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Cost Minimization Of Reinforced Concrete Pile Cap Using Optimization Techniques

Regupathi R[1], Sugumar R[2]

[1]*Department of Civil Engineering, Government College of Engineering, Bodinayakanur, Tamilnadu, India,*
[2]*Scientist/Engineer 'SC'(Civil), Vikram Sarabhai Centre, Trivendrum, Kerala, India,*

Abstract- *In general the optimization techniques enable designers to find the best economical design for the structure under consideration. In this paper, Cost Minimization of RC pile cap using Optimization techniques such as fmincon SQP algorithm is presented. The cost of RC structures is influenced by several cost items including the cost of concrete and reinforcement. Therefore in case of RC structures, the minimum weight design is not necessarily the same as the minimum cost design. In fact, for RC structures the optimum cost design is a compromise between the consumption of concrete, reinforcement which minimizes the total cost of the structure and satisfies the design requirements. The structure is designed economically without impairing the functional purposes of the structural elements is supposed to serve and not violating provisions given in IS456-2000 & IS 2911 (part I)-2010 using the cross-sectional dimensions & area of longitudinal steel as design variables. An fmincon solver is incorporated with a cost function & constraint function as an alternative to traditional iterative methods for cost optimization of RC elements. An fmincon SQP Algorithm Program has been developed for the cost optimization of reinforced pile cap using MATLAB software. In order to validate the developed program for the proposed RC pile caps, conventional design was arrived with manual calculation and the results were compared.*

Keywords *– SQP Algorithm, Evolutionary Algorithm, Cost Optimization, Iterative Procedure, Constraint Function .*

I. Introduction

Optimum design of structures has been the topic of many studies in the field of structural design. A designer's goal is to develop an "optimal solution" for the structural design under consideration. An optimal solution normally implies the most economic structure without impairing the functional purposes the structure is supposed to serve. There are some characteristics of RC structures which make design optimization of these structures distinctly different from other structures. The cost of RC structures is influenced by several cost items including the cost of concrete and reinforcement. Therefore, in case of RC structures, the minimum weight design is not necessarily the same as the minimum cost design. In fact, for RC structures the optimum cost design isa compromise between the consumption of concrete, reinforcement which minimizes the total cost of the structure and satisfies the design requirements. In the design optimization of RC structures the cross-sectional dimensions of elements and detailing of reinforcement, e.g. size and number of steel bars, need to be determined. Consequently, the number of design parameters that need to be optimized depends on cracking and durability requirements of RC structures. These requirements increases the number of design constraints of the optimization problem of RC structures. The reinforced concrete (RC) elements may be subjected to axial loads, Bending Moment, Shear Force. The width, depth and area of longitudinal reinforcement of member sections are taken as the design variables. The optimality criteria (OC) method is applied to minimize the cost of the concrete, steel and formwork for the structure.

A. Literature Review

The optimality criteria method has been applied to various field of structural Optimization. This method is more efficient for design optimization of large scale Problems when the number of constraints is small compared to the number of design variables. In this method, the optimization problem is treated as a continuous problem (Andres Guerra et al. (2002)). The use of modern Heuristic Optimization techniques is rapidly increasing. They have become increasingly popular for solving optimization problems in these recent decades. These techniques have been made possible optimization of a large-scale structure according to practical design codes. These techniques can be used for solving continuous or discrete optimization problems (Govindaraj et al. (2004)). In RC structures, the cost of concrete, reinforcement and formwork can be involved in the total cost of the structure. Therefore, the minimum weight for these structures is not necessarily equivalent to the minimum cost, or in other Words, the total cost of the structure is not generally proportional to its weight (Richard et al.(2004)). In most structural design optimization problems, design variables are essentially discrete. For example, the area of a reinforcing bar can take some discrete values from the catalogue. However, in many publications in the field of structural optimization the problem has been treated as a continuous problem (Charles et al.(2008)).

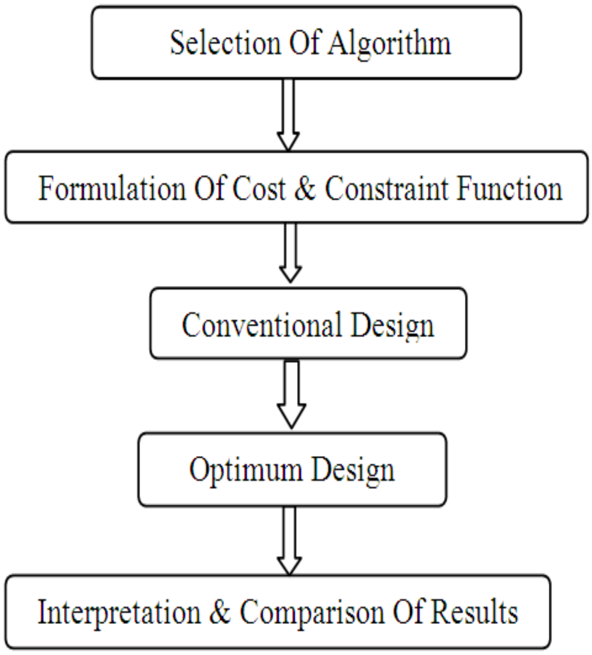


Fig. 1 Flowchart of Working Principle of a GA

II. OPTIMIZATION TECHNIQUES

Optimization is a branch of mathematics which is concerned with obtaining the conditions that give the extreme value of function under given circumstances. An optimization problem can be mathematically stated as follows:

Find $\boldsymbol{X} = (x1, x2, \ldots, an)$ which minimizes $if(\boldsymbol{X})$ I =1, 2, . . .,

Subject to

$g\,j\,(\boldsymbol{X}) \leq 0,\ j = 1, 2, \ldots, ng$

$He(\boldsymbol{X}) = 0,\ k = 1, 2, \ldots, ne$

$x^l_m \leq x_m \leq x^u_m = 1, 2, \ldots, ns$

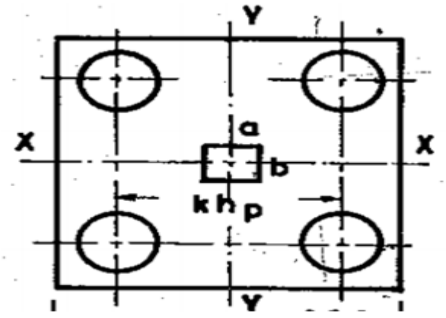
Where X is the vector of n design variables, $if(\boldsymbol{X})$ is an objective or merit function, $gj(\boldsymbol{X})$ and $he(\boldsymbol{X})$ are the inequality and the equality constraints, respectively. These constraints represent limitations on the behavior or performance of the system. Therefore, they are called behavioral or functional constraints. Side constraints restrict the acceptable range of potential solutions of the problem based on non-behavioral constraints. In this expression x^l_m, x^u_m is the lower and upper limits on the design variable, respectively. In the above expressions ng, ne and ns are the number of objective functions, number of inequality, equality and side constraints, respectively. Depending on the specific choice of design variables, objective functions, and constraints, various types of optimization problems may exist.

A. Fmincon SQP Algorithm

Fmincon SQP methods represent the state of the art in nonlinear programming methods. Schittkowski has implemented and tested a version that outperforms every other tested method in terms of efficiency, accuracy, and percentage of successful solutions, over a large number of test problems. Based on the work of Biggs , Han , and Powell , the method allows one to closely mimic Newton's method for constrained optimization just as is done for unconstrained optimization. At each major iteration, an approximation is made of the Hessian of the Lagrangian function using a quasi-Newton updating method. This is then used to generate a QP sub problem whose solution is used to form a search direction for a line search procedure. The SQP algorithm takes every iterative step in the region constrained by bounds. Furthermore, finite difference steps also respect bounds. Bounds are not strict; a step can be exactly on a boundary. This strict feasibility can be beneficial when your objective function or nonlinear constraint functions are undefined or are complex outside the region constrained by bounds. During its iterations, the SQP algorithm can attempt to take a step that fails. This means an objective function or nonlinear constraint function you supply returns a value of Inf, NaN, or a complex value. In this case, the algorithm attempts to take a smaller step. The sqp algorithm uses a different set of linear algebra routines to solve the quadratic programming sub problem, These routines are more efficient in both memory usage and speed than the active-set routines.

III.DEVELOPMENT OF OPTIMIZATION PROBLEM

A column 550 mm square has to carry a factored load of 2600 kN to be supported on 4 piles each of 450 mm diameter and spaced at 1350 mm centers. Suitable pile cap was optimized assuming M25 and Fe415.



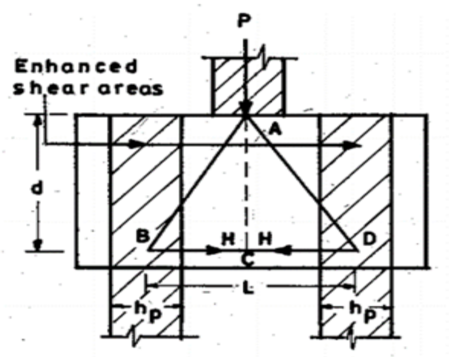


Fig. 2.Truss action in pile cap

Design Parameters:Cc=3500/m3, Cs=60/Kg, Cf =320/m3, M25 and Fe415.

A.Objective Function

The objective function consists of sum of cost of the concrete, cost of steel reinforcement, cost of formwork involved in the particular structure.

Function = concrete cost + steel cost + formwork cost

Function = $(C_c*((B^2*(d+d') – 2*A_{st}) + (C_s*A_{st}*L*\dot{\rho}) +$
$(C_f*(((2*D+B)*L)-4*d_p)$;

B.Design Constraints

Constraints are nothing but conditions which must be satisfied according to relevant Indian Code (IS 2911(part I)-2010) to arrive the design satisfying both safety & serviceability criteria

- $d \leq 2*d_p + 100$ % Maximum depth
- $d > S/2$ % Minimum depth
- $d/a_v > 2$ % Truss Action
- $A_{st} > 0.12\%$ % Minimum Reinforcement
- $T < P*(3L^2-b^2)$ % Tension Force
- $\tau_v < \tau_c * (2d/a_v)$ % Check for Shear

TABLE 1. ITERATION VALUES OF PILE CAP OPTIMIZATION

Iteration	F(x)
0	4.444545e+003
1	6.075217e+003
2	9.359094e+003
3	1.365654e+004
4	1.432142e+004
5	1.432142e+004

In Iteration process ,at first there will be a huge violation in satisfying the constraints, on further process of iteration the constraints are satisfied and at one point it reach the optimality characteristics.

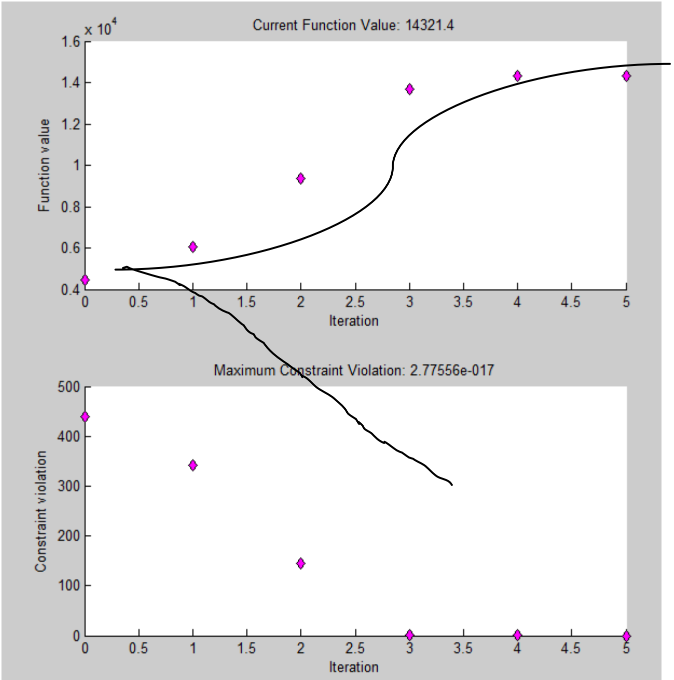


Fig.3.Objective function value & constraint violation for pile cap

C. Optimization process for Pile Cap

fmincon solverwith SQP algorithm is used to find the constraint and non-linear optimization. The optimized results satisfied all the constraints as per IS 2911(part I)-2010. The optimization process will be terminated when the objective function is non decreasing in feasible directions, to within the default value of function tolerance, and constraints were satisfied.

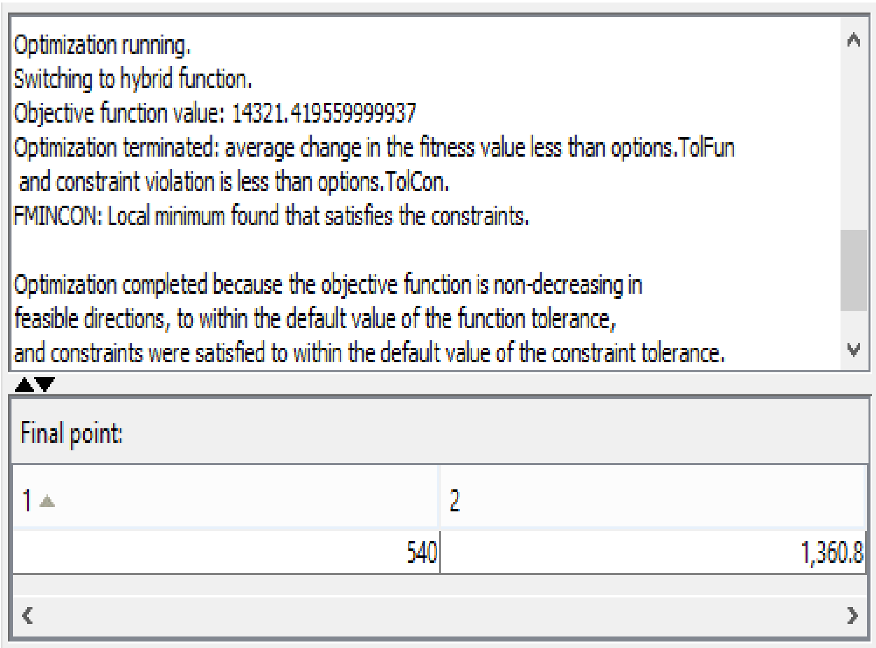


Fig. 4. Optimization process for pile cap

IV. COMPARATIVE STUDY ON AXIALLY LOADED COLUMN

The sizes, reinforcement of axially loaded column for different grades concrete& steel are compared between optimized design and conventional design as given in Table 2.

TABLE 2. COMPARATIVE RESULTS OF SIZE & REINFORCEMENT OF COLUMN

Case	Pu (kN)	f_{ck}	f_y	Breadth (mm)		Depth (mm)		Area of Steel (mm^2)	
				$b_{con.}$	$b_{opt.}$	$d_{con.}$	$d_{opt.}$	A_{stc}	A_{sto}
1	1000	20	415	275	315	275	315	1465	788
2	1000	25	415	250	290	250	290	1398	660
3	1000	20	250	275	330	275	330	2476	870
4	1000	25	250	250	300	250	300	2380	720

TABLE 3 COMPARATIVE RESULTS OF COST OF COLUMN

Case	Conventional Cost in Rs	Optimized Cost in Rs	% of saving
	$C_{con.}$	$C_{opt.}$	P_s
1	3905	3343	14.30
2	3576	2890	19.18
3	5322	3602	32.31
4	4954	3106	37.30

The sizes, reinforcement of singly reinforced beam for different grades concrete& steel are compared between optimized design and conventional design as given in Table 4

TABLE 4 COMPARATIVE RESULTS OF SIZE & REINFORCEMENT OF BEAM

Case	M_u (kNm)	f_{ck}	f_y	Breadth mm		Depth mm		Area of Steel mm^2	
				$b_{con.}$	$b_{opt.}$	$d_{con.}$	$d_{opt.}$	A_{stc}	A_{sto}
1	145.00	20	415	300	235	470	470	1002	1128
2	145.00	25	415	300	220	450	440	1020	1140
3	145.00	20	250	300	240	470	500	1663	1603
4	145.00	25	250	300	240	450	480	1694	1626

TABLE 5 COMPARATIVE RESULTS OF COST OF BEAM

Case	Conventional Cost in Rs	Optimized Cost in Rs	Percentage of saving
	$C_{con.}$	$C_{opt.}$	$P_{saving.}$
1	8404	7772	7.52
2	8252	7506	9.04
3	10259	9677	5.71
4	10143	9455	6.78

A. Comparative Study On Rc Pile Cap

The sizes, reinforcement of pile cap for different grades concrete& steel are compared between optimized design and conventional design as given in Table 6

TABLE 6COMPARATIVE STUDY OF SIZE & REINFORCEMENT OF PILE CAP

Case	P_u (kN)	f_{ck}	f_y	Breadth mm		Depth mm		Area of Steel mm^2	
				B_{con}	B_{opt}	D_{con}	D_{opt}	$A_{st\,con}$	A_{stopt}
1	2600	20	415	2100	2100	675	540	1701	1360
2	2600	25	415	2100	2100	675	540	1701	1360
3	2600	20	250	2100	2100	675	530	1663	1603
4	2600	25	250	2100	2100	675	530	1694	1626

TABLE 7 COMPARATIVE STUDY OF COST OF PILE CAP

Case	Convention al Cost in Rs	Optimized Cost in Rs	Percentage of s aving
	$C_{con.}$	$C_{opt.}$	P_s
1	17260	14321	17.02
2	17260	14321	17.02
3	20475	18575	9.2
4	20475	18575	9.2

V.CONCLISIONS

Concrete is a cheap & economical material in resisting compression. Therefore usage of higher grade of concrete and lower grade of steel in axially loaded column members leads to optimized design. Beams are flexural members, should be capable of resisting both bending tension & bending compression. Therefore usage of higher grades of both concrete and steel materials will lead to optimized solution. Pile caps subjected to heavy loads obviously be very deep and it is analogous to Truss. Hence the pile cap designed by truss theory must have sufficient depth of concrete & suitable tension reinforcement at the bottom. Therefore use of higher grade of steel reinforcement leads to optimized design.

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