Robust Optimization Design of Overhead Crane with Constraint Using the Characteristic Functions

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This study uses a characteristic function to explain correlations between the objective function and design variables. For the use, structural analysis and buckling analysis are carried out. the dimensional change of an original overhead crane is made based on the table of orthogonal array. For two functions or more, the effectiveness of design change can be evaluated in accordance with change in design parameters. Also, the overhead crane's weight is reduced by up to 10.55 percent while its structural stability maintained.

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1. Introduction

It is very important and essential to make the overhead crane lighter in the economic aspect of the cost minimization and reduction of the material usage. The flange and web in the girder and saddle of the existing cranes have been designed by using conventional dimensions for a long time. This means that those cranes have been redundantly designed in strength. Thus, it is necessary to design a lighter overhead crane while the strength is kept unchanged.

To this end, the crane is subjected to the dimensional optimization with such design variables as flange and web thicknesses of the girder and the saddle. All conditions of the design are given in accordance with standards of KS A1627(JIS B8821)[1,2]. Constraints used are that maximum stress and maximum deflection do not exceed allowable stress and deflection, respectively, and that buckling critical load is larger than maximum vertical or horizontal dynamic load. Further the structural analysis, buckling analysis and the table of orthogonal array are used for optimal design[3,4]. The table does not reflect a constraint function as defined in the optimum design, so a characteristic function is introduced[5~8]. In the characteristic function, a response value with weight, stress, deflection and buckling strength all considered is quantified through analysis of means.

2. Constraint Problem Using Characteristic Function

2.1 Characteristic Function

To solve a constraint problem, it is first needed to define a characteristic function, $\Psi(x)_{new}$. The characteristic function is a penalty function, $P(x)$ which involves an initial response value and a deviation from the constraint. Obtained from experiments based on the table of orthogonal array, response values do not include some constraints that are applied for an optimal design.

Procedures of the optimum design of an overhead crane can be expressed as the following equations.

Minimize :

$$W(t_{vr},\cdots,sth_{down}) \tag{1}$$

Subject to :

$$\frac{|\sigma_{\max}|}{\sigma_{al}} - 1 \leq 0 \tag{2}$$

$$\frac{|u_{\max}|}{u_{al}} - 1 \leq 0 \tag{3}$$

$$\frac{p_{al}}{p_{\max}} - \frac{1}{2} \leq 0 \tag{4}$$

$W(t_{vr},\cdots,sth_{down})$ as shown in the above equation (1) are weights of the overhead crane which is subject to such variables as thicknesses of upper and lower flanges and those of right and left webs in its girder and saddle. As shown in the other equations, (2) to (4), σ_{al}, u_{al} and p_{al} are respectively an allowable stress, allowable deflection and allowable buckling load.

In each experiment based on the table of orthogonal array, a characteristic function that has feasible constraints is defined. As shown in the following equations, (5) to (7), penalty functions are first defined to treat such constraints.

$$P_1(t_{vr},\cdots,sth_{down}) = \alpha \cdot Max\left[0, \frac{|\sigma_{\max}|}{\sigma_{al}} - 1\right] \tag{5}$$

$$P_2(t_{vr},\cdots,sth_{down}) = \beta \cdot Max\left[0, \frac{|u_{\max}|}{u_{al}} - 1\right] \tag{6}$$

$$P_3(t_{vr},\cdots,sth_{down}) = \gamma \cdot Max\left[0, \frac{p_{al}}{p_{\max}} - \frac{1}{2}\right] \tag{7}$$

, where α, β and γ are penalty coefficients that adjust the extent to which objective and penalty functions contribute to constraints. In the above equation, (5), the maximum value of the penalty function will be zero(0) if the stress meets its constraint and $\alpha(\sigma_{max}/\sigma_{al}-1)$ if not. Here, if $\alpha(\sigma_{max}/\sigma_{al}-1)$ is too high, response value minimization is meaningless. If $\alpha(\sigma_{max}/\sigma_{al}-1)$ is too low, a certain optimum level as calculated is likely to be within an infeasible region.

In the above equations, (5) to (7), the extent to which the penalty functions are influential should be adjusted with the coefficients, α, β and γ. Thus the characteristic function can be defined as follows. W_0 is the initial weight of the overhead crane.

$$\Psi(t_{vr},\cdots,sth_{down})_{new} = \frac{W(t_{vr},\cdots,sth_{down})}{W_0} + \sum_{i=1}^{3} P_i(t_{vr},\cdots,sth_{down}) \qquad (8)$$

2.2 Sensitivity Analysis using Signal-to-Noise Ratio

With the table of orthogonal array, it is possible to realize and determine a desirable optimal condition and evaluate the stability of the condition. The table also makes it possible to reduce the size of experiments by confounding some ignorable design variables with main effects. In this study, the researchers analyzed effects of design factors on design values. In the analysis, signal-to-noise ratios were basically used. Taguchi defined several ratios of signal to noise in accordance with performance characteristics. Induced from a quality loss function, the ratio of signal to noise is a measure that considers both the mean and distribution of performance characteristics. Maximum stress and maximum deflection are smaller-the-better type, while buckling coefficient is a larger-the-better type. Signal-to-noise ratio is shown here for each of the types.

.smaller-the-better type

$$\eta_s = -10\log_{10}\left(\frac{1}{n}\sum_{i=0}^{n} y_i^2\right) \qquad (9)$$

.larger-the-better type

$$\eta_l = -10\log_{10}\left(\frac{1}{n}\sum_{i=0}^{n} \frac{1}{y_i^2}\right) \qquad (10)$$

, where n is the frequency of repeated measurements under a combination of similar control factors and y_i is a value for each measurement.

2.3 Optimum Design

For an optimum design, the table of orthogonal array and factors and their level are first determined. Then both structural analysis and buckling analysis are carried out to obtain response values of maximum stress, maximum deflection and buckling coefficient. If any of the values exceeds its constraint, it is necessary to get a new specific value, or a new characteristic function by adjusting coefficients that control the influence of penalty functions. When each of the matrices on the table is experimented, a corresponding objective function can be obtained.

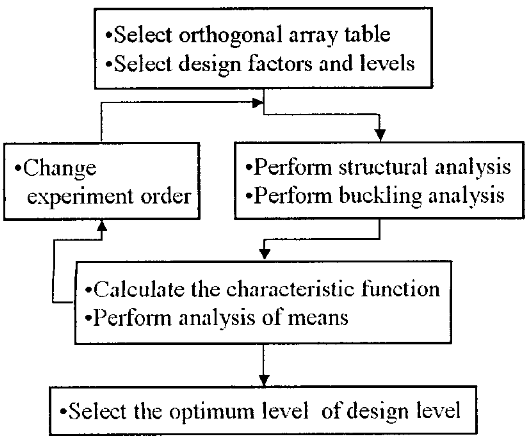

Fig. 1 Process of the application design optimization

Then it is possible to obtain a response value by using the characteristic function which corresponds to the objective function. Finally, an optimum design level can be determined through analysis of means under the characteristic function. All these procedures are illustrated in Fig. 1.

3. Finite Element Analysis of Overhead Crane

Finite elements are isotropy, homogeneity and linear elasticity. An overhead crane used is magnet overhead crane(25/20 tons × 27.6 m) which was manufactured by a company named W. Those elements were geometrically modeled in accordance with ANSYS' shell 181, beam 188 and solid 45. the model in Fig. 2 consists of 101,899 elements and 104,944 nodes.

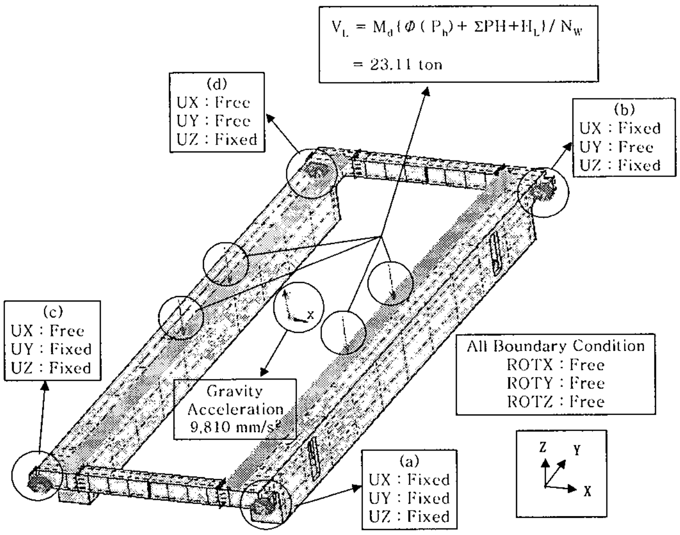

Fig. 2 Load and boundary condition of crane

The program this study used for finite element analysis is ANSYS Ver. 7.1. As shown in Fig. 2, boundary conditions are applied to joints between the saddle and the bogie. In the figure, (a) bounds transitional displacement in

Table 3 Load conditions

Load condition (KS A1627 / JIS B8821 : Class Ⅲ)	Value
Wheel reaction force(R_{max})	17.53 ton
Vertical dynamic load(V_L)	23.11 ton
Horizontal load(H_L)	0.54 ton
Applied 3D self weight (Seismic effect)	11.78 m/s^2

Table 3 shows load conditions of the crane. And Table 4 lists resources of the crane.

To calculate the vertical load, the wheel reaction force, generated on a contact between the wheel of trolley and the rail, was first obtained by using the equation (11).

Table 4 Resources of crane

Item list	Value
Trolley self weight(ΣPH)	27.5 ton
Main hoisting load(P_h)	40 ton
Trolley wheel base(W_B)	4,600 mm
Number of T/S wheel(N)	4 ea.
Trolley hook approach(d_a)	2,150 mm
Duty load coefficient(M_d)	1.1
Impact load coefficient(Φ)	1.4
Traversing speed(V_S)	60 m/min
Acceleration of gravity(g)	9.814 m/s^2
Seismic coefficient(Θ)	1.2

The vertical dynamic load(V_L) was calculated by using the equation (12). For this calculation, impact load(Φ) and duty load coefficients(M_d) for the crane group III, respectively 1.4 and 1.1 as shown in Table 5, were used. The area of contact between the wheel and the rail is 2,341 mm^2, which is a multiplication of the contact breadth by the rail's upper width, 50 mm × 46.82 mm, in accordance with KS A1627(JIS B8821). On the surface of contact between the wheel and the rail, a distributed load which is the division of the vertical dynamic load by the contact area was imposed.

$$R_{max} = \frac{\Sigma PH}{N} + \frac{2 \times P_h \times (W_B - a)}{W_B \times N_w} \tag{11}$$

$$V_L = \frac{M_d \{ (\Phi \times P_h) + \Sigma PH + H_L \}}{N_w} \tag{12}$$

$$\beta = 0.008 \sqrt{V_S} \tag{13}$$

Table 5 Coefficients of duty load and impact load

Coefficient \ Group of crane	Ⅰ	Ⅱ	Ⅲ	Ⅳ
Impact load(Φ)	1.1	1.25	1.4	1.6
Duty load(M_d)	1.0	1.05	1.1	1.2

For the calculation of the horizontal load(H_L), as shown in the equation (14), an inertial force that is generated in accordance with the horizontal movement, running, lead-in or turning of the crane, is multiplied by the weight of the moving part of the crane and then by the winch load and finally by β. Here, β is a coefficient for the horizontal movement or running of the crane. It equals to the value indicated in the equation (13). The horizontal load of 0.54 tons, which is a multiplication of β by the sum of the winch load and the trolley's net weight, is substituted in the equation (12). Then the vertical dynamic load of 23.11 tons(226,802 N) is divided by the area of contact between the wheel and the rail to obtain a distributed load. Finally, the distributed load is imposed on the surface of contact between the wheel and the rail.

Wind load is one of the horizontal loads. However, wind load is not considered in this study because the magnet overhead crane is installed indoors. In contrast, earthquake load is considered here. As shown in the equation (15), the acceleration of gravity is multiplied by a seismic coefficient(Θ).

$$H_L = \Sigma PH \times P_h \times \beta \tag{14}$$

$$G = g \times \Theta \tag{15}$$

The allowable stress(σ_{al}) of the overhead crane is 163.3 MPa in maximum. This maximum value was obtained by considering a yield strength(σ_y : 245 MPa) specified in KS A1627(JIS B8821) and the safety ratio of 1.5(S_s) specified in Table 6. Another constraint of the crane, allowable deflection(u_{al}) is 34.5 mm which is 1/800 of the total length of the girder(span : 27,600 mm). The last constraint, or allowable 1st buckling strength is a multiplication of maximum working load by the safety ratio of 2(S_b).

In the multiplication, the structural safety of the crane was considered. According to JIS B8821, the allowable value of local buckling coefficient is 1.4 under FEM. All allowable conditions of the overhead crane are shown in Table 7.

Fig. 3 shows web thicknesses as design variables of the girder and the saddle. The variables of the girder are four in number and those of the saddle three in number.

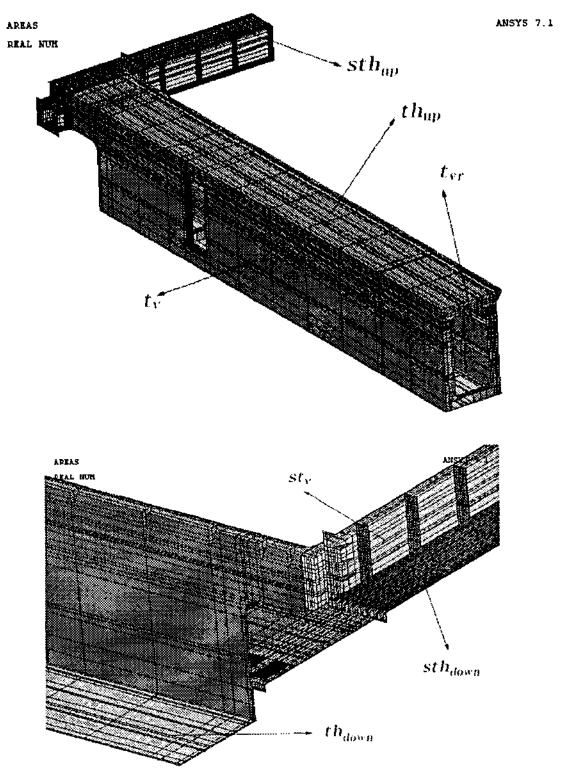

Fig. 3 Design variables of girder and saddle

Table 6 Safety ratio

Load state	Safety ratio	
	Yield point	Tensile strength
A	1.5	1.8
B	1.3	1.6
C	1.15	1.4

Table 7 Allowable conditions

Allowable conditions	Value
Allowable stress($\sigma_{al} \leqq \sigma_y / S_s$)	163.3 MPa
Allowable deflection($u_{al} \leqq Span/800$)	34.375 mm
Allowable 1st buckling strength ($p_{al} \geqq p_{max} \times S_b$)	$2 \times p_{max}$

4. Results & Discussion

4.1 Optimal Crane Design using Table of Orthogonal Array

Table 8 shows results of structural and buckling analyses with the table of mixed orthogonal array, $L_{18}(2^1 \times 3^7)$. It provides maximum stress, maximum deflection, 1st buckling coefficient and crane weight for each experiment. Here, crane weight does not include rail weight.

In Table 9, the value of each factor at its 3rd level indicates the thickness of the factor in the initial model of the overhead crane. The thickness is based on KS Standards, but somewhat reduced here in order that the crane can be lighter in weight than the initial model

Table 8 Analysis results according to table of orthogonal array $L_{18}(2^1 \times 3^7)$

Exp. no.	Maximum stress (MPa)	Maximum deflection (mm)	1st buckling coefficient	Weight (ton)
1	272.892	46.090	1.101	28.520
2	267.276	36.946	1.213	33.704
3	264.057	31.369	1.224	38.887
4	192.933	36.789	1.231	32.886
5	192.357	32.890	2.937	36.847
6	179.613	35.386	3.264	37.145
7	158.911	37.905	1.249	33.937
8	149.076	33.183	3.170	37.136
9	178.610	29.606	2.705	41.571
10	279.572	37.952	1.140	31.523
11	264.664	39.999	1.237	33.331
12	257.374	35.214	1.249	36.257
13	191.819	35.052	1.264	33.349
14	190.802	37.682	2.779	34.409
15	186.086	32.420	3.203	39.118
16	190.711	35.732	1.287	34.655
17	171.410	30.872	3.264	38.328
18	141.250	33.147	4.997	39.661

Table 9 Factors and levels

Level \ Factor	t_{vr}	t_v	th_{up}	th_{down}	st_v	sth_{up}	sth_{down}
1	4	4	4	4	6	6	6
2	6	6	6	6	8	8	8
3	8	8	8	8	10	10	10

4.2 Characteristic Function for Constraint Problem

Constraint and non-constraint problems can be solved with the table of orthogonal array. For the solution of a constraint problem, however, it is required to prepare a formula by which the feasibility of constraints can be evaluated.

Table 10 shows results when constraints listed in Table 8 were substituted into a characteristic function, or the equation (8). Thus the optimum level of each factor could be determined through the characteristic function with constraints considered.

Table 10 Characteristic function and S/N ratio

Exp. no.	Characteristic function	S/N ratio
1	2.501	-7.96227
2	2.139	-6.60422
3	2.153	-6.66088
4	1.420	-3.04577
5	1.129	-1.05388
6	1.045	-0.38233
7	1.194	-1.54009
8	0.869	1.21960
9	1.113	-0.92990
10	2.283	-7.17012
11	2.179	-6.76514
12	2.034	-6.16702
13	1.350	-2.60668
14	1.150	-1.21396
15	1.125	-1.02305
16	1.375	-2.76605
17	0.971	0.25562
18	0.928	0.64904

4.3 Dimensional Optimum Design of Overhead Crane

Table 11 shows effects of factors, deviations and percentage contributions for the characteristic function that is smaller-the-better in type.

Table 11 Factors affecting the characteristic function

Factor	Effect		
	1	2	3
t_{vr}	2.2148	1.2032	1.0750*
t_v	1.6872	1.4062	1.3997*
th_{up}	1.5515	1.4623*	1.4792
th_{down}	1.4995	1.4937*	1.4998
st_v	1.4617*	1.5055	1.5258
sth_{up}	1.5503	1.4595*	1.4832
sth_{down}	1.4725*	1.5335	1.4870

* Optimum level

For example, the effect of factor t_{vr} at its lst level is evaluated through determining a deviation from the mean of characteristic function values for the experiments 1, 2, 3, 10, 11 and 12. The effect of every factor can be evaluated in the same way.

Fig. 4 illustrates the analysis of factor effects on the characteristic function. For the analysis, a statistical software program, MINITAB R(13)[9] was used. In addition, the mean value was calculated over all factor levels. The factor effects were compared to find that it is optimal to combine t_{vr}(level 3), t_v(level 3), th_{up}(level 2), th_{down}(level 2), st_{vr} (level 1), sth_{up}(level 2) and sth_{down}(level 1). These are indicated with asterisk marks(*) in Table 11.

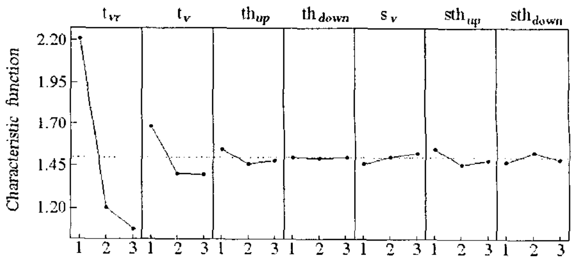

Fig. 4 Illustration of factor effect for the characteristic function

Table 12 shows results of structural and buckling analyses of the initial model, and those of experiments with the optimum model based on the table of orthogonal array. As shown in the results, values of maximum stress and maximum deflection for the initial model are smaller than those of allowable stress and allowable deflection. 1st buckling coefficient is larger than allowable buckling coefficient.

The weight of the initial model is 42.73 tons. This means that the model was redundantly designed. When experiments with the optimum model were made based on the table of orthogonal array, the weight of the model was obtained 37.14 tons in the 8th experiment and 39.66 in the 18th. The two values, 37.14 and 39.66 tons are both allowable, indicating that the weight of the optimum model is lighter by 10.55 or 4.48 % than that of the initial model. Thus results of the 8th experiment based on the table of orthogonal array are considered optimal.

Finally, results of the characteristic function's analysis of means all satisfy allowable stress, allowable deflection and allowable 1st buckling coefficient. This indicates that the weight of the overhead crane was reduced by 6.31 % to 40.03 tons.

Table 12 Results of initial model & optimum model

Item list	Magnet overhead crane			
	Initial model	ANOM result	Optimum Orthogonal array result	Allowable value
Maximum stress(MPa)	144.38	162.76	149.08	163.3
Maximum deflection(mm)	28.12	31.66	33.18	34.5
1st buckling coefficient	5.34	3.99	3.17	2
Weight(ton)	41.52	40.03	37.14	-
Weight reduction(%)	10.55			

Results of experiments based on the table of orthogonal array and those of the characteristic function's analysis of means show that the optimum model satisfies all constraints and is lighter in weight than the initial model. When those results are compared, the obtained weight of the optimum model is lighter in the experiments than in the analysis of means. If an optimal solution obtained through experiments based on the table of orthogonal array is better than that obtained through the characteristic function's analysis of means, the former solution must be finally selected. In this study, therefore, results from the experiments with the table of orthogonal array based were finally selected as optimal[5].

Figs. 5 to 7 show stress, deflection and maximum stress distributions of the optimum model.

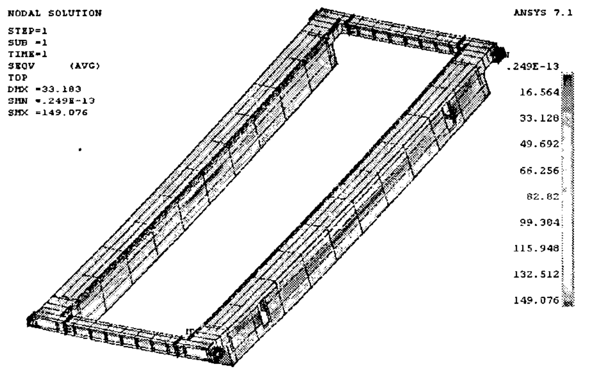

Fig. 5 Stress distribution of the optimum model

The maximum stress, or 149.08 MPa is observed at a rounding where the area of contact between the girder and the saddle is reduced. It satisfies the allowable stress of 163.33 MPa. The maximum deflection, or 33.18 mm is observed at the center of the girder.

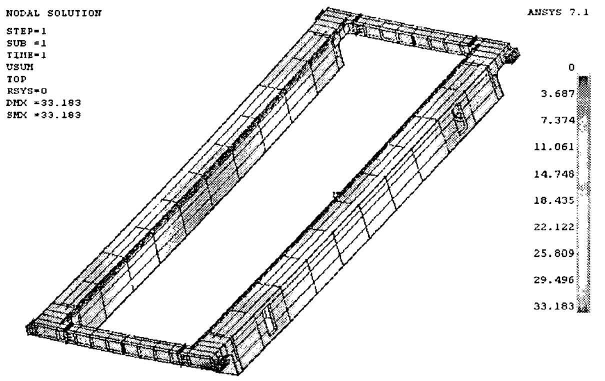

Fig. 6 Deflection distribution of the optimum model

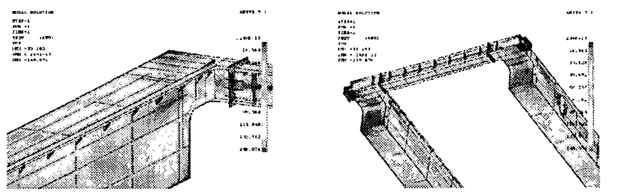

Fig. 7 Maximum stress distribution of the optimum model

Fig. 8 shows the overhead crane's 1st buckling mode. It also shows the existence of local panel buckling at the center of the girder. The optimum model of the crane is 3.15 % higher in maximum stress than the initial model. The former model is also 15.25 % higher in maximum deflection than the latter. The buckling coefficient of the optimum model is 40.63 % lower than that of the initial model. The maximum stress, maximum deflection and buckling coefficient of the optimum model all meet their constraints. Finally, the weight of the optimum model is 10.55 % lighter than that of the initial model.

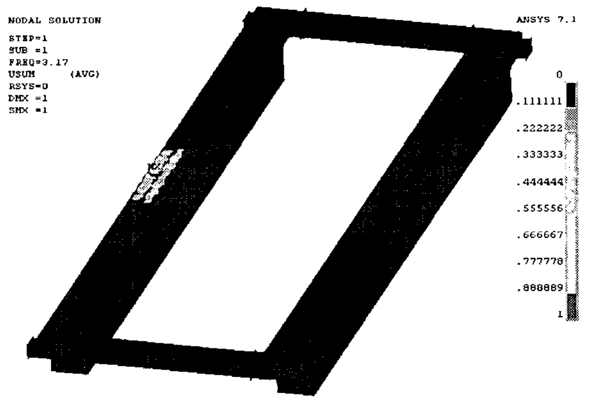

Fig. 8 1st buckling mode of the optimum model

5. Conclusions

The attempt is made to design an overhead crane optimally by using the table of orthogonal array and a characteristic function with constraints considered. As a result, the following conclusion can be obtained.

For changes in the dimension of the overhead crane, the weight, stress, deflection and buckling strength of the crane were quantified through structural and buckling analyses and through the use of objective and characteristic functions on the basis of the table of orthogonal array.

The weight of the overhead crane could be reduced by 10.55 % through changes in flange and web thicknesses of the girder and the saddle. Irrespective of the weight reduction the structural stability of the crane was maintained.

The initial model of the overhead crane is redundant in strength because it reflected no effects of vibration, fatigue and shock and used too high safety ratio and conventional flange and web thicknesses. But the optimum model of the crane is more excellent and lighter in weight than the initial model because it was designed by using a characteristic function with all constraints considered.

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