Civil Engineering and Architecture 10(4): 1243-1252, 2022 http://www.hrpub.org
DOI: 10.13189/cea.2022.100401

Minimum Weight Design of Transversely Stiffened Plate Girder Using Genetic Algorithm

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Received April 17, 2021; Revised June 10, 2021; Accepted July 19, 2021

Cite This Paper in the following Citation Styles

(a): *[1] Priya A Jacob, R Mercy Shanthi, S Justin, Daniel C , "Minimum Weight Design of Transversely Stiffened Plate Girder Using Genetic Algorithm" Civil Engineering and Architecture, Vol. 10, No. 4, pp. 1243-1252, 2022. DOI: 10.13189/cea.2022.100401.*

(b): *Priya A Jacob, R Mercy Shanthi, S Justin, Daniel C (2022). Minimum Weight Design of Transversely Stiffened Plate Girder Using Genetic Algorithm. Civil Engineering and Architecture, 10(4), 1243-1252. DOI: 10.13189/cea.2022.100401.*

Abstract Fundamental advantage of using transversely stiffened plate girders (TSPG) rather than plane web plate girders is in achieving increased strength and stiffness of the web panel. As these girders are made of steel plates, they can be custom designed to suit consumer's requirements. Weight minimization of TSPG by satisfying strength and serviceability conditions, further enables in achieving higher strength to weight ratios. The utilisation of these girders in the building sector in India is growing, and optimising these girders can lead to more cost-effective and structurally sound designs. No significant research has been carried out in the field of optimization of plate girders based on specifications according to IS 800 (2007): General Construction in Steel - Code of Practice (Bureau of Indian Standards). Therefore, in the present study, the main goal is to develop a formulation for optimum weight design of TSPG using genetic algorithm (GA) with weight minimization as objective function. The breadth of flange (b_f), thickness of flange (t_f), depth of web (d), thickness of web (t_w), breadth of stiffener (b_s), thickness of stiffener (t_s) and spacing between stiffeners(c) are adopted as the design variables. The optimum girder weight is compared with weight obtained through conventional design using IS 800 (2007). The results demonstrate that conventional design overestimates the girder weight by about 30% on an average and therefore the developed formulation helps in attaining economical girder weight. The viability of the GA formulation is verified by comparing the optimized results with existing experimental and numerical data from literature. Parametric studies are also carried out to understand the behaviour of design variables. Results from these studies show that deeper web reduces flange thickness but requires thicker web in order to ensure ample shear capacity and to prevent shear buckling.

Keywords Plate Girder, Structural Optimization, Transverse Stiffeners

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1. Introduction

Transverse stiffeners in a plate girder can assist in attaining buckling resistance and out-of-plane stiffness when compared with a thick web plate thereby saving girder manufacturing cost. Because of the high strength-to-weight ratio of stiffened plate girders, span lengths can be increased. Plate girders are widely utilized in a variety of applications, including bridges and buildings, due to their numerous advantages. It is important to note. However, that optimization of stiffened girders is required to fully exploit several advantageous features. In this regard, Genetic Algorithm (GA) has succeeded as a tool in optimizing civil engineering structures [1].

Various researchers have conducted substantial experimental and theoretical studies on the ultimate shear resistance of transversely stiffened plate girders [2-7]. A closer look into the numerical and experimental investigations on transversely stiffened plate girders reveals that with closely spaced transverse stiffeners, failure mode is governed by web, flange and stiffener spacing whereas with largely spaced stiffeners, the failure mode is governed by folding of web panel only [8]. Researchers compared the design requirements for plate girders with bolted transverse stiffeners with that of welded transverse stiffeners [9]. A modified formula to evaluate the ultimate resistance of plate girders subjected to shear and patch loading is also proposed, which shows satisfactory correlation with existing experimental data [10].

Optimizing the dimensions of a plate girder can lead to a material economy driven plate girder design. Design of welded plate girder bridges has been successfully carried out by using GA with elitism [11]. However, computer programmes created for non-uniform stiffened steel plate girder design optimization using plate thickness, span ratio, and steel yield strength as parameters also prove to be an effective optimization tool [12]. The optimal cost design of a steel box-girder is achieved by altering plate thickness, and design recommendations are offered to determine fundamental structure dimensions that are close to optimum. [13]. Over time, studies on optimization of steel cross sections of a stiffened plate girder by using Generalised Reduced Gradient (GRG) algorithm and Constrained Artificial Bee Colony (CABC) algorithm are effectively carried out [14].

In this study, GA based formulation developed for optimum design of transversely stiffened plate girder (TSPG) is discussed. Later, the optimum weights obtained using the formulation is compared with the girder weights from conventional designs using IS 800:2007. The formulation's validity is additionally confirmed by comparing the optimised findings to experimental and numerical data published in the literature. Parametric studies are then carried out to apprehend the relationship between the design variables. Figure 1 shows the profile of a transversely stiffened plate girder.

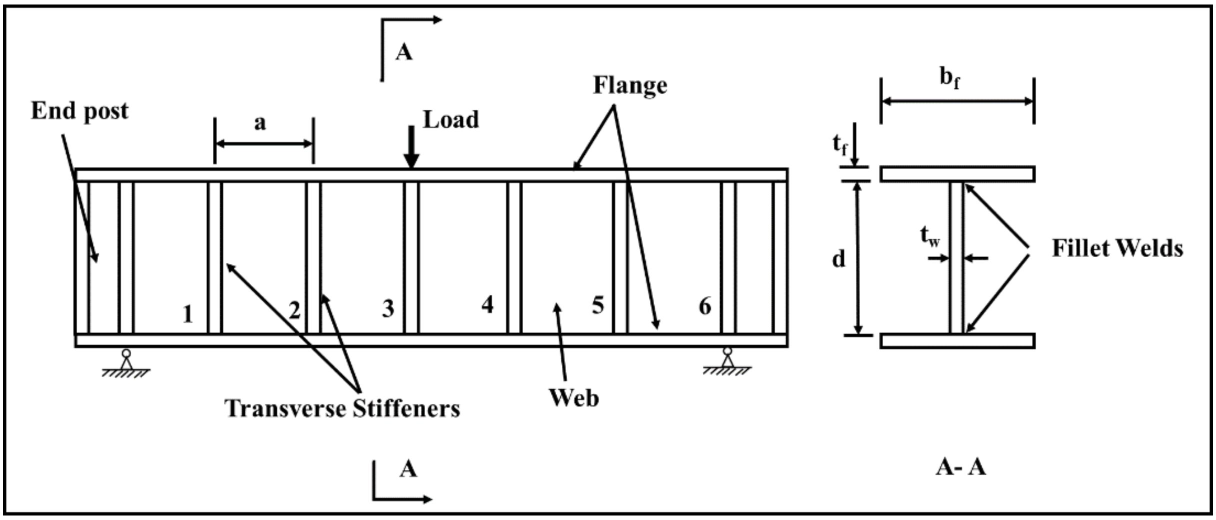

Figure 1. Profile of a transversely stiffened plate girder

2. Design Standards of TSPG

Designer has maximum freedom to choose the girder dimensions while designing a plate girder. The quest for an efficient design sometimes results in conflicting requirements, particularly with regard to the web. The design requirements of a plate girder are specified in section 8 of IS 800:2007 [16]. While designing the web, the serviceability and compression flange buckling requirements are to be met. In terms of stiffener provision, the code provides a minimum web thickness need from a serviceability standpoint for various situations. Equations (1) and (2) specify the limiting web slenderness ratios when no transverse stiffeners are available.

(a) When no transverse stiffeners are available

$$\frac{d}{t_w} \le 200\varepsilon \tag{1}$$

(web connection to flanges along both longitudinal edges)

$$\frac{d}{t_w} \le 90\varepsilon \tag{2}$$

(web connection to flanges along one longitudinal edge only)

The limiting web slenderness ratios when there are just transverse stiffeners available depending on stiffener spacing are given by (3), (4) and (5).

(b) When there are just transverse stiffeners available

i) When $3d \ge c \ge d$

$$\frac{d}{t_w} \le 200\varepsilon \tag{3}$$

ii) When $0.74\,d \le c \le d$

$$\frac{c}{t_w} \le 200\varepsilon_w \tag{4}$$

iii) When $c < d$

$$\frac{d}{t_w} \le 270\varepsilon \tag{5}$$

iv) for c > 3d, web is considered as unstiffened

The web thickness should satisfy (6), (7), or (8) to avoid buckling of the compression flange into the web.

(a) When transverse stiffeners are not provided

$$\frac{d}{t_w} \le 345\varepsilon_f^{\,2} \tag{6}$$

(b) When transverse stiffeners are available and

i) When $c \ge 1.5\,d$

$$\frac{d}{t_w} \le 345\varepsilon_f^{\,2} \tag{7}$$

ii) When $c < 1.5d$

$$\frac{d}{t_w} \le 345\varepsilon_f \tag{8}$$

The general yield stress ratio (ε), yield stress ratio of web (ε_w) and yield stress ratio of flange (ε_f) are given in (9), (10) and (11).

$$\varepsilon = \sqrt{\frac{250}{f_y}} \tag{9}$$

$$\varepsilon_w = \sqrt{\frac{250}{f_{yw}}} \tag{10}$$

$$\varepsilon_f = \sqrt{\frac{250}{f_{yf}}} \tag{11}$$

where
d = depth of web in mm
t_w = thickness of web in mm
c = spacing between stiffeners in mm
f_{yw} = yield stress of web in MPa
f_{yf} = yield stress of compression flange in MPa

When plate elements buckle, they do not collapse; rather, they have a significant post-buckling strength of resistance. The ultimate limit strength is to be determined considering the post-buckling action also into account. This is especially true in the case of a plate girder panel subjected to pure shear, when tension field action can cause significant post-buckling resistance. It is necessary to examine the buckling and post-buckling activities of the web in shear and of the flange plates in compression when constructing a plate girder.

The web's shear buckling resistance depends on two factors.

a) Depth to thickness of web (d/t_w)
b) Spacing between stiffeners (c)

Any one of the following methods described in IS 800:2007, Clause 8.4.2.2, are used to determine the nominal shear resistance of a plate girder.

a) Simple post-critical method
b) Tension field method

The simple post-critical method is an allowable stress design method based on shear buckling strength. This method can be utilized with or without intermediate transverse stiffeners for I-girder webs, as long as the web has transverse stiffeners at the supports. The post shear buckling strength is used in the tension field method. This method is employed for webs that have intermediate transverse stiffeners in addition to transverse stiffeners at the supports, as long as the panels adjacent to the panel under tension field action or the end posts offer tension field anchorage.

3. Optimum Design of TSPG Using GA

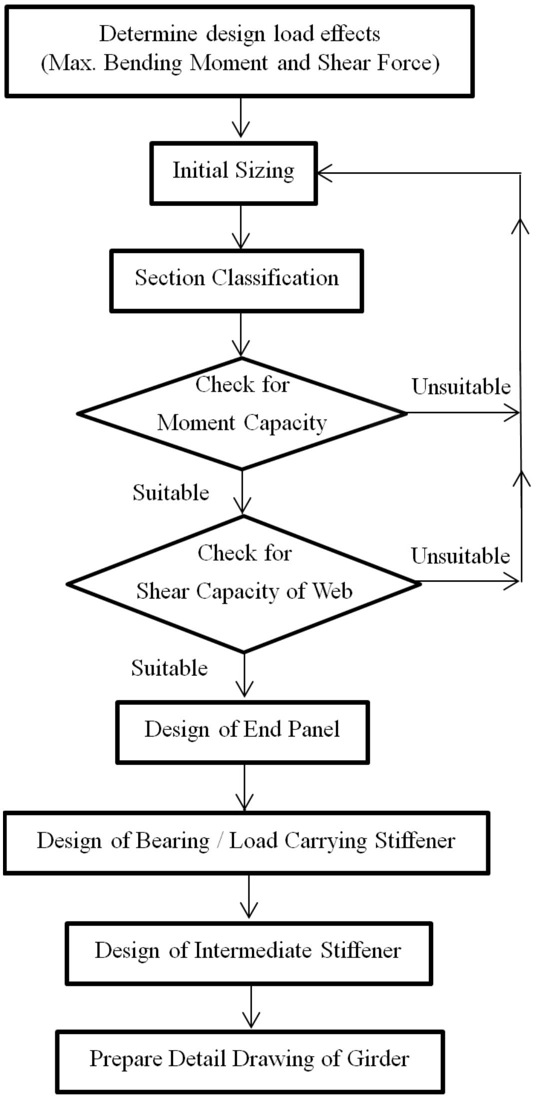

Figure 2. Flowchart of design procedure of TSPG

GA is a robust optimization technique that mirrors the mechanism of living things' natural laws of adaptation. GA takes structure design variables as genes and encodes them as a binary string. According to Darwinian evolutionary theory of survival of the fittest, the genes with better characteristics are more presumably to be inherited to the next generation. As a result, based on fitness, the weak die off while the strong survive. Reproduction, crossover, and mutation are the randomized operators used in GA. In general, the iteration process in GA is completed when all of the population's chromosomes are the same, i.e. convergence, or when the population achieves a fixed number of generations, whichever comes first. Shear strength, flexural strength, overall girder weight, and serviceability all play a role in TSPG design. As a result, the best design for this girder may be expressed as a weight minimization problem that must satisfy the design code's strength and serviceability requirements. Figure 2 shows the flow chart of design procedure commonly used for TSPG.

3.1. Objective Function

Equation (12) gives the objective function for optimum weight of transversely stiffened plate girder [15].

$$f(x) = \left[\left(2*b_f*t_f + d*t_w\right)*L + \left(2*n*b_s*t_s*d\right)\right]*\rho \qquad (12)$$

3.2. Design Variables

The design variables are the breadth of flange (b_f), thickness of flange (t_f), depth of web (d), thickness of web (t_w), breadth of stiffener (b_s), thickness of stiffener (t_s) and spacing between stiffeners (c).

3.3. Design Constraints

The constraints are obtained from IS 800:2007. The first one is strength constraint which consists of shear stress, buckling stress and flexural stress. The second one is dimensional constraint which takes into account the limiting values of span by depth ratio, web slenderness ratio (d/t_w), panel aspect ratio (c/d) and flange rigidity ratio (b/t_f). The third one is serviceability constraint which considers the deflection and vibration limits specified by the code. Equation (13), (14) and (15) provide the three constraints in the normalized form [15].

$$\frac{\sigma_c}{\sigma_a} - 1 \le 0 \qquad (13)$$

$$\frac{u_c}{u_a} - 1 \le 0 \qquad (14)$$

$$\frac{v_c}{v_a} - 1 \le 0 \qquad (15)$$

where

σ_c = stress in member
σ_a = permissible stress in member
u_c = calculated dimension
u_a = permissible dimension
v_c = calculated deflection
v_a = permissible deflection

Equations (16) – (21) are used to compute violation coefficient C [15].

$$C_i = g(x), if \rightarrow g(x) > 0 \qquad (16)$$

$$C_i = 0, if \rightarrow g(x) \le 0 \qquad (17)$$

$$C = \sum_{i=1}^{n} C_i \tag{18}$$

where n represents the number of constraints.

$$g_i(x) = \frac{\sigma_c}{\sigma_a} - 1 \tag{19}$$

$$g_i(x) = \frac{u_c}{u_a} - 1 \tag{20}$$

$$g_i(x) = \frac{v_c}{v_a} - 1 \tag{21}$$

Equation (22) gives the modified objective function [15].

$$\phi(x) = f(x) * (1 + KC) \tag{22}$$

K is the value in (22) that is carefully chosen based on the desired influence of a violation individual in the next generation. The values of the constraint violation and the penalty function values are computed using (19), (20), (21) and (22).

4. Design Inferences and Parametric Studies

In order to accommodate the best plate girder design in terms of both economy and performance, GA based formulation is developed for the optimum design of TSPG using MATLAB. The feasibility of the formulation is examined using a benchmark problem with girder span of 20m and subjected to uniform load of 40kN/m. The elastic modulus E, yield stress f_y and poisson's ratio μ are 210GPa, 250MPa and 0.3 respectively. The values of design variables are varied from a lower bound to an upper bound. It is ensured that the final optimum solution has no constraint violations and that the range of violations is appropriately chosen. The plot of variation in weight of TSPG with number of generations is shown in Figure 3.

Figure 3 shows that after the first 40 generations, a significant reduction in weight occurs. A few unfavorable jumps can be seen in the graph, which can be attributed to GA's random character. The graph converges to the final optimum design within 260 generations. The graph also shows that an optimum design has no constraint violations and solely produces feasible solutions.

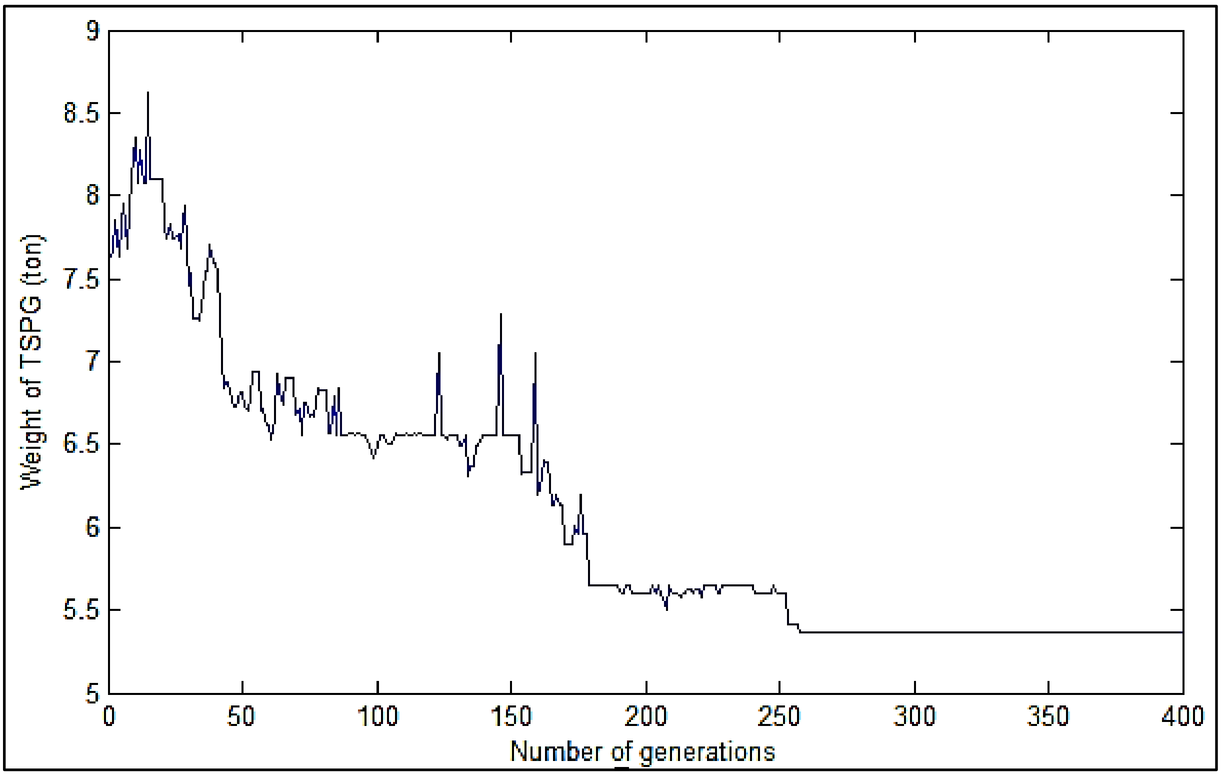

Figure 3. TSPG weight versus number of generations

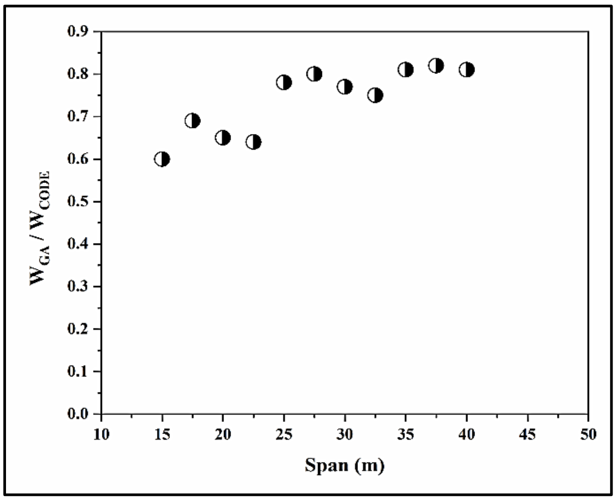

Figure 4. Weight comparison between optimized and conventional design

Furthermore, a study is made to investigate the optimum girder weight for span lengths from 15 to 40m in 2.5m increments for a single-span girder. For evaluating the effectiveness of proposed GA formulation in arriving at an optimal design of TSPG, the results of GA (W_{GA}) are compared with conventional design (W_{CODE}) carried out using IS 800:2007. Figure 4 shows that optimization can result in weight reductions of 30-40% for TSPG spans of less than 25m. For spans greater than 25m, however, the weight decrease drops to 15-25 %. This kind of variation can be explained by the fact that as the span lengthens; the solution space shrinks due to greater stress and deflection values. As a result of optimization, more cost-effective solutions for shorter spans can be achieved. The comparison study also demonstrates that utilizing IS 800:2007 to design transversely stiffened plate girders, the girder weight is overestimated by roughly 30% on average. These findings show that GA holds a lot of promise for finding the best solution to a problem influenced by complex parameters.

The reliability of the GA formulation is also verified by comparing the optimized results with experimental and numerical test results available from literature. A total of 23 girders from 6 experimental campaigns are considered for this verification of GA formulation. Slenderness ratio of web (d/t_w), aspect ratio of panel (c/d), rigidity ratio of flange (b/t_f) and yield stress of flange to web ratio (f_{yf}/f_{yw}) of these girders are determined. The database with particulars of these tested specimens is given in table 1.

The proposed GA formulation is valid for all ranges of parameters given in the experimental database. The span, ultimate load, material and geometric properties are given as the input. Breadth of flange (b_f), thickness of flange (t_f), depth of web (d) and thickness of web (t_w) are the design variables considered for GA testing. Modifications in stress and dimensional constraint functions are made in the proposed formulation in order to suite with the experimental conditions. The results of the proposed formulation and actual experimental values are given in table 2. This table also gives the ultimate loads reported through numerical studies of the same experimental database along with the analysis software.

Table 2 compares the optimised results with the experimental data in terms of mean (GA/EXP), standard deviation, and correlation coefficient (R) to determine the accuracy of the proposed GA formulation. The proposed formulation shows perfect agreement with experimental values (R = 0.996).

Figure 5 demonstrates the overall verification study of the proposed formulation through the ratio between optimized weight ($GA_{wt.}$) and experimental weight ($Exp_{wt.}$).

Table 1. Summary of data used in literature-TSPG

Researcher (Year)	N	d/t_w	c/d	b/t_f	f_{yf}/f_{yw}	Type of loading
Lee & Yoo (1999)	8	100-150	1-2	4.33-10	0.95-1.06	Shear
Gomes et al. (2000)	3	150	1-3	10	1	Shear
Estrada et al. (2007)	8	100-175	1.5-3	3-5.25	0.88	Shear
Alinia et al. (2009)	1	250	1	16.67	1	Shear
Zhu & & Zhao (2015)	1	75	1.5	5.63	0.86	Shear
Kulkarni & Gupta (2017)	2	30.6-37.6	3	5.38-7.16	1	Flexural

Table 2. Comparative analysis of proposed GA formulation for TSPG with experimental results

References	Sample details	L (mm)	bf (mm)	tf (mm)	d (mm)	tw (mm)	bs (mm)	ts (mm)	Girder weight (t)	GA/EXP	Ultimate load(kN)	
											EXP	FEM
Lee & Yoo	PG1-EXP	1700	130	15	400	4	52	6	0.087	1.02	564.9	560.1
	PG1-GA		132	15	402	4	52	6	0.088			
	PG2-EXP	2100	200	10	600	4	80	6	0.142	0.97	664.9	662.6
	PG2-GA		194.32	10	588	3.66	80	6	0.137			
	PG3-EXP	2100	200	15	600	4	80	6	0.175	0.97	674.7	680.3
	PG3-GA		200	14	587.67	4	80	6	0.169			
	PG4-EXP	2100	130	15	400	4	52	6	0.104	1.00	537.6	523
	PG4-GA		130	13.2	400	4	52	6	0.104			
	PG5-EXP	2700	200	10	600	4	80	6	0.172	0.96	572.7	582.7
	PG5-GA		200.04	9.3	587.18	4	80	6	0.165			
	PG6-EXP	2700	200	20	600	4	80	6	0.257	0.97	625.7	609.2
	PG6-GA		200	20	569.2	3.65	80	6	0.250			
	PG7-EXP	3300	200	10	600	4	80	6	0.202	0.99	517.8	517.2
	PG7-GA		198.1	11	526	4.1	80	6	0.200			
	PG8-EXP	3300	200	15	600	4	80	6	0.254	0.98	552.9	532.5
	PG8-GA		202.5	14.5	573.87	3.6	80	6	0.248			
Gomes et al	PG9-EXP	1800	100	5	300	2	40	5	0.025	1.00	110	113
	PG9-GA		100	4.5	290	2.4	40	5	0.025			
	PG10-EXP	1800	100	5	300	2	40	5	0.026	1.01	110	115.4
	PG10-GA		103.2	5	303	2	40	5	0.027			
	PG11-EXP	1800	100	5	300	2	40	5	0.029	1.00	150	143.9
	PG11-GA		100.66	4.8	298	2	40	5	0.029			
		SAFIR			ANSYS			ABAQUS				

Table 2 (continued)

References	**Sample details**	**L (mm)**	**bf (mm)**	**tf (mm)**	**d (mm)**	**tw (mm)**	**bs (mm)**	**ts (mm)**	**Girder weight (t)**	**GA/EXP**	**Ultimate load(kN)**	
											EXP	**FEM**
Estrada et al	nr700ad15-EXP	2360	210	20	700	4	84	20	0.263	0.97	309.21	319.22
	nr700ad15-GA	2360	220	19	650	3.8	84	20	0.256			
	r700ad15-EXP	2360	210	20	700	4	84	20	0.300	0.96	327.17	354.64
	r700ad15-GA	2360	210	19	680	3.8	84	20	0.286			
	nr600ad2-EXP	2660	180	20	600	4	72	20	0.241	0.98	260.65	270.89
	nr600ad2-GA	2660	170	21	582	4	72	20	0.238			
	r600ad2-EXP	2600	180	20	600	4	72	20	0.264	0.93	262.92	287.89
	r600ad2-GA	2600	165	20	580	3.8	72	20	0.245			
	nr500ad25-EXP	2760	150	20	500	4	60	20	0.202	0.89	228.05	231.37
	nr500ad25-GA	2760	144	18	460	4	60	20	0.179			
	r500ad25-EXP	2760	150	20	500	4	60	20	0.220	0.88	236.54	232.54
	r500ad25-GA	2760	142	20	498	4	60	20	0.194			
	nr400ad325-EXP	2860	120	20	400	4	48	20	0.162	0.87	217.9	210.41
	nr400ad325-GA	2860	120	16	387	3.88	48	20	0.140			
	r400ad325-EXP	2860	120	20	400	4	48	20	0.174	0.90	215.33	210.57
	r400ad325-GA	2860	117	18.5	386	4	48	20	0.156			
Kulkarni & Gupta	H1-EXP	2202	86	6.01	188.6	4.96	34	5	0.036	0.97	65	70
	H1-GA	2202	86	5.79	180	5	34	5	0.035			
	H2-EXP	2198	86.2	7.92	183.9	5.96	34	6	0.044	0.98	102	130
	H2-GA	2198	86	7.52	180.46	6	34	6	0.043			
Alinia et al	Non-rigid-EXP	4000	300	9	1000	4	120	8	0.401	1.00	–	805
	Non-rigid-GA	4000	286	8	1000	4	120	8	0.402			
Zhu & Zhao	G1-EXP	2700	180	16	600	8	72	8	0.246	0.97	1200	1200
	G1-GA	2700	170	16	580	8	72	8	0.238			
		SAFIR			ANSYS			ABAQUS	MEAN	0.9640		
									STD.DEV	0.0416		
									R	0.9960		

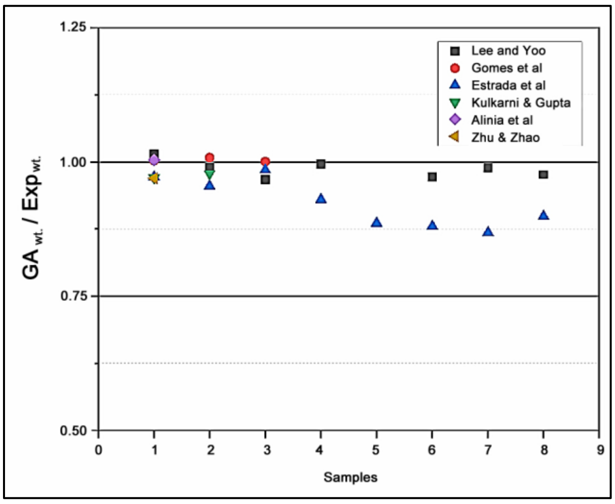

Figure 5. Weight comparison between optimized data and literature data

Due to optimization, reduction in girder weight is observed for majority of cases compared. This in turn indicates good performance of the proposed formulation for optimum design of transversely stiffened plate girder. A girder with a reduced weight (up to 12.5% reduction) can perform well in the experimental studies without affecting the strength and serviceability conditions.

To further understand the relationship between the design variables (d, t_f and t_w), more parametric studies are carried out. Using the GA formulation for optimum design of TSPG, totally 56 parametric studies are carried out. The first parametric study is based on the relationship between d and t_f. These design variables are varied within the parametric range and Figure 6 shows results from this study.

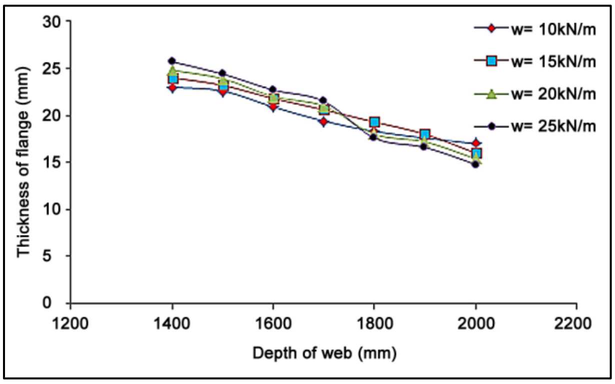

Figure 6. Variation in depth of web with thickness of flange

It is observed that when the depth of the TSPG web increases, the thickness of the flange decreases. As a result, a deeper web reduces the thickness of the flange plate, lowering the flanges' weight.

Second parametric study is on relationship between d and t_w. In line with the first parametric study, these design variables are varied within the parametric range. The result from this study is illustrated in Figure 7.

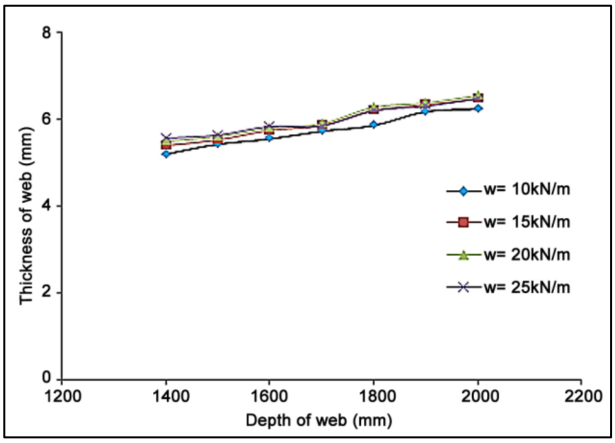

Figure 7. Variation in depth of web with thickness of web

From the results, it is clear that as the depth of the web increases, thickness of web also increases. The reason for this behaviour can be attributed towards the fact that a web needs to have ample capacity to withstand large shear force and also to prevent shear buckling. Thus, too slender webs are to be avoided in order to maintain adequate strength and stiffness.

5. Conclusions

In this study, a GA-based formulation for the optimal design of transversely strengthened plate girders is proposed. From the convergence of optimum solution, it is revealed that the design based on the developed GA formulation contain no constraint violation and are feasible solutions. With the developed formulation, the optimum girder weight is compared with the traditional design using IS 800:2007. Results conclude that conventional design overestimates the girder weight by about 30% on an average.

Furthermore, comparison of optimization results with existing experimental and numerical data from literature indicates that an optimized girder can perform well without affecting the strength and serviceability criteria. Moreover, parametric studies on design variables of transversely stiffened plate girder show that deeper web reduces flange thickness but requires thicker web in order to ensure ample shear capacity and to prevent shear buckling.

In conclusion, this study has given an account of the effectiveness of using GA in the economical design of transversely stiffened plate girder.

REFERENCES

[1] Deb, K., “Optimal design of a class of welded structures via genetic algorithms”, Collection of Technical Papers - AIAA/ASME/ASCE/AHS/ASC Structures, in the Structural Dynamics and Materials Conference, 1990, pp. 444–453. DOI: 10.2514/6.1990-1179

[2] Lee, S. C., and Yoo, C. H., “Experimental study on ultimate shear strength of web panels”, Journal of Structural Engineering, Vol. 125, No. 8, pp. 838–846, 1999.

[3] Estrada, I., Real, E., and Mirambell, E.,“General behaviour and effect of rigid and non-rigid end post in stainless steel plate girders loaded in shear. Part I: Experimental study”, Journal of Constructional Steel Research, Vol. 63, No. 7, pp. 970–984, 2007. DOI: 10.1016/j.jcsr.2006.08.009

[4] Kulkarni, A. S., and Gupta, L. M., “Experimental investigation on flexural response of hybrid steel plate girder”, KSCE Journal of Civil Engineering, pp. 1-17, 2017. DOI: 10.1007/s12205-017-0313-7

[5] Zhu, Y. Y., and Zhao, J. C., “Experimental study and numerical simulation on steel plate girders with deep section”, in the 6th International Conference on Advances in Experimental Structural Engineering, University of Illinois, Urbana Champaign, United States, August, 2015. http://sstl.cee.illinois.edu/papers/aeseancrisst15/202_Zhu_Experimental.pdf

[6] Gomes, C., Cruz, P., and Silva, L., “Experimental evaluation of shear behaviour of slender steel beams”, Engineering Civil Magazine of University of Minho, No. 7, 2000.

[7] Alinia, M. M., Shakiba, M., and Habshi, H. R., “Shear failure characteristics of steel plate girders”, Thin-Walled Structures, Vol. 47, No. 12, pp. 1498-1506, 2009. DOI: 10.1016/j.tws.2009.06.002

[8] Chacón, R., Mirambell, E., and Real, E., “Transversally stiffened plate girders subjected to patch loading. Part I. Preliminary study”., Journal of Constructional Steel Research, Vol. 80, pp. 483-491, 2013. DOI: 10.1016/j.jcsr.2012.06.008

[9] Vasseghi, A., “Design requirements for plate girders with bolted transverse stiffeners”, International Journal of Engineering - Transactions B: Applications, Vol. 18, No. 1, pp. 21-26, 2005. http://www.ije.ir/article_71566_1346b50627d1ebc3a7cd41dfed56daf2.pdf

[10] Shahabian, F., and Haji-Kazemi, H., “A proposed method to evaluate ultimate resistance of plate girders subjected to shear and patch loading”, International Journal of Engineering - Transactions A: Basics, Vol. 17, No. 4, pp. 347–356, 2004. http://www.ije.ir/article_71547_2dbcd3115628a0fcdd96fa652ab804ff.pdf

[11] Fu, K.-C., Zhai, Y., and Zhou, S., “Optimum Design of Welded Steel Plate Girder Bridges Using a Genetic Algorithm with Elitism”, Journal of Bridge Engineering, Vol. 10, No. 3, pp. 291-301, 2005. DOI: 10.1061/(ASCE)1084-0702(2005)10:3(291)

[12] Alghamdi, Saeid A., “Design optimization of non-uniform stiffened steel plate girders - A computer code”, Advances in Engineering Software, Vol. 34, No. 6, pp. 357–386, 2003. DOI: 10.1016/S0965-9978(02)00130-8

[13] Thang, D. D., Koo, M. S., and Hameed, A., “Optimum cost design of steel box-girder by varying plate thickness”, KSCE Journal of Civil Engineering, Vol. 13, No. 1, pp. 31–37, 2009. DOI: 10.1007/s12205-009-0031-x

[14] Faluyi, F., and Arum, C., “Design optimization of plate girder using generalized reduced gradient and constrained artificial bee colony algorithms”, International Journal of Emerging Technology and Advanced Engineering (IJETAE), vol. 2, no. 7, pp. 304–312, 2012.

[15] Priya A Jacob., S Justin., and R Mercy Shanthi., “Development of efficiency based standards for optimum design of stiffened plate girders”, International Journal of Civil Engineering and Technology (IJCIET), Vol. 10, No. 01, pp. 891-903, 2019.

[16] IS:800-2007, “Indian standard code of practice-General construction in steel”, Bureau of Indian Standards, New Delhi, India.