**International Academic Institute for Science and Technology**

International Academic Journal of Science and Engineering
Vol.11, No.1, 2024, pp.138-152.

ISSN 2454-3896

International Academic Journal of Science and Engineering

www.iaiest.com

# Optimum Design of Reinforced Concrete Beams with Large Opening Using Neural Network Algorithm

Inas M. Ahmed [a]

[a] *Technical Engineering College, Northern Technical University, Kirkuk, Iraq. Email: inas.mahmood@ntu.edu.iq*

## Abstract

It is quite rare to find researches in the literature connecting neural networks to design challenges in civil engineering, particularly with regard to beam with large openings. Therefore, to ascertain the best cost design for such a beam, an optimization technique is developed, written using MATLAB functions, and verified in this study. Because of the efficiency and dependability of the iterative Particle Swarm Optimization (PSO) process, the ACI 318-19 code method is adopted via this algorithm. Using four beam design (decision) variables, which are: beam width $b$, longitudinal tension reinforcement area $A_s$, longitudinal compression reinforcement area $A'_s$, and vertical shear reinforcement area $A_v$; the objective is to minimize the overall beam cost function. The constraints for each of the 60 randomly chosen particles are handled using the self-adaptive penalty function technique, which is applied in all the 100 iterations for each of the four proposed beam design case studies with identical openings. For the developed method, completing all iterations serves as a stopping criterion. Comparative studies are conducted to demonstrate how the compressive strength of concrete and the live load scheme affect the optimal overall beam cost and the associated design variables. The relations between cost of beams and the four design variables, which are presented through graphs and tables, indicate that the beam's cost is significantly impacted by the loading condition. This is shown by increasing the cost of beam B1, with no sustained live loads, from 722 US dollars to 984 US dollars for beam B4, which has concentrated and distributed sustained live loads. Future research is advised to include modern strengthening techniques for beams with openings, and apply this research to a PSO algorithm with several objectives.

**Keywords:** Beams, Optimization, Opening, Cost, PSO.



DOI:10.9756/IAJSE/V11I1/IAJSE1117
Received: 03 February 2024/Accepted: 27 February 2024/Published: 15 March 2024

## Introduction

There is a tendency in tall building constructions to provide service duct holes in the reinforced concrete beams' web. This has the effect of producing a less dead space above the fake ceiling, resulting in a more condensed and cost-effective design. Regarding the beams' strength design with large web holes under different loading combinations, a number of approaches have been offered in the past. These techniques, however, are only easily applicable to statically determinate beams since they necessitate the predetermination of the moments and forces in the middle of the opening. When webs are used to create gaps in continuous beams, which are typically found in practice, the stiffness is reduced. As a result, internal forces and moments are redistributed, the magnitude of which must be determined before a design can move on. A compatible, robust, and safe design is achieved by an iterative process in the classic design method for beam with openings, which greatly benefits from the experience, intuition, and ability of the designer [1]. When a design specifies that the recognized criterion is reached means that this process comes to an end. Dimensions of the cross-section and material grades are typically chosen initially in design scenarios due to widespread experience or convention. The remaining issue is to create effective and economical structures without compromising system integrity [2]. Thus, another more methodical approach is the design by optimization [3] that works by evaluating a trial design to see if it represents the "*best*" or not. Best in the context of reinforced concrete beams with openings refers to the most economical, dependable, long-lasting, and efficient design condition [4]. Rules for the location of large web holes in reinforced concrete beams are provided based on test findings, and a straightforward design process is then recommended [5]. Ordinarily, openings ought to be placed such that chords have enough concrete area to form the final compression block in flexure and enough depth to offer useful shear reinforcement. The recommended strategy assumes the applied shear that must be supported in relation to the chords' flexural stiffness and utilizes an effective length of the hole and an equivalent shear stiffness that integrates it for assessments of elasticity moments of bending and shear loads by conventional methods. The ACI code method is followed in the design of chords for strength. The behavior of shallow simply supported beams, both simple and continuous and with or without holes, made of reinforced normal and high strength concrete under experimental testing was examined [6]. Considering the existing experimental findings about internal stress trajectories, failure modes, and patterns of cracks determined from the Strut and-Tie Models (STM) for all such selected beams and based on elastic Finite Element (FE) analysis. Test results are compared with the obtained STM results.

The Particle Swarm Optimization (PSO), as an effective neural network evolutionary algorithm, is firstly utilized to investigate the behavior of the biological bacterial colony [7]. The process of combining two evolutionary algorithms is used to compare variations in the bacteria algorithm component. The responsive actuality of the bacterium algorithm is demonstrated by analyzing its applications across multiple areas, including civil engineering. In accordance with ACI 318-19 code [8], the PSO method was utilized here to minimize the cost of four reinforced concrete beams having relatively large holes. The limited design challenge was tackled with a multi-stage dynamic penalty approach with the aim of minimizing the overall expense of the four beams while fulfilling all design constraints. Using the PSO algorithm, a process was developed [9] for the design of FRP reinforced concrete beam sections in accordance with ACI 440.1 R-06 standards. Two design elements were taken into consideration for a rectangular cross-section beam: the beam's width and height, in addition to the value of reinforcing bars' diameter. The best cost design for reinforced concrete deep beams was found by developing, validating, and coding an optimization algorithm utilizing MATLAB functions [10]. Because of the efficiency and dependability of the iterative particle swarm optimization process, the ACI code method was adopted. Using four decision variables, the objective function was to minimize the overall cost of reinforced concrete deep beams. The restrictions for each of the 300 randomly chosen particles were handled using the self-adaptive penalty function technique, which was adopted in the total of 50 iterations for each of the four proposed deep beam design cases. Investigations were conducted to demonstrate how the length of the deep beam, the live load scheme, and the compressive strength of the concrete affect the optimal overall cost and the associated choice variables. The findings, which were displayed as tables and graphs, indicated that the loading condition significantly affects the deep beams' overall cost. A particular differential evolutionary technique for pre-stressed beams in accordance with the European Building Code was used to propose a single objective cost optimization algorithm [11]. A hybrid PSO and genetic algorithm was created to address force method-based concurrent design frame and analysis structure difficulties [12]. To illustrate the effectiveness and superiority of the method, comparisons were done for a few design challenges in that study, particularly for constructions that use a lot of redundant forces.

Although the traditional reinforced concrete beam design with openings produces safe designs, the structural designer's experience has a significant impact on the design's economy. Engineers have been compelled by today's competitive environment, in which the efficiency and scarcity are essentials to show an increased curiosity in cost-effective and optimum cost-effective designs by advising the utilization of modern algorithms and techniques. Conversely, as far as the current author was aware, there are almost few studies in the past articles that link artificial neural network optimization algorithms to design issues in structural engineering, particularly with regard to beam with openings. Therefore, the development of an algorithm like PSO that can effectively and optimally address a variety of reinforced concrete beam with openings design problems appears to be crucial. An algorithm like this should yield the most economical design state that meets all of the desired safety and serviceability requirements.

## Design Procedure for Beam Section with Openings

Unless specified differently, the ACI Code [8] provisions and recommendations have been adhered throughout the design process suggested in this work. Typically, the process of reinforced concrete structural design entails:

1. **Structural Analysis:** This method involves examining the structure to ascertain how shear stresses and moments resulting from ultimate loads are distributed. The shear force and bending moment envelopes are calculated taking into account every potential loading combination.
2. **Strength Design:** In which the key components are made to have the maximum strength possible in both shear and bending. The entire structure satisfies the standards for strength.
3. **Serviceability Design:** This requirement ensures that the structure meets its intended purposes and operates well under operating loads.

### 1. Structural Analysis

Shear force and bending moment envelopes for a statically determinate beam can be found in statics. The technique outlined in [13] can be used to continuous beams; in other words, an opening-containing component is treated as a non-prism beam having distinct cross-sectional characteristics, such as those of an equivalent section for opening segments and those of a solid section. By adding two additional joints for every web opening, the problem can be simplified to a standard analysis of continuous beam as long as the previously mentioned rules are followed. To do this, the stiffness values for the several segments that make up the member must be estimated.

#### a. Stiffness of Beam Segment

As specified by the ACI Code [8], the concrete gross section may serve as the basis for stiffness computations, and the elasticity modulus $E_c$ of concrete is calculated as follows:

$$E_c = 4730\sqrt{f_c'} \qquad (1)$$

where $f_c'$ is the 28-day concrete cylindrical compressive strength (in MPa). One way to compute shear modulus is:

$$G = \frac{E_c}{2(1+\nu)} \qquad (2)$$

BS 8110-3 [14] recommended value for concrete's Poisson's ratio $\nu$ is 0.2. The equivalent flexural stiffness ($EI_{eq.}$) of an opening part could be calculated by subtracting the void created by the opening from the inertia obtained from the section. For an opening segment, the equivalent shear stiffness $GA_{eq.}$ can be calculated as follows [13]:

$$(GA)_{eq.} = \frac{12E_c(I_{gt}+I_{gb})}{l_e^2} \qquad (3)$$

where $l_e$ is the opening's effective length, which has been found through experimentation to be:

$$l_e = \frac{l_o}{1-\left(\frac{d_o}{h}\right)^{1.5}} \qquad (4)$$

where the gross moment of inertia of the upper and lower chord members are, respectively, $I_{gt}$ and $I_{gb}$. And the opening length, opening depth, and total beam depth are, respectively, $l_o$, $d_o$, and $h$. Usually, it is recommended to disregard the shearing distortion of the solid parts.

#### b. Shear Force and Bending Moment Envelopes

Bending moment and shear force values for the beam can be got by analyzing it under all potential load combinations using any elastic method.

### 2. Strength Design Methodology

Solid beam segments can be designed normally if the shear force and bending moment values are known. Considering the chord members' observed Vierendeel behavior during an opening, a recommended design approach for the opening section has been developed. In line with test findings [15–17], that is, mid-span chord member contraflexure points are considered, and the axial load for these sites is calculated by the beam moment division at the opening's center by the separation between the chord members' plastic centroids. The constituents of chord respective flexural stiffnesses determine how much of the shearing force is applied at opening's center. It has been discovered that making this assumption makes calculations simpler and yields an adequate applied shear distribution [18]. Next, using statics, the moments at the chord member's ends are determined. The following is a summary of the steps involved;

### a. Chord Member Forces and Moments

From the shear force and bending moment values, determine the ultimate design shear force $V_m$ and bending moment $M_m$ at the center of the beam zone that has opening. Then, compute the axial tension and compression forces ($N_t$ and $N_b$, respectively) (compression is taken positive) operating in the upper and lower chords, respectively, as follows:

$$N_t = \frac{M_m}{z} \quad (5)$$

$$N_b = -N_t \quad (6)$$

where $z$ is the distance across the upper and lower chords' plastic centroids. Assign the imposed shear to the upper and lower chords in the following manner:

$$V_t = V_m\left(\frac{I_{gt}}{I_{gt}+I_{gb}}\right) \quad (7)$$

$$V_b = V_m\left(\frac{I_{gb}}{I_{gt}+I_{gb}}\right) \quad (8)$$

Use statics to determine the chords' end moments, as shown in Fg. 1:

$$M_1 = -\frac{w{l_o}^2}{8} - \frac{V_t\, l_o}{2} \quad (9)$$

$$M_2 = -\frac{w{l_o}^2}{8} + \frac{V_t\, l_o}{2} \quad (10)$$

$$M_3 = -\frac{V_b\, l_o}{2} \quad (11)$$

$$M_4 = \frac{V_b\, l_o}{2} \quad (12)$$

where $M$ is the moment and $w$ represents the evenly distributed load acting directly on the upper chord. As illustrated in Fig. 1, the opening corners are denoted by subscripts 1, 2, 3, and 4.

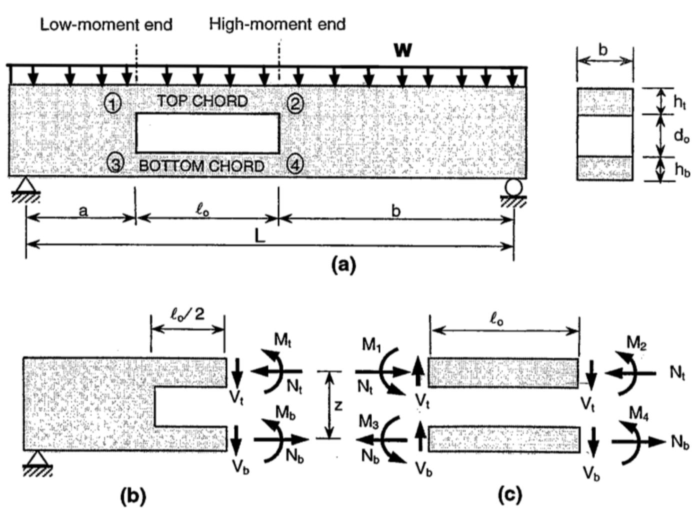



**Figure 1: Beam Subjected to Shear and Bending. (a) Typical Beam with Opening, (b) Loadings on the Opening Segment, (c) Loadings on the Chords**

### b. Design of Chord Member Longitudinal Reinforcement

The opening segments should all have the same main reinforcement as the upper and lower of the solid part near to the opening. As an experiment [5], the extra reinforcement needed to withstand the combined each chord member's axial force and moment might be constructed to symmetrically reinforce each chord. Once the chord members' reinforcement has been determined, the strain compatibility principle can be used to generate the matching idealized column interaction diagrams equations. The interaction diagrams equations then show the essential combinations of axial load and bending moment for the chord members, as previously determined. Provided that every combination fits inside the relevant interaction diagrams, the amount of reinforcement is to be adequate. If not, the reinforcement has to be revised. In addition, the upper chord's flexural capacity must be adequate to withstand any direct external loading placed on it. The steps for constructing the nominal column (chord) interaction diagram equations are as follows: The concrete force and steel strains and stresses can be simply estimated for any chosen value of the distance from the upper chord face to its neutral axis, "*c*", in the following way:

- **For the Chord's Tension Steel**

$$\varepsilon_s = \varepsilon_u \frac{d-c}{c} \tag{13}$$

$$f_s = E_s\, \epsilon_u \frac{d-c}{c} \le f_y \tag{14}$$

- **For the Chord's Compression Steel**

$$\varepsilon'_s = \varepsilon_u \frac{c-d'}{c} \tag{15}$$

$$f'_s = E_s\, \epsilon_u \frac{c-d'}{c} \le f_y \tag{16}$$

The depth of concrete stress block $a$ at a chord is:

$$a = \beta_1 c \le h \tag{17}$$

where; $\varepsilon_s$, and $f_s$ are strain and stress at chord tension steel, respectively. $\varepsilon'_s$, and $f'_s$ are strain and stress at chord compression steel, respectively. $d$, and $d'$ are depth to lower and upper chord reinforcement, respectively. $E_s$, and $f_y$ steel modulus of elasticity and yield stress of longitudinal steel bars, respectively. $h$, and $\varepsilon_u$ are chord depth and ultimate steel strain corresponding to its ultimate stress, respectively. $\beta_1$ is a reduction factor = 0.85. The values of $f_s, f'_s$, and $a$ are to be substituted in the upcoming relations to calculate nominal normal force $P_n$ and nominal moment $M_n$ corresponding to the assumed $c$ value:

$$\sum F_y = 0 \;\Rightarrow\; P_n = 0.85\, f'_c ab + A'_s f'_s - A_s f_s \tag{18}$$

$$\sum M = 0 \Rightarrow M_n = P_n\, e = 0.85\, f'_c ab \left(\frac{h}{2} - \frac{a}{2}\right) + A'_s f'_s \left(\frac{h}{2} - d'\right) - A_s f_s \left(d - \frac{h}{2}\right) \tag{19}$$

where; *As* and *A's* are the longitudinal tension and compression steel areas, respectively. As working with compression controlled chord section (i.e. with a section has $\varepsilon_t < 0.002$) then the strength reduction factor is $\phi$ = 0.75, and the design (reduced) force and moment values are:

$$P_{Design} = \emptyset P_n \tag{20}$$

$$M_{Design} = \emptyset M_n \tag{21}$$

**c. Design of Chord Member Shear Reinforcement**

Equations (7) and (8) and Fig. 2 give the shear forces that the upper and lower chords, respectively, are carrying. By recognizing these forces, the necessary reinforcement may be constructed in a way that is comparable to that of reinforced concrete beams. In case if chord cross section is insufficient to produce the required shear strength, then the required vertical shear reinforcement can be calculated using the ACI code method. First, compute of shear strength provided by concrete chord section $V_{cn}$ is given by:

$$V_{cn} = 0.17\lambda\sqrt{f'_c}\; bd \tag{22}$$

where, $\lambda$ = 1.0 for concrete with normal weight. The required design shear force to be shared by vertical steel reinforcement (short stirrups) is:

$$V_{s,Design} = (V_u - \emptyset V_{cn})/\phi \tag{23}$$

For a given vertical stirrup reinforcement area $A_v$, stirrups yield stress $f_{yv}$, and stirrups spacing $s$, the above calculated design value is to be compared with the value shared by the existing suggested stirrups and satisfying the condition:

$$V_{s,Design} \le \frac{A_v\, f_{yv}\, d}{s} \tag{24}$$

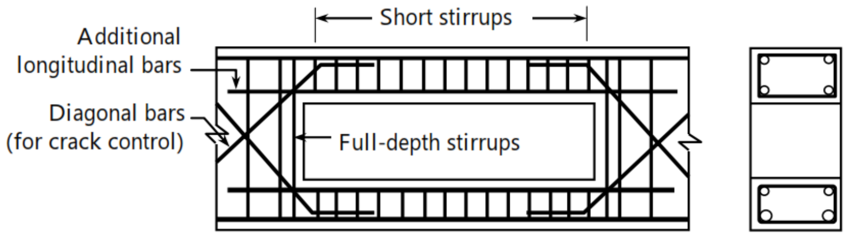



**Figure 2: A typical Reinforcement Details for Large Opening**

**d. Design of Post between Openings**

To support the entire applied shear, the post needs to be constructed as a solid piece. It is best to disregard the corner reinforcement's contribution at the two nearby apertures. The design process adopted for the solid section of the beam mid-span is as follows: The depth of compression stress block $a$ is determined by solving the following quadratic equation:

$$M_u = 0.85\, f_c' ba * [d - \frac{a}{2}] \qquad (25)$$

$$A_s \geq \frac{0.85\, f_c' ba}{f_y} \qquad (26)$$

**3. Serviceability Design Methodology**

Cracking and deflection are the two primary requirements for serviceability that must be fulfilled [19].

*Cracking:* The coming crack control measures are advised for the crucial areas at the opening's corners, assuming that the solid segments' needs for crack control are satisfied by appropriate reinforcing details or by physical calculation. A vertical stirrups and diagonal bars combination would be employed at each vertical edge of the opening, with a $\eta = 2$ shear concentration factor, so that the diagonal bars supply at least 75% of the shear resistance [19], therefore, crack serviceability requirements is conditioned by:

$$V_{s,Design} \leq \frac{\phi A_v f_{yv}}{0.25\, \eta} \qquad (27)$$

According to $A_d$, which is the required diagonal reinforcement area, another serviceability conditions is raised and conditions the design shear force $V_{s,\,Design}$ shared by shear reinforcement by:

$$V_{s,Design} \leq \frac{\phi A_d f_{yd} \sin(\varphi)}{0.27\, \eta} \qquad (28)$$

where; $f_{yd}$, and $\varphi$ are stress at yield and inclination angle of diagonal bars with respect to beam axis. To avoid confusions, the same diagonal reinforcement amount is to be provided at each upper and lower corners.

*Deflections:* The cracked section moment of inertia, or $I_{cr}$, is as follows, assuming that the applied moment is greater than the cracking moment and that the cracks that occur will result in a decrease in stiffness:

$$I_{cr} = \frac{bc^3}{3} + n\, A_s(d-c)^2 \qquad (29)$$

where $c$ is the distance between the top beam face and the neutral axis, and is determined by solving a second degree formula that depicts moments for areas taken about the section neutral axis, and $n$ is the modular ratio ($E_s/E_c$);

$$n\, A_s(d-c) = b\, c\, \frac{c}{2} \qquad (30)$$

The inertia's effective moment $I_e$ is determined by the value for the ultimate moment applied $M_u$ and the cracking moment $M_{cr}$ according to the following equation:

$$I_e = (\frac{M_{cr}}{M_u})^3\, I_g + \left[1 - (\frac{M_{cr}}{M_u})^3\right]\, I_{cr} \qquad (31)$$

$$M_{cr} = \frac{1240\sqrt{f_c'}.I_g}{h} \qquad (32)$$

where $I_g$ is the section's gross moment of inertia. Using the concrete elastic modulus $E_c$, the general immediate mid-span deflection caused by concentrated and distributed dead loads and live loads is calculated via the elastic formula below:

$$\Delta_i = \frac{5\, w_u\, L^4}{384\, E_c\, I_e} + \frac{P_u\, L^3}{48\, E_c\, I_e} \quad (33)$$

ACI code [8] limits state that the instantaneous deflection cannot be more than *L/360*. For long-term deflections, the weighted average formula below should be used to separate the immediate live load deflection $(\Delta i)_{LL}$ and immediate dead load deflection $(\Delta i)_{DL}$ induced by the living loads $w_{LL}$ and the dead $w_{DL}$:

$$(\Delta_i)_{DL} = \frac{W_{DL}}{w_{DL} + w_{LL}} . \Delta_i \quad (34)$$

$$(\Delta_i)_{LL} = \frac{W_{LL}}{w_{DL} + w_{LL}} . \Delta_i \quad (35)$$

In conclusion, the long-term deflection can be computed using:

$$\Delta_{LT} = (\Delta_i)_{LL} + 0.6\, \xi\, [(\Delta_i)_{DL} + (\%)(\Delta_i)_{LL}] \quad (36)$$

where (*%*) is the portion of the sustained live load (about 20%), and $\xi = 2$ taken for periods longer than five years, knowing that the ACI code suggests a long-term deflection value of no more than *L/480*.

## Particle Swarm Optimization Technique

PSO is a process of iteration in which the optimum solution at any given time is followed by the prospective solutions, also known as particles, as they fly through the problem space. Every particle maintains a record of its coordinates within the issue space, which correspond to the most optimal solution found thus far [20]. Every particle possesses a unique memory section where it stores the best location visited in the search space so that it can recall the past experience. We refer to this value as *pbest*. The best value that any particle in the particle's vicinity has so far achieved is another best value that the particle swarm optimizer keeps track of. This value is known as *lbest*. Global best, or *gbest*, is the value obtained when a particle takes into account the whole population to be its neighbors in topology. The idea behind particle swarm optimization is to modify each particle's velocity toward its *pbest* and *gbest* at each time step. Each particle modifies its position and velocity in accordance with the following equations after determining the optimal values:

*Vij(t)= w(t) * Vij(t-1) + iw(t)* U(0,1) * (pbestij(t-1) - Xij(t-1)) + sw(t)* U(0,1) * ( gbestj(t-1) - Xij(t-1))* (37)

*Xij(t) = Xij(t-1) + Vij(t)* (38)

where; *Xij:* the *jth* component of particle *i*'s location at time step *t*, or iteration.

*Vij(t):* is the *jth* component of particle *i*'s velocity at time step *t*.

*w(t), iw(t), sw(t)*: at time step *t*, the weights of inertia, individualism, and sociality, respectively.

*U(0,1)*: is a random number produced in the interval [0,1] using a uniform distribution.

*pbestij(t-1), gbestj(t-1)*: coordinate *j* of the best position discovered up to time step *t-1* by *i* particle and its entire swarm individuals, respectively.

To find *w(t)*, a technique named "Annealing Algorithm" is employed [21]. Maximum iterations number serves as a stopping criterion, which is utilized as a prerequisite for the search process to end. Fig. 3 summarizes the entire optimization PSO procedure that was used in this investigation.

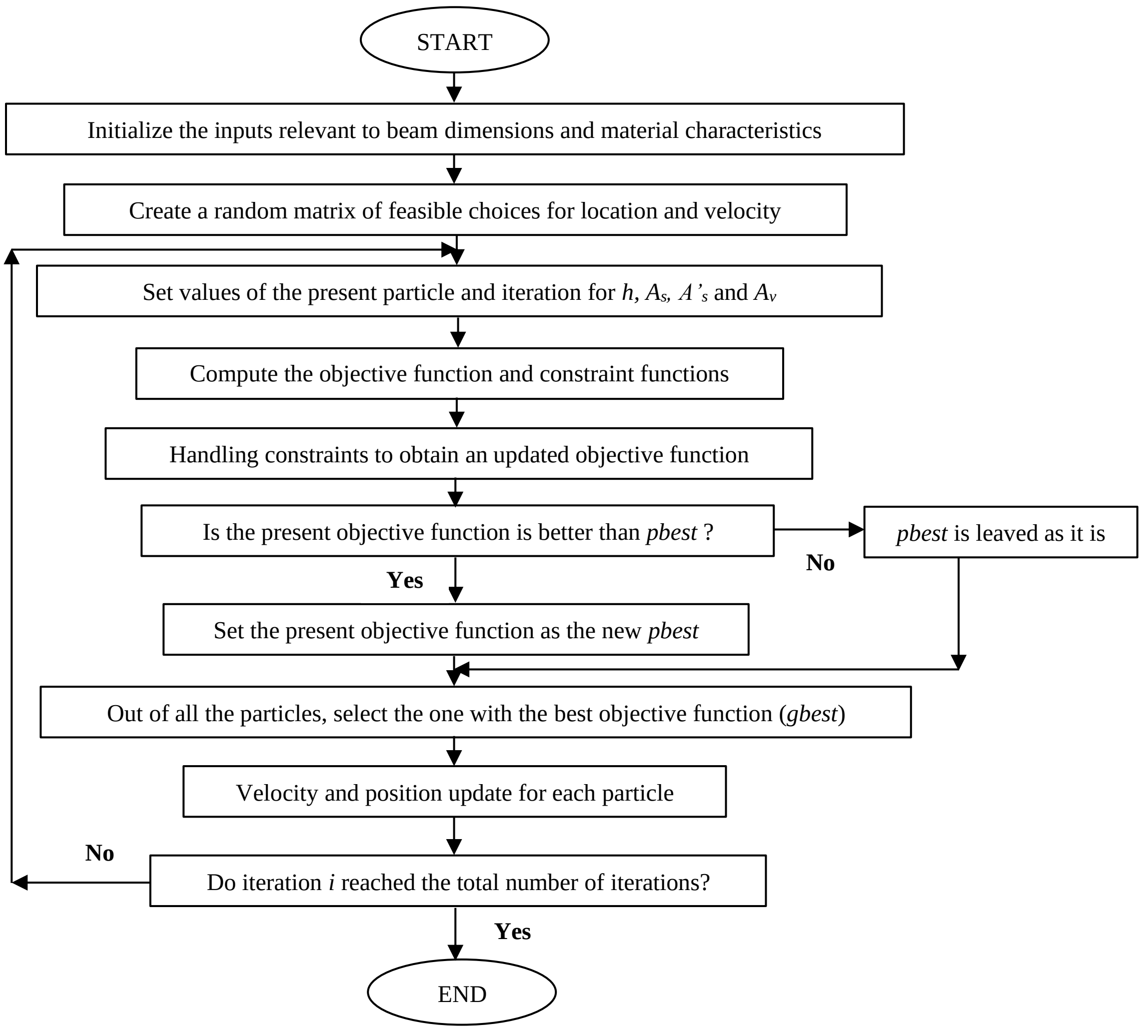



**Figure 3: Flowchart for the PSO algorithm**

## Handling Constraints

Constrained optimization problems are those in which the decision variables are subject to specific restrictions, as is the case with realistic optimization problems [21]. A comprehensive overview of several approaches for handling limitations is provided in [22]. The analyst turns to one or more issues with unconstrained optimization in place of the primary objective function with its restrictions in the majority of these techniques [23]. The search space can be split into areas or points that are feasible and those that are not in any given restricted optimization issue (infeasible). Every condition is satisfied at feasible sites, but at infeasible places, at least one constraint is broken. The so-called "Penalty Function" technique, first put forth by [24], is the most widely used method in this area. By adding or removing a value from the original objective function according to the violation degree of constraint in a particular solution, using this technique, an unconstrained penalized optimization problem is created from a restricted one. The outcomes acquired by employing dynamic penalty functions are consistently better in the literature than that obtained with static penalty functions [7, 25]. The "Self-Adaptive Penalty Function" is one of the most recent dynamic penalty functions, defined in [26, 27]. Using this technique, it is possible to compute an alternative penalized goal function for the impracticable individuals using the following equation:

$$F(\vec{x}) = d(\vec{x}) + p(\vec{x}) \tag{39}$$

where, for each individual, the distance and penalty values are denoted by $d(\vec{x})$ and $p(\vec{x})$, respectively. While the second part is the result of adding a two-part punishment function for the function of distance, the first part can be expressed in the normalized objective function terms and the normalized violation of constraint. In addition to precisely defining and formulating the beam design problem, this technique relies on constraints that are in line with the actual problem; otherwise, the solution may not be possible.

## Optimum Cost Design for Beams with Opening

The majority of literature recommendations and all regulations provide design standards for various concrete structures, including beams with opening, which address meeting numerous restrictions related to strength and serviceability. It is desirable to look for designs that result in the lowest possible structure cost among the countless design scenarios that could satisfy those requirements [28, 29]. The aim is to build a computer program that designs reinforced concrete beam with openings in accordance with the standard process described in the literature. This allows for the examination of multiple design states and the selection of the case that results in the lowest cost. But each time the program runs, it produces a unique and independent design state, ignoring important knowledge gleaned from past encounters. This process will undoubtedly be laborious and time-consuming as well. Because there is currently no such algorithm in the literature, it is more crucial than ever to build an algorithm to optimally design a cost-effective sections for the reinforced concrete beam with openings while taking standard strength and serviceability limitations into account. In this study, the current author takes on the task of creating this necessary method. The four decision variables (beam width $b$, area for longitudinal tension reinforcement $A_s$, area for longitudinal compression reinforcement $A'_s$, area for vertical shear reinforcement $A_v$) perform the problem's representation. The objective function is developed to compute the beam with openings cost, which is then optimized to obtain the design with minimal cost including reinforcements and section dimensions. At least four distinct cost elements should be taken into account during optimization in a reinforced concrete beam design: the concrete cost ($C_c$), the longitudinal (tension and compression) reinforcement cost ($C_s$), the shear reinforcement cost ($C_v$), and the framework cost ($C_f$). The cost of labor, materials, and transportation is implicitly included in each cost item. Now, we can calculate the beam total cost function ($C_T$), which is defined as follows:

$$C_T = C_c + C_s + C_v + C_f \tag{40}$$

The following formula can be used to get the concrete cost ($C_c$), calculated per unit beam:

$$C_c = (L\, b\, h - n\, l_o d_o b)\, C_c^1 \tag{41}$$

Where the length, height, width of the beam, and plain concrete cost specified per unit volume are denoted by: $L$, $h$, $b$, and $C_c^1$, respectively. $n$, $l_o$, and $d_o$ are number, length, and depth of opening, respectively. The cost of the main steel reinforcement, $C_s$, specified per beam is determined from the costs' sum of the main upper and lower reinforcements for the sold portion of the beam and for each chord, as follows:

$$C_s = \sum w_s\ L\, A_s\, C_s^1 + \sum w_s\ L\, A'_s\, C_s^1 \tag{42}$$

Where $C_s^1$, and $w_s$ are as per unit weight costs of main steel bars, and unit weight of main steel bars, respectively. The shear reinforcement (stirrups) is calculated in difference from main steel because it is relatively more expensive than the main reinforcement due to its higher labor cost working with the stirrups preparation. The stirrups cost, $C_v$, per beam is calculated from the sum of the costs developed from the stirrups of solid portion and of the chords, as follows:

$$C_v = \sum w_v\ L\, A_v\, C_v^1 \tag{43}$$

Where $C_v^1, and\ w_v$ are costs of stirrups per unit weight, and stirrups unit weight, respectively. The following formula can be used to get the framework cost $C_f$ per beam based on the framework cost $C_f^1$ per unit area. The framework cost specified per unit beam can be calculated according to the cost of framework determined by unit area by using:

$$C_f = C_f^1\ (L * (b + 2h) + n\, l_o d_o) \tag{44}$$

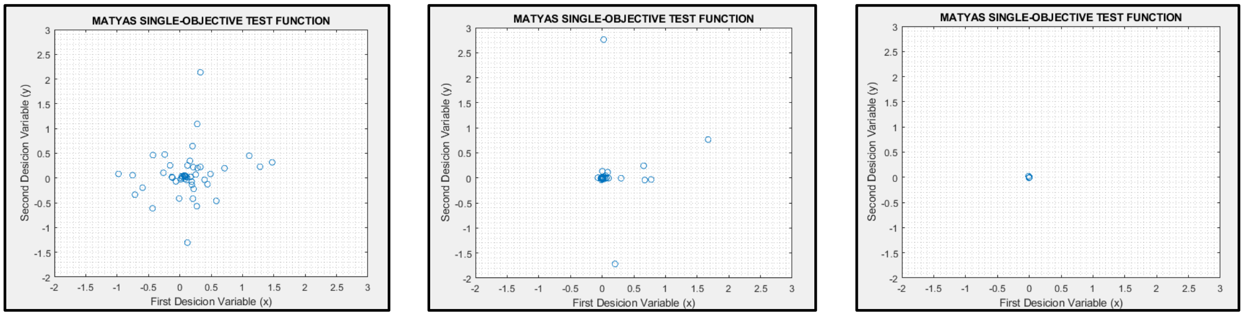
## Results and Discussion

### 1. Algorithm's Two-step Verification

The feature of convergence for the suggested approach is demonstrated, firstly, in a common famous optimization test problem called "Matyas Test Function" [30] to verify the accuracy and applicability of the suggested process and the associated MATLAB codes and functions. The objective function to be minimized in this test problem is:

$$F(x, y) = 0.26\ (x^2 + y^2) - 0.48\ x\ y \tag{45}$$

where the decision variables are $x$ and $y$. $F = 0$ is the typical minimized optimal solution for this test problem at $x = 0$ and $y = 0$. The present algorithm used an input particles data set of 50 running through 80 iterations to calculate the answer. Increasing convergence, shown in Fig. 4, illustrates an adequate agreement with the optimum solution found in the literature.




**a) At the 10th iteration** **b) At the 30th iteration** **c) At the 80th iteration**

**Figure 4: Particles iteratively search for the best answer for the "Matyas" test function**

The second step of verification is made though examining a rectangular simply supported beam with two concentrated and symmetrical factored loads with two openings [6], as shown in Fig. 5. Given that $f'_c$ = 52 MPa, $f_y$ = 400 MPa, and $f_{yv}$ = 240 MPa. The convergence of the 60 particle results calculated over 100 iterations, as presented in Table 1, shows how the current algorithm is reliable and adequate in locating the optimal design case that closely matches the non-optimized design results found in [6], with the calculated optimum vertical, horizontal, and diagonal reinforcement areas decreased by 10% to 15%. This indicates that the reinforced concrete beam with openings' optimum design may be determined in a practical way using the current algorithm of PSO and the written and verified MATLAB code.

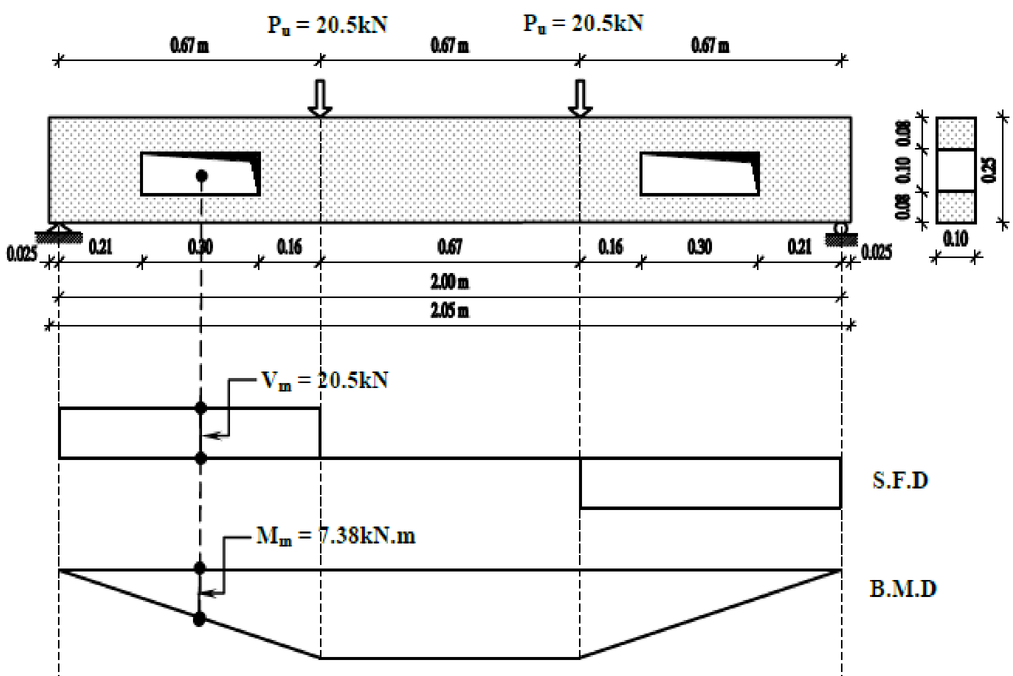



**Figure 5: Beam details and loading used for verification, (Group C) [6]**

**Table 1: Dimensions and results of the verification group C beam**

| *h* | *b* | *L* | Openings | | Result in [6] | | | Calculated Result | | | Difference (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| m | m | m | $l_o$ (m) | $d_o$ (m) | $A_s$ (mm$^2$) | $A_v$ (mm$^2$) | $A_d$ (mm$^2$) | $A_s$ (mm$^2$) | $A_v$ (mm$^2$) | $A_d$ (mm$^2$) | $A_s$ | $A_v$ | $A_d$ |
| 0.25 | 0.1 | 2.0 | 0.3 | 0.1 | 169.73 | 50.25 | 113.7 | 152.31 | 42.84 | 101.21 | 10 | 15 | 11 |

## 2. Beam with Opening Case Studies

This work develops MATLAB codes, verifies, and applies a PSO algorithm for designing reinforced concrete beams with opening. The technique is then used to four case studies with simply supported beams having the same center opening with the dimensions of ($l_o$ = 0. 5 and $d_o$ = 0.15) m. There are two groups of these optimized beams. Two beams, designated B1 and B2, comprise the first group. They share the identical loading circumstances and Table 2 data. Table 3 shows the concrete's compressive strength (*f 'c*) and the related concrete's cost as the comparison variables for these two beams. While B1 is built from *f 'c* having a value of 40 MPa, B2 is built from *f 'c* having a value of 25 MPa. With the same *f 'c* having a value of 25 MPa and the same details provided in Table 2, the two beams in the second group, B3 and B4, differ in the loading conditions that are applied. According to Table 3, the beam B3 has an ultimate uniformly distributed live load ($w_{LL}$) of 30 kN/m, whereas the beam B4 has an ultimate uniformly distributed live load of 30 kN/m and an ultimate concentrated live load ($P_u$) of 70 kN applied at its center. The dead weight of the tested beams is added through the design process. The four design variables (*h*, $A_s$, $A'_s$, and $A_v$) are optimized for all the four beams with opening and the overall cost function should be minimized while taking ACI code constraints, specifications, and limitations into account. For every beam case study, a total swarm size of 60 particles and 100 iterations are used.

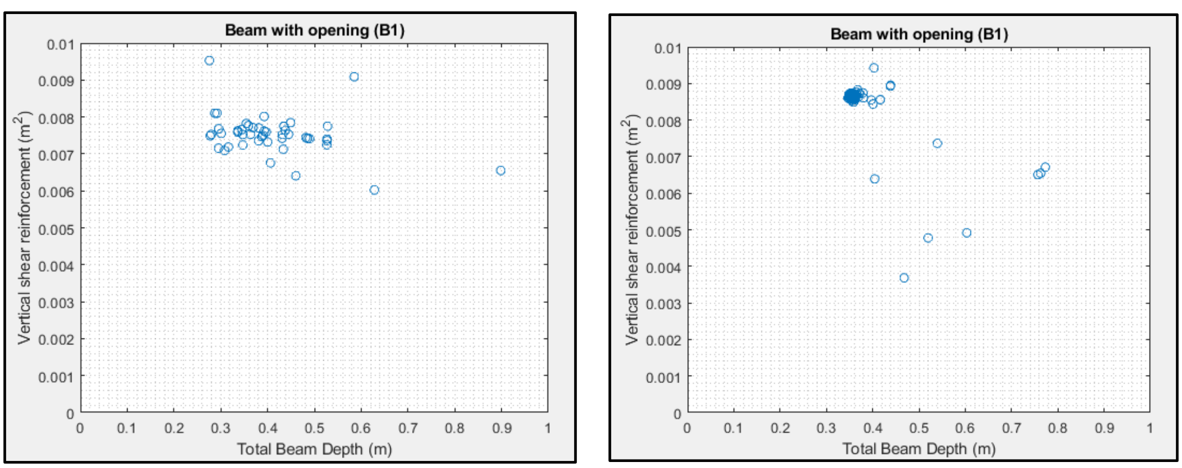
**Table 2: The four optimized beams with openings input parameters**

| Parameter | $C^1_s$ | $C^1_v$ | $C^1_f$ | $w_s$ | $w_v$ | $L$ | $b$ | $f_y$ | $f_{yv}$ |
|---|---|---|---|---|---|---|---|---|---|
| | \$/kg | \$/kg | \$/m$^2$ | kg/m$^3$ | kg/m$^3$ | m | m | MPa | MPa |
| Beams B1, B2, B3, and B4 | 1.6 | 2.0 | 30 | 7820 | 7820 | 4 | 0.3 | 520 | 450 |

**Table 3: The four optimized beams' variable parameters**

| Beam | $w_{LL}$ | $P_u$ | $f'_c$ | $C^1_c$ |
|---|---|---|---|---|
| | kN/m | kN | MPa | \$/m$^3$ |
| B1 | 0 | 0 | 40 | 100 |
| B2 | 0 | 0 | 25 | 80 |
| B3 | 30 | 0 | 25 | 80 |
| B4 | 30 | 70 | 25 | 80 |

For the developed approach, completing all iterations serves as a stopping criterion. In Fig. 6, the positions of those 60 particles are displayed for the two design variables (*h* against $A_v$) search space for beam B1 at two chosen iterations (30$^{th}$, and 80$^{th}$ iterations). This figure supports the established method by showing the progressive search of the swarm philosophy for the optimized objective function, which is done by minimizing the overall cost of the defined four beams with opening. Most of the competing swarm particles reach a stable and optimized answer after about 60-70 iterations. With a cost of about 722 US dollars at this point, beam B1 yields height *h* of 0.37 m and shear steel reinforcement area $A_v$ of 0.00866 m$^2$, as shown in Table 4.




**a) at 30$^{th}$ iteration** **b) at 80$^{th}$ iteration**

**Figure 6: Optimal values of (*h* and $A_v$) for beam B1 at two stages of iterations**

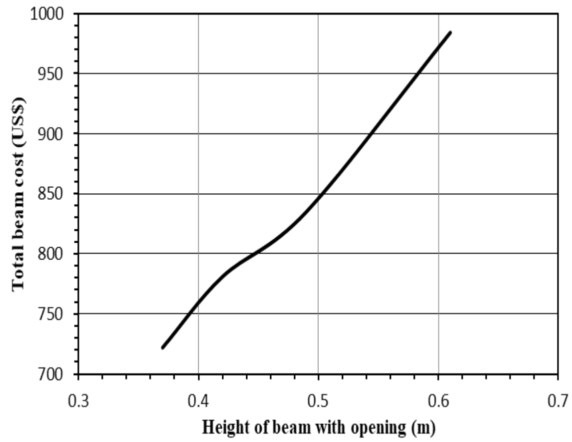
As indicated from the results presented in Table 4, beam B2 (with $f'_c$ of 40 MPa) produces an 8.2% increase in optimum cost (781 US dollars) compared with control beam B1 (722 US dollars) with $f'_c$ of 25 MPa. This increase in cost is represented in increasing $h$ by 13.5%, $A_s$ by 13.7%, $A'_s$ by 6.5%, and $A_v$ by 6.4%, compared to beam B1. This increase is cost is due to the decrease in concrete compressive strength (from 40 MPa to 25 MPa), which affects the beam shear and flexural strength. The compressive strength decrease is accompanied by increase in total beam height and different steel reinforcement amounts needed to perform safe and optimum cross section design. Applying additional sustained load, represented by a distributed live load of 30 kN/m, causes an optimum cost increase by 15.7% for beam B3 (835 US dollars), compared to beam B1. This increase in cost is represented in increasing $h$ by 32.4%, $A_s$ by 19.1%, $A'_s$ by 13.2%, and $A_v$ by 12.8%, compared to beam B1. The effect of loading is obvious through increasing the cost of beam B4 (984 US dollars) by 36.3%, compared to beam B1, when adding an additional concentrated sustained live load of 70 kN at the beam mid-span. This increase in cost is represented in increasing $h$ by 64.9%, $A_s$ by 22.3%, $A'_s$ by 18.1%, and $A_v$ by 20.3%, compared to beam B1. The loading conditions, thus, represents the most effective factor controlling the optimum cost design of such beams with opening.

**Table 4: Optimized cost and their related design variables concerning the four beams with opening**

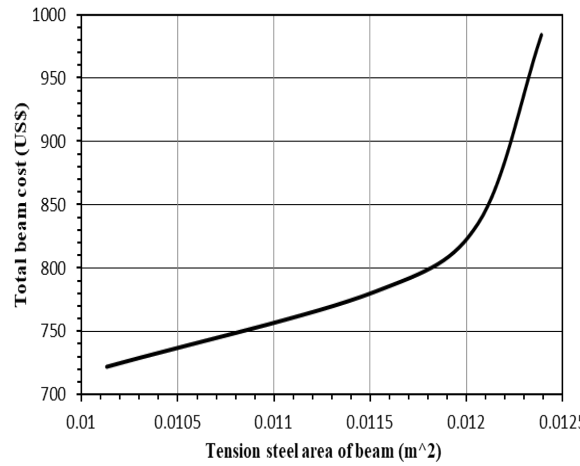
| Beam | Optimum cost | Increase in cost | $h$ | Increase in $h$ | $A_s$ | Increase in $A_s$ | $A'_s$ | Increase in $A'_s$ | $A_v$ | Increase in $A_v$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | US$ | % | m | % | $m^2$ | % | $m^2$ | % | $m^2$ | % |
| B1* | 722 | - | 0.37 | - | 0.01013 | - | 0.00785 | - | 0.00866 | - |
| B2 | 781 | 8.2 | 0.42 | 13.5 | 0.01152 | 13.7 | 0.00836 | 6.5 | 0.00921 | 6.4 |
| B3 | 835 | 15.7 | 0.49 | 32.4 | 0.01206 | 19.1 | 0.00889 | 13.2 | 0.00977 | 12.8 |
| B4 | 984 | 36.3 | 0.61 | 64.9 | 0.01239 | 22.3 | 0.00927 | 18.1 | 0.01042 | 20.3 |

* Control beam

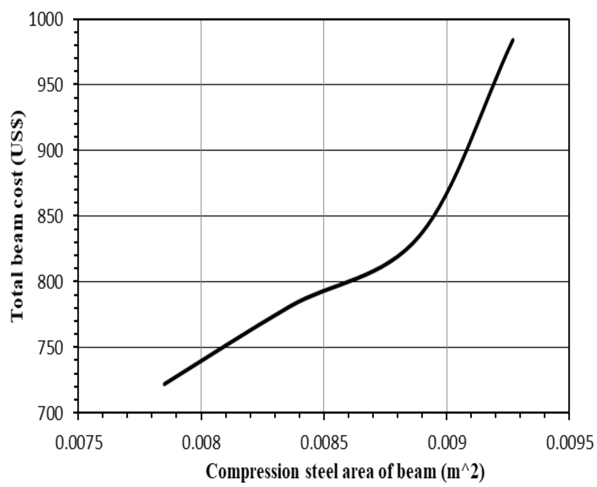
Among the four decisions variables ($h$, $A_s$, $A'_s$, and $A_v$), it may be noticed that the algorithm prefers to increase the total beam depth $h$, when increasing loading or even decreasing concrete compressive strength, rather than increasing the steel reinforcement amount. This behavior is, certainly, due to the high cost of reinforcing steel, which is clear in the limited and restricted increase in shear reinforcement which is assigned to be the most expensive reinforcement type due to its relatively higher labor cost. The relations between the cost of the tested beams with opening and with the beams' four design variables ($h$, $A_s$, $A'_s$, and $A_v$) are presented through Fig. 7. The cost of the four beams show an increasing response and is directly proportional to the amount of the four design variables, especially the beam height $h$. Among the four relations drawn, the curve shown in Fig. 7a, relating the beam cost to beam height $h$, indicate that the increase in beam height $h$ produces, mostly, slight-linear increase in beam's cost. This slight-linear behavior describes well the relation between beam's cost and its related height, in which that as we increase the beam height $h$ we may get, in most of the time, a linear increase in its cost. The other three behaviors, concerned with the relation between beam cost and the other design variables ($A_s$, $A'_s$, and $A_v$), are almost nonlinear and showing that the maximum increasing rate of cost is for beam B4, which has a load pattern represented by the distributed and concentrated live loads. This finding, which is obvious at the behavior drawn of each of the four curves at the portion concerned with B4 (at the final stage of each curve), means that the loading pattern, as mentioned previously, has the most significant impact on the beam's cost. This may be attributed to the relatively small identical beam length, taken as 4 m for all the four tested beams, which makes the beam is more susceptible to loading increase, especially when applying a relatively high shear force represented by the applied ultimate concentrated live load $P_u$ = 70 kN at the center of beam B4. This susceptibility is reflected to the beam with opening cost as a final step in the design calculations.



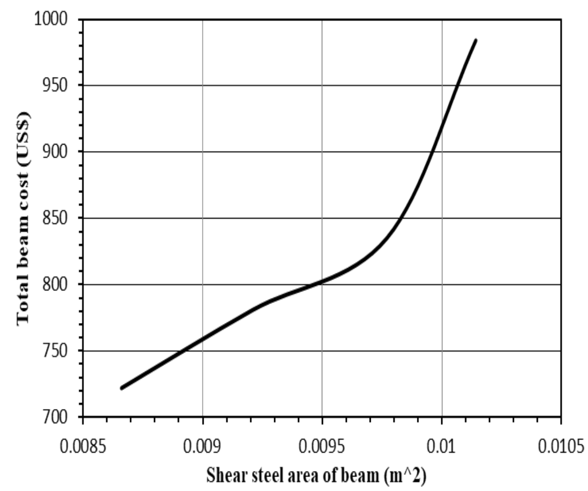

**a) Total cost vs height of beam (*h*)**




**b) Total cost vs tension steel area ($A_s$)**




**c) Total cost vs compression steel area ($A'_s$)**




**d) Total cost vs shear steel area ($A_v$)**

**Figure 7: Relation between Beam's Cost and the Four Design Variables (*h*, $A_s$, $A'_s$, $A_v$)**

## Conclusions and Recommendations

The current work presents a PSO algorithm with four decision variables for designing affordable optimum reinforced concrete beams with openings that meet all serviceability and safety requirements. The approach is developed using a MATLAB code. The findings from the two verifications and the case studies for the four beams show that the process can do well in optimizing cost designs for beams with opening. An analysis is conducted to compare the expenses of two distinct concrete compressive strengths. To demonstrate the impact of such parameters on the optimal total beam cost function, a second comparison analysis is conducted for two distinct live load scenarios. The cost of beams with openings is shown to be significantly impacted by the loading condition. Future research is advised to include modern strengthening strategies for beams with openings, optimize deep beams with openings, apply a strut and tie model to the design of beams with openings, and extend this work to a PSO algorithm with multi-objective functions.

## References

ASCE-ACI Committee 445 on Shear and Torsion. (1998). Recent approaches to shear design of structural concrete. *Journal of structural engineering*, *124*(12), 1375-1417.

Saka, M.P., Hasançebi, O.Ğ.U.Z.H.A.N., & Geem, Z.W. (2016). Metaheuristics in structural optimization and discussions on harmony search algorithm. *Swarm and Evolutionary Computation*, *28*, 88-97.

Lagaros, N.D. (2014). A general purpose real-world structural design optimization computing platform. *Structural and Multidisciplinary Optimization*, *49(6),* 1047-1066.

Sarma, K.C., & Adeli, H. (1998). Cost optimization of concrete structures. *Journal of structural engineering*, *124*(5), 570-578.

Sweeney, G., & Salawdeh, S. (2020). Design of Reinforced Concrete Beams with Web Openings, Civil Engineering Research in Ireland, CERI 2020, Cork, Ireland.

El-Demerdash, W.E. (2014). Design of Reinforced Concrete Beams With Openings, M.Sc thesis, El-Mansoura university, Egypt.

Rani, B., & Kumar, C. (2015). A comprehensive review on bacteria foraging optimization technique, In: Dehuri S., Jagadev A., Panda M. (eds), Multi-objective Swarm Intelligence, Theoretical Advances and Applications, Studies in Computational Intelligence, Springer, Berlin, Heidelberg, *592*(1).

ACI Code 318-19, Building Code Requirements for Structural Concrete and Commentary, Reapproved 2022.

Innocente, S., Torres, L., Cahis, X., Barbeta, G., & Catalan, A. (2007). Optimal flexural design of FRP-reinforced concrete beams using a particle swarm optimizer, FRPRCS-8 Conference, University of Patras, Greece.

Hasan, Q.F., Al-Mamany, D.A., & Fayadh, O.K. (2019). Design of reinforced concrete deep beams using particle swarm optimization technique. *Karbala International Journal of Modern Science*, *5*(4), 7. https://doi.org/10.33640/2405-609X.1180.

Quaranta, G., Fiore, A., & Marano, G.C. (2014). Optimum design of prestressed concrete beams using constrained differential evolution algorithm. *Structural and Multidisciplinary Optimization*, *49*(3), 441-453.

Kaveh, A., & Malakoutirad, S. (2010). Hybrid genetic algorithm and particle swarm optimization for the force method-based simultaneous analysis and design. *Iranian Journal of Science and Technology, Transaction B: Engineering, 34*(B1), 15-34.

Mansur, M.A., Huang, L.M., Tan, K.H., & Lee, S.L. (1992). Deflections of reinforced concrete beams with web openings. *Structural Journal*, *89*(4), 391-397.

British Standard Institution (BS 8110-3), Structural Use of Concrete: Part 1, London, 2003.

Nasser, K.W., Acavalos, A., & Daniel, H.R. (1967). Behavior and design of large openings in reinforced concrete beams. *In Journal Proceedings*, *64*(1), 25-33.

Barney, G.B., Corley, W.G., Hanson, J.M., & Parmelee, R.A. (1977). Behavior and design of prestressed concrete beams with large web openings. *PCI Journal*, *22*(6), 32-61.

Mansur, M. (1983). Combined bending and torsion in reinforced concrete beams with rectangular openings. *Concrete International*, *5*(11), 51-58.

Tan, K.H., Mansur, M.A., & Huang, L.M. (1996). Reinforced concrete T-beams with large web openings in positive and negative moment regions. *Structural Journal*, *93*(3), 277-289.

Mansur, M.A., Tan, K.H., & Lee, S.L. (1985). Design method for reinforced concrete beams with large openings. In *Journal Proceedings*, *82*(4), 517-524.

Eberhart, R., & Kennedy, J. (1995). A new optimizer using particle swarm theory. *In MHS'95. Proceedings of the sixth international symposium on micro machine and human science*, 39-43.

Michalewicz, Z., & Schoenauer, M., (1996). Evolutionary algorithms for constrained parameter optimization problems. *Journal of Evolutionary Computation*, *4*(1), 1-32.

Coello, C.A.C. (2002). Theoretical and numerical constraint-handling techniques used with evolutionary algorithms: a survey of the state of the art. *Computer methods in applied mechanics and engineering*, *191*(11-12), 1245-1287.

Saleh, I.K., Özkaya, U., & Hasan, Q.F. (2018). Improving multiobjective particle swarm optimization method. In *New Trends in Information and Communications Technology Applications: Third International Conference, NTICT 2018, Baghdad, Iraq, October 2–4, 2018, Proceedings,* Springer International Publishing, 143-156.

Courant, R. (1943). Variational methods for the solution of problems of equilibrium and vibration. *Bulletin of the American Mathematical Society, 49*, 1-23.

Joines, J.A., & Houck, C.R. (1994). On the use of non-stationary penalty functions to solve nonlinear constrained optimization problems with GA's. *In Proceedings of the first IEEE conference on evolutionary computation. IEEE world congress on computational intelligence*, 579-584.

Berhe, H.W. (2012). Penalty function methods using matrix laboratory (MATLAB). *African Journal of Mathematics and Computer Science Research*, *5*(13), 209-246.

Wang, D., & Du, G. (2014). A self adaptive penalty function based genetic algorithm for value-bilevel programming problem. *International Journal on Computer Science and Engineering*, *3*(2), 136-146.

Kaveh, A., & Shakouri, M.A.A. (2011). Cost optimization of reinforced concrete one-way ribbed slabs using harmony search algorithm. *Arabian Journal for science and engineering*, *36*(7), 1179-1187.

Alankar, K.S., & Chaudhary, (2012). Cost optimization of composite beams using genetic algorithm and artificial neural network. *International Conference on Computer Technology and Science (ICCTS 2012)*.

Jamil, M., & Yang, X.S. (2013). A literature survey of benchmark functions for global optimisation problems. *International Journal of Mathematical Modelling and Numerical Optimisation*, *4*(2), 150-194.