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Design Optimization of Reinforced Concrete Slabs using Various Optimization Techniques

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ABSTRACT

This paper presents Reinforced Concrete (RC) slab design optimization technique for finding the best design parameters that satisfy the project requirements both in terms of strength and serviceability criteria while keeping the overall construction cost to a minimum. In this paper four different types of RC slab design named as simply supported slab, one end continuous slab, both end continuous slab and cantilever slab are optimized using three different metaheuristic optimization algorithms named as Genetic Algorithms (GA), Particle Swarm Optimization (PSO) and Gray Wolf Optimization (GWO). The slabs with various end conditions are formulated according to the ACI code. The formulated problem contains three optimization variables, the thickness of the slab, steel bar diameter, and bar spacing while objective involves the minimization of overall cost of the structure which includes the cost of concrete, cost of reinforcement and the constraints involves the design requirement and ACI codes limit. The proposed method is developed using MATLAB. Finally, to validate the performance of the proposed algorithm the results are compared with the previously proposed algorithms. The comparison of results shows that the proposed method provides a significant improvement over the previously proposed algorithms.

KEYWORDS: *RC Slab Design Optimization, Structural Optimization, Structure Cost Reduction, GA, PSO, GWO*

1. INTRODUCTION

A reinforced concrete slab is a key structural component and is used in houses to provide flat surfaces (floors and ceilings). Concrete slabs are effective systems where putting columns interrupts the structure's (Audiences, parking lots, hotels, airports, etc.) serviceability to cover the lengthy spans. In recent past, metaheuristic optimization algorithms have been applied to many structural problems, and RC slabs are no exception as a result a number of articles on RC slabs optimization have been published. However, to find extensive use among practicing engineering, structural optimization algorithms need to be formulated as cost optimization and applied to realistic constructions that are subject to the real constraints of frequently used design codes such as the American Concrete Institute Code (ACI, 1999).

In this paper the slabs with various end conditions are formulated according to the ACI code. The formulated problem contains three optimization variables, the thickness of the slab, steel bar diameter, and bar spacing while objective involves the minimization of overall cost of the structure which includes the cost of concrete, cost of reinforcement and the constraints involve the design requirement and ACI codes limit.

In the presented work the metaheuristic optimization approach is utilized instead of deterministic optimization approach because the addressed optimization problem is highly nonlinear and multimodal and contains various complex constraints. In such cases sometimes, optimal solutions may not exist at all. In most practical design problems, finding an optimal solution or even sub-optimal solutions is a difficult task. Furthermore, the metaheuristic approaches involve lesser computational complexity than deterministic approaches.

The rest of the paper is arranged as the section II presents a brief literature review, in section III the mathematical modeling of different types of slabs are discussed, section IV provides a brief overview of metaheuristic algorithms used, section V presents the simulation results, and finally section VI presents the conclusions.

2. Literature Review

K. C. Sharma et. al. [1], presented a review on cost optimization of concrete structures. These structures include beams, slabs, columns, frame structures, bridges, tanks of water, folded plates, shear walls, pipes and tensile components. It summarizes interesting and important outcomes and conclusions. The paper also includes a review of cost optimization based on reliability. The results of such research will be of great value to engineering practitioners. S.M.R. Tabatabai et. al. [2], introduced a system for optimal reinforcement design and non-linear reinforced concrete structure analysis. The specially tailored ORCHID (Optimum Reinforced Concrete Highly Interactive Dimensioning) program is used for the design and optimization of reinforcement. F. Ahmadkhanlou et. al. [3], presents a general formula for cost optimization of single-and multi-span RC slabs with different end conditions (simply supported, one end continuous, both end continuous and cantilever) subject to all ACI code constraints. M.G. Sahaba et. al. [4], presents the cost of optimizing reinforced concrete flat slab buildings under the British Code of Practice (BS8110). The objective function is the building's total cost including floor, column and foundation costs. The cost of each structural element is that of reinforcement, concrete and shaping material and labor. A genetic algorithm is used for a global search in this hybrid algorithm, followed by a discrete form of the method Hook and Jeeves. B.A. Nedushan et. al. [5], This article deals with cost optimization of single-way concrete slabs in accordance with the latest American Code of Practice (ACI 318-M08). The goal is to minimize the slab's total cost including concrete and reinforcement bar costs while meeting all design requirements. Particle Swarm Optimization (PSO) is used to solve the restricted problem of optimization. As PSO is designed for unconstrained problems of optimization, a multi-stage dynamic penalty was also implemented to solve the constrained problem of optimization. A. Kaveh et. al. [6], The cost optimization of a single-way reinforced concrete floor system consisting of a hollow slab is presented in this article. The system cost is considered the objective function and the design is based on the ACI 318-05 standard of the American Concrete Institute. This function is minimized using the harmony search algorithm, subject to design constraints. A. Kaveh et. al. [7], a new modified particle swarm optimization algorithm (PSO) is used in this paper to optimize the design of large-scale pre-stressed concrete slabs. The modification is accomplished by adding some probabilistic coefficients to particle velocity and is called probabilistic swarm optimization of particles (PPSO). These coefficients provide the algorithm with simultaneous exploration and exploitation and decrease PSO's dependence on its constants. A. H. Gandomi et. al. [8], a new metaheuristic optimization algorithm called cuckoo search (CS) for solving structural optimization tasks is introduced in this study. Combined with Le'vy flights, the new CS algorithm is first verified using a nonlinear benchmark restricted optimization issue. CS is subsequently applied to 13 design problems reported in the specialized literature to validate against structural engineering optimization problems. The CS algorithm's performance is further compared with different algorithms that represent the state of the art in the area. For the most part, the optimal solutions obtained by CS are far better than the best solutions obtained through existing methods. A. Akin et. al. [9], This paper presents the application of the harmony-based search algorithm to the optimal detailed design of special seismic moment reinforced concrete (RC) frames under earthquake loads based on American Standard specifications. The objective function is selected as the total frame cost that includes the concrete, formwork and reinforcing steel costs for individual frame members. M. Aldwaik et. al. [10], a model for cost optimization of reinforced concrete (RC) flat slabs of arbitrary configuration in irregular high-rise construction structures is presented in this article. The model is general and can include any combination with or without openings and perimeter beams of columns and shear walls in the plane. For flat slabs of arbitrary configurations, a general cost function is formulated taking into consideration not only the cost of concrete and steel materials but also the cost of construction. Using Adeli and Park's robust neural dynamics model, the nonlinear cost optimization problem is solved. The methodology has been applied in a real-life 36-story building structure to two flat slab examples. Not only does the methodology automate the RC slab design process, it also results in cost savings of 6.7–9 %.

3. Model Formulation

This section presents the mathematical modeling of slab designs and formulation of the objective functions.

3.1. One-way reinforced concrete slabs

3.1.1. Objective function

A total cost function can be written as follows:

$$C_t = C_c + C_r + C_f, \#(1)$$

Where C_c, C_r and C_f are, respectively, the costs of concrete, reinforcing bars and formwork and finishing materials. For any given location, the cost of formwork does not vary significantly and can therefore be dropped from formulation (Ahmadkhanlou and Adeli [3]). The definition is as follows:

$$C_c = LbhC_c^1, \#(2)$$

$$C_r = w_s L A_s C_r^1 \#(3)$$

Where L, b, h, C_c^1, w_s, A_s, and C_r^1 are the span length, span width, slab thickness (Fig. 1), concrete cost per unit volume, unit weight per unit volume of steel, cross section area of reinforcement bars, and reinforcement bar cost per unit weight, respectively. The calculation of quantity A_s is as follows:

$$A_s = \frac{\pi d_b^2}{4}\left(\frac{b}{s}\right), \#(4)$$

Where d_b and s are the reinforcement bar diameter and spacing, respectively.

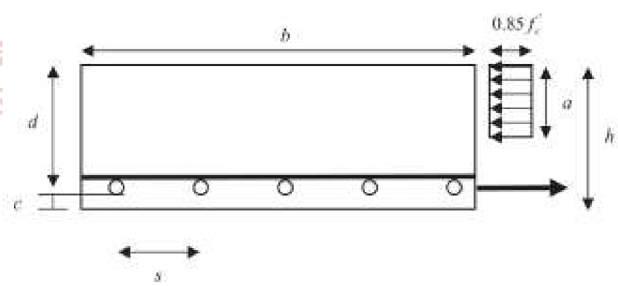

Figure 1: Typical cross-section of RC slab.

3.1.2. Design constraints

As mentioned earlier, cost function optimization is based on the limitations defined by ACI 1999 code [29]. The constraints included flexural constraint, shear constraint, limitation of serviceability, and limitation of deflection. As stated below, they are defined and expressed in a normalized form.

FLEXURAL CONSTRAINT

Nominal flexural strength, ΦM_n, should be greater than the ultimate design moment, M_u;

$$g_1(x) = \frac{M_u}{\phi M_n} - 1 \leq 0, \Phi = 0.9, \#(5)$$

In Eq. (4.5), M_u is calculated as follows:

$$M_u = kwl_n^2, \#(6)$$

Where l_n and k are the clear span length and the moment coefficient for the continuous slab depending on the slab support type, respectively. Table 1 shows the values of k. In Eq. (4.6) the maximum moment coefficient value given in Table 2 for four different support conditions (simply supported, continuous at one end and simply supported at the other end, continuous at both ends and cantilever). In Eq. (4.6), w is a uniformly distributed charge factored. The Ahmadkhanlou and Adeli article [8] considered loading cases as suggested by the 1999 code of the ACI [30]:

$$w = 1.4 \times (DL \times b \times DL_s) + 1.7 \times LL \times b, \#(7)$$

Where DL, LL, and DL_s are dead floor loads excluding slab self-weight, live load, and slab self-weight. The calculation of DL_s as follows:

$$DL_s - (bh - A_s)w_c + A_s w_s, \#(8)$$

where W_c is the weight of the concrete per unit volume.

Table 1: Moment coefficient for continuous slabs

Exterior Span		
Support	Middle	Support
$-\frac{1}{24}$	$+\frac{1}{14}$	$-\frac{1}{10}$
Interior Span		
Support	Middle	Support
$-\frac{1}{11}$	$+\frac{1}{16}$	$-\frac{1}{11}$

Table 2: Maximum moment coefficient, k, used for design of RC slabs.

Simply Supported	One End Continuous	Both End Continuous	Cantilever
$\frac{1}{8}$	$\frac{1}{10}$	$\frac{1}{11}$	$\frac{1}{2}$

The nominal bending moment, M_n, is calculated as follows: Where f_y is the specified yield strength of the reinforcement bars and the corresponding depth of the concrete compressive stress block from which it is calculated (Fig. 1).

$$a = \frac{A_s f_y}{0.85 f_c' b}, \#(9)$$

where f_c is the specified compressive strength of concrete.

SHEAR CONSTRAINT

The nominal concrete shear strength, ΦV_n, should be greater than the ultimate factored shear strength, V_u;

$$g_2(x) = \frac{V_u}{\Phi V_n} - 1 \le 0, \Phi = 0.85, \#(10)$$

The ultimate factored shear force is defined as follows:

$$V_u = k_v \frac{wl_n}{2}, \#(11)$$

where k_v is the shear coefficient for continuous slab that depends on the type of slab supports. The values of k_v are given in Table 3. The nominal shear strength of concrete is defined as follows:

$$V_c = 2\sqrt{f_c'}bd, \#(12)$$

Table 3: Shear coefficient for continuous slabs.

Simply Supported	One end Continuous	Both ends Continuous	Cantilever
1	1.15	1	2

SERVICEABILITY CONSTRAINT

The percentage in one-way RC slabs of longitudinal reinforcement steel, ρ, and bar spacing, s, should be between minimum and maximum limits permitted by the design specification.

$$g_3(x) = \frac{\rho}{\rho_{max}} - 1 \le 0, \#(13)$$

$$g_4(x) = \frac{\rho_{min}}{\rho} - 1 \le 0, \#(14)$$

$$g_5(x) = \frac{s_{min}}{s} - 1 \le 0, \#(15)$$

$$g_6(x) = \frac{s}{s_{max}} - 1 \le 0, \#(16)$$

where the ρ_{max} is given by:

$$\rho_{max} = 0.75\rho_b, \#(17)$$

ρ_b is defined as follows:

$$\rho_b = 0.85\beta_1 \frac{f_c'}{f_y}\left(\frac{87000}{87000 + f_y}\right), \#(18)$$

$$in\ S.I.\ units, \rho_b = 0.85\beta_1 \frac{f_c'}{f_y}\left(\frac{600}{600 + f_y}\right),$$

$$where\ f_c'\ and\ f_y\ are\ in\ MPa \#(18a)$$

and β_1 is calculated from

$$for\ f_c' \le 4000psi, \beta_1 = 0.85,$$

$$\beta_1 = \begin{cases} 0.85 & for\ f_c' \le 4000psi \\ 0.85 - 0.05\left(\frac{f_c' - 4000}{1000}\right) \ge 0.65 & for\ f_c' > 4000psi \end{cases} \#\#\#(19)$$

$$in\ S.I.\ units, for\ f_c' \le 27.58MPa, \beta_1 = 0.85,$$

$$\beta_1 = \begin{cases} 0.85 & for\ f_c' \le 27.58MPa \\ 0.85 - 0.05\left(\frac{f_c' - 27.58}{6.895}\right) \ge 0.65 & for\ f_c' > 27.58MPa \end{cases} \#\#\#(19a)$$

The minimum area of flexural reinforcement longitudinal) is selected as follows:

$$A_{s\,min} = \begin{cases} 0.0020bh, & for\ steel\ grade\ 40\ and\ 50 \\ 0.0018bh, & for\ steel\ grades\ 60 \end{cases} \#(20)$$

and the minimum and maximum bar spacing are defined as follows:

$$S_{min} = \max(1", d_b), \#(21)$$

$$in\ S.I. units, \quad S_{min} = \max(25.4mm, d_b), \#(21a)$$

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$$S_{max} = \min(18", 3h), \#(22)$$

$$in\ S.I.units, \quad S_{max} = \min(457.2mm, 3h), \#(22a)$$

DEFLECTION CONSTRAINTS

Slab thickness, h, shall not be less than the minimum slab thickness, h_{min};

$$g_7(x) = \frac{h_{min}}{h} - 1 \leq 0, \#(23)$$

Where h_{min} has a minimum thickness of 1.5 in (38.1 mm) in Table 4. Table 4 values apply to normal concrete weight and $f_y = 413.7MPa\ (60{,}000\ psi)$. For f_y other than $413.7MPa\ (60{,}000\ psi)$, α_1 (specified in Eq. (24)) multiplies the values. For lightweight concrete with w_c between $14.14\ kN/m^3\ (90lb/ft^3)$ and $18.06\ kN/m^3\ (115lb/ft^3)$, the values must be multiplied by α_2 (as set out in Eq. (25)).

$$\alpha_1 = 0.4 + \frac{f_y}{100{,}000}, \#(24)$$

$$in\ S.I.units, \quad \alpha_1 = 0.4 + \frac{f_y}{689.5},$$
$$where\ f_y\ in\ MPa\#(24a)$$

$$\alpha_2 = \max(1.65 - 0.005w_c, 1.09), \#(25)$$

Table4: Minimum thickness for solid one-way slab according to ACI code

Simply Supported	One end continuous	Both ends continuous	Cantilever
$\frac{L}{20}$	$\frac{L}{24}$	$\frac{L}{28}$	$\frac{L}{10}$

3.1.3. Design variables

Single-way RC concrete slab design variables consist of three variables: slab thickness (h), reinforcement bar diameter (d_b), and reinforcement bar spacing (s). Slab thickness and reinforcement spacing can be considered as integer variables, such as multiples of 5mm and 10mm respectively in the SI system, or multiples of $1/8"$ or $1/4"$ in the usual US system. Since it is necessary to assign the diameter of the reinforcement bars from limited numbers, it must be considered as a discrete variable. ACI supplies eleven different bar sizes with a diameter of $0.375"(9.53\ mm)$ from bar size $\#3$ to bar size $\#18$ with a diameter of $2.257"$ $(57.33\ mm)$.

3.2. Reinforced concrete flat slabs

3.2.1. Design constraints

This paper analyzes the concrete flat slabs by Direct Design Method based on [29]. For using direct design method, ACI presents six limitations;

1. In each direction, there have to be at least three continuous spans.
2. Successive span lengths (center-to-center supports) must not differ by more than one-third of the longer span in each direction.
3. The panels must be rectangular, with the ratio of panel dimensions longer to shorter, the center-to-center of supports measured, and not exceed 2.
4. Column offset in the direction of offset from either axis between centerlines of successive columns shall not exceed 10 percent of the span.
5. All loads shall be distributed uniformly over a whole panel due to gravity only. 6. Unfactored live load shall not exceed the unfactored dead load twice.
6. Unfactored live load shall not exceed the unfactored dead load twice.

These constraints include flexural restrictions, one-way shear constraints, two-way shear constraints, serviceability constraints, and deflection constraints. The limitations are explained below and expressed in a standardized form.

FLEXURAL CONSTRAINT

The design moments are distributed across each panel in the direct design method. As shown in Fig 2, the panels are divided into columns and middle strips. In each strip, positive and negative moments are achieved. The column strip is a slab with a width on each side of the centerline of the column.

$$b_c = \min\left(\frac{l_1}{4}, \frac{l_2}{4}\right), \#(26)$$

$$b_m = l_2 - 2 \times b_c, \#(27)$$

where b_c and b_m are the width of half column strip and middle strip, respectively.

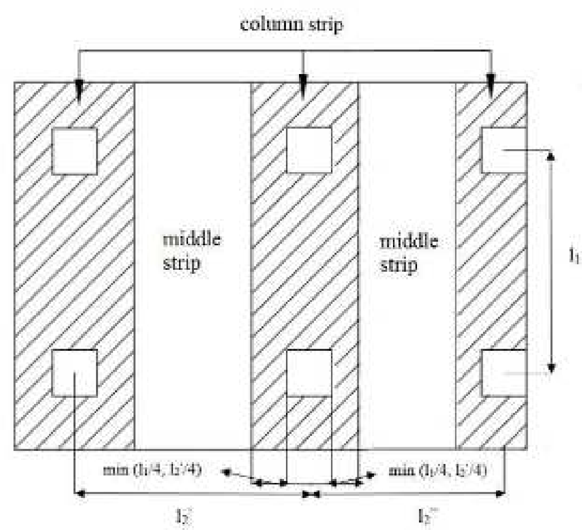

Figure 2: Middle and Columns Strips.

Positive nominal bending strength at the middle and negative nominal bending strength at both ends of the column strip and middle strip, ΦM_n, should be greater than the ultimate design moment in column strips (column) and middle strips (mid) at those ends, M_u;

$$g_{1\,col}(x) = \frac{M_{ul}^-}{\Phi M_n^-} - 1 \leq 0, \#(28)$$

$$g_{2\,col} = \frac{M_u^+}{\Phi M_n^+} - 1 \leq 0, \#(29)$$

$$g_{3\,col}(x) = \frac{M_{ur}^-}{\Phi M_n^-} - 1 \leq 0, \#(30)$$

$$g_{4\,mid}(x) = \frac{M_{ul}^-}{\Phi M_n^-} - 1 \leq 0, \#(31)$$

$$g_{5\,mid}(x) = \frac{M_u^+}{\Phi M_n^-} - 1 \leq 0, \#(32)$$

$$g_{6\,mid}(x) = \frac{M_{ur}^-}{\Phi M_n^-} - 1 \leq 0, \#(33)$$

In Eqs. (4.28-4.33), $\Phi = 0.9$, and M_u is calculated as follows:

$$M_{u\,cs} = k_\alpha k_m M_o, \#(34)$$

$$M_{u\,ms} = (1 - k_\alpha) k_m M_o, \#(35)$$

Where k_m is the distribution of the total span moment coefficient for four different span conditions (inner span, outer edge unrestrained, outer edge fully restrained, slab without beam between inner support and edge beam) and k is the portion of the negative inner moment, the negative outer moment, and the positive moment resisted by the column strip. The values of k_m and k_α are respectively expressed in Table 5. and Table 6. M_o is the total static factor for a span defined as:

$$M_o = \frac{w_u l_2 l_n^2}{8}, \#(36)$$

Where ln is the clear range of supports in the direction of considered moments, the face-to-face measurement of the supports is not less than $0.65 l_1$, and the factored uniformly distributed load is defined as:

$$w_u = 1.2 \times (DL + w_{Rc} h) + 1.6 \times LL, \#(37)$$

Where w_{Rc} is the reinforced concrete density and h the slab thickness.

Table5: Distribution of total span moment, k_m.

	Exterior edge Unrestrained	Slab without beam between interior support and edge beam	Exterior edge fully restrained	Interior span
Interior negative factored moment	0.75	0.70	0.65	0.65
Positive factored moment	0.63	0.52	0.35	0.35
Exterior negative factored moment	0	0.26	0.65	0.65

Table 6: Portion of interior negative moment, exterior negative moment, and positive moment resisted by column strip, k_α

	$\frac{l_2}{l_1}$		
	0.5	1	2
Interior negative moment	0.75	0.75	0.75
Exterior negative moment	1	1	1
Positive moment	0.6	0.6	0.6

The nominal bending moment, M_n, is defined as follows:

$$M_{n\,col} = A_{s\,cs} f_y \left(d - \frac{a}{2}\right), \#(38)$$

$$M_{n\,mid} = A_{s\,ms} f_y \left(d - \frac{a}{2}\right), \#(39)$$

Where a is the corresponding depth of the concrete compressive stress block calculated as follows:

$$a_{col} = \frac{A_{s\,col} f_y}{0.85 f_c' \times 2b_c}, \#(40)$$

$$a_{mid} = \frac{A_{s\,mid} f_y}{0.85 f_c' b_m}, \#(41)$$

the quantity of A_s is calculated by;

$$A_{s\,col} = \frac{\pi d_b^2}{4}\left(\frac{2b_c}{s} + 1\right), \#(42)$$

$$A_{s\,mid} = \frac{\pi d_b^2}{4}\left(\frac{b_m}{s} + 1\right), \#(43)$$

In effective slab width, a fraction of factored slab moment resisted by the column, $\gamma_f M_{sc}$ should be less than the nominal flexural strength, ΦM_n;

$$g_7(x) = \frac{\gamma_f M_{sc}}{\Phi M_n} - 1 \leq 0, \Phi = 0.9, \#(44)$$

The effective slab width shall be the width of column plus $1.5h$ of slab. M_{sc} in interior column (int col) and edge column (edge col) and γ_f are defined as follows:

$$M_{sc\,int\,col} = 0.07[(q_{Du} + 0.5 q_{lu}) l_2 l_n^2 - q'_{Du} l'_2 (l'_n)^2], \#(45)$$

where q'_{Du}, l'_2, and l'_n refer to the shorter span

$$M_{sc\,edge\,col} = 0.3\, M_o, \#(46)$$

$$\gamma_f = \frac{1}{1 + \frac{2}{3}\sqrt{\frac{b_1}{b_2}}}, \#(47)$$

The maximum values for γ_f is provided in Table 7.

Table 7: Maximum modified values of γ_f.

Column location	Span direction	v_{ug}	ϵ_t (within b_{slab})	Maximum modified γ_f
Corner column	Either direction	$\leq 0.5\Phi v_c$	≥ 0.004	1.0
	Perpendicular to the edge	$\leq 0.75\Phi v_c$	≥ 0.004	1.0
Edge Column	Parallel to edge	$\leq 0.4\Phi v_c$	≥ 0.010	$\frac{1.25}{1+\left(\frac{2}{3}\right)\sqrt{\frac{b_1}{b_2}}} \leq 1.0$
Interior column	Either direction	$\leq 0.4\Phi v_c$	≥ 0.010	$\frac{1.25}{1+\left(\frac{2}{3}\right)\sqrt{\frac{b_1}{b_2}}} \leq 1.0$

Where b_1 is the shear perimeter length perpendicular to the bending axis, and b_2 is the shear perimeter length parallel to the bending axis. c_1 is also the width of the column perpendicular to the bending axis, whereas c_2 is the width of the column parallel to the bending axis. Fig. 3 calculates these perimeters.

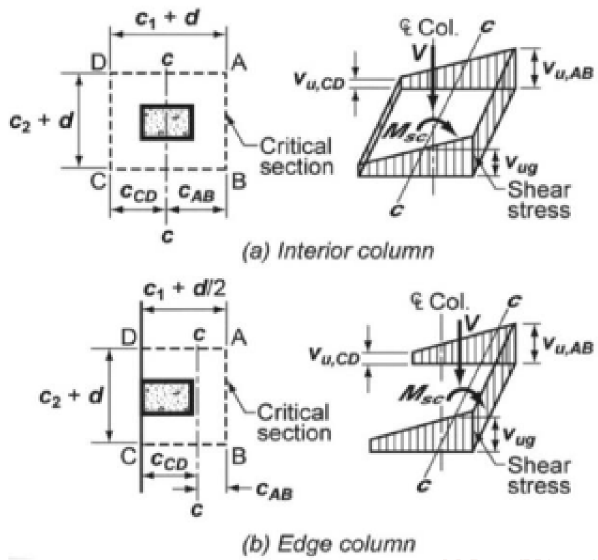

Figure 3: Assumed distribution of shear.

ONE-WAY SHEAR CONSTRAINT

The nominal concrete shear strength, ΦV_n, should be greater than the ultimate factored shear strength, V_u;

$$g_8(x) = \frac{V_u}{\Phi V_n} - 1 \leq 0, \Phi = 0.75, \#(48)$$

The ultimate factored shear force is calculated as follows in the interior spans (int) and edge spans (edge):

$$V_{u\,int} = w_u l_2 \left(\frac{l_n}{2} - d\right), \#(49)$$

$$V_{u\,edge} = w_u l_2 \left(\frac{1.15 l_n}{2} - d\right), \#(50)$$

The nominal concrete shear strength is defined as:

$$V_n - V_c - 2\sqrt{f_c'}\, l_2 d, \#(51)$$

TWO-WAY SHEAR CONSTRAINT

The shear stress strength, Φv_n, should be greater than the ultimate factored shear stress, v_u;

$$g_9(x) = \frac{v_u}{\Phi v_n} - 1 \leq 0, \Phi = 0.75, \#(52)$$

In Eq. (4.52), v_u is defined as follows:

$$v_u = \frac{V_{ug}}{A_c} + \frac{\gamma_v M_{sc} c}{J_c}, \#(53)$$

Where V_{ug} = the ultimate shear calculated by Eq. (4.55), A_c = concrete area calculated by Eqs (4.55-4.56) along the assumed critical section. J_c = the assumed critical section property analogous to the Eqs (4.57-4.58) calculated polar moment of inertia. c = the distance in the critical section calculated by Eqs (4.59-4.60) between the central axis and outlines. and in Eq (4.61), γ_v is given. (4.61):

$$V_{ug} = w_u(l_1 l_2 - b_1 b_2), \#(54)$$

$$A_{c\,int\,col} = 2(b_1 + b_2) \times d, \#(55)$$

$$A_{c\,edge\,col} = (2b_1 + b_2) \times d, \#(56)$$

$$J_{c\,int\,col} = d\left(\frac{b_1^3}{6} + \frac{b_2 b_1^2}{2}\right) + \frac{b_1 d^3}{6}, \#(57)$$

$$J_{c\,edge\,col} = d\left(\frac{2b_1^3}{3} - (2b_1 + b_2) \times c^2\right) + \frac{b_1 d^3}{6}, \#(58)$$

$$c_{int\,col} = \frac{b_1}{2}, \#(59)$$

$$c_{edge\,col} = \frac{b_1^2}{2b_1 + b_2}, \#(60)$$

$$\gamma_v = 1 - \gamma_f, \#(61)$$

Where c_1 is the column width perpendicular to the bending axis and c_2 is the column width parallel to the bending axis. For two-way members without shear reinforcement, the shear stress strength is calculated by:

$$v_n = v_c = \min\left(4\sqrt{f_c'}, \left(\frac{\alpha_s d}{b_0} + 2\right)\right), \#(62)$$

In Eq. (62), for interior columns, the value of α_s is 40 and for edge columns is 30.

SERVICEABILITY CONSTRAINS

The area of reinforcement bars, A_s, should be greater than the minimum area of reinforcement, $A_{s\,min}$, and bar spacing, s should be between minimum and maximum limits allowed by the design specification in reinforced one-way slabs.

$$g_{10}(x) = \frac{A_{s\,min}}{A_s} - 1 \leq 0, \#4.63$$

$$g_{11}(x) = \frac{s_{min}}{s} - 1 \leq 0, \#4.64$$

$$g_{12}(x) = \frac{s}{s_{max}} - 1 < 0, \#4.65$$

Table 8 presents the minimum area of flexural reinforcement:

Table 8: The minimum area of flexural reinforcement, $A_{s\,min}$.

Reinforcement Type	f_y, psi	$A_{s\,min}$
Deformed bars	$< 413.7\,MPa$ $(60000psi)$	$0.0020A_g$
Deformed bars or welded wire reinforcement	$\geq 413.7\,MPa$ $(60000psi)$	$\max\left(0.0018 \times \frac{60000}{f_y} A_g, 0.0014A_g\right)$ $in\,S.I.\,units, f_y\,in\,MPa$ $\max\left(0.0018 \times \frac{413.7}{f_y} A_g, 0.0014A_g\right)$

The minimum and maximum spacing of the bar is defined as follows:

$$s_{min} - \max\left(1", d_b, \frac{4}{3} d_{agg}\right), \#(66)$$

$$in\ S.I.\ units,\quad s_{min} = \max\left(25.4mm, d_b, \frac{4}{3} d_{agg}\right), \#(66a)$$

where d_{agg} is the diameter of aggregate.

$$s_{max} = \begin{cases} \min(18", 2h), & at\ critical\ sections \\ \min(18", 3h), & at\ other\ sections \end{cases}, \#(67)$$

$$in\ S.I.\ units,\quad s_{max} = \begin{cases} \min(457.2mm, 2h), & at\ critical\ sections \\ \min(457.2mm, 3h), & at\ other\ sections \end{cases}, \#(67a)$$

in this paper the formula for critical sections is assumed for all sections of the RC flat slabs.

DEFLECTION CONSTRAINS

Slab thickness, h, shall not be less than the minimum slab thickness, h_{min};

$$g_{13}(x) = \frac{h_{min}}{h} - 1 \leq 0, \#(68)$$

where h_{min} is presented in Table 9.

Table 9: Minimum thickness of slabs without interior beams, h_{min}.

f_y, psi	Without drop panels	
	Exterior Panels	Interior Panels
	Without edge beams	
40000	$\frac{l_n}{33}$	$\frac{l_n}{36}$
60000	$\frac{l_n}{30}$	$\frac{l_n}{33}$
75000	$\frac{l_n}{28}$	$\frac{l_n}{31}$

where l_n is the clear span in the long direction, measured face-to-face of supports.

3.2.2. Design variables

The concrete (f_c') compressive strength, the slab thickness (h), the reinforcement bar diameter (d_b), and the reinforcement (s) spacing were included as the design variables. The diameter numbers of the reinforcement bars (d_b) vary for four end spans because they differ in the ultimate design moment. The thickness of the slab (h) and the spacing of the reinforcement (s) may be considered as integer variables (multiple of 5mm and 10mm respectively), while discrete variables must be assigned to the compressive strength of the concrete (f_c') and the diameter of the reinforcement bars (d_b).

Table 10:List of possible values for f_c'.

S. No.	Concrete strength (f_c')
1.	$14MPa$ $(2000psi)$
2.	$17MPa$ $(2500ps)$
3.	$21MPa$ $(3000psi)$
4.	$24MPa$ $(3500psi)$
5.	$28MPa$ $(4000psi)$
6.	$31MPa$ $(4500psi)$
7.	$34MP$ $(5000psi)$
8.	$41MPa$ $(6000psi)$
9.	$55MPa$ $(8000psi)$
10.	$69MPa$ $(10000psi)$

Table 11: List of possible values for d_b'.

S. No.	Diameter of reinforcement bars (d_b)
1.	10mm
2.	12mm
3.	16mm
4.	20mm
5.	25mm
6.	28mm
7.	32mm
8.	36mm
9.	40mm
10.	50mm

3.2.3. Objective Function

A total cost function can be defined as follows for the reinforced concrete flat slab:

$$C_t = C_r^1\left(C_c + C_r + C_f\right), \#(69)$$

Where C_c is the concrete cost. C_c can be computed as:

$$C_c = r_1 l_1 l_2 h, \#(70)$$

Where l_1 is the span length, center to center of supports in the direction in which moments are considered, l_2 is the span length, center to center of supports in the transverse direction to l_1, and r_1 is the cost ratio of the unit volume of concrete to the unit volume of concrete (C_c^1/C_r^1). C_r and C_f are the costs, respectively, of negative and positive reinforcement bars in interior and exterior supports,

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shaping and finishing materials. As mentioned in section 3, it is possible to drop the cost of formwork from the formulation.

4. OPTIMIZATION ALGORITHMS

The design goal in optimizing a design could be simply to minimize cost of production or maximize efficiency in production. An optimization algorithm is a process that is performed iteratively by comparing various solutions until an optimal or satisfactory solution is found. With the advent of computers, optimization has become part of computer-aided design activities. The metaheuristic optimization approach is used in the presented work instead of deterministic optimization approach because the optimization problem addressed is highly nonlinear and multimodal and contains different complex constraints. Sometimes there may be no optimal solutions at all in such cases. Finding an optimal solution or even sub-optimal solutions is a difficult task in most practical design issues. In addition, metaheuristic approaches involve less complexity computational than deterministic approaches.

4.1. Genetic Algorithm (GA)

GAs uses probabilistic transition rules to give research a way, as opposed to numerous methods. Creating a tool that depends on mutually exclusive events such as throwing a coin is neither a simple arbitrary hunt nor a choice. However, GAs use random choice as a tool to accompany a search to the search space areas with expected progress. In the following stages, the basic principles of a GA are explained.

INITIAL POPULATION

Population of randomly selected chromosome-shaped solutions.

TERMINATION CRITERIA

In practice, this is the termination criterion; for instance, if the current generation $t > t_{max}$ the maximum permissible number of generations is given, then the end condition is given.

OBJECTIVE OR FITNESS FUNCTION

IT defines the goal the GA needs to achieve.

SELECTION

Genetic algorithm reproduction begins with selection. Selection is a method of selecting separate strings (chromosomes) for next generations.

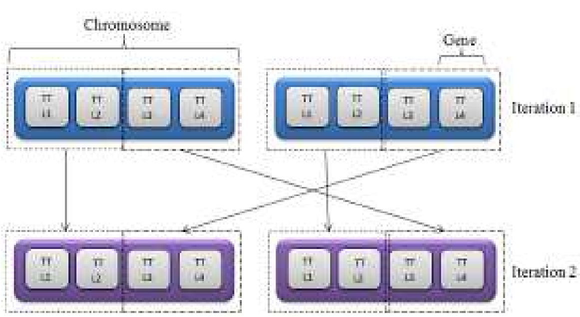

Figure 4: Presentation of Gene, Chromosome and Population in GA.

CROSSOVER

Crossover is nothing but a reproductive process that creates different individuals in successive generations by combining bits from two chromosomes of the previous generation.

MUTATION

Mutation is the process that haphazardly alters genetic information to avoid trapping into local minima.

NEW GENERATION

We get new chromosomes at the end of the generation through production processes such as selection; crossover and mutation applied to a population of n chromosomes until a new set of n persons is created. Thus, this set becomes the new population.

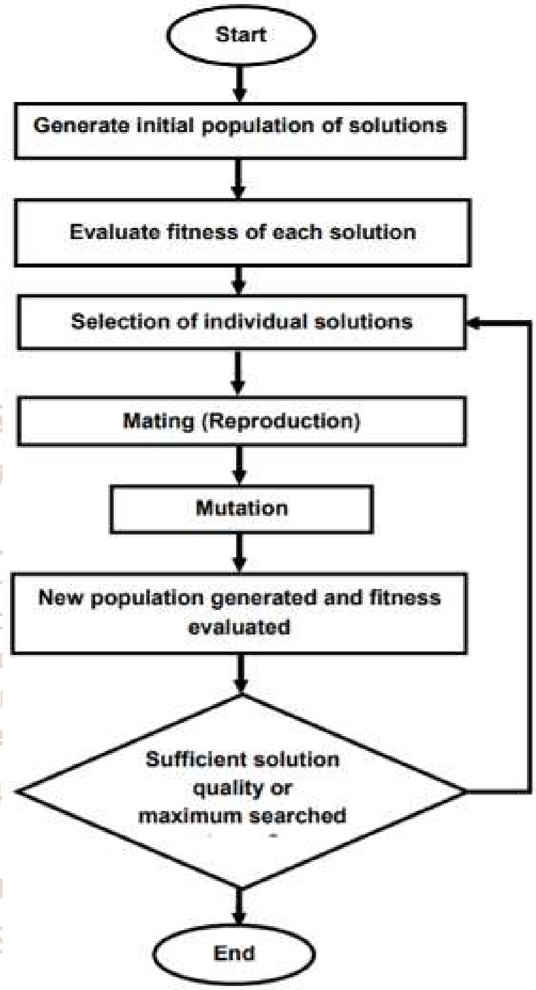

Figure 5: Flowchart of Genetic Algorithm (GA).

Particle Swarm Optimization (PSO)

PSO is a population-based stochastic optimization technology based on the social behaviors observed in animals and insects, e.g. bird flocculation, fish schooling and animal herding [27].

BASIC STRUCTURE

In PSO, through a systematic approach, a number of particles are moved in search space. Each particle i have a position, $x_i(t)$, and a velocity, $v_i(t)$, in PSO, at time t. The particles current position and best position ever are stored in a memory. The particle velocity will be changed based on the historical data stored in the memory as well as random information. The new velocities will be used to update the particles' current position,

INITIAL POPULATION OR SOLUTIONS

A number of initial solutions are needed for the proposed algorithm to initiate space exploration solution. Basically, these initial solutions are the particles used in the search.

PARTICLE POSITION, VELOCITY, UPDATION AND STOPPING CRITERION

Because L particles are used by the proposed PSO algorithm to explore the feasible space. Initially, the PSO algorithm generates L random numbers as particle velocity to update the particle position. After updating iteration in k^{th} for each particle, the appropriate velocity ensures the feasibility of each particle. The algorithm also needs to modify particle velocities during the search to guide the particles through the region's most desirable regions. Originally, the PSO algorithm uses the following equation to update the speed:

$$V_k = V_k + C_1 r_1 (P_{kbest} - P_k) + C_2 r_2 (G_{kbest} - P_k),\#$$

Where V_k is the particle at k^{th} velocity, P_k is the current particle (solution) at k^{th} iteration, P_{kbest} is the particles personal best, G_{kbest} is the particles global best, r_1 and r_2 is a random number between (0 and 1) Assume $r1 = 0.78, r2 = 0.48$. C_1, C_2 are learning factors (or) social and cognitive parameters. Usually C_1 equals to C_2 and ranges from 0 to 4. Assume $C_1 = C_2 = 1$.

With the new velocity V_k, the particle's updated position equation is given as:

$$P_k = P_k + V_k,\#$$

The two above equations imply that a new design is searched for the global optimum by using the velocity vector being explored based on the local and global bests. Thus, through neighborhood learning and previous design, the PSO design update is done.

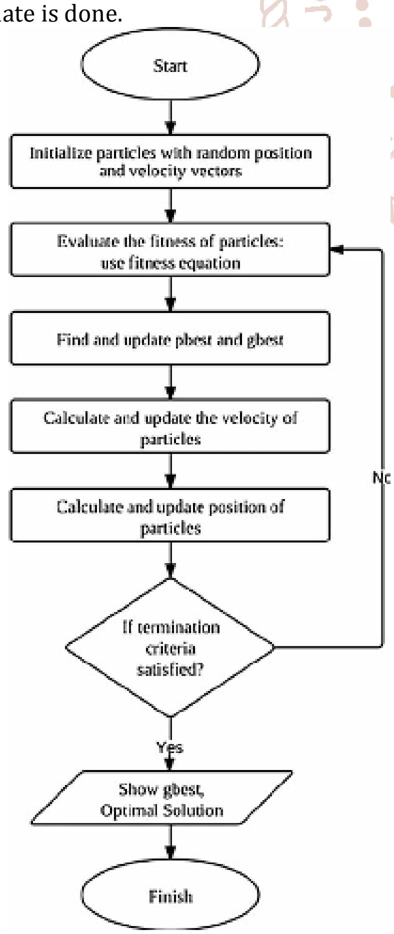

Figure 6: Flowchart of PSO Algorithm.

GREY WOLF OPTIMIZATION (GWO)

The Grey Wolf Optimization (GWO) was proposed by Mirjalili et al [28]. The GWO is inspired by the social structure and hunting behavior of the gray wolves.

The gray wolves are strictly following the social hierarchy of leadership. The alpha (α) wolf, still at the top of the hierarchy, leads the hierarchy group. Likewise, after alpha, beta (β) wolf is called the wolf's second level, the wolves of the third and fourth level are called delta (δ) and omega (ω) respectively. The alpha wolf is followed by all wolves (beta, delta and omega), while delta and omega follow the beta wolves, and delta wolves follow only omega. Since the omega remains at the lowest level, they have no followers.

Hunting is now led by alpha, beta and delta wolves and restful wolves (omega). The movement of the entire population is guided by the top three best solutions in the optimization problem and these solutions are referred to as alpha, beta and delta respectively the other solutions are considered as omega.

ENCIRCLING THE PREY

The first hunting step is to surround the prey. Gray wolve's encircling process is equivalent to the optimal solution being encircled by all the population and is given by:

$$\vec{D} = \left|\vec{C} \cdot \vec{X}_{prey}(i) - \vec{X}_{wolf}(i)\right|,\#3.8$$

$$\vec{X}_{wolf}(i+1) = \vec{X}_{prey}(t) - \vec{A} \cdot \vec{D},\#3.9$$

Here i represent the current iteration number, while $\vec{A}$ and $\vec{C}$ are the coefficient vectors, $\vec{X}_{wolf}$ and $\vec{X}_{prey}$ are the wolf and prey position vectors respectively. The $\vec{A}$ and $\vec{C}$ vector coefficients are calculated as follows:

$$A = 2\vec{a} \cdot \vec{r}_1 - \vec{a},\#3.10$$

$$\vec{C} = 2\vec{r}_2\#3.11$$

In eq. 3.10 the value of vector $\vec{a}$ is linearly decreased from 2 to 0 with the iterations and $\vec{r}_1, \vec{r}_2$ are random vectors within the interval of [0, 1].

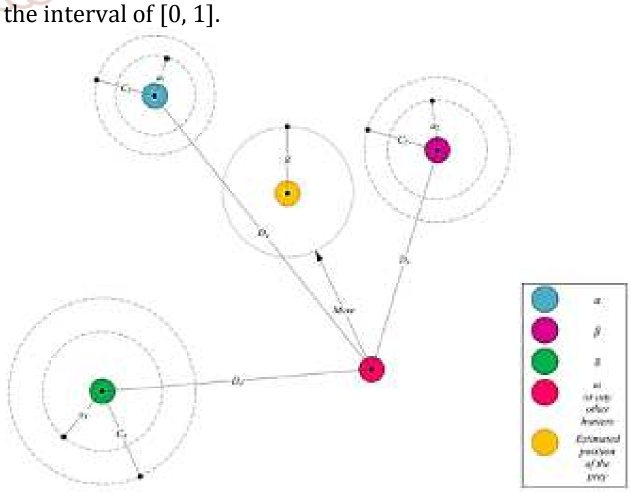

Figure7: The position updating process in GWO as presented by Mirjalili et al [4].

HUNTING

The prey position is known in the actual hunting scenario, but the optimal solution is not known in the problem of optimization, so alpha, beta and delta solutions estimate a rough estimation of the optimum location knowing they have the best knowledge of the solution. The update of the wolve's position is as follows:

$$\vec{X}_{wolf}(i+1) = \frac{\vec{X}_1 + \vec{X}_2 + \vec{X}_3}{3}, \#$$

The above equation estimates how the wolf (population) should move to obtain the prey (optimum) and the mean of the possible locations of pray. The $\vec{X}_1$, $\vec{X}_2$ and $\vec{X}_3$ are the expected position of prey (optimum solution) on the basis of the position of α, β and δ respectively. These positions are estimated as follows:

$$\vec{X}_1 = \vec{X}_\alpha - A_1 \cdot (D_\alpha), \qquad D_\alpha = |C_1 \cdot X_\alpha - X_{wolf}|, \#$$
$$\vec{X}_2 = \vec{X}_\beta - A_2 \cdot (D_\beta), \qquad D_\beta = |C_1 \cdot X_\beta - X_{wolf}|, \#$$
$$\vec{X}_3 = \vec{X}_\delta - A_3 \cdot (D_\delta), \qquad D_\delta = |C_1 \cdot X_\delta - X_{wolf}|, \#$$

ATTACKING

As the gray wolf starts tightening grip to prey the movement of the prey becomes smaller and smaller as the wolves move, and finally the prey stops moving and the wolf performs the final attack. In a mathematical model, the vector value (a) to be reduced from two to zero by every iteration in the linear movement of prey and wolf (population position) is reduced and finally, the prey (optimum) gets the movement of the prey.

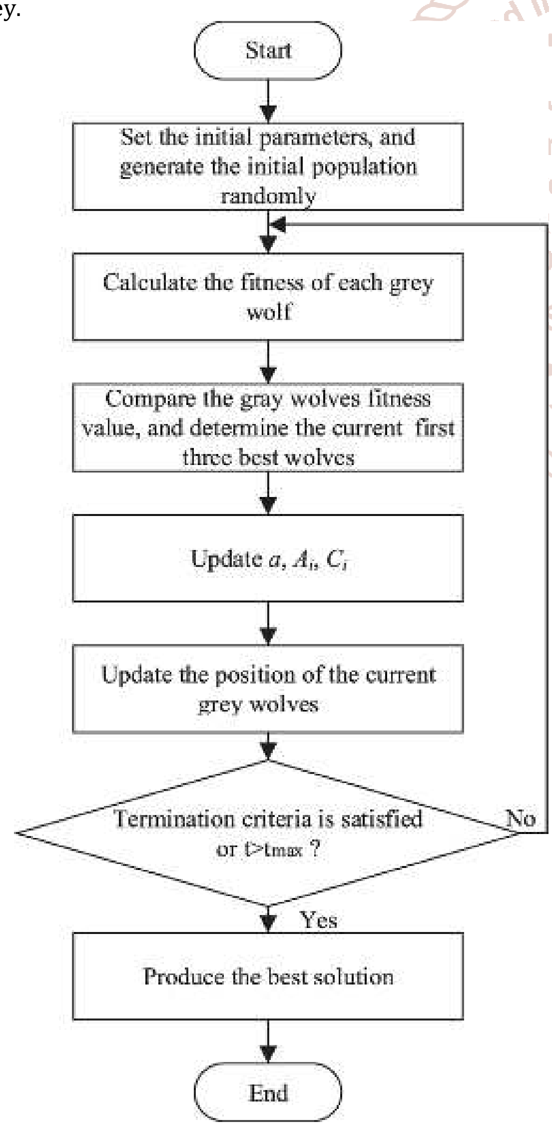

Figure 8: Flowchart for Graywolf Optimization Algorithm (GWO).

5. Simulation Results

Optimization findings are provided in this chapter for four kinds of one-way RC slabs with distinct support circumstances. Table 12 presents the prevalent data used for the simulation. The initial design variables values are selected according to the ACI code for the design of concrete slabs. C_r^1 is set at $\$1300/ton\ (\$1.43/kg)$ for reinforcement steel. The concrete price differs with the strength of the concrete as shown in Table 13. Practical values for variables h and s are assumed to be $5\ mm$ and $10\ mm$ multiples respectively.

Table12: Common Data used for Simulation

Parameter Name	Parameter Description	Parameter Value
f_y	Specified yield strength of reinforcement bars	$275.8\ MPa$, or $(40\ ksi)$
w_s	Weight of steel per unit volume	$76.9729\ kN/m^3$, or $(490\ lb/ft^3)$
f_c'	Specified compressive strength of concrete	$20.68\ MPa$ or $(3\ ksi)$
w_{RC}	Weight of concrete per unit volume	$23.6\ kN/m^3$, or $(150\ lb/ft^3)$
Cover	Cover	$19.05\ mm$, or $(0.75\ in)$
C_c^1	Cost of concrete per unit volume	$99.56\ \$/m^3$, or $(76\ \$/cyd)$
L	Span length	$3.96\ m$, or $(13\ ft)$
DL	Dead load of floor excluding the self-weight of slab	$0.48\ KN/m^2$, or $(10\ lb/ft^2)$
LL	Live load	$2.39\ KN/m^2$, or $(40\ lb/ft^2)$
C_r^1	Cost of reinforcement bars per unit weight	$1300\ \$/ton$, or $(1.43\ \$/kg)$

Table13: Concrete specified compressive strength f_c' and its cost, C_c^1.

Specified compressive strength of concrete (f_c')	Cost of concrete per unit volume (C_c^1)
$14MPa\ (2000psi)$	$93.655\ \$/m^3$
$17MPa\ (2500ps)$	$96.94\ \$/m^3$
$21MPa\ (3000psi)$	$99.56\ \$/m^3$
$24MPa\ (3500psi)$	$102.18\ \$/m^3$
$28MPa\ (4000psi)$	$106.765\ \$/m^3$
$31MPa\ (4500psi)$	$108.73\ \$/m^3$
$34MP\ (5000psi)$	$110.695\ \$/m^3$
$41MPa\ (6000psi)$	$126.415\ \$/m^3$
$55MPa\ (8000psi)$	$206.98\ \$/m^3$
$69MPa\ (10000psi)$	$293.44\ \$/m^3$

Table 14: Genetic Algorithm (GA) Configuration.

Parameter's Name	Parameter's Value
Population Size	100
Max Generations	200
Initialization Technique	Random (Uniformly Distributed)
Crossover Technique	Scattered
Crossover Probability	0.8
Mutation Technique	Random (Gaussian with mean = 0)
Mutation Probability	0.01
Selection	Stochastic uniform

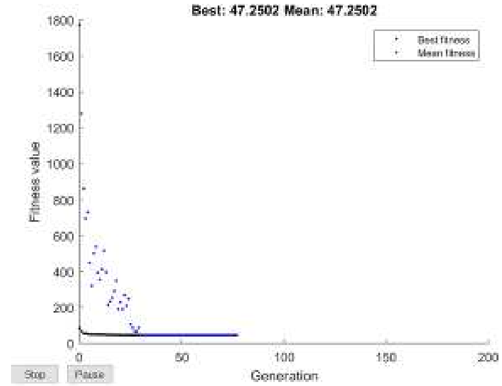

Figure 9: Convergence Plot of Genetic Algorithm (GA).

Table 15: Particle Swarm Optimization (PSO) Configuration.

Parameter's Name	Parameter's Value
Number of Particles	100
Max Iterations	200
Initialization Technique	Random (Uniformly Distributed)
Inertia Weights ($[w_{min}, w_{max}]$)	[0.1000 1.1000]
Acceleration Coefficients ($[c_1, c_2]$)	[1.49, 1.49]

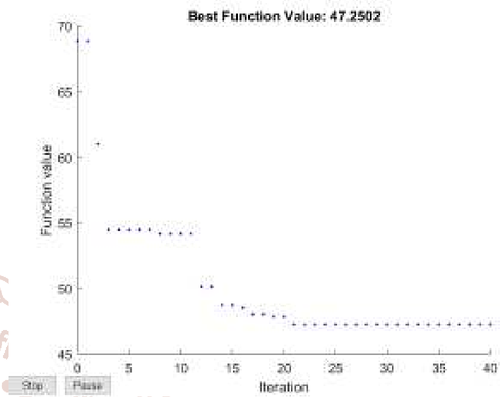

Figure 10: Convergence Plot of Particle Swarm Optimization (PSO).

Table 16: Gray Wolf Optimization (GWO) Configuration.

Parameter's Name	Parameter's Value
Number of Wolfs	100
Max Iterations	200
Initialization Technique	Random (Uniformly Distributed)

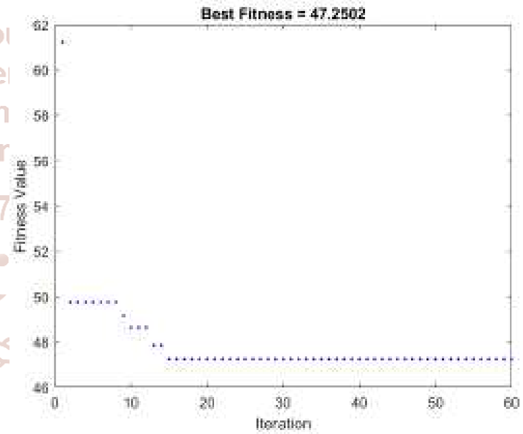

Figure 11: Convergence Plot of Gray Wolf Optimization (GWO).

Table 17: Optimization results for simply supported slab.

	Slab thickness (h)	Rebar diameter (d_b)	Rebar Spacing (s)	Total Cost ($)
Ref [3]	171.45mm (6.75in)	9.525mm (0.375in)	165.1mm (6.5in)	26.45
Ref [5]	158.75mm (6.25in)	12.7mm (0.5in)	228.6mm (9.0in)	26.57
Ref [23]	158.75mm (6.25in)	15.875 mm (0.625in)	368.3mm (14.5in)	26.36
GA	160.02mm (6.30in)	12mm (0.47in)	350.52mm (13.8in)	23.61
PSO	160.02mm (6.30in)	12mm (0.47in)	350.52mm (13.8in)	23.61
GWO	160.02mm (6.30in)	12mm (0.47in)	350.52mm (13.8in)	23.61

Table 18: Optimization results for one end continuous slab.

	Slab thickness (h)	Rebar diameter (d_b)	Rebar Spacing (s)	Total Cost ($)
Ref [3]	141.48mm (5.57in)	9.525mm (0.375in)	177.8mm (7.0in)	22.98
Ref [5]	133.35mm (5.25in)	9.525mm (0.375in)	139.7mm (5.5in)	22.76
Ref [23]	133.35mm (5.25in)	12.7mm (0.5in)	254.0mm (10.0in)	22.78
GA	135.13mm (5.32in)	12mm (0.47in)	398.78mm (15.7in)	20.06
PSO	135.13mm (5.32in)	10mm (0.39in)	289.56mm (11.4in)	19.89
GWO	135.13mm (5.32in)	10mm (0.39in)	289.56mm (11.4in)	19.89

Table 19: Optimization results for both ends continuous slab.

	Slab thickness (h)	Rebar diameter (d_b)	Rebar Spacing (s)	Total Cost ($\$$)
Ref [3]	120.65mm (4.75in)	9.525mm (0.375in)	177.8mm (7.0in)	19.93
Ref [5]	114.3mm (4.5in)	9.525mm (0.375in)	139.7mm (5.5in)	20.64
Ref [23]	114.3mm (4.5in)	12.7mm (0.5in)	254.0mm (10.0in)	20.5
GA	115.06mm (4.53in)	12mm (0.47in)	289.56mm (11.4in)	19.1
PSO	115.06mm (4.53in)	10mm (0.39in)	340.36mm (13.4in)	16.95
GWO	115.06mm (4.53in)	10mm (0.39in)	340.36mm (13.4in)	16.95

Table 20: Optimization results for cantilever slab.

	Slab thickness (h)	Rebar diameter (d_b)	Rebar Spacing (s)	Total Cost ($\$$)
Ref [3]	342.9mm (13.5in)	9.525mm (0.375in)	50.8mm (2.0in)	60.22
Ref [5]	317.5mm (12.5in)	15.875mm (0.625in)	317.5mm (12.5in)	59.31
Ref [23]	317.5mm (12.5in)	17.145mm (0.875in)	241.3mm (9.5in)	59.96
GA	320.04mm (12.6in)	10mm (0.39in)	119.89mm (4.72in)	47.33
PSO	320.04mm (12.6in)	16mm (0.63in)	309.88mm (12.2in)	47.25
GWO	320.04mm (12.6in)	16mm (0.63in)	309.88mm (12.2in)	47.25

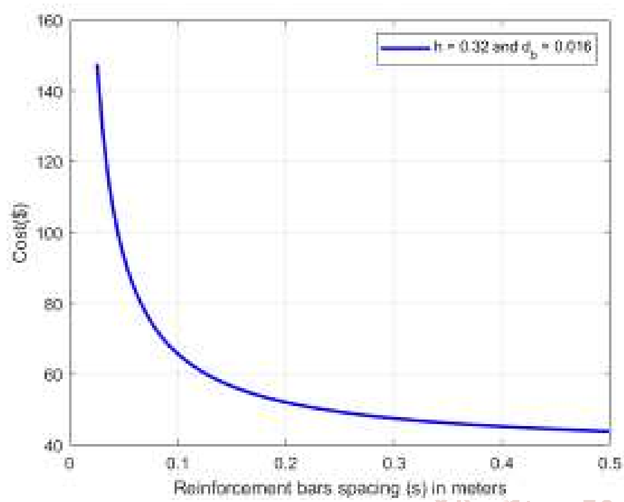

Figure 12: Variation of the total cost function versus s while the other two design variables h and d_b are kept constant.

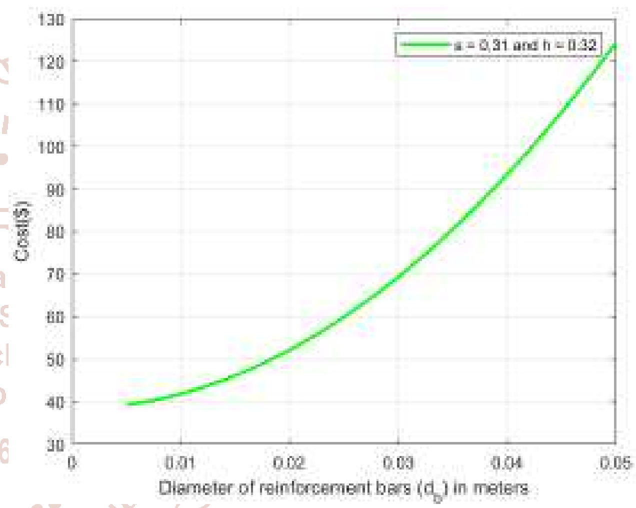

Figure 14: Variation of the total cost function versus d_b while the other two design variables s and h are kept constant.

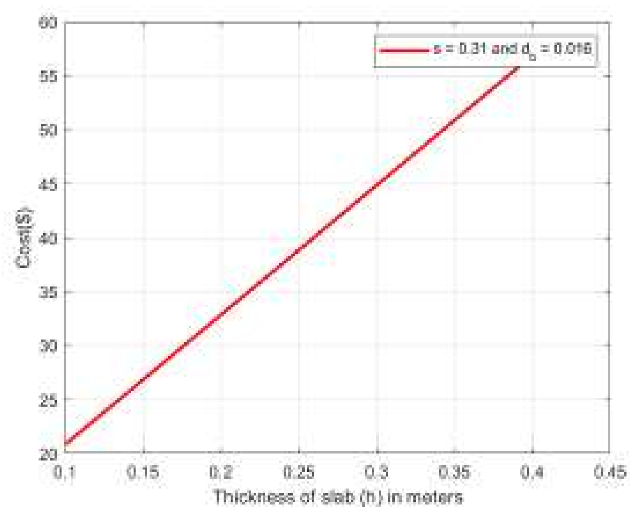

Figure 13: Variation of the total cost function versus h while the other two design variables s and d_b are kept constant.

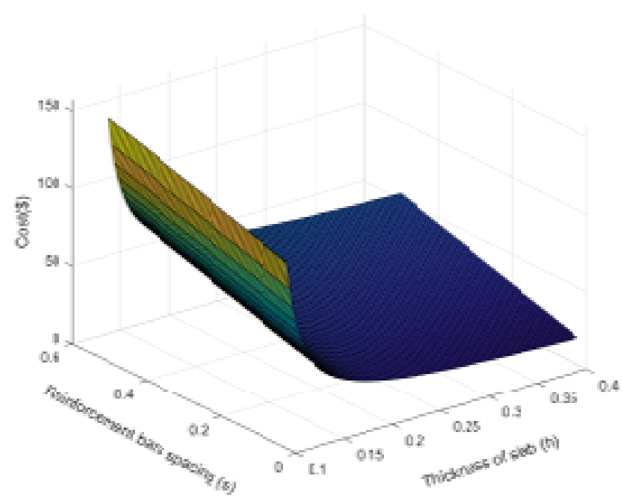

Figure 15: Variation of total cost function versus h and s when d_b is kept constant to 0.0160m.

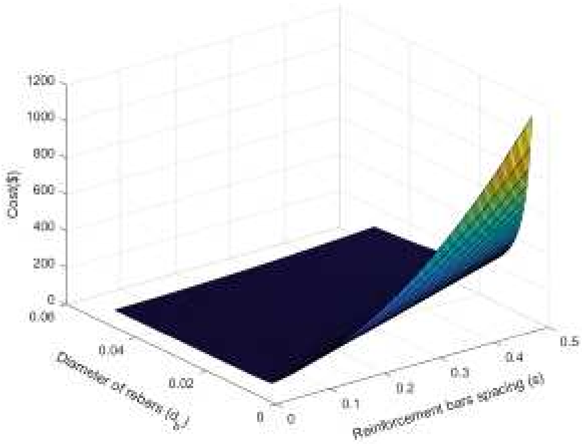

Figure 16: Variation of total cost function versus d_b and s when h is kept constant to 0.3200m.

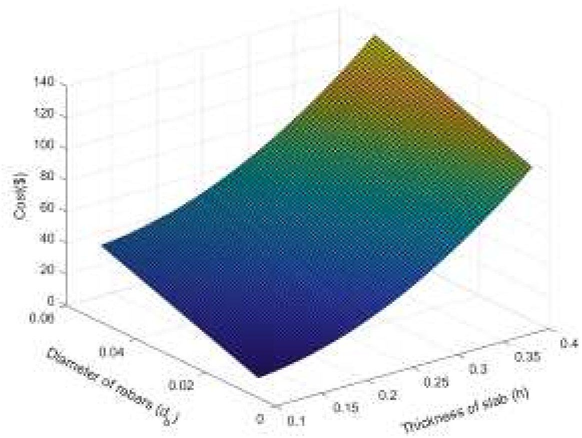

Figure 17: Variation of total cost function versus d_b and h when s is kept constant to 0.3100m.

The cost optimization model described in the paper can also be used as a tool for conducting parametric research, gaining insight into the entire design, and gaining trend data and answering questions when asked. For instance, Fig. 12-14 displays variation in the overall cost function versus a single design variable h, d_b, or s while the other two design factors remain fixed. Fig. 12 depicts that the cost reduces very quickly when bars spacing (s) is increased up to 100mm, however the further increase in bar spacing doesn't affect the cost that much. On the other hand, The Fig. 13 shows that cost increases linearly with rise in slab thickness (h). Finally, the Fig. 14 shows that the cost rises drastically with rise in the size of the reinforcement bar (d_b).

Fig. 15-17 displays variation in the overall cost function versus two design variables while the third design variable kept fixed. Fig. 15 depicts that the complete cost function variation versus h and s if d_b is held constant. This figure indicates a significant cost increase when the spacing of the bar is low (less than 80mm). Fig. 16 Displays the complete cost function vs. d_b and s if h is held constant. This figure indicates a significant rise in cost function with reduction in the size of the reinforcement bar and increment in spacing of bar. Fig. 17 Displays the complete cost function vs. h and d_b if s is held constant. This figure indicates a significant rise in cost function with rise in the size of the reinforcement bar and rise in slab thickness.

6. Conclusions

In this research, cost optimization of RC slabs with distinct support conditions (simply supported, one end continuous, both end continuous and cantilever) was provided using the three distinct optimization methods (Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Gray Wolf Optimization (GWO)). The slab design was based on ACI code as discussed in section 3, and the procedure involved finding the optimum slab thickness, reinforcement bar diameter, and reinforcement spacing the details of these variables are presented in section 3.

According to the outcomes, the GWO, which was first used to optimize the concrete slab, showed (refer to Fig. 9-11) better convergence speed to optimize concrete structures relative to the GA and PSO algorithms. The GWO achieves the best result in just 15 iterations (Fig. 9), while the PSO and GA take around 25 iterations (Fig. 10 and Fig. 11). Furthermore, the GWO and PSO both achieve similar and better outcomes than the GA for one end continuous slab (Table 18**Error! Reference source not found.**), both end continuous slab (Table 19) and cantilever slab (Table 20), although for simply supported slab all three algorithms give similar results.

The comparison of the presented method with the previously proposed methods, shows (refer to Table 17-20) that the presented method achieves better outcomes than the previously proposed works. The presented method achieves 10.43% cost reduction (Table 17) for the simply supported condition, 12.61% cost reduction (Table 18) in one end continuous support condition, 14.95% cost reduction (Table 19) in both end continuous support condition and 20.33% cost reduction in cantilever support condition (Table 20).

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