MATHEMATICAL MODEL FOR ESTIMATION OF SELF WEIGHT OF FLEXURAL STEEL MEMBERS

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ABSTRACT

The first step in the design of plate girder is to estimate the self-weight of it. Although empirical formulae for the same are available, the level of their accuracy (underestimate or overestimate) with respect to actual self-weight is not known. In this paper, optimized sections are obtained for different spans subjected to different live load carrying capacities and self-weights are estimated. EXCEL solver, which adopts Reduced Gradient Method (RGM) was applied for optimization. The objective function was chosen as Cross-sectional area with twelve constraints based on LRFD (IS 800: 2007) design specification for safety and serviceability. Simply supported (laterally restrained) plastic symmetric cross section without stiffeners is adopted for study. A mathematical model was developed based on best-fit curves between self-weight, span and live load carrying capacity and their trend line equations are obtained. The study revealed that, the ratio of self-weight to load carrying capacity was parabolic for a given span. The results from this equation are compared with the conventional formula and the standard deviation of the proposed model with respect to actual self-weight is in the range of -0.03 to 2.29 while that from the conventional model is in the range of -0.04 to 9.18.

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1. INTRODUCTION

The first and most important step in design of structural steel plate girder is to find it is self-weight, for which an empirical formula is generally used. Experimental or theoretical studies on Plate girder might be the basis for these formulae. Self-weight forms important criteria in design of plate girder. Suitable accuracy in determination of self-weight is important due to following reasons.

    1. Overestimated self-weight of plate girder will lead to uneconomical design.

    2. Underestimated self-weight will lead to into unsafe design region.

However, literature is silent on whether they overestimate or under-estimate the self-weight. In addition, different countries are using different self-weight empirical formulas in their application aspect. However, their reliability (comparison) with respect to actual self-weight of plate girder is unknown. This paper presents a mathematical model for estimation of self-weight. By adopting an optimization technique, which is a class of direct search algorithm called 'Reduced Gradient Method', executed by EXCEL solver. Determining the resistance (strength) of structural steel component requires the designer to consider first the cross-section behavior and second the overall member behavior-whether in the elastic or inelastic material range; the effects of local buckling limit cross-sectional resistance and rotation capacity.

In codes of practice of most of the countries (for example IS 800: 2007), cross sections are placed into four behavioral classes depending upon the material yield strength, the width-to-thickness ratios of the individual components (e.g., webs and flanges) within the cross section, and the loading arrangement. However, this study is limited to Plastic or class one cross sections, which can develop plastic hinges and have the rotation capacity required for the failure of the structure by the formation of a plastic mechanism (only these sections are used in plastic analysis and design). The optimization of steel structures is formulated as a weight minimization problem keeping in view the serviceability, flexural and shears strength aspects as suggested by the design codes. The plates available in the market have discrete thicknesses and hence the thickness and size of plates are chosen to satisfy the design code provisions and to minimize the overall weight of the structure.

2. LITERATURE REVIEW

The literature available on the subject indicates that numerous studies have been performed to automate the design process of plate girder. Notable among these studies are Ravindran *et al* [1], Lagaros *et al* [2], Alghamdi [3], Abuyounes and Adeli [4], Adeli and Mak [5], Azad and Alghamdi [6], El-Boghdadi [7] and Kuan-chen *et al.* [8]. The results obtained by Yasir and Diaz [9] convey that the use of EXCEL solver to find the minimum weight for a composite trapezoidal box cross section for a two lane bridge is acceptable. He developed a spreadsheet that can be used to obtain design recommendations for different deck widths, number of lanes, and type of railings. In addition, did not include the fatigue and deflection checks. Ozgur Yeniay [10] presented a comparative study that is performed on fifteen test

problems selected from the literature and compared the performance of these methods with the genetic algorithms. Zingg et al [11] compared the Genetic Algorithm and Gradient Based Algorithm and concluded that the gradient-based algorithm using the adjoint approach scales roughly linearly with the number of design variables, while the genetic algorithms cost increases more rapidly as the number of design variables is increased. According to Faluyi and Arun [12] results obtained using the GRG and the ABC algorithms are very close. The GRG algorithm was slightly superior, giving a 7.44% reduction in area compared to the initial design. Vinay Agarval [13] presented the capability of genetic algorithm as a directed search technique for optimum design of welded plate girder governed by the mixed nature of design variable. His results covey that a minimum of 8.5% and a maximum of 10.5% reduction in weight of plate girder are encountered when the design is done using GA. Shahbian [14] described the application of GA to the optimization of steel 0plate girder. Girders with various span and loading are studied. Marta Silyok and Alen Selimbegovie [15] evaluated the statistical parameters of the experimental results and FOSM method is used for the procedure of the calibration. Classical optimization algorithms are based on steepest gradient descent approach and are designed for continuous nature of variables. On the other hand, GRG, based optimization approach can work well on discrete, continuous, or mixed search spaces. Most of the engineering optimization problems require discrete variables. Many researchers including Jenkins [16], Rajeev and Krishnamoorthy [17], Koumousis and Arsenis [18], Lin and Haleja [19], Wu and Chow [20], Camp et al [21], Erbatur et al [22] and Lee and Ahn [23] performed discrete optimization of structures using GRGs. Razani and Goble [24] were the first to attempt cost optimization of steel girders. Holt and Heithecker [25] studied the minimum weight design of symmetrical welded plate girders without web stiffeners. Annamalai et al [26] studied cost optimization of simply supported, arbitrarily loaded, welded plate girders with transverse stiffeners. Anderson and Chong [27] presented the minimum cost design of homogeneous and hybrid stiffened steel plate girders. Goldberg and Samtani [28] carried out the first application of GRG for structural engineering. Minimum cost design of composite continuous welded plate girders is presented. Ghanem [29] et al used the GRG optimization technique for behavior and strength of built up plate girders subjected to localized edge loading in the plane of the web. Fu, K. et al [30] used GA with elitism for optimum design of welded steel plate girder used for a single-span bridge and a two span continuous bridge. In the field of computational intelligence, the natural phenomenon is used for developing tools for solving the problems, which are normally difficult to be solved using traditional means of computing. It is called Evolutionary Computation, a branch of Computational Intelligence whose roots lie in the principle of natural evolution. Evolutionary algorithms are a class of non-gradient population-based algorithms used in many areas of engineering optimization Hare et al. [31] One of the evolutionary computation techniques is the Genetic Algorithms (GA). GAs are considered directed search algorithms based on the mechanics of biological evolution Akerker and Sajja [32]. GAs can rapidly identify discrete regions within a large search space to concentrate.

Summarizing the review, research on discrete variable optimization of steel structures was predominant during 1960 - 1970. After rhen, algorithms for optimization for simpler

continuous nonlinear programming (NLP) problems were developed. Various algorithms like sequential quadratic programming (SQP) and augmented Lagrangian methods are now available for NLP problems. With the advent of re-classification of steel flexural members, there is a need to study optimization of their cross-sections.

3. OBJECTIVE AND SCOPE

The objective of this work is to obtain a mathematical model for estimating the self-weight of flexure steel member. The scope of the work is limited to

- Spans ranging from 5 m 40 m
- Loading - from 10 kN/m to 80 kN/m in increments of 10

A simply supported plastic symmetric cross-section is considered for this study. The Plate girder is analyzed without transverse and longitudinal stiffeners (except bearing stiffener)

The other assumptions involved in the analysis of this plate girder are

1. Steel girder has uniform cross section through its length and is homogeneous and isotropic.
2. Web and flange made from the same homogenous material.
3. Plate girder is subjected to uniformly distributed load.
4. The structural plate girder is assumed to be laterally restrained at both ends.
5. The yield strength of steel is taken as $f_y = 250 N/mm^2$.
6. The partial safety factor is taken as $\gamma_{mo} = 1.1$.

4. METHODOLOGY

Load and span within the scope were considered and safe and serviceable dimensions of plate girder were determined as per LRFD (IS 800: 2007). They are given as input to EXCEL solver to obtain optimized dimensions. The procedure is repeated for all spans and loads to obtain optimum dimensions and corresponding self-weights. A mathematical model is developed based on this data and compared with conventional formula.

4.1 About excel solver

An optimization tool resides in Microsoft Excel spreadsheet software (named solver). This study adopts Microsoft Excel, the windows XP version of which has on line help on solver algorithm, options, completion messages, and other information. Linear and nonlinear optimization problems can be solved by the Solver option in EXCEL. For nonlinear optimization problems, EXCEL Solver uses the Newton and conjugate methods to find the optimum solution for a given problem. Solver can solve problems up to 200 decision variables, 100 explicit constraints, and 400 simple constraints (lower and upper bounds and/or integer restrictions on the decision variables). To invoke Solver, select Tools from the

main menu and then Solver. The Solver Parameters dialog box will appear as shown below in Fig. 1. The way Microsoft Excel' solver tool performs its analysis can be configured in the solver options Dialogue box.
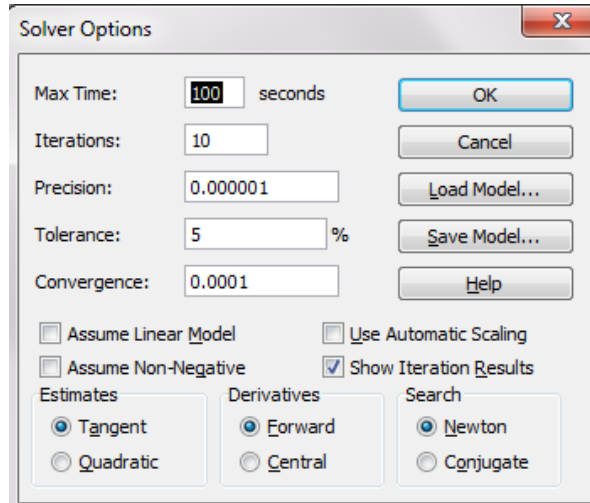

Figure 1. Solver parameters dialogue box

The default settings are:

Precision 10^{-6}, Quadratic estimate, central derivative, and Newton search.

Other available options for search include tangent estimate, forward derivative, and Conjugate search. These options are described in solver option's help file. The default setting is generally adequate, at least for the cases prescribed above. When solver reports a Converged solution, the solution can often be improved but remaining solver (based on the Converged solution) until it found a solution.

The dependent variables in this study are the variables that depend on the cross section of the girder; they include the section properties, moment, and the shear from the girder self-weight. A typical cross section and the corresponding notation is shown in Fig. 2.

They are Width of the top flange (b_f), Thickness of top flange (t_f), Depth of the web (d_w), Thickness of the web (t_w).
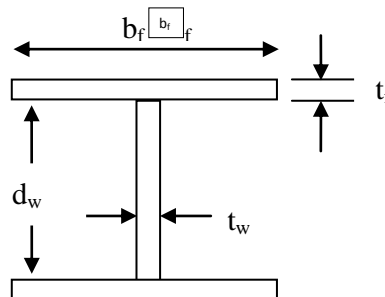

Figure 2. Components of a symmetrical plate girder

4.2 Objective function and constraints (based on IS 800: 2007)

The objective function is the area of the structural steel cross section given by $A = 2(b_f * t_f) + (d_w * t_w)$

This is minimized subject to some constraints using EXCEL solver. These Constraints are based on prevention of top flange buckling, shear buckling, elastic buckling due to shear, web height-to thickness ratio (depends on class of cross section), minimum web thickness based on serviceability requirements, check for moment capacity, shear resistance of web, general practical requirement of plate girder, strength and rigidity requirement s of non-composite plate girder, and thickness of web from corrosion point of view. The variables in the constraints e.g. depth of web d_w, width of flange b_f, thickness of web t_w and thickness of flange t_f are discrete in nature as these are dependent on certain sizes of steel sections available in the market. An optimum design of plate girder envisages the use of the discrete variable to arrive at a safe and economically feasible section subject to the following constraints.

1) Requirement of thickness of web to avoid buckling of compression flange into the web

Constraint 1 $\frac{d_w}{t_w} \leq 345\varepsilon_f^2$ Clause No. 8.6.1.2(a) of IS: 800-2007

2) Resistance of shear buckling verified when

Constraint 2 $\frac{d_w}{t_w} > 67\varepsilon_f$ Clause No. 8.4.2.1 of IS: 800-2007

3) Elastic buckling due to shear can be prevented when

Constraint 3 $\frac{d_w}{t_w} < 82$ According to practical requirement

4) Limiting width to thickness ratio of flange of an I-section to be in plastic category

Constraint 4 $\frac{b_f}{t_f} < (8.4*\varepsilon_f)$ Table No. 2 of IS: 800-2007 $(\beta_b * Z_p * f_y)/\Upsilon_{mo})$

5) Limiting depth to thickness ratio of web of an I-section to be in plastic category

Constraint 5 $\frac{d_w}{t_w} < (84*\varepsilon_f)$ Table No. 2 of IS: 800-2007

6) Minimum web thickness based o serviceability requirements without transverse stiffeners

Constraint 6 $\frac{d_w}{t_w} \leq (200*\varepsilon_f)$ Clause No. 8.6.1.1 of IS: 800-2007

7) Check for moment capacity of plate girder, Factored design moment M at any section due to external loads must be less than the designed bending strength of the section.

Constraint 7 $M < M_d$ { $\frac{\beta_b * Z_p * f_y}{\gamma_{mo}}$ } Clause No. 8.2 of IS: 800-2007

8) Check for shear resistance of the web

Constraint 8 $V < V_d$ Clause No. 8.4 of IS: 800-2007

9) For general practical requirement of plate girder

Constraint 9 $b_f - t_f > 0$ According to practical requirement

10) For strength and rigidity requirement of non-composite plate girder

Constraint 10 $(b_f - 0.3 * d_w) > 0$ According to practical requirement

11) From corrosion point of view, thickness of the web is

Constraint 11 $t_w - 8 > 0$ According to practical requirement

4.3. A typical calculation

The following data is taken for demonstrating the methodology.

Imposed Load = 35 N/mm.

Factored live load = 35 x 1.5 = 52 N/mm.

Self-weight w of the Plate Girder is assumed as equal to $W/200$ where w is in kN/m and $W = w \times span$ is the total factored load applied to the girder in kN.

Self-weight $= \frac{(52.5 \ X \ 24)}{(200 \ X \ 1000)} = $ 6.3 N/mm.

Total load $= 52.5 + 6.3 = 58.8$ N/mm.

The moments and shears for a span of 24 m are calculated as follows.

Maximum moment $M = \frac{wL^2}{8} = \frac{58.8 X 24^2}{8} = 4233.6 =$ N/mm

Maximum shear force $V = \frac{wl}{2} = \frac{58.8 X 24}{2} = 705.6$ N.

The dimensioning of Plate girder based on IS 800: 2007 codal provisions is presented as follows.

(a) Depth of the web or rib plate

If stiffeners are to be avoided k $= \frac{d_w}{t_w} \leq 67$

Economical depth of the web $d_w = \sqrt[3]{\frac{Mk}{f_y}} = \sqrt[3]{\frac{4233.6 X 67}{250}} = 1042.17$ mm

(b) Selection of thickness of web or rib

We know that $t_w \geq \frac{1042.17}{67} \geq$ 15.56 mm

(c) Selection of flange

Neglecting the moment capacity of web, area of flange required is

$A_f = \frac{M*\gamma_{mo}}{f_y*d_w} = \frac{4233.6 \ X \ 1.1}{250 \ X \ 1043} = 17859.97 \ mm^2$

To keep the flange in plastic category $\frac{b_f}{t_f} \leq 8.4$

Assuming $t_f = \frac{b_f}{8}$, We get, $A_f = (8 \ x \ t_f{}^2) = 17859.97$ mm^2.

Therefore $t_f = \sqrt{\frac{A_f}{8}}$ mm $= \sqrt{\frac{17859.97}{8}} = 47.249$ mm.

Then we get $b_f = (8 \ X \ 47.249) = 377.99$ mm

The final dimensions of the design plate girder are as shown below.

$b_f = 377.99$ mm, $t_f = 47.249$ mm, $d_w = 1042.17$ mm, $t_w = 15.56$ mm

4.4 Solution using excel solver

These dimensions are optimized using EXCEL solver. The setup for the spreadsheet on the 'Solver Parameter' window includes the target cell that contains the objective function, which is the area of cross of the steel plate girder with a goal to minimize the area of steel plate girder. The option 'min' is selected and all the constraint is assigned to the objective

function. As a first choice, the guess cell contains Top flange thickness and width, bottom flange thickness and width, and web height and thickness that are obtained initially. By changing cells, all the elements that influence the minimization of steel plate girder subject to the constraints are arrived by the solver after a series of iterations. The procedure is repeated for different load carrying capacities and spans to generate design aid tables for structural steel Grade 250.

5. RESULTS

After getting different values from the excel solver optimization tool, for various spans and loading conditions, different design aid tables were generated. From these values, variations of Load carrying capacity with respect to self-weight for different spans (Fig. 3) were generated and their best-fit equations were obtained.
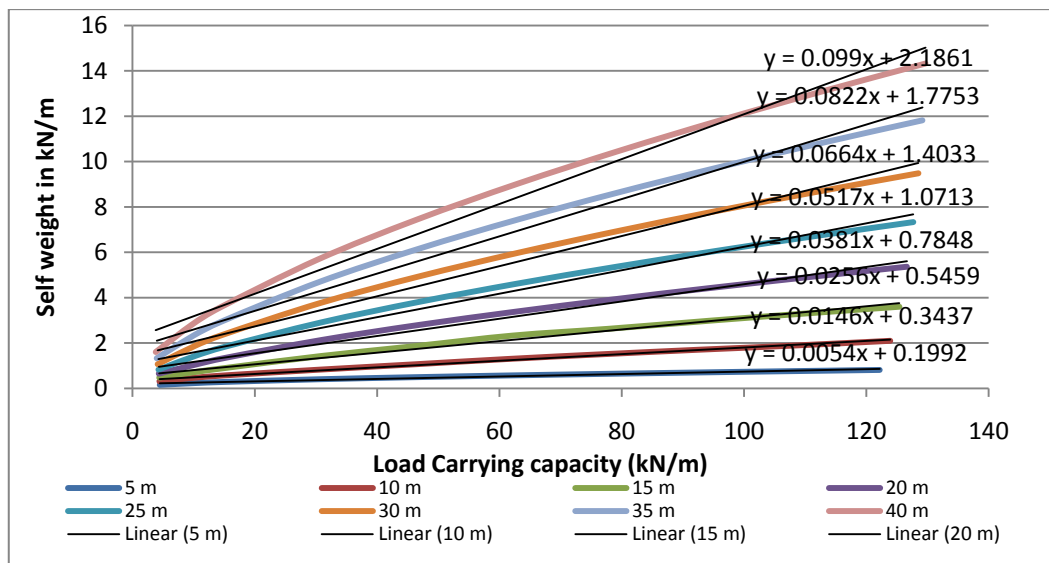
Figure 3. Graph between the self-weight, span and load carrying capacity

Assuming a linear variation,
$$self\ weight_{model} = A\,(w) + B$$
where
    w = Load carrying capacity
    A = coefficient of 'w' which is a function of span
    B = another function of span
    Now the graphs and the corresponding best fit equations between the coefficients A and B are obtained based on the constants taken from the equation in graph, for various spans (5 m to 40 m) and loading conditions (3 N/mm,7 N/mm 10 N/mm to 80 N/mm with 10 N/mm as increment). These values are represented in Table 1.

Table 1: Constants in modeled equation

Sl. No.	Span	Coefficient of w (A)	Second Coefficient (B)
1	5	0.0054	0.1992
2	10	0.0146	0.3437
3	15	0.0256	0.5459
4	20	0.0381	0.7848
5	25	0.0517	1.0713
6	30	0.0664	1.4033
7	35	0.0822	1.7753
8	40	0.099	2.1861

Graphs are developed between the coefficients A & B and span L as shown in Fig. 4 and Fig. 5.
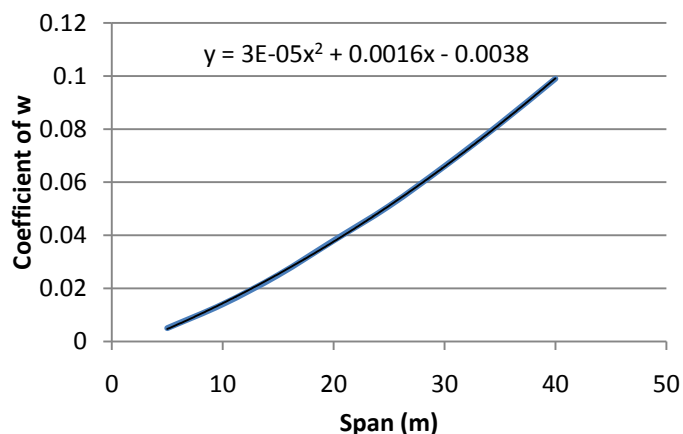

$y = 3E\text{-}05x^2 + 0.0016x - 0.0038$

Figure 4. Graph between the span and Coefficient of w (A)
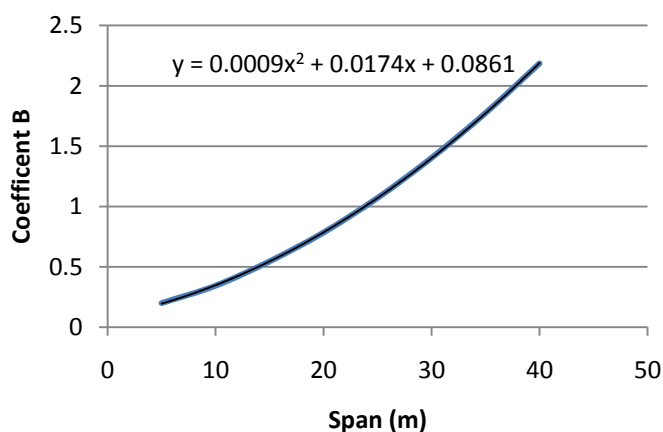

$y = 0.0009x^2 + 0.0174x + 0.0861$

Figure 5. Graph between the span another function of the span (B)

Therefore, model for the self-weight of optimized plate girder is obtained as

$self\ weight_{model} = A\ (w) + B$
$self\ weight_{model} = (3\ X\ 10^{-5}\ l^2 + 0.0016\ l - 0.0038)w + 0.0009 l^2 + 0.0174\ l + 0.0861$

where,

W = Actual weight of the plate girder (Load carrying capacity-Self Weight) after optimization

L = Length of the member

6. DISCUSSION ON RESULTS

6.1 Sample demonstration of the use of the model

Self-Weight of Simply Supported beam with span of 10 m and uniformly distributed load of 10 kN/m can be found by using above formulae as below:

$self\ weight_{model}$

$$= \left[\left(3\ X\ 10^{-5}\left(\frac{10X10}{1000000}\right) + 0.0016\left(\frac{10}{1000}\right) - (0.0038)\right](15.171) + 0.0009\left(\frac{10}{1000}\right)^2 + 0.0174\left(\frac{10}{1000}\right) + 0.0861$$

$$= \left\{\left[\left((3X10^{-9}) + (1X10^{-5}) - (0.003)\right)\right](15.171) + 0.016\left(\frac{10}{1000}\right) + 0.086\right\}$$

$$= 0.40774\ N/mm$$

Now, Self-Weight of the Plate Girder from the obtained optimized dimensions is obtained as follows.

Area of Cross-Section obtained

A = 7459.48 mm^2

Self-Weight $= \left(\frac{7459.48X7850X9.81}{1000000}\right)$

= 0.28266 N/mm

So, from the above calculations, the deviation obtained as 0.2.

Similarly the self-weights from model and those based on optimized sections are obtained and tabulated as follows after running EXCEL Solver for different spans from 5 m – 40 m.

Similarly, the deviation tables are generated for spans 15 m, 25 m and 35 m also and presented in Tables 3, 4 and 5.

Table 2: Deviation of developed proposed model from Empirical value for 5 m span.

Live load	Self-weight (actual)	Self-weight (Empirical)	Self-weight (proposed)	Deviation for Empirical model	Deviation for proposed model
W_{Actual}	$W_{Self\ weight}$	wl/200	$W_{S.\ w.\ model}$	wl/200- $W_{S.\ w.\ model}$	Δ
N/mm	N/mm	N/mm	N/mm	N/mm	N/mm
4.46	0.15	0.11	0.18	-0.04	-0.03
10.53	0.24	0.26	0.20	0.03	0.04
15.09	0.28	0.38	0.21	0.09	0.07
30.35	0.40	0.75	0.25	0.35	0.14
45.63	0.49	1.13	0.30	0.63	0.19
60.93	0.57	1.50	0.34	0.93	0.23
76.23	0.64	1.88	0.38	1.24	0.25
91.55	0.70	2.25	0.42	1.55	0.28
106.86	0.76	2.63	0.46	1.87	0.29
122.18	0.82	3.00	0.51	2.18	0.31

Table 3: Deviation of developed proposed model from Empirical value for 15 m span

Live load	Self-weight (actual)	Self-weight (Empirical)	Self-weight (proposed)	Deviation for Empirical model	Deviation for proposed model
W_{Actual}	$W_{Self\ weight}$	wl/200	$W_{S.\ w.\ model}$	wl/200- $W_{S.\ w.\ model}$	Δ
N/mm	N/mm	N/mm	N/mm	N/mm	N/mm
4.36	0.48	0.34	0.42	-0.14	0.06
10.55	0.74	0.79	0.54	0.05	0.21
15.22	0.90	1.13	0.63	0.22	0.28
30.82	1.43	2.25	0.92	0.82	0.52
46.50	1.87	3.38	1.21	1.50	0.67
62.17	2.33	4.50	1.51	2.17	0.83
77.99	2.63	5.63	1.80	2.99	0.84
94.81	2.99	6.75	2.12	3.76	0.88
109.58	3.29	7.88	2.40	4.58	0.91
125.40	3.60	9.00	2.69	5.40	0.92

Table 4: Deviation of developed proposed model from Empirical value for 25 m span

Live load	Self-weight (actual)	Self-weight (Empirical)	Self-weight (proposed)	Deviation for Empirical model	Deviation for proposed model
W_{Actual}	$W_{Self\ weight}$	wl/200	$W_{S.\ w.\ model}$	wl/200- $W_{S.\ w.\ model}$	Δ
N/mm	N/mm	N/mm	N/mm	N/mm	N/mm
4.23	0.83	0.56	0.68	-0.27	0.16
10.37	1.44	1.31	0.93	-0.13	0.53
15.04	1.83	1.88	1.12	0.04	0.73
30.84	2.91	3.75	1.77	0.84	1.16
46.81	3.81	5.63	2.42	1.81	1.41
62.88	4.62	7.50	3.07	2.88	1.56
79.02	5.36	9.38	3.73	4.02	1.65
95.20	6.05	11.25	4.39	5.20	1.68
111.42	6.71	13.13	5.05	6.42	1.67
127.67	7.33	15.00	5.71	7.67	1.64

Table 5: Deviation of developed proposed model from Empirical value for 35 m span

Live load	Self-weight (actual)	Self-weight (Empirical)	Self-weight (proposed)	Deviation for Empirical model	Deviation for proposed model
W_{Actual}	$W_{Self\ weight}$	wl/200	$W_{S.\ w.\ model}$	wl/200- $W_{S.\ w.\ model}$	Δ
N/mm	N/mm	N/mm	N/mm	N/mm	N/mm
3.96	1.32	0.79	0.95	-0.54	0.40
10.01	2.33	1.84	1.37	-0.49	0.99
14.67	2.95	2.63	1.69	-0.33	1.29
30.56	4.69	5.25	2.78	0.56	1.94
46.73	6.15	7.88	3.89	1.73	2.28
63.05	7.45	10.50	5.02	3.05	2.46
79.49	8.64	13.13	6.15	4.49	2.52
95.99	9.76	15.75	7.28	5.99	2.50
112.56	10.81	18.38	8.42	7.56	2.42
129.18	11.82	21.00	9.56	9.18	2.29

As a general trend, it can be observed that as the live load increases, the self-weight of plate girder also increases for different spans starting from 5 m, 15 m, 25 m, 30 m and loading condition varies between the values from 3 kN/m, 7 kN/m to 80 kN.m with 10 kN/m as increment. The deviation for the proposed model is obtained in the range of -0.03 to 2.29. This range of outcome agrees with the practical design consideration that we are empirically using formula that is most of the times over estimating and sometimes underestimating which is varying in the range of -0.04 to 9.18.

7. CONCLUSIONS

In conclusion, GRG method has been successfully applied to the design of welded plate girder. The mathematical model for obtaining the self-weight of the Plate Girder is developed. While the conventional models vary in the range of - 0.04 to 9.18, the deviation of this model is only in the range of - 0.03 to 2.29.

NOTATIONS

The following symbols are used in this paper
   b_f = Width of the flange (mm);
   t_f = Thickness of flange;
   d_w = Depth of the web or rib in its plane;
   t_w = Thickness of the web or rib;
   A = Area of the plate girder;
   ε_f = Yield stress ratio($250/f_y$ $)^{1/2}$;
   f_y = Yield strength of steel plate;

D = Overall depth of the steel plate girder;
I_{xx} = Moment of inertia of the flange with respect to normal axis at mid depth;
L = Span of the steel plate girder;
M_d = Design bending strength of the section;
M = Bending moment;
V_d = Design shear strength;
V = Factored applied shear force;
β_b = 1 for plastic and compact sections;
Z_p = Plastic section modulus;
γ_{mo} = Partial safety factor against yield stress and buckling;
W = Total factored load applied to the girder
w = Self-weight of plate girder ($W/200$)

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