

Design of Structural Element Employing Optimization Approach

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ABSTRACT: In the design and development of the structural configuration, many design engineers put extra time for repeated and well-defined tasks. The development of optimization approach which could be used to reduce such laborious jobs will increase the productivity of the organization. Till date there is no rational tool available in the market to portend the probable optimum design of building components. Optimization can be done with Generalized Reduced Gradient (GRG) method. This approach intends to reduce the computational costs normally associated with structural design problem.

The optimization techniques in general enable designer to find the best design for the structures under consideration. In this particular case, the principal design objective is to minimize the self-weight of RCC structural element. The resulting structure, not only give optimum size but also it give optimum cost with all strength & serviceability requirements for a given applied load. This approach necessitates iterations for coming up with an economical & safe design.

This study will provide the way to develop a programme in advance excel that can be used not only for the analysis and design of the building but also to estimate the optimum design of a building components such as beam, column. The present dissertation provides the comparison between regular IS code design and optimum design of components. Firstly the comparison between two optimization methods is done, after comparing both method most feasible method is selected and then with using that method structural elements are designed with optimization approach. For using classical method like GRG method ADVANCE EXCEL is used. SOLVER TOOLBOX is used to optimize the design problem which is non-linear in behavior.

The investigation is then carried out to study the use of optimization technique for design of structural element and similarly the comparative study of Standard design method and design optimization method. RCC singly reinforced beam and short axially loaded column analyzed and compared.

KEYWORDS: Generalized reduced gradient method, Sequential quadratic programming, Optimal member sizing, Reinforced concrete, Nonlinear programming, Design optimization

I. INTRODUCTION

In today's world of cut-throat competition and increased consumer demands, solutions often require not only feasible solution but most importantly it should be the most optimum solution. Maximization of profit and minimization of cost is the major objective of any industry nowadays. Optimization in broad sense is maximization or minimization of an objective function subject to certain conditions or constraints. In structural engineering design problems cost or weight of the structure is considered to be objective function subjected to stress, displacement constraints and variable bounds.

General form of optimization problem is consist of four sections such as constant parameters which are given, design variables are unknown which have to be find, objective function have to be minimized and design constraints have to be satisfied [8]. There are some characteristics of RCC structural element which makes design optimization of these structures distinctly different from other structures. The self-weight of RCC structural element is influenced by several weight items including the weight of concrete in RCC structural element and weight of steel in RCC structural element.

International Journal of Innovative Research in Science, Engineering and Technology

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Vol. 5, Issue 7, July 2016

Therefore, in RCC structure case, the minimum cost design is not necessarily the same as the minimum weight design requirement. But, it is totally different. In fact, for RCC structural element the optimum weight design is compromised between the consumption of concrete, reinforcement which minimizes the total self-weight of the structural element and satisfies design requirements. The self-weight optimization and cost optimization not necessarily same because in cost optimization sometimes cost of formwork or framework are also included. But it have similarities in design constraints because the requirement for design RC beam as per limit state method, IS 456-(2000) [9].

In the design optimization of RCC structural element, the cross-sectional dimension, reinforcement detailing, e.g. depth of structural element and area of steel required for structural element have to be determined. The number of design parameters required for RCC structural elements which have to be optimized is relatively more than steel structural elements. Two important characteristic properties of RCC structures are cracking and durability requirement. Simultaneously all other design requirements of RCC structures are considered while designing by employing optimization approach. All the limit state method requirements are considered for designing the RCC structural element [10]. Depend on that requirements optimization model is developed. Appropriate method or technique is depend upon type of problem [1].

This research focuses on studying the behaviour of self-weight optimization having uniformly distributed vertical loads on the structural elements like beam or column. The aim of the study is to develop design optimization models for simply supported singly reinforced beam and axially loaded short column using Generalized Reduced Gradient (GRG) method as an optimization technique.

II. LITERATURE REVIEW

H. Sudarshana Rao and B. Ramesh Babu, (2006), this paper demonstrates the design of short columns under biaxial bending with use of optimization techniques. In this research the optimization techniques used are artificial neural network (ANN) and genetic algorithm (GA). When the results of GA based hybrid neural network model compared with the results of optimizer for design of short column with biaxial bending, it is observed that the maximum difference between both methods is 1.6% only. The result predicted by hybrid neural network model are compared with solution of optimizer which uses the interior penalty function method as optimization technique which is one of the type of classical optimization technique and genetic algorithm is the type of non-traditional method In this paper the conclusion is made such that developed neural network model can provide a safe and economical design for the design of short columns under biaxial bending.

Matthias De Munck. et.al, (2015), this paper focuses the study on formation of problem statement. As we know the optimization is nothing but maximizing or minimizing the any function or our main target as per problem statement. Composite material itself maximize strengths by combining two or more than two materials and simultaneously if we see the composite material like FRP, CFRP and material used with light weight material it reduces the self-weight of the structure we can say it is practically done optimization of structure. In this paper it is multi-objective optimization is done, both cost and mass minimization of structure is done simultaneously. The method used for optimization is Non-dominated Sorting Genetic Algorithm (NSGA - II) and meta-model is used to get the optimum solutions. Meta-model is formed first before starting the optimization procedure by doing structural analysis and structural response. Here in this research work design variables used are cross-sectional dimensions of the structure to get optimum cost and weight both. Multi-objective optimization finds different solutions by changing design variables which minimize the objective and satisfy the all constraints requirements. Many optimization techniques are there to solve the constrained multi-objective problems. Appropriate method or technique is depend upon type of problem. NSGA – II method is popular, especially for strength, and it's no of engineering applications. Entire procedure of the optimization implemented in Matlab (Math work tool). First off all the initial population of individuals is founded, which defines the geometry. These responses of population are used to form new generation of population of individual and refine the choice of variable. The first step of optimization is to define the design variables. The different responses means objective function and constraints are formed in the form of design variables.

R. Deepan. et.al, March (2016), Optimum design of RC beam is done in this paper for two types of beam with two types of loading conditions that is concentrated load and uniformly distributed load. The RC beams are manually designed with limit state design as per IS 456-(2000). In this paper two different optimization techniques are used non-traditional and classical one. Design optimization of RC structures distinctly different from other structures due to some

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 7, July 2016

characteristics of RC structure. In this research the optimization of design parameters such as cross sectional dimension of element and detailing of reinforcement. In this paper also the cost optimization is set as a target which includes the cost of all materials used for structure such as cost of concrete, cost of steel and cost of framework. As the cost optimization is main aim, basically it is the type of size optimization. The self-weight optimization and cost optimization not necessarily same because in cost optimization sometimes cost of formwork or framework are also included. But it have similarities in design constraints because the requirement for design RC beam as per limit state method, IS 456-(2000). In this paper two methods used for optimization are classical and non-traditional technique satisfying all requirements such as limit state of serviceability, deflection and collapse. The codal provision not gives directly the optimal solution it just provide the bounds on the optimization. Which gives the feasible region where the possible design points are available. Some codal provision gives the lower and upper bound and some requirements provide the other strength feasibility for every optimized section. In this paper both singly reinforced beam and doubly reinforced RC beam is optimized. But to design the doubly reinforced beam, number of design variable required are more compared to singly reinforced beam. In this paper total four cases are done singly reinforced beam with concentrated load at centre, singly reinforced beam with uniformly distributed load, doubly reinforced beam with concentrated load at centre and doubly reinforced beam with uniformly distributed load. Comparison of accuracy between two methods are done. Non-traditional method used is Artificial Neural Network and traditional or classical method used for optimization is Gradient Decent Method. MS-Excel software is used for design give 96% accuracy over the classical method. Whereas optimization with ANN gives 98% of accuracy as compared with classical method.

Arnulfo Luevanos-Rojas, April (2016), in this paper the model for singly reinforced rectangular beam is developed. The model is analytical and it is developed to minimize the weight of beam and cost of beam. The model is developed for satisfy the design requirements as per code ACI 318S – 13. Nonlinear mathematical programming is used for problem formation. In this paper 4 cases are discussed two cases for weight optimization and 2 cases for cost optimization. In 2cases of material cost optimization constant parameters used are moment, depth, f_{ck} , f_y are taken constant and depth ρ , A_s and b where ρ is ratio of A_s to bd , A_s is area of steel and b is width of rectangular beam. Remaining 2 cases for weight optimization constant parameters are moment, width, f_{ck} , f_y and design variables are ρ , A_s , d . If we analyze the mathematical results of standard design method and optimal design method are equal.

III. PROBLEM FORMULATION

The general form of an optimization problem is as shown below:

1. Given - Constant Parameters
2. Find - Design variables
3. Minimize - Objective function
4. Satisfy - Design Constraint

The constant parameters for design of both structural elements, beam and column are given below in Table 1 and Table 2 respectively.

Table 1 Constant Parameters for Singly Reinforced Beam

Constant Parameter	Value	Unit
Effective span length (L)	3230	mm
f_{ck}	20	N/mm ²
F_y	415	N/mm ²
Nominal cover (d_c)	30	mm
Density of concrete (ρ_c)	25	kN/m ³
Density of steel (ρ_{st})	78.5	kN/m ³
External Imposed Load (W)	37.59	kN/m

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 7, July 2016

Table 2 Constant Parameters for Axially loaded Column

Constant Parameter	Value	Unit
Unsupported length (L)	3000	mm
f _{ck}	20	N/mm ²
f _y	415	N/mm ²
Nominal cover (d _c)	40	Mm
Density of concrete (ρ _c)	25	kN/m ³
Density of steel (ρ _{st})	78.5	kN/m ³
Width of column (b)	300	mm
Axial Load (P)	3000	kN

Design variables of beam

Width of beam = b = x₁

Overall Depth of beam = D = x₂

Area of steel in tension = A_{st} = x₃

Design variables for column design

One dimension of column = D = x₁

Area of steel in compression = A_{sc} = x₂

Objective function for beam

$$f(x) = \rho_c(bD - A_{st}) + \rho_{st}(A_{st}) \quad (1)$$

$$f(x) = 25 \times 10^{-6}(x_1x_2 - x_3) + 78.5 \times 10^{-6}(x_3)$$

$$f(x) = 25 \times 10^{-6}(x_1x_2) + 53.5 \times 10^{-6}(x_3) \quad (2)$$

Objective function for Column

$$f(x) = \rho_c(bD - A_{sc}) + \rho_{st}(A_{sc}) \quad (3)$$

$$f(x) = 25 \times 10^{-6}(bx_1 - x_2) + 78.5 \times 10^{-6}(x_2)$$

$$f(x) = 25 \times 10^{-6}(bx_1) + 53.5 \times 10^{-6}(x_2) \quad (4)$$

Design Constraints for simply supported rectangular beam

a) Geometrical Constraints

1. Ductility Constraint

$$x_u \leq x_{u \max} \quad (5)$$

2. Constraint for minimum area of tension steel

$$A_{st \min} \leq A_{st} \quad (6)$$

$$\frac{0.85 b d}{f_y} \leq A_{st} \quad (7)$$

3. Constraint for maximum area of tension steel

$$A_{st} \leq A_{st \max} \quad (8)$$

$$A_{st} \leq 0.04bD \quad (9)$$

(b) Behavioral constraints

1. Durability Constraint

$$\text{Nominal cover} \geq 20\text{mm} \quad (10)$$

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 7, July 2016

As above requirement is important as per durability criteria, but in present problem nominal cover is taken as constant parameter so it cannot be considered as constraint. Mathematically we can say constraint is that which contain at least one design variable. As it is important criteria for design section of beam this requirement is considered and depend on that requirement this constant parameter is fixed.

2. Moment equilibrium constraint

$$M_u \leq M_{u \text{ lim}} \quad (11)$$

3. Deflection constraint

$$\delta_{\text{actual}} \leq \delta_{\text{available}} \quad (12)$$

4. Shear constraint

$$\tau_v \leq \tau_{c \text{ max}} \quad (13)$$

Design Constraints for short axially loaded column

1. Slenderness limit for column

$$L \leq 60D \quad (14)$$

2. Minimum Eccentricity

$$e_{\min} = \frac{L}{500} + \frac{h}{30} \quad \text{but } \nless 20\text{mm} \quad (15)$$

$$\frac{L}{500} + \frac{h}{30} \geq 20\text{mm}$$

3. Axial Load

$$P_u = 0.4 f_{ck} A_c + 0.67 f_y A_{sc} \quad (16)$$

$$P_u = 0.4 f_{ck} (A_g - A_{sc}) + 0.67 f_y A_{sc} \quad (17)$$

4. Minimum Area of Compression Steel

$$0.008 A_c \leq A_{sc} \quad (18)$$

$$0.008 bD \leq A_{sc} \quad (19)$$

5. Maximum Area of Compression Steel

$$A_{sc} \leq 0.04 A_c \quad (20)$$

$$A_{sc} \leq 0.04 bD \quad (21)$$

6. Check for eccentricity ratio

$$\frac{e_{\min}}{b} < 0.05 \text{ or } \frac{e_{\min}}{D} < 0.05 \quad (22)$$

All mathematical programming is done which is required for optimization work. Problem formulation is done in the form of objective function, design variables are defined, constant parameters is decided and design constraints are formed which is most important part of the project which defines the feasible region for optimization work. Which gives the optimal solution between that region.

IV. ANALYSIS RESULTS

Figures (1) and (2) shows the optimization and design variables and self-weight for the RC simply supported singly reinforced beam and figure (3) and (4) shows the optimization of design variables and self-weight of short axially loaded column.

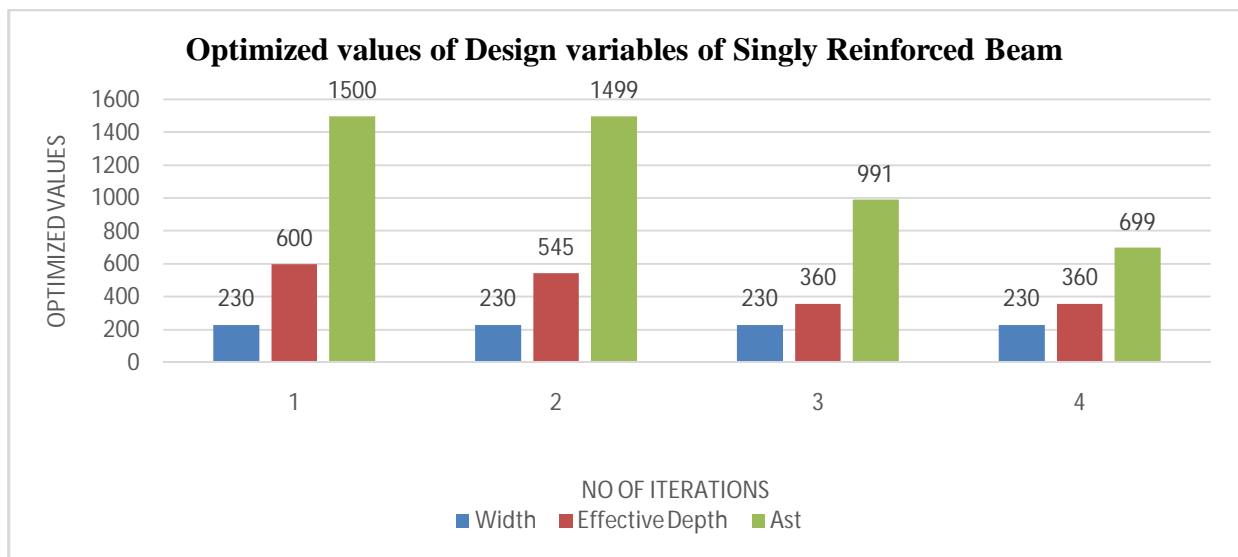


Fig. (1) Optimized values of Design variables of Singly Reinforced Beam

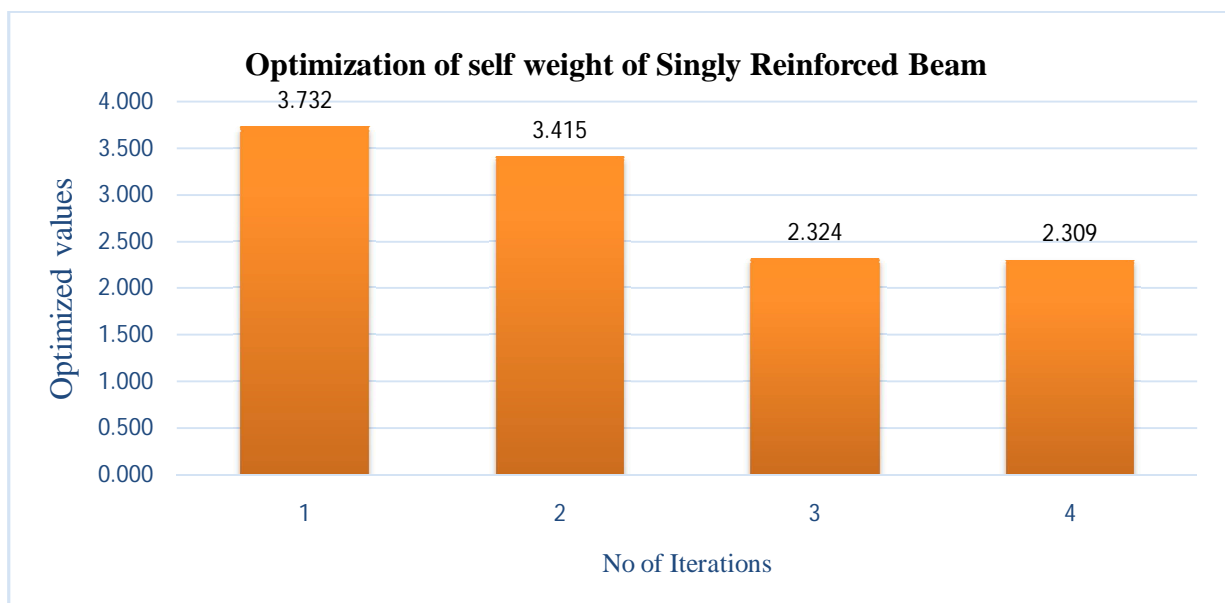


Fig. (2) Optimized values of Self-weight of Singly Reinforced Beam

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 7, July 2016

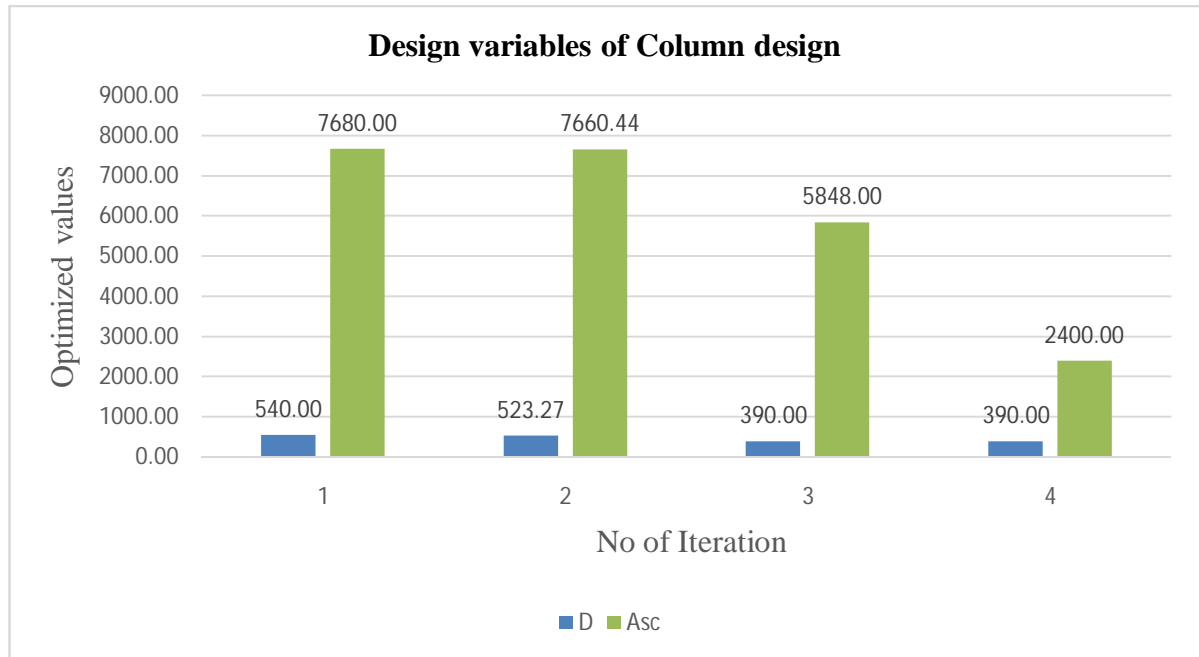


Fig. (3) Design variables of Column design

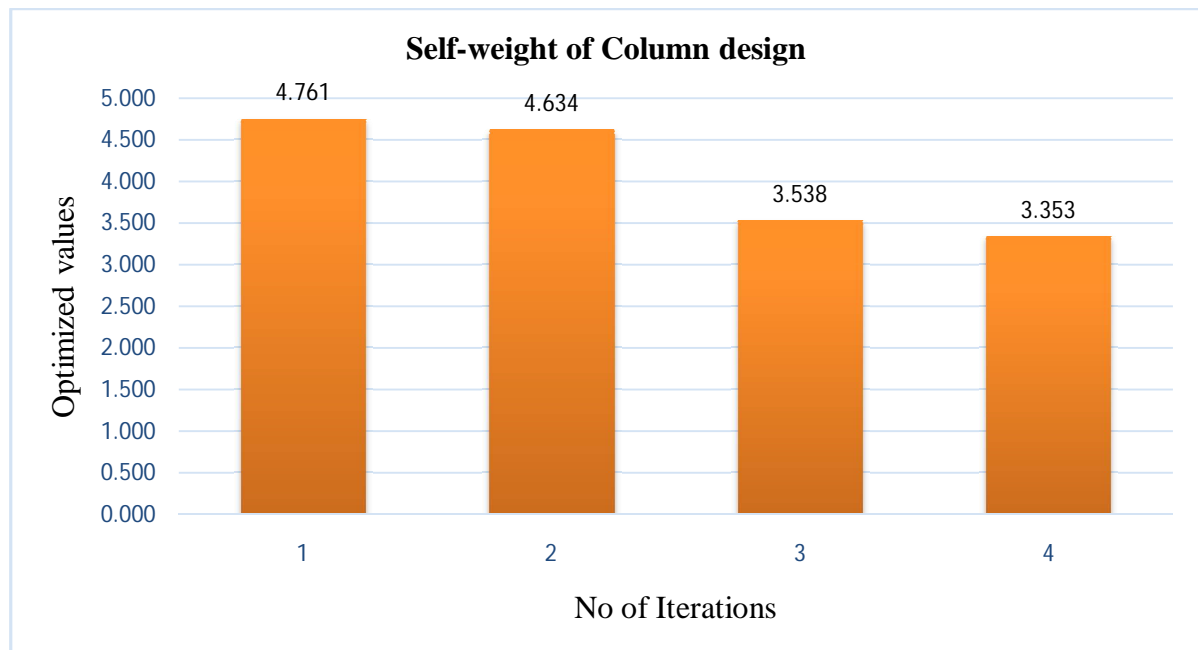


Fig. (4) Self-weight of Column design

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 7, July 2016

After comparisons between two methods GRG and SQP method for unit load instead of shown in table (1) and design optimization give difference between both results are very less so for beam and column design GRG method is used which is classical type of optimization technique.

V. CONCLUSION

- The study carried out on the numerical examples showed that when the bounds of the design variables were extended, the results obtained were better. Therefore, the design variables bounds should be set carefully to satisfy the aesthetic, architectural, practical and code limitation issues, but should not give rough values, since they affect the value of the optimum solution.
- In this study design optimization results are validated by comparing Excel Solver results with standard IS code design results & its appropriateness is established. The main basis is to understand the method of Generalized Reduced Gradient Method.
- The results obtained from the first optimization model SQP optimization technique showed a self-weight that is less than the self-weight obtained from the GRG technique by 1.1436 kN/m and 1.1457 kN/m for the RC beam problem respectively. This comparison showed the superiority of the SQP technique over the classical GRG technique. But the difference between both methods is too small so easiest method for handling is preferred for present study. Self-weight is reduced by near about 25% over IS code design and difference between both methods is about 0.18%.
- Simply supported singly reinforced beam, second optimization model gives result that self-weight of beam is reduced by near about 37% over standard IS code design method.
- Short axially loaded column, third optimization model gives result that self-weight of column is reduced by near about 29.57% over standard IS code design method.
- It can be said that research is carried out for finding optimum design of concrete structures are of great value to practicing engineers. The optimum solution satisfies the provisions of the code and minimizes the self-weight of the structure.

VI. FUTURE SCOPE

- There are many literatures are available on doubly reinforced beam design but that is for cost optimization but the research have to be done for self-weight optimization.
- Many researchers have done work on cost optimization for structural elements, there is need to work on self-weight optimization of structural element. Here in this project work only two structural elements have done for other remaining structural elements like footing, slab have to be done.
- Research should be done by requirements considering all required IS codes for safe design of structures.
- In steel structures also optimization for design elements are possible, additional research in all steel structure elements needs to be done.
- It is also important that additional research needs to be done on other types in beam design and column design like doubly reinforced beam, uniaxial column, biaxial column.

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