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DESIGN OPTIMIZATION OF BOX TYPE GIRDER OF AN OVERHEAD CRANE*

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Abstract– Double bridge girder overhead cranes are used for heavy duty applications in the industry. In this paper a detailed parametric design optimization of the main girder of box type is performed for a 150Ton capacity and 32m long span crane, after its basic design using available design rules. Design optimization is performed using detailed 3D finite element analysis by changing the number, shape and location of horizontal stiffeners along the length of the girder and number and location of stiffeners along the vertical direction to control any possible buckling, with minimum possible weight and for safe stress and deflection. Optimization is performed in two steps. In the first step, keeping plates thickness constant different types and number of stiffeners are added and optimized geometry is found. In the second step, the best geometry of the first step is further optimized for maximum allowable bending stress by changing thickness, height and width of the box girder with minimum possible weight. Effect of added stiffeners is highlighted in controlling its buckling.

Keywords– Box, girder, optimization, overhead, crane, buckling, stress, deflection

1. INTRODUCTION

Overhead cranes are used for the handling and transfer of heavy loads from one position to another, thus they are used in many areas of industry such as in automobile plants and shipyards, [1, 2] etc. Their design features vary widely according to their major operational specifications such as: the type of motion of crane structure, weight and type of the load, location of the crane, geometric features and environmental conditions. Since the crane design procedure is highly standardized with these components, most time and effort is spent mostly for interpretation and implementation of available design standards [3]. There are many the published studies on their structural and component stresses, safety under static loading and dynamic behavior [4-16]. Solid modeling of bridge structures and finite element analysis (FEA) to find the displacements and stress values has been investigated by Demirsoy [17]. Solid modeling techniques applied for the road bridge structures, and these structures analysed with finite element method have been given by [18-20]. DIN-Tashenbuch and F.E.M (Federation Européan de la Manutention) rules offer design methods and empirical approaches and equations that are based on previous design experiences and widely accepted design procedures. DIN-Tashenbuch 44 and 185 are a collection of standards related to the crane design. DIN norms generally state standard values of design parameters. F.E.M rules are mainly an accepted collection of rules to guide the crane designers. They include criteria to decide on the external loads to select crane components. In this paper a detailed parametric design optimization of the main

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girder of box type is performed for a 150Ton capacity and 32m long span crane, after its basic design using available DIN and F.E.M design rules. Design optimization is performed using detailed 3D finite element analysis by changing the number, shape and location of horizontal stiffeners along the length of the girder and number and location of stiffeners along the vertical direction to control any possible buckling, with minimum possible weight and for safe stress and deflection. Optimization is performed in two steps. In the first step, keeping plates thickness constant different types and number of stiffeners are added and optimized geometry is found. In the second step, the best geometry of the first step is further optimized for maximum allowable bending stress by changing thickness, height and width of the box girder with minimum possible weight. Effect of added stiffeners is highlighted in controlling its buckling. Four case studies are carried out for optimization using:

- horizontal stiffeners only (study-1)
- vertical stiffeners only (study-2)
- both the horizontal and vertical stiffeners (study-3)
- parametric optimization of box girder (study-4)

2. MODELING, MATERIAL PROPERTIES AND MESHING

A complete box girder is modeled in ANSYS software and is shown in Fig. 1 with all its dimensions. Thickness of side, top and bottom and stiffener plates are 6mm, 22mm, 10mm respectively. Width of top and bottom plates is 960mm and maximum height of side plates is 2600mm. However, during FEA, due to its symmetry only half of the model is used and is optimized with different geometries under applied loading conditions. Initially box with rail at the top is analyzed without any stiffener. Then different horizontal and vertical stiffeners at different stages were modeled and glued to the outer box keeping in view the manufacturing process and symmetry in front. Linear elastic material model is used for steel RST-37.2 with Young's modulus of 207GPa, Poisson's ratio of 0.3, allowable stress 157MPa and density of 7.86x10^{-6} kg/m^3. 3-D, 10 nodded higher order quadrilateral SOLID187 elements having three degrees of freedom at each node are used. Free Mesh option is used to mesh the entire geometry and is shown in Fig. 2 in ANSYS software.

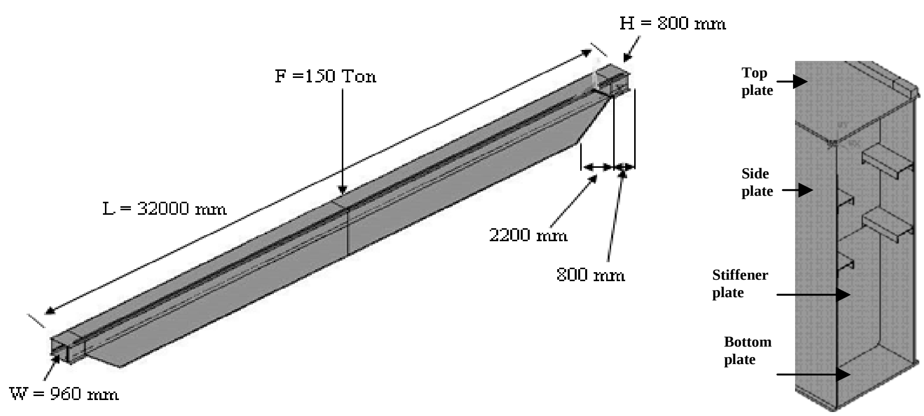


Fig. 1. Initial geometry of the overhead crane girder

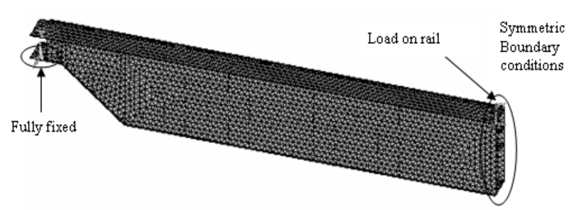


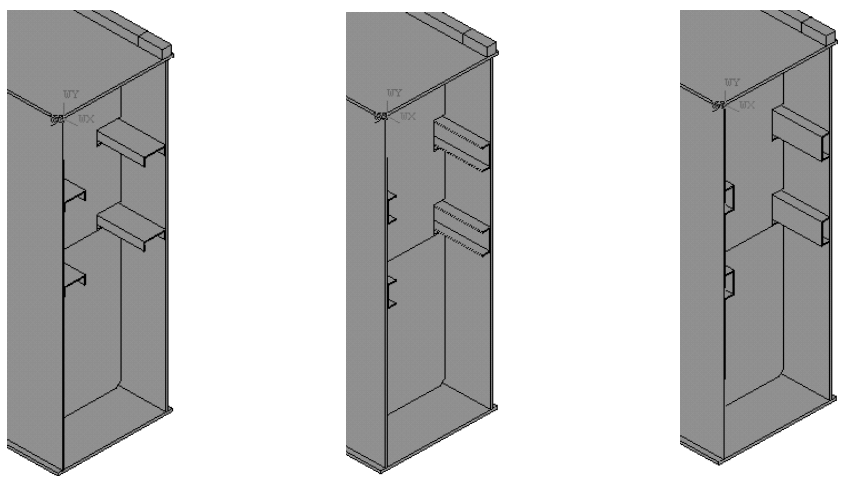
Fig. 2. FE model with applied boundary conditions

3. BOUNDARY CONDITIONS

Considering crane parked at one position and lifting the load is the usual recommendation for crane operation. Hence during design calculation and finite element analysis, no horizontal force is considered to be acting on the main girder. Main girder is fully fixed at the ends where it is joined to the end carriages. A three point bending loading strategy is applied considering the distance between two wheels of the trolley to be very small. Load is applied along the rail width equally distributed on all the 6 nodes. For different case studies load applied is considered with the self weight of the main girder and is discussed in related sections below. Due to the symmetry of the geometry, symmetry boundary conditions are applied on the plates as shown in Fig. 2.

4. RESULTS AND DISCUSSION

In this paper 37 optimization cases of box girder for allowable bending stress, deflections and minimum mass without and with different types, number of horizontal stiffeners and their different orientations (Fig. 3) and different number of vertical stiffeners are summarized in Table 1. Maximum bending stress for the box girder with no stiffener with and without stress concentration points are shown in Figs. 4 and 5.



(a) **(b)** **(c)**

Fig. 3. (a,b,c) Different orientations of horizontal stiffeners

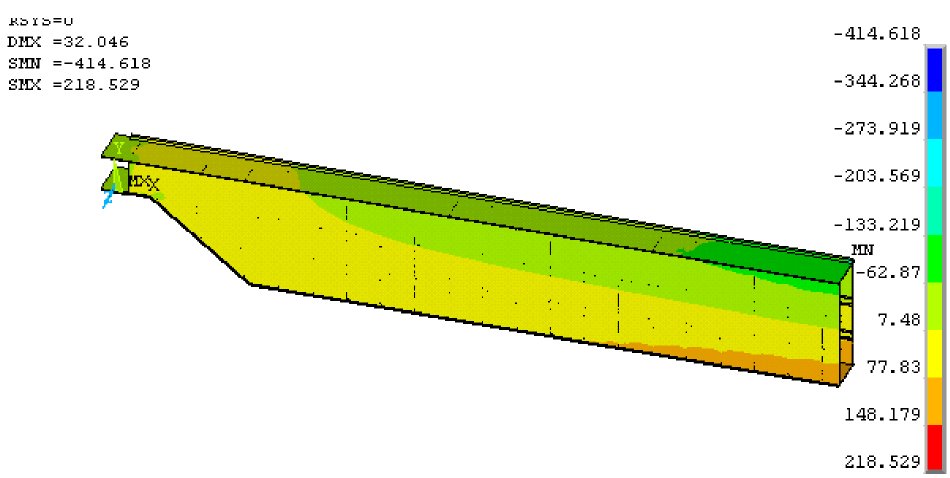


Fig. 4. Bending stress in girder with maximum at rail due to stress concentration where load is applied

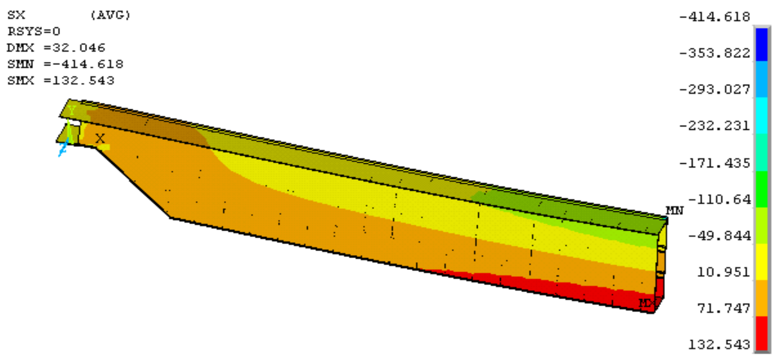


Fig. 5. Bending stress in girder by removing the volumes to avoid stress concentration, hence redistributing the stresses

Table 1. Case studies Results comparison by changing the shape, number and location of horizontal stiffeners

Number and type of stiffeners	Case Study	Location
Location and number of horizontal stiffeners		
No stiffener	C1	-----
1 C-Shape horizontal Stiffener (180x70x8)	C2	Touching top plate
	C3	@400mm from top plate
	C4	@650mm from top plate
	C5	@890mm from top plate(aligned with lower plate)
2 C-Shape horizontal stiffener (180x70x8)	C6	Equally divided throughout the height
	C7	1st@710mm, 2nd@1655 mm from top plate
	C8	1st@400mm, 2nd@1700mm from top plate
		1st@400mm, 2nd@1700mm from top plate(WORKBENCH)
3 C-Shape horizontal stiffener (180x70x8)	C9	Equally divided throughout the height
	C10	1st@710mm, 2nd@1340 mm, 3rd@1970mm from top plate
1 L-Shape horizontal stiffener (156x156x8)	C11	Touching upper plate
	C12	@400mm from top plate
	C13	@878mm from top plate
2 L-Shape horizontal stiffener (156x156x8)	C14	Equally divided throughout the height
	C15	1st@722mm, 2nd@1661 mm from top plate
3 L-Shape horizontal stiffener (156x156x8)	C16	Equally divided throughout the height
	C17	1st@722mm, 2nd@1348 mm, 3rd@1974mm from top plate
Location and number of vertical stiffeners		
Stiffener plate	C18	1@6500mm from center
Stiffener plate	C19	2@12000mm from each other
Stiffener plate	C20	3@6000mm from each other
Stiffener plate	C21	4@4000mm from each other
Stiffener plate	C22	5@3000mm from each other
Stiffener plate	C23	6@2400mm from each other
Stiffener plate	C24	7@2000mm from each other
Stiffener plate		7@2000mm from each other (WORKBENCH)
Location and number of vertical stiffeners in addition to 2 C-shape horizontal stiffeners		
Stiffener plate	C25	3@6000mm
Stiffener plate	C26	5@3000mm
Stiffener plate	C27	7@2000mm
Stiffener plate		7@2000mm (WORKBENCH)
Location and number of vertical stiffeners in addition to 2 c-shape horizontal stiffeners and with different orientation of horizontal stiffeners		
As per Figure 6a	C28	17@750mm along uniform height
		17@750mm along uniform height (WORKBENCH)
	C29	21@600mm along uniform height
	C30	31@400mm along uniform height
As per Figure 6b	C31	2 C-Shape horizontal stiffeners
As per Figure 6c	C32	2 C-Shape horizontal stiffeners
Changing position of horizontal stiffeners		
2 C-Shape stiffeners	C33	@866 and 1733mm from top plate
2 C-Shape stiffeners		@866 and 1733mm from top plate (WORKBENCH)
2 L-Shape stiffeners	C34	

a) Study-1: Optimization using horizontal stiffeners

In this case optimization is performed by changing the number, position and shape of horizontal stiffeners only. It is noted that there is no considerable decrease in the maximum deflection by using the L-shape stiffeners, however better results are achieved using the C-shape horizontal stiffeners. Using two C-shape horizontal stiffeners at 400 and 1700mm from the top plate, the best optimized results (maximum deflection=37.32mm and maximum bending stress=176MPa, mass of girder=16999kg) are achieved. Analysis is also performed by modelling the girder in ANSYS Workbench. Using built in solid elements and free meshing and removing the stress concentration points, maximum deflection = 36.24mm and bending stress = 165 MPa is observed. Although maximum bending stress is more than the allowable it can be neglected due to the stress concentrations in all the cases. Results for maximum bending stress and deflection are plotted in Fig. 6 and Fig. 7 respectively.

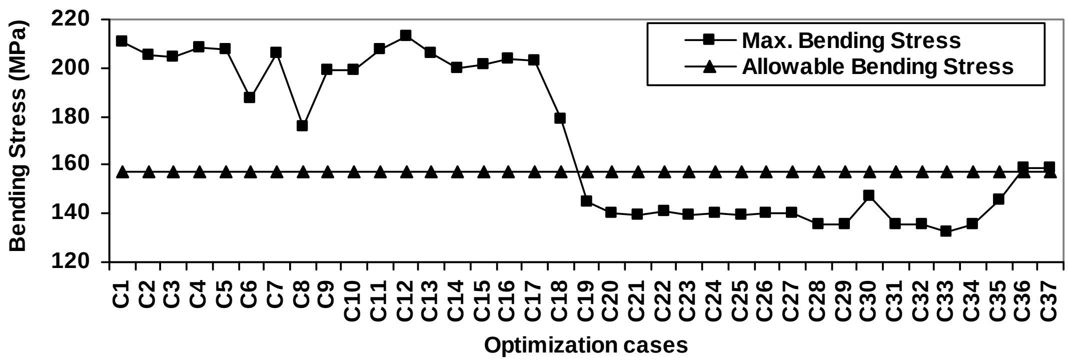


Fig. 6. Maximum Bending Stress in the Box Girder for all cases after removing stress concentration/raiser points

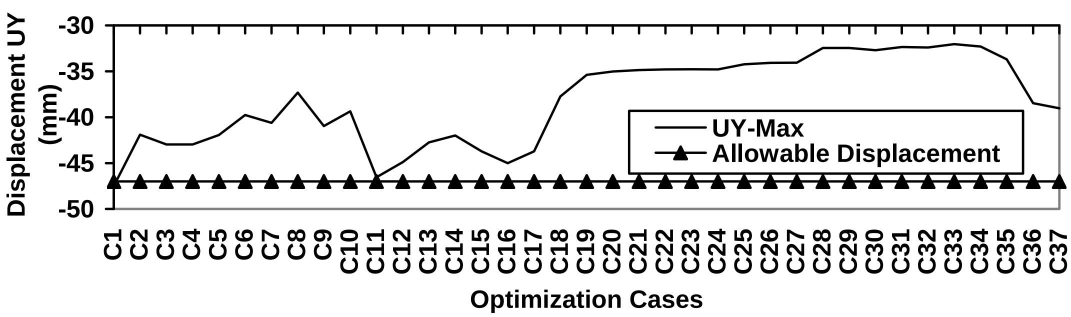


Fig. 7. Displacement of corner points of plates of box girder in Y-direction for different optimization cases

b) Study-2: Optimization using vertical stiffeners

In this case optimization is performed by changing the number and position of plate stiffeners along the length of the girder. It is observed that by increasing the number of vertical stiffeners from one to two and so on, a decrease in the maximum deflection from 37.74mm to 34.79mm is observed. By increasing the number of vertical stiffeners, corresponding decrease observed is small. Hence, using seven vertical stiffeners 2000 mm apart from each other, deflection is reduced to 34.79mm, but an increase in mass (1042kg) of the girder is observed as we increase the stiffeners from 1 to 7. A maximum bending stress of 140MPa is observed which is close to the allowable stress of the flange material. Using Workbench and neglecting the stress concentration, maximum deflection is reduced to 29.52mm and maximum bending stress is reduced to 135MPa respectively, and is within the allowable limits. Results for maximum bending stress and deflection are plotted in Fig. 6 and Fig. 7 respectively.

c) Study-3: Optimization using both the horizontal and vertical stiffeners

In this case, analyses are performed by changing the number and location of the vertical stiffeners along the length of the girder in addition to the two C-shape horizontal stiffeners positioned equally along the height of the girder. Two C-shape horizontal stiffeners are used as most optimized results were concluded using these in study-1. In these cases, the number of vertical stiffeners is increased, the value of maximum deflection decreases from 34.24 to 34.06mm and the value of maximum bending stress increases from 139 to 140MPa. It is interesting to note that using vertical stiffeners from 3 to 7, maximum deflection and bending stress remains the same. But using more vertical stiffeners, mass of girder is increased. Vertical plates are used here in order to avoid lateral buckling. Using Workbench model and neglecting stress concentrations, maximum deflection and stress is reduced to 29.32mm and 131MPa and is within the allowable limits.

After that, box girder is modeled by using the dimensions such that two C-shape horizontal stiffeners are placed 625mm and 1250mm far from the top plate and twenty-one vertical stiffeners are used in the half model of girder. The first four vertical stiffeners are located along the support and varying cross section and the remaining 17 vertical stiffeners are located along the length of the girder where the height of the girder is uniform. For optimization 21 and 31 vertical stiffeners are also used and analysis is performed. In addition position and orientation of the horizontal stiffeners is also changed such as using inverted C-shape stiffeners and so on. Using 17 vertical stiffeners in addition to two C-shape stiffeners equally divided along the height of the girder, a maximum deflection of 32.05mm and maximum bending stress of 132MPa is observed. Using Workbench model with 17 vertical stiffeners and removing stress concentrations, maximum deflection and stress is reduced to 28.18mm and 129MPa. By using L-shape horizontal stiffeners in addition to vertical stiffeners results are also found in good agreement to that using 2 C-shape stiffeners but with a slight increase in the weight of the girder. Using inverted 2 C-shape stiffeners, no difference in results is observed but from manufacturing point of view, this is not appreciated. Concluding Table 2 shows the optimized dimensions of the girder, maximum bending stress, maximum displacement, mass and volume for the case where 2 C-Shape horizontal stiffeners are equally distributed along the height with 17 vertical stiffeners along the uniform height and 4 along the support point and varying section for case C33. Results for maximum bending stress and deflection are plotted in Fig. 6 and Fig. 7 respectively.

Table 2. Dimensions of the girder, maximum bending stress, maximum displacement, mass and volume for cases C33-C37

Case	Height (mm)	Thickness of side plate (mm)	Thickness of top & bottom plate (mm)	Thickness of stiffener plate (mm)	Width (mm)	Max bending stress (MPa)	Max deflection (mm)	Mass (kg)
C33	2600	16.00	22.00	10.00	850	132.00	32.050	20123
C35	2599	14.84	21.49	9.93	849	147.23	33.694	19264
C36	2600	11.85	19.09	10.00	850	157.45	38.482	16853
C37	2600	11.63	20.17	7.28	800	156.90	39.042	15588

d) Study-4: parametric optimization of box girder

In this case study, keeping length of the girder constant, width, height and thickness of the geometry of box girder are further optimized for minimum possible weight within the allowable stress limits. In order to perform design optimization the following variables are defined and optimized results of three case studies (C35-C37) are summarized in Table 2, where minimum mass is concluded 15588 kg for C37. Results for maximum bending stress and deflection are plotted in Figs. 6 and 7 respectively.

Design Variables: These independent variables directly affect the design objective, hence width, height and thickness of the plates of the girder are the design variables. Changing either of these variables has a direct effect on the solution of the problem.

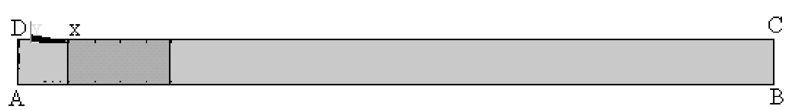
State Variables: These are dependent variables that change as a result of changing the design variables and are necessary to constrain the design. Hence maximum bending stress and the displacement vector sum are the state variables.

Objective Variable: It is necessary to minimize these variables, hence volume/weight of the girder is minimized.

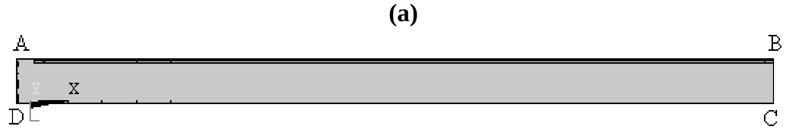
e) Buckling behavior of box girder

Buckling is a failure mode characterized by a sudden failure of a structural member subjected to high compressive stresses, where the actual compressive stresses at failure are smaller than the ultimate compressive stresses that the material is capable of withstanding. This mode of failure is also described as failure due to elastic instability. This type of failure should be considered in case of thin walled structures as they are particularly prone to buckling and in general must be designed against several different types of buckling. Buckling rather than strength considerations thus dictate the Box girder's performance. In order to control buckling of the box girder, optimization was performed in two steps. In the first step, a static optimization, i.e. introducing different stiffeners of fixed dimensions and keeping box girder plates thickness constant was performed and the most optimized geometry was obtained. In the second step, a dynamic optimization, i.e. using the most optimized geometry of first step, keeping only horizontal stiffeners dimension constant, all other dimensions of the box girder plates, i.e. top, bottom, side and vertical stiffeners were optimized. Height and width of the girder was also optimized.

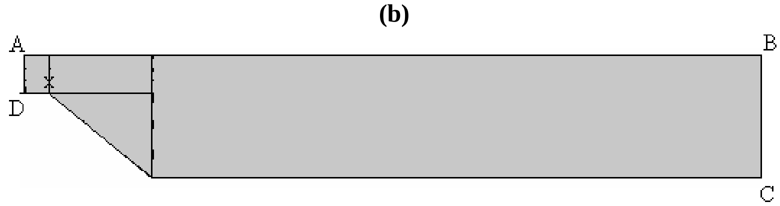
In order to control the buckling of the box girder, a number of case studies were performed using vertical stiffeners and different types of horizontal stiffeners and results are discussed in detail. Displacement results under applied load and self weight of box girder at marked corner points of the bottom, top and side plates are taken and shown in Figs. 8a, b and c.



(a)



(b)



(c)

Fig. 8. Location of points on (a) Bottom plate; (b) Top Plate; (c) Side Plates (Front and Back)

In all the plates of box girder, some of the corner points have almost zero displacements in all the cases. The displacement (UX) of points B and C for all plates will remain zero as these two points exist along the plane of the application of load, so there is no displacement of these points along the length of the girder. Similarly, the displacements (UX and UY) of points A and D are also almost zero because the section containing all these points is constrained in all directions at the bottom plate. The displacement (UZ) of point D for front and back plate is almost zero in all the cases. It is because point D of the front plate is very close to the area which is constrained in all directions as this area is at the end support of the girder. The displacement (UZ) of points A and D is zero for the bottom plate after the application of applied load in all the cases because the area containing these two points is constrained in all directions. Visible Displacement Results for different plates are discussed in the following sections. Displacement in Y & Z directions, i.e. UY and UZ are plotted in Figs. 9 and 10 respectively for different plates.

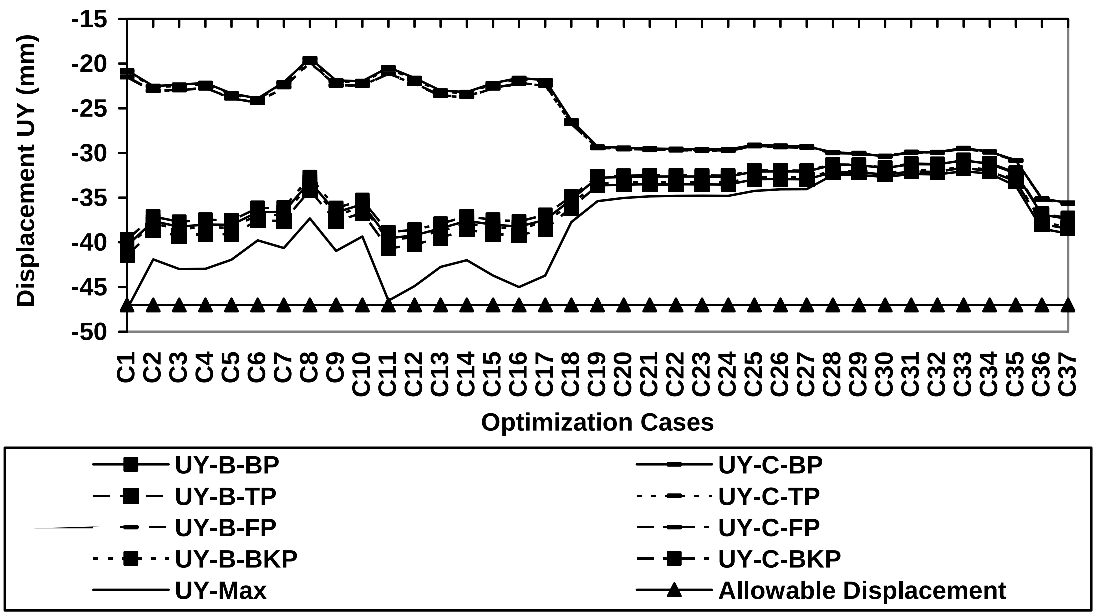


Fig. 9. Displacement of corner points of plates of box girder in Y-direction for different optimization cases

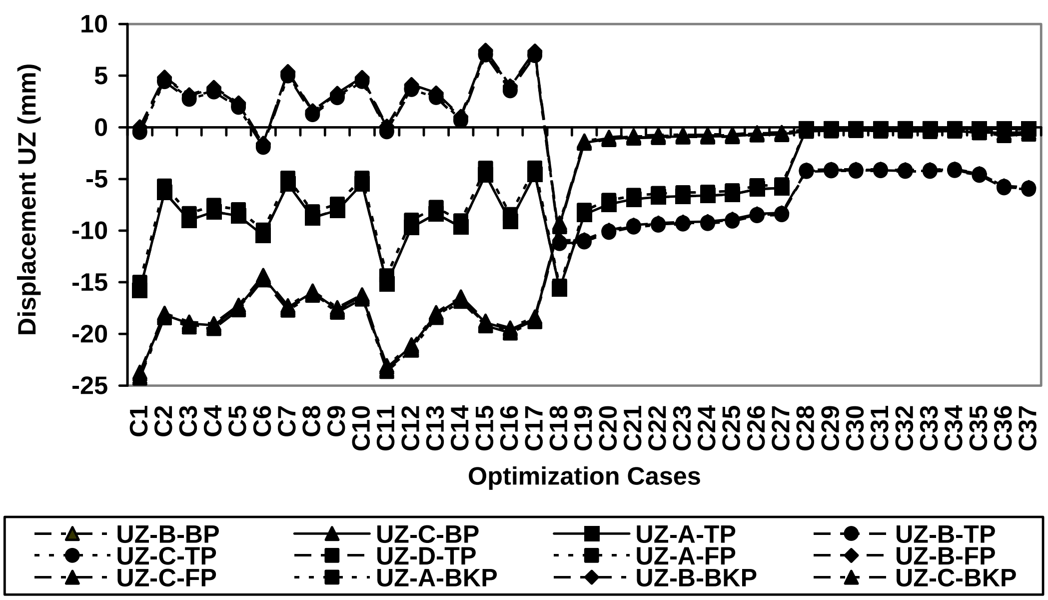


Fig. 10. Displacement of corner points of plates of box girder in Z-direction for different optimization cases

1. Displacement of Plates in Y-direction (UY)

The displacement of point C for bottom and top plate; and of point B and C of front plate in Y-direction show the increasing behavior from 21mm to 31mm approximately. The displacement of point B for bottom and top plate; and of point B and C of back plate in Y-direction is reduced from 41mm to 32mm approximately. This finally results in almost the same displacement values in Y-direction showing its rotation to almost negligible and concluding the stability of the box girder.

The dynamic optimization is run for cases 35 and 37. Here, thickness of the plates of box girder, and width height of the girder are design variables that are to be optimized; bending stress and the deflection of the girder are state variables which directly change as the design variables change and care is taken that the state variables will not exceed the allowable limit of 157MPa (allowable bending stress). The objective variable is the volume of the girder which needs to be minimized. The displacement of point B and C in Y-direction for bottom, top and side plates shows the increasing behavior due to optimized dimensions of the girder in these cases. But still, the displacement values are in an allowable range and mass of the girder is reduced. Results are plotted in Fig. 9. Figure 11 shows the comparison of buckling of the plates for different optimization cases. It is clear that by introducing only the horizontal stiffeners, the buckling of the plates is not controlled. But by introducing the vertical stiffeners along with the horizontal stiffeners, the buckling of the plates is controlled to some extent in the final optimized case.

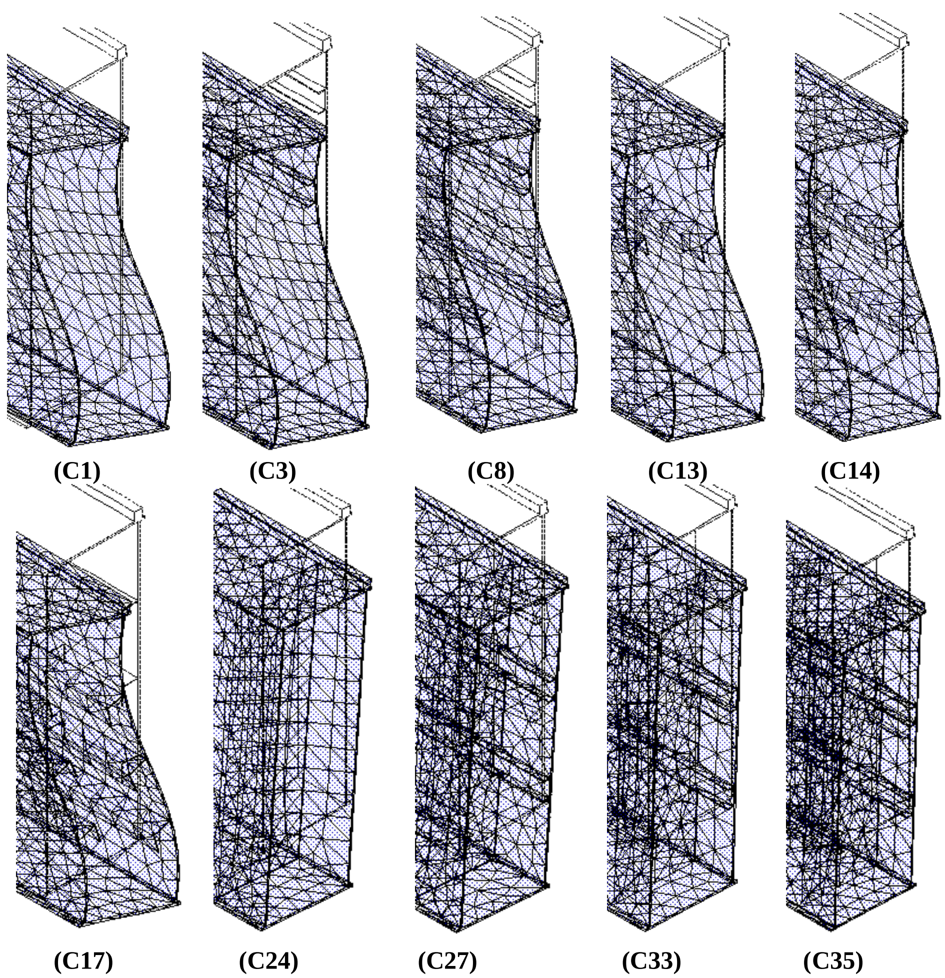


Fig. 11. Comparison of lateral buckling of plates for different case studies

2. Displacement of plates in Z-direction (UZ)

The displacements (UZ) of points B and C for top plate, and of point B for front and back plate show almost the same behavior in all the cases as these four points are very close to each other. Almost zero displacement of these four points is observed in the case of no horizontal and vertical stiffener. But with the introduction of both the horizontal and vertical stiffeners, the displacement of these points increased to almost 4mm in the final case (C33) which is also negligible value and can be neglected.

The displacements of points A and D for top plate; and of point A for front and back plate show almost the same behavior for all the cases as these four points are also very close to each other. In case of no stiffener, the displacement of these points is almost 16mm. But with the introduction of stiffeners, the displacement of the points is reduced to almost zero for case study 28 (C28) and above.

In the case of girder having no vertical and horizontal stiffeners, the displacements of the points B and C of bottom plate, and of point C of front and back plate is almost 24 mm. By introducing different numbers of horizontal stiffeners in the girder from case 1 to case 17, a variation in the displacement is observed. All these points have almost the same displacement behavior. But as the vertical stiffeners along the horizontal stiffeners are introduced, the displacement values of these points are reduced to almost zero for case study 19 (C19) and above. Results are plotted in Fig. 10.

f) Mass of the girder

Results of the mass of the box girder during optimization for all cases are shown in Fig. 12. In order to control the buckling of box girder plates and to make the box girder stable, different number and types of stiffeners are added so that the mass of the girder is increased from case1 to case 34. The maximum value of the mass is observed for case 30, because 31 vertical stiffeners along with two horizontal stiffeners along the height are used along the span of the girder where height of the girder is uniform. During the dynamic optimization in the cases 35 and 37, a substantial decrease in the mass of the girder is observed for cases 36 and 37. As a result, the optimized dimensions of the girder are achieved.

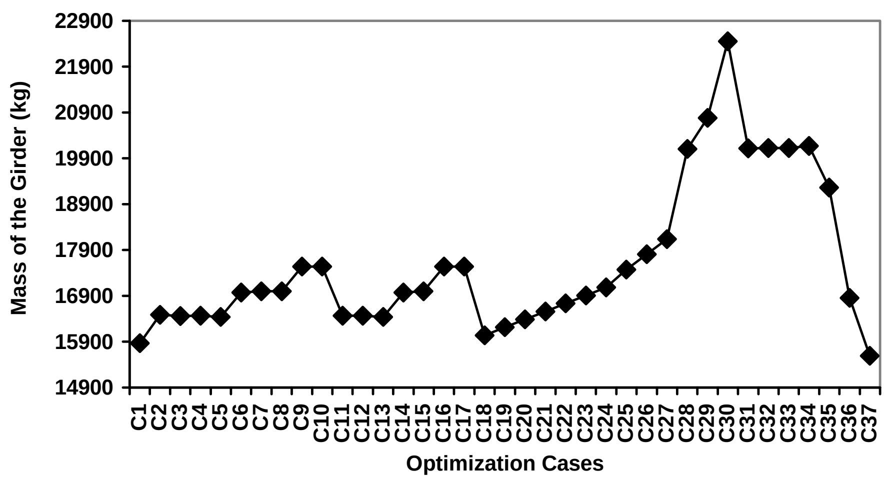


Fig. 12. Mass of the box girder for all cases

g) Maximum bending stress

Results of the maximum bending stress in the box girder during optimization for all the cases are shown in Fig. 6. The allowable bending stress for the material used is 157MPa. In order to avoid the value of bending stress to exceed the allowable value, different number and types of stiffeners are added. The value of bending stress is decreased from the allowable value for case study 19 (C19) and above. During the dynamic optimization in the case 35-37, the value of the maximum bending stress is increased to 157MPa (allowable bending stress). As a result, the optimized dimensions of the girder are achieved.

5. CONCLUSION

From detailed optimization studies the following results are concluded;

1. The most optimized case concluded is with 2 C-Shape horizontal stiffeners equally distributed along the height with 17 vertical stiffeners along the uniform height and 4 along the support point and varying section. The results achieved from the model of ANSYS Workbench are more accurate as ANSYS model has more shape distortion errors.
2. Orientation of the horizontal stiffeners does not make visible difference in the results.
3. The minimum deflection is achieved by equally dividing the horizontal stiffeners along the height.
4. To control longitudinal and lateral buckling, use of horizontal and vertical stiffeners is strongly recommended.
5. Inclusion of stiffeners increases the strength of the girder.

A reasonable weight reduction of the box girder by optimizing the width, height and thickness of plates of the girder is concluded.

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