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 girders 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].

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 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 GIRDERS

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 steel girder 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, \( S_w = \{ q_w, q_s, P_s \} \). Where \( q_w, q_s \) and \( P_s \) are shown in Fig. 2. The working loads due to lifting or lowering loads \( \psi Q \) and due to unstable horizontal movements are \( S_w \). The dynamic coefficient is \( \psi \geq 1.15 \), \( \psi = 1 + \xi \nu_s \). Where \( \xi \) is the coefficient for the crane [1], \( \xi = 0.6 \), \( \nu_s \) 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:
\[ P = \frac{wQ + G_s}{4} \]  

Where \( Q \) is the load including the weight of the hanger (N), \( G_s \) is the weight of the trolley (N).

\[ q_c - \text{distributed weight of main girder (N/mm)}, \quad q_s - \text{weight distribution side girder (N/mm)}, \]  
\[ P - \text{force from the wheel on the girder (N)}, \quad P_c - \text{cabin weight (N)}, \]  
\[ P_z - \text{load due to the inertia force when moving the crane due to the weight of the trolley and the load through the wheel acting on the girder (N)}, \]  
\[ P_x - \text{load due to the inertia force when moving the trolley over the wheel acting on the girder (N)}, \]  
\[ q_c - \text{load due to inertia force when moving crane due to crane girder weight (N)}, \]  
\[ L_c - \text{crane aperture (mm)}, \quad B_s - \text{distance of two wheels (mm)}, \quad L_H - \text{distance from Cabin to girder end (mm)} \]

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:

\[ \gamma_c (S_G + P) + \gamma_s S_H \]  
\[ S_H = \{ P_c, P_z, q_c, q_s \} \]  

Where \( P_c, P_z, q_c \) and \( q_s \) are shown in Fig. 2, \( \gamma_c \) 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].

Fig. 3. Internal force diagram of the main girder

a) – due to vertical forces, b- due to horizontal forces.
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 \( M_y \) (Nmm):

\[
Q_y = Q_1 + Q_2, \quad M_y = M_1 + M_2
\]

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:

\[
\sigma_x = \frac{M_y h_c}{2 J_x}, \quad \tau_y = \frac{Q_y S}{2 J t_1}
\]

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, \( S \) is the static moment of \( \frac{1}{2} \) 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 \( M_x \) (Nmm):

\[
Q_x = Q_{x1} + Q_{x2}, \quad M_x = M_{x1} + M_{x2}
\]

Where \( Q_{x1}, Q_{x2}, M_{x1}, \) and \( M_{x2} \) are the shear force and bending moment caused by the horizontal force.

The stress at the critical section in this case is:

\[
\sigma_y = \frac{M_x h_c}{2 J_y}, \quad \tau_x = \frac{Q_y S}{2 J t_2}
\]

Where \( h_c \) 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 \( \frac{1}{2} \) section with the \( y \) axis in Fig.4.

![Diagram of Crane Girder Structure](image)

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), \( h_t \) - girder width (mm), \( t_2 \) - upper and lower flange thickness (mm), \( t_1 \) - wall plate thickness (mm), \( h_y \) - width of the vertical wall (mm), \( h_z \) - distance of rib to upper flange (mm), \( b \) - spacing of 2 longitudinal ribs (mm).

The stresses in the load cases I and II are:

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

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 \( \gamma_c = 1, \psi =1 \). The load factor during load testing is 1.25, similar to the case of vertical load in the \( y \) direction:

\[
\sigma_{3y} = \frac{M_y h_c}{2 J_y}, \quad \tau_{3y} = \frac{Q_y S}{2 J t_2}, \quad \sigma_{3y} \leq \{\sigma_3\}, \quad \tau_{3y} \leq \{\tau_3\}
\]

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) \( \gamma_c = 1 \). The load factor during load testing is 1.1, it is similar to load cases I and II including vertical and horizontal loads.

\[
\begin{align*}
\sigma_{3x} &= \frac{M_{h}}{2J_y}, \quad \tau_{3y} = \frac{Q_{y}S_{y}}{2J_y}, \quad \sigma_{3y} = \frac{M_{b}}{2J_y}, \quad \tau_{3x} = \frac{Q_{x}S_{x}}{2J_y} \quad \text{(10)} \\
\sigma_{3x} &= \sigma_{3x} + \sigma_{3y} < [\sigma_3], \quad \tau_{3y} = \tau_{3x} + \tau_{3y} < [\tau_3] \quad \text{(11)}
\end{align*}
\]

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 \( \sigma_{v_{cr}} (\text{N/mm}^2) \) and the ultimate shear stress \( \tau_{v_{cr}} (\text{N/mm}^2) \) are considered to be multiples of the Euler stress determined by formula [1]:

\[
\sigma_{v_{cr}} = k_{\sigma} \sigma_{R_{cr}}, \quad \tau_{v_{cr}} = k_{\tau} \tau_{R_{cr}}, \quad \sigma_{R_{cr}} = 189800 \left( \frac{t_f}{b} \right)^2 \quad \text{(12)}
\]

Where \( \sigma_{R_{cr}} \) is the Euler stress (N/mm\(^2\)), \( a \) 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:

\[
k_{i1} = \frac{\sigma_{i1}}{\sigma_{12}} \geq \left[ k_{i} \right], \quad k_{i} = \frac{\tau_{i}}{\tau_{12}} \geq \left[ k_{i} \right] \quad \text{(13)}
\]

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

\[
k_{i} = \frac{\sigma_{i}}{\sigma_{12}} \geq \left[ k_{i} \right], \quad k_{i} = \frac{\tau_{i}}{\tau_{3}} \geq \left[ k_{i} \right] \quad \text{(14)}
\]

Where \( \sigma_{12}, \tau_{12}, \sigma_{i}, \) and \( \tau_{i} \) 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 \( G_t \) (N) in the middle of the girder.

\[
f = \frac{0.5(Q + G_t) L^2}{48EJ_x} \leq \left[ f \right] \quad \text{(15)}
\]

Where \( E \) is the elastic modulus of the material, with steel \( E = 2.1*10^5 \) (N/mm\(^2\)), \( \left[ f \right] \) is the allowable static displacement depending on the girder aperture determined by [3].

Vibration frequency of crane girder in vertical direction is \( f_v \) (Hz) [3]:

\[
f_v = \frac{1}{2\pi} \sqrt{\frac{48EJ_x}{L^2(m_{b} + m_{t} + 0.4857m_{g})}} \geq \left[ f_v \right] \quad \text{(16)}
\]

Where \( m_{t} \) is the mass of the trolley, with \( m_{t} = \frac{G_t}{g} \) (kg), \( m_{b} \) is the crane girder mass, with \( m_{b} = \frac{G_t}{g} \) (kg), \( m_{g} \) is the payload mass, with \( m_{g} = \frac{Q}{g} \) (kg), \( \left[ f_v \right] \) is the allowed vertical vibration frequency (Hz). In this formulation, the unit of \( E \) is (N/m\(^2\)), and the unit of \( J_x \) is (m\(^4\)).

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

\[
f_h = \frac{1}{2\pi} \sqrt{\frac{k_{s}EJ_{s}}{L^2(m_{b} + k_{mg}m_{g})}} \geq \left[ f_h \right] \quad \text{(17)}
\]

Where \( k_{s} \) and \( k_{mg} \) are the coefficients, the crane has two girders, with \( k_{s} = 125 \), \( k_{mg} = 0.43 \), \( \left[ f_h \right] \) is the permissible frequency of oscillation in the horizontal direction (Hz). In this formulation, the unit of \( J_{s} \) is (m\(^4\)).
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:

$$G_{dc} = 2.10^{-7} \rho g \left[ \left( b_t + \left( h_t - 2t_c \right) t_c \right) + \frac{t_c \left( b_e - 2t_t \right) b_c + \left( b_e - 2t_t - 2h_t \right) b_t}{a} \right] + n_v LG_e + G_c$$  \hspace{1cm} (18)

Where $t_c$ is the wall thickness (mm), $n_v$ is the number of longitudinal ribs, $G_c$ is the weight of the longitudinal ribs per unit length (N/mm), $\rho$ is the density, with $\rho = 7800$ kg/m$^3$, $g$ is the acceleration gravity, with $g = 9.81$ m/s$^2$, $G_c$ 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):

$$S / N = -10 \log \left[ \frac{1}{n} \sum_{i=1}^{n} T_i^2 \right]$$  \hspace{1cm} (19)

Maximum problem (Larger better):

$$S / N = -10 \log \left[ \frac{1}{n} \sum_{i=1}^{n} \frac{1}{T_i^2} \right]$$  \hspace{1cm} (20)

Where, $u_i$ 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.

$$T_i = \{G_{dc}, \sigma, f_v, f_h\}$$  \hspace{1cm} (21)

Equation (22) describes the response functions of girder weight $\sigma_{dc}$ (N), normal stress $\sigma$ (N/mm$^2$), static displacement $f$ (mm), vertical vibration frequency $f_v$ (Hz), and vibration frequency horizontally $f_h$ (Hz).

$$\begin{align*}
G_{dc} &= \min G_{dc}(X_0, X) \\
\sigma &= \min \sigma(X_0, X) \\
f &= \min f(X_0, X) \\
f_v &= \max f_v(X_0, X) \\
f_h &= \max f_h(X_0, X)
\end{align*}$$  \hspace{1cm} (22)

Where $X_0$ is the set of given factors, $X$ 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):

$$X = \{h_t, b_t, t_c, t_e, a\}$$  \hspace{1cm} (23)

The remaining parameters $X_0$ are the independent parameters given. In the test example, there are values in Table 1.
Design factor given $X_{oi}$, original parameters $\{X_{oi}\}$

Results of the original plan girder weight $G_{0i}$, stress $\sigma_{0i}$, static displacement $f_{0i}$, oscillation frequency $f_{0i}, f_{ai}$

Design and analysis according to Taguchi method
Analyze the effects of design variables $\{X_i\}$

Change the design variable value $\{X_i\}$ design

Choose reasonable parameters $\{X_{rep}\}$

Check parameters $\{X_{rep}\}$ in load cases I, II, and III:
$\sigma < [\sigma], f < [f], \rho < [\rho], f_i < [f_i], k_i < [k_i], f_i > [f_i]$,
$\text{End}$

Fig. 5. Reasonable design diagram of crane main girder

Table 1. Independent parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loads and equipment to carry objects</td>
<td>$Q$</td>
<td>2500000</td>
<td>N</td>
</tr>
<tr>
<td>Lifting speed</td>
<td>$v_x$</td>
<td>0.05</td>
<td>m/s</td>
</tr>
<tr>
<td>Crane aperture</td>
<td>$L_c$</td>
<td>31000</td>
<td>mm</td>
</tr>
<tr>
<td>Coefficient of working mode group</td>
<td>$\gamma_c$</td>
<td>1.05</td>
<td>A3</td>
</tr>
<tr>
<td>Girder length</td>
<td>$L$</td>
<td>30000</td>
<td>mm</td>
</tr>
<tr>
<td>Trolley weight</td>
<td>$G_x$</td>
<td>700000</td>
<td>N</td>
</tr>
<tr>
<td>Cabin weight</td>
<td>$P_c$</td>
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<td>N</td>
</tr>
<tr>
<td>Distance of two wheels of the trolley on the girder</td>
<td>$B_c$</td>
<td>2250</td>
<td>mm</td>
</tr>
<tr>
<td>Elastic modulus of steel</td>
<td>$E$</td>
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<td>Material yield strength for crane girder</td>
<td>$\sigma_{ch}$</td>
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<td>N/mm$^2$</td>
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<td>Weight of one rib per unit length</td>
<td>$G_g$</td>
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<td>Number of vertical horns</td>
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<tr>
<td>Spacing of two longitudinal ribs</td>
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<td>Wall thickness</td>
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<td>The specific gravity of steel</td>
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<td>Gravity acceleration</td>
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<td>Weight of girder substructures</td>
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<td>N</td>
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<tr>
<td>Distance from cabin to girder end</td>
<td>$L_i$</td>
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Table 2. Influential factors and value levels

<table>
<thead>
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<th>Influential factors</th>
<th>Symbol</th>
<th>Value levels</th>
<th>Range of change</th>
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<tr>
<td>Girder height, (mm)</td>
<td>( h_x )</td>
<td>2200 2600 3000 3400</td>
<td>1200</td>
</tr>
<tr>
<td>Girder width, (mm)</td>
<td>( b_x )</td>
<td>800 900 1000 1100</td>
<td>250</td>
</tr>
<tr>
<td>Wall thickness, (mm)</td>
<td>( t_x )</td>
<td>8 10 12 14</td>
<td>6</td>
</tr>
<tr>
<td>Flange thickness, (mm)</td>
<td>( t_x )</td>
<td>14 16 18 20</td>
<td>6</td>
</tr>
<tr>
<td>Distance between the two vertical walls, (mm)</td>
<td>( a )</td>
<td>1000 2500 4000 5500</td>
<td>3500</td>
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</table>

3 RESULTS AND DISCUSSION

3.1 Original design plan

Design of double girder overhead crane with payload weight \( Q = 2500000 \) N, crane aperture \( c_L = 31000 \) 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 \( h = 2800 \) mm, girder width \( b = 900 \) mm, wall plate thickness \( t = 18 \) mm, flange thickness \( t_f = 25 \) 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

<table>
<thead>
<tr>
<th>N</th>
<th>( x_1 )</th>
<th>( x_2 )</th>
<th>( x_3 )</th>
<th>( x_4 )</th>
<th>( x_5 )</th>
<th>( G_{dc} ) (N)</th>
<th>( \sigma ) (N/mm(^2))</th>
<th>( k )</th>
<th>( f ) (mm)</th>
<th>( f_v ) (Hz)</th>
<th>( f_v ) (Hz)</th>
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<td>1.37</td>
<td>31</td>
<td>6.5</td>
<td>8.2</td>
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</table>

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 height \( h \), \( x_2 \) is the girder width \( b \), \( x_3 \) is the wall plate thickness \( t \), \( x_4 \) is the flange thickness \( t_f \), \( x_5 \) 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 stress $\sigma$ (N/mm$^2$), girder weight $G_{dc}$ (N), local stability safety factor $k$, static displacement in the middle of girder $f$ (mm), vibration frequency vertical $f_v$ (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 $\sigma$ (N/mm$^2$). Fig. 7 shows the influence of the vertical cell sizes which are the factors $x_1$ and $x_2$ 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 $k = 1.5$ then $x_3$ 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.

![Surface Plot of $x_1$ vs $G_{dc}(N)$, Stress (N/mm$^2$)](image1)

![Surface Plot of $x_2$ vs $G_{dc}(N)$, Stress (N/mm$^2$)](image2)

![Surface Plot of $x_3$ vs $G_{dc}(N)$, Stress (N/mm$^2$)](image3)

![Surface Plot of $x_4$ vs $G_{dc}(N)$, Stress (N/mm$^2$)](image4)

![Fig. 6. Surface plot of factors $(x_1, x_2, x_3, x_4)$ with stress $\sigma$ (N/mm$^2$) and girder weight $G_{dc}$ (N)](image5)

![Fig. 7. Surface plot of factors $x_1, x_2$ with the stable factor of safety](image6)

![Fig. 8. Graph of the relationship between girder weight and maximum stress](image7)
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 factor $x_3$ 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](image1)

![Fig.10. Main effect plot for Signal to Noise ratios, response value is stress](image2)

![Fig.11. Main effect plot for Signal to Noise ratios, response value is displacement](image3)
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 factor $x_5$. 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 is $x_2$, 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 $x_5$ 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 height $x_1$. 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

<table>
<thead>
<tr>
<th>Encode</th>
<th>S</th>
<th>R-sq</th>
<th>R-sq(adj)</th>
<th>R-sq(pred)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_1$</td>
<td>36250.6</td>
<td>37.63 %</td>
<td>22.04 %</td>
<td>0.00 %</td>
</tr>
<tr>
<td>$x_2$</td>
<td>45093.9</td>
<td>3.49 %</td>
<td>0.00 %</td>
<td>0.00 %</td>
</tr>
<tr>
<td>$x_3$</td>
<td>31276.3</td>
<td>53.57 %</td>
<td>17.46 %</td>
<td>0.00 %</td>
</tr>
<tr>
<td>$x_4$</td>
<td>44840.6</td>
<td>4.57 %</td>
<td>0.00 %</td>
<td>0.00 %</td>
</tr>
<tr>
<td>$x_5$</td>
<td>45732.3</td>
<td>0.74 %</td>
<td>0.00 %</td>
<td>0.00 %</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Encode</th>
<th>S</th>
<th>R-sq</th>
<th>R-sq(adj)</th>
<th>R-sq(pred)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_1$</td>
<td>46.9362</td>
<td>60.94 %</td>
<td>51.17 %</td>
<td>30.56 %</td>
</tr>
<tr>
<td>$x_2$</td>
<td>70.3964</td>
<td>12.13 %</td>
<td>0.00 %</td>
<td>0.00 %</td>
</tr>
<tr>
<td>$x_3$</td>
<td>68.1841</td>
<td>17.57 %</td>
<td>0.00 %</td>
<td>0.00 %</td>
</tr>
<tr>
<td>$x_4$</td>
<td>72.0100</td>
<td>8.06 %</td>
<td>0.00 %</td>
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<tr>
<td>$x_5$</td>
<td>74.6067</td>
<td>0.74 %</td>
<td>0.00 %</td>
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### Table 6. Reasonable parameters

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<th>Influential factors</th>
<th>Symbol</th>
<th>Encode</th>
<th>Reasonable level</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Girder height, (mm)</td>
<td>$h$</td>
<td>$x_1$</td>
<td>4</td>
<td>3400</td>
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<tr>
<td>Girder width, (mm)</td>
<td>$b$</td>
<td>$x_2$</td>
<td>3</td>
<td>1000</td>
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<tr>
<td>Wall thickness, (mm)</td>
<td>$t_1$</td>
<td>$x_3$</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>Flange thickness, (mm)</td>
<td>$t_2$</td>
<td>$x_4$</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>Distance between the two vertical wall, (mm)</td>
<td>$a$</td>
<td>$x_5$</td>
<td>3</td>
<td>4000</td>
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</tbody>
</table>

### Table 7. Evaluation of calculation results

<table>
<thead>
<tr>
<th>Computational response value</th>
<th>Reasonable design/Original design</th>
<th>Load case I, II</th>
<th>Load case III</th>
<th>(+) Increase, (-) Reduce</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal stress, (N/mm²)</td>
<td>$\sigma_{OP}/\sigma_{OG}$</td>
<td>150/142.52</td>
<td>155/146</td>
<td>+6.16 %</td>
</tr>
<tr>
<td>Shear stress, (N/mm²)</td>
<td>$\tau_{OP}/\tau_{OG}$</td>
<td>17/12.2</td>
<td>17.3/12.5</td>
<td>+39 %</td>
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<tr>
<td>Safety factor of local stability of normal stress</td>
<td>$k_{OP}^n/k_{OG}^n$</td>
<td>1.53/5.26</td>
<td>1.49/5.12</td>
<td>-70.9 %</td>
</tr>
<tr>
<td>Safety factor for local stability of shear stress</td>
<td>$k_{OP}^\sigma/k_{OG}^\sigma$</td>
<td>4.65/12</td>
<td>2.6/11.7</td>
<td>-77.77 %</td>
</tr>
<tr>
<td>Vertical static displacement, (mm)</td>
<td>$f_{OP}/f_{OG}$</td>
<td>26.64/31.73</td>
<td>-16 %</td>
<td></td>
</tr>
<tr>
<td>Frequency of vertical oscillation, (Hz)</td>
<td>$f_{OP}/f_{OG}$</td>
<td>6.97/6.35</td>
<td>+9.76 %</td>
<td></td>
</tr>
<tr>
<td>Frequency of oscillation in the horizontal direction, (Hz)</td>
<td>$f_{OP}/f_{OG}$</td>
<td>7.59/7.87</td>
<td>-3.55 %</td>
<td></td>
</tr>
<tr>
<td>Girder weight, (N)</td>
<td>$G_{OP}/G_{OG}$</td>
<td>275327/363893</td>
<td>-24.33 %</td>
<td></td>
</tr>
</tbody>
</table>

### 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

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

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.

5 Acknowledgment

The author would like to thank the Hanoi University of Civil Engineering for giving me the opportunity to conduct this research.

6 References


Paper accepted: 27.02.2024.
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