Design Optimization of R.C.C. Buildings using Genetic Algorithm

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Abstract : A design problem is usually iterative in nature and requires a number of trials to arrive at a feasible solution. As such, a suitable optimization algorithm can help the engineer in achieving a solution which not only satisfies all the requirements stipulated in the codes but also possesses optimality in terms of structural cost. This paper proposes the use of Genetic Algorithm (GA) to carry out the optimization of a G+5 R.C. building with shear walls. The results of the optimization process illustrate the scope, applicability and practicality of the proposed method.

***IndexTerms* - seismic design, cost optimization, genetic algorithm, R.C. frame, shear wall.**

I. Introduction

Optimization aims in achieving the best outcome of a given operation while satisfying certain restrictions. The objective of structural optimization is to find design variables for the system that minimize the cost and satisfy various code-specified requirements.

An optimization problem consists of an objective (or objectives) and some constraints expressed in terms of the design variables. In structural optimization, the minimum weight or minimum cost (such as construction cost, life-cycle cost, etc.) is usually taken as the objective. The constraints define the limitations imposed on structural behavior, which can be from design codes or specified by structural engineer. These constraints can be a combination of strength capacity, displacement or deflection limitation, structural instability, frequency range, ductility requirement and fabrication considerations. The constraints are generally formulated as inequality constraints, and are often implicit functions of the design variables. The solution of the design optimization problem requires the constraints to be first transformed into explicit functions of the design variables.

In this paper, the constraints have not been transformed into explicit functions of the design variables since this can be extremely difficult to achieve. Instead the constraints are evaluated by assigning the design variables to a model created in a commercial finite element software [1] and then reading the analysis (and design) results returned by the software. This allows the application of optimization to a wide range of constraints without requiring explicit formulation of constraints into a function of design variables.

Some assumptions adopted in the analysis and design are as follows:

1. The geometric layout of building structure is predefined and fixed throughout the design process. Design is defined as a process of finding section sizes, grade of concrete and grade of steel for structural elements such as columns, beams and walls.
2. All members are prismatic and straight, and the cross-section sizes, grade of concrete and grade of steel are chosen as the design variables.
3. Connections between members are assumed to be fully rigid or ideally pinned.
4. Deformation of the panel zone at column-beam joints is not considered.
5. The contribution of floor slabs to beam stiffness and strength is not considered but the floor slabs are assumed to be semi-rigid diaphragms playing the role of transferring inertia loads to the lateral load resisting framework.
6. Earthquake loading is idealized as equivalent lateral static loading.

II. Optimization Algorithm

Considering the nature of problems encountered in structural engineering, an algorithm which supports nonlinear objective and nonlinear constraint functions was required. Also, considering the discrete nature of design variables (as the section sizes and grade of materials can only take certain predefined values), an algorithm with support for integer variables was needed. Due to considerable time required for analysis and design and the availability of multi-core processors, the algorithm should have the ability to evaluate objective and constraint functions in parallel. Furthermore an algorithm with the ability to find the global optimum was required. Keeping in view all the above requirements, MATLAB's [2] Genetic Algorithm (GA) was selected which was the only algorithm in MATLAB's optimization toolbox to meet all the above requirements.

Genetic algorithms try to mimic the process of natural evolution [3][4][5]. The basic elements of natural genetics – reproduction, crossover, and mutation – are used in the genetic search procedure. Brief outline explaining the working of GA is as follows:

1. Algorithm generates a number of possible solutions to the design problem which are within the range of maximum and minimum value specified by the user. Such a set of solutions is called population.
2. Each possible solution in the original population is evaluated (i.e. structure cost and code-specified requirements are checked). The algorithm then creates a sequence of new populations based on the evaluations for previous populations. To create the new population, the algorithm performs the following steps:

a. Scores each member of the current population by computing its fitness value (which represents structure cost and violation of code-specified criteria, if any).

b. Selects members, called parents, based on their fitness.

c. Solutions in any generation having lowest fitness values (i.e. less structural cost and/or less violation of code-specified design criteria) are retained and passed on to the next population. Such solutions are called elite solutions.

d. Produces children (i.e. new solutions based on previous population) from the parents (i.e. solutions belonging to previous population). Children are produced either by making random changes to a single parent—mutation—or by combining the vector entries of a pair of parents—crossover.

e. Replaces the current population with the children to form the next generation.

The algorithm stops when any of the user-specified stopping criteria is met. These could range from maximum number of generations to any time limit specified by the user.

III. Design Problem Formulation

3.1 Objective Function:

This paper has adopted the sum of cost of the members of the structure as the objective function. The total cost of all the structural members has been calculated as follows:

$$\text{Total structure cost} = C_b + C_c + C_w$$

where, C_b = Sum of cost of all the beams in the building, C_c = Sum of cost of all the columns in the building and C_w = Sum of cost of all the reinforced concrete walls in the building.

Furthermore, the cost of a single structural member (i.e. beam, column or a concrete wall) includes the cost of concrete, cost of steel required for main steel, cost of steel required for secondary steel (such as stirrups in beams, ties in columns and horizontal steel in walls). The cost of concrete and steel also include the cost of lifting the material, i.e. cost of a structural member which is at a higher floor level will be more than what it would have been if the same structural member had been at a lower floor level. Concrete and steel costs further vary based on the grade of material used in a particular structural member. The units costs adopted are as follows[6]:

Table 1 Concrete cost up to 6m height from ground level

Grade of concrete	Member	Cost (Rs/m^3)
M25	Beams	7943
	Columns	8842
	Walls	7506
M30	Beams	8071
	Columns	8953
	Walls	7644
M35	Beams	8199
	Columns	9064
	Walls	7782

Table 2 Unit costs of steel reinforcement up to 6m height from ground

Grade of steel	Cost (Rs./kg)
HYSD 415	40
HYSD 500d	43

Table 3 Additional cost of raising material for every 3m height

Material	Unit Cost
Concrete	202 Rs./m^3
Steel	0.445 Rs./kg

The building considered in this paper is a dual system building. As per IS 1893 [7], for a dual system building, it is necessary to ensure that the moment resisting frame members of the building (i.e. beams and columns) are designed for at least 25% of the total design seismic base shear. To incorporate this provision, the objective function and the constraint function have the facility to modify the load combinations used for carrying out the design of the frame components of the building. Thus, if it is found, during the evaluation of the objective function or constraint function, that the frame components are taking less than 25% of the design seismic base shear then the load factors for seismic loads in the load combinations are increased suitably to ensure that the frame components are designed for 25% design seismic base shear.

3.2 Design Variables:

Structural design optimization is the process to find the values of design variables which, for this study, are taken to be the cross-section sizes of the members and the grade of materials. Discrete design variables have been adopted here which means that the design variables can only take a value from among a finite set of permissible values. Grade of concrete for lower stories and upper stories have been considered as separate design variables.

A list of sections sizes and the grade of materials has been prepared for beams, columns and walls in the building and the same are given below:

Table 4 List of section sizes for beams

Beam section	Width(mm)	Depth(mm)
B1	230	300
B2	230	450
B3	230	600
B4	230	750
B5	300	300
B6	300	450
B7	300	600
B8	300	750

Table 5 List of section sizes for columns

Column section	Width(mm)	Depth(mm)
C1	450	450
C2	600	600
C3	750	750
C4	300	600
C5	300	750
C6	600	300
C7	750	300
C8	450	600
C9	450	750
C10	600	450
C11	750	450

Table 6 List of concrete grades

Design variable value	Grade of concrete
1	M25
2	M30
3	M35

Table 7 List of steel grades

Design variable value	Grade of steel
1	HYSD 415
2	HYSD 500d

Table 8 List of section sizes for concrete walls

Wall section	Thickness (mm)	Vertical steel spacing in central portion of the wall (mm)	Vertical steel spacing in end quarter portion of the wall (mm)
W1	230	200	200
W2	300	200	200
W3	350	200	200
W4	400	200	200
W5	230	200	100
W6	300	200	100
W7	350	200	100
W8	400	200	100

Note: Apart from wall thickness, some sections in the list above have more vertical reinforcement in the quarter length at each end of the wall. Such sections are included in the list because they are known to have higher moment of resistance compared to sections which have uniform distribution of vertical steel throughout the section.

3.3 Design Constraints:

In the design optimization process, the variable values cannot be chosen arbitrarily; rather they have to satisfy certain specified requirements called design constraints. The following constraints have been considered:

1. Drift constraints: These ensure that the inter-story drifts of the building remain within 0.4%.
2. Strength constraints: These ensure that the various structural members possess sufficient capacity to resist the forces carried by them in accordance with the code requirements [8].
3. Strong column-weak beam constraints: These ensure that the column-beam capacity ratio at any joint in the building is greater than or equal to 1.4 [9].
4. Side constraints: These ensure that the design variables are chosen from within the user-specified table.

IV. Design Optimization Example and Results

The optimization methodology was tried on a G+5 building having a typical floor plan as shown in Figure 1. The model has been subjected to dead and live loads in accordance with IS 875 Part-1[10] and Part-2 [11](for loads corresponding to office buildings) respectively. Lateral seismic load has been applied in accordance with IS 1893 (Part-1):2002 [7] considering the building to be in Zone-III and resting on medium soil. Wind loads have not been considered assuming that the base shear due to wind will be less than that due to seismic effects. Load combinations for serviceability and strength have been defined as per IS 875 Part-5 [12].

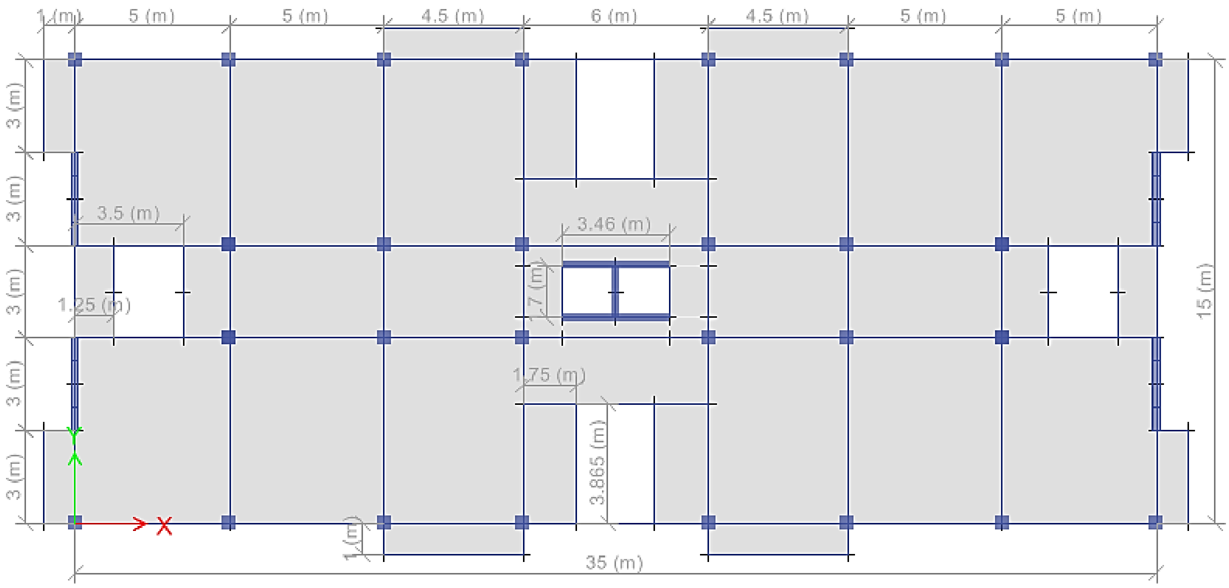

Figure 1 Typical floor plan of the G+5 building

Considering the number of design variables and the time required for a single analysis and design cycle, optimization algorithm was run for 200 generations with a population size of 70.

Optimization was run once with all constraints except strong column-weak beam constraint and then with all constraints on. The results of the former run of optimization were compared with those of manual design (where strong column-weak beam constraints had not been considered) to understand the efficacy of the optimization process. The results of the latter run of the optimization illustrate the impact of strong column-weak beam constraint (as proposed in the draft version of IS 13920[9]) on the cost of the structure (Refer Table 9).

Since GA is a stochastic algorithm, the optimum solution obtained can be different at the end of each optimization run. Hence, the optimization run was repeated for 3 times (for a given set of constraints) and the solution corresponding to lowest structure cost was assumed to be the optimum solution of the design problem.

Table 9 Comparison of costs

Description	Penalized objective function (Cost in Rs.)	Time for optimization (in hours)	Percentage difference w.r.t. lowest value (%)
Manual design	Rs. 6,442,000	N.A.	3.81
Optimization w/o strong column-weak beam constraints	Rs. 6,205,780	19.68	0.00
Optimization w/ strong column-weak beam constraints	Rs. 7,302,700	18.68	17.68

V. Conclusion

The paper proposes a systematic approach to arrive at design which satisfies various criteria specified in the code. All the constraints were found to be satisfied in the optimization process. The cost of optimized structure was found to be lower than that of the manually designed building. Also, the solution with strong column-weak beam constraints was found to have a substantial increase in the cost of the structure due to comparatively higher column sizes.

However, the time required for the optimization process could prove to be discouraging particularly where there is a lack of sufficient computational power. Design criteria such as strong column-weak beam constraint which could be difficult to implement manually can be implemented as constraints in the optimization process. The parameters of optimization such as population size and number of generations affect the optimum result and should be appropriately selected by the user. In some cases, it was observed that the design variables suggested by the algorithm could be modified based on engineering intuition to further lower the cost of the structure. Thus, the optimum solution given by such an automated process should be thoroughly scrutinized such an automated process should be considered as a complementary tool for the structural engineer rather than a complete substitute.

The proposed methodology can also be extended for nonlinear analyses of buildings. Due to the discrete nature of design variables, the proposed method can be easily extended for optimization of steel structures where the section sizes have to be selected from the available sections.

With the increase in computation power in recent times, the use of such an automated process promises a very effective approach to structural design problems.

VI. References

[1] Computers and Structures Inc., SAP2000 Version 18.0.1, Berkley, 2015.

[2] The Mathworks Inc., MATLAB R2015a, 2015.

[3] J. Holland, Adaptation of Natural and Artificial Systems, Ann Arbor, Michigan: The University of Michigan Press, 1975.

[4] I. Rechenberg, Cybernetic Solution Path of an Experimental Network, Farnborough: Library Translation 1122, Royal Aircraft Establishment, 1965.

[5] S. Rao, Engineering Optimization Theory and Practice, New Delhi: New Age International(P) Ltd., 1996.

[6] GWSSB, Schedule of Rates 2014-15, Gandhinagar, Gujarat: Gujarat Water Supply & Sewerage Board, 2014.

[7] Bureau of Indian Standards, IS 1893 (Part 1):2002 Criteria for Earthquake Resistant Design of Structures, New Delhi, 2002.

[8] Bureau of Indian Standards, IS 456: 2000 Plain and Reinforced Concrete-Code of Practice, New Delhi, 2000.

[9] Bureau of Indian Standards, First Revision of IS 13920: Ductile Design and Detailing of Reinforced Concrete Structures Subjected to Seismic Forces-Code of Practice, New Delhi, 2014.

[10] Bureau of Indian Standards, IS 875 (Part 1):1987 Code of Practice for Design Loads (Other than Earthquake) for Buildings and Structures Part 1: Dead Loads, New Delhi, 1987.

[11] Bureau of Indian Standards, IS 875 (Part 2):1987 Code of Practice for Design Loads (Other than Earthquake) for Buildings and Structures Part 2: Imposed Loads, New Delhi, 1987.

[12] Bureau of Indian Standards, IS 875 (Part 5):1987 Code of Practice for Design Loads (Other than Earthquake) for Buildings and Structures Part 5: Special Loads and Combinations, New Delhi, 1987.