Optimum Design of Composite Corrugated Web Beams
Using Hunting Search Algorithm

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Abstract

Over the past few years there has been sustainable development in the steel and composite construction technology. One of the recent additions to such developments is the I-girders with corrugated web beams. The use of these new generation beams results in a range of benefits, including flexible, free internal spaces and reduced foundation costs. Corrugated web beams are built-up girders with a thin-walled, corrugated web and wide plate flanges. The thin corrugated web affords a significant weight reduction of these beams, compared with hot-rolled or welded ones. In this paper, optimum design of corrugated composite beams is presented. A recent stochastic optimization algorithm coded that is based on hunting search is used for obtaining the solution of the design problem. In the optimization process, besides the thickness of concrete slab and studs, web height and thickness, distance between the peaks of the two curves, the width and thickness of flange are considered as design variables. The design constraints are respectively implemented from BS EN1993-1:2005 (Annex-D, Eurocode 3) BS-8110 and DIN 18-800 Teil-1. Furthermore, these selections are also carried out such that the design limitations are satisfied and the weight of the composite corrugated web beam is the minimum.

Keywords: Composite structures; corrugated beams; optimum design; structural optimization; stochastic search methods; hunting search algorithm.

1. Introduction

The use of long span steel beams results in a range of benefits, including flexible, free internal spaces and reduced foundation costs. Many large clear-span design solutions are also well adapted to simplify the integration of mechanical or utility services. Corrugated steel web beams provide economical solution and pleasing appearance for space structures. In steel construction applications, the web part of beam usually carries the compressive stress and transmits shear in the beam while the flanges support the applied external loads. By using greater part of the material for the flanges and thinner web, materials saving could be achieved without weakening the load-carrying capability of the beam. In this case, the compressive stress in the web has exceeded the critical point prior to the occurrence of yielding, the flat web loses its stability

and deforms transversely. Corrugated web beams shown in Figure 1 are built-up girders with a thin-walled, corrugated web and plate flanges.
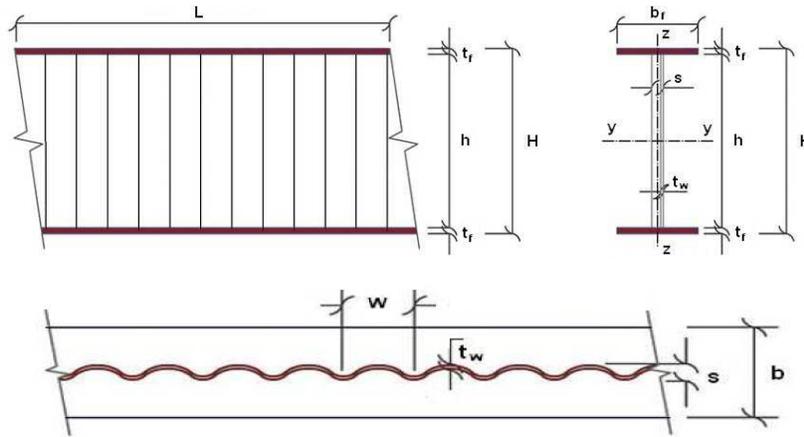

Fig. 1 Geometric properties of Corrugated Web Beam

Corrugated structure of the web cross-section not only increases the resistance of the beam against to shear force and other possible local effects, but also prevents the buckling due to loss of moment of inertia before the plastic limit. This specific structure of the web leads to a decrease in the beam unit weight and increase in the load carrying capacity. These efficient construction materials, commonly used in developed countries over years, can be utilized at the roofs as an alternative to space truss and roof truss, at the slabs as floor beams or columns under axial force. Although the designers are aware of the advantages of the composite systems to be produced with that beams, there is still not a detailed technical specification about their design and behavior. The first studies on the corrugated web beams were focused on the vertically trapezoidal corrugation. Elgaaly investigated the failure mechanisms of trapezoidal corrugation beams under different loading conditions, namely shear mode [1], bending mode [2]. They found that the web could be neglected in the beam bending design calculation due to its insignificant contribution to the beam's load-carrying capability. Besides that, the two distinct modes of failure under the effect of patch loading were dependent on the loading position and the corrugation parameters. These are found agreeable to the investigation by Johnson and Cafolla and were further discussed in their writings [3]. In addition, the experimental tests conducted by Li et al. [4] demonstrated that the corrugated web beam has 2 times higher buckling resistance than the plane web type. According to Pasternak et al., [5], the buckling resistance of presently used sinusoidal corrugated webs is comparable with plane webs.

In the present study, the ultimate load carrying capacities of optimally designed steel corrugated web beams are tested in a self-reacting frame to perform critical loads for all tested specimens. For this purpose, six corrugated beams are tested in a self-reacting frame to determine the ultimate load carrying capacities of mentioned beams under different loading conditions. The tested specimens are designed by using one of the stochastic search techniques called hunting search optimization method. This meta-heuristic algorithm is successfully applied to the optimum design problems of steel cellular beams where the design constraints

are implemented from BS EN1993-1:2005 (Annex-D, Eurocode 3) BS-8110 and DIN 18-800 Teil-1 provisions [6-10]. In this formulation, the thickness of concrete slab and studs, web height and thickness, distance between the peaks of the two curves, the width and thickness of flange in the composite corrugated web beams are considered as design variables. The computational steps of the optimization algorithm and the design process are not demonstrated in the paper due to space limitations, yet the detailed implementation specifics of the hunting search method and optimum design process of corrugated web beams can be found in Erdal et al. [11] with parameter sets.

2. The Design of Composite Corrugated Web Beams

The ultimate state design of a steel beam necessitates check of its strength and serviceability. The computation of the strength of a corrugated web beam is determined by considering the interaction of flexure and shear at the sinusoidal web. Consequently, the constraints to be considered in the design of a corrugated web beam include the displacement limitations, transverse force load carrying capacity of webs, normal force load carrying capacity of flanges, lateral torsional buckling capacity of the entire span, rupture of the welded joint, formation of a flexure mechanism and practical restrictions for corrugated web and flanges [9-11].

2.1. Stochastic Optimization Techniques

A combinatorial optimization problem requires exhaustive search and effort to determine an optimum solution which is computationally expensive and in some cases may even not be practically possible. Meta-heuristic search techniques are established to make this search within computationally acceptable time period. Amongst these techniques are simulated annealing [12], evolution strategies [13], particle swarm optimizer [14], tabu search method [15], ant colony optimization [16], harmony search method [17], genetic algorithms [18] and others [19-22]. All of these techniques implement particular meta-heuristic search algorithms that are developed based on simulation of a natural phenomenon into numerical optimization procedure. They have gained a worldwide popularity recently and have proved to be quite robust and effective methods for finding solutions to discrete programming problems in many disciplines of science and engineering, including structural optimization.

2.1.1. Hunting Search Algorithm

Hunting search method based optimum design algorithm has six basic steps, which is outlined in the following [23-24].

Step 1 Initializing design algorithm and parameters: *HGS* defines the group size which is the number of solution vectors in hunting group, *MML* represents the maximum movement toward the leader and *HGCR* is hunting group consideration rate which varies between 0 and 1.

Step 2 Generation of hunting group: On the basis of the number of hunters (*HGS*), hunting group is initialized by selecting randomly sequence number of steel sections (I_i) for each group.

$$I_i = INT\left[I_{min} + r\left(I_{max} - I_{min}\right)\right] \quad i = 1,....,n \tag{1}$$

where; the term *r* represents a random number between 0 and 1, I_{min} is equal to 1 and I_{max} is the total number of values in the discrete set respectively. *n* is the total number of design variables.

Step 3 Moving toward the leader: New hunters' positions are generated by moving toward the leader hunter.

$$I_i^{'} = I_i + r\ MML\left(I_i^L - I_i\right) \quad i = 1,....,n \tag{2}$$

where; I_i^L is the position value of the leader for the *i-th* variable.

Step 4 Position correction-cooperation between hunters: After moving toward the leader, hunters tend to choose another position to conduct the `hunt' efficiently, i.e. better solutions. Position correction is performed in two ways, one of which is real value correction and the other is digital value. In this study, real value correction is employed for the position correction of hunters.

$$I_i^{j'} \leftarrow \begin{cases} I_i^{j'} \in \left\{I_i^1, I_i^2, ..., I_i^{HGS}\right\} \textit{with probability HGCR} \\ INT\ (I_i^{j'} = I_i \pm Ra) \quad \textit{with probability (1-HGCR)} \end{cases} \tag{3}$$

Step 5 Reorganizing the hunting group: Hunters must reorganize themselves to get another chance to find the global optimum. If the difference between the objective function values obtained by the leader and the worst hunter in the group becomes smaller than a predetermined constant (ε_1) and the termination criterion is not satisfied, then the group reorganized. By employing the Eq. 6, leader keeps its position and the others randomly select positions.

$$I_i^{'} = I_i^L \pm r\left(\max(I_i) - \min(I_i)\right)\alpha\ (-\beta\ EN) \tag{4}$$

Where; I_i^L is the position value of the leader for the *i-th* variable, *r* represents the random number between 0 and 1, *min(I_i)* and *max(I_i)* are min. and max. values of variable I_i, respectively, *EN* refers to the number of times that the hunting group has trapped until this step. *α* and *β* are determine the convergence rate of the algorithm.

Step 6 Termination: The steps 3 and 5 are repeated until a pre-assigned maximum number of cycles is reached.

3. Optimum Design Problem

The design of a composite corrugated web beam requires the selection of width and thickness of a plate from which the corrugated web is to be produced, distance between the peak points of each corrugate, the length of corrugate web, the selection of width and thickness of a plate for upper and lower flanges in the beam, thickness of the concrete slab and connection members between the concrete slab and corrugated beam are considered as design variables. For this purpose, a design pool is prepared. The optimum design problem formulated considering the design constraints explained in the previous sections yields the following mathematical model [6-11]. Find a integer design vector $\{I\} = \{I_1, I_2, I_3, I_{4,}, I_5, I_6, I_7\}^T$ where I_1 is the sequence number of for the width of upper and lower flanges, I_2 is the sequence number for the thickness values of upper and lower flanges, I_3 is the thickness of corrugated web, I_4 is distance between the peak points of each corrugate web and I_5 the height of corrugate web, I_6 thickness of the concrete slab and I_7 is the connection members between the concrete slab and corrugated beam. Hence the design problem turns out to be minimize the weight of the composite corrugated web beam (W_{kom}).

$$W_{kom} = \rho_s \left(\left(2 \times b_f \times t_f \times L\right) + \left(h \times t_w \times L_{düz}\right)\right) + \rho_{bet}\left[A_{bet}L + \left(A_{stu}N_{stu}\right)\right] \tag{5}$$

where, ρ_s density of steel, b_f the width of flange, t_f thickness of flange, L span of beam, h height of corrugated web, t_w thickness of corrugated web ve $L_{düz}$ span of beam before corrugation process. ρ_{bet} the density of concrete class, A_{bet} the section area of the concrete slab, A_{stu} the net section are of connection members between the concrete slab and corrugated beam and N_{stu} the number of connection members between the concrete slab and corrugated beam along beam span. The demonstration of composite corrugated web beams under loading conditions is given in Figure 2 with more detail.
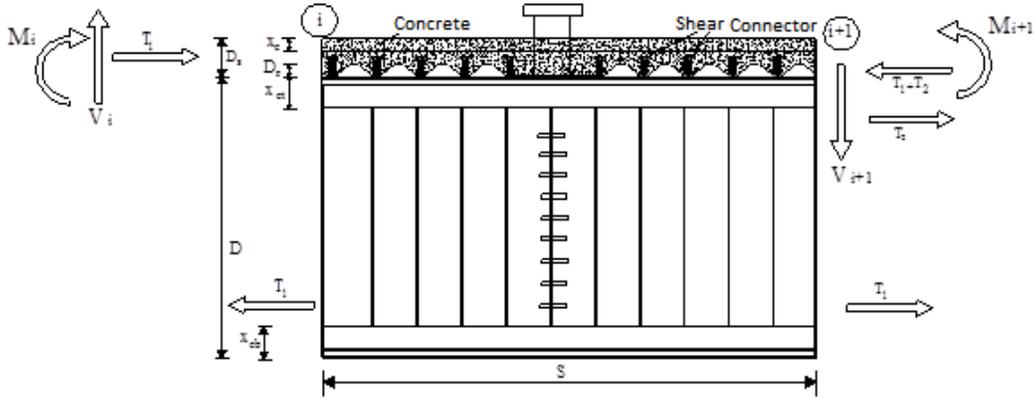
Fig. 2. The demonstration of Composite Corrugated Web Beam

Design of a corrugated beam requires the satisfaction of some geometrical restrictions that are formulated through Eqns. (6-9).

Web dimensions:

$$333 \ mm \leq h \leq 1500 \ mm \qquad (6) \qquad\qquad 1.5 \ mm \leq t_w \leq 5.0 \ mm \qquad (7)$$

Flange dimensions:

$$120 \ mm \leq b_f \leq 450 \ mm \qquad (8) \qquad\qquad 6.0 \ mm \leq t_f \leq 30.0 \ mm \qquad (9)$$

3.1. Transverse load carrying capacity of corrugated webs

Based upon the experimental tests and finite element analysis results, the following design procedure has been suggested: The corrugated web is regarded as an orthotropic plate with rigidities Dx and Dy. According to [5], the following formula therefore applies to the corrugated web:

$$D_x = \frac{E \times w \times t^3}{12 \times s}, \ D_y = \frac{E \times I_y}{w} \ \text{for} \ D_x \leq D_y \qquad (10)$$

For transverse buckling stress of corrugated web;

$$\tau_{EG} = \frac{162}{5 \times t_w \times h^2} \sqrt{(D_x \times D_y^3)} \qquad (11)$$

For slenderness parameter of corrugated web;

$$\lambda_{GN} = \sqrt{\frac{f_y}{\sqrt{3} \times \tau_{EG}}} \qquad (12)$$

With the buckling coefficient of corrugated web;

$$K_B = \frac{1}{(\lambda_{GN})^{3/2}} \qquad (13)$$

the transverse force load carrying capacity for the corrugated web finally results in:

$$V_{TK-MAX} = \frac{K_B \times f_y \times h \times t_w}{\sqrt{3}} \qquad (14)$$

3.2. Normal load carrying capacity of flanges

In determining the normal bearing force of the flanges, a distinction must be made between tensile and compressive stresses. In the case of tensile stress, the load carrying capacity of the flange is derived as follows:

$$\sigma_{ALLOW} = \frac{N_{T-MAX}}{b_f \times t_f} \qquad (15)$$

Reformulation of the expression for $\psi = 1$ leads to the following elastic limit stress:

$$\sigma_{EL} = \frac{4000}{\left(b_f \times t_f\right)^2} \qquad (16)$$

Therefore the reduced normal force on the flange:

$$N_{NORMAL} = \sigma_{EL} \times b_f \times t_f \qquad (17)$$

Global failure of stability - lateral buckling of the flange - is equivalent to the verification against torsional-flexural buckling. If the restraining effect of the web is ignored, the torsional-flexural verification is carried out as the buckling verification for the "isolated" flange in accordance with [5]. The following condition for the distance between lateral supports is obtained:

$$\tau_{EG} = \frac{\pi}{4\sqrt{3}} \sqrt{E \times f_y} \times \frac{b_f^2 \times t_f}{k_c \times c} \qquad (18)$$

3.3. Behavioral and Geometrical Restrictions of Composite Beam

The moment capacity of composite corrugated web beam with sinusoidal web function (M_{RD}) has been defined as following equations.

For the neutral axis on concrete slab;

$$T_{AD} = A \times \frac{f_y}{\gamma_a} \qquad \text{and} \qquad a = \frac{T_{AD} \times \gamma_c}{0.85 \times f_{ck} \times b_c} \qquad (19)$$

$$M_{RD} = T_{AD} \times (d_1 + h_F + t_c - a/2) \qquad (20)$$

For the neutral axis on steel profile;

$$C_{CD} = 0.85 \times \frac{f_{ck}}{\gamma_c} b_c \times t_c \qquad \text{and} \qquad C_{ad} = \frac{1}{2} \times (T_{AD} - C_{CD}) \qquad (21)$$

$$M_{RD} = C_{AD} \times (d - y_t - y_c) + C_{CD}((t_c/2) + h_f + d - y_t) \qquad (22)$$

In these equations, d height of steel section, d_1 distance between the centre of steel section and upper part, y_c distance between the centre of pressure region of steel section and upper part, y_t distance between the centre of tension region of steel section and lower part, t_c height of concrete slab, b_c effective slab width, h_F height of steel deck, f_y yield strength of steel, f_{ck} compressive strength of concrete, γ_a and γ_c are coefficients for steel and concrete materials N_{stu}.

3.4. The Design of Concrete Slab for Corrugated Web Beams

The effective length of concrete slab and number of shear connectors have been calculated for OGK_330 corrugated web beams according to EC4, BS-5950 Part-3, Section 3-1.

$$b_{eff} = \frac{l_0}{4} = \frac{470cm}{4} = 117,5cm \qquad (23)$$

$$R_S = 0{,}95 f_y A_a \tag{24}$$

In these equations, b_{eff} is effective length of concrete slab and l_0 is span of beam.

$$R_C = 0{,}45 f_{cu} b_{eff} h_c \tag{25}$$

In the equation 25, R_c is compressive force of concrete, h_c the depth of the concrete slab, A_a is section area of steel, h height of steel section, h_p the depth of concrete slab at tab of the deck. If plastic neutral axis is on the upper flange of steel section, moment is defined as;

$$M_{pl,Rd} = R_S \frac{h}{2} + R_C \left(\frac{h_c}{2} + h_p \right) \tag{26}$$

The calculation of shear connectors for composite corrugated web beams has been defined in equations 41, 42 and 43. In these equations, f_u maximum tensile stress of steel shear connectors, h the height of shear connectors, d the diameter of shear connectors, γ_v safety factor, and α is constant.

$$P_{Rd} = 0{,}29\alpha d^2 \frac{\sqrt{f_{ck}E_c}}{\gamma_v} \tag{27}$$

$$P_{Rd} = 0{,}8 f_u \frac{\pi d^2}{4\gamma_v} \tag{28}$$

$$\alpha = 0{,}2 \left(\frac{h}{d} + 1 \right) \le 1 \rightarrow \tag{29}$$

The depth of concrete slab (h_c) and forces (R_s, R_c and $M_{pl,Rd}$) are calculated for OGK_330 corrugated web beam under point loading.

R$_s$=0,95x355x16x160=863,36 kN

$\sum$Y=0 ; R$_s$=R$_c$=0,45x20x1175xh$_c$; h$_c$<=81,64 mm ;h$_c$=8cm.

$$R_c = 0,45 \times 20 \times 1175 \times 80 = 846 \text{ kN}$$

$$M_{pl,Rd} = 863,36 \times 173 + 846 \times 70 = 208,58 \text{kNm} = 21,262 \text{ tm}$$

4. Design Example

Optimum design algorithms presented are used to design a corrugated steel web beam (OGK_330) with 5-m span shown in Fig. 3. The beam is subjected to point loading. The upper flange of the beam is laterally supported by the floor system that it supports. The maximum displacement is limited to 17 mm. The modulus of elasticity is 205 kN/mm^2.
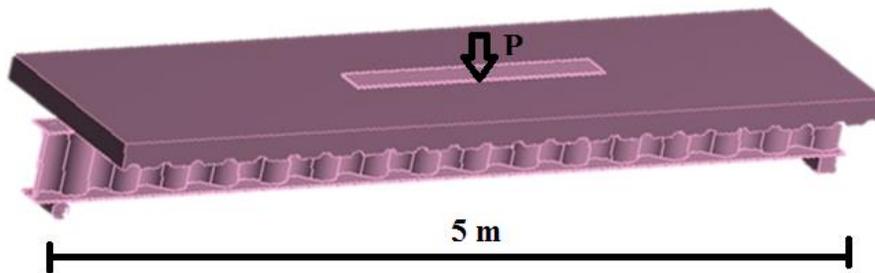

Fig. 3. Loading of 5-m span Corrugated Web beam

The design example is solved by hunting search algorithm (HSA). The maximum number of generations is taken as 5000 (Table 1).

Table 1. The Parameters of HAS and FFO Techniques

Technique	The values of parameters
HSA	$HGS = 90$ $MML = 0.002$ $HGCR = 0.90$ $Ra_{max} = 0.01$, $Ra_{min} = 0$ $par = 0.45$ $\alpha = 0.9, \beta = 0.02, IE = 25, N_{cyc} = 50000$

The result of the sensitivity analysis carried out for the HSA parameters is given in Table 2. In steel construction applications, the web part of beam usually carries the compressive stress and transmits shear in the beam while the flanges support the applied external loads. By using greater part of the material for the flanges and thinner web, materials saving could be achieved without weakening the load-carrying

capability of the beam. In this case, the compressive stress in the web has exceeded the critical point prior to the occurrence of yielding, the flat web loses its stability and deforms transversely.

Table 2. Optimum Design of Corrugated Beam with 5-m Span

Optimum Section	Conrete Part			Steel Part					Minimum Weight (kg)
	h_c (mm)	b_{eff} (mm)	S_n	t_w (mm)	h(mm)	t_f (mm)	H_c (mm)	L_c (mm)	
OGK_330	80	1175	44	5	330	9	43	155	1317.38

The optimum corrugated web beam should be produced such that it should have 5 mm web thickness 330 mm web height, 9 mm flange thickness and 160 mm flange width for steel part and 80 mm slab depth, 1175 mm effective length of slab, 44 shear connectors for concrete part. HSA produces 1317.38 kg weight for composite corrugated web beam OGK_330. The dimensions of OGK_330 and OGK_500 beam are also given in Table 2. The maximum value of the strength ratio is 0.98 which is almost upper bound. This reveals the fact that the strength constraints are dominant in the problem. The design history curve for HSA techniques is shown in Fig. 4. It is apparent from the figure that HSA method performs good convergence rate and acceptable solution in this design problem.
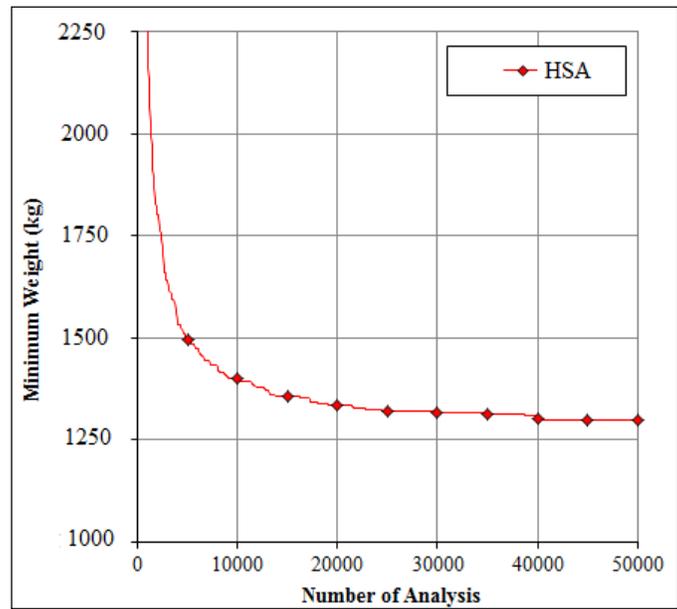

Fig. 4. Design History Graphic of 5-m Corrugated Web Beam

5. Conclusion

This study concerns with the application of a hunting search algorithm to demonstrate the robustness of the proposed algorithm and to find the optimum design of composite corrugated web beams. The design algorithm is mathematically simple but effective in finding the solutions of optimization problems. Fly-back mechanism is employed for handling the problem constraints and feasible ones being candidate solutions to give the minimum weight are determined. A composite corrugated web beam example is designed to illustrate the efficiency of the algorithm. In the optimization process, besides the thickness of concrete slab and studs, web height and thickness, distance between the peaks of the two curves, the width and thickness of flange are considered as design variables. The optimum design attained by HSA method clearly shows that the proposed method give good solution. In view of the results obtained, it can be concluded that the HAS method is an efficient and robust technique that can successfully be used in optimum design of corrugated web beams.

Acknowledgment

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