ANALYTICAL INVESTIGATION AND OPTIMUM DESIGN OF A DOUBLE GIRDER OVERHEAD CRANE

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ABSTRACT: *Lifting equipment's have a wide range of use in all commercial and industrial area from small to large. The machine that enables the lifting of a substance and transporting it from one place to another under conditions where human power is not enough is called a crane. Overhead cranes are frequently used in workshops and construction sites. Overhead cranes are a bridge construction that travels between two runway girders that form the high-rise crane running path. Initial investment cost in facilities is very important. High-weight equipment, such as bridge cranes, must both work efficiently without any security weakness and be of optimum weight. For this, optimum system design should be made. The aim of this study is to optimize the cross-section values of the girder in order to bring the unit weight to the most reasonable level. In this study, analytical calculations based on FEM and DIN standards were used for calculations. Practical Design Optimization steps were determined for optimization by using analytical solutions. Optimization has been performed on the cross sectional values of girders so as to reduce the unit weight which is the main cause of production costs. Results indicate that the unit weight of girder decreased 32.16% after comprehensive optimization process was performed.*

KEYWORDS: *Optimization; stress analysis; overhead cranes*

1.0 INTRODUCTION

Cranes can be found in the form of portal cranes, overhead cranes, cantilever cranes and tower cranes, portal cranes, rotary cranes, cable cranes, vehicle cranes, depending on their usage, location and shape [1]. Cranes are steel transport elements used for lowering and lifting loads by moving in three axes. They have a very important place in terms of engineering. Overhead cranes are manufactured as single and double girder. They are defined by their lifting capability, that is, the maximum value of the load to be transported and the bridge span [2]. Initial investment cost is very important in businesses. It is essential that high-weight equipment such as overhead cranes can both do their job efficiently without any security weakness and be at optimum weight. For this, optimum system design should be made. It is very important to work in optimum conditions in the field of application for an engineer. In literature, studies on overhead cranes have generally been carried out on either theoretical calculations or numerical analyses based on finite element method instead of detailed optimum crane design.

Alkın et al. [3] studied a bridge crane having double box girder and analysed a crane with 13 m span length and 35 tons' capacity. Ling et al. [4] established the finite element analysis model of a bridge crane and analyzed the stress distribution of the critical structure under different loading conditions. Sowa and Kwiaton [5] presented a numerical simulation and mathematical model of the gantry crane beam. Patel [6] made structural analysis of overhead crane girder using finite element analysis technique. Sushma and Malviya [7] performed a load analysis on electric overhead travelling crane girder in order to find out the safe load bearing capacity of girder. Ramamurthy and Nagababu [8] built three dimensional geometry of the workstation gantry crane in CATIA and performed stress analysis. Yeşilbel et al. [9] reached optimum design of an overhead crane construction by using bee algorithm in order to have minimum weight while fulfilling the desired technical and functional features. Abid et al. [10] performed optimization via parametric design of the main girder box type for a 150 tons' capacity and 32m long span crane. Mohamed and Abdelwahab [11] performed structural design optimization box-type double-girder overhead crane using weighted decision matrix. Przybylek and Wieckowski [12] presented a method for assessing the technical condition of overhead crane equipment by means of non-destructive methods and numerical simulation. Molnar et al. [13] performed strength analysis of the main girder of a single girder bridge crane model in the means of comparing analytical and numerical solutions. Investigated crane capacity was 500 kg.

It is very important to reduce costs in facilities. Bridge cranes are heavy and carry heavy loads. Those must both work safely and be of optimum weight. For this, optimum system design should be made. The aim of this study is to optimize the cross-section values of the girder in order to bring the unit weight to the most reasonable level. In this study, the crane bridge of a double-girder overhead crane, which was already designed for production but abandoned due to production costs, was studied. First, analytical calculations were made according to FEM and DIN norms. Then, optimization steps were determined on the existing girder. As a geometric constraint, which is one of these optimization steps; bridge span-side plate height ratio, side plate height-top plate width ratio, and side plate thickness-top plate thickness pairs were determined. In this study, a reduction in beam cross-sectional dimensions has been attempted by taking into account the stresses that the crane material can withstand according to operating conditions. These calculations, which are made to reach the smallest size and weight by trying many different combinations, are called optimization. The optimum result was obtained among these values. The initial state of the bridge and the final state with the obtained values were modeled in the Solidworks and finite element analyses were made in the ANSYS. The analytical results obtained and the numerical analysis results obtained in ANSYS were compared and discussed. The results were found to be consistent with each other.

2.0 MATERIALS AND METHOD

There are two main situations in crane girder calculations, these are the calculation of the beam material and the calculation of the elements that combine the beam material. The way to be followed for the calculation of the beam material is to calculate the stresses in the component first and then strength value of the material is found, crane design is completed according to the selected or given safety size at last. A weld joint is often used to join the girder materials. Bolts are also used as connecting elements to facilitate the transportation and assembly of main elements such as girder and crane runway. In crane calculations, first of all, the force and therefore the force coefficients must be determined. Values such as the type and location of the crane, cross section dimensions, strengths, loading status, loading group, loading class, manufacturing type for the girder, material used are either accepted or selected in crane calculations. After the working place and type of the crane are determined by the customer, the crane design is made by means of analytical calculations [14]. The accuracy of the crane design can also be checked by numerical analysis studies using the finite element method. Optimization studies are used for the design according to the minimum material principle and to minimize the manufacturing costs. In this study, optimization has been made for a double-girder overhead crane with a lifting capacity of 26 tons and a bridge span of 13 meters with A100 type rail on K08 box girder. The girder section before optimization is given in Figure 1.

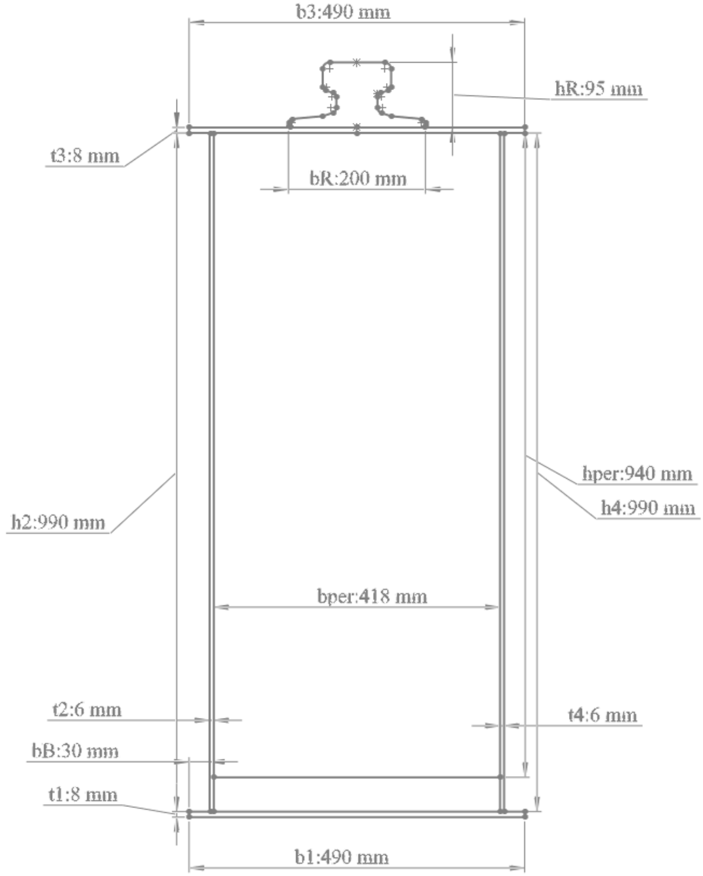

Figure 1: Initial state cross-sectional area before optimization

Before the optimization phase, mathematical modeling and analysis were made and our reference state was determined before the optimization. Static load calculations based on FEM and DIN standards were used for this mathematical modeling and analysis.

The design values for the crane construction studied can be listed as follows: crane capacity is 26 ton, lifting velocity is 4 m/min, trolley weight is 5 ton, trolley running velocity is 16 m/min, lifting height is 8 m, trolley axle clearance is 2 m and bridge length is 13 m. Loading status is *H*. The loading group and lifting class are determined as *B3* and *H2*, the driving and notch groups are determined as *2m* and *K3*. Lifting load coefficient (Ψ), specific weight coefficient (φ) and loading group coefficient (k_B) are determined as 1,218, 1,1 and 1,05 respectively considering DIN norm [11]. In the analytical calculation of crane girder of double-girder overhead crane according to FEM [15] and DIN norms, deflection limit, wheel vertical force, moments of inertia of the girder about the x and y axes, cross sectional area of girder structure, coordinate of centroid, section modulus, unit weight of girder, stresses on girder (stress due to girder self-weight, stress due to trolley weight, stress due to rated load, stress due to inertia forces, stress due to trolley contraction, maximum shear stress), static strength control and dynamic strength control values are calculated and those yield to assess crane safety condition. Static strength control formula is given in Equation (1) [14].

$$\frac{\sigma_{çEM}}{\sigma_V} \geq 1 \tag{1}$$

Dynamic strength control formula is given in Equation (2a) and (2b)[14].

$$\sigma_{DÇEm} = \frac{5}{3}\ x\ \frac{\sigma_{DEm}}{1-\left(1-\frac{5}{3}\ x\ \frac{\sigma_{DEm}}{0{,}75\ R_m}\right) x\ \kappa} \tag{2a}$$

$$\frac{\sigma_{DÇEm}}{\sigma_V} \geq 1 \tag{2b}$$

where $\sigma_{çEM}$ is safety strength value of the material under static loading considering loading status (*H*), σ_V is Von-Mises stress, σ_{DEm} is safety strength value of the material under dynamic loading considering notch groups (K_3), $\sigma_{DÇEm}$ is dynamic tensile stress, R_m is tensile strength of material, κ is stress ratio.
Von-Mises stress formula on overhead crane girder is given in Equation (3) [14].

$$\sigma_V = \sqrt{{\sigma_{max}}^2 + (3\ x\ {\tau_{max}}^2)} \tag{3}$$

Girder maximum and minimum stresses and maximum shear stress formula for *H* loading status are given in Equation (4), (5) and (6) [14].

$$\sigma_{max} = k_B\ x\ (\sigma_1 + \sigma_2 + (\Psi\ x\ \sigma_3) + \sigma_4 + \sigma_5) \tag{4}$$

$$\sigma_{min} = \sigma_1 + \sigma_2 \tag{5}$$

$$\tau_{max} = \frac{(\Psi\ x\ F_Y) + (k_B\ x\ F_A)}{4\ x\ t_2}\left[\frac{X_{S4} + (0.2\ x\ Y_{SR})}{(X_{S2} + X_{S4})x(Y_{S1} + Y_{S3})} + \frac{1}{h_2}\right] \tag{6}$$

where σ_1 is stress due to girder self-weight, σ_2 is stress due to trolley weight, σ_3 is stress due to rated load, σ_4 is stress due to inertia forces,

σ_5 is stress due to trolley contraction, τ_{max} is maximum shear stress, σ_{max} is maximum normal stress, F_Y is rated load (26 ton), F_A is trolley weight (5 ton), t_2 is side plate thickness (6 mm), X_{S4} is x-distance of right side plate from centroid (212 mm), X_{S2} is x-distance of left side plate from centroid (212 mm), Y_{S1} is y-distance of bottom side plate from centroid (677,2 mm), Y_{S3} is y-distance of top side plate from centroid (320,8 mm), Y_{SR} is y-distance of rail from centroid (367,7 mm), h_2 is length of right vertical plate (990 mm). Optimization is based on the aim of ensuring that the least material can be used so that the static and dynamic safety coefficients do not fall below 1. Crane material is St37 steel where yield strength is 235 MPa, breaking strength is 340 MPa, modulus of elasticity is 210 GPa, poisson ratio is 0.3 and density is 7850 kg/m^3.

After the mathematical formulation, Practical Design Optimization steps were determined for optimization. The objective function is to identify design variables and determine their constraints. Unit weight was chosen as the objective function. This is because, as stated above, the most important parameter affecting costs is unit weight. Unit weight (q_{kk}) formula of the girder is given in equation (7).

$$q_{kk} = A_t x\, \rho_{st}\, x\, k_t = 0.02928\, m^2\, x\, 7850\, \frac{kg}{m^3} x\, 1.03 = 236.7 \frac{kg}{m} \quad (7)$$

Overhead crane girder also contains support plates inside. Unit weight of an inside support plate is found by using Equation (8).

$$q_{kp} = h_{per}\, x\, b_{per}\, x\, t_{per}\, x\, \rho_{st} = 0.94\, x\, 0.418\, x\, 0.006\, x7850 = 18{,}5\, kg \quad (8)$$

Total unit weight (q_k) formula of the girder is given in equation (9).

$$q_k = q_{kk} + \frac{q_{kp}}{L_p} = 236.7\, \frac{kg}{m} + \frac{18.5\, kg}{2\, m} = 245.9\, \frac{kg}{m} \quad (9)$$

where A_t is cross sectional area of Figure 1, ρ_{st} is density of material, k_t is tolerance, h_{per}, b_{per} and t_{per} are height, width and thickness of inside support plate.

As a result of the analysis, the unit weight of the original crane girder was found to be 245.9 kg/m. In addition, as a result of the literature, it was determined that the A type rail used in the crane is rare in the industry. However, for the crane with a lifting capacity of 26 tons investigated, it was observed that the A100 type rail was not functional in terms of cross-sectional area, so in the next stages of the optimization, standard 40 mm x 40 mm (rail width x rail height) flat rails were used instead of the A Type rail in order not to increase the unit weight. In order to determine the optimum unit weight, its cross-section should also be optimum. For this reason, the optimization variables forming the section are as follows [16,17]

$$\vartheta = f(b, t_1, t_2, h)$$

where b is top plate width, t_1 is bottom plate thickness, t_2 is side plate thickness and h is side plate height. The geometric constraints created according to the determined optimization variables are as follows.

$$12 \leq \frac{L_K}{h} \leq 15; \text{ (girder clearance / side plate height)}$$

$$1 \leq \frac{h}{b} \leq 3{,}5; \text{ (side plate height / top plate width)}$$

$$6\, mm \leq t_1, t_2 \leq 10\, mm \text{ (each within 6 mm-10mm)}$$

Finite element method is used to analyze the physical effects of loads and deformations in structural elements. The system creates a wide mesh by combining the mathematical equations on each element. Computer aided software is used to solve this divided structure. Finite element analysis has been done on crane construction before and after optimization by means of ANSYS.

3.0 RESULTS AND DISCUSSION

In this study, the crane bridge of a double-girder overhead crane has been investigated. Analytical calculations were made in accordance with FEM and DIN norms. Optimization steps were determined on the existing girder regarding analytical solutions. Unit weight was chosen as the objective function. Optimization has been made for a double-girder overhead crane with a lifting capacity of 26 tons and a bridge span of 13 meters with A100 type rail on K08 box girder. Optimum section dimensions were determined considering the determined ratios and combinations of pairs. The initial and final state of the girder were modeled in the Solidworks and finite element analyses were made in the ANSYS.

Optimum section dimensions were determined considering geometric constraints within the ranges mentioned above by making 126 combinations of the determined ratio and intervals, analytical calculations of the values selected from the geometric constraint intervals were made. Optimization results when the factor of safety and unit weight decreases to the lowest allowable values only are presented in the Table 1.

Optimization results indicate that when L_K/h=13, h/b=2.5, t_1=8 mm and t_2=6 mm values were used unit weight of the girder q_k is found as 169 kg/m. When a more sensitive analysis was made, it was seen that the unit weight of girder decreased to 166,8 kg/m when the h/b ratio was 2.6. It was observed that all safety factors were within reliable limit at the h/b=2,6 ratio. Due to this reason, the optimum girder sizes and unit weight results obtained as a result of the optimization are: b=385 mm, h=1000 mm, t_1= 8 mm, t_2 = 6 mm, L_k/h= 13, h/b= 2,6 and q_k = 166.8 kg/m. The cross-sectional area after optimization is shown in Figure 2.

The unit weight of the girder in its initial state was found to be 245.9 kg/m. As a result of the analytical calculations, the improvement provided by the optimization was found to be 32.16%.

Table 1: Optimization results of investigated girder

b(mm)	h(mm)	t_1(mm)	t_2(mm)	q_K (kg/m)	L_K/h	h/b	Static safety	Dynamic safety
286	1000	8	6	151,7	13	3,5	0,849	1,123
333	1000	8	6	158,9	13	3	0,956	1,265
385	**1000**	**8**	**6**	**166,8**	**13**	**2,6**	**1,064**	**1,408**
400	1000	8	6	169	13	2,5	1,094	1.447
500	1000	8	6	184,2	13	2	1,28	1,693
667	1000	8	6	209,6	13	1,5	1,554	2,056
1000	1000	8	6	260,1	13	1	2,008	2,657

Crane construction before and after optimization was modelled by means of SolidWorks and analysed by means of ANSYS. Each end of double-girder is fixed and standard gravity and rated load (26 ton) are exerted upon the crane structure. Boundary conditions and forces applied are shown in Figure 3. Hexahedral elements were used for meshing. Mesh structure had 961549 nodes and 903095 elements. Static structural analysis type was selected. The stress contour on the crane before the optimization is shown in Figure 4. The maximum Von-Mises stress occurred on the girder was found as 141.76 MPa as a result of the applied force of 254973 N (26 tons). The stress contour on the crane after the optimization is shown in Figure 5.

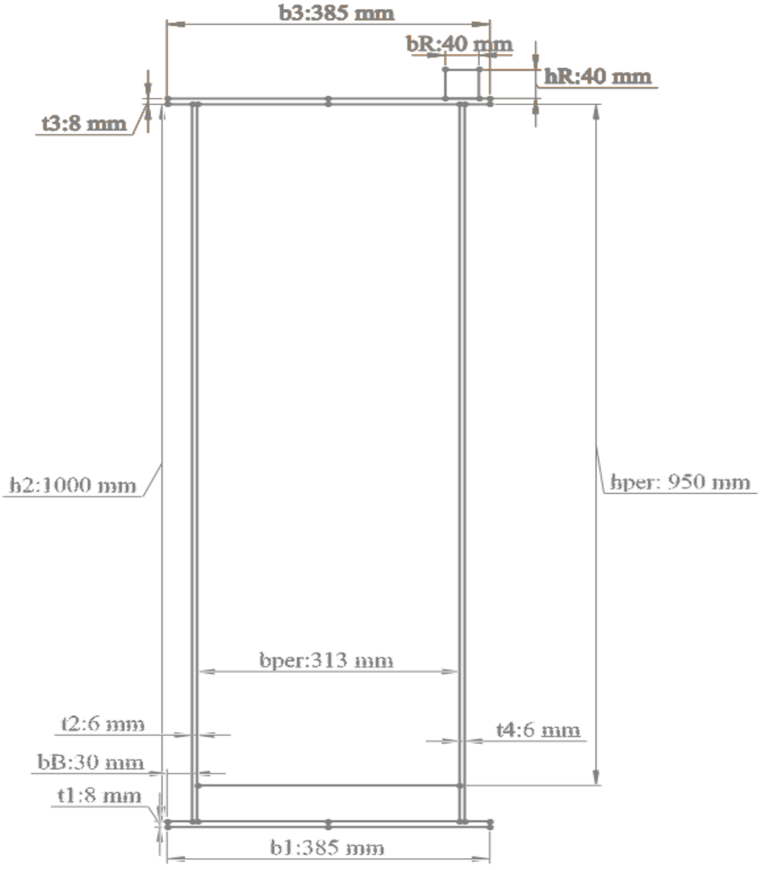

Figure 2: The cross-sectional area after optimization

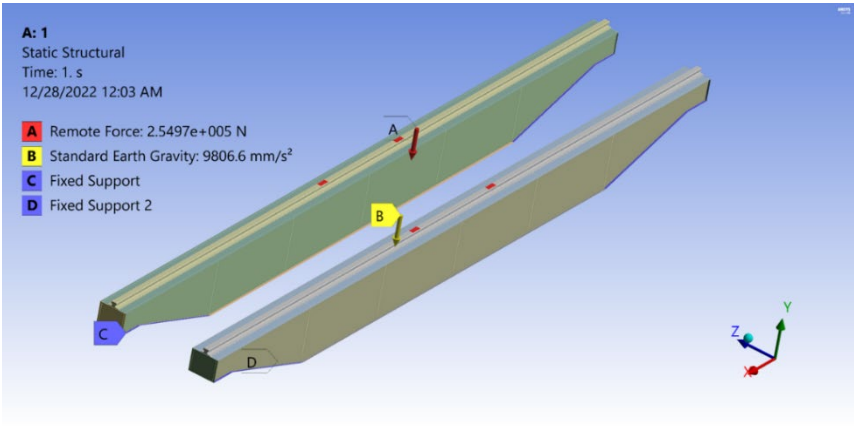

Figure 3: Boundary conditions in the finite element analysis

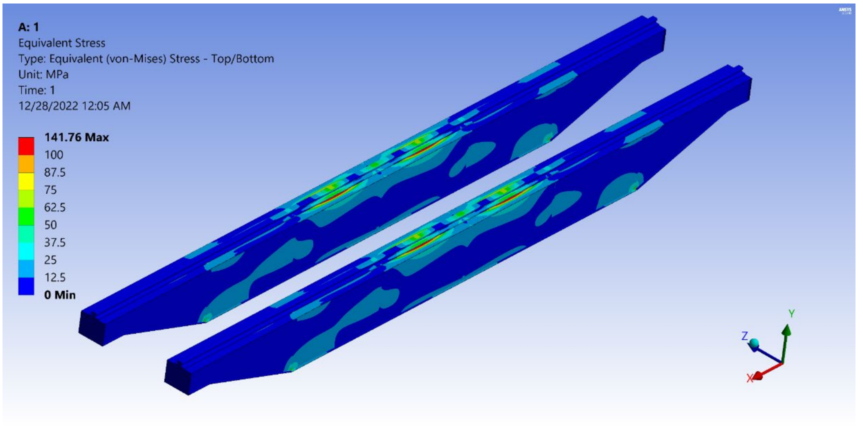

Figure 4: Stress contour on crane before optimization

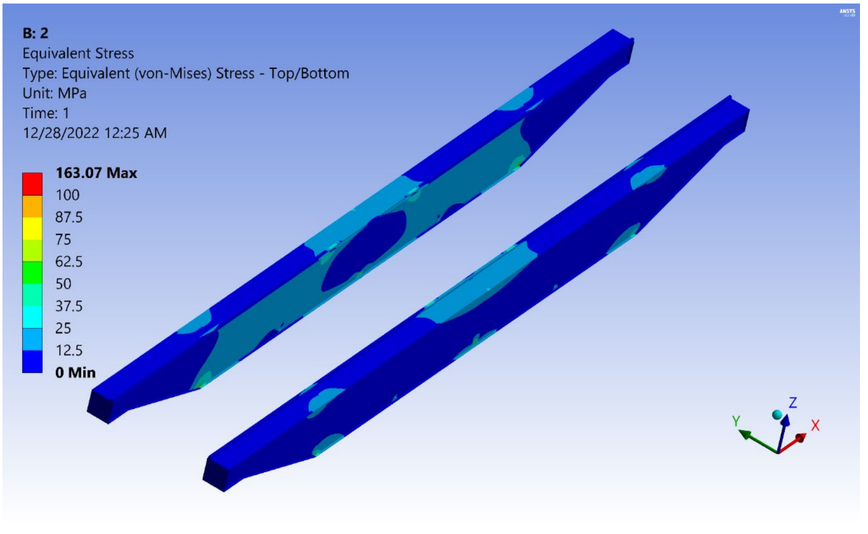

Figure 5: Stress contour on crane after optimization

The maximum Von-Mises stress occurred on the girder after optimization was found as 163.07 MPa. The maximum Von-Mises stresses occurred on the girder before/after optimization have been shown in Table 2.

Table 2: Von-Mises stresses on investigated girder

Girder	q_K (kg/m)	σ_V (Analytical)	σ_V (FEA)
K08 box girder	245.9	121.3	141.76
K08 box girder (optimized)	166,8	150.4	163.07

Von-Mises stress increased by 23.99% and 15.03% after optimization in terms of analytical calculation and FEA results. It is seen that there are 14.43% and 7.76% differences respectively when the before/after optimization results of analytical and finite element analysis (FEA) are examined. In [11], authors investigated double girder crane having 10-ton capacity and 23,412 m span and they found that Von-Mises stress was 89.71 MPa. In [13], authors investigated single girder crane having 500 kg capacity and 1.6 m girder length and they found that bending stress was 88.823 MPa.

3.0 CONCLUSION

The cross-section dimensions and weights of the cranes can be reduced and the initial investment costs of the facility can be reduced significantly by taking into account the allowable stress values of the used material. Considering the design constraints stipulated by the standards, certain improvements are aimed according to the initial situation. In this study, the crane bridge of a double-girder overhead crane, which was already designed for production but abandoned due to production costs, was studied. Analytical calculations based on FEM and DIN standards, optimization of section properties of girder and finite element analyses were performed. The unit weight of the original crane girder was found to be 245.9 kg/m. It was seen after the comprehensive optimization process that the unit weight of girder decreased to 166.8 kg/m when the h/b ratio was 2.6. It brought 32.16% reduction in unit weight after optimization on crane structure. The maximum Von-Mises stress occurred on the girder before optimization was found as 121.3 MPa analytically and 141.76 MPa numerically. The maximum Von-Mises stress occurred on the girder after optimization was found as 150.4 MPa analytically and 163.07 MPa numerically. The results were found to be consistent with each other.

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