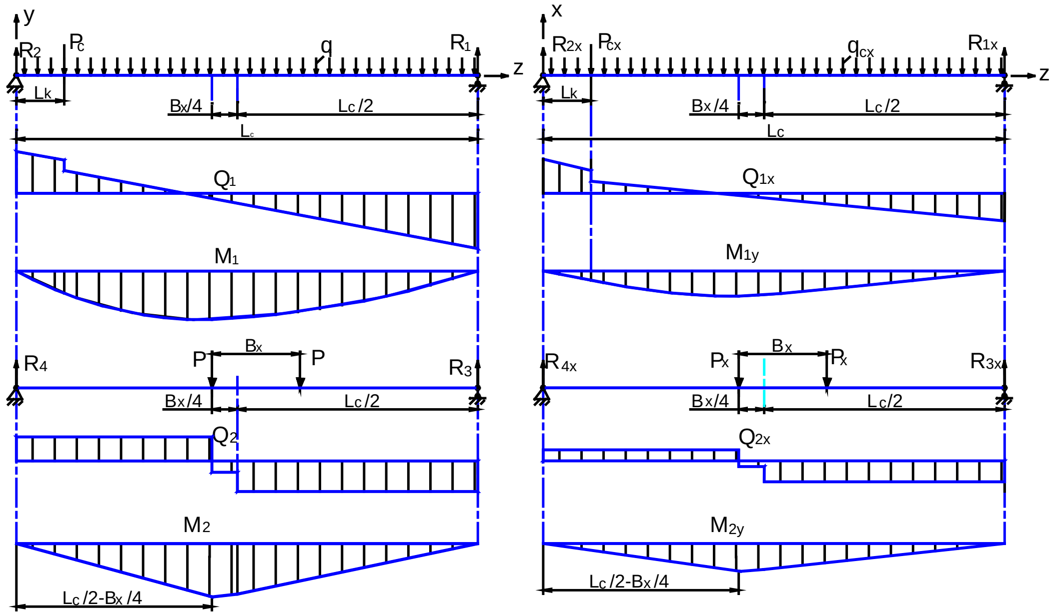
The steel structure of the box girder overhead crane is calculated according to the allowable stress method. For cranes working indoors, according to [1] load cases I and II are represented by the principle of cooperative action:

$$\gamma_c\{S_G + P\} + \gamma_c S_H \quad (2)$$

$$S_H = \{P_x, P_z, q_{cx}, q_{bx}\} \quad (3)$$

Where P_x, P_z, q_{cx} and q_{bx} are shown in Fig. 2, γ_c is the coefficient depending on the group of working equipment and selected according to [1].

In the case of load III when the crane is subjected to abnormal load, in this problem only static load test and dynamic load test cases are considered$\{S_G + P_{test}\}$. Where P_{test} is the test load. The dynamic test load factor and the static test load factor are specified by [1].



a) b)

a – due to vertical forces, b- due to horizontal forces.

Fig. 3. Internal force diagram of the main girder

2.2 Conditions of strength, local stability, and stiffness main girder

The research object is the main girder of the Crane. The problem will be designed according to the cross-section between the girders. In the case of crane girders subjected to vertical loads y (Fig. 3a). In the y-direction, the total shear force is Q_y (N), and the bending moment is M_x (Nmm):

$$Q_y = Q_1 + Q_2, M_x = M_1 + M_2 \quad (4)$$

Where Q_1, Q_2, M_1, and M_2 are the shear force and bending moment due to the vertical force of self-weight and the compression force of wheel of trolley.

The stress at the critical section in this case is:

$$\sigma_x = \gamma_c \frac{M_x h_c}{2J_x}, \tau_y = \gamma_c \frac{Q_y S_x}{2J_x t_1} \quad (5)$$

Where h_c and t_1 are shown in Fig. 4, J_x is the moment of inertia with the central axis x in Fig.4, $S_x$is the static moment of ½ section with the x-axis in Fig.4.

In the case of crane girder subjected to horizontal loads x (Fig 3b).

In the horizontal x direction, total shear force Q_x (N), bending moment M_y (Nmm):

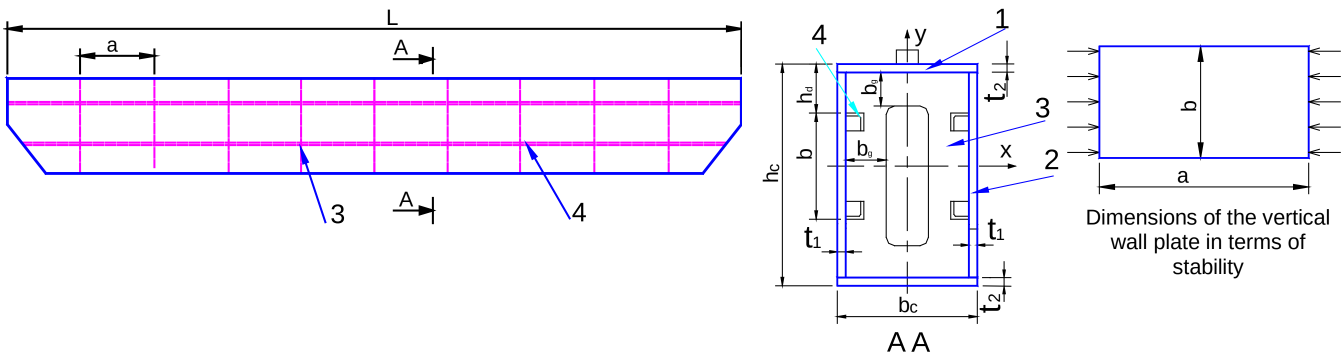
$$Q_x = Q_{x1} + Q_{x2}, M_y = M_{y1} + M_{y2} \quad (6)$$

Where Q_{1x}, Q_{2x}, M_{1y}, and M_{2y} are the shear force and bending moment caused by the horizontal force.

The stress at the critical section in this case is:

$$\sigma_y = \gamma_c \frac{M_y b_c}{2J_y}, \tau_x = \gamma_c \frac{Q_x S_y}{2J_y t_2} \quad (7)$$

Where b_c and t_2 are shown in Fig.4, $J_y$is the moment of inertia with the central y axis in Fig.4, $S_y$is the static moment of ½ section with the y axis in Fig.4.



1. upper and lower flange, 2. wall plate, 3. vertical wall, 4. longitudinal ribs

L - girder length (mm), a - distance of two vertical walls (mm),h_c- girder height (mm), b_c- girder width (mm), t_2- upper and lower flange thickness (mm), t_1- wall plate thickness (mm), b_g- width of the vertical wall (mm), h_d- distance of rib to upper flange (mm), b - spacing of 2 longitudinal ribs (mm).

Fig. 4. Box crane girder structure

The stresses in the load cases I and II are :

$$\sigma_{12} = \sigma_x + \sigma_y < [\sigma_{12}], \tau_{12} = \tau_x + \tau_y < [\tau_{12}] \quad (8)$$

Where $[\sigma_{12}]$ and $[\tau_{12}]$ are the allowable normal and shear stresses, for load cases I and II.

For load case III when testing static load, the value is calculated by formula (1), (2) with γ_c = 1, ψ =1. The load factor during load testing is 1.25, similar to the case of vertical load in the y direction:

$$\sigma_{31x} = \frac{M_x h_c}{2J_x}, \tau_{31y} = \frac{Q_y S_x}{2J_x t_1}, \sigma_{31} \le [\sigma_3], \tau_{31} \le [\tau_3] \quad (9)$$

Where $[\sigma_3]$ and $[\tau_3]$ are the allowable normal and shear stresses, corresponding to load case III.

In the case of load III in dynamic load testing with the value calculated by formula (1), (2) γ_c = 1. The load factor during load testing is 1.1, it is similar to load cases I and II including vertical and horizontal loads.

$$\sigma_{32x} = \frac{M_x h_c}{2J_x}, \tau_{32y} = \frac{Q_y S_x}{2J_x t_1}, \sigma_{32y} = \frac{M_y b_c}{2J_y}, \tau_{32x} = \frac{Q_x S_y}{2J_y t_2} \quad (10)$$

$$\sigma_{32} = \sigma_{32x} + \sigma_{32y} < [\sigma_3],\ \tau_{32} = \tau_{32x} + \tau_{32y} < [\tau_3] \tag{11}$$

The wall plate of the crane girder as shown in Fig.4 is tested according to the theory of the structure subjected to transverse bending. The ultimate lateral bending stress σ_{cr}^{v} (N/mm²) and the ultimate shear stress τ_{cr}^{v} (N/mm²) are considered to be multiples of the Euler stress determined by formula [1]:

$$\sigma_{cr}^{v} = k_\sigma \sigma_R^E, \tau_{cr}^{v} = k_\tau \tau_R^E,\ \sigma_R^E = 189800\left(\frac{t_1}{b}\right)^2 \tag{12}$$

Where σ_R^E is the Euler stress (N/mm²), a and b are the vertical wall plate size (mm), $k_\sigma$is the coefficient for the normal stress, $k_\tau$is the coefficient for the shear stress.

At the position of the cross-section between the main girder, the wall plate is subjected to pure bending, when $\alpha = \frac{a}{b} \geq \frac{2}{3}$, according to $k_\sigma = 23.9$ [1]. At the head section of the main girder, the wall plate is in pure shear, when $\alpha = \frac{a}{b} \leq 1$, according to [1] $k_\tau = 4 + \frac{5.34}{\alpha^2}$.

Local stability factor of safety in the case of loads I and II:

$$k_1 = \frac{\sigma_{cr}^{v}}{\sigma_{12}} \geq [k_1],\ k_1 = \frac{\tau_{cr}^{v}}{\tau_{12}} \geq [k_1] \tag{13}$$

Locally stable factor of safety in case of load coordination III:

$$k_3 = \frac{\sigma_{cr}^{v}}{\sigma_3} \geq [k_3], k_3 = \frac{\tau_{cr}^{v}}{\tau_3} \geq [k_3] \tag{14}$$

Where σ_{12},τ_{12},σ_3 andτ_3 are the normal stress and the shear stress of the girder in question corresponding to the load case in the formulas (8), (11).

Static displacement f (mm) caused by the weight of the load Q (N) and the weight of the trolley G_x (N) in the middle of the girder.

$$f = \frac{0.5(Q+G_x)L_c^3}{48EJ_x} \leq [f] \tag{15}$$

Where$E$is the elastic modulus of the material, with steel$E$ = 2.1*10⁵ (N/mm²), $[f]$ is the allowable static displacement depending on the girder aperture determined by [3].

Vibration frequency of crane girder in vertical direction isf_v (Hz) [3]:

$$f_v = \frac{1}{2\pi}\sqrt{\frac{48EJ_x}{L_c^3(m_{Gx}+m_Q+0.4857m_B)}} \geq [f_v] \tag{16}$$

Where $m_{Gc}$is the mass of the trolley, with $m_{Gc} = \frac{G_x}{g}$ (kg), $m_B$is the crane girder mass, with $m_B = \frac{G_{dc}}{g}$ (kg), $m_Q$is the payload mass, with $m_Q = \frac{Q}{g}$ (kg), $[f_v]$ is the allowed vertical vibration frequency (Hz). In this formulation, the unit of is (N/m²), and the unit of $J_x$is (m⁴).

The vibration frequency of the crane girder in the horizontal direction isf_h (Hz) [3]:

$$f_h = \frac{1}{2\pi}\sqrt{\frac{k_{sc}EJ_y}{L_c^3(m_{Gx}+k_{mg}m_B)}} \geq [f_h] \tag{17}$$

Where $k_{sc}$and $k_{mg}$are the coefficients, the crane has two girders, with k_{sc}=125, k_{mg}= 0.43, $[f_h]$ is the permissible frequency of oscillation in the horizontal direction (Hz). In this formulation, the unit of $J_y$is (m⁴).

2.3 Methods and design parameters

Weight of one main girder G_{dc} (N) when ignoring the change of girder head, according to the structure as shown in Fig. 4, we have:

$$G_{dc} = 2.10^{-9}L\rho g\left\{[b_c t_2 + (h_c - 2t_2)t_1] + \frac{t_g[(b_c-2t_1).b_g + (h_c-2t_2-2b_g)b_g]}{a}\right\} + n_o L G_g + G_S \tag{18}$$

Where $t_g$is the wall thickness (mm), n_o is the number of longitudinal ribs, G_g is the weight of the longitudinal ribs per unit length (N/mm), ρ is the density, with ρ = 7800 kg/m³, g is the acceleration gravity, with g =9.81 m/s², G_S is the weight of the substructures (N).

The idea of the Taguchi method is to determine the factors to achieve the highest efficiency by detecting and eliminating the effect of disturbance as much as possible. A design variable that affects the results in two directions, the effect that moves the results closer to the goal is a useful signal, called "Signal", and the effect that makes the result move away from the goal is "Noise". The S/N ratio represents the performance indicator, used to evaluate and select parameters. The parameter set is good for large S/N. The optimal set of parameters when giving the largest S/N [16-20].

Minimization problem (Smaller better):

$$S/N = -10\,lg\left(\frac{1}{n}\sum_{u=1}^{n} T_{iu}^{2}\right) \tag{19}$$

Maximum problem (Larger better):

$$S/N = -10\,lg\left(\frac{1}{n}\sum_{u=1}^{n} \frac{1}{T_{iu}^{2}}\right) \tag{20}$$

Where, u is the experimental sequence number; n is the number of experiments; T_i is the response value.

In this problem, five response values are used to analyze the results.

$$T_i = \{G_{dc}, \sigma, f, f_v, f_h\} \tag{21}$$

Regardless of whether the objective function is minimum or maximum, a large S/N ratio is good. This method has the disadvantage that the data is discrete, so the obtained solution is only close to the optimal, it is difficult to introduce the constraint condition. In the problem of crane girder design variables, the parameters related to size and material are standard, so it is also discrete data, so the reasonable solution is acceptable. To solve the constrained conditions, the problem in Taguchi design is by selecting the value levels and considering the influence of the parameters on the response values. Fig.5 is a diagram of the algorithm for rationally designing crane girders according to Taguchi method to meet the above requirements.

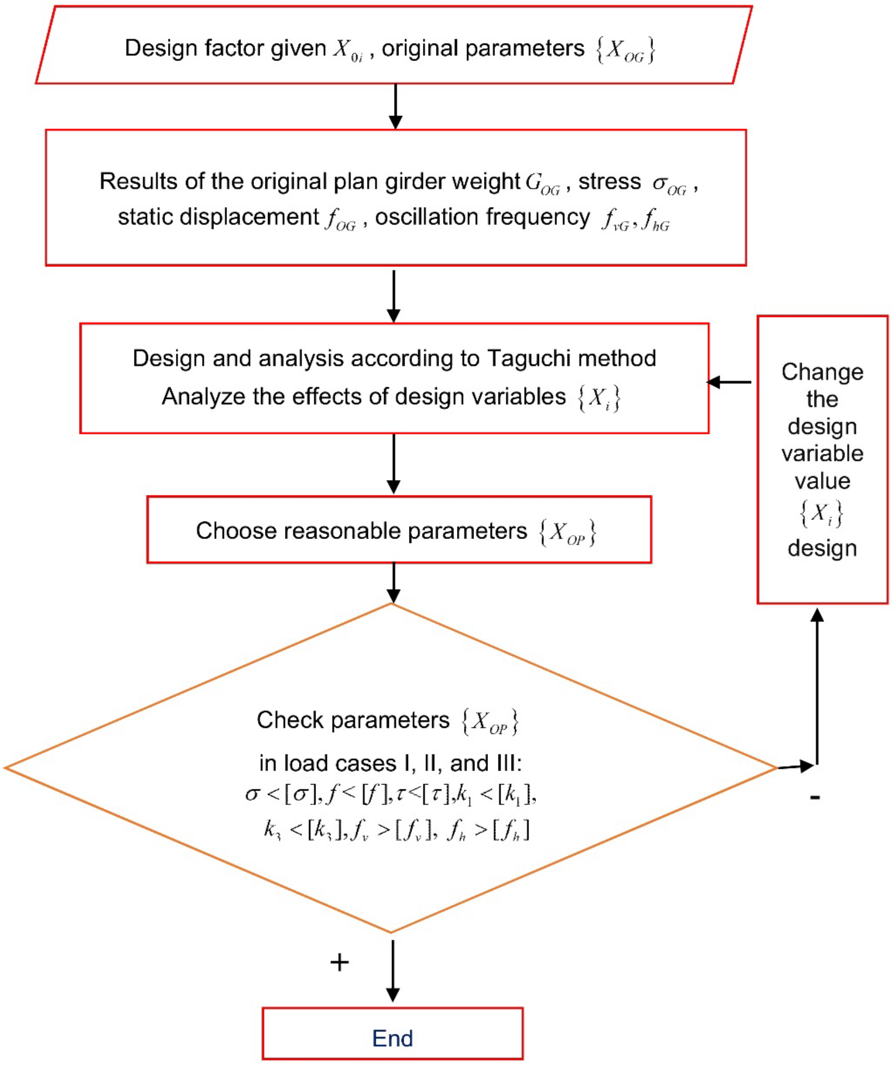


Fig. 5. Reasonable design diagram of crane main girder

Equation (22) describes the response functions of girder weight σ_{dc} (N), normal stress σ (N/mm²), static displacement f (mm), vertical vibration frequency f_v (Hz), and vibration frequency horizontally f_h (Hz).

$$\begin{cases} G_{dc} = min\, G_{dc}\,(X_{0i}, X_i) \\ \sigma = min\, \sigma\,(X_{0i}, X_i) \\ f = min\, f\,(X_{0i}, X_i) \\ f_v = max\, f_v\,(X_{0i}, X_i) \\ f_h = max\, f_h\,(X_{0i}, X_i) \end{cases} \quad (22)$$

Where $X_{0i}$is the set of given factors, X_i is the set of design parameters.

This study is reasonably designed for five geometric parameters, the design parameters are presented as the following set (Fig.4):

$$X_i = \{h_c, b_c, t_1, t_2, a\} \quad (23)$$

The remaining parameters X_{0i} are the independent parameters given. In the test example, there are values in Table 1.

Table 1. Independent parameters

Parameter	Symbol	Value	Unit
Loads and equipment to carry objects	Q	2500000	N
Lifting speed	v_n	0.05	m/s
Crane aperture	L_c	31000	mm
Coefficient of working mode group	γ_c	1.05	A3
Grider length	L	30000	mm
Trolley weight	G_x	700000	N
Cabin weight	P_c	10000	N
Distance of two wheels of the trolley on the girder	B_x	2250	mm
Elastic modulus of steel	E	2.1*10^5	N/mm^2
Material yield strength for crane girder	σ_{ch}	240	N/mm^2
Weight of one rib per unit length	G_g	0.0484	N/mm
Number of vertical horns	n_o	4	
Spacing of two longitudinal ribs	b	1400	mm
Width of vertical wall	b_g	160	mm
Wall thickness	t_g	6	mm
The specific gravity of steel	ρ	7800	kg/m^3
Gravity acceleration	g	9.81	m/s^2
Weight of girder substructures	G_s	10000	N
Distance from cabin to girder end	L_k	1000	mm

Table 2. Influential factors and value levels

Influential factors	Symbol		Value levels				Range of change
	Nature	Encode	1	2	3	4	
Girder height, (mm)	h_c	x_1	2200	2600	3000	3400	1200
Girder width, (mm)	b_c	x_2	800	900	1000	1100	250
Wall thickness, (mm)	t_1	x_3	8	10	12	14	6
Flange thickness, (mm)	t_2	x_4	14	16	18	20	6
Distance between the two vertical walls, (mm)	a	x_5	1000	2500	4000	5500	3500

3 RESULTS AND DISCUSSION

3.1 Original design plan

Design of double girder overhead crane with payload weight Q = 2500000 N, crane aperture L_c= 31000 mm, working mode group is A3. Table 1 is the given parameters. Technical data are cranes designed for the Dong Nai 3 hydropower plant in Vietnam. The initial design parameters for the main girder of the overhead crane include girder height h_c= 2800 mm, girder width b_c= 900 mm, wall plate thickness t_1= 18 mm, flange thickness t_2= 25 mm, and spacing of two vertical walls a = 4000 mm. The initial girder weight is G_{dc}= 363893 N. The initial values for the results of stress, local stability conditions, displacement, and vibration frequency meet the requirements in [1 -3].

Table 3. Experimental design using L16 orthogonal array

N	x_1	x_2	x_3	x_4	x_5	G_{dc} (N)	σ (N/mm^2)	k	f (mm)	f_v (Hz)	f_v (Hz)
1	1	1	1	1	1	157200	412	0.35	116	3.35	4.53
2	1	2	2	2	2	191400	319	0.72	92	3.77	5.65
3	1	3	3	3	3	228900	256	1.3	75	4.17	6.83
4	1	4	4	4	4	268500	211	1.3	62	4.56	8.06

N	x_1	x_2	x_3	x_4	x_5	G_{dc} (N)	σ (N/mm²)	k	f (mm)	f_v (Hz)	f_v (Hz)
5	2	1	2	3	4	209400	264	0.87	62	4.59	5.56
6	2	2	1	4	3	202200	249	0.59	57	4.77	5.65
7	2	3	4	1	2	258600	218	2.1	55	4.87	7.62
8	2	4	3	2	1	262200	206	1.6	51	5	8
9	3	1	3	4	2	265500	191	1.7	38	5.8	6.1
10	3	2	4	3	1	297900	171	2.64	35	6	7.3
11	3	3	1	2	4	208200	219	0.67	44	5.4	6.57
12	3	4	2	1	3	234600	199	1.16	42	5.56	7.8
13	4	1	4	2	3	305700	161	2.80	29	6.65	6.75
14	4	2	3	1	4	272400	174	1.9	31	6.4	7.2
15	4	3	2	4	1	278700	150	1.53	27	7	7.6
16	4	4	1	3	2	254700	168	1.37	31	6.5	8.2

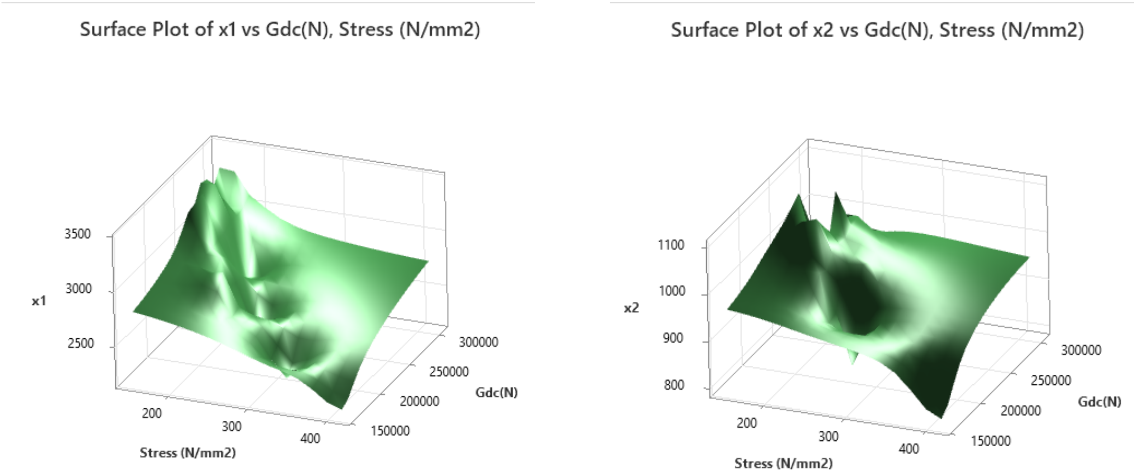
3.2 Orthogonal array and response value

The design factors in this problem are five factors. These factors are encoded respectively, $x_1$is the girder heighth_c, $x_2$is the girder width b_c, $x_3$is the wall plate thickness t_1,$x_4$is the flange thickness t_2,$x_5$is the distance between the two vertical wall$a$. Based on technical conditions and constraints, the problem selects 4 levels of values (Table 2).

According to the Taguchi method, the orthogonal programming matrix is L16. The response value is determined according to the analytical formula in Section 2.2. The S/N ratio represents the performance indicator, it is used to evaluate and select parameters. The S/N ratio is calculated according to the problems by formulas (19) and (20). Table 3 is the orthogonal matrix of the problem according to the Taguchi method.

Using Minitab software to design Taguchi and analyze and evaluate the influence of parameters on response values.

The response values calculated according to Section 2.2 include stressσ (N/mm²), girder weight G_{dc} (N), local stability safety factor$k$, static displacement in the middle of girder$f$ (mm), vibration frequency verticalf_v (Hz), and horizontal vibration frequency f_H (Hz). The response value in Table 3 is according to the planning matrix L16 and the calculated values in Table 2. Fig.6 shows the relationship of each factor to the response value of girder weight G_{dc} (N), and stress σ (N/mm²). Fig.7 shows the influence of the vertical cell sizes which are the factors x_3, and x_5 on the stable factor of safety k. For the local stability coefficient of the vertical wall, it depends a lot on the vertical wall thickness factor x_3. When the factor of safety is k =1.5 thenx_3 must be greater than 10 mm and when is greater than 4000 mm then x_3 increases. The general rule is that as the stress increases, the weight of the girder decreases (Fig.8), but each factor affects the response value to a different degree.



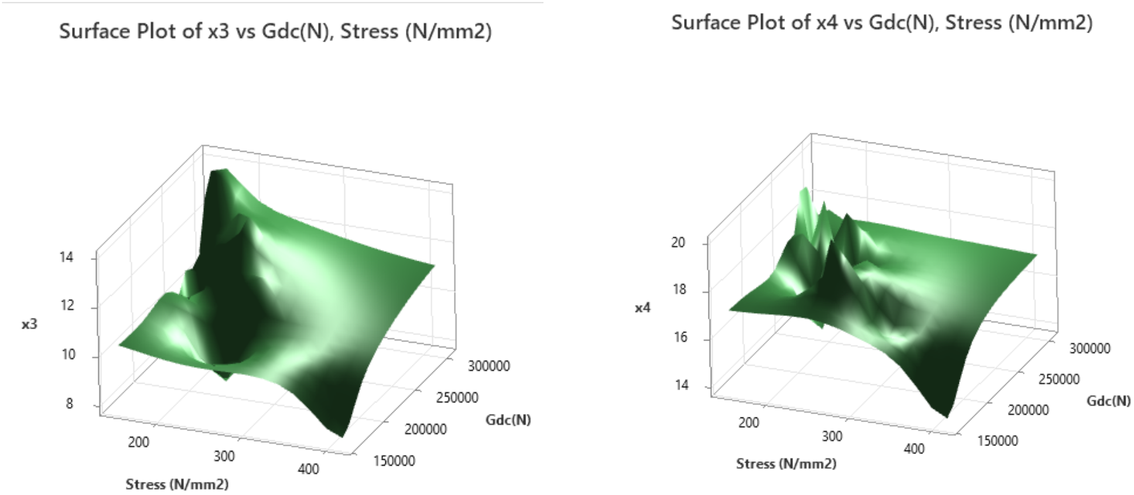


Fig. 6. Surface plot of factors (x_1, x_2, x_3, x_4) with stress σ (N/mm²) and girder weight G_{dc} (N)

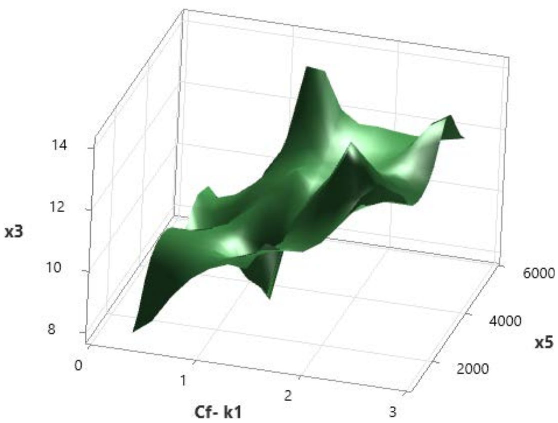


Fig. 7. Suface plot of factors$x_3, x_5$with the stable factor of safety

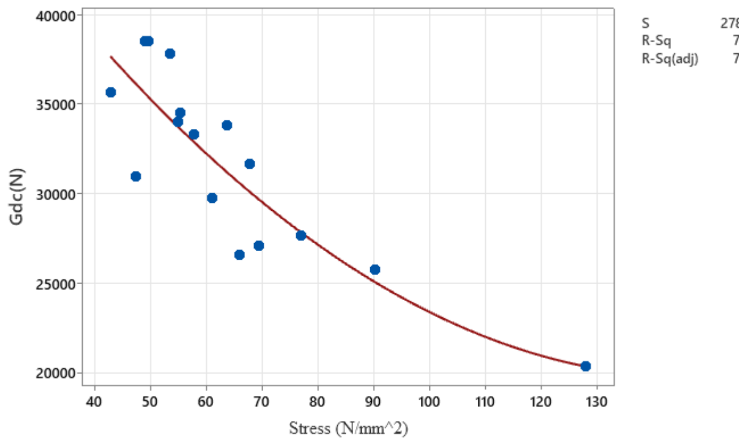


Fig. 8. Graph of the relationship between girder weight and maximum stress

3.3 *Analyze the influence of parameters*

Analysis of the S/N ratio for the objective function of girder weight is the Minimization problem. The results of the analysis of the S/N ratio are shown in Fig.9. In general, factors at the lowest value are good, but the degree of influence is different. Table 4 is the results of ANOVA analysis, showing that the vertical wall thickness factorx_3 has the most influence on the girder weight, it is 53.57 %, followed by girder height, it is 37.63 %. Other factors have an influence but are not significant.

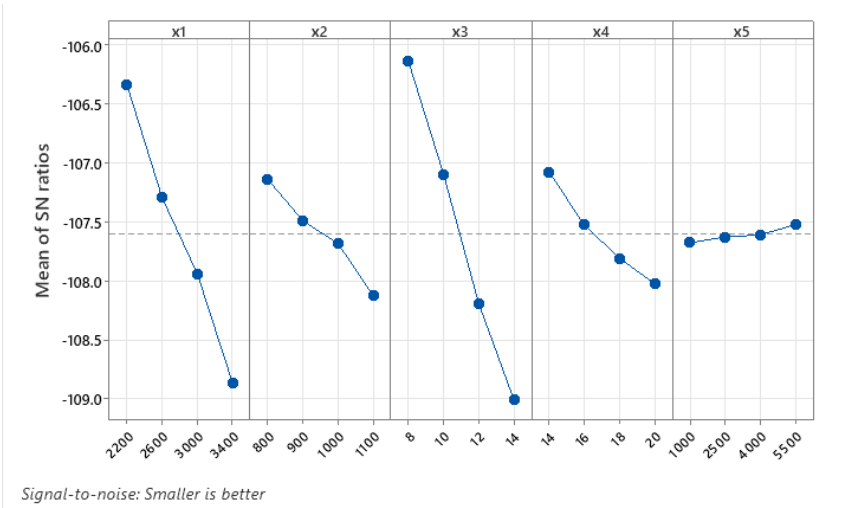


Fig. 9. Main effect plot for Signal to Noise ratios, response value is girder weight

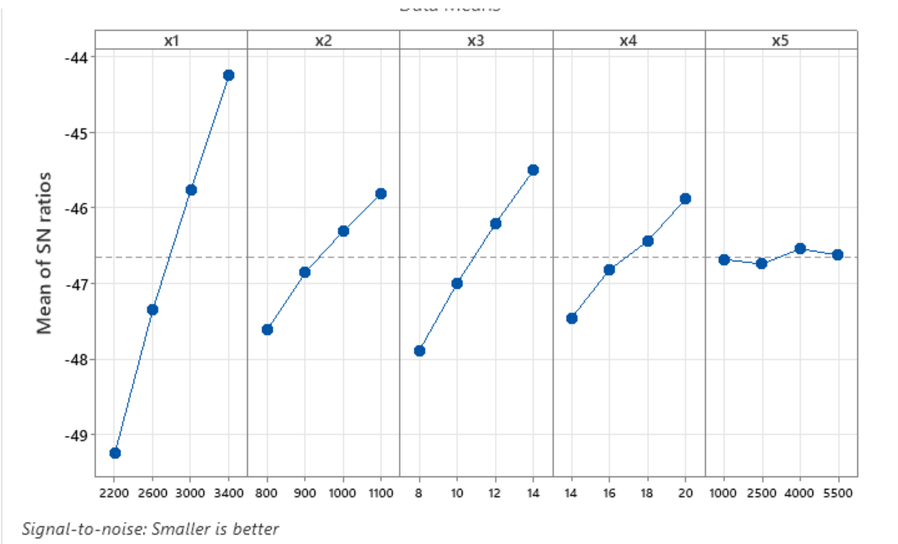


Fig. 10. Main effect plot for Signal to Noise ratios, response value is stress

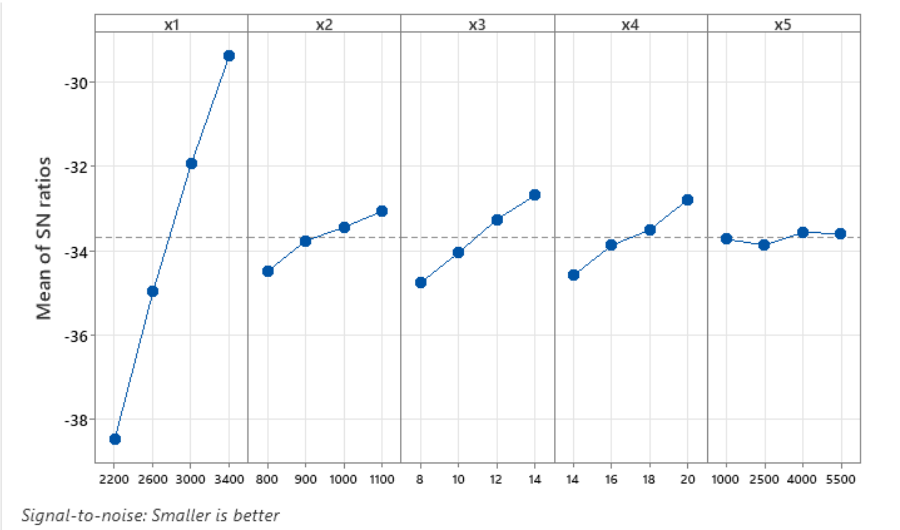


Fig. 11. Main effect plot for Signal to Noise ratios, response value is displacement

Analysis of the S/N ratio for the stress objective function is also a minimization problem. The results of the analysis of the S/N ratio are shown in Fig.10. In general, factors at the highest value are good, except for the factorx_5. Similar to above, ANOVA analysis (Table 5) shows that the factor that is girder height$x_1$has the most influence on stress, it's 60.94 %, followed by the vertical wall thickness x_3, it is 17.57 %. The flange width factor isx_2,the influence is 12.13 %. Thus,x_1 and x_3 are the two most important factors for girder weight and stress in the calculated example. Factor x_3 under local stability conditions must be greater than 10 mm.

Analysis of the S/N ratio for a displacement objective function is a minimization problem. The results show that girder height is the most influential factor (Fig.11). The influence of parameters on stress and displacement is the same, it is opposite to the target girder weight. For the response value is the oscillation frequency, the problem is maximum. The frequency of vertical oscillation is highly dependent on the girder heightx_1. while the frequency of horizontal vibration depends heavily on the girder width x_2, and wall thickness x_3. Factors x_4, and $x_5$have little influence on the static displacement and the oscillation frequency.

Table 4. Summary of results one-way ANOVA model, response value is girder weight

Encode	S	R-sq	R-sq(adj)	R-sq(pred)
x_1	36250.6	37.63 %	22.04 %	0.00 %
x_2	45093.9	3.49 %	0.00 %	0.00 %
x_3	31276.3	53.57 %	41.97 %	17.46 %
x_4	44840.6	4.57 %	0.00 %	0.00 %
x_5	45732.3	0.74 %	0.00 %	0.00 %

Table 5. Summary of results one-way ANOVA model, response value is stress

Encode	S	R-sq	R-sq(adj)	R-sq(pred)
x_1	46.9362	60.94 %	51.17 %	30.56 %
x_2	70.3964	12.13 %	0.00 %	0.00 %
x_3	68.1841	17.57 %	0.00 %	0.00 %
x_4	72.0100	8.06 %	0.00 %	0.00 %
x_5	74.6067	1.31 %	0.00 %	0.00 %

Table 6. Reasonable parameters

Influential factors	Symbol	Encode	Reasonable level	Value
Girder height, (mm)	h_c	x_1	4	3400
Girder width, (mm)	b_c	x_2	3	1000
Wall thickness, (mm)	t_1	x_3	2	10
Flange thickness, (mm)	t_2	x_4	4	20
Distance between the two vertical wall, (mm)	a	x_5	3	4000

Table 7. Evaluation of calculation results

Computational response value	Reasonable design/Original design	Load case I, II	Load case III	(+) Increase, (-) Reduce
Normal stress, (N/mm^2)	σ_{OP}/σ_{OG}	150/142.52	155/146	+6.16 %
Shear stress, (N/mm^2)	τ_{OP}/τ_{OG}	17/12.2	17.3/12.5	+39 %
Safety factor of local stability of normal stress	$k^{\sigma}_{OP}/k^{\sigma}_{OG}$	1.53/5.26	1.49/5.12	-70.9 %
Safety factor for local stability of shear stress	$k^{\tau}_{OP}/k^{\tau}_{OG}$	4.65/12	2.6/11.7	- 77.77 %
Vertical static displacement, (mm)	f_{OP}/f_{OG}	26.64/31.73		-16 %
Frequency of vertical oscillation, (Hz)	f_{vOP}/f_{vOG}	6.97/6.35		+9.76 %
Frequency of oscillation in the horizontal direction, (Hz)	$f_{h_{OP}}/f_{h_{OG}}$	7.59/7.87		-3.55 %
Girder weight, (N)	G_{OP}/G_{OG}	275327/363893		-24.33 %

3.4 Reasonable parameter selection and discussion

Reasonable parameters are selected based on analyzing the influence on response function and stability condition of a vertical wall of girder.

- The factor x_1 is the girder height, which significantly affects the vertical stress, displacement, and frequency. The larger the value of x_1 is the better. Therefore, we choose the value level 4.
- Factor x_2 is the girder width, it has little influence on stress and weight. The effect of the value level is opposite. For stress and frequency of oscillation in the horizontal direction, the effect is more. Therefore, x_2 prefers to choose the high level, the value level is 3.
- Factor x_3 is the vertical wall thickness, this factor determines the crane girder weight (the smaller the better). We choose the minimum value according to the condition of local stability to vertical, the value of x_3 is 2.
- Factor x_4 is the flange thickness, selected according to the best conditions of stress, displacement, and frequency of vertical oscillation, the value level of $x_4$is 4.
- Factor x_5 is the distance between two vertical walls, it does not affect much to stress, displacement, and frequency of vibration. The value of x_5 is selected according to the condition of local stability to the vertical of the graph Fig 8. So, the value level of x_5 is 3.

Table 6 is the final result of choosing reasonable parameters for the crane girder. Using reasonable parameters in Table 6 to design the main girder with technical data is the crane designed for the Dong Nai 3 hydropower plant in Vietnam. Calculation results from the original data set are compared with the results from the new design numbers. Table 7 shows the results of the comparison and discussion. The most obvious thing is that the girder weight was reduced by 88566 N (-24.33 %) while the stress only increased (+6.16 %). All calculation results meet the technical conditions specified in [1], and [3] in Table 8. Compared with the original design, the displacement and the natural frequency of oscillation are not much deviated. The new layout design ensures suitable local stability conditions due to better utilization of the material's capabilities.

Table 8. Allowable response value

Parameter	Symbol	Load case I, II	Load case III	Condition
Normal stress, (N/mm^2)	$[\sigma]$	160	210	$\sigma \leq [\sigma]$
Shear stress, (N/mm^2)	$[\tau]$	96	126	$\tau \leq [\tau]$
Safety factor of local stability of normal stress	$[k]$	1.33	1.1	$k \geq [k]$
Safety factor for local stability of shear stress		1.33	1.1	
Vertical static displacement, (mm)	$[f]$	44.3		$f \leq [f]$
Frequency of vertical oscillation, (Hz)	$[f_v]$	2.3		$f_v \geq [f_v]$
Frequency of oscillation in the horizontal direction, (Hz)	$[f_h]$	1.8		$f_h \geq [f_h]$

4 CONCLUSIONS

The article has studied the reasonable design of the crane box girder, the goal is to find the parameters to get the lighter structure to reduce the market price of the crane. This study used the Taguchi method, ANOVA analysis to evaluate the influence of parameters by Minitab software. The paper also established the optimal algorithm. The orthogonal planning matrix is L16 for response values including girder weight, stress, local coefficient of stability, static displacement, and vibration frequency. Analysis of the S/N ratio and ANOVA have selected the optimal parameters to satisfy the constraints and reduce the volume compared to the original design.

In the application example, the girder mass is reduced by -24.33 % while the normal stress is only increased by +6.16 %. New parameters applied to the calculation ensure the specified conditions of the technique. Compared with the original design, the displacement and oscillation frequency do not deviate much. The new design ensures more consistent lump stability conditions due to better utilization of the material's capabilities. In future studies, fatigue conditions will be considered a response function when using the Taguchi method.

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