Design Optimization Of RC Column Footings Under Axial Load Of Beam And Rooftop Surfaces

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Abstract: Mechanism of load transform starts from Roof surface and beams and finally goes to columns and footings and further on the soil. There is wide variety of literature available in beam optimization but column and footing reinforcement optimization still needs exploring. Present work proposes manual as well as meta-heuristic optimization based approach which provides optimum value of design variables of a reinforcement used in RC column footing design. The column transfers the load to footing by bearing in which two types of shear stresses are co-existed named as one way and two way shear. In order to keep to under maximum shear stress, effective depth needs of to be optimized on which area of reinforcement steel , no. of steel bars etc. are dependent. GSA selects random values from given range with initial input values of length and width of the column along with axial load from bema and roof surfaces. Another parameter is also provided which is bearing capacity of soil. GSA converges to optimum solution by taking into account shear stress constraints and provides optimum values for design parameters of reinforcement. Experimental results show approx. 8% decrease in reinforcement material by compensating it with effective length and provides optimum values of development length, area of steel reinforcement, number of steel bars and spacing of bars among them.

Index Terms: RC, column footings, GSA, PSO.

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1. INTRODUCTION

Construction projects require costly investments of time and money. In the last decade, environmental costs of construction have also become a primary concern. One example of an environmental cost is carbon dioxide and other greenhouse gases emitted into the atmosphere as a result of construction activities. Therefore, engineers exercise their abilities early on in the design phase of construction projects to help reduce the cost and carbon footprint by lessening the amount of materials required. One way to achieve these results is to optimize the design of structural members. Because concrete is the most commonly used construction material on the planet, and with the cement industry responsible for 5% of the world's carbon dioxide emissions [16], the current research focuses on the optimization of reinforced concrete (RC) members. By optimizing these RC structures, engineers can scale down the volume of concrete and/or steel used in a structure, consequently lowering the discharge of carbon dioxide emissions, as well as other environmental costs, and the economic costs associated with construction. This study will focus on optimizing RC beams for embodied energy, which is defined as the quantity of energy needed to develop and manufacture a product, as if that energy were manifested within the product itself.

1.1 Column Footings

In a typical structure built on ground, that part of the structure which is located above ground is generally referred to as the superstructure, and the part which lies below ground is referred to as the substructure or the 'foundation structure' (or simply, foundation). The purpose of the foundation is to effectively support the superstructure by

- Transmitting the applied load effects (reactions in the form of vertical and horizontal forces and moments) to the soil below, without exceeding the 'safe bearing capacity' of the soil, and
- Ensuring that the settlement of the structure is within tolerable limits, and as nearly uniform as possible.

Further, the foundation should provide adequate safety against possible instability due to overturning or sliding and/or possible pullout. Design against forces inducing overturning and sliding are of special importance in the design of retaining walls, whose very purpose is to provide lateral support to earthfill/embankment in order to retain the side of the earthfill in a vertical position. The choice of the type of foundation depends not only on the type of the superstructure and the magnitudes and types of reactions induced at the base of the superstructure, but also on the nature of the soil strata on top of which the substructure is to be founded.

1.2 TYPES OF FOOTINGS

'Footings' belong to the category of shallow foundations (as opposed to deep foundations such as piles and caissons) and are used when soil of sufficient strength is available within a relatively short depth below the ground surface. Shallow foundations comprise not only footings (which support columns/walls, and have a limited area/width in plan) but also rafts which support multiple columns on a large plan area). The shallow foundation (footing or raft) has a large plan area in comparison with the cross-sectional area of the column(s) it supports because:

- the loads on the columns (axial thrust, bending moments‡) are resisted by concrete under compression and reinforcing steel under tension and/or compression, whereas these load effects are transmitted by the footing/raft to a relatively weak supporting soil by bearing pressures alone;
- the 'safe bearing capacity' of the soil is very low (100 – 400 kPa) in comparison with the permissible compressive stresses in concrete (5–15 MPa) and steel (130–190 MPa) in a column under service loads.

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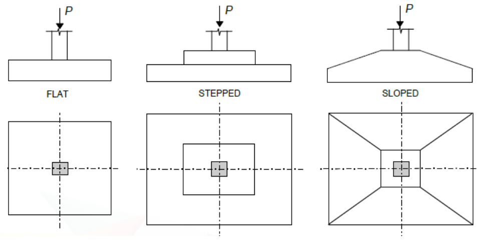
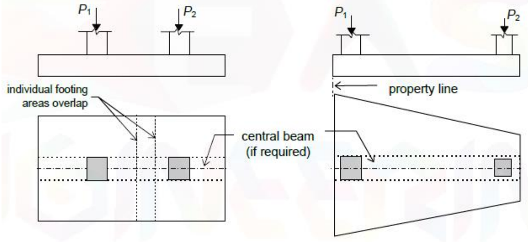
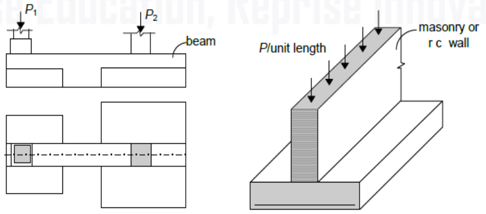


(a) isolated Footings



(b) Combined Footings



(c) Strap Footing (d) Wall Footing

Figure 1: *Types of Footings*

Isolated Footings

For ordinary structures located on reasonably firm soil, it usually suffices to provide a separate footing for every column. Such a footing is called an isolated footing. It is generally square or rectangular in plan; other shapes are resorted to under special circumstances. The footing basically comprises a thick slab which may be flat (of uniform thickness), stepped or sloped (on the upper surface), as shown in Fig. 1(a).

Combined Footings

In some cases it may be inconvenient to provide separate isolated footings for columns (or walls) on account of inadequate areas available in plan. This may occur when two or more columns (or walls) are located close to each other and/or if they are relatively heavily loaded and/or rest on soil with low safe bearing capacity, resulting in an overlap of areas if isolated footings are attempted.

Wall Footings

Reinforced concrete footings are required to support reinforced concrete walls, and are also sometimes employed to support load-bearing masonry walls†. Wall footings distribute the load from the wall to a wider area, and are continuous throughout the length of the wall [Fig. 1(d)]. The footing slab bends essentially in the direction transverse to the wall (a 'one-way' slab), and hence is reinforced mainly in the transverse direction, with only distributors in the longitudinal direction.

Allowable Soil Pressure

The main considerations in determining the allowable soil pressure, as well as fixing the depth of foundation, are (i) that the soil does not fail under the applied loads, and (ii) that the settlements, both overall and differential, are within the limits permissible for the structure. The safety factor, used in soil mechanics, lies in the range 2 – 6, and depends on the type of soil, and related uncertainties and approximations.

2 LITERATURE REVIEW

Hesam Varaee et al. (2011) [15] present the cost optimization of one-way slabs with different support conditions using the PSO algorithm, one of the most recent evolutionary algorithms. Obviously the results depends of on the relative cost of concrete and reinforcement and therefore are location dependent. However, the presented algorithm can be applied in design offices in any location by using the relevant unit costs of concrete and reinforcement. This, in turn, generally reduces the cost of the construction and saves the natural resources. M. J. Fadaee et al. (2012) [9] presented an automated procedure to design optimization of RC structures under the time-history earthquake loads. The construction cost was regarded as an objective function of the defined optimization problem. The design criteria called optimization constraints were selected and classified in three sets, primary allowable section conditions, capacity criteria and seismic provisions in accordance with the ACI318-08 and 2800 codes. Finally, after the implementation of optimization process on a three-bay eighteen-story RC frame, the optimum design was obtained. The optimum results reveal that by using the automated design process, it can be achieved a design candidate associated with the minimum construction cost that conforms to the standard codes provisions. S. Gholizadeh et al. (2013) [10] proposed an efficient algorithm to layout optimization of structures by adopting two computational strategies. In the first strategy, the trajectories of the particles are improved in the design space using a novel CA-based PSO scheme denoted as CPSO algorithm. In the second strategy, the proposed CPSO is employed in the framework of the SUMT using the EPFM for efficient handling the design constraints. The resulted algorithm is denoted as sequential cellular particle swarm optimization (SCPSO). Four benchmark layout optimization problems of truss structures are tackled to illustrate the efficiency of the proposed SCPSO algorithm. In the presented numerical examples, a sensitivity analysis carried out to find the best combination of SCPSO internal parameters. M. H. Arafa et al. (2013) [11] obtained the optimum design of reinforced concrete beams conforming to the provisions of the ACI 318-08 Code using the Artificial Bee Colony (ABC) Algorithm. The objective function is taken as the cost of the continuous beam. Fine tuning of ABC algorithm's main control parameters has been successfully done and necessary values and correlations have been suggested. They show that ABC is a reliable and robust technique that can be effectively used in finding the optimum detailed design of reinforced concrete continuous beams. Abdrabbo F., Mahmoud Z.I., and Ebrahim M. (2016) [1] explored the precision of code provisions related to the structural design of isolated column footings, and to illustrate their relations from the test results. To achieve this target, comparisons between predicted failure loads of column footings based on code provisions and the laboratory measured failure loads were conducted. The research concluded that the predicted failure loads of isolated column footings subjected to uniformly distributed contact stress in accordance with ACI318-08 code provisions are controlled by punching shear at code-defined critical section, contrary to ECP (203- 2011) code provisions which the predicted failure loads are controlled by one-way shear at code defined critical section. FAR H. & FLINT D. (2017) [7] proposed a technique for constructing footings without the restriction of 75mm of characteristic movement on all site classifications. The approach most commonly adopted in Australia is to stiffen the foundation to resist soil movement. As this type of footing can be used on all site classifications, there is no need for human judgment when dealing with problematic sites which can reduce the construction cost if the footings are over deigned and reduce the post construction costs if the footings are under designed. Jagbir Singh et al. (2017) [5] explored the optimal solutions for reinforced concrete beams. Undoubtedly, this study is specifically carried out for simply supported beams, but the scope of proposed algorithm is wide enough to seek the optimum solution for other beams and structures. It has been viewed that reduction in both steel area as well as concrete volume contributes towards optimization of reinforced concrete beams and cost optimization is directly proportional to the ratio of depth to width of a beam. El-kady M.S., Badrawi E. F. (2017) [6] presented experimental tests and numerical verification for the folded and flat isolated footings resting on sandy soil. The aim of the current paper is to highlight the effectiveness of the folding angle (0) on the soil settlement and footing stresses. The influence of the folding inclination angle (0) on the results is also studied. Eric L. et al. (2019) [12] performed the two demonstrations showed the feasibility of both ACC formwork and RACC walls. The first demonstration resulted in a building structure that resembled the geometries possible using current technology. The second demonstration pushed the limits of the technology to show that optimized geometries and specific reinforcing methods could be utilized. Results demonstrated that the ACC technology can utilize conventional reinforcing and anchoring methods and can be integrated with existing structural systems. Both demonstrations also highlighted potential issues with design, construction, materials, and the machine that must be solved before implementation of the technology. This implies that these new methods have the potential for industry implementation. The reduction in time and complexity on top of the reduced cost will ensure that additive construction methods will have a place in future construction projects. Jianwei Zhang et al. (2019) [17] investigated six full-sized, high-strength concrete columns with high-strength steel bars. One traditional RC column and five STRC composite columns were tested under horizontal cyclic loading. The influences of the addition of steel tubes, the cross-sectional shape of the inner steel tube, the strength matching of the outer concrete and the core concrete, and the presence of steel fiber in outer concrete were compared and analyzed. However, the results were based on limited data, thus further studies are needed for sectional design and bearing capacity calculations of high-strength STRC composite columns under different working In existed work, a rectangular reinforced concrete beam with simple supports was optimized to find the minimum cost and embodied energy for a given set of spans and applied loads. This work has been advanced to the footing of the columns used in bridges by taking motivation from Beam optimization. Thus, the objective functions minimized in this study is the total cost of the reinforced concrete footing. This function is dependent upon the total volume of concrete and steel, which were each multiplied by the unit cost or unit embodied energy of each corresponding material. The unit cost of concrete and steel may include any combination of material production, product fabrication, labor, and transportation, as well as formwork for concrete. The unit embodied energy of concrete and steel may include any combination of material extraction, plant processes, and transportation. Some studies include all processes while other studies may omit one or more steps to emphasize the impact of a particular process. For this study, only the operations from material extraction to production were considered.

3 METHODOLOGY

The cost of RC isolated footing is given as:

$$\mathrm{C} = C_{st}V_{st} + C_cV_c \text{ ……..(3.1)}$$

Where, C = total cost of footing,

C_{st} = cost of steel per unit volume of steel (rate of steel),

V_{st} = total volume of steel,

C_C = cost of concrete per unit volume of concrete (rate of concrete),

V_C = total volume of concrete.

Divide Eq. (3.1) by C_C;

$$\frac{\mathrm{C}}{C_c} = \frac{C_{st}V_{st}}{C_c} + V_c \text{ ……….(3.2)}$$

And substitute

$$\frac{\mathrm{C}}{C_c} = Z, \quad \frac{C_{st}}{C_c} = \alpha\,(\text{cost ratio})$$

$$V_c = V_G - V_{st}$$

Where, VG is the gross volume of footing. Thus, objective function Z is defined as:

$$\text{Minimize Z} = (\alpha - 1)V_{st} + V_G \text{ …..……(3.3)}$$

Volume of steel Vst depends upon area of steel and it's provided length. Similarly gross volume of concrete depends upon cross sectional area and length of footing.

- Fixed Parameters

In the present model, all input design parameters have been considered fixed. These include span of footing, grade of reinforcement and concrete, intensity of dead and live loads, effective cover of concrete and cost ratio (ratio of unit cost of reinforcement to unit cost of concrete).

- Design Variables

Independent design variables considered in the present model are width (b) and effective depth (d) of the footing. Cross-sectional area of longitudinal reinforcement (Ast) and shear reinforcement (Asv) have been calculated as dependent design parameters. Four design variables were used in the optimization of the footing: the height of the footing, the width of the footing, the number of rebar, and the size of the rebar. A typical cross-section with these features is shown in Figure 2. Different combinations of these four discrete variables were checked to identify designs that satisfied constraints for shear and flexure as well as others. From the feasible set, the design with the lowest total cost or embodied energy was chosen as the optimum solution.

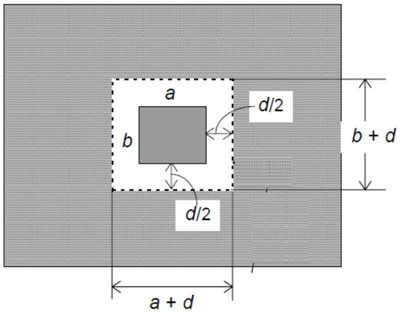


Figure 2: *Typical cross-section of a squared reinforced concrete footing.*

In this analysis, optimization method named as GSA will be utilized to obtain the global minimum of either the total embodied energy or total cost of the reinforced concrete footing. An objective function will be written and constraints will be defined; given four discrete variables, a random number generator produced values for the four variables that were fed through the constraint function and the objective function, converging on a footing design that would minimize the objective function while still existing within the limits set forth by the constraints.

3.1 Gravitational search algorithm

The science of gravity was founded by Galileo and explained more by Isaac Newton and Albert Einstein. In physics, mass is the amount of matter in an object. In general, there are three kinds of mass [HH38]: active gravitational mass, passive gravitational mass, and inertial mass. In Newtonian physics, every particle in the universe attracts every other particle with a force that is directly proportional to the product of the active mass of the particle exerting the force by the passive mass of the particle experiencing the force, and inversely proportional to the square of the distance between them. When the force is applied to an object, the resulting acceleration depends on both the force and the inertial mass of the object. The concepts of gravity and mass were the main inspiration of GSA [13].

3.2 Algorithm- Pseudo-code of GSA

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a) Problem definition
b) Initialization: Generate an initial population of objects randomly:
   $X_i = \left(x_i^1, \ldots., x_i^d \ldots.. x_i^m\right) i, \ldots., \mathrm{N}$
while the stopping criterion is met do
   c) Evaluate each Xi : $fobj_i$
   d) Calculate each $M_i : M_{ai}\left(t\right), M_{pi}\left(t\right), M_{ii}\left(t\right) \alpha\, fobj_i(t)$
   e) Updating gravitational constant: $\mathrm{g}(t)$
   f) Calculate Forces: $F_i^d = \sum_{j \in kbest, j \neq i} \left(rand_i F_{ij}^d\right)$
   g) Update acceleration: $a_i^d\left(t\right) = \frac{F_i^d\left(t\right)}{M_{ii}\left(t\right)}$
   h) Update velocities: $v_i^d\left(t+1\right) = rand_i \times v_i^d\left(t\right) + a_i^d\left(t\right)$
   i) Update positions: $x_i^d\left(t+1\right) = x_i^d\left(t\right) + v_i^d\left(t\right) + v_i^d\left(t+1\right)$
end.
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Design variables and constraints for isolated Footing optimization.

A code for design of RC isolated footing has been coded in matlab software in which the inputs has to be provided in matlab. Inputs required for footing are Axial load (P), column size (b and d), cover (d'), diameter of bars, grade of concrete (fck), footing size and safe bearing capacity of soil.

1. Assume self-weight of footing as 10% of Pu Self-weight $0.1 \times Pu$ Total load, P= $\frac{Pu \times 1.1}{1.5}$
2. Area of footing required, $A = \frac{P}{SBC}$
   - If square footing, then size of footing: B or L = $\sqrt{A}_{reqd}$
   - If rectangular footing, assume one side L Then, B= $\frac{A}{L}$
3. Upward soil pressure: $P_{uplift=} \frac{P}{A} + \frac{M}{1.5Zx}$ Were, sectional modulus $Z_x = \frac{bd^2}{A}$
4. BM calculations: a. Moment along x-x passing: $Muyy = PuB\left(\frac{L-l}{2}\right)\left(\frac{L-l}{4}\right)$
   - Moment along y-y passing: $Muxx = PuL\left(\frac{B-b}{2}\right)\left(\frac{B-b}{4}\right)$
5. Calculation of depth required: The maximum moment (Mumax) is considered for further design and the depth required according to IS 456:2000 will be [8].

$$\mathrm{Mu\,lim}\ 0.36 \frac{Xu\max}{d}\left(1\ 0.42 \frac{Xu\max}{d}\right) \mathrm{Fckbd}^2$$

6. Area of tensile reinforcement [14]:

$$A_{st\min} = 0.0012\,\mathrm{BD}$$

Area of one bar, ast ast $= \frac{\pi d^2}{4}$

Spacing for the reinforcement, Sv

$$S_v = \frac{ast}{Ast}$$

7. Check for one-way shear: Shear force, V_u

$$V_u = P_{uplift} B\left(\left(\frac{L-D}{2}\right) - d\right)$$

Shear stress $\tau_v \tau_v = \frac{V_u}{bD}$

Percentage of steel provided $p_t p_t = \frac{100 A_{st}}{bD}$

The design shear is calculated according to SP16 will be [8]

$$\tau_c = \frac{0.85\sqrt{0.8 f_{ck} (\sqrt{1+5\beta-1}}}{6\beta}$$

Condition for one-way shear check: If, τv < τc, safe in oneway shear.

8. Check for two way shear: The critical section will lie at a distance of d from the face of
the column

$$V_u = P_{uplift} B(A-(D+d)^2$$

Nominal shear stress τ_v

$$\tau_v = \frac{V_u}{b_o D}$$

Where, b_o o perimeter:

$$b_o = 2(D+d) + 2(\mathrm{B}+\mathrm{b})$$

$$\tau_c = 0.25 F_{ck}$$

Condition for two-way shear check:
If, τv < τc, safe in two-way shear.

9. Development length of bar is calculated from clause 26.2.1 of IS-456-2000 [14].

$$L_d = \frac{\phi \sigma_s}{4\tau_{bd}}$$

4 RESULTS AND DISCUSSIONS

Results were found by traditional method for evaluating parameters for RC column footing as well as by the proposed method which uses Gravitational search algorithm for optimization of different attributes of column footing. In this work, numerical example has been taken from [4].The input parameters used are given in the Table 1.

Table 1: *Input parameters used for the design of RCC column footing*

Parameter	Value
Length	400 mm
Breadth	400 mm
Diameter of longitudinal bars carrying service loads	[16 17 18 19 20]
Service Load	1500 kN
Type of concrete mix	M 20
Type of steel Grade	Fe 415
Safe bearing Capacity of soil	250 kN/m2

Table 2: *Parameters evaluated for isolated column footing with and without optimization process*

Parameters	Unit	Value Optimized without using GSA	Optimized value using GSA optimizer
Sizing the footing	m * m	2.6 m * 2.6 m	2.6 m * 2.6 m
factored soil pressure (p) or Moment of resistance	N/mm^2	0.3328	0.3328
Bending Moment at the face of column (Mu)	KN.m	523.5	523.5
Allowable Moment of resistance	KN.m	0.138 * f_{ck} * b*d^2	0.138 * f_{ck} * b*d^2
effective depth required (d)	mm	963.64	963.84
Area of tension reinforcement (Ast)	mm^2	3187.54	3150.196
Number of bars		16 bars	16 bars
Diameter of bars	mm	16	16
Spacing of bars (S)	mm	164.2667	162.20 mm
Maximum shear stress permitted (Tauc1)	N/mm^2	0.2683	0.2697
Nominal shear stress (tauv1) for one way shear	N/mm^2	0.2534	0.2402
Maximum shear stress permitted for two way shear (Tauc2)	N/mm^2	1.1180	1.1180
Nominal shear stress (tauv2) for two way shear	N/mm^2	0.3103	0.3073
Development Length (Ld)	mm	752.1875	752.1875

As shown in the table above, first manual optimization is carried out without using any optimization technique on the example given in [4]. The idea behind this is to increase effective depth by 50mm in a sequence unless nominal shear stress less than the maximum stress is achieved. Further, similar work is tried to be optimized using gravitational search algorithm which selects random values of effective depth from 50 mm to 1000mm and try to converge the solution for the constraints of maximum one way and two shear stresses and keep the nominal stresses below this value.

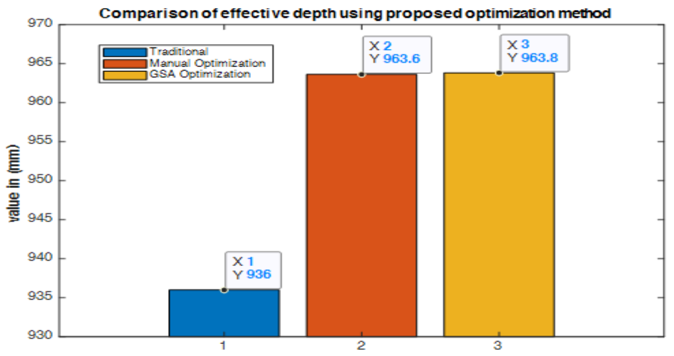

Figure 3: *Comparison of effective depth using proposed optimization method*

Manual optimization reduced area of steel and no. of bars from 3484 mm^2 to 3187.54 mm^2 which is 296.46 mm^2 or 8.5092 % of steel area reduction in withstanding the desired one way and two shear forces.

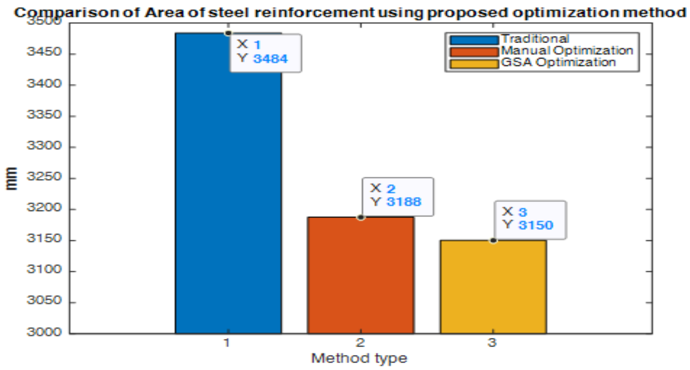

Figure 4: *Comparison of Area of steel reinforcement using proposed optimization method*

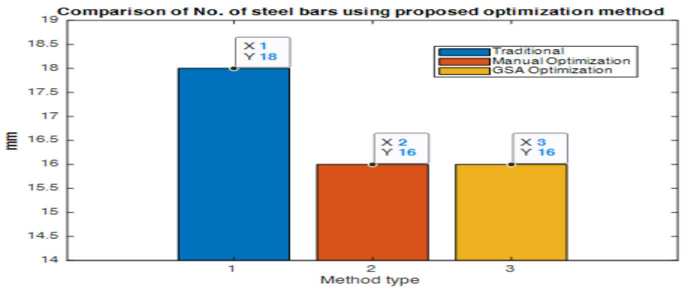

Figure 5: *Comparison of No. of steel bars in both directions using proposed optimization method*

It has been found that proposed GSA optimizer further reduces needed area of steel with 333.46 mm^2 less quantity of steel than the traditional method. Hence results in 9.5712 %

decrease in Area of steel. This has been compromised by getting an optimized effective length that has been increased to 963.6mm and 963.84 for manual and GSA based optimized respectively.

CONCLUSION

As the optimisation is solved, a set of design dimensions is obtained, and the geo-structure is specified or designed that not only satisfies all design requirements, but also results in the minimum construction cost. Comparison of the economically optimised design example with conventional designs shows that the savings in construction cost could be as much as 8% in steel reinforcement, reduced number of steel bars which has been compensated by the effective length. After running few iterations, GSA converges to the optimum solution and provides all details of reinforcement required for a partial axial load of beam and self-weight of footing. The proposed method can be used for any type of initial parameters and optimum values can be obtained from the algorithm. The motive of present work was taken from beam optimization process found in existed literature. And this work is an advancement to add column footings optimization if axial load of the beam on column ad footing is available. Further work can be amended to consider combined type of isolated footing which has two columns on the sides.

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