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Optimum Design of Plate Girder

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Abstract: *This study concerns with finding the geometric dimensions of a plate girder which minimize the total weight and satisfy the design requirements using Genetic Algorithm (GA), Sequential Quadratic Programming (SQP), Goal Attainment (GATT), and Multilevel Optimization methods. The total volume of a stiffened plate girder is minimized subjected to the provisions of the British Standard (BS 5950: 2000-1). The design variables are taken as the cross-section dimensions. The results indicate that the considered optimization methods are successfully and efficiently used in this study but the SQP method is easier in use and faster in finding the global minimum. The GATT method can successfully be used to minimize both single and multi-objective optimization problems but the results depend on the goal and weight vectors. The multilevel optimization method makes the process faster but choosing the problem of each level and the coordination variables are so important to find the right results. Also, the results show that the web depth should be increased as possible to decrease the flanges weight which represents more than 50% of the total weight.*

Keywords: *Plate girder, Optimization, Genetic Algorithm (GA), Sequential Quadratic Programming (SQP), Goal Attainment (GATT), and Multilevel Optimization***.**

I. Introduction

Plate girders are deep built-up flexural members used to resist high bending moments and shear forces over long spans where the standard rolled or compound beams cannot satisfy the design requirements. Generally, plate girders consist of two flange plates welded to web plate to form an I-section. The major function of the flange plates is to resist the stresses arising from the applied bending moments. The major aim of the web plate is to resist the applied shear forces. For making the plate girders light and economical, the web depth must be increased as possible to decrease the required flanges area while keeping the web thickness thin as possible. Therefore, the web would be slender plate. Hence, the girder may fail due to web bucking under shear force less than its capacity. Vertical and horizontal stiffeners should be used to avoid web buckling[1].

The designer has various choices to form plate girder and many designs, satisfy the design requirements, may be formed, but these designs may not be economical. The design of plate girder that satisfies the design requirements and minimizes its cost or weight is called optimum design. Therefore, it is required that the designer has a powerful tool to find the optimum design. Many effective optimization methods are considered to get the ideal design of various applications in civil engineering such as genetic algorithm (GA), sequential quadratic programming (SQP), goal attainment (GATT), and multilevel optimization methods, etc.

Some authors examined the behavior and design of plate girder and also, many studies considered optimization in civil engineering. Kirsch (1983)[2]used multilevel optimization to discover the best design of continuous reinforced concrete beams. A three levels optimization was used to find the concrete dimensions and amount of steel to minimize the total cost. It was found that using multilevel optimization makes the process very simple. AL-Tabtabai et al. (1999)[3] used the Genetic Algorithm method to find the economical design of slab formwork. A new method to design the concrete slab formwork was suggested in their study by using genetic algorithm approach. Chen et al. (2005)[4]used GA with elitism to find the geometric variables which minimize the cost of welded steel girder bridge. It was found that GA is very simple and can successfully be used to find the design of welded plate girder bridge. Agrawal et al. (2013)[5]presented the use of GA for optimal design of welded plate girder according to IS 800:2007 design code. The result showed that GA is very simple and suitable to find the optimum solution to the problem.

The main aim of the paper is to find the dimensions of the steel plates which form the plate girder to minimize the total weight and satisfy the design considerations. Also, the ability and efficiency of GA, SQP, GATT, and multilevel optimization methods to find the optimum design are explored. The efficiency of GATT to solve multi-objective optimization and the applicability of multilevel optimization are examined.

The study consists of six sections. First section gives the introduction, the aim, and a review of the related studies. In the second section, the optimization methods are explained. Third section presents the problem formulation. In the fourth section, the results are given. In the fifth section, the results are discussed. Lastly, the sixth section presents the conclusion of the study.

II. Optimization Methods

Optimization is the process of finding the best result under definite conditions. In daily life, people use optimization for simple things such as shopping, traveling, work, etc. Many optimization problems exist in civil engineering applications. They concern with finding the geometric dimensions which called the design variables, in such way that the total cost or weight is minimized (this is called the objective), while satisfying the design requirements which represents the constraints. Most optimization problems can be stated as follows[6]:

Find X, which minimizes $f(X)$

$$\begin{aligned} &\text{subject to} \quad g_i(X) \leq 0, \quad i = 1,2,\dots,m \\ &\text{and} \quad h_j(X) = 0, \quad j = 1,2,\dots,l \\ &\text{and} \quad X^L \leq X \leq X^U \qquad \dots\dots(1) \end{aligned}$$

where X is a column vector of n design variables. $f(X)$is the objective function, $g_i(X)$ are inequality constraints, $h_j(X)$ are equality constraints, and $X^L and X^U$ are known as lower and upper limits of the design variable, respectively. Many methods can be used to solve the above problem. The considered optimization methods in this study are given as follows:

1. Genetic Algorithm (GA) Method

Genetic algorithms (GAs) were presented by John Holland in the 1960s. GA is common, general, powerful, derivative-free, easy to use and program, and global optimization approach. It is based on Darwin’s theory of survival of the fittest. GA tries to maximize a fitness function by considering three genet operations: selection, crossover, and mutation[6].GA works by creating an initial population (possible solutions) then selecting the best individuals depending on their fitness by using one of the selection methods such as roulette wheel. The selected individuals go through crossover operation depending on a given crossover probability to create new chromosomes. Every gen in the new chromosomes may be change depending on a mutation probability to get new population. This process is continued until finding an optimum solution or reaching a stop criterion. It should be noticed that GA is affected by the local optimum solutions.

2.Sequential quadratic programming (SQP) Method

Sequential quadratic programming (SQR) method was suggested in the Ph.D. thesis of Wilson (1963) [7].SQP method is one of the most powerful direct methods for solving constrained nonlinear optimization problems. SQP generates steps by solving quadratic subproblems. Quadratic problem is the simplest nonlinear optimization problem with a quadratic function and linear constraints. This method uses the derivatives of objective and constraint functions and can reaches the global optimum faster.

2. Goal Attainment (GATT)Method

The optimization problems involving more than one objective function are called multi-objective optimization. In this case, finding single solution to optimize all the objective functions is not possible. Therefore, the best solution which called Pareto Optimum is considered. GATT is one of the best optimization methods that can be used to solve multi-objection optimization problems. It was proposed by Gembicki in 1973[8]. It combines the objective functions into a single function that considers each function in an expressive way. This method works by setting a design goal (F^*) for each function and trying to achieve it. The probability of achieving the fixed goal is controlled by weight ($w \geq 0$) for each function. Hard constraint can be introduced by setting the weight value equal to zero. The best solution for a multi-objective functions $F_i(X)$ can be obtained by presenting a scalar γ as new design variable to get the following single objective problem[6]:

Find X and γ which minimizes $F(x1, x2, \dots . xn, \gamma) = \gamma$

$$\begin{aligned} &\text{subject to} \quad F_i(X) - w_i\gamma \leq F_i^*, \; i=1,2,\dots k \\ &\text{and} \quad g_j(X) \leq 0, \qquad j = 1,2,\dots,m \\ &\text{and} \quad h_d(X) = 0, \qquad d = 1,2,\dots,l \\ &\text{and} \quad X^L \leq X \leq X^U \qquad \dots\dots(2) \end{aligned}$$

2. Multilevel Optimization

Kirsch introduced multilevel optimization method to optimum structural design in 1978[9]. It is an efficient tool adapted to simplify the complex problems by breaking the problem into a system level and a set of smaller subsystems. A coordination problem at system level is considered to revising subsystems to make the final solution same as that of the original problem[6]. The solution is found by making iterations between the system level and subsystems until convergence of the objective function is reached.

III. Problem Formulation

In this study an attempt is made to obtain an economical design of a simply supported plate girder, used in an office building, which satisfies the design requirements of British Standard BS 5950 part1:2000[10]. The optimum design problem involves the following features:

1. Analysis of the Plate Girder

Figure (1) shows the plate girder loading that gives maximum bending moment (M_u = 17595 kN.m) at the center of the span and maximum shear force (F_v=2070 kN) at the supports. Also, the bending moment and shear force arising from the self-weight of the girder will be taken into consideration later. For deflection check, the total uniformly distributed live load (W_l) = 15 kN/m and the total point live load (P_l) =150 kN are used in calculations.

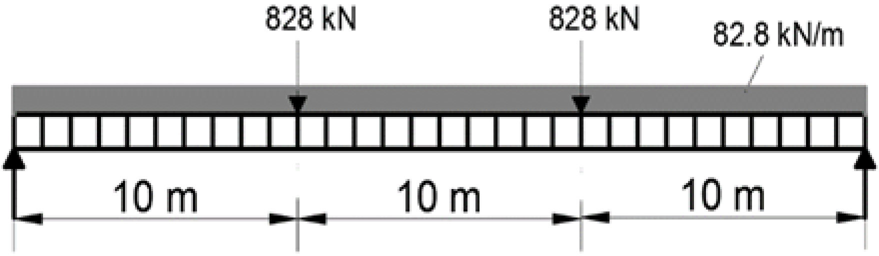
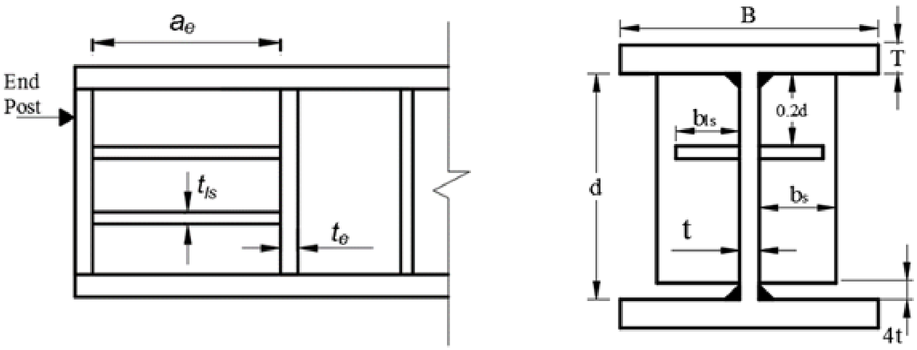


Figure 1: Plate girder loading

2. Design Parameters

Some parameters should be considered as constants during the optimization process, these parameters include the span length (L=30 m), the unit weight of steel (γ_s=77 kN/m^3), modulus of elasticity of steel sections (E= 205000 N/mm^2), Grade of steel (S355), and the applied loads. Other parameters should be taken as variables during the optimization process, these include: flanges width (B), flanges thickness (T), web depth (d), web thickness (t), transverse stiffeners spacing (center-to-center) (a),transverse stiffeners width (outstand) (b_s), transverse stiffeners thickness (t_s), longitudinal stiffeners width (b_{ls})(outstand), longitudinal stiffeners thickness (t_{ls}), end post thickness (t_e), end post width (outstand) (b_e), and the spacing of anchorage panel stiffeners (center-to-center) (a_e). Figure (2) shows the design variables.



(a) Anchor panel (b) Cross-section

Figure 2: Plate girder layout

3.Design Constraints

According to BS 5950-1:2000, the design of a plate girder should satisfy the following requirements:

a. The thickness of the web should be chosen to satisfy the serviceability requirements and prevent the vertical buckling of the compression flange(Cl. 4.4.3).

For serviceability requirements:

where $a > d$: $t \geq d/250$ ……(3)

where $a \leq d$: $t \geq (d/250)(a/d)^{0.5}$ ……(4)

To prevent the compression flange buckling:

where $a > 1.5d$: $t \geq (d/250)(p_{yf}/345)$ ……(5)

where $a \leq 1.5d$: $t \geq (d/250)(p_{yf}/445)^{0.5}$ ……(6)

where p_{yf} is the design strength of flange depends on the flange thickness (CL. 3.1.1)

b. The dimensions of the flanges should be chosen to prevent the local buckling in the compression flange(CL. 3.5.3):

$$B - t - 26T(275/p_{yf})^{0.5} \leq 0 \qquad \text{……(7)}$$

c. The applied bending moment should not exceed the moment capacity of the plate girder. If the applied shear force is higher than 60% of the simple buckling shear of the plate girder, one of these methods can be used to calculate the moment capacity(Cl. 4.4.4):

1. Simplified (flange only) method: the flanges resist the entire moment alone. The following constraint should be satisfied: $M_u + M_s - BT(T+d)p_{yf} \le 0$ ……(8)

2. The general method: the flanges and web resist the applied moment using the design strength of flanges. The following constraint should be satisfied:

$$M_u + M_s - BT(T+d)p_{yf} - 0.1667d^2tp_{yf} \le 0 \qquad ……(9)$$

where M_s is the maximum bending moment arising from the self-weight of the plate girder.

d. The applied shear force should not exceed the shear buckling resistance of the plate girder. If $d/t \ge (62(275/p_{yw})^{0.5})$, the web should be design by considering the shear buckling. Generally, the webs are designed by one of the following methods (Cl. 4.4.5):

1. Simplified method: the post buckling strength of the web is considered to calculate the shear buckling resistance of the web. The following constraint should be satisfied:

$$F_v + F_s - dtq_w \le 0 \qquad ……(10)$$

2. Tension field method: the web can resist shear stress beyond the post-buckling stress depending on the tension field action where the stiffeners and flanges carry the additional shear stresses. The following constraint should be satisfied:

$$F_v + F_s - dtq_w - \frac{P_v(d/a)\left[1-(f_f/p_{yf})^2\right]}{1+0.15(M_{pw}/M_{pf})} \le 0 \qquad ……(11)$$

where p_{yw} is the design strength of the web, F_s is the maximum shear force arising from the self-weight of the plate girder, q_w is the shear buckling strength of the web given in (Annex H.1 of the code), f_f is the mean longitudinal stress in the smaller flange due to moment and/or axial force, M_{pf} is the plastic moment capacity of the smaller flange, and M_{pw} is the plastic moment capacity of the web.

e. The stiffeners spacing and dimensions should be designed to prevent the local buckling of the web and increase the shear buckling resistance. Also, a proper load carrying and bearing stiffeners should be provided to prevent bearing and buckling failure in the web under the point loads or reactions. According to the code, the following constraints should be satisfied(Cl. 4.4.6.4 and Cl. 4.5.2.2):

1. Maximum outstand: the design of stiffeners should be based on an outstand not greater than $(13t_s(275/p_{ys})^{0.5}$ to prevent the local buckling in the stiffeners, this gives:

For vertical stiffeners: $b_s - 13t_s(277/p_{ys})^{0.5} \le 0$ ……(12)

For horizontal stiffeners: $b_{ls} - 13t_{ls}(277/p_{ys})^{0.5} \le 0$ ……(13)

For end post stiffeners: $b_e - 13t_e(277/p_{ye})^{0.5} \le 0$ ……(14)

where p_{ys} is the design strength of the vertical and horizontal stiffeners and p_{ye} is the design strength of the end post stiffeners.

2. Minimum stiffness: the vertical and horizontal stiffeners should have adequate stiffness to prevent the web buckling. Therefore, the following constraints should be satisfied:

For a pair of rectangular vertical stiffeners for $a/d < \sqrt{2}$: $1.5(d/a)^2dt^3 - t_s(t+2b_s)^3/12 \le 0$ ……(15)

For a pair of rectangular horizontal stiffeners: $I_{ls} - t_{ls}(t+2b_{ls})^3/12 \le 0$ ……(16)

where I_{ls} is considered according to the code of practice IS 800:2007[11], given by $4at^3$ for the first stiffener at $0.2d$ from the compression flange and dt^3 for the second stiffener at $0.5d$ from the compression flange.

3. Bearing and buckling resistance of end post stiffeners:

By assuming that the end post stiffener is cut back 15 mm for welding the web with flange, the end post stiffeners should satisfy the following constraint to prevent bearing failure of the web(Cl. 4.5.2.2):

$$F - 2t_e(b_e - 15)p_{ye} \le 0 \qquad ……(17)$$

where F is the total applied concentrated load or reaction plus the compression force caused by tension field if considered. Also, the end post stiffeners should satisfy the following constraint to prevent the web buckling failure(Cl. 4.5.3.3):

$$F - (t_e(2b_e + t) + t(15t - 0.5t_e))p_c \le 0 \qquad ……(18)$$

where P_c is the compressive strength given by (Annex C.1 of the code).

f. Adequate anchorage should be provided to the end panels to resist the horizontal force caused by the tension field. End anchorage is not required if the following constraint is satisfied(Cl. 4.4.5.4):

$$F_v + F_s - dtq_{cr} \le 0 \qquad ……(19)$$

where q_{cr} is the critical shear buckling strength given by (Annex H.2 of the code)

In other cases, end anchorage should be provided to resist the horizontal component of the tension field action in the end panels (H_q) given by: $H_q = 0.5dtp_{yw}[1 - V_{cr}/P_v]^{0.5}$ ……(20)

Many methods can be used to provide end anchorage. Anchor panel method is considered in this study, the end panels are designed without considering the tension field action and the other panels are designed using tension field. The end panel should be designed as a vertical beam panning between the flanges and the following constraints should be satisfied:

$$M_{tf} - t_e(2b_e + t)a_ep_{ye} \le 0 \qquad ……(21)$$

$$R_{tf} - ta_eq_{cr.ep} \le 0 \qquad ……(22)$$

where: M_{tf} is the bending moment arising from the tension field, given by: $M_{tf} = 0.15dH_q$ ……(23)
R_{tf} is the shear force arising from the tension field, given by: $R_{tf} = 0.75H_q$ ……(24)
g. The stresses in the web caused by the applied loads between the transverse stiffeners should not exceed the web resistance. The following constraint should be satisfied(Cl. 4.5.3.2): $W/t - p_{ed} \leq 0$ ……(25)
where W is the total uniformly distributed load and p_{ed} is the compressive strength of the web. For the restrained compression flange against rotation relative to the web, p_{ed} is given by:

$$P_{ed} = \left[2.75 + \frac{2}{(a/d)^2}\right]\frac{E}{(d/t)^2} \qquad \text{……(26)}$$

h. The vertical deflection of the plate girder should not exceed the allowable limit. The studied plate girder should satisfy the following constraint:

$$\frac{5W_l L^4}{384EI} + \frac{23P_l n^3}{24EI} - \frac{L}{200} \leq 0 \qquad \text{……(27)}$$

where n=10 m and I is the second moment of area about the centreline of the section in the x-direction, given by:

$$I = \frac{B(d+2T)^3}{12} - \frac{(B-t)d^3}{12} \qquad \text{……(28)}$$

4. Objective Function

For the present study, the objective function (F) is defined as the total weight of the plate girder. Because the unit weight of steel (γ_s) is constant and the same homogenous steel is used, then the total volume of the plate girder is considered as the objective function, given as follows:

$$\boldsymbol{F = 2BTL + dtL + t_s b_s (d - 4t) N_s + 2t_{ls} b_{ls} L_{ls} + t_e b_e d N_e} \qquad \text{……(29)}$$

where N_s is the total number of the transverse stiffeners, given by $2(\frac{L}{a} - 1)$ if the tension field is not used, otherwise given by $2(\frac{(L-2a_e)}{a} - 1)$. L_{ls} is the total length of the longitudinal stiffeners given by $(L - N_s t_s - 2t_e)$ when the longitudinal stiffeners are used along the length of the plate girder or $8a_e$ when two longitudinal stiffeners are used on each side of the girder in the anchor panels only. N_e is the number of end post stiffeners given as 4 if the tension field is not considered or 8 if the anchor panel method is considered.

IV. Results

Many numerical examples have been considered to well understand the optimum design of plate girder, illustrate the efficiency of the considered optimization methods, and study the effect of design method, longitudinal stiffeners, end anchor, web dimensions, and flange dimensions on the plate girder weight. The optimization problem is solved using *Matlab* program. The number of iterations (i) and the running time (t) required to find the solution are recorded for each application. The results of this study are as follows:

1. Results of GA and SQP methods

The simplified design method, for a vertically stiffened only plate girder (App.1) and for a plate girder stiffened vertically and horizontally at 0.2d from the compression flange (App.2), is considered. Also, two applications are solved using the exact design methods: one considers the general method of moment resistant (App.3) and the other uses tension field method for shear buckling resistance (App.4) in which the location where the critical combination of shear and bending makes the web and flanges fully stressed is defined by a variable (x) representing the distance from the support to the critical section. The results of SQP and GA methods are given in Tables (1) and (2) respectively. Also, other four applications are solved by adding additional constraint relating to the overall depth of the girder which is restricted to 2 m. The SQP method is used. The results of these applications are shown in Table (3).

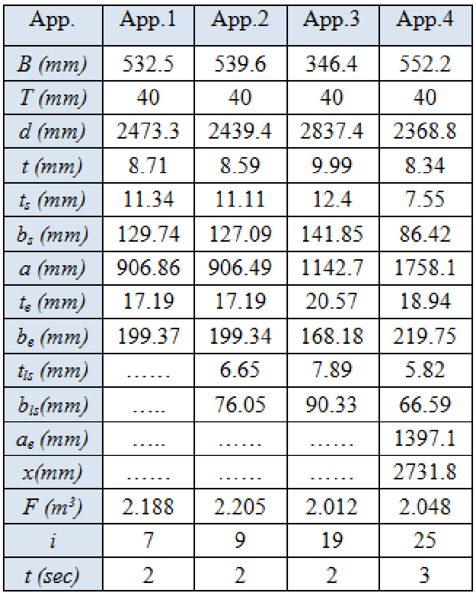
2. Results of GATT method

Three applications are studied for vertically and horizontally stiffened plate girder using the general method for calculating the moment resistance. Firstly, single objective function is optimized to minimize the total volume of the plate girder. Secondly, two objective functions are solved to minimized the total volume of plate girder and maximize the critical shear buckling capacity. Thirdly, three objective functions are solved to minimize the total volume of plate girder and to maximize the critical shear buckling resistance and moment capacity subjected to the remaining constraints. Table (4) shows the results of these applications.

3. Results of Multilevel Optimization

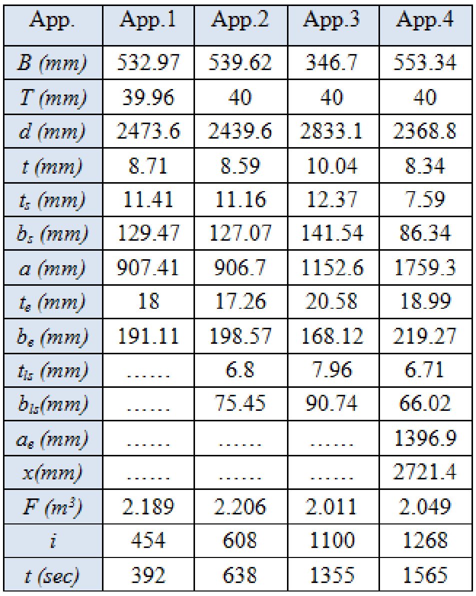
This method is used to minimize the total volume of a transversely and longitudinally stiffened plate girder using the general method of moment resistance (App. 1). The optimization problem is broken into two levels as shown in Fig. (3). Another application is solved using tension field design method (App. 2). The total volume of a vertically stiffened plate girder is minimized in the first level while the volume of the anchor panels stiffeners is minimized in the second level. The web thickness is considered as a coordination variable and started as 6 mm in the first application and 10 mm in the second application. The SQP method is used in all iterations to minimize the objective function of each level. The results of these application are shown in Table (5).

Table1: Results of SQP method



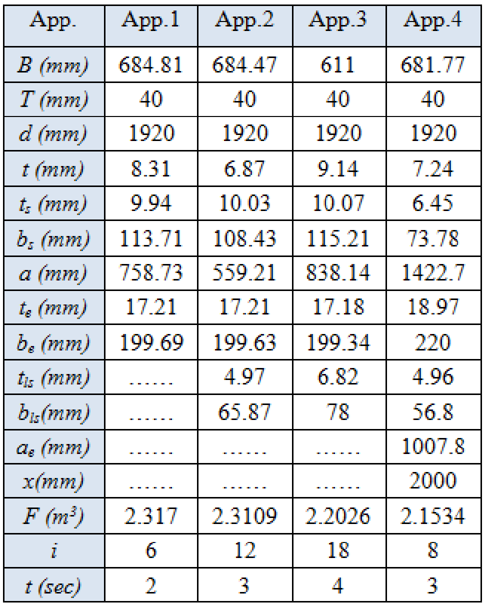
App.	App.1	App.2	App.3	App.4
B (mm)	532.5	539.6	346.4	552.2
T (mm)	40	40	40	40
d (mm)	2473.3	2439.4	2837.4	2368.8
t (mm)	8.71	8.59	9.99	8.34
t_s *(mm)*	11.34	11.11	12.4	7.55
b_s *(mm)*	129.74	127.09	141.85	86.42
a (mm)	906.86	906.49	1142.7	1758.1
t_e *(mm)*	17.19	17.19	20.57	18.94
b_e *(mm)*	199.37	199.34	168.18	219.75
t_{ls} *(mm)*	……	6.65	7.89	5.82
b_{ls}*(mm)*	…..	76.05	90.33	66.59
a_e *(mm)*	…..	……	……	1397.1
x(mm)	……	……	……	2731.8
F (m^3)	2.188	2.205	2.012	2.048
i	7	9	19	25
t (sec)	2	2	2	3

Table2: Results of GA method



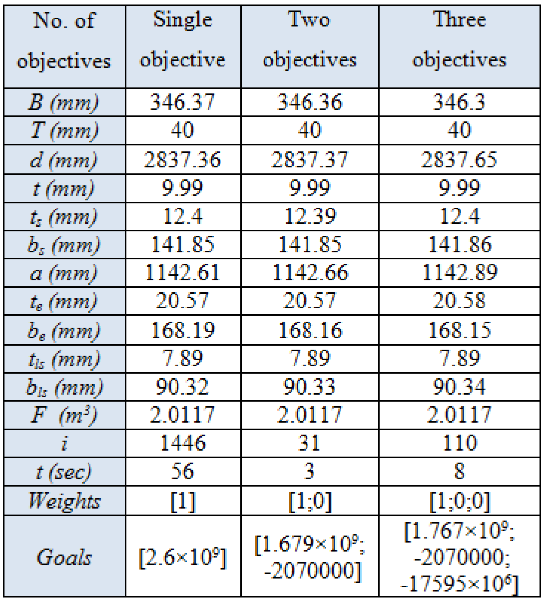
App.	App.1	App.2	App.3	App.4
B (mm)	532.97	539.62	346.7	553.34
T (mm)	39.96	40	40	40
d (mm)	2473.6	2439.6	2833.1	2368.8
t (mm)	8.71	8.59	10.04	8.34
t_s *(mm)*	11.41	11.16	12.37	7.59
b_s *(mm)*	129.47	127.07	141.54	86.34
a (mm)	907.41	906.7	1152.6	1759.3
t_e *(mm)*	18	17.26	20.58	18.99
b_e *(mm)*	191.11	198.57	168.12	219.27
t_{ls} *(mm)*	……	6.8	7.96	6.71
b_{ls}*(mm)*	……	75.45	90.74	66.02
a_e *(mm)*	……	……	……	1396.9
x(mm)	……	……	……	2721.4
F (m^3)	2.189	2.206	2.011	2.049
i	454	608	1100	1268
t (sec)	392	638	1355	1565

Table3: Design results of 2 m depth plate girder



App.	App.1	App.2	App.3	App.4
B (mm)	684.81	684.47	611	681.77
T (mm)	40	40	40	40
d (mm)	1920	1920	1920	1920
t (mm)	8.31	6.87	9.14	7.24
t_s *(mm)*	9.94	10.03	10.07	6.45
b_s *(mm)*	113.71	108.43	115.21	73.78
a (mm)	758.73	559.21	838.14	1422.7
t_e *(mm)*	17.21	17.21	17.18	18.97
b_e *(mm)*	199.69	199.63	199.34	220
t_{ls} *(mm)*	……	4.97	6.82	4.96
b_{ls}*(mm)*	……	65.87	78	56.8
a_e *(mm)*	……	……	……	1007.8
x(mm)	……	……	……	2000
F (m^3)	2.317	2.3109	2.2026	2.1534
i	6	12	18	8
t (sec)	2	3	4	3

Table4: Results of GATT method



No. of objectives	Single objective	Two objectives	Three objectives
B (mm)	346.37	346.36	346.3
T (mm)	40	40	40
d (mm)	2837.36	2837.37	2837.65
t (mm)	9.99	9.99	9.99
t_s *(mm)*	12.4	12.39	12.4
b_s *(mm)*	141.85	141.85	141.86
a (mm)	1142.61	1142.66	1142.89
t_e *(mm)*	20.57	20.57	20.58
b_e *(mm)*	168.19	168.16	168.15
t_{ls} *(mm)*	7.89	7.89	7.89
b_{ls} *(mm)*	90.32	90.33	90.34
F (m^3)	2.0117	2.0117	2.0117
i	1446	31	110
t (sec)	56	3	8
Weights	[1]	[1;0]	[1;0;0]
Goals	$[2.6\times10^9]$	$[1.679\times10^9;$ $-2070000]$	$[1.767\times10^9;$ $-2070000;$ $-17595\times10^6]$

V. Discussion

1. The efficiency of the considered optimization methods

The results clearly indicated that the four optimization methods are efficient and can successfully be used to find the optimum design of plate girder. Also, the following points are noticed through optimization process:

1. GA method is affected by the local minimum points and does many evaluations in each generation. Therefore, it takes a long time to find the global point while the other methods can successfully find the optimum point in shorter time and good guarantee.
2. SQP method is simple, powerful, and can find the global minimum in shorter time and fewer iterations. Thus, SQP is of more efficiency than GA, easier to use, and giving reliable results in a short time.
3. The number of generations and the required time to find the global optimum in GA method can be reduced by assuming an initial population near the global solution. Also, in the other methods, choosing a start point near the global point can makes the process faster and reduces the number of iterations. Table (6) shows the

effect of initial population or start point on number of iterations and running time required to find the global point given as [532.5 40 2473.23 8.71 11.34 129.74 906.86 17.86 199.37].

4. GATT method can successfully be used to minimize both single and multi-objective optimization problems. But, the global solution depends on the goal and weight vectors. Therefore, choosing the right goal and weight vectors is an extremely important issue. Figure (4) shows the effect of changing the goal of one objective function on the optimum value of two objective functions optimization problem with one hard constraint.

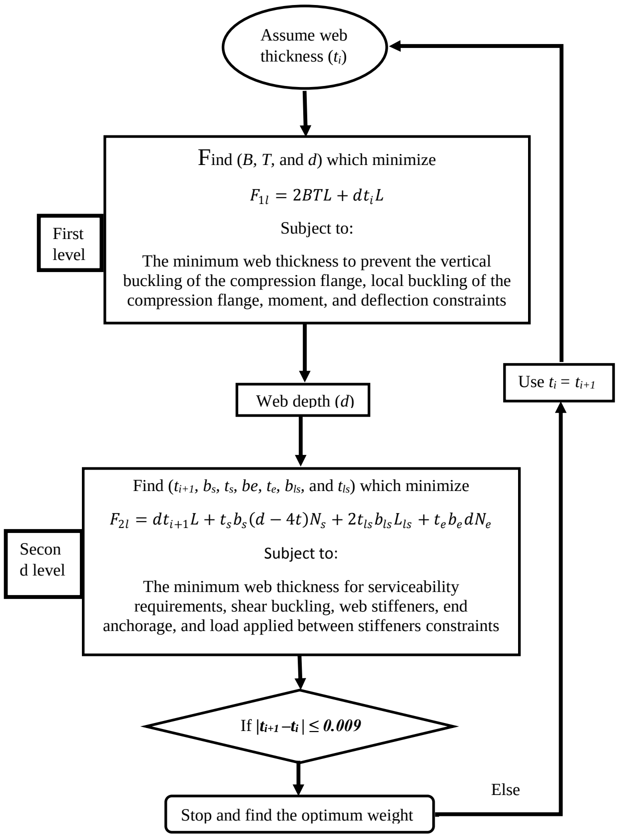
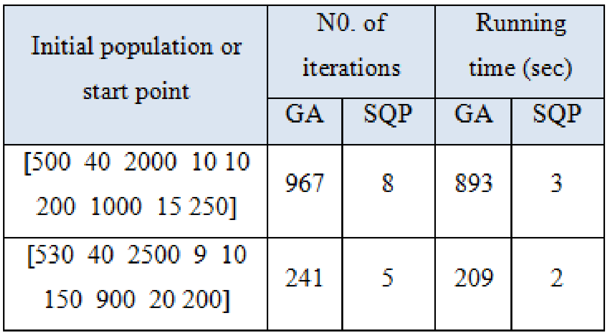


Figure 3: Optimum design of plate girder using two-levels optimization

Table5: Results of Multilevel Optimization

Application	App.1	App.2
B (mm)	409.7	489.1
T (mm)	40	40
d (mm)	2306.1	2686.6
t (mm)	8.12	9.46
t_s (mm)	11.5	8.4
b_s (mm)	131.6	95.8
a (mm)	718.8	2081.9
t_e (mm)	17.1	19
b_e (mm)	198	220.4
t_{ls} (mm)	6	6.6
b_{ls} (mm)	68.7	75.5
a_e (mm)	………	1401.3
x(mm)	………	2721.4
F (m^3)	2.073	2.083
i	4	5
t (sec)	3	3

Table6: The effect of initial population and start point on number of iteration and running time of GA and SQP methods respectively



Initial population or start point	N0. of iterations		Running time (sec)	
	GA	SQP	GA	SQP
[500 40 2000 10 10 200 1000 15 250]	967	8	893	3
[530 40 2500 9 10 150 900 20 200]	241	5	209	2

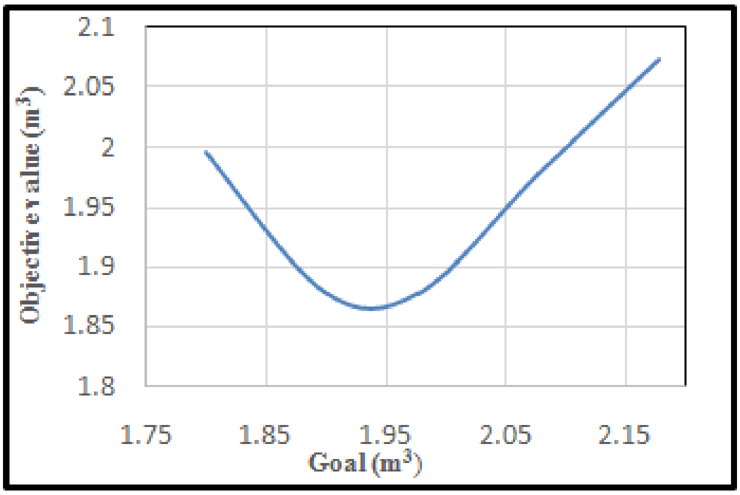


Figure4: The relationship between goal and objective function value

a. Multilevel optimization makes the optimization process faster and easier because it reduces the problem to small ones. Although it does many iterations for all levels in each loop, but the running time is shorter due to the increase of the running speed.

2. Effect of design method

Tow design methods can be used to design the plate girders: the simplified method and the exact method. In the simplified method, the flanges resist all the applied moment, the web resists all the applied shear force, and the end panels must provide adequate shear buckling resistance. In the exact method, flanges and web can be designed to resist the applied bending moment and shear force and the end anchorage can be provided by special provisions. Using the general moment method may reduce the shear buckling capacity of the web[10]. The induced stress in the flanges should be less than its design strength to use the tension field method of shear buckling. The results show that using the exact method for calculating the moment resistance reduces the total weight of a vertically and horizontally stiffened plate girder by 8.06% while using tension field method and anchor panel reduce the total weight of a vertically stiffened plate girder by 6.4%. As a result, the general moment method or tension field method should be considered to reduce the plate girder weight.

3. Effect of the longitudinal stiffeners

The longitudinal stiffeners are used to prevent the bend buckling and increase the shear buckling resistance in the deep webs. The results show that using horizontal stiffeners at 0.2*d* from the compression flange increase the total weight by 0.76% while using horizontal stiffeners at two levels of 0.2*d* and 0.5*d*from the compression flange reduces the total weight by only 0.88%. These results clearly indicate that the longitudinal stiffeners have a small effect on the weight of the plate girder. These stiffeners should be welded to the web, therefore, extra cost should be taken into account. Table (7) shows the effect of longitudinal stiffeners where App.1, App.2, and App.3 refer to a vertically stiffened girder, girder stiffened vertically and longitudinally at o.2 from the compression flange, and girder stiffened vertically and longitudinally at two levels of 0.2*d* and 0.5*d* from the compression flange, respectively.

4. Effect of end anchorage

End anchorage should be provided to resist the horizontal component of the tension field action. The end anchorage needs not be provided if the applied shear force is less than the critical shear buckling resistance. The critical shear buckling is an active constraint, therefore, the plate girder should be designed based on critical shear buckling or based on exact design method with providing proper end anchorage. The results show that using anchor panel method to design the end panels and the simplified design method to design the interior panels reduce the total weight by 1.66%. Also, using anchor panel and exact design method reduce the total weight by 6.4%. These results show that the use of end anchor method can reduce the total weight of plate girder even if the tension field action is not utilized, i.e. the simplified method is used. It is also noticed from Tables (1) and (5) that the change in the web thickness causes a small change in the end post dimensions. Therefore, the plate girder may be optimized without considering the end post which may be optimized alone to make the problem simpler.

5. Effect of the transverse stiffeners

The vertical stiffeners are welded to the web to prevent the shear buckling. It is found that the weight of the vertical stiffeners is 10.52% of the total weight for the unrestricted girder depth and 7.1% for 2 m limited depth. The weight of the vertical stiffeners or their cross-section area (A_s) depends on the stiffeners spacing and web dimensions. Figure (5) show the relationship between the web depth-to-thickness (d/t) ratio and the vertical stiffener cross-section area (A_s). The web of plate girder tends to buckle in shear while increasing web depth-to-thickness (d/t) ratio, therefore, the vertical stiffeners spacing (a) should be reduced to prevent the shear buckling as shown in Fig. (6).

6. Effect of web dimensions

The web depth and thickness play an important role in the optimum design. It is found that the weight of the web for a vertically stiffened plate girder is 29.53% of the total weight for the unrestricted girder depth and 20.7% for 2 m limited depth. The deep web reduces the weight of flanges but the weight of the web will be increased and also the weight of the stiffeners will be increased due to the increase of the required stiffness to prevent the lateral buckling of the deep web. Therefore, there is an optimum web depth which can minimize the total weight of the plate girder. Figure (7) shows the relationship between the total steel volume of the plate girder and the web depth (d). The web depth should be increased as possible to reduce the flange weight, but in this case, the web thickness should be increased to prevent the lateral buckling in the deep webs and the vertical buckling of the compression flange into the web. Also, the thickness of the web plate should be increased in the short webs to increase the cross-section of the web to resist the applied shear stress. Therefore, there must be an optimum value for web depth and thickness which can minimize the total weight of the plate girder and provide the required shear buckling resistance. Figure (8) shows the relationship between web depth and web thickness.

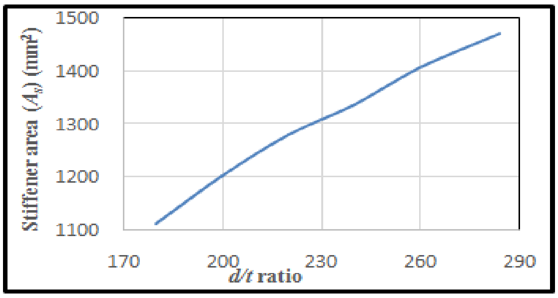


Figure 5: The relationship between web depth-to-thickness ratio and the vertical stiffener cross-section area

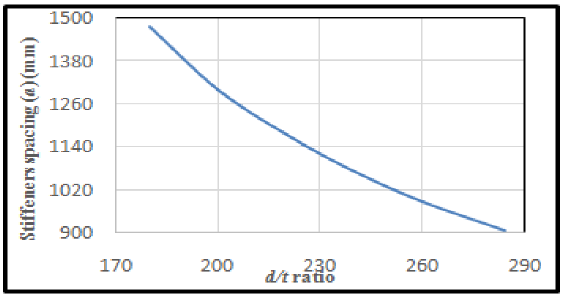


Figure 6: The relationship between web depth-to-thickness ratio and the vertical

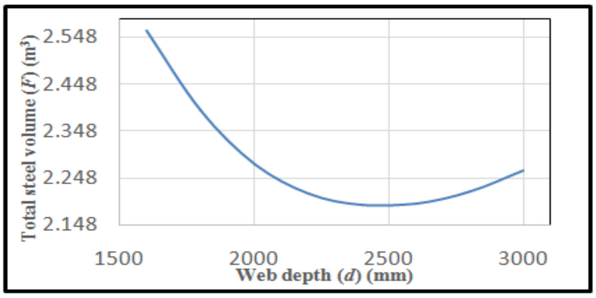


Figure 7: The relationship between web depth and total steel volume

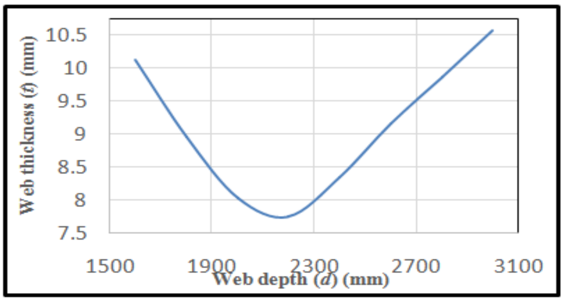


Figure 8: The relationship between web depth and web thickness

7. Effect of flange dimensions

It is found that the weight of the flanges for the plate girder vertically stiffened only is 58.4% of the total weight for the unrestricted girder depth and 71.05% for 2 m limited depth. These results show that the total weight of the plate girder depends primary on the flanges weight. Figure (9) shows the relationship between the flange width and the total steel volume for a fixed value of flange thickness. To reduce the weight of plate girder, the flanges thickness should be increased to the maximum allowable values. Increasing the flange thickness may cause a reduction in the design strength of the flanges, therefore, the flanges width should be increased to provide the required design moment resistance. As a result, there are a flange thickness that minimizes the total girder weight and satisfies the moment constraint which may be considered as 40 mm for this application. Increasing the flange thickness beyond the required thickness to prevent the local buckling in the compression flange, leads to decrease the flange width as shown in Fig. (10).

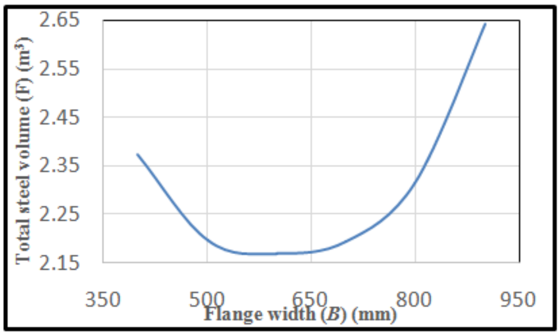


Figure 9: The relationship between flange width and total steel volume

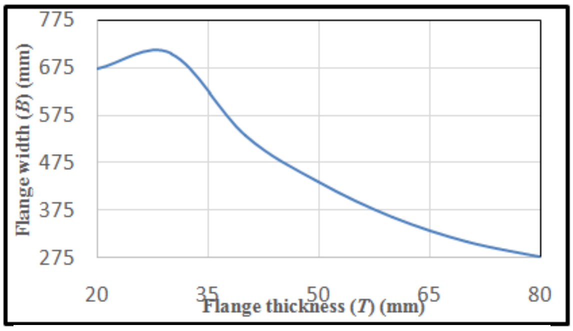


Figure 10: The relationship between flange thickness and flange width

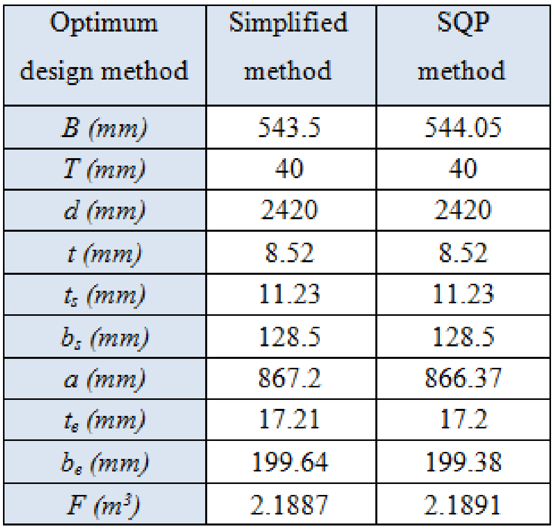
8. Simplified optimum design of plate girder

According to the obtained results, a design method is suggested to design optimally a plate girder for specified load, span, and total girder depth. In this method, the active constraints are determined and used to design each element of the plate girder. The flange thickness can be taken as 40 mm. The web depth can be taken as the total allowable depth minus the thickness of the two flanges. The flange width can be found from the moment constrain given by Eq. (8). The web thickness can be found by considering the minimum required web thickness to prevent the vertical buckling of the compression flange given by Eq.(6). The vertical stiffeners spacing can be found from the critical shear buckling constraint given by Eq.(19). Stiffeners dimensions can be found by considering the maximum outstand and minimum stiffness constraints given by Eq.s 12, 13, 15 and 16. End post stiffeners dimensions can be found from maximum outstand and buckling constraints given by Eq.s 14 and 18. Table (8) shows the results of this method compared with the results of SQP method for 2.5 m restricted depth plate girder and same load and span length previously used.

Table 7: Effect of longitudinal stiffeners

App.	App.1	App.2	App.3
B (mm)	532.5	539.6	532.35
T (mm)	40	40	40
d (mm)	2473.3	2439.4	2470
t (mm)	8.71	8.59	8.7
t_s *(mm)*	11.34	11.11	10.33
b_s *(mm)*	129.74	127.09	118.16
a (mm)	906.86	906.49	1084
t_e *(mm)*	17.19	17.19	17.17
b_e *(mm)*	199.37	199.34	199.19
t_{ls1} *(mm)*	……	6.65	7.03
b_{ls1}*(mm)*	…..	76.05	80.4
t_{ls2} *(mm)*	…..	……	6.07
b_{ls2}*(mm)*	……	……	69.43
F (m^3)	2.188	2.205	2.173

Table8: Compartment between the results of SQP and the simplified optimum design



Optimum design method	Simplified method	SQP method
B (mm)	543.5	544.05
T (mm)	40	40
d (mm)	2420	2420
t (mm)	8.52	8.52
t_s (mm)	11.23	11.23
b_s (mm)	128.5	128.5
a (mm)	867.2	866.37
t_e (mm)	17.21	17.2
b_e (mm)	199.64	199.38
F (m^3)	2.1887	2.1891

VI. Conclusion

The GA, SQP, GATT, and multilevel optimization methods can effectively be used to find the optimum design of plate girders. The SQP method is simpler and can find the optimum design in short time and few iterations. GATT can successfully be used to minimize both single and multi-objective optimization problems provided that the right goal and weight vectors is well defined. Multilevel optimization makes the optimization process faster and easier if the coordination variables and the problem of each level is well chosen to find the right results.

It is found that the weight of the plate girder depends majorly on the flanges weight which represents approximately 60% of the total weight and inversely proportional with the web depth. The weight of web represents approximately 30% of the total weight. The stiffeners have a small effect on the girder weight therefore, decreasing the web thickness and increasing the number of stiffeners to prevent shear buckling of web, leads to reduce the girder weight. Also, it is found that the vertical buckling of the compression flange controls the web depth-to-thickness ratio in the deep webs.

A simplified process can be used to minimize the total weight of plate girder by considering the active constraints.

References

[1] A.G.J Way, and P.R. Salter, *Introduction to Steelwork Design to BS 5950-1:2000* (The Steel Construction Institute: Silwood Park, 2003).

[2] U. Kirsch, Multilevel optimal design of reinforced concrete structures, *Engineering Optimization, 6, 1983, 207-212*.

[3] H. AL-Tabtabai, A.P. Alex, and R. James, Slap formwork design using genetic algorithm, *Durability of Building Materials and Components, 4, 1999, 2407-2418*.

[4] K. Fu, Y. Zhai, and S. Zhou, Optimum Design of Welded Steel Plate Girder Bridges Using a Genetic Algorithm with Elitism, *Journal of Bridge Engineering, 10(3), 2005, 291-301*.

[5] V. Agrawal, V. Chandwani, and A. Porwal,Optimum design of welded steel plate girder using genetic algorithms, *International Journal of Current Engineering and Technology, 3(4), 2013, 1209-1213*.

[6] S. Rao, *Engineering Optimization* (John Wiley & Sons, Inc.: Canada, 2009).

[7] J.F. Bonnans, J.C. Gilbert, C. Lemaréchal, and C.A. Sagastizabal, *Numerical Optimization* (Springer Verlag: Berlin Heidelberg, 1997).

[8] V. Chankong, and Y.Y. *Haimes, Multiobjective Decision Making* (North Holland: NewYork, 1983).

[9] A. Aravelli, *Multi-objective Design Optimization of Engineering Systems: Uncertainty Approach and Practical Applications*, Ph.D. Thesis,AparnaAravelli, University of Miami, USA, 2014.

[10] British Standard, *Structural use of steelwork in building*, BS 5950, Part 1: Code of practice for design Rolled and Welded sections, 2000.

[11] Indian Standard, *General construction in steel-code of practice*, 1S 800, 2007.