

OPTIMIZATION OF BOX TYPE GIRDER WITH AND WITHOUT INDUSTRIAL CONSTRAINTS

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ABSTRACT: In this paper three dimensional nonlinear finite element analysis is performed for the optimization of an overhead crane box girder for capacity (50~120ton) and span (10 ~ 32 m) for safe bending stress and deflection with minimum mass and volume. A customized optimization code is developed using interpolative relations and correction factors to achieve optimized results with and without considering industrial constraints. A cutting and welding plan is developed to provide a standard operating procedure for the manufacturing of the box girder. Bill of materials, box girder design dimensions, and cutting and welding lengths are recorded with considerable time saving.

ABSTRAK: Kertas ini mengkaji tentang analisis tidak linear tiga dimensi unsur terhingga bagi mengoptimumkan kotak kren galang atas kepala bagi kapasiti (50 ~ 120 tan) dan pada kadar (10 ~ 32 m) bagi takat lentur selamat dan pesongan dengan jisim minimum dan isipadu. Kod optimum penyesuaian telah direka mengguna pakai kaitan interpolatif dan faktor-faktor pembetulan bagi mencapai keputusan yang optimum, dengan dan tanpa mengambil kira kekangan industri. Pelan pemotongan dan kimpalan telah dicipta bagi menyediakan prosedur operasi biasa bagi pembuatan kotak galang. Rang undang-undang bahan, dimensi reka bentuk kotak galang, pemotongan dan panjang kimpalan telah direkodkan dengan penjimatan masa yang besar.

KEYWORDS: *box girder; optimization; industrial; bill of materials; cutting; welding; finite element analysis; industrial constraints*

1. INTRODUCTION

Overhead cranes are machines that are used to handle and transfer heavy loads from one place to another in shipping, automotive, logistics, and construction industries [1-2]. The use of cranes enhances efficiency, reliability, and productivity of processes by reducing the human effort and time for handling and moving heavy objects [3-4]. The cranes are regarded as critical material handling devices [5-15]. Therefore, crane safety during operation is immensely important. ASME - ANSI [16]; ISO [17]; CMAA [18]; DIN-Taschenbuch [19]; F.E.M. rules [20]; British standards [21]; and Polish standards [22] are

organized to standardize and regulate the manufacturing and safe operation of these cranes. Greiner's Crane Handbook [23] provides important information regarding crane design, manufacturing, and operation. Otani *et al.* [24] described the vertical seismic response of a 150-ton box girder crane of 35m and concluded that a linear analysis was sufficient to find the reaction forces on the wheels even when the leap phenomenon had occurred in the overhead crane. Alkin *et al.* [25] used shell and solid elements for the optimization of 32-ton and 13 m span crane. Farkas [26] studied the economy of the crane as a function of yield strength of the material used for the crane construction. Niezgodzinski and Kubiak [27] used experimental, analytical and numerical methods to study the effect of a local stability problem in box girder cranes and concluded that the addition of strips stiffens the web and reduces the chance of buckling. Zuberi *et al.* [1] used non-linear Generalized Reduced Gradient optimization code for the optimization of overhead crane box girders using available standards by CMAA and Greiner's Crane Handbook. Case studies were performed using 10-50 ton capacity and 22 m, 25.5 m, 27.5 m, and 30 m span cranes. The diaphragm spacing and proper thickness was concluded vital for mass minimization. Imrak *et al.* [28] studied the linear and non-linear finite element behavior of a portal crane of 200×2 ton capacity and 100 m span. Beam and shell elements were used during the modeling of the crane. Blum and Chodorowska [29] investigated the pre-stressing phenomenon in plate welded girders, mostly of the fillet welds. They concluded that the pre-stressed model is significantly stable and stiffened as compared to the non-pre-stressed model. Abid *et al.* [30] optimized box girders of 150 ton and 32 m span to control buckling with proper quantity and positions of stiffeners. Pinca *et al.* [31, 32] performed finite element analysis using shell elements for box girders and achieved a 21% theoretical mass reduction. Gerdemeli *et al.* [33, 34] performed finite element analysis using ANSYS and ABACUS software for gantry cranes and concluded that simulation helps in the optimization of structures, increased reliability, durability, reduced cost, and manufacturing duration. Gašić *et al.* [35] performed a dynamic analysis of cranes. Zhang *et al.* [36] presented finite element analysis of box girder beams for transport bridges. Bećirović *et al.* [37] analyzed box girders of a 7 ton and 20 m span crane for cross-section optimization by changing its height-to-width ratio and the thicknesses of the plates and concluded a 38% mass reduction. Gaska and Pypno [38] studied static and dynamic stability of 20 ton cranes of various spans according to Polish and English standards. Lerga [2] proposed a design modification in existing designs of box girders of overhead cranes and concluded a 5.5% mass reduction. Djelosevic *et al.* [39] studied the local stress parameters of box and trapezoidal girders and concluded that trapezoidal sections have lower localized stress influence as compared to the straight sections. Capacity and span-wise optimization were performed by Abid *et al.* [40, 41] and relations and optimization factors were developed for a capacity range of 50~120 ton and a span range of 10 m ~ 32 m. Chauhan and Bhatt [42] performed finite element analysis using three different steels (EN-22, Steel-20 and Forged steel) for the hook for a 10 ton and 22 m span crane girder to study possible increase in its durability and minimum stresses were recorded for EN-22. Suratkar and Shukla [43] performed finite element simulation of a 10 ton and 12 m span crane box girder using a five-point load model i.e. four points for the divided load and one point for the displaced centered load for the payload. It was concluded that the stresses produced were much less than the allowable stress values, thus proposed the optimization of the analyzed model. Rabey [44] using a ST-3-PS steel girder, performed an analysis with 1, 8, and 16 ton payloads and studied the behavior of the girder under collision. He proposed to implement standardized dynamic parameters for the collisions of bridge cranes and end stops. Haniszewski [45] performed dynamic modeling of an overhead travelling crane and interaction of the dynamic geometric model with the finite element mode. An intricate geometric model was generated for a 5 ton and 20 m span crane for both

static and Lanczos modal analysis. The static analysis was carried out for self-weight and applied load cases for loaded and unloaded cases. The loaded case was concluded critical under both the static and dynamic loading conditions.

Most of the available works have considered a single capacity or single span for optimization and take almost no consideration for industrial or manufacturing strategies. This paper discusses the results of automated optimization code developed using ANSYS Parametric Design Language (APDL) and implemented for design optimization using developed correction factors without considering the industrial constraints. The box girder without industrial constraints (WOIC) is the one in which design variables such as H_{MAX} - maximum height of the girder, RD - web plate thickness factor, and PT- flange plate thickness factors are modified independently as mentioned by Abid et al. [40, 41]. Later, using an automated optimization routine considering industrial constraints, optimized cutting lengths, welding lengths, edge preparation lengths, and manufacturing strategy is developed for reduced waste, mass, and efforts, after which the results are recorded. The box girder with industrial constraints (WIC) is one in which H_{MAX} is constrained equal to the sizes available in the market. The width of the top plate is also constrained to one-third of H_{MAX} . Two approaches for box girders with industrial constraints have been considered: (1) keeping all thicknesses the same i.e. T_{SP} (thickness of side plate) = T_{TP} (thickness of top plate) = T_{BP} (thickness of bottom plate); (2) keeping web and flange thickness different.

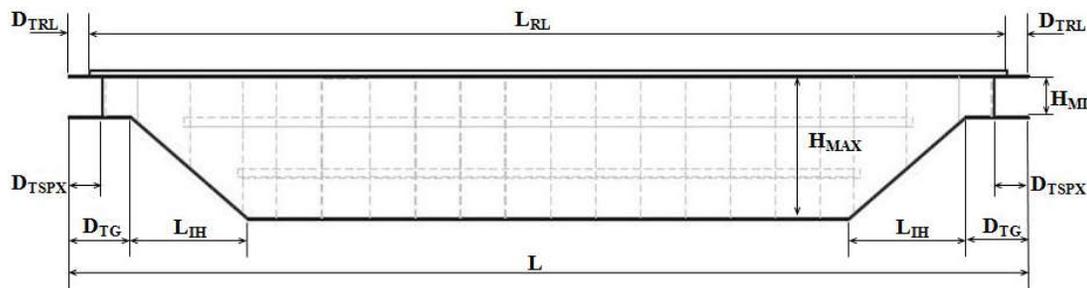


Fig. 1: Front view of box girder .

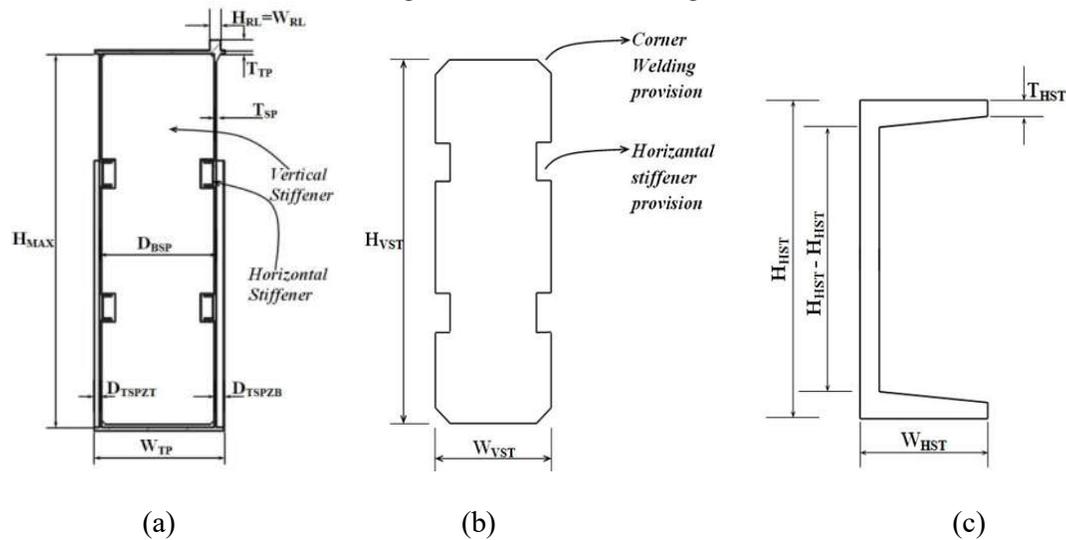


Fig. 2: Section view of box girder, (b) vertical stiffener, (c) horizontal stiffener

reference optimization is used for capacity-wise [40], span-wise [41] and combined optimizations in the present study.

2. BOX GIRDER MODELING; MESHING, BOUNDARY CONDITIONS AND MATERIAL SELECTION

Figure 1 shows the front view of a box girder with general parameters; Figure 2a-c shows the sectioned view of the box girder, and vertical and horizontal stiffeners, respectively; Figure 4a-c show applied boundary conditions (constraints, loading and reflective symmetry). Figure 4d shows meshing of the half box girder model using Solid186 elements; Figure 4e shows a section view of the full geometry modeled with horizontal and vertical stiffeners. Most of the researchers used shell elements dealing with finite element analysis of box girders [1, 27~45]. Researchers have selected shell elements owing to fact that the box girder cranes are classified as thin walled structures [45]. The geometries they use is therefore simplified, neglecting features like rails and horizontal sections. Use of solid elements is also found in the literature [3, 25, 30, 43], as these can be used for both thick and thin sections. Due to the use of solid elements, only a single element type is required, therefore avoiding interfacing of element types. Also, because the present study uses batch mode (by using APDL code), better control during parametric modeling is incurred. In the present study, Solid186 (20 noded) element is used for discretization of the geometric model (Fig. 3 and meshed model in Fig. 4(d)). A half model was created due to the symmetry of the geometry. For meshing, the element edge length at this stage was set to 180 mm and at a later stage, during optimization, the edge length was selected by performing element sensitivity analysis to reduce error. Because the optimization includes various sizes, the element edge length and the number of elements changes. For all optimized sizes, the element edge length was between 50 – 150 mm. A sample mesh sensitivity study is presented by authors in previous work [41]. ANSYS software [47] was used for finite element analysis. An ANSYS Parametric Design Language (APDL) code was developed that was utilized to run the simulations in batch mode. The code, when entered in ANSYS, asks for two entities i.e. span and capacity. Only these two inputs and the interpolative relations and correction factors determined in the present work are utilized to present the optimized parameters of the required size and capacity crane.

The boundary conditions are as follows:

- (1) A single line load on the halfway of a rail equally divided on three nodes thus reducing stress singularity;
- (2) A loading impact factor of 1.25 is selected i.e. a 120 ton crane has a load of $120 * 1.25 = 150$ ton and additionally its own weight.
- (3) A zero degree-of-freedom boundary condition is applied for all nodes on the support area (this is a purposely selected conservative approach);
- (4) Symmetry condition at half length of girder;
- (5) Gravitational acceleration to include the effects of self-weight are applied.

Structural materials for the construction of overhead crane girders i.e. RST-37-2 [25,30], St-42 [33], St-52-3 [34], structural steel [2], IS: 2062, E 250B [42], structural steel S235 [45], and others are used. The most commonly available structural steel according to ASTM standard is A36 / A36M [46] and is an equivalent alternative of RST-37-2 according to DIN standard 17100. Material A36 having elastic modulus = 200 GPa, yield strength = 250 MPa, ultimate tensile strength = 400~550 MPa, allowable stress = 160 MPa and density = 7.86×10^{-6} kg/mm³ is used for analysis in this study. Although allowable deflection is a matter of professional judgment, the values of deflection must be between L/360 - L/180 to

avoid visible sagging [50]. A box girder without proper stiffening will show lateral buckling (Fig. 5). Reference [30] utilized optimized positions and number of vertical and horizontal stiffening elements to reduce the deflection in the lateral direction, hence to avoid lateral buckling. The present study utilizes this approach to control lateral buckling.

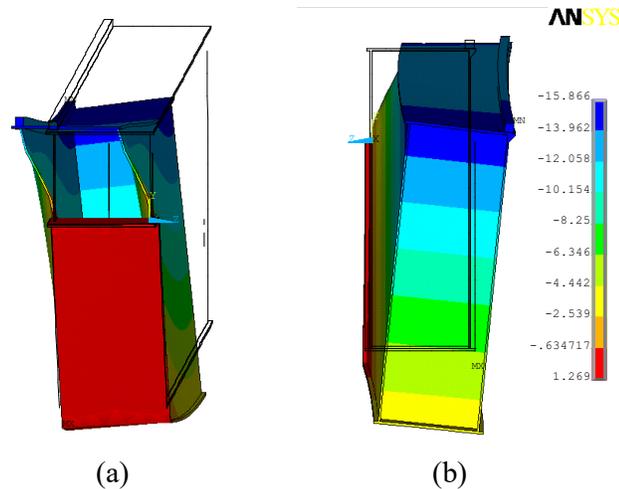


Fig. 0: lateral buckling (UZ Plot in mm) at (a) Support; (b) Center.

3. OPTIMIZATION METHODOLOGY WITHOUT CONSIDERATION OF INDUSTRIAL CONSTRAINTS

Capacity-wise optimization optimizes box girders of different capacities of the same span and thus has capacity as the only input and is presented in [40]. Span-wise optimization optimizes box girders of different spans and same capacity, thus has span as the only input and is presented in [41]. These studies use first order optimization using the ANSYS design optimization module with the overall mass and volume of the box girder as the objective parameter. The maximum number of iterations was set to 50. The maximum height (H_{MAX}) and web and flange thicknesses were design variables. Other size parameters are related to these design variables. The maximum normal stress and normal deflections were the state variables. For capacity-wise optimization, this is repeated for 32 m box girders and different capacities between 50–120 tons. Likewise, during span-wise optimization, design optimization is carried out with 100 ton girders with span between 10–32 m. The results of each are generalized in the form of interpolative relations. Although, the authors first optimized capacity-wise and then span-wise, the reverse approach is considered equally valid. The capacity-wise and span-wise optimization methodologies are presented in Fig. 6a and 6b, respectively. The interpolative relations developed during the capacity-wise and span-wise optimization are presented in relations (1–3) and (4–6), respectively. Relations (1–3) are only valid for 32 m box girders of capacity range of 50–120 ton and relations (4–6) are only valid for 100 ton box girders of span range of 10–32 m.

$$(H_{MAX})_C = (H_{MAX})_R - \{[(H_{MAX})_R \times (RC - CC) / 400] + HCF \times (RC - CC)\} \quad (1)$$

$$(RD)_C = (RD)_R - [(RC - CC) / 400] \quad (2)$$

$$(PT)_C = (PT)_R - [(RC - CC) / 200] \quad (3)$$

$$(H_{MAX})_C = \{(H_{MAX})_R - \{0.11 \times [(HL)_R - (HL)_C]\}\} + 75 \quad (4)$$

$$(RD)_C = \{(RD)_R + \{0.0000365 \times [(HL)_R - (HL)_C]\}\} - 0.05 \quad (5)$$

$$(PT)_C = \{(PT)_R - \{0.00009375 \times [(HL)_R - (HL)_C]\}\} - 0.002 \quad (6)$$

Where, RC is the capacity of the reference girder; CC is the capacity of the current girder; HCF is the height correction factor; $(HL)_R$ and $(HL)_C$ are half of the span length of reference and current girder respectively; and RD and PT are reduction factors.

In order to develop relations for any given span and capacity, a generalized (APDL) code is developed based on the factors and relations developed during the span-wise and capacity-wise optimization routines and a generalized optimized code for combined capacity and span is developed and tested, with its results discussed in detail.

The following relations are introduced for more useful dependencies:

$$H_{MAX} = f(H_{MAX1}, HL) \quad (7)$$

$$RF = f(RF1, HL) \quad (8)$$

$$PT = f(PT1, HL) \quad (9)$$

Where, H_{MAX1} , $RF1$ and $PT1$ are the maximum height, web thickness, and flange thickness optimization factors calculated during the capacity-wise optimization and H_{MAX} , RF and PT are the height and thickness factors calculated during span-wise relations. The aim is to define dependencies in such a way that the span-wise optimization relations are in terms of capacity-wise relations. Thus, the optimization factors calculated in the capacity-wise calculations become inputs for the relations developed in the span-wise calculations. There are some correction or combination factors used to make these relations compatible with each other. Finally, the capacity-wise relations act as the capacity control block and correction factors form correction block and finally the span-wise relations control the span related issues.

$$(H_{MAX})_1 = 2600 - ((2600 \times 0.0025 \times (120 - CC)) + (120 - CC)) \quad (10)$$

$$(RF)_1 = 0.727 - (0.0025 \times (120 - CC)) \quad (11)$$

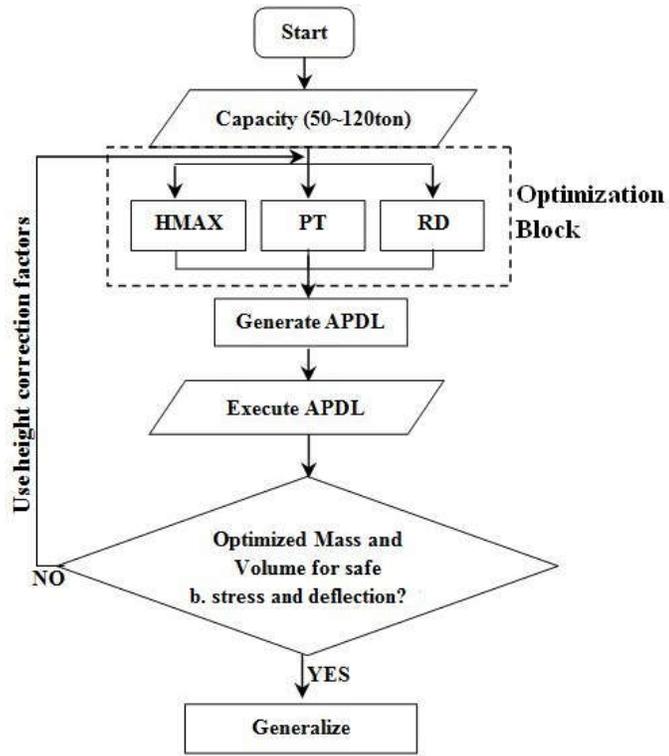
$$(PT)_1 = 1.85 - (0.005 \times (120 - CC)) \quad (12)$$

The span control block consists of the following modified span-wise interpolative relations:

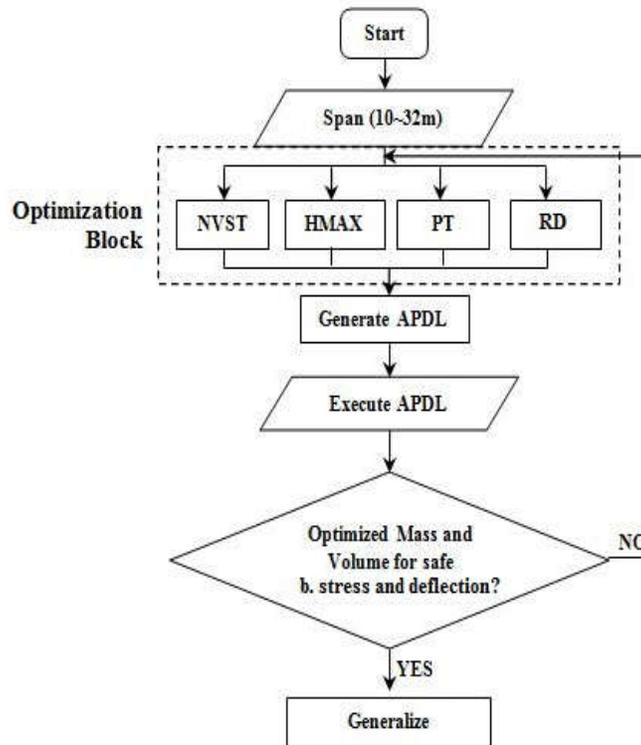
$$(H_{MAX}) = ((H_{MAX})_1 - (CMF \times (16000 - HL))) + SPC \quad (13)$$

$$(RF) = (RF)_1 + (0.0000365 \times (16000 - HL)) - RDC \quad (14)$$

$$(PT) = (PT)_1 - (0.00009375 \times (16000 - HL)) - PRC \quad (15)$$



(a)



(b)

Fig. 6: (a) Capacity wise optimization (b) Span wise optimization.

The capacity control block consists of the following modified capacity-wise interpolative relations:

Where SPC is the maximum span control factor with a value of -125 and is only used for 32 m span box girders for any capacity; CMF is the height compensation factor for all spans; RDC is the side plate control factor that works for all spans in the range; PRC is the top and bottom plate control factor; CC is the capacity of the given sized girder; and HL is the half of the span.

The general methodology for combined optimization is given in Fig. 7. As a case study, correction factors for 50~120 ton capacity and different spans are summarized in Table 1.

Table 1: Correction factors for capacity 50~120 ton for different span ranges

Capacity (ton)	Span (m)		Correction Factors		
	from	to	CMF	RDC	PRC
50~60	30	32	0.180	0.050	0.002
	24	26	0.115	0.050	0.002
	10	12	0.100	0.050	0.002
60~80	30	32	0.175	0	0
	22	26	0.115	0	0
	10	16	0.097	0.050	0.002
80~100	30	32	0.175	0	0
	24	28	0.115	0	0
	10	12	0.102	0.050	0.002
100~120	30	32	0.175	0	0
	24	26	0.115	0	0
	10	12	0.114	0.100	0.002

As a case study, calculations are presented below using combined optimization strategy for a sample girder of 75 ton capacity and 26 m span box girder.

3.1 Capacity Control Block

Using equations 10 through 12; the values of H_{MAX} , $(RF)_1$ and $(PT)_1$ are calculated to be 2262.5 mm, 0.6145, and 1.625 respectively.

3.2 Correction Block

The correction factors are used from Table 1 i.e. for 75 ton \times 26 m, $SPC=0$ (as the span is not equal to 32 m), $CMF=0.143$, $RDC=0$, and $PRC=0$.

3.3 Span Control Block

From relations 13 through 15; as the span is 26 m, HL (half-length in mm) = $26/2 \times 1000$ = 13000 mm, H_{MAX} , RF , and PT are calculated as 1833.5 mm, 0.724, and 1.34375, respectively. Therefore, the optimized 75 ton \times 26 m girder will have the $H_{MAX} = 1833.5$ mm, $RD = 0.724$, $PT = 1.34375$. However, thickness of side and top plates can be calculated using equations 16 and 17 respectively,

$$T_{SP} = 16 \times RF \quad (16)$$

$$\begin{aligned}
 \text{So, } T_{SP} &= 16 \times 0.724 = 11.584 \text{ mm} \\
 \text{and, } T_{TP} &= T_{SP} \times PT \\
 T_{TP} &= 11.584 \times 1.34375 = 15.566 \text{ mm}
 \end{aligned}
 \tag{17}$$

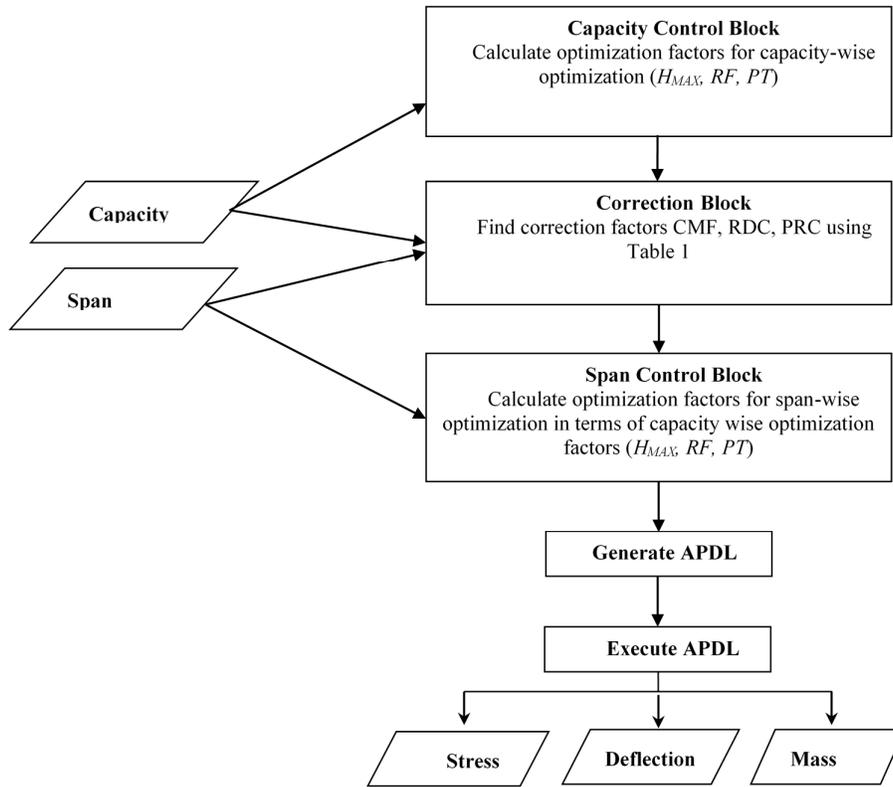


Fig. 7: Methodology for combined optimization.

Figure 8a presents a comparison of results of capacity-wise optimizations with 32 m span of girders with the results of the combined optimization methodology. Figure 8b presents the comparison of span-wise optimization results of 100ton girders with the combined optimization methodology. As case study, results of combined optimization methodology for 120 ton, 80 ton, and 50 ton capacity and 10, 20, 30, and 32 m span box girders are summarized in Table 2.

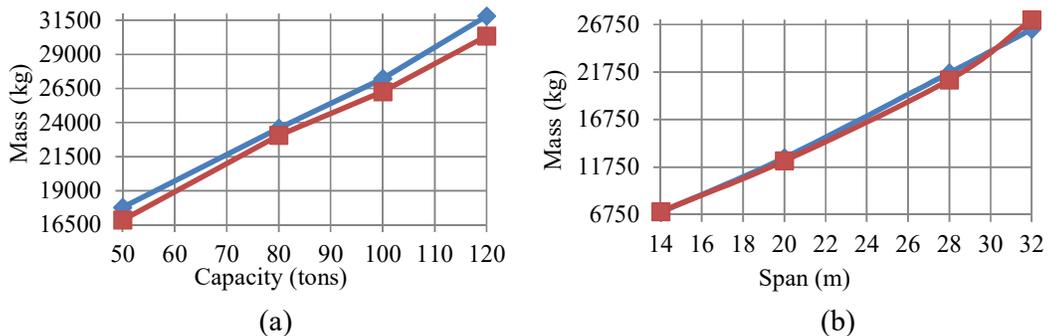


Fig. 8: (a) Comparison of capacity-wise and combined results of 32 m span box girders, (b) Comparison of span-wise and combined results of 100 ton capacity box girders.

Table 2: 50, 80, and 120 ton capacity girders after combined optimization

Capacity Ton	Span m	H _{MAX} mm	T _{SP} mm	T _{TP} mm	W _{TP} mm	H _{RL} mm	T _{HS} mm	MBS MPa	USUM mm	UZ mm	MASS kg
120	32	2525	12	22	878	70	8	154.1	39.4	6.1	30330
	30	2400	13	22	834	66	7.5	156.4	35.1	5.3	27900
	20	1850	16	21	643	51	6	154.4	18.9	3.0	14604
	10	1313	17	14	457	36	3.5	154.8	6.5	1.6	3058
80	32	2160	11	19	751	60	6.75	155.9	44.2	6.0	23050
	30	2125	11	18	739	59	6.75	154.4	39.0	5.5	20910
	20	1670	14	16	580	46	5.25	151.5	19.5	2.9	11150
	10	1178	16	10	410	33	3.75	150.2	6.4	1.4	3530
50	32	1950	9	14	678	54	6	154.4	46.5	6.3	16848
	30	1895	9	13	659	53	6	156.5	42.3	5.8	15002
	20	1445	12	12	502	40	4.5	155.5	21.7	2.9	8020
	10	975	15	8	339	27	3	155.2	7.1	1.2	2640

4. OPTIMIZATION METHODOLOGY CONSIDERING INDUSTRIAL CONSTRAINTS

The aim of the research is not only the optimization of the overhead crane box girders but also to optimize it in accordance with industrial constraints. The size of the plates for side, top, bottom, and vertical stiffeners; rail and horizontal stiffener sections calculated during the optimization were not realistic, being in fractions and mostly not corresponding to sizes available in the market. Therefore, in order to make the optimized design more practical: standard libraries for the standard sections i.e. standard plates, rails, and horizontal stiffeners [48] as available in the market are added. The optimized parameters are modified according to the standard size libraries. Finally, standard section libraries are added in the APDL code and optimized sections are achieved by selecting the closest available option for a given design variable that is used in the modeling and analysis instead of the ones calculated without considering industrial constraints.

Figure 9 compares the mass of 100 ton box girders before and after the addition of standard sizes. With the inclusion of standard sizes, the mass of the optimized box girders is increased and the maximum bending stresses are mostly found to have decreased due to the fact that a bigger or thicker section is always selected. Hence, the over-design caused is unavoidable as the selection of the small or thin sizes mostly tends to cause under-design. However, in order to control mass and waste of material during cutting, and to reduce manufacturing cost: cutting and welding plans, modification of height and width of the plates is introduced and are discussed in the following sections.

4.1 Height Modification

The design variables of the box girders optimized without industrial constraints are modified and re-optimized to design box girders with industrial constraints. The sizes of A36 structural steel plates, in terms of height and width, are according to State Steel USA's product catalogue [48], and are presented in Table 3. It is observed that the difference between the heights is 304mm ($1524-1219.2 = 304.8$ mm) except the last size. Therefore, if a constraint is added in such a way that the APDL code selects the closest, then the mass increases, which is not desired. Another methodology is to sustain the heights of the plates calculated during the WOIC optimization and cutting and welding the plates together. This

causes an increase in the cost of manufacturing. This also causes an increase in deformations during welding, resulting in structural weakening. In order to overcome the above mentioned issues, the box girders are re-optimized for maximum height (H_{MAX}) equal to the ones that are available in the market. The first four sizes (1219.2 mm, 1524 mm, 1828.8 mm and 2133.6 mm), as mentioned in the Table 3, were selected. As all parameters other than the height and thickness of plates depend upon the H_{MAX} optimization factor, therefore, the only design variables left after having H_{MAX} , is the thickness of the side, top, and bottom plates. Thus, the optimization for height modification is done by changing the thicknesses of web and flange plates. The height of the plates is selected according to the H_{MAX} calculated in the previous optimizations and is divided into ranges as mentioned in Table 4.

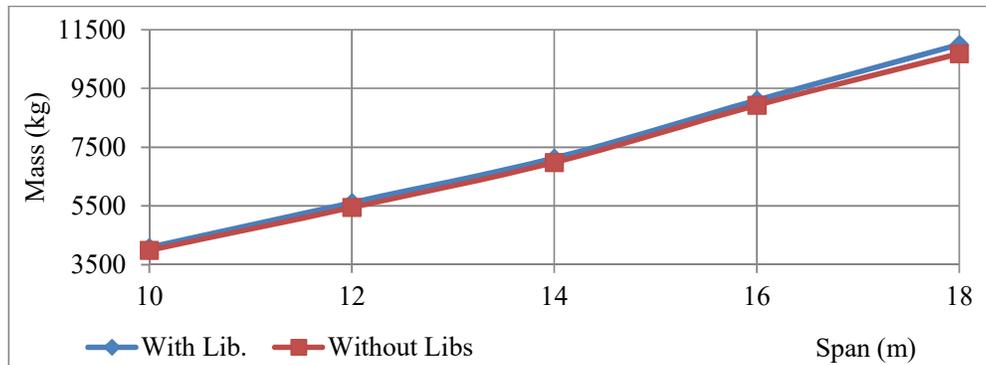


Fig. 9: Mass comparison of 100 ton girder with and without industrial constraints.

Two approaches were used during this optimization:-

- Keeping all thicknesses the same i.e. $T_{SP} = T_{TP} = T_{BP}$. (Approach 1).
- Keeping web thicknesses and flange thicknesses different from one another, but keeping the thickness of the top and bottom flange the same and left and right web plates the same. (Approach 2).

Table 3: Standard available heights and widths of plates

W (mm)	H (mm)	Difference between heights (mm)
6000	1219.2	304
6000	1524.0	304
6000	1828.8	304
6000	2133.6	304
6000	2438.4	---
6000	3048.0	---

Table 4: Ranges for height modification

H_{MAX} (mm)	H_{MAX} (mm)
850 ~ 1500	1219.2
1500 ~ 1755	1524.0
1755 ~ 2049	1828.8
2049 ~ 2650	2134.0

4.2 Approach – 1 with Same Flange and Web Plate Thickness

The methodology is to select the thickness of all webs and flanges to be almost equal to the average of T_{TP} and T_{SP} calculated in the previous methodologies. Hence, direct relationships are developed between the thicknesses of web or flange (as they are taken to be the same) with the capacity and span. These relations are different for different capacities and spans and are incorporated in the APDL code. As a case study, for 20 and 21 m span and 50~120 ton capacity cranes, the plate thicknesses are calculated as mentioned in Table 5. The output stresses and deflections, thus produced, are within the allowable limits.

Table 5: Height Modification Thickness for 20 m and 21 m span girders

Span (m)	Capacity (ton)	CPT (mm)
20	50~60	$((40+CC)/5)$
	60~95	$((60+6*CC)/30)$
	95~120	$((5*CC-125)/25)$
21	50~55	18
	55~85	$((6*CC-5)/25)$
	85~120	$((6*CC-20)/35)$

4.3 Width (WTP) Modification

The width of the box girder was calculated to be $H_{MAX}/2.71$ during previous optimizations. The ratio of H_{MAX} to W_{TP} (width of top plate) or W_{BP} (width of bottom plate) was set as 3 i.e. cutting it into three pieces, hence saving the loss in height of the plate. This also follows the Bećirović et al. [37] recommendation that increasing the height to width ratio i.e. H_{MAX}/W_{TP} , increases the static as well as dynamic stability of the box girders.

4.4 Approach-2: With Different Flange and Web Thickness (DFW)

Using thicknesses initially calculated in the approach-1 and modifying the web and flange thicknesses so as to be ratios of approach-1 thicknesses. The study concluded that the web and flange plate thicknesses must be 0.9 times and 1.25 times of approach-1 thicknesses respectively. For example, if a thickness of 15 mm was concluded for a particular specification box girder, then the plate thicknesses used in approach-2 analysis will be 14 mm (i.e. $15 \times 0.9 \approx 14$) for the side plates and 19mm (i.e. $15 \times 1.25 \approx 19$) will be used for the top and bottom flanges. As an example the mass calculated for 85 ton capacity and 26 m span crane box girder using approach-2 was 19742 kg i.e. 1047 kg (5.04%) less than the mass of the girder according to approach-1. Although the stresses and deflections are observed to be more than those observed for approach-1 but are still within the allowable limits.

5. COMPARISON OF WOIC AND WIC OPTIMIZATION RESULTS

This section compares the optimization results in a case when no standard size for height was used (old method), to the case when standard heights were used. Additionally, a comparison of cases where thicknesses of top/bottom and side plates were kept constant for approach-1 and not constant for approach-2 (diff-thick) were also used. Finally, the case with width modification is also compared with the prior. The aim of this comparison is to analyze the feasibility of the later optimizations. The case study presented shows results of crane capacity 120 ton box girders of various spans. Figure 10a-b show a comparison of

mass, U_Z , and H_{MAX} results with and without considering industrial constraints. It is observed that as span increases, the difference between the old (WOIC) and new methodology (WIC-SFW) increases. The mass of a 32 m span WOIC and WIC optimized girder is 30060 kg and 36373 kg (~21% increase), respectively (Fig. 10a). It concludes that the mass of the girders in WIC increases as compared to the WOIC during an increase in span length and/or capacity. A similar trend is observed with W_{TP} modification different thickness, but the difference is smaller in comparison to WIC-SFW. Abid et al. [30] have compared lateral buckling (U_Z) for different designs of the box girders and have concluded that lateral buckling control is better for WIC compared to the WOIC. No notable difference in the bending deflections (U_Y) and shear buckling (U_X). Figure 10b compares H_{MAX} for the various case studies and shows that the height with WIC is smaller compared to WOIC and width of the girders is directly related to H_{MAX} , thus, the volume (space) occupied by the WIC is less than that of WOIC girders. The variety of plate sizes for manufacturing is greatly reduced as now the thickness of top and side plates is the same for the approach-1. Although the mass of the girders is increased with WIC methodology yet it is inconclusive to state that it is not cost effective, as cost effectiveness can only be known after knowing the cutting and welding as well as material costs for manufacturing and the already available inventory. Therefore, approach-2 is proposed as the final design for the box girders. The cutting plan and welding methodologies are all based on this particular design. The features of the finalized design are summarized below;

- The height of the girder web plate is selected as per ranges defined in the Table 4.
- The width of the flange plates (both top and bottom) is one-third of the maximum height of the girder web plate.
- The ratio of thickness top/bottom flange to the web plates is 1.389.
- All horizontal stiffeners and rail sections are selected according to the standard library.

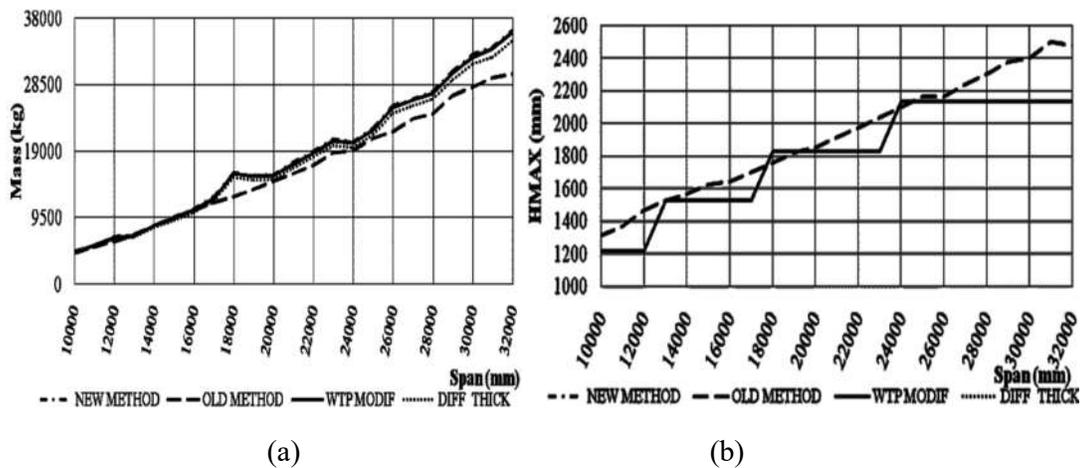


Fig. 9: Comparisons for 120 ton capacity with different spans; (a) mass, (b) H_{MAX} .

6. CONCLUSIONS

After detailed FEA of box girders, the following conclusions are made;

- Optimization of an overhead crane box girder for capacity (50~120 ton) and span (10~32 m) is performed for safe bending stress and deflection with minimum mass and volume with and without consideration of industrial constraints using a customized developed optimization resulting in accuracy and automation.
- The cutting and welding plan is optimized to reduce wastage and control manufacturing overheads.
- The finite element model used solid186 elements because their use offers better control during parametric modeling. The shell elements on the other hand are not suitable for horizontal stiffener and rail sections as they cannot be treated as shells. Also, after the inclusion of height modification in the height reduction in specific cases is made possible at the cost of thickness addition, thus, the error in shell element calculation is avoided.
- The parametric optimization of the reference girder (120 ton \times 32 m) concluded a 14.63% (or 5449 kg) mass reduction, 27.3% and 2.18% thickness reduction of web and flange plates respectively with respect to the existing box girder model. Similar savings are observed in all the range of capacity and spans.
- Linear interpolated capacity-wise and span-wise relations were developed for the calculation of the design parameters (H_{MAX} , PT and RD) for the required capacity (50 ton~120 ton) and span (10 m ~ 32 m) of the box girder. Before performing span-wise optimization, with the only input as span and fixed capacity (100 ton), mesh sensitivity analysis was carried out and an element edge length of 170 mm was concluded (for a 100 ton girder).
- The combined optimization using combination/correction factors was performed in three steps (capacity, correction and span control block).
- The optimized parameters concluded were modified according to the industrial constraints i.e. standard section libraries of plates and rolled sections available in the market. The addition of standard libraries increased the mass of the girder as the code selected an upper bound thickness.
- The height of the girder (H_{MAX}), as calculated during the earlier optimizations, was modified keeping in mind the losses during the crane construction. H_{MAX} was concluded to be equal to the size of a given standard plate to avoid cutting along the height of the web. W_{TP} was concluded to be 1/3 of the height of the girder (H_{MAX}). Two optimization studies were performed to modify the height considering first web and flange thicknesses to be equal (approach-1), and secondly top/bottom plate thickness of 0.9 times and 1.25 times the thickness calculated in approach-1. All the optimization case studies performed were compared and it was concluded that the case studies with no height modifications had lower masses for greater spans (15 m ~ 32 m). The addition of mass due to height modification increases with the increase in both span and capacity. Hence, the mass of the height modified cases for lower spans was observed to be less than the non-modified case studies.

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