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Structural Optimization of Reinforced Concrete Structures

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***Abstract*— The structural optimization plays a vital role in today's highly competitive industry, where there is continuous increase in customer demand for superior quality, better safety and affordable cost. The conventional ways of design development largely depends on excessive material usage, very high design margins – hence, in turn ending up consuming more material into the structures, buildings. Since last couple of decades, computational power is becoming more efficient and affordable to everyone. This availability of high capacity computational power gave of designer the opportunity for evaluating multiple options during the development phase itself, using finite element analysis methods. Also, the efforts of the researchers helped our field with many innovative and matured algorithms for optimizing the multiple design variables considering given constraints, scenarios at the same time. The combination of high power computation with these algorithms is giving the designers limitless opportunities for managing the development more effectively and efficiently.**

This paper discusses various optimization techniques and apply them to real world cases like reinforced concrete structures in virtual environment. The study includes survey of structural optimization principles, procedures, software tools available for structural design & analysis. Further, it discusses about the optimization of multi-storey reinforced concrete structures (RCC) building structure using structural analysis software like STAAD-PRO along with modern optimization tools like MINITAB and Evolutionary Algorithm.

***Keywords*— Optimization, Structural analysis, STAAD-Pro, Evolutionary algorithm, DOE**

I. INTRODUCTION

While designing the structures, the optimization plays a crucial role in order to develop cost effective, more robust and safe designs. In general, the structural optimization is performed by "trial and error" or "one factor at a time" methods, although fact is that they are very less effective as well as less efficient. Present optimization techniques are improved significantly over years. The exponential advancement in the computational capabilities in last few decades helped the seamless integration of optimization procedures in structural designs. The primary requirements for optimization are detailed mathematical models based on the physics. Once these models or transfer functions are developed – they can be coupled with suitable optimization algorithm. Specifically for structural design problems, the structural analysis and optimization algorithms are combined through optimization procedure, in order to achieve the desired objectives and solutions.

A. Objectives:

The objectives of this project work, structural optimization of reinforced concrete structures are mainly as follows:

- Survey of historical & recent development in this field
- Survey of Optimization Techniques, types, methodologies
- Design Analysis and optimization of multi-storey building with the help of STAAD-PRO, MINITAB software and Evolutionary Algorithm.

II. LITERATURE REVIEW

In order to understand the latest trends and ongoing research development – a focused survey of the white papers, technical articles and journals was performed. Following is the summary of few of the relevant and important papers in the field of optimization of RCC structures.

James B. Deaton from Georgia Institute of Technology in Aug 2005, elaborated in details "*A finite element approach to Reinforced Concrete Slab Design*". In this work, he explains step by step development of a procedure in GT STRUDL to design reinforced concrete flat plate system based on the results of finite element analysis. The current state-of-practice of reinforced concrete flat plate design was reviewed, including the ACI direct design and equivalent frame techniques, the yield line method, and the strip design method. Additionally, the current state-of-the-art of flat plate design based on finite element results was presented, along with various flat plate modeling techniques. Design methodologies studied included the Wood and Armer approach, based on element stress resultants, and the resultant force approach, based on element forces. Design examples presented include single-panel flat plate systems with various support conditions as well as multi-panel systems with regular and irregular column spacing. The examples additionally showed that when cuts were not oriented orthogonally to the directions of principle bending, resulting designs based on element forces could significantly under-reinforce the cross-section due to significant torsional effects.

Another paper presented by Andres Guerra and Panos D. Kiousis from Colorado School of Mines, USA titled "Design optimization of reinforced concrete structures" discusses a novel formulation aiming to achieve optimal design of reinforced concrete (RC) structures is presented here. Optimal sizing and reinforcing for beam and column members in multi-bay and multistory RC structures

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incorporates optimal stiffness correlation among all structural members and results in cost savings over typical-practice design solutions. A Nonlinear Programming algorithm searches for a minimum cost solution that satisfies ACI 2005 code requirements for axial and flexural loads. Material and labor costs for forming and placing concrete and steel are incorporated as a function of member size using RS Means 2005 cost data. Successful implementation demonstrates the abilities and performance of MATLAB's (The Mathworks® Inc.) Sequential Quadratic Programming algorithm for the design optimization of RC structures. A number of examples are presented that demonstrate the ability of this formulation to achieve optimal designs.

While discussing the discrete optimization of reinforced concrete structures based on the efficient combination of multiple optimization strategies, the author Matej Leps from Czech Technical University, Prague, explains in details in his technical paper presented in 6th World Congresses of Structural and Multidisciplinary Optimization held in Jun, 2005. The paper mostly focuses on the application of multi-objective stochastic optimization algorithm applied to complete structures for optimizing basic structural characteristics like types of materials, dimensions of elements or profiles of steel bars. He further demonstrates with benchmark problems like cantilever beam, simply supported beam. The paper emphasis on the fact that in today's world structural design problems need Multi Objective Optimization which is a necessity, rather than a choice.

In an industrial white paper titled "Scia Engineer MOOT: Automatic Optimization of Civil Engineering Structures" authors Radim Blažek, Martin Novák, Pavel Roun from Nemetschek Scia, Belgium explained in details an example of new generation of software for the design of civil engineering structures. It is software which calculates internal forces, checks the compliance to the code, and on top of that, this software is able to "find" the final optimal structural design. To reach really optimal structural design, it is necessary to consider all relevant aspects and demands. These are rather general and complex and, therefore, the software tool supposed to cope with them must be also very general and flexible. The ongoing development in computing technologies enables that computers can analyze in a reasonable time a huge number of variants and thus search for optimal structure variant or variants and propose them to the designer. Mathematically explained, optimization methods search for local extremes of a prescribed objective function, which describes a certain characteristic of the optimized structure, and quite often it is possible to find more than one local extreme. Those local extremes are always kind of "interesting" variants. In the final step, it is up to the designer of the structure to evaluate them and choose one. Alternatively, if the solutions found do not meet the designers' expectations, they can modify the input data for the optimization and run search for other variants.

Another paper presented by Sara A. Babiker, Fathelrahman. M. Adam, Abdelrahman E. Mohamed titled "Design Optimization of Reinforced Concrete Beams Using Artificial Neural Network" discusses an Artificial Neural Networks (ANN) model for the cost optimization of simply supported beams designed according to the requirements of the ACI 318-08 code. The model formulation includes the cost of concrete, the cost of reinforcement and the cost of formwork. A simply supported beam was designed adopting variable cross sections, in order to demonstrate the model capabilities in optimizing the beam design. Computer models have been developed for the structural design optimization of reinforced concrete simple beams using NEURO SHELL-2 software. The results obtained were compared with the results obtained by using the classical optimization model, developed in the well-known Excel software spreadsheet which uses the generalized reduced gradient (GRG). The results obtained using the two modes are in good agreement.
These papers and research work gives a clear idea about the latest direction of the research in the field of RCC structural optimization. While cost remain the major driving factors

III. PROBLEM DEFINITION

A residential multi-storey building (ground + 12 floors) with unique layout is considered for the optimization study – the building plan is as shown in Fig. 1. The considered site is located in Pimpri Chinchwad with medium soil. Design of building is adhering to structural design requirements as per IS-456-2000. The challenge was to achieve the optimum cost of construction while complying with plan layout, load conditions and standard safety guidelines.

Figure 1: plan of the building under consideration

IV. APPROACH AND METHODOLOGY

The optimization approach for the case under study was to identify the control variables, develop a generalized governing equation for cost function with use of Design of Experiments technique, further to find the optimized set of control variables for achieving target cost of the building. The various advanced software tools used for this approach are STAAD-PRO, MINITAB, and Evolutionary Algorithm.

V. CONSIDERATIONS FOR STAAD-PRO MODELING

A model as per the plan dimensions was created in STAAD-PRO environment. While creating the model, following are the considered made:

A. General:

1) The residentail building consists of 6 flats per floor. A set of two flats placed on each side of an imginary equilateral triangle – further connected with each other through a unique arrangement of structural arrangement which gives passage ways, stair cases, lift bays, emergency exits routes.

2) The general use of the building is for the residential purpose only. All the walls are considered as 0.15m thick along with 6mm thick gypsym finish plaster on both sides.

3) At ground level, the primary usage planned is for parking purpose. Hence, height is considered as 2.92m – while other all floors are planned with floor to floor height as 3.09m.

4) At ground floor, the ground beams are passing through the columns are provided as tie beams. Hence, the floor was considered as rigid and represented with fixed supports. No tie beams were modeled in STAAD-PRO.

5) Center line dimensions are considered for design and analysis. The joint width in real practice need to consider while interpating results.

6) The concrete options under consideration are M20, M25, M30 grades considering the practical and cost constraints.

7) For beams with length less than 1.5m, the depth of beam constrained at 0.5m – for adhering the IS-456-2000 guideline of legnth to depth ratio of 2.5

8) Limits of the width and depth sizes are considered based on the practical building situations and space availabilities.

9) All dimensions are in m (meters) unless and otherwise specified.

B. Step-wise development of STAAD-PRO model

The building plan was generated from CAD model and imported to STAAD-PRO – which further transformed using translation repeat command to represent complete structure of the building. The 3D rendered model of the building is as shown in figure 2.

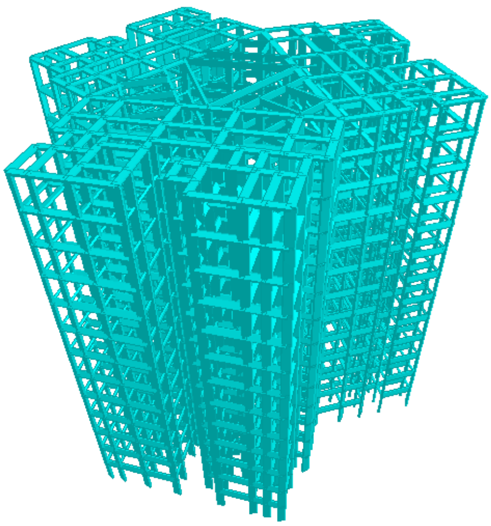

Figure 2: 3d rendered building model

All the nodes at the ground floor level were constrained using fixed supports as shown in figure 3.

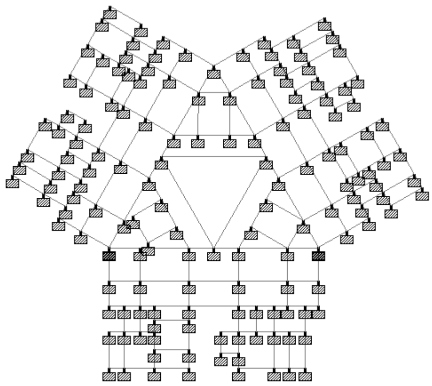

Figure 3: Support Definition For The Staad Pro Model

General sections for the beams were defined as reference, which further were revisited as per the specific values at which the structure was getting analyzed.

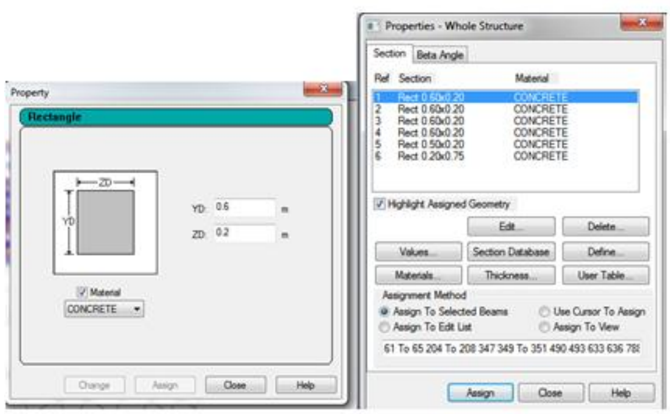

Figure 4: Section Definition

Loads were considered as dead load of the structure (as per IS-875: Part 1 1987), uniformly distributed load at the top floor, further live load of magnitude 4kN/m^2 as per IS-875: Part 2 1987 guidelines for residential building. Also, a combination load case combining both dead and live loads was created and applied to the structure.

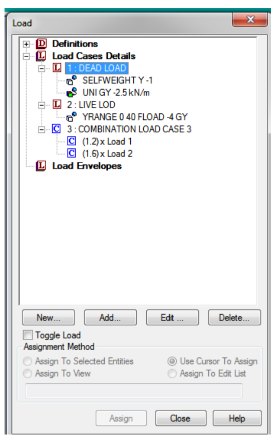

Figure 5: Load Case Definition

Material parameters for concrete design were considered as compressive strength of concrete, yield strength of steel.

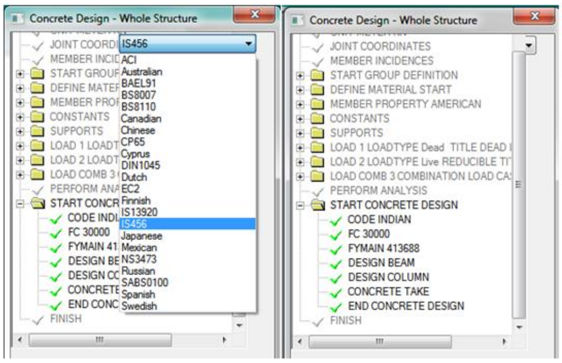

Figure 6: Concrete Design Parameter Definition

After all the definitions were in place, the model was checked for any errors and warnings. When "None" found, it was analyzed for getting concrete and steel design. The main objective of these analyses was to determine the total weight of concrete and steel required while complying with standard requirements.

VI. DESIGN OF EXPERIMENTS & GOVERNING EQUATION DEVELOPMENT

The design variables considered here are sizes of beams and columns for each grade of concrete M20, M25 and M30. In principle, the layout of structure remains same for all the variations. Considering a general and practical relationship among the sizes of beam and columns for simplicity of analysis (i) width of both beam and column remains equal (ii) Depth of column is 1.25 times of that of beam; following scheme for design of experiments was generated.

Design Variables:
Width of Beam = W
Depth of Beam = D
Width of column = W
Depth of column = 1.25D
Grade of Concrete = M20, M25, M30
Output from STAAD PRO analysis:
Weight of Concrete = $W_{Concrete}$
Weight of Steel = W_{Steel}

The design of experiment scheme is illustrated in Table 1.

Table 1: Design of Experiments

Run #	Width (W) in m	Depth (D) in m	Concrete Grade
1	0.175	0.450	M20
2	0.250	0.450	M20
3	0.175	0.600	M20
4	0.250	0.600	M20
5	0.175	0.450	M25
6	0.250	0.450	M25
7	0.175	0.600	M25
8	0.250	0.600	M25
9	0.175	0.450	M30
10	0.250	0.450	M30
11	0.175	0.600	M30
12	0.250	0.600	M30

The structural analysis for each of the combinations above was performed and results were captured. The variable W has minimum and maximum values as W = 0.175m to 0.250m considering the wall thickness and maximum thickness of bricks being used. While variable D has minimum and maximum limits as 0.450m to 0.600m – considering the practical space availability due to overall floor height, door frame and other basic user requirements.

Further, the grade of concrete is a discrete variable and has three options available. Hence, it was decided to have separate governing equations for each of cement grade separately. The DOE was having 4 runs for each of the grade option. The 4 runs were considering 2 levels of 2 parameters. Following table 2 shows the summary of the results obtained after design and analysis from STAAD-PRO.

TABLE 2: STAAD PRO Results for DOE Combinations

Run #	Concrete Grade	Width W	Depth D	Volume of concrete	Weight of Steel
Units		M	M	Cu m	kg
1	M20	0.175	0.450	891	828833
2		0.250	0.450	1782	1341147
3		0.175	0.600	877	723329
4		0.250	0.600	2385	1507938
5	M25	0.175	0.450	948	882640
6		0.250	0.450	1790	1267363
7		0.175	0.600	877	724159
8		0.250	0.600	2390	1481812
9	M30	0.175	0.450	1004	938717
10		0.250	0.450	1792	1228180
11		0.175	0.600	877	723833
12		0.250	0.600	2391	1476115

Using MINITAB, a statistical tool, the above results data was analyzed. The governing equations for weight of concrete, weight of steel depending on the grade of concrete were developed. Following are the governing equations:

For M20 grade concrete:

$$W_{Concrete} = 3170.86 - 12788W - 9689D + 54830WD$$

$$W_{Steel} = 1856015 - 4.06 \times 10^{6}W - 4.94 \times 10^{6}D + 2.42 \times 10^{7}WD$$

For M25 grade concrete:

$$W_{Concrete} = 3890.67 - 15601W - 10909D + 59633WD$$

$$W_{Steel} = 3070902 - 9.79 \times 10^{6}W - 6.86 \times 10^{6}D + 3.31 \times 10^{7}WD$$

For M30 grade concrete:

$$W_{Concrete} = 4623.48 - 18506W - 12133D + 64486WD$$

$$W_{Steel} = 4147686 - 1.5 \times 10^{7}W - 8.63 \times 10^{6}D + 4.11 \times 10^{7}WD$$

The cost function was further generated using general relationship as:

Total cost of the structure = P in INR.

$$P = W_{Concrete} \times R_{Concrete} + W_{Steel} \times R_{Steel} + R_{Formwork}$$

Cost of Fe500 ,R_{Steel} = INR. 50/kg
Cost of concrete, $R_{Concrete}$ is taken as in table 3.

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Table 3: Rate of Concrete Based on the Grade

Concrete Grade	Strength (N/m^2)	Cost in INR. Per cubic meter
M20	20000	4000
M25	25000	4900
M30	30000	6000

It is assumed that cost of form work and labor is 12% of total cost of concrete and steel, from practical experiences.

Given all these values, following is the summary of the cost for each of the variant under consideration:

Table 4: Cost of Structure

Run #	Concrete Grade	Width W	Depth D	Cost of Structure
Units		M	m	INR.
1	M20	0.175	0.450	75,60,930
2		0.250	0.450	1,31,71,890
3		0.175	0.600	68,71,491
4		0.250	0.600	1,58,58,055
5	M25	0.175	0.450	90,91,462
6		0.250	0.450	1,47,07,822
7		0.175	0.600	78,40,846
8		0.250	0.600	1,83,39,975
9	M30	0.175	0.450	1,13,09,527
10		0.250	0.450	1,74,31,448
11		0.175	0.600	92,85,196
12		0.250	0.600	2,22,51,448

VII. OPTIMIZATION FOR TARGET COST

Using Evolutionary algorithm on the governing equations with constraints for W, D – optimum solutions for each of the grade of the concrete were obtained. There was target given by client to keep the overall cost of structure as lowest as possible without compromising on the strength or regulations. Following is the snapshot of the optimization setup using evolutionary algorithm.

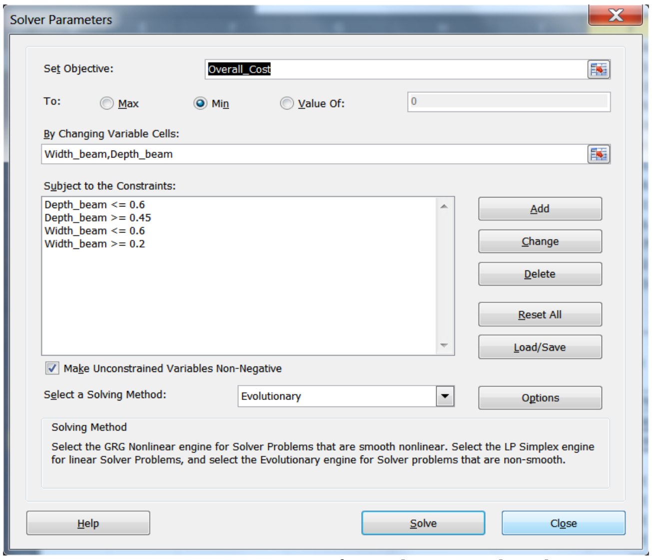

Figure 7: Optimization Setup for Evolutionary Algorithm

The summary of the optimum solution for each of the grade of concrete is as follows:

Table 5: Summary of the Optimization Results

Grade	Width W	Depth D	Volume of concrete Vc	Weight of steel Ws	Overall Cost
	m	m	kg	kg	INR.
M20	0.2	0.45	1187.82	999604	94,31,236
M25	0.2	0.45	1228.39	1010880	1,09,63567
M30	0.2	0.45	1266.51	1035204	1,12,60361

VIII. CONCLUSION

The optimum section found out from this exercise was 0.200mx0.450m with M20 grade of concrete. This resulted into overall approx. cost of INR.94,31,236 . This result was further checked for any further possible structural risks – every member of the structure was within the safety limits as per the guidelines of IS-456 : 2000.

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