Optimal Design of Axially Loaded RC Columns

G. Preethi and Prince G. Arulraj

Abstract--- *The aim of this investigation is to achieve optimal design of reinforced concrete columns. Optimal design of columns gives economical results in cost saving. This optimum results provides the designers to indentify the best design for the structures. The most economic structure means that could able to withstand the structure without impairing any damages and supposed to serve as a best design of a structure. The objective function is the total cost of the column. The cost of each column includes the cost of concrete and reinforcement. The optimization process is done for different grade of concrete and diameter of rods. The optimal design is carried out using MATLAB's (The Mathworks, Inc.) software. Optimization problem is formulated which is a Nonlinear constrained minimization problem. This is solved using fmincon SQP Algorithm. Each of the designed columns was handled by fmincon SQP Algorithm solver according to its loading condition specifications. Many solved examples are developed and proved that the optimal design is economical. Also it is proved that the developed program is efficient and versatile.*

Keywords--- *Optimization, Nonlinear Programming Problem, Constrained Nonlinear Minimization, SQP Algorithm, Matlab, Columns*

I. Introduction to Optimization of RC Elements

OPTIMIZATION is the process of finding a minimum or maximum value of a function for some constraints. The optimization approach is based on the design of reinforced concrete columns. Optimum design of reinforced concrete elements plays an important role in economical design of reinforced concrete structures. An attempt has been made to achieve the optimal design of RC columns can be done by using matlab software. The optimization problem is resolved by formulating the design variables for the structural elements. The objective function was the total cost of the concrete element is the sum of the costs of its constituent materials, the transportation cost, fabrication, mixing, placing, compacting and curing cost. During the present study, Optimization process is done for different grades of concrete and diameter of rods. The optimization problem is a Constrained Nonlinear minimization problem and is solved by using fmincon SQP Algorithm of matlab. The cost function represent the cost of concrete and reinforcement. The results obtained from the analytical study is carried out based on effect of grade of concrete and diameter of reinforcement is achieved with minimum cost construction. Design of RC column has been ensured under the provision of IS : 456-2000. Many solved examples are developed for the design optimization of columns. In such a situation an optimization procedure can help designers to find the best design or at least, a good design among different possible designs. The efficiency of the sqp algorithm was examined and found to be good. All the examples proved that the results are economical and gives minimum construction cost.

II. Formulation of Optimization Problem

In a more advanced formulation, the objective function, f(x), to be minimized or maximized, might be subject to constraints in the form of equality constraints, $G_i(x) = 0$ ($i = 1,...,m_e$); inequality constraints, $G_i(x) \leq 0$ ($i = m_e + 1,...,m$); and/or parameter bounds, x_l, x_u.

The general optimization problem has the form given in Equation (1)

$$\min_x f(x) \quad (1)$$

subject to

$$G_i(x) = 0 \quad i = 1,...,m_e$$

$$G_i(x) \leq 0 \quad i = m_e + 1,...,m$$

$$x_l \leq x \leq x_u$$

Equality constraints are called m_e.

III. Optimization of RC Columns

Optimization of RC columns are used to examine the advantages of a design such as minimum construction cost. Which gives safety, serviceability and economy of a structure. Some restrictions, called design constraints, may limit the acceptable values of the design variables.

A. Objective Function

The objective function is a criterion by which one or many acceptable designs are preferred to others. It is often assumed that the objective function has to be minimized but in some cases maximization of the objective function (e.g. maximization of mechanical efficiency) is aimed. Although in many cases the weight of structure is considered as the objective function. The total cost of RC structure is considered as the objective function. In general, the cost function may include the initial cost, maintenance cost and expected failure cost. In this research the minimization of the cost of the column is carried out.

B. Design Constraints

The constraints reflect design requirements in the optimization problem. In other words they limit the range of acceptable designs in the problem. In this research, the constraints relevant to the design of RC column are applied using function.

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C. *Starting Solution*

Starting solution is nothing but initial point where solver begins its search for a minimum value between this ranges.

IV. Effect of Concrete Grade on the Cost Column

Optimal Design of RC Columns

In this section, the RC column of cross section is described, showing the fixed parameters, the design variables, the design constraints and the objective function.

Column By Limit State Method (b = 230(constant), P_u = variable, Grade of concrete = variable, f_y = 415 N/mm^2)

Objective Function

$$(X_1 X_2 - X_3) 0.008 + X_3 0.43175$$

where:

- X_1 = b = width of column
- X_2 = d = depth of column
- X_3 = A_{sc} = Area of longitudinal reinforcement for column
- 0.008 = C_c = Cost factor for concrete
- 0.43175 = C_s = Cost factor for steel

Design Constraints

i. Axial load on the member

$$0.4 f_{ck} A_c + 0.67 f_y A_{sc} \geq P_u$$

ii. Maximum reinforcement percentage is incorporated in the following constraint

$$X_3 / X_1 X_2 \leq 0.06$$

iii. Minimum reinforcement percentage is incorporated in the following constraint

$$X_3 / X_1 X_2 \geq 0.008$$

iv. Width of the column

$$X_1 = 230$$

Starting Solution

$$X_0 = [\ 200\ 200\ 600\ ]$$

where:

- A_{sc} = Area of longitudinal reinforcement for column
- A_c = Area of concrete
- A_g = Gross area of concrete section
- P_u = Factored axial load on the member
- f_{ck} = Characteristic compressive strength of the concrete
- f_y = Characteristic strength of the compression reinforcement
- X_1 = b = width of column
- X_2 = d = depth of column
- X_3 = A_{sc} = Area of longitudinal reinforcement for column

MATLAB Programs

Objective Function

```
function f=objfun(x)
f = (x(1)*x(2) - x(3))*0.008 + x(3)*0.43175;
end
```

Constraints

```
function [c,ceq]=confun(x)
c = [-8*(x(1)*x(2) - x(3)) - 278.05*x(3) + 7.5*10^5;
-0.06 + x(3)/(x(1)*x(2));
-x(3)/(x(1)*x(2)) + 0.008];
ceq = x(1) - 230;
end
```

The output of the above function is given in following Tables

Effect of Grade of Concrete on the Cost of Column

In order to determine the effect of grade of concrete on the cost of R.C columns, the optimal design of columns were found for various grade of concrete. The details of the optimal design are given in Table 1 for the factored load of 750 kN

Table 1: Optimal Results for the Design of Columns for a Factored Load of 750kN

Grade of Concrete	*b(mm)*	*d(mm)*	*A_{sc}(mm^2)*	*Cost(Rs)*
M20	230	320.94	590.53	840.76
M25	230	268.51	494.06	734.04
M30	230	230.80	424.68	657.29
M35	230	230	423.2	602.53
M40	230	230	423.2	602.53
M45	230	230	423.2	602.53
M50	230	230	423.2	602.53

From Table 1, it can be seen that the cost of the column is least when M_{35} grade of concrete is adopted.

The results of the optimization problem for a factored load of 1000kN is given in Table 2

Table 2: Optimal Results for the Design of Columns for a Factored Load of 1000kN

Grade of Concrete	*b(mm)*	*d(mm)*	*A_{sc}(mm^2)*	*Cost(Rs)*
M20	230	427.92	787.37	1121.02
M25	230	358	658.74	978.72
M30	230	307.74	566.24	876.39
M35	230	269.84	496.51	800
M40	230	240.26	442.08	739.04
M45	230	230	423.2	602.53
M50	230	230	423.2	602.53

From Table 2, it can be seen that the cost of the column is least when M_{45} grade of concrete is adopted.

The results of the optimization problem for a factored load of 1250kN is given in Table 3

Table 3: Optimal Results for the Design of Columns for a Factored Load of 1250kN

Grade of Concrete	*b(mm)*	*d(mm)*	*$A_{sc}(mm^2)$*	*Cost(Rs)*
M20	230	534.90	984.21	1401.27
M25	230	447.51	832.43	1223.40
M30	230	384.67	707.79	1095.49
M35	230	337.30	620.64	1000
M40	230	300.32	552.60	923.80
M45	230	270.65	498	1141.29
M50	230	246.32	453.22	1319.66

From Table 3, it can be seen that the cost of the column is least when M_{40} grade of concrete is adopted.

The results of the optimization problem for a factored load of 1500kN is given in Table 4

Table 4: Optimal Results for the Design of Columns for a Factored Load of 1500kN

Grade of Concrete	*b(mm)*	*d(mm)*	*$A_{sc}(mm^2)$*	*Cost(Rs)*
M20	230	641.88	1181.06	1681.53
M25	230	537.02	988.11	1468.08
M30	230	461.61	849.35	1314.59
M35	230	404.77	744.77	1198.89
M40	230	360.78	663.12	1108.56
M45	230	324.78	597.60	1369.54
M50	230	295.56	543.86	1583.59

From Table 4, it can be seen that the cost of the column is least when M_{40} grade of concrete is adopted.

The results of the optimization problem for a factored load of 1750kN is given in Table 5

Table 5: Optimal Results for the Design of Columns for a Factored Load of 1750kN

Grade of Concrete	*b(mm)*	*d(mm)*	*$A_{sc}(mm^2)$*	*Cost(Rs)*
M20	230	748.86	1377.90	1961.78
M25	230	626.52	1152.80	1712.76
M30	230	538.54	990.91	1533.68
M35	230	472.23	868.90	1398.71
M40	230	420.45	773.64	1293.32
M45	230	378.91	697.20	1597.80
M50	230	344.84	634.51	1847.52

From Table 5, it can be seen that the cost of the column is least when M_{40} grade of concrete is adopted.

The results of the optimization problem for a factored load of 2000kN is given in Table 6

Table 6: Optimal Results for the Design of Columns for a Factored Load of 2000kN

Grade of Concrete	*b(mm)*	*d(mm)*	*$A_{sc}(mm^2)$*	*Cost(Rs)*
M20	230	855.84	1574.74	2242.04
M25	230	716.02	1317.48	1957.45
M30	230	615.47	1132.47	1752.78
M35	230	539.69	993.02	1598.52
M40	230	480.52	884.15	1478.08
M45	230	433.04	796.80	1826.06
M50	230	394.10	725.15	2111.46

From Table 6, it can be seen that the cost of the column is least when M_{40} grade of concrete is adopted.

V. Effect of Reinforcement Diameter on The Cost Column

In order to determine the effect of diameter of reinforcement on the cost of R.C columns, the optimal design of columns were found for various diameter of reinforcement. The details of the optimal design are given in Table 7 for the factored load of 750kN. The grade of concrete assumed was M_{35}.

Table 7: Optimal Results of Various Diameter of Reinforcement for a Load of 750kN

Dia of Rods	*b(mm)*	*d(mm)*	*$Asc(mm^2)$*	*$A_{sc\ pro}$ (mm^2)*	*Cost (Rs)*
12	230	230	423	452	693
16	230	230	423	603	757
20	230	230	423	628	768
25	230	230	423	981	917
32	230	230	423	1608	1181
40	230	230	423	2512	1563

From Table 7, it can be seen that 12mm diameter of reinforcement give the least cost.

The results of the optimization problem for a load of 1000kN for M_{45} grade of concrete are given in Table 8.

Table 8: Optimal Results of Various Diameter of Reinforcement for a Load of 1000kN

Dia of Rods	*b(mm)*	*d(mm)*	*$Asc(mm^2)$*	*$A_{sc\ pro}$ (mm^2)*	*Cost (Rs)*
12	230	230	423	452	982
16	230	230	423	603	1045
20	230	230	423	628	1055
25	230	230	423	981	1202
32	230	230	423	1608	1464
40	230	230	423	2512	1840

From Table 8, it can be seen that 12mm diameter of reinforcement give the least cost.

The results of the optimization problem for a load of 1250kN for M_{40} grade of concrete are given in Table 9.

Table 9: Optimal Results of Various Diameter of Reinforcement for a Load of 1250kN

Dia of Rods	*b(mm)*	*d(mm)*	*$Asc(mm^2)$*	*$A_{sc\ pro}$ (mm^2)*	*Cost (Rs)*
12	230	300	553	565	929
16	230	300	553	603	945
20	230	300	553	628	956
25	230	300	553	981	1105
32	230	300	553	1608	1369
40	230	300	553	2512	1750

From Table 9, it can be seen that 12mm diameter of reinforcement give the least cost.

The results of the optimization problem for a load of 1500kN for M_{40} grade of concrete are given in Table 10.

Table 10: Optimal Results of Various Diameter of Reinforcement for a Load of 1500kN

Dia of Rods	*b(mm)*	*d(mm)*	*Asc(mm²)*	$A_{sc\ pro}$ *(mm²)*	*Cost (Rs)*
12	230	360	663	678	1115
16	230	360	663	804	1168
20	230	360	663	942	1226
25	230	360	663	981	1243
32	230	360	663	1608	1507
40	230	360	663	2512	1888

From Table 10, it can be seen that 12mm diameter of reinforcement give the least cost.

The results of the optimization problem for a load of 1750kN for M_{40} grade of concrete are given in Table 11.

Table 11: Optimal Results of Various Diameter of Reinforcement for a Load of 1750kN

Dia of Rods	*b(mm)*	*d(mm)*	*Asc(mm²)*	$A_{sc\ pro}$ *(mm²)*	*Cost (Rs)*
12	230	420	774	791	1301
16	230	420	774	804	1306
20	230	420	774	942	1364
25	230	420	774	981	1381
32	230	420	774	1608	1645
40	230	420	774	2512	2026

From Table 11, it can be seen that 12mm diameter of reinforcement give the least cost.

The results of the optimization problem for a load of 2000kN for M_{40} grade of concrete are given in Table 12.

Table 12: Optimal Results of Various Diameter of Reinforcement for a Load of 2000kN

Dia of Rods	*b(mm)*	*d(mm)*	*Asc(mm²)*	$A_{sc\ pro}$ *(mm²)*	*Cost (Rs)*
12	230	481	884	904	1487
16	230	481	884	1005	1529
20	230	481	884	942	1502
25	230	481	884	981	1519
32	230	481	884	1608	1783
40	230	481	884	2512	2165

From Table 12, it can be seen that 12mm diameter of reinforcement is found to give least cost.

VI. CONCLUSION

A Matlab program for the optimization of reinforced concrete elements has been developed using Constrained Nonlinear minimization of fmincon SQP Algorithm. The main conclusions drawn from the current research can be summarized as follows:

- The efficiency of the SQP algorithm optimization was examined and found to be good.
- Optimization of R.C Columns indicate that minimum percentage of steel must be used as reinforcement. Higher percentage of steel results in higher cost.
- The effect of grade of concrete on the cost of Columns were studied and it was found that grade of concrete has an impact on the cost of R.C Columns. Here, M_{35}, M_{40} and M_{45} grade of concrete are found to give least cost.
- The effect of diameter of reinforcement on the cost of Columns were studied and it was found that diameter of concrete has an impact on the cost of R.C Columns. Here, 12mm diameters of reinforcement are found to give least cost.

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