JIMMA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

JIMMA INSTITUTE OF TECHNOLOGY

FACULTY CIVIL AND ENVIRONMENTAL ENGINEERING

STRUCTURAL ENGINEERING STREAM

Comparative Study on the Super-Structural Design Optimization of Multi Storied Reinforced Concrete Building Under Multiple Design Constraints Using Different Optimization Techniques.

A Research Thesis Submitted to Jimma University in Partial Fulfillment of the Requirements for the Degree of Master of Science in Structural Engineering.

By

ABITI TUFA KUMBITE

MARCH, 2020

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FACULTY OF CIVIL AND ENVIRONMENTAL ENGINEERING

STRUCTURAL ENGINEERING CHAIR

COMPARATIVE STUDY ON THE SUPER-STRUCTURAL DESIGN OPTIMIZATION OF MULTI-STORIED REINFORCED CONCRETE BUILDING UNDER MULTIPLE DESIGN CONSTRAINTS USING DIFFERENT OPTIMIZATION TECHNIQUES

ABITI TUFA KUMBITE

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DECLARATION

I, the undersigned, declare that this thesis entitled "Comparative Study on the Super-Structural Design of Optimization Multi Storied Reinforced Concrete Building Under Multiple Design Constraints Using Different Optimization Techniques is my original work, and has not been presented by any other person for an award of a degree in this or any other University.

The thesis contains 23 figures, 19 tables and less than 19944 words

Abiti Tufa Kumbite (Candidate)

Signature_______________ Date 26/05/2020

This thesis has been submitted for examination with my approval as a university advisor.

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Abstract

Nowadays, the demand of constructing high-rise (multi-story) buildings is increasing from time to time in different cities due to land scarcity. The structural design of these reinforced concrete buildings was performed by Conventional methods of designing, which follows the paradigm "estimate-analysis-check" made the design process extremely time-consuming, very large design margins and excessive material usage.

In this research, weight optimization of multi-storied reinforced concrete building under multiple design criteria was carried out. The research mainly focused on minimizing the weight of reinforced concrete building while satisfying the limitations and specifications described by EBCS EN 1992-1-1:2013 design code. Optimization problems were formulated with inclusion of weight minimization as objective function, design variables and constraint functions. The design variables were taken as the area of steel and the cross-sectional dimension of the structural members. The design constraints on dimensions, strength capacities and areas of reinforcement were based on the specifications of Ethiopia Building Code Standard. As a research study, a four bay, twelve story RC building was optimized for minimum weight using optimization toolbox in MATLAB software and Evolutionary algorithm through advanced excel solver as optimizers. The case study was analyzed under earthquake and gravity loads by coefficient method using commercial software ETABS. The research has focused on comparing the results of two distinct methods of optimization and convectional method of design as control. The comparative parameters were total weight, story displacements and story drifts.

The optimization toolbox in MATLAB and Evolutionary algorithm were able to reduce the structural weight of this building by 15.89% and 18.801% respectively as compared to the original design weight. Again, story displacements, and story drift for the optimized building was reduced by 18.18% and 15.89% for the optimization toolbox in MATLAB and Evolutionary algorithm respectively as compared to the original design story displacement and drift. In conclusion, as result showed, optimization tool box in MATLAB reduces total weight than Evolutionary algorithm embedded in excel solver. So, it is better to use optimization tool box in MATLAB rather than Evolutionary algorithm embedded in excel solver.

***Key words**: Structural optimization, optimization tool box, Evolutionary algorithm, structural weight, story drift, story displacement*

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Acronyms

ACI	American Concrete Institute
GA	Genetic Algorithm
ANN	Artificial Neural Network
DNLP	Discrete Non-Linear Programming
EBCS EN	Ethiopia Building Code Standard
EC -2	Euro code 2
ETABS	Extended Three-Dimensional Analysis of Building System
FL	Floor Level
GL	Ground Level
GRG	Generalized Reduced Gradient
ILP	Integer Linear Programming
L/C	load combination
LP	Linear Programming
MATLAB	Mathematics laboratory
NLP	Non-Linear Programming
RC	Reinforced Concrete
SQP	Sequential Quadratic Programming
STAAD-PRO	Structural analysis and design program
W	Total weight of structure

List of Symbols

A_{sc}	area of compressive steel
A_{st}	area of tensile steel
Av	Area of shear reinforcement
B_b	width of beam
d_b	effective depth of beam
Bc	width of column
B_{min},	minimum overall width of beam and columns
B_{max}	maximum overall width of beam and columns
Cc	Cost of concrete
Cs	Cost of steel
dc	effective depth of column
D_{min},	minimum overall depth of beams and columns
D_{max}	maximum overall depth of beams and columns
f_{yk}	characteristics strength of steel
F_{ck}	characteristics strength of concrete
f_{ctm}	mean axial tensile strength of concrete
M_d	Design moment
Mu	Ultimate moment for a member
N_{ED}	Axial design load on a member
Pu	Ultimate load capacity for a member
S	spacing of shear reinforcement
S_{min}	minimum spacing of shear reinforcement
S_{max}	maximum spacing of shear reinforcement
St	Spacing of transverse reinforcement
Sv	Spacing of shear reinforcement
W_{beam}	Weight of beam
W_{column}	Weight of column
W_{slab}	Weight of slab

CHAPTER ONE

INTRODUCTION

1.1 Back ground of the Study

Reinforced concrete structure is nowadays widely used in a variety of structures owing to its versatility, high compressive strength, durability and resistance to fire and water damage. Therefore, structural design of reinforced concrete structure has always been a very interesting and creative segment in a large variety of engineering projects. But, the design of these structures is performing by convectional way. In the convectional way of reinforced concrete structures design approach, the dimension of structural elements is defined and the structural analyses are done in order to obtain internal forces. According to these forces, the design requirements are checked and the reinforcement design is done. In this process, there are structural rules according to the design codes. If a rule is not satisfied, the dimension of the elements must be changed and it means that the structural analyses for internal forces must be redone for statically indeterminate structures. This process is known as **"estimate-analysis-check** "which results in extremely time-consuming, very large design margins and excessive material usages. Therefore, it becomes necessary to employ structural optimization through software options for optimization to satisfy the safety and the economy requirements. Structural optimization is the selection of design variables to achieve its goal of optimality defined by the objective function for specified loading or environmental conditions, within the limits (Constraints) placed on the structural behavior, geometry or other factors. The main factors affecting weight are the amount of concrete and steel reinforcements required. The main objective of this research is to optimize the total weight of multi storied reinforced concrete building under multiple design criteria while satisfying the limitations and specifications described by EBCS EN 1992-1-1:2013 design code through structural optimization using software options for optimization.

Extensive studies and evolutions on the optimal design of reinforced concrete structures concerning cost of the structure have been proposed. Computer-based, design optimization of 3D RC frameworks with shear wall was investigated [1]. In their study, section sizes and reinforcement area were considered as design variables concerning minimum cost of the structure.

A novel optimization algorithm for a minimum cost solution of multi-bay portal frame and multistory RC structure, integrating optimal stiffness correlation among members was proposed[2].

Design optimization for RC plane frame structure was proposed by adopting Artificial Neural Network computational model through the neuro Shell-2 software program[3]. In their study, member sizes and the area of longitudinal reinforcement were considered as design variables to obtain the optimal design cross sections conforming to the ACI code criteria. Optimization of real-world 3D RC frames using multi-criterion decision making and particle swarm optimization algorithm was proposed to minimize the cost of RC frames, whereas satisfying ACI design code provision [4].

A review of the available literature on the design optimization of reinforced concrete beams as structural members was presented. It has been elaborated that the optimal design of concrete beams, either individually or as part of a frame, has been addressed by many research studies using various optimization approaches depending on the problem formulation. It was also explained that the objective of optimization (e.g. minimum cost, weight ...), the design variables and the constraints considered by different studies vary widely and hence, different optimization methods have been employed to provide the optimal design[5].Optimum design on the dimensions of beams and columns was performed and came up with total volume of concrete and total weight of steel together with various grade of concrete for a residential multi-story building (ground + 12 floors) using structural analysis software like STAAD-PRO along with modern optimization tools like MINITAB and Evolutionary Algorithm [2].

The feasibility in formulating the structural design problem as a minimization problem and solving it by numerical optimization algorithms was presented. With the help of the numerical optimization algorithms, the trial-and-error design process can be carried out in a systematic and, even more important, automatic manner and the design process is formulated as the minimization of the total weight of the building under a series of constraints, which are designed to consider different design criteria [6].

Cost optimization of reinforced concrete cantilever beam was carried out by using Genetic algorithm considering depth, the number and diameter of bars and the diameter and spacing of stirrups as design variables. It was concluded that genetic algorithm-based design of cantilever beam gave reasonable results, satisfying all constraints [7].

Paper focusing on the concept how to provide a successful optimization method for a particular building type has been presented. Accordingly,30-story-high high-rise residential building was analyzed and optimized. Finally, it was concluded that Post grouting, shear-wall reduction and slab reduction have been shown to be an effective way of reducing the overall cost of the structure, but with the additional improvement of the structure's behavior [8].

Notwithstanding, several authors conducted research on the different aspects of structural optimization of reinforced concrete structures, they focused on cost as objective function and limited design constraints at a time which made variation of structural optimization reinforced concrete structures from one country to another. This study focused on weight as objective function with multiple design constraints to fill the gap made between variation of reinforced concrete structural optimization from one country to another.

The main approach in structural optimization is the use of applicable methods of mathematical programming. Some of these are Linear Programming (LP), Non-Linear Programming (NLP), Integer Linear Programming (ILP), and Discrete Non-Linear Programming (DNLP). In this study, optimization problems in the form of Non-Linear mathematical programming which contained objective function and constraint functions was developed and solved by optimization tool in MATLAB and Evolutionary algorithm embedded in excel solver. the comparison between regular by EBCS EN 1992-1-1:2013 design code 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.

1.2 Statement of the Problem

Nowadays, the demand of constructing high-rise(multi-story) buildings is increasing from time to time in different cities due to land scarcity. The structural design of these reinforced concrete buildings is performing by Conventional methods of designing, which follows the paradigm "estimate-analysis-check" made the design process extremely time-consuming, very large design margins and excessive construction materials usage. As a result, many projects under construction are going through financial crises because of high financial budgets which is the consequence of excessive material usages. Even in some areas of countries there is also sudden collapse of buildings due to trial and error design approach. Following the requirements of any code of practice in order to design structural elements and with obtaining many acceptable cross sections, most engineers are in hesitation with selecting suitable cross sections that lead to minimize cost without further calculations. The combination of these major problems and others increase the demand of structural optimization of reinforced concrete structures.

Previous researchers dealt with the cost optimization of individual structural elements of reinforced concrete structure subjected to gravity loads, plane frames and space frames subjected to either gravity and wind loads or gravity, wind and seismic loads under the limited design constraints using different optimization techniques.

In this study, the design process is formulated as the minimization of the total weight of the whole structure under consideration under a series of design constraints, which are designed to consider different design criteria. The considered design criteria include the section capacity (moments and shear forces), minimum and maximum steel required, top and inter-story drifts and deflections requirements specified in the Ethiopian Building Code Standard (EBCS EN 1992-1-1:2013). There are some reasons for choosing a weight function instead of a cost function, as explained in the following.

- Material and labor costs were varied from one country to another and, therefore, the use of relative cost as an objective function would be deeply dependent on the location at which these structures were built.

- Because of the aim of this study was to reduce the dimensions of member sections as far as possible which results in less amount of steel used.
- In fact, the weight function looks for suitable sections without giving priority to a particular material.

1.3 Research Questions

The research questions addressed in this study were as follows:

1. How economically optimum cross-sections of structural elements can be obtained under the forces structure handle while satisfying requirements specified by the design code without trial and error mechanism?
2. What are the percentage reduction of comparative parameters by optimization techniques?
3. Which optimization methodology is the most economical in terms of stipulated time and less material wastages?

1.4 Objectives of the Study

1.4.1. General Objective of the Study

The general objective of this research was

- ✓ To optimize and compare the total weight of super-structures of multi storied reinforced concrete building under multiple design constraints using different optimization techniques.

1.4.2. Specific Objectives of the Study

The specific objectives of the study were

- To determine the most economical cross-sections of structural elements which satisfy requirements specified by the design code without trial and error mechanism.
- To analyze percentage reduction of comparative parameters by optimization techniques
- To determine the most economical way of optimizing as a design tool for the practicing engineers in order to complete the project in stipulated time and less material wastages.

1.5 Significance of the Study

Since structural optimization of reinforced concrete structure is the subject of making an assemblage of materials sustain loads in the best way, it will make the designed structure economical by minimizing the total materials usages as structure is built under constraints. Simple mathematical expressions for objective function and constraints have been developed and solved by optimization tool in MATLAB and evolutionary algorithm in excel solver. Through that process, simplification of complex design problems was developed. Following that, best optimization tool for engineer was proposed based on the optimum solution obtained from software options for optimization at the end of this study. This study can also be used as reference material for students and others professionals those who in need for conducting research on the area of structural design optimization. The filed document of this study can help the university in saving additional costs required to provide such similar materials.

1.6 Scope and Limitation of the Study

This study is an attempt to study the state of art of structural optimization of performance – based RC building. In the present work, an analytical study on the structural optimization of RC 12-stories building was under taken. The comparison parameters considered are total weight of the building, story drift and story displacement of the building at each story. The 3D analysis has been carried out by coefficient method using structural analysis software ETABS and upgraded for optimization by using optimization tool box and evolutionary algorithm as optimizers.

Moreover, the building under consideration as the case study to benchmark the comparisons was residential building subjected to gravity and lateral seismic loads under the constraints such as sections capacity and shear capacity. Again, building under consideration was also limited to be regular both in plan and elevation which was located in zone four and not installed with energy dissipation devices such as shear walls or bracing systems. Moreover, the optimization was mainly focused on main structural elements such as beams, columns and slabs in terms their dimensions and steel used.

CHAPTER TWO

RELATED LITERATURE REVIEW

2.1. General

In this chapter, development of commonly used optimization problem formula, previous studies on structural optimization of reinforced concrete structures, and reviews on optimization methods and optimization procedures for effective optimum design of RC are summarized and comments on previous studies are drawn. Optimization is the process of finding a minimum or maximum value of a function subject to some constraints. Optimization techniques play an important role in structural design, the very purpose of which is to find the best solutions from which a designer or a decision maker can derive a maximum benefit from the available resources. The basic requirement for an efficient structural design is that the response of the structure should be acceptable as per various specifications. There can be large number of feasible designs, but it is desirable to choose the best from these several designs. The best design could be in terms of minimum cost, minimum weight or maximum performance or a combination of these [9].

2.2. Optimum Design of Reinforced Concrete Structures

Extensive studies and evolutions on the optimal design of reinforced concrete structures concerning cost of the structure have been proposed. Computer-based, design optimization of 3D RC frameworks with shear wall was investigated[1]. In their study, section sizes and reinforcement area was considered as design variables concerning minimum cost of the structure. A novel optimization algorithm for a minimum cost solution of multi-bay portal frame and multistory RC structure, integrating optimal stiffness correlation among members was proposed[2].

Design optimization for RC plane frame structure was proposed by adopting Artificial Neural Network computational model through the neuro Shell-2 software program [3]**.** In their study, member sizes and the area of longitudinal reinforcement were considered as design variables to obtain the optimal design cross sections conforming to the ACI code criteria. Optimization of real-world 3D RC frames using multi-criterion decision making and particle swarm optimization algorithm was proposed to minimize the cost of RC frames, whereas satisfying ACI design code provision[4].

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 was discussed. The model formulation included 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). Based on the results, it was concluded that the results obtained using the two modes are in good agreement. These papers and research work gave a clear idea about the latest direction of the research in the field of RC structural optimization while cost remain the major driving factors [10].

A review of the available literature on the design optimization of reinforced concrete beams as structural members was presented. It has been elaborated that the optimal design of concrete beams, either individually or as part of a frame, has been addressed by many research studies using various optimization approaches depending on the problem formulation. It was also explained that the objective of optimization (e.g. minimum cost, weight ...), the design variables and the constraints considered by different studies vary widely and hence, different optimization methods have been employed to provide the optimal design [5].

An optimal design of three-dimensional multi-story reinforced concrete structures using recently developed meta-heuristic algorithms, namely; the charged system search and the enhanced charged system search was presented. The design was based on the ACI 318-05 code and loadings were based on ASCE7-05. Analysis of the structures was performed by the standard stiffness method. All members are subjected to biaxial moments and axial loads. Pre-determined sections are assumed for beams and columns, and the corresponding interaction curves are utilized to check whether the selected section for each member is acceptable. The objective function is taken as the weight of the structure, and constraints consist of the slenderness of compression members, the maximum allowable drift of the structure and the natural frequency of the structure. It should be mentioned that second order effects are also considered and that the end moments of the columns are magnified when needed. First, a 7-story frame with 3 spans is considered and optimized. Then, a sensitivity analysis is performed by optimal design of nine frames having 3 stories and 2 spans. In each story, different span lengths and loading conditions are assumed, and the results are compared[11].

T-beam for both the minimum cost and weight under the Behavior, shear strength, deflection and Geometric constraints was optimized. Optimal solutions for minimum cost and minimum weight was compared and it was concluded that the construction cost was affected significantly by the optimal sizes. In that optimization process, not only the mass used as objective function but also the cost was used as objective function as the cost contains the material and construction provision costs. The difference was caused by construction details costs[12].

Optimum design on the dimensions of beams and columns was performed and came up with total volume of concrete and total weight of steel together with various grade of concrete for a residential multi-story building (ground + 12 floors) using structural analysis software like STAAD-PRO along with modern optimization tools like MINITAB and Evolutionary Algorithm[2].

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A G+50 story structure having the tube in tube, shear wall and core out-trigger system in ETABS V9.7.4 software was analyzed and an attempt was made to compare the performance of the three systems on basis of story shear, story displacement, time period, story drift and cost and results are compared to arrive at the most optimum of the three systems for the given particular plan. Accordingly, tube in tube was economically the cheapest[13].

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 and column was provided. 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 bound 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 that study, design optimization results were validated by comparing Excel Solver results with standard IS code design results & its appropriateness was established [14].

Cost optimization of three bay-four story RC frame composed of beam and column using hybrid algorithm by considering design constraints for both elements separately was presented. They concluded that reductions of cost in the steel area play a greater role in optimization as compared to reductions in the cross-sectional area of frame elements [15].

Optimum design in terms of the minimum cost of reinforced concrete rectangular columns subjected to axial compression force and biaxial bending moments about x and y axes using the optimization process, the Generalized Reduced Gradient (GRG) technique, which is embedded within Excel Solver add-in tool, was investigated. From that investigation it was concluded that the optimum cost of the column section increases with the cost ratio Cs/Cc from 5 to 10 and 20, for the same h/b ratio. Furthermore, the influence cost ratio, Cs/Cc, is more obvious at larger loads and higher eccentricities [16].

study focused on analysis of (G+10) RCC space frame structure using various optimization methodologies was presented. The analysis of space frame was done by Seismic Coefficient Method and Response Spectrum Method using ETABS Software[17].

Cost optimization of G+6 reinforced concrete buildings considering various aspects of design was presented. In that work, nineteen different models of frames were modeled. Models were analyzed and designed in STAAD .PRO with the agenda of cost reduction without compromising the quality of material and safety of the whole structure. Each model was compared with the conventional model and accordingly quality of steel and concrete was compared. Also, there was not much cost difference with concrete quality so the main focus was on the quality of steel [18].

A G+20 storied RC building in construction with only frame, frame with shear wall, frame with shear core and the frame with shear core and shear wall was analyzed and optimized for gravity and lateral loads. After optimization, it was concluded that, cross-sectional properties of beams and columns are high, and the axial forces, moments, shear force, tensile force, story lateral load, drifts and base shear are maximum in the case of only Frame Structure. By providing a ductile shear wall for the above special moment resisting frame (dual system the cross-sectional properties of beams and columns have been reduced marginally and also base shear and story drifts are reduced. Axial forces, moments, shear force are reduced when compared to Only Frame Structure. The Frame with only shear core resulted in the high reduction of concrete volume than Frame with only shear core and Frame with only shear wall [19].

Optimization of three bay three story frame composed of beams and columns using Genetic Algorithm have been performed. It was considered that the depth of beams and columns and area of reinforcement in both structural elements are design variables while the remaining are considered as constants. These authors validated outputs obtained by Genetic Algorithm (GA) by comparing them with manual calculations and concluded that the outputs are safe and economical. They also compared the optimized result with the design results obtained by ETABS. From their comparison they concluded that more reduction was found in the columns by both variables (depth and area of reinforcement) due to the fact that less variables and constraints considered[20].

Sizing of columns dimensions" from up to" mechanism throughout the building height by keeping constant the dimensions of beams and slabs throughout the structure for different building story has been done. According to these authors, the cost of structure is dominated by the cost of structural steel which is approximated to 70% of the total cost of structure. But after repeated trials for optimization of structural elements the cost of structural steel was reduced by 10%.[21].

2.3. Inference of the Related Literature Review

Still now, so many authors conducted research on the structural optimization of reinforced concrete structures using different optimization methodologies. Specifically, the authors did research on the optimum design of frames (beams and columns) excluding floor sabs and slabs separately.

Some authors used different modern optimization methods at a time. But some authors used hybrid optimization techniques as optimizers. The design variables and constraints they used were also limited by making constant some design variables. In this study, major design variables and all necessary and mandatory constraints as per the design code used were considered for the formulation of optimization problems. Two optimization techniques, the optimization tool in MATLAB and Evolutionary algorithm embedded in excel solver were used to identify the visibility of the optimizers in terms of economy.

2.4. Optimization Techniques in Structural Engineering

The use of numerical optimization techniques to design in the field of structural engineering has been recorded since 1956. One of the seminal studies of optimization techniques for frame structures was done by Heyman in 1956. Optimization techniques shorten the time consumed by designers in creating better conceptual structures. In the field of structural engineering, optimization techniques have been used to solve many different problems, especially in design. These problems cover every aspect of structural engineering, ranging from the smallest structural

elements such as a bolt up to the whole structure. These optimization techniques can be generally grouped into three distinct categories, which are cross-sectional optimization, topology optimization and geometry optimization. The cross-sectional optimization focuses on sizing structural elements by assuming fixed topology and geometry. The sizing of the structural elements in this manner is approached using methods such as performance-based design or strength-based design. The topology optimization studies the placement of structural elements in a design. One of the common techniques used in topology optimization is the element removal technique based on stress limits. Geometry optimization is a technique that combines the usage of both the cross-sectional optimization and the topology optimization [22].

2.5. Optimization Modeling

The first step of optimization design is to create an optimization model in mathematical formulations. This step is called optimization modeling. In this step, several decisions are to be made, such as what will be optimized, what design variables will be changed to produce an optimal design, and what requirements should be met. Modeling is the most important step in optimization design, and designers may spend a significant portion of time on modeling during the optimization process. In this study, a general mathematical optimization model presented in standard form as shown below

$$\begin{cases} \text{Minimize } f(d_1,d_2,d_3\ldots\ldots\ldots d_n) \\ \text{Subject to} \\ g_i(d_1,d_2\ldots\ldots\ldots d_n) \le 0, i=1,2,\ldots n \\ g_j(d_1,d_2\ldots\ldots\ldots d_n) \le 0,\ j=1,2,..,\ n \\ \quad\vdots \\ g_n(d_1,d_2\ldots\ldots\ldots d_n) \le 0,\ n=1,2,\ldots,n \\ d_k^l \le d_k \le d_k^u\ \ k=1,2,\ldots,n \end{cases} \qquad 2.1$$

where

d = $(d_1,d_2\ldots\ldots\ldots d_n)$) is the vector of design variables that is to be determined during the design; f (d1 2 , , , d d L n) is a design objective function that is to be minimized; $g_i(d_1,d_2\ldots\ldots\ldots d_n) \le 0$, $g_j(d_1,d_2\ldots\ldots\ldots d_n) \le 0$,….$g_n(d_1,d_2\ldots\ldots\ldots d_n) \le 0$ are an inequality constraints function and d_k^l and d_k^u are lower bound and upper bound of design variable d_k respectively. The above model can be interpreted as follows: find an optimal set of design variables **d** = $(d_1,d_2\ldots\ldots\ldots d_n)$ over the range $d_k^l \le d_k \le d_k^u$ (k=1,2,…,n) that minimizes the design objective function $f(d_1,d_2,d_3\ldots\ldots\ldots d_n)$ while satisfies the design constraints $g_i(d_1,d_2....d_n) \leq 0, g_j(d_1,d_2....d_n) \leq 0, ...g_n(d_1,d_2....d_n) \leq 0$. It is noted that there are three basic components in an optimization problem – design variables, design objective, and design constraints.

2.5.1. Design Variables

A design variable is also called a decision variable or control variable. A design variable is under the control of a decision maker (designer) and could have an impact on the solution of the optimization problem. Essentially, a design is determined by a set of design variables. Different combinations of design variables represent different designs. The goal of the design optimization is to find the best combination of design variables that optimizes designer's preference (design objective) and maintains certain requirements (constraints).

A design variable can be in the following forms.

- **A continuous variable.** In the above vessel design problem, the dimensional design variables are continuous design variables.
- **An integer.** The number of the teeth of a gear and the type of materials (type 1, type 2, and so on) are examples of the integer design variables.
- **A discrete variable.** The variable can take values from only a discrete real set. For example, when designing a standard component, designers are required to choose the design variables from a list of recommended values from design standards or design codes.

2.5.2. Objective Function

The purpose of optimization is to design a structure that resists the applied loads; the members have a minimum possible size to reduce the structure's weight. It is obvious that when the weight of the structure reduces, the lateral forces also reduce, and this results in a reduction in the section size of the structure [23].

In this paper, the objective function of the optimization is considered to be the weight function of the structure

2.5.3. Design Constraints

Designer's desires (for example, increasing the profit) cannot be optimized infinitely since there are limited resources that can be used in product development. The limited resources and other restrictions imposed by government and corporate regulations have to be met strictly. These requirements are expressed by constraint functions in optimization design. A constraint function is also expressed in a mathematical form in terms of design variables

2.6. Classification of Optimization Problem

Generally, optimization problems can be classified based on the nature of equation involved in to two categories [24]. This is based on the expression for the objective function and the constraints.

Linear optimization problems: If the objective function and all the constraints are 'linear'

functions of the design variables, the optimization problem is called a linear programming problem (LPP).

Non-linear optimization problem: -If any of the functions among the objectives and constraint functions is nonlinear, the problem is called a nonlinear programming (NLP) problem. This is the most general form of a programming problem and all other problems can be considered as special cases of the NLP problem

2.7. Design constraints for the whole building

2.7.1. Drift constraint

Although the safety of a tall building can be ensured by considering the strength constraints, the drift requirement, which always plays an important role in tall buildings design, cannot be overlooked. In the ultimate limit state design, the second-order P-Delta effect is prevented by limiting the lateral deflections of the building. In the serviceability limit states design, the proper functioning of non-structural components, such as elevators, is ensured by limiting the lateral deflections of the building to a sufficiently low level [6].

In this study, Lateral building deflections were evaluated for the building as a whole, since the applicable parameter is total building drift, defined as the lateral building deflection at the top-most occupied floor (Δ) divided by the height from grade to the uppermost floor (Δ / H).

In such serviceability check, typical value of the limit specified by some building codes to this parameter is H / 100 to H / 600 for total building drift and in this study H/250 which is the limitation by the design code [25].

2.7.2. Story Displacement

Story displacement is the parameter under consideration as easily affected by lateral loads like wind loads and earthquake loads. Story displacement at each story level is obtained from ETABS software analysis out puts. Limitation for the story displacements is H/300 at each story as per the design code.

2.8. Optimization Techniques

Once the optimization problem is fully defined by its objective(s) and constraints, a suitable method can be chosen to find the optimal solution**.** The optimization techniques in general enable designers to find the best design for the structure under consideration. A vast range of optimization techniques are available that can be categorized into two main types: linear and non-linear programming techniques. Linear programming approaches can be applied to problems where the objective functions and constraints can all be expressed by linear equations. The most widely used algorithm for linear programming problems with a small number of variables is the simplex method. However, the RC structures design is usually neither a linear nor a convex problem. Regardless of the different problem formulations adopted by various authors, there exists nonlinearity in both the objective function and the constraints of the optimization of RC flexural sections of structural elements. Hence, nonlinear methods should be explored. Non-linear programming approaches can be divided into three large categories: Enumerative, Deterministic, and Heuristic methods [5].

For the purpose of this study, two methods of design optimization were adopted. These include; Optimization Tool Box in MATLAB and Solver Add-in of Microsoft Excel

2.8.1. Optimization Tool Box in MATLAB

MATLAB's Optimization Toolbox includes a family of algorithms for solving optimization problems. The toolbox provides functions for solving linear programming, mixed-integer linear programming, quadratic programming, nonlinear programming, and nonlinear least squares problems[26].

There are so many functions of MATLAB Optimization tool box. Based on the nature of optimization problems, there are several functions of MATLAB Optimization Toolbox. These functions [26].

Linear and Quadratic Minimization problems.

- linprog - Linear programming.
- quadprog - Quadratic programming.

Nonlinear zero finding (equation solving).

- fzero - Scalar nonlinear zero finding.
- fsolve - Nonlinear system of equations solve (function solve).

Linear least squares (of matrix problems).

- lsqlin - Linear least squares with linear constraints.
- lsqnonneg - Linear least squares with nonnegativity constraints.

Nonlinear minimization of functions.

- fminbnd - Scalar bounded nonlinear function minimization.
- fmincon - Multidimensional constrained nonlinear minimization.

- fminsearch - Multidimensional unconstrained nonlinear minimization, by Nelder-Mead direct search method.
- fminunc - Multidimensional unconstrained nonlinear minimization.
- fseminf - Multidimensional constrained minimization, semi-infinite constraints.

Nonlinear least squares (of functions).

- lsqcurvefit - Nonlinear curvefitting via least squares (with bounds).
- lsqnonlin - Nonlinear least squares with upper and lower bounds.

Nonlinear minimization of multi-objective functions.

- fgoalattain - Multidimensional goal attainment optimization

- fminimax - Multidimensional minimax optimization.

For the purpose of this research, the Nonlinear minimization of function, fmincon was used to solve the formulated optimization problems

Minimum of Constrained Multivariable Function Solver(fmincon)

Constrained minimization is the problem of finding a vector *x* that is a local minimum to a scalar function f(x) subject to constraints on the allowable *x*: min f(x) such that one or more of the following holds: $c(x) \leq 0$, $ceq(x) = 0$, $A \cdot x \leq b$, $Aeq \cdot x = beq$, $l \leq x \leq u$.

Where $c(x) \leq 0$ is for inequality constraints, $ceq(x) = 0$ is for equality constraints, $A \cdot x \leq b$ is for inequality constraints in matrix form, $Aeq \cdot x = beq$, is for equality constraints in matrix form and l and u are stand for lower and upper bounds.

Algorithms for Constrained Nonlinear Minimization Solver(fmincon)

The following are algorithms for Constrained Nonlinear Minimization Solver [27].

Trust Region Reflective Algorithm

Many of the methods used in Optimization Toolbox solvers are based on trust regions, a simple yet powerful concept in optimization**.** To use Trust Region Reflective Algorithm, the formulated problem must have: objective function includes gradient, only bounds, or only linear equality constraints (but not both). More it is used for unconstrained minimization problem.

Active Set Algorithm

In constrained optimization, the general aim is to transform the problem into an easier sub problem that can then be solved and used as the basis of an iterative process. The active set algorithm can take large steps, which adds speed. The algorithm is effective on some problems with non-smooth constraints. It is not a large-scale algorithm.

Interior-point

The interior-point approach to constrained minimization is to solve a sequence of approximate minimization problems. It handles large, sparse problems, as well as small dense problems.

The algorithm satisfies bounds at all iterations

Sequential Quadratic Programming (SQP)

SQP methods represent the state of the art in nonlinear programming methods. This algorithm satisfies bounds at all iterations. It is not a large-scale algorithm. For the purpose of this research the Sequential Quadratic Programming (SQP) was used as algorithm for fmincon solver to solve the formulated optimization problems.

Tolerances and Stopping Criteria

The number of iterations in an optimization depends on a solver's stopping criteria. These criteria include several tolerances one can set. Generally, a tolerance is a threshold which, if crossed, stops the iterations of a solver.

2.8.2. Solver Add-in of Microsoft Excel

Microsoft Excel solver is a powerful add-on tool to solve and analyze optimization problems. Optimization deals with selecting the best option among a number of possible choices that are feasible or don't violate constraints. Solver can be used to adjust parameters in a model to best fit data, increase profitability of a potential engineering design, or meet some other type of objective that can be described mathematically in a spreadsheet. The Solver Add-in of Microsoft Excel is widely used optimization tool which contains the simplex algorithm, a general-reduced-gradient algorithm and evolutionary algorithm

The evolutionary solver of Microsoft Excel's Solver Add-in belongs to the class of metaheuristic methods for optimization problems. The Evolutionary algorithm is more robust than GRG Nonlinear because it is more likely to find a globally optimum solution. However, this solver method is also very slow. The Evolutionary method is based on the Theory of Natural Selection which works well in this case because the optimum outcome has been defined beforehand. In simple terms, the solver starts with a random "population" of sets of input values. These sets of input values are plugged into the model and the results are evaluated relative to the target value. The sets of input values that result in a solution that's closest to the target value are selected to create a second population of "offspring". The offspring are a "mutation" of that best set of input values from the first population. Options of The Evolutionary Solver were listed below

Population Size: Similar to genetic algorithms, the evolutionary solver works with a series of populations, i.e. sets of solutions. Starting with an initial population, the evolutionary solver iteratively generates subsequent populations by applying a selection procedure, various cross-over operators, and several mutation strategies. The value of this parameter can be chosen between 10and 200 and defines the number of elements of each population[28].

Random Seed: The procedure for generating the initial population, the cross-over operators, and the mutation strategies rely in part on random sampling. The value 0 for this parameter indicates that in each run of the algorithm, a different series of pseudo-random numbers is used. Values other than 0 prescribe the starting point of the pseudo-random number generator, i.e., in each run of the algorithm the same series of pseudo-random numbers is used, and this series depends on the value chosen [28].

Mutation Rate: The value of this parameter defines the relative frequency with which mutation is applied to some member of the population. A higher value increases the diversity of the population and thus in general the chance to find a better solution, but also the total solution time. [28].

Convergence: This parameter defines a stopping criterion: the search process ends when the percentage difference in objective function values for the top 99% of the population does not exceed the value of this parameter [28].

Maximum Time without improvement*:* This parameter also defines a stopping criterion: the solver stops the search process when the objective function value of the best solution in the

population did not improve for this prescribed amount of time (in seconds)[28].

CHAPTER THREE

RESEARCH METHODOLOGY

3.1. General

Structure optimization is the procedure of improving a preliminary design established by the architectural layout and the engineer's opinion without exceeding the design criteria (strength, serviceability, stability and human comfort). This improvement is done bearing in mind the requirements on each element, cross-section and structural member, and should be as near as possible to the limit established by the criteria to achieve a better economic reduction on the project. A number of powerful optimization techniques software have been becoming available. These include Optimization Tool Box in MATLAB, Genetic algorithms, Simulated annealing, Particle swarm optimization, Ant colony optimization, Excel Solver Fuzzy optimization and Neural-network-based methods. The optimization techniques in general enable designer to find the best design for the structures under consideration

To meet the objectives of this study, the methodology describes in brief how to execute the work, what will be done, what tools are prosed, and the methods of analysis used to know force envelopes involved in the design optimization of reinforced concrete building, standardized form of optimization models, optimization techniques for solving the formulated problems were presented. The used optimization techniques were based on the nature of optimization problems. Various optimization algorithms can be used depending on the mathematical structure of the problem. Optimization techniques play an important role in structural design, the very purpose of which is to find the best ways so that a designer or a decision maker can derive a maximum benefit from the available resources**.** The code of practice applied was new Ethiopian Building Code Standard, EN 1992-1-1:2013, Structural use of concrete in buildings.

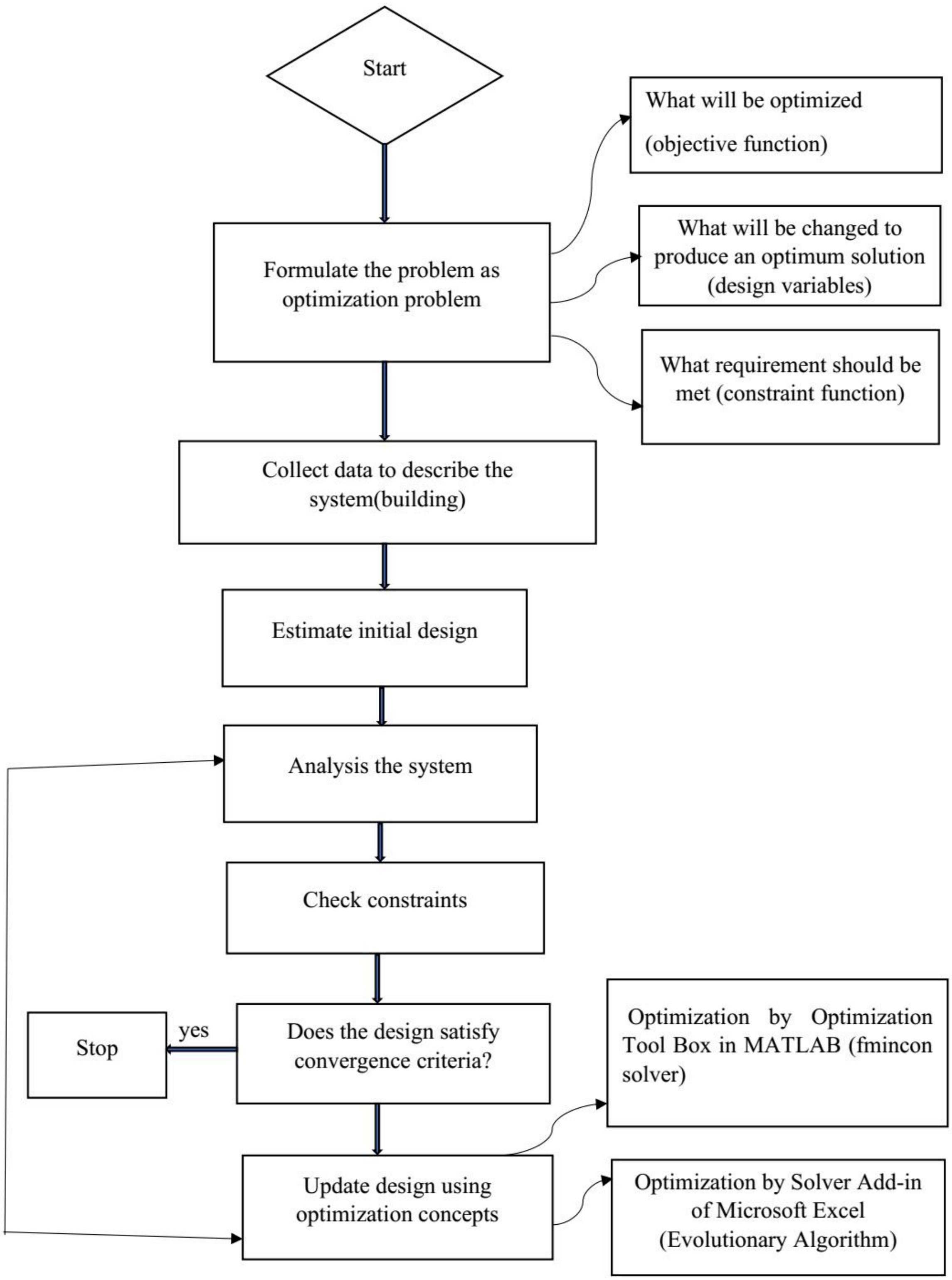

Figure 3.1 research methodology flow chart (source: [29])

3.2. Study Variables

3.2.1. Dependent Variables

The dependent variables in this study were total Weight o structure, story drift and story displacement of structure which depend on the cross-sectional dimensions and area of steel.

3.2.2. Independent Variables

The independent variables in this study were material properties (concrete and steel), Loads (gravity and seismic loads) and geometry of structure (Number of stories, Number of bays, Story height and Bay width)

3.3. Formulation of the Optimization Problem for Reinforced Concrete Building

Formulation of the optimal design problem requires identification of design variables for the structural systems, objective function that needs to be minimized, and design constraints that must be imposed on the systems [3]. In generally, the general form of an optimization problem is as follows

1. **Given:** constant parameters 2. **Find:** design variables
3. **Minimize:** objective function. 4. **Satisfy:** design constraints

3.3.1. Constant Parameters

In this study, the constant parameters specified prior to the solution of the optimization problem were given in the following table. All constant parameters that may have an impact on the weight optimization of the whole structure.

Table 3.1. constant parameters

Constant parameters		**Value**	**Unit**
Geometry	number of stories	12	-
	Number of bays	4	-
	Story heights	3.65	Meter
	bay widths	3,3,3&3	Meter

	Concrete cover to beams and columns (center to rebar's)	50	Meter
	Concrete cover to slabs (center to rebar's)	35	Millimeter
Loads	dead load due to external walls on all beams except roof beams	16.96	KN/m
	dead load due to partition walls on all internal beams except roof beams	13.22	KN/m
	Live load on each floor except roof floor	2.5	KN/m^2
	Live load on roof floor	0.5	KN/m^2
Material properties	Characteristics strength of concrete, f_{ck}	30	Mpa
	Characteristics strength of main steel, f_{yk}	460	Mpa
	Characteristics strength of shear steel, f_{yk}	300	Mpa
	Unit weight of concrete	25	KN/m^3
	Unit weight of steel	78.5	KN/m^3

3.3.2. Design Variables

An important first step in the formulation of an optimization problem is to identify the design variables. Design variables should be independent of each other. For the present formulation, cross sectional dimensions and reinforcement areas (tensile, compressive and shear reinforcement) for beams, columns and slabs are taken as design variables. Specifically, for beams there exist six design variables: the width, B_b, the effective depth, d_b, the longitudinal tensile reinforcing steel area, A_{st}, the longitudinal compression reinforcing steel area, A_{sc}, shear reinforcement area, $A_{v.}$ and spacing of shear reinforcements, Sv. Also, for columns there exist five design variables: the width, B_c, the effective depth, d_c, the longitudinal reinforcing steel area, A_s transverse reinforcement area, $A_{v.}$ and spacing of transverse reinforcements, St. For slab, there exist three design variables: effective depth of slab, d_s, area of reinforcement (main and secondary reinforcements in both directions) and spacing of reinforcement in both directions. For each story, the same design variables are assigned for all respective structural elements (beams, columns and slabs). The final task of the formulation procedure is to set the minimum and the maximum bounds on each design variable. Certain optimization algorithms do not require this information. In this research problems, the constraints completely surround the feasible region. Other problems require the search algorithm with in these bounds. The variables bound result from different issues such as the provisions of the code under consideration, the aesthetic of the structural elements in the building, the practical issues and the availability of some sizes of the material at the local market [10]. The lower and upper bounds designate the range of permissible values for the decision variables. Upper bounds decrease the range of feasible solutions by excluding excessively large members. The following Equations are the bounds considered for the model of optimization problems for this research.

$D_{min}, \leq D \leq D_{max}$ for overall depth of beams and columns

$B_{min}, \leq B \leq B_{max}$ for overall width of beam and columns

$A_{s,\ min} \leq A_s \leq As,_{msssax}$ for main tensile reinforcements

$A_{s,\ min} \leq A_s \leq As,_{max}$ for main compressive reinforcements

$A_{v,\ min} \leq A_s \leq As,_{\ max}$ for shear reinforcements

$S_{min} \leq S \leq S_{max}$ for spacing of shear reinforcements

Minimum and Maximum Cross-Sectional Dimensions of Structural Elements

Considering a general and practical relationship among the sizes of beam and columns, minimum width of beams should not be greater than minimum width of column for safe transmission of loads. In this study, the minimum width of beam and column are taken from EBCS EN 1998-1-1:2013, section 5.5.1.2. Accordingly, the width of primary seismic beams shall be not less than 200 mm. The minimum cross-sectional dimension of primary seismic columns shall be not less than 250mm. The maximum allowable width of the beam is limited to the thickness of the beam section b_{max} =h. The maximum width of column is determined based on the compatibility constraint to ensure that the width of the columns at a given story is not less than the corresponding beam width to allow continuation of beam reinforcing steel bars through the columns. In the normalized form, this constraint can be written as:

$b_w - b_c \leq 0$ where b_w and b_c are width of beam and column respectively

In general, the ratio of overall depth (D) to width (b) in rectangular RCC beam sections is in the range of 1.5 to 2. It can be as high as up to 3 for beams carrying very heavy loads. The width and depth of beams are also governed by the shear force on the beam section. Often beam sizes are determined by architectural and aesthetic factors. In most cases the depth of the beam is increased, not the width, when redesigning the section as it increases the moment resisting capacity and the flexural stiffness of the beam (this in turn ensures results in less deflections, curvatures and crack-widths). Since the deflection of a beam is a function of the loading and the time when the loading is applied, it can be difficult to determine an accurate beam deflection. In this study, minimum depth of beam was determined based on deflection requirement.

$D_{min} = d + \phi_{min}/2 + \phi_t$ + concrete cover d= effective span /20 for continuous beams of highly stressed Concrete (EBCS EN 1992-1-1:2013, section 7.4). The upper bounds imposed on beam, column dimension, and slab thickness based on architectural and/or geometrical criteria [3]. The maximum depth beam column and slab were determined based on EBCS EN 1992-1-1:2013 code recommendation on depth limitation as follows

- A beam is a member for which the span is not less than 3 times the overall section depth. Otherwise it should be considered as a deep beam.
- A column is a member for which the section depth does not exceed 4 times its width and the height is at least 3 times the section depth. Otherwise it should be considered as a wall [30].

The depth of a concrete slab is dependent on the manner in which it spans, i.e. one-way or two-way, the magnitude of load being placed upon it and the form of the frame it sits on. If the structure is a flat slab for example, then there are no beam elements to consider, other than the beam and column strips that exist within the depth of the slab. The maximum thickness of the slab should not be greater than the minimum depth of beam and is assumed to be 250mm.The maximum practical thickness for residential / office / public buildings is 200mm while minimum is 100mm**.** The maximum thickness for one-way and two-way solid slabs should be less than minimum dimension of slab/5 (EBCS EN 1992-1-1:2013 Code, section 5.3). In this study the minimum thickness of slab is taken as 100 mm for slabs exposed mainly to distributed loads and fire resistance. In general, the height "h" of slabs is controlled by the deflection limits (EC2 7.4). In the case of flat slabs, punching frequently also governs. In EC2 the deemed-to-satisfy rule for verifying SLS deflection is based on the limitation of elements' "slenderness" by setting maximum "slenderness ratios" (l_{eff} /d) of the "effective span" l_{eff} (axis-to-axis distance in the case of supporting beams, or centre-to-centre distance of columns in the case of flat slabs) to the "effective depth", d, (distance of the centroid of the tensile forces from the most compressed concrete fiber).

3.3.3. Objective Function

The purpose of optimization is to design a structure that resists the applied loads; the members have a minimum possible size to reduce the structure's weight. It is obvious that when the weight of the structure reduces, the lateral forces also reduce, and this results in a reduction in the section size of the structure. In this paper, the objective function of the optimization is considered to be the weight function of the structure. It is expressed in terms of beam weight, column weight and slab weight. The total weight of reinforced concrete building can be expressed:

Minimize $W=W_{beam}+W_{column}+W_{slab}$ --(3.1)

where W_{beam}= weight of beam for the whole building,

W_{column}=weight of column for the whole building and

W_{slab}= weight of slab for the whole building

These weights can be calculated according to the following formulations

$$W_{beam} = \sum_{i=1}^{Ns} \mathrm{Nbg}\left[\, \gamma\mathbf{c}\ (\mathrm{Vbc} - \mathrm{Vbs} - \mathrm{Vv}) + \gamma\mathbf{s}(\mathrm{Vbs} + \mathrm{Vv})\,\right] \text{ --------------(3.2)}$$

$$W_{column} = \sum_{i=1}^{Ns} Ncg \left[\gamma \mathbf{c} \, (Vcc - Vcs - Vv) + \gamma \mathbf{s} (Vcs + Vt) \right] \quad \text{------------(3.3)}$$

$$W_{slab} = N_{ps} \left[\boldsymbol{\gamma_c} (V_{sc} - V_{ss}) + \boldsymbol{\gamma_s} V_{ss} \right] \quad \text{---(3.4)}$$

Where

Ns, N_{bg} and N_{cg} are number of stories, beams and columns in one group respectively

N_{ps}, γ_c and γ_s are numbers of panels of slab and unit weight of concrete and steel respectively

$V_{b\,c}$= volume of concrete in a beam, calculated by using Equation (3.5).

$V_{b\,s}$= volume of reinforcing steel in a beam, calculated using Equation (3.6).

V_v = volume of stirrups in a beam, calculated using Equation (3.7).

V_{cc} =volume of concrete in a column, calculated by using Equation (3.8)

V_{cs} = volume of longitudinal reinforcing steel in a column, calculated by using Equation (3.9).

V_t= volume of lateral ties in a column, calculated by using Equation (3.10).

V_{sc} = volume of concrete in a slab, calculated by using Equation (3.11).

V_{ss} = volume of main and secondary reinforcing steel in both direction of slab calculated using Equation (3.12).

$$V_{bc} = A_{gb} L_b$$

where: A_{gb} = gross cross-sectional area of beam.

L_b = length of beam between column center lines.

$$V_{bc} = B_b D_b L_b = B_b(d_b + d') L_b \quad \text{---(3.5)}$$

where B_b and d_b are width and effective depth of beam and

d′ is concrete cover (to center of reinforcing steel bars)

$$V_{bs} = A_s L_{bbars}$$

where As = cross-sectional area of longitudinal bars include tension and compression steel.

L_{bbars} = length of beam longitudinal reinforcing steel bars.

Since As= Ast +Asc where Ast and Asc areas of tensile and compressive steel respectively, V_{bs} can be rewritten as

$$V_{bs} = (Ast + Asc)\, L_{bbars} \quad \text{--(3.6)}$$

$$V_v = A_v\, L_v\, n_s$$

Where A_v = cross-sectional area of bars used for stirrups.

L_v = length of one stirrup.

n_s = number of stirrups in one beam.

$Lv = 2(B_b + d_b + d') - 8(d' - \Phi/2 - \phi_t)$, Φ= diameter of longitudinal bar and ϕ_t = diameter of stirrups and $\Phi = (4/\pi)^{1/2} As^{1/2} = 1.128As^{1/2}$, $\phi_t = 1.128Av^{1/2}$

$$n_s = \frac{Length\ of\ beam}{spacing} + 1$$

$$V_v = A_v[\, 2(B_b + d_b + d') - 8(d' - \Phi/2 - \phi_t)](\frac{Lenth\ of\ beam}{spacing} + 1)$$

$$V_v = A_v[\, 2(B_b + d_b + d') - 8(d' - 0.564As^{1/2} - 1.128Av^{1/2})](\frac{Length\ of\ beam}{spacing} + 1) \text{---------------(3.7)}$$

$$V_{cc} = A_{gc}\, L\, u$$

where A_{gc} = gross cross-sectional area of column.

Lu = unsupported length (clear height) of column.

$$V_{cc} = A_{gc}\, Lu = Bc\, Dc\, Lu = Bc(dc + d')Lu \quad \text{---(3.8)}$$

where B_c and d_c are width and effective depth of column

$$V_{cs} = A_s\, L_{cbars} \quad \text{---(3.9)}$$

where A_s = cross-sectional area of longitudinal steel.

L_{cbars} = length of column longitudinal reinforcing steel bars.

$V_t = A_t L_{tie} n_t$

where A_t = cross-sectional area of bars used for ties in column

L_{tie} = length of one tie in column

nt= number of stirrups in one column.

$L_{tie} = 2(B_c + d_c) - 8(d' - \Phi/2 - \phi_t)$ where $\Phi = (4/\pi)^{1/2} As^{1/2} = 1.128 As^{1/2}$

$\phi_t = (4/\pi)^{1/2} Av^{1/2} = 1.128 Av^{1/2}$

$$n_t = \frac{height\ of\ column}{spacing} + 1$$

$$V_t = A_t[\ 2(B_c + d_c) - 8(d' - \Phi/2 - \phi_t)]\left(\frac{height\ of\ column}{spacing} + 1\right)$$

$$V_t = A_t[\ 2(B_c + d_c + d') - 8(d' - 0.564As^{1/2} - 1.128Av^{1/2})]\left(\frac{height\ of\ column}{spacing} + 1\right) \text{----}(3.10)$$

$V_{sc} = LWh = LW\,(d_s + d')$ --(3.11)

Where L and W are clear span length and clear span width of slab respectively

h= overall thickness of slab=effective depth and d' =concrete cover

$V_{ss} = A_{sL}\,(\frac{L^2}{S} + L) + A_{ssW}\,(\frac{W^2}{S} + W)$ ---(3.12)

Where A_{SL} = cross section area of reinforcement bars parallel to span length of slab

A_{SW} = cross section area of reinforcement bars parallel to span width of slab

3.3.4. Design Constraints

Optimization constraints are the functional and structural requirements of the structure expressed as equality or inequality equations. The constraints on the design consist of two types: structural constraints, such as code requirements and serviceability criteria, and size limitation constraints[3]. In this study, Structural constraints are in accordance with the EBCS EN 1992-1-1:2013 Code provisions. In the following there are column's constraints, beam's constraints and slab's constraint categorized as geometric constraint and constraints deducted according to the requirements of EBCS EN Code for the design of column, beam and slab. The mathematical formulation contains only inequality constraints, as equality constraints are usually not found in the case of structural optimizations.

Beam Constraints

For this optimal design problem of beams, the dimensions or quantities taken as design variables are width of beams (B_b), effective depth of beams(d_b)**,** area of tensile reinforcement (Ast), area of compressive reinforcement (Asc) area of shear reinforcement, (Av) and spacing of shear reinforcement (Sv).

A) Flexural Capacity

The moment resistance capacity of the cross-section should be higher than the applied bending moment. The applied bending moment generally includes the effects of the self-weight of the beam. The bending moment capacity imposes a nonlinear constraint to the optimization [5].

i) Singly Reinforced Rectangular Section

Concrete beams subjected to pure bending must resist both tensile and compressive stresses. However, concrete has very low stresses, and therefore tension steel is placed these location (below neutral axis). The most economical solution is to place the steel bars as far as possible from neutral axis except the concrete. For a singly reinforced beam, the stress block is as shown in the following figure

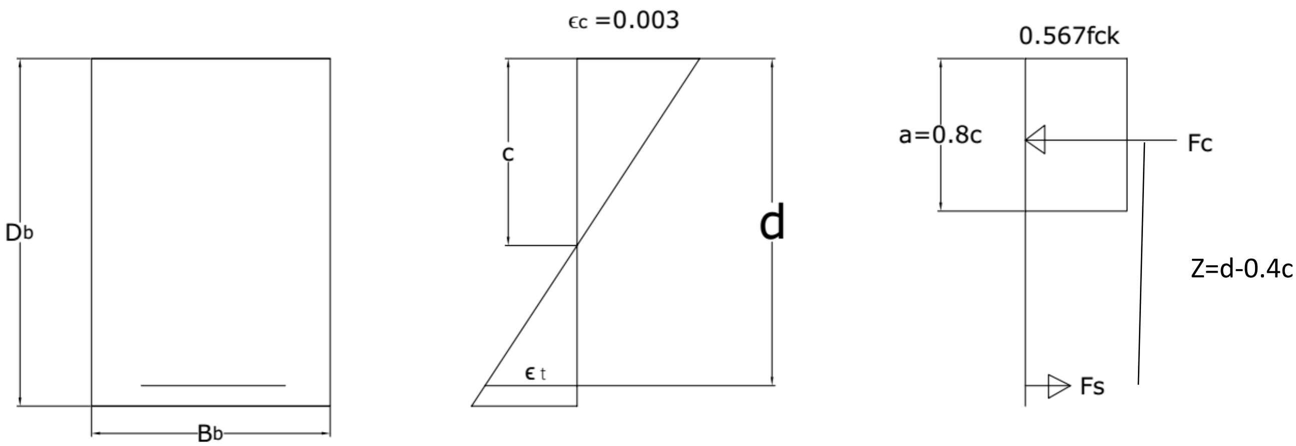

Figure 3.2. Reinforced concrete cross section and resistive forces for singly reinforced sections (source: [31])

From the equilibrium of forces, $Fc = Fs$

$Fc = 0.567 f_{ck}\, a B_b$

$Fs = 0.87 f_{yk} As$

$a = 0.87 fyk\, A_{st} / 0.567 fck B_b$

moment resistance of the section $Mu = FsZ = 0.87 f_{yk}\, A_{st}\, (d - a/2)$

$= 0.87 f_{yk}\, A_{st}\, (d - 0.87 f_{yk}\, A_{st} / 1.134 f_{ck} B_b)$

All beams are designed to ensure that the moment produced by factored loads M_d does not exceed the available flexural design strength M_u of the cross section at any point along the length of the beam.

$$M_d \leq M_u = 0.87 f_{yk}\, A_{st} \left[d_b - \frac{0.87 fykAst}{1.134 fckBb} \right]$$

$$M_d - 0.87 f_{yk}\, A_{st} \left[d_b - \frac{0.87 fykAst}{1.134 fckBb} \right] \leq 0 \text{ --(3.13)}$$

ii) Doubly Reinforced Rectangular Section

If a section is subjected to bending moment greater than its limiting moment of resistance as a singly reinforced section, doubly reinforced sections will be used. Doubly reinforced sections are those that include both compression and tension steel reinforcement. In most case they become necessary when architectural requirement restrict the beam depth. From the economic point of view, it is recommended to design the member as singly reinforced section with tension reinforcement only. If the required area of tension steel exceeds the maximum area of steel recommended by the code, compression steel should be added. Adding compression steel reinforcement may change the mode of failure from compression failure to tension failure or may change the section status from over-reinforced section to under reinforced section. Compression steel also reduces long-term deflection and beam ductility. A rectangular section with compression reinforcement at the ultimate limit state as shown in the following figure is considered.

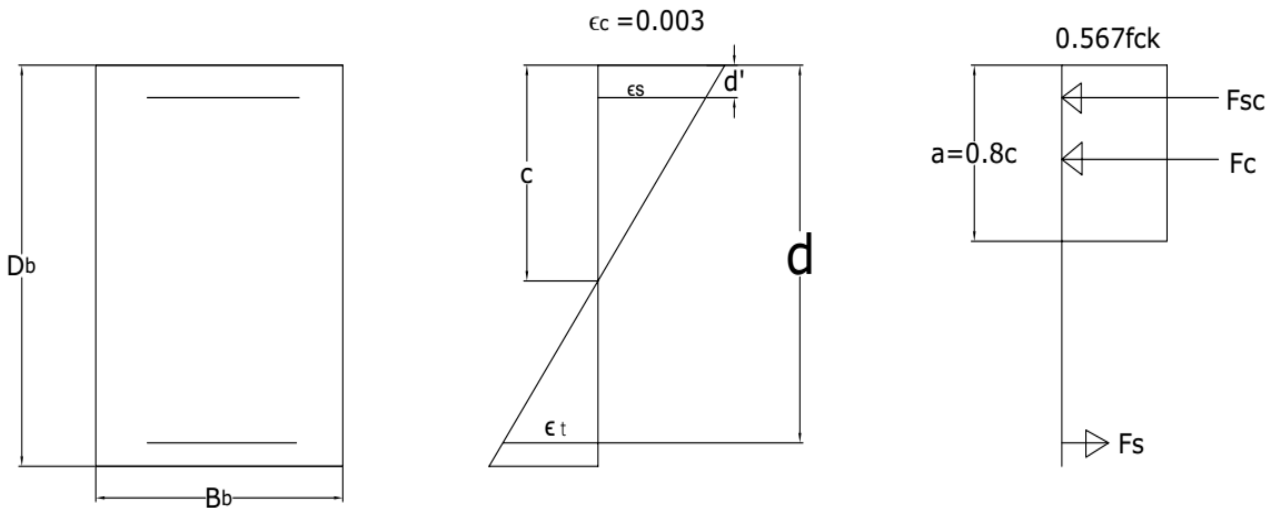

Figure 3.3. Reinforced concrete cross section and resistive forces for doubly reinforced sections (source: [31])

From the section properties and taking moments about centre of tensile steel,

$$Mu=Fc\ (d_b - a/2) + Fsc\ (d_b - d')$$

$Fc=0.567f_{ck}\ aB_b$, $Fsc=0.87f_{yk}Asc$, $a=0.8c$, Asc is area of compression reinforcements

Where c is the depth of neutral axis from the top outer most surface of beams and a is the depth of stress block. To ensure that all beams have the desirable characteristics of visible warning, if failure is sudden as well as reasonable ductility at failure, it is recommended that depth of neutral axis should be limited.

In EBCS 2, article 3.7.9, $\frac{c}{d} \leq 0.8(\delta - 0.44)$, where δ = % moment redistribution,

$$= \frac{\text{Moment after redistribution}}{\text{Original moment}}$$

When no moment is redistributed, $\delta = 1$.

In such a case, $\frac{c}{d} = 0.45$, or, c = 0.45d, a= 0.8*0.45d =0.36d

$$Mu=0.1674f_{ck}B_b d_b^2 + 0.87f_{yk}\ Asc\ (d_b - d')$$

All beams are designed to ensure that the moment produced by factored loads M_d does not exceed the available flexural design strength M_u of the cross section at any point along the length of the beam

$M_d \leq M_u = 0.1674 f_{ck} B_b d_b^2 + 0.87 f_{yk} Asc\ (d_b - d')$

$M_d - 0.1674 f_{ck} B_b d_b^2 - 0.87 f_{yk} Asc\ (d_b - d') \leq 0$ ---(3.14)

B) Shear Strength Requirement

For reinforced concrete members with vertical shear reinforcement, the shear resistance, $V_{Rd,s}$, should be taken to be the lesser, either (Euro Code -2,part 1, EN 1992-1-1 section 6.2.3)

$$V_{Rd;s} = \frac{Av}{s} z f_{yd} \cot\theta \text{ or } V_{Rd;max} = \alpha_c b z v f_{cd} / (\cot\theta + \tan\theta)$$

where $V_{Rd,s}$ is the design value of the shear force which can be sustained by the yielding shear reinforcement; $V_{Rd,max}$ is the design value of the maximum shear force which can be sustained by the member, limited by crushing of the compression struts; Av is the cross sectional area of the shear reinforcement; s is the spacing of the stirrups; z is the lever arm, that may be considered as z = 0.9d; fyd is the yield strength of the shear reinforcement; θ is the angle of the inclined struts; b is the width of the member; f_{cd} is the design compressive cylinder strength of concrete at 28 days; and αc is a coefficient that takes into account the effect of normal stresses on the shear strength. The recommended value of αc follows from the following expressions:

$$\alpha_c = \begin{cases} 1 & \text{for non-pre stressed structures} \\ (1 + \sigma_{cp}/f_{cd}) & \text{for } 0 < \sigma_{cp} \leq 0{,}25\ f_{cd} \\ 1.25 & \text{for } 0.25\ f_{cd} < \sigma_{cp} \leq 0{,}5\ f_{cd} \\ 2{,}5\ (1 - \sigma_{cp}/f_{cd}) & \text{for } 0.5\ f_{cd} < \sigma_{cp} < 1.0\ f_{cd} \end{cases}$$

σ_{cp} is the mean compressive stress, measured positive, in the concrete due to the design axial force. v is a coefficient that takes into account the increase of fragility and the reduction of shear transfer by aggregate interlock with the increase of the compressive concrete strength.

It may be taken to be 0.6 for $f_{ck} \leq 60$ MPa, and $0.9 - f_{ck}/200 > 0.5$ for high-strength concrete beams. The recommended limiting values for cotθ are given by $1 \leq \cot\theta \leq 2.5$ and tanθ is zero for vertical shear reinforcement. For the purpose of this study, αc =1 as the building under consideration is non pre-stressed, v=0.6 since fck considered is less than 60Mpa and cotθ =1 which is the initial value. Therefore the maximum shear resistance of beam member, $V_{Rd;max}$ is given by

$$V_{Rd;max} = \alpha_c bzvf_{cd} = B_b*0.9db*0.6*f_{cd} = 0.54\ B_b d_b f_{cd}$$

$$V_{Rd;s} = \frac{Av}{s} zf_{yd} = \frac{Av}{s}*0.9df_{yd}$$

Factored design shear force of member must be lesser of shear resistance of the sections

$$V_d \leq V_{Rd;max} = 0.54\ B_b d_b f_{cd}$$

$$V_d - 0.54\ B_b d_b f_{cd} \leq 0 \text{ --(3.15)}$$

$$V_d - \frac{Av}{s}*0.9df_{yd} \leq 0 \text{ ---(3.16)}$$

C) Minimum Reinforcing Steel Area Constraint

Euro code 2 specifies, the area of longitudinal tension or compression reinforcement should not be taken as less than $A_{s,min}$

$$A_{s,min} = 0.26\frac{fctm}{fyk} B_b d_b \text{ but not less than } 0.0013 B_b d_b$$

For tensile reinforcing steel,

$$0.26\frac{fctm}{fyk} B_b d_b - A_{st} \leq 0 \text{ or } 0.0013 B_b d_b - A_{st} \leq 0 \text{ --(3.17)}$$

For compression reinforcing steel,

$$0.26\frac{fctm}{fyk} B_b d_b - A_{sc} \leq 0 \text{ or } 0.0013 B_b d_b - A_{sc} \leq 0 \text{ --(3.18)}$$

D) Maximum Reinforcing Steel Area Constraint

Euro code 2 again specifies**,** The cross-sectional area of tension or compression reinforcement should not exceed $A_{s,max}$ outside lap locations.

$A_{s,max}$ = 0.04Ac =0.04B_b (d_b +d')

For tension reinforcement,

Ast -0.04B_b (d_b +d') ≤ 0 ---(3.19)

For compression steel,

Asc -0.04B_b (d_b +d') ≤ 0 ---(3.20)

E) Shear Reinforcement Spacing Constraints

The transverse spacing of the legs in a series of shear links should not exceed $S_{t,max}$

St,max = 0.75d ≤ 600 mm

$Sv - 0.75d \leq 0$---(3.21)

$Sv - 600mm \leq 0$ ---(3.22)

Column Constraints

For this optimal design problem of columns, the dimensions or quantities taken as design variables are width of column (B_c), effective depth of columns (d_c)**,** area of longitudinal reinforcement (As), area of shear reinforcement, (Av) and spacing of shear reinforcement (St).

1) Geometric Constraint

The column constraints based on EC 2 specification are derived in terms of the design variables as follows. For the present formulation, columns may be square or rectangular. In order to ensure that the width of the column will not exceed its depth (which is assumed to be in the direction of bonding), the column dimensions are constrained as follows

$B_c \leq D_c$ where Bc = width of column, Dc = overall depth of column

$B_c / D_c - 1 \leq 0$ or $B_c - D_c \leq 0$

$Bc - (dc+d') \leq 0$ --(3.23)

2) Strength Constraints

A) Axial Capacity

Present design practice in calculating the nominal strength of an axially loaded member is to assume a direct addition law summing the strength of the concrete and that of the steel. The usual assumption is made that steel and concrete strains are identical at any load stage. The ultimate Load Capacity of a section from EC 2 clause 4.3.5.6.3 is given by

$Pu=0.57fckAc+0.87fykAs$

The ultimate axial load should be less than the axial capacity of the column
Therefore, $N_{Ed} \leq Pu = 0.57fckAc+0.87fykAs$

where N_{Ed} and Pu are ultimate design axial load and axial capacity of the column respectively; Ac and As are areas of concrete and longitudinal reinforcement respectively.

$N_{Ed} - Pu \leq 0$, $N_{Ed} - 0.57\, f_{ck}BcDc - 0.87f_{yk}As \leq 0$

$N_{Ed} - Pu \leq 0$, $N_{Ed} - 0.57\, f_{ck}Bc(dc+d') - 0.87f_{yk}As \leq 0$ ---(3.24)

N_{Ed} will be obtained from structural analysis

B) Flexural capacity

A column rectangular reinforced concrete column section is shown in Figure3.4

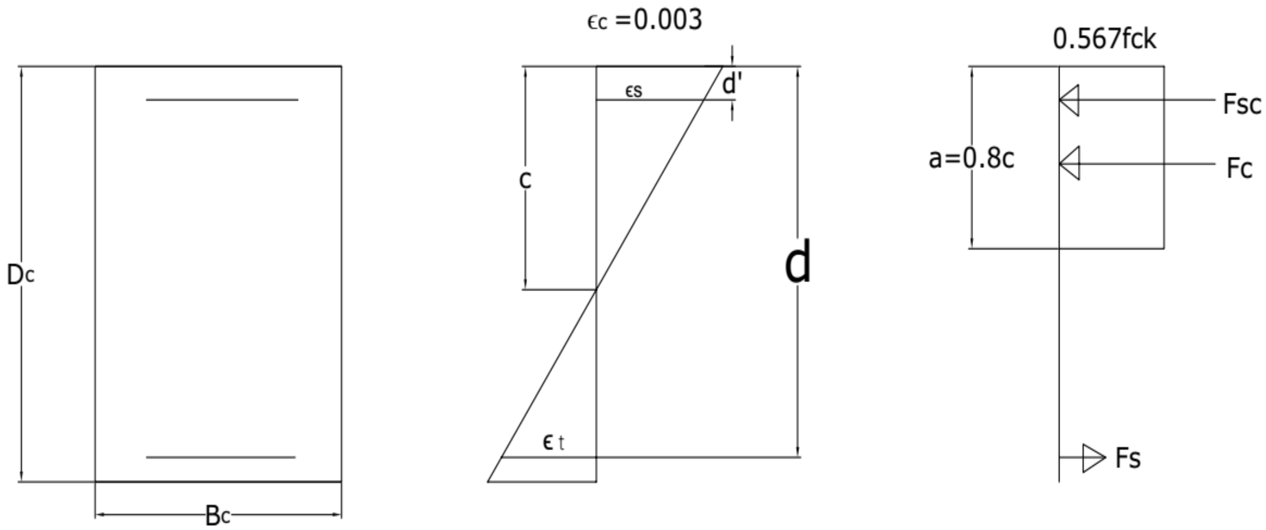

Figure 3.4. Reinforced concrete cross section and resistive forces for column reinforced sections (source: [31])

From the section properties shown above taking moments about Centre of tensile steel,

Mu =Fc(d- a/2)+Fsc(d- d') a=0.8c

$Fc=0.567f_{ck}aB_c$, $Fsc= 0.87f_{yk}As'$ As'=area of compression steel

Where a and c are depth of stress block and depth of neutral axis respectively. To ensure that all columns and beams have the desirable characteristics of visible warning, if failure is sudden as well as reasonable ductility at failure, it is recommended that depth of neutral axis should be limited.

In EBCS 2, article 3.7.9, $\frac{c}{d} \leq 0.8(\delta - 0.44)$, where δ = % moment redistribution,

$$= \frac{\text{Moment after redistribution}}{\text{Original moment}}$$

When no moment is redistributed, δ = 1.

In such a case, $\frac{c}{d} = 0.45$, or, c = 0.45d, a = 0.8x0.45d=0.36d

$Mu = 0.567f_{ck}*0.36d*Bc(d - 0.36d/2) + 0.87f_{yk}As'(d - d')$

$Mu = 0.1674f_{ck}d^2Bc + 0.87fykAs'(d - d')$

In the case of column, the area of compression reinforcement is half of the total area of reinforcement. Therefore, As' =As/2

$Mu = 0.1674f_{ck}d^2Bc + 0.435fykAs(d - d')$

All columns are designed to ensure that the moment produced by factored loads M_d does not exceed the available flexural design strength M_u of the cross section.

$M_d \leq Mu = 0.1674f_{ck}d^2Bc + 0.87fykAs(d - d')$

$M_d - 0.1674f_{ck}d^2Bc - 0.435fykAs(d - d') \leq 0$ --(3.25)

3) Minimum Area of Reinforcing Steel Constraint

Columns are designed on the basis of the interaction between combined bending and axial load. However, since the axial load has direct influence on the moment capacity of the column, and vice versa, there is no simple way of uncoupling the two effects. The EBCS EN1992-1-1:2013 Code allows the minimum steel ratio of 0.2 percent.

$A_{s,min} = 0.10N_{ED}/f_{yd}$ or 0.002Ac whichever is the greater

$A_{s,min} - A_s \leq 0$

$0.10N_{ED}/f_{yd} - A_s \leq 0$ or $0.002Bc\,(dc + d') - A_s \leq 0$ --(3.26)

4) Maximum Reinforcing Steel Area Constraint

The EN 1992-1-1:2013 Code allows the maximum steel ratio of 4 percent of gross area at location of no laps and 8 percent of gross area at location of laps.

$As - A_{s,max} \leq 0$

$As - 0.04Bc\,(dc + d') \leq 0$ at location of no lap --(3.27)

$As – 0.08Bc (dc + d') \leq 0$ at location of lap ---(3.28)

5) Transverse Reinforcement

The diameter of the transverse reinforcement (links, loops or helical spiral reinforcement) should not be less than 6 mm or one quarter of the maximum diameter of the longitudinal bars, whichever is the greater. The spacing of the transverse reinforcement along the column should not exceed *s*cl,tmax. The recommended value is the least of the following three distances:

- ✓ 20 times the minimum diameter of the longitudinal bars
- ✓ the lesser dimension of the column
- ✓ 400 -------------------([30])

based on the principles laid down by the specified code, the constraint for transverse reinforcement is as follows

$Av \geq Av,min$, $Av,min – Av \leq 0$ --(3.29)

Spacing of transverse reinforcement is also constrained as follow

$St - 20\, \Phi_{min} \leq 0$ ---(3.30)

$St - Bc \leq 0$ --(3.31)

$St – 400 \leq 0$ --(3.32)

Slab Design Constraints

Flexural Resistance

As the ratio of longer side to shorter side is less than 2, the slab of case study building in this study is two-way slab. In case of two-way slabs, Bending will take place in the two directions in a dish-like form. Therefore, the reinforcement against bending is estimated for both short and long directions for two-way slabs. A rectangular stress distribution is assumed as shown in figure below.

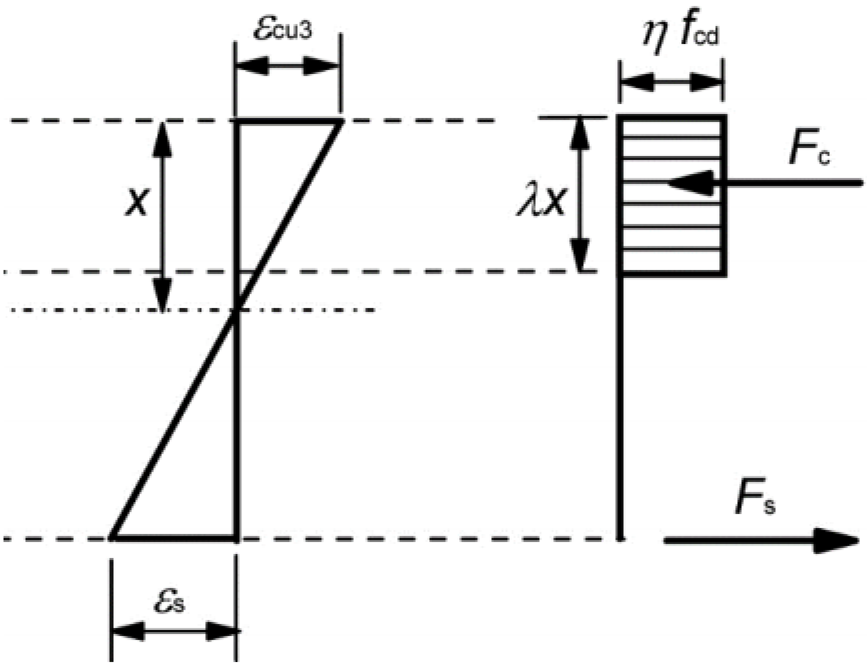

Figure 3.5. Rectangular Stress Distribution (source: [30])

The factor λ defining the effective height of the compression zone and the factor η defining the effective strength, follow from:

$\lambda = 0.8$ for $f_{ck} \leq 50$ MPa $\eta = 1.0$ for $f_{ck} \leq 50$ MPa

$\lambda = 0.8 - (fck - 50)/400$ for $50 < f_{ck} \leq 90$ MPa $\eta = 1.0 - (f_{ck} - 50)/200$ for $50 < f_{ck} \leq 90$ MPa

In this study, since f_{ck} is less than 50Mpa, $\lambda = 0.8$ and $\eta = 1.0$

Bending Moment Resistance Capacity Along Longer Direction

From the section properties shown above taking moments about Centre of compressive steel, moment resistance of the section is given by

$M_{ul} = F_s\,(d - \lambda x/2) = 0.87 f_{yk} A_{sl} \left(d - \frac{0.87 fykAsl}{1.6 fcdb}\right)$ where b is per meter length and A_{sl} is area of reinforcement along longer direction

Moment due to external actions, M_{ED} which is along the longer side should not be greater than the section capacity, M_{ul}

$M_{edl} \leq M_{ul} = F_s\,(d - \lambda x/2) = 0.87 f_{yk} A_{sl} \left(d - \frac{0.87fykAsl}{1.6fcdb}\right)$

$M_{edl} - 0.87 f_{yk} A_{sl} \left(d - \frac{0.87fykAsl}{1.6fcdb}\right) \leq 0$ ---(3.33)

Bending Moment Resistance Capacity Along Shorter Direction

Again, from the section properties shown above taking moments about Centre of compressive steel, moment resistance of the section is given by

$M_{us} = F_s\,(d - \lambda x/2) = 0.87 f_{yk} A_{ss} \left(d - \frac{0.87fykAss}{1.6fcdb}\right)$ where b is per meter width and A_{ss} is area of reinforcement along shorter direction.

Similarly, in this direction, moment due to external actions, M_{ED} which is along the shorter side should not be greater than section capacity, M_{us}.

$M_{eds} \leq M_{us} = F_s\,(d - \lambda x/2) = 0.87 f_{yk} A_{ss} \left(d - \frac{0.87fykAss}{1.6fcdb}\right)$

$M_{eds} - 0.87 f_{yk} A_{ss} \left(d - \frac{0.87fykAss}{1.6fcdb}\right) \leq 0$ ---(3. 34)

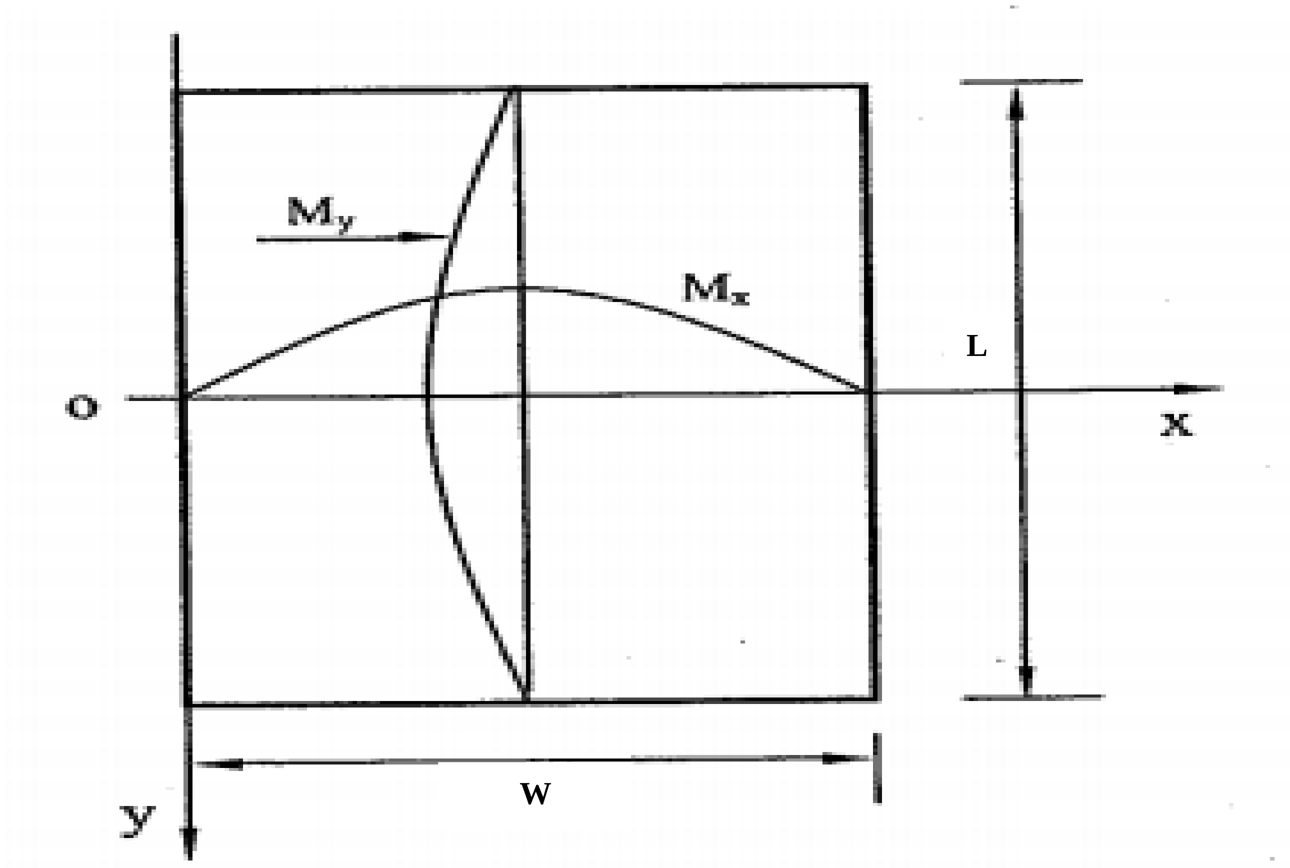

Figure 3.6 moment along shorter and longer directions of panel of slab (Source: [32])

Minimum Area of Reinforcing Steel Constraint

Minimum areas of steel reinforcement must be provided to control crack. The provision of minimum area ensures that the steel reinforcement does not yield when the concrete in the tension zone cracks with a sudden transfer of stress to the reinforcement. The area of reinforcement in primary direction should not be less than $0.26\frac{fctm}{fyk}$ bd_s or $0.0013bd_s$ where b is width per meter or length per meter and d_s is effective depth of slab.

$0.26\frac{fctm}{fyk}$ bd $-A_{ss} \leq 0$ or 0.0013bd - $A_{ss} \leq 0$ ---(3.35)

Maximum Area of Reinforcing Steel Constraint

As -0.04B (d_s +d') ≤ 0 ---(3.36)

Spacing of Reinforcements

The spacing of bars should not exceed $S_{max,slabs.}$

The recommended value of $S_{max,slabs.}$ is:

- for the principal reinforcement, $3h \leq 400$ mm, where h is the total depth of the slab;

- for the secondary reinforcement, $3.5h \leq 450$mm.

Based on the mentioned specification for the maximum spacing of bars, constraints on spacing can be set out as shown below in equations 39 and 40.

$S - 3h \leq 0, S - 3(d + d') \leq 0$ ---(3.37)

$S - 400 \leq 0$ --(3.38)

3.4. Description of Case Study

To establish a benchmark for comparative reasons, in this study, G+10 office building located in high seismic zone four is selected as optimization problem[33]. Note that the location of the structure is specified for the sake of considering seismic effect as the structure is exposed to earthquake. The structure has four pans with length of 3m, 3m,3m and 3m in horizontal and vertical directions. The structural plan layout and 3D ETABS model are shown in Figure 3.7. Predetermined section sizes are considered for beams, columns and slabs for all floors where the beams and columns have a rectangular shape. The entire story's height is assumed to be 3.65m. The characteristic cylindrical strength of concrete is 30 MPa and characteristic yield strength of main reinforcements and shear reinforcements are 460 MPa and 300Mpa for all member sizes respectively. Dimensional details are given in the following table.

Table 3.2. case study dimension details

Parameters	**Values**
Plan dimension	12mx12m
Elevation from depth of fixity	43.8m

Floor/floor height	3.65m
Total number of stories	12
Beam dimension	0.35mx0.4m
Column dimension	0.5mx0.6m
Slab thickness	0.15m

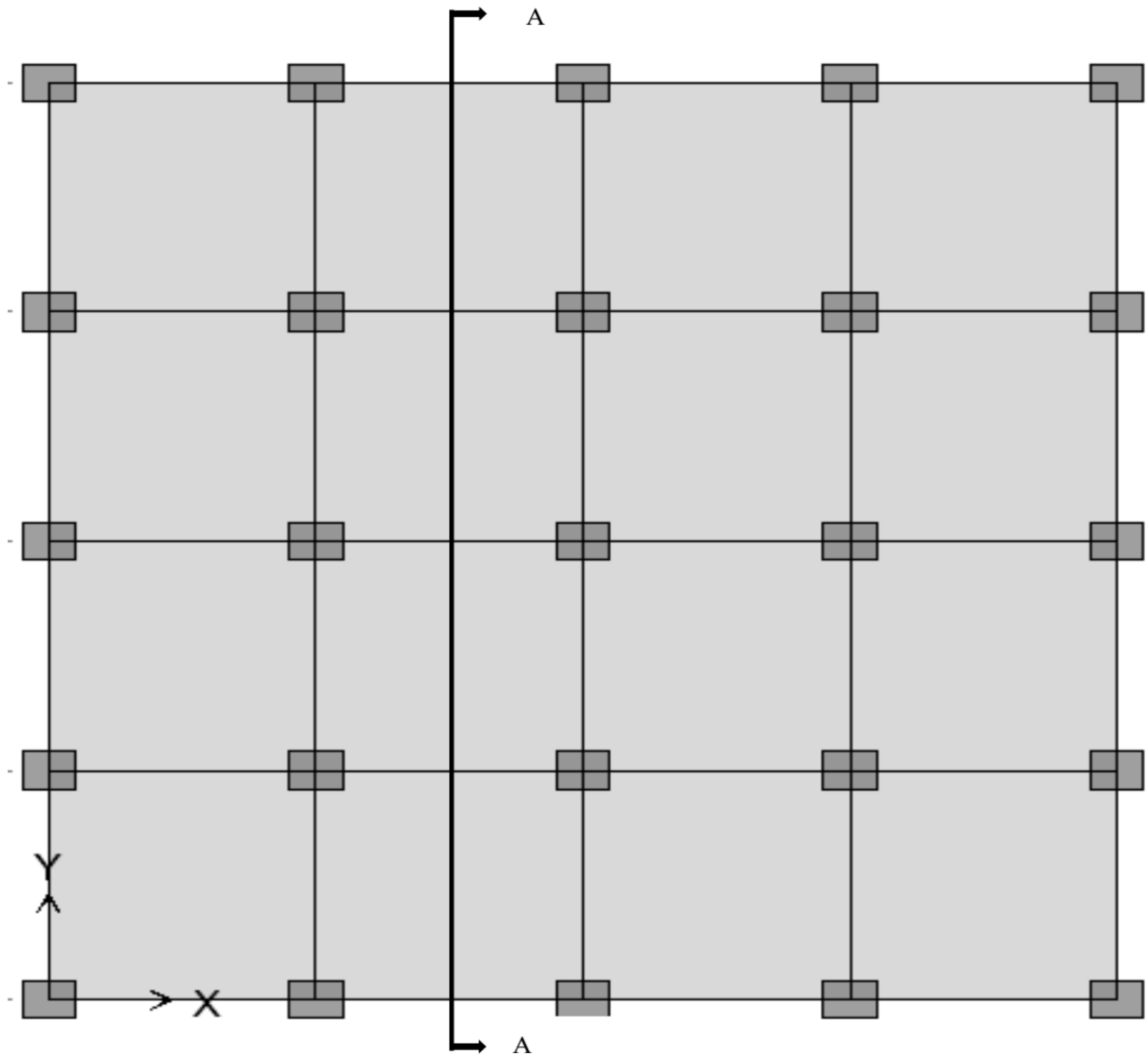

Figure 3.7. Typical floor plan of the case study

3.5. Design Strength of Concrete and Reinforcing Steel

Concrete

In Euro code 2 the design of reinforced concrete is based on the characteristic cylinder strength rather than cube strength. The value of the design compressive strength concrete is defined as

$fcd = \alpha_{cc} f_{ck}/\gamma_c$ γ_c=1.5, ---------[30].(Table 2.1N page 20)

α_{cc} is the coefficient taking account of long-term effects on the compressive strength and of unfavorable effects resulting from the way the load is applied and equal to 0.85

The value of the design tensile strength, f_{ctd} is defined as $f_{ctd} = \alpha ct fctk,0.05/ \gamma_c$

α_{ct} is coefficient taking account of long-term effects on the tensile strength and of unfavorable effects, resulting from the way the load is applied and equal to 0.85 [30].

Reinforcing Steel

Eurocode 2 can be used with reinforcement of characteristic strengths ranging from 400 to 600 MPa. In this study,460mpa and 300mpa grade of main and shear reinforcements respectively were used as characteristics yield strength.

$f_{yd} = f_{yk}/\gamma_s$, γ_s =1.15 ---------[30]. (Table 2.1N page 20)

Concrete Cover

The concrete cover is the distance between the surface of the reinforcement closest to the nearest concrete surface (including links and stirrups and surface reinforcement where relevant) and the nearest concrete surface. The nominal cover shall be specified on the drawings. It is defined as a minimum cover, C_{min} plus an allowance in design for deviation, Δc_{dev}

$C_{nom} = C_{min} + \Delta c_{dev}$

Minimum Cover, C_{min}

Minimum concrete cover, c_{min} shall be provided in order to ensure:

- ✓ the safe transmission of bond forces
- ✓ the protection of the steel against corrosion (durability)

- ✓ an adequate fire resistance

The greater value for c_{min} satisfying the requirements for both bond and environmental conditions shall be used.

c_{min} = max {$c_{min,b}$; $c_{min,dur} + \Delta c_{dur,\gamma} - \Delta c_{dur,st} - \Delta c_{dur,add}$; 10 mm [30].

where: $c_{min,b}$ is minimum cover due to bond requirement,

$c_{min,dur}$ is minimum cover due to environmental conditions,

$\Delta c_{dur,\gamma}$ is additive safety element,

$\Delta c_{dur,st}$ is reduction of minimum cover for use of stainless steel,

$\Delta c_{dur,add}$ is reduction of minimum cover for use of additional protection,

in this study, $cmin_{,b}$ =12mm, $c_{min,dur}$ =20mm for beam and column, $c_{min,dur}$ =10mm for slab $\Delta c_{dur,\gamma}$ =0 ,$\Delta c_{dur,st}$ =0 and $\Delta c_{dur,add}$ =0

c_{min} = max {12mm; 20mm + 0- 0 –0; 10 mm} =20mm for beam and column

c_{min} = max {12mm; 10mm + 0- 0 –0; 10 mm} = 12mm for slab and the recommended value for Δc_{dev} is 10 mm.

Therefore, the nominal cover, $C_{nom} = C_{min} + \Delta c_{dev}$ =20mm+10mm=30mm for beam and column 20mm for slab is used.

3.6. Optimization of Structural Elements

3.6.1. Grouping of Structural Elements

In order to reduce the complexity of optimization, grouping of beams, columns and slabs have been done based on the position, the same cross-sectional properties and loading conditions. Accordingly, Members of frames are first grouped into beams and columns. Therefore, members in the identified group will have the same cross-sectional dimensions and reinforcement details.

In the present formulation, one beam refers to the continuous beam at one level of the frame. It may be a single-span beam (in the case of single-bay frames) or a multi span beam. More of such beams can be combined to form one group such that all the are the same for all the beams in the group. For the considered case study, there are 60 columns and 48 beams in the sub-frame.

They are divided into 24 beams member groups and 36 column member groups. The grouping of beams and columns is done as shown in figure below.

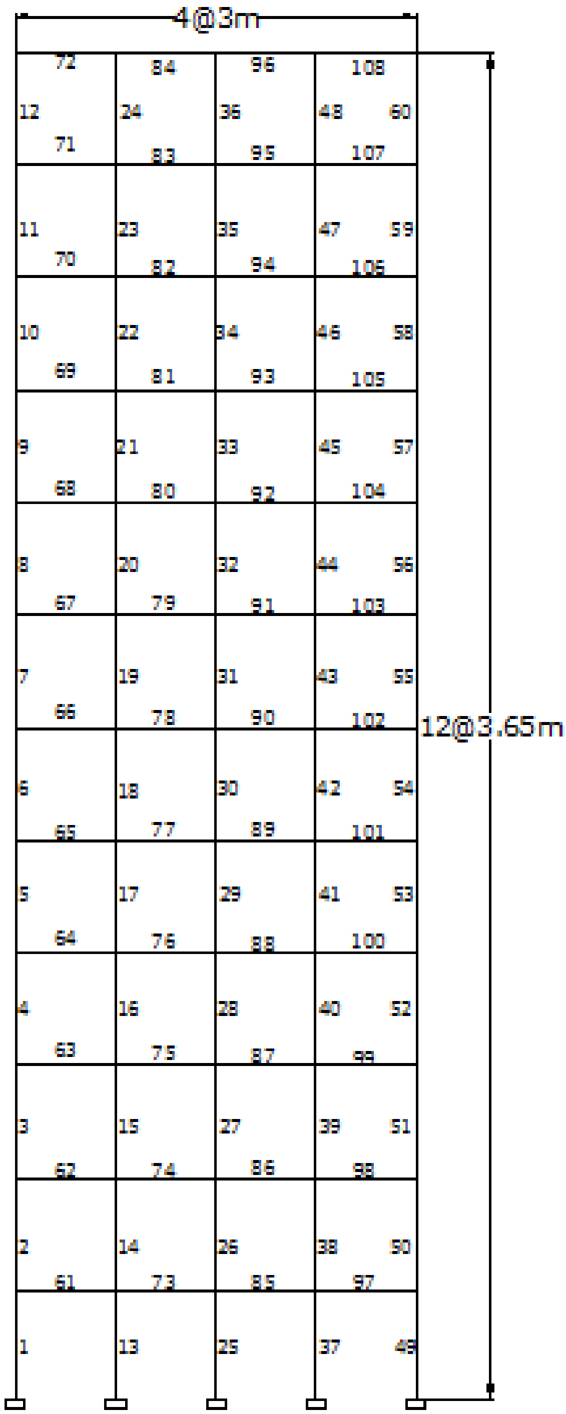

Figure 3.8: Member numbers for the case study (Section A-A in Figure 1)

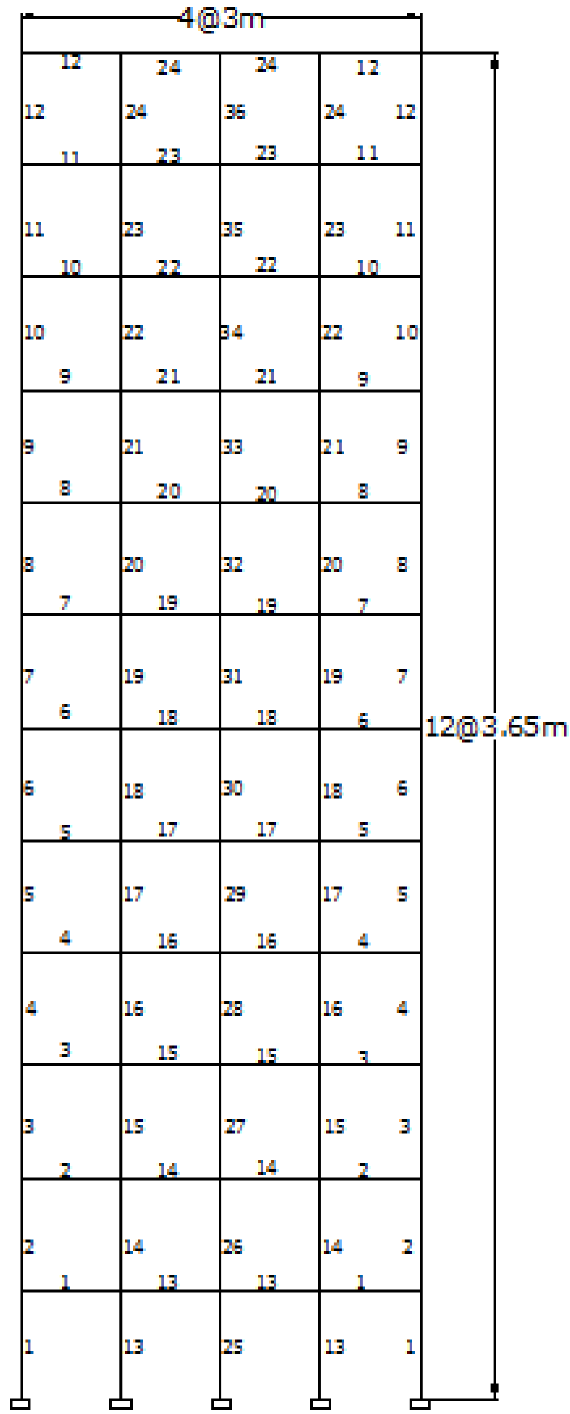

Figure 3.9: Member group numbers for the Case study (Section A-A in Figure 1)

3.6.2. Initialization Values for Design Variables.

The algorithm requires a feasible point to start. If the initial point is not feasible, then it can be found by solving the linear programming. This feasible point is the initial value for design variables. For the purpose of this study, the initial values for decision variables (cross-sectional dimensions of structural elements) are taken from the case study under consideration and for other design variables has been obtained using limit state design as per EBCS EN 19921-1-2013 for the verification of optimization methods (MATLAB Optimization tool box and Evolutionary algorithm embedded in Excel solver). Accordingly, the initial, lower and upper bound values of cross-sectional dimensions of structural elements are given in Table 3.3 shown below. The initial values for the remaining decision variables were determined after the analysis and design of the case study. The quantities initial values(x0), lower bound (LB), and upper bound (UB) are arguments in f_{mincon} and evolutionary solver. These quantities are given in the following table.

Table 3.3. Initial, lower and upper values for design variables

Structural elements	Design variables	Initial value(mm)	Lower bound value(mm)	Upper bound value(mm)
Beam	Width	350	200	400
	Effective depth	350	300	500
Column	Width	500	350	500
	Effective depth	550	380	600
Slab	Effective thickness	150	80	200

3.6.3. Solution of Formulated Optimization Problems Using Optimization Tool Box in MATLAB

In order to solve optimization problems using optimization tool box in MATLAB the formulated nonlinear programming problems should be converted from nonlinear programming mathematical form into MATLAB's Optimization Toolbox solver syntax through the following steps

1. Define the objective function in the MATLAB® language, as a function file or anonymous function.
2. Define the constraints as a separate file or anonymous function

The nonlinear programming problems were separately formulated for each group of beam, column and slab

Solution for* Formulated *Optimization Problems of Beams

The optimization problems formulated for each beam element were solved by using optimization tool box in MATLAB. All Beams of the structure (the case study) were grouped based on their locations and loading conditions. Accordingly, beams were grouped into 24 groups as shown in the figure 3.9 of sub-frame of the case study. The formulated optimization problems for the grouped beams were solved through the following steps.

1. Creating M-file for objective and constraint functions
2. Running optimization for obtaining optimum solution for design variables.

For the proposed case study for this study, the grouped beams have the same objective functions but different constraint functions. Therefore, for each group of beams, M-file for constraint functions were created as shown for group one below.

M-file for Objective Function for all Grouped Beams

An M-file is a text file containing MATLAB commands with the extension.m. the new M-file can be created in any text editor, or using the built-in MATLAB Editor. The objective function for all grouped beams is written in M-file as shown below.

```
function f= beam(x)
f=0.075*x(1)*x(2)+3.75*x(1)+0.1605*x(3)+0.1605*x(4)+(0.321*x(1)*x(5))/x(6)+(0.321*x(2)*x
(5))/x(6)-48.15*x(5)/x(6)+(0.7246*x (3) ^0.5*x (5))/x (6) +1.4482*x (5) ^1.5/x (6)
 +0.000107*x (1) *x (5) +0.000107*x (2) *x (5)-0.01605*x (5)
 + 0.0002414*x (3) ^0.5*x (5) +0.0004844*x (5) ^1.5;
```

M-File for Constraint Function

Constraint functions must be formulated so that they are in the form $c(x) \leq 0$(for inequality constraint) or $ceq(x) = 0$(for equality constraint). In this study, there is only an inequality constraint, so the equality constraint was passed by an empty array [ ] as the equality constraint function *ceq*. The constraint function for group one beam is written in M-file as shown below.

```
function [c, ceq] = constraint(x)
c(1)= 157.411*10^6-400.2*x(2)*x(3) +(4707.95*x(3)^2)/x(1);
c(2) =157.411*10^6-5.022*x(1)*x(2)^2-400.2*x(2)*x(4)
+20010*x(4 );
c(3)= 131.74*10^3-7.344*x(1)*x(2);
c(4)= 131.74*10^3 -360*x(2)*(x(5)/x(6));
c(5)= 0.00141*x(1)*x(2)-x(3);
c(6)= x(3)-0.04*x(1)*x(2)-2*x(1);
c(7) = x(4)-0.04*x(1)*x(2)-2*x(1);
c(8) = x(6)-0.75*x(2);
c(9) =x(6)-600;
ceq =[];
end
```

The constraint function for the remaining beam groups were written in similar format shown above only by changing the values of design actions (moments and shear forces)

Running the Optimization

There are two ways to run the optimization: Using the Optimization Tool and Using command line functions. For this study, the optimization tool was used for obtaining the optimized value of design variables and objective functions. Accordingly, the created M-files for objective function and constraint functions for all grouped beams were ran for optimum solution as shown below.

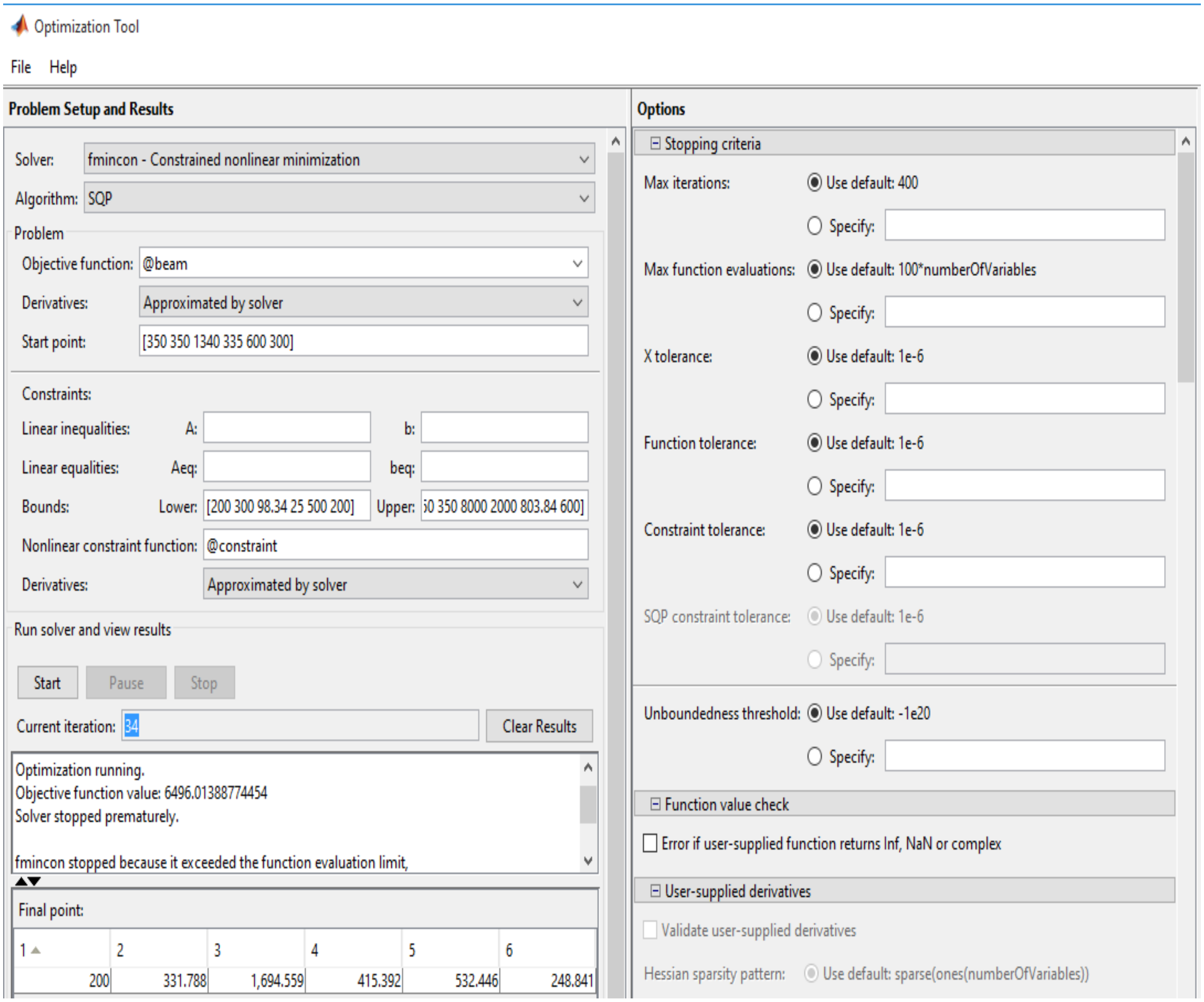

Figure 3.10. graphical user interface of optimization tool box for grouped beams

Solution for Formulated Optimization Problems of columns

M-file for Objective Function for all Grouped Columns

An M-file is a text file containing MATLAB commands with the extension.m. the new M-file can be created in any text editor, or using the built-in MATLAB Editor.

The objective function for all grouped column is written in M-file in similar fashion as in case of grouped beams.

```
function f= column(x)
f=0.075*x(1)*x(2)+3.75*x(1)+0.1605*x(3)+321*x(1)*x(4)/x(5)+0.321*x(2)*x(4)/x(5)-
48.15*x(4)/x(5)-0.7246*x(3)^0.5*x(4)/x(5)+2.8018*x(4)^1.5/x(5)
+0.000107*x(1)*x(4)+0.000107*x(2)*x(4)-0.01605*x(4)
+0.0002412*x(3)^0.5x(4)+0.0009356*x(4)^1.5
```

M-File for Constraint Function

. The constraint function for grouped column is written in M-file as shown below.

```
function [c, ceq] = constraints(x)
c(1)= x(1)-x(2)-50;
c(2)=1407.97*10^3-13.68*x(1)*x(2)-684*x(1)400.2*x(3);
c(3)=353.6*10^6-4.0176*x(1)*x(2)^2-200.1*x(2)*x(3)
+10005*x(3);
c(4)= 0.002*x(1)*x(2)+0.1*x(1)-x(3);
c(5)= x(3)-0.04*x(1)*x(2)-2*x(1);
c(6)= 28.26-x(4);
c(7)= x(5)-x(1) ;
c(8)=x(5)-400;
ceq =[];
end
```

The constraint function for the remaining column groups were written in similar format shown only by changing the values of design actions (moments and shear forces)

Running the Optimization

the created M-files for objective function and constraint functions for all grouped column were ran for optimum solution as shown below.

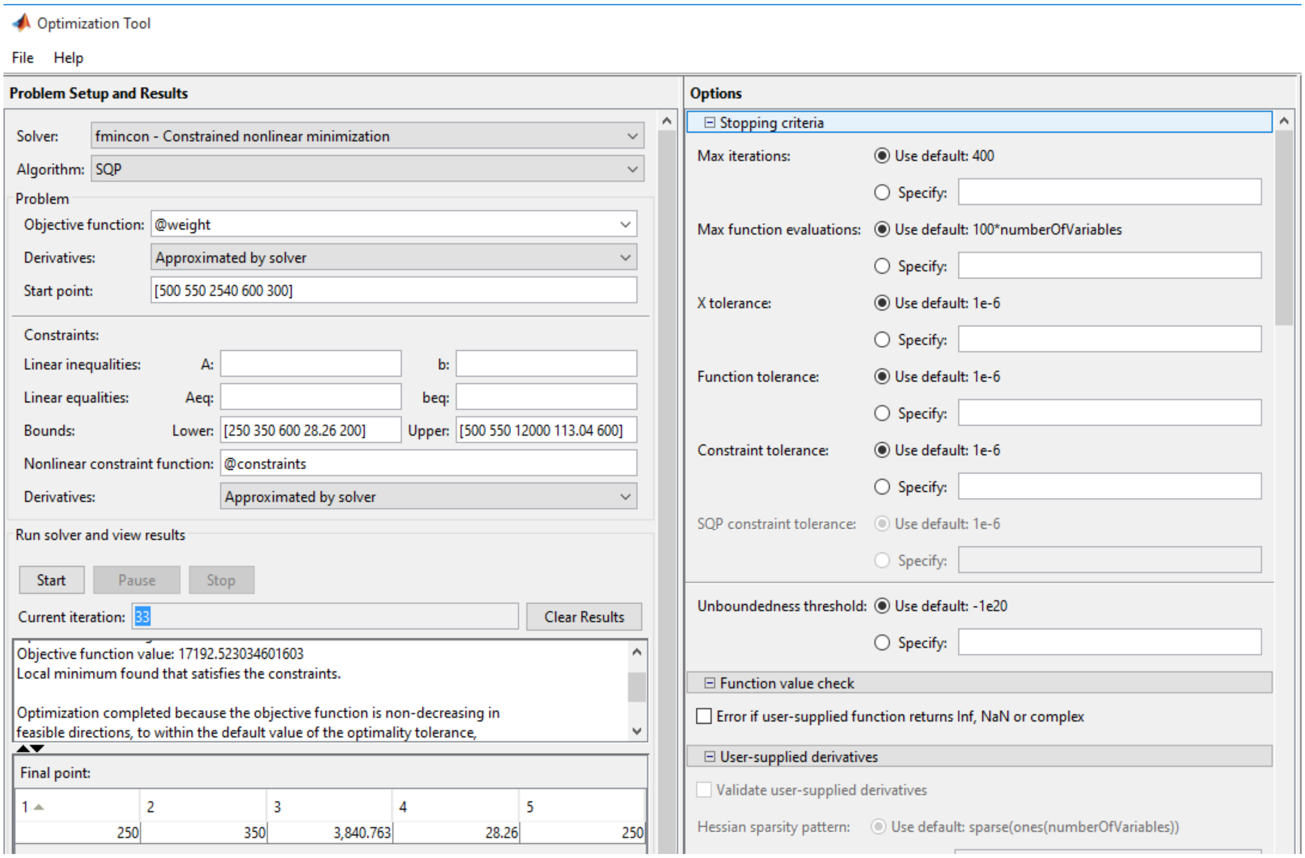

Figure 3.11. graphical user interface of optimization tool box for grouped columns

Solution for Formulated Optimization Problems of Slab

M-file for Objective Function for all Grouped Slabs

```
function f= slab(x)
f = 225*x(1)+7875+481.5*x(2)/x(4) +0.1605*x(2) +481.5*x(3)/x(4) +0.1605*x(3);
```

M-File for Constraint Function

The constraint function for grouped slab is written in M-file as shown below.

```
function [c, ceq] = constrs(x)
    c(1)=  33*10^6 -400.2*x(1)*x(2)+6.256*x(2)^2;
    c(2) = 33*10^6 -400.2*x(1)*x(3)+6.256*x(3)^2;
    c(3)= 1.41*x(1)-x(2);
    c(4)= 1.41*x(1)-x(3);
```

```
c(5)= x(2)-40*x(1)-1400;
c(5)=x(3)-40*x(1)-1400;
c(6)= x(4)-3*x(1) -105;
c(7)= x(4) -400;
 end
```

The constraint function for the remaining for roof slab was written in similar format shown above only by changing the values of design actions (moments)

Running the Optimization

the created M-files for objective function and constraint functions for all grouped slabs were ran for optimum solution as shown below.

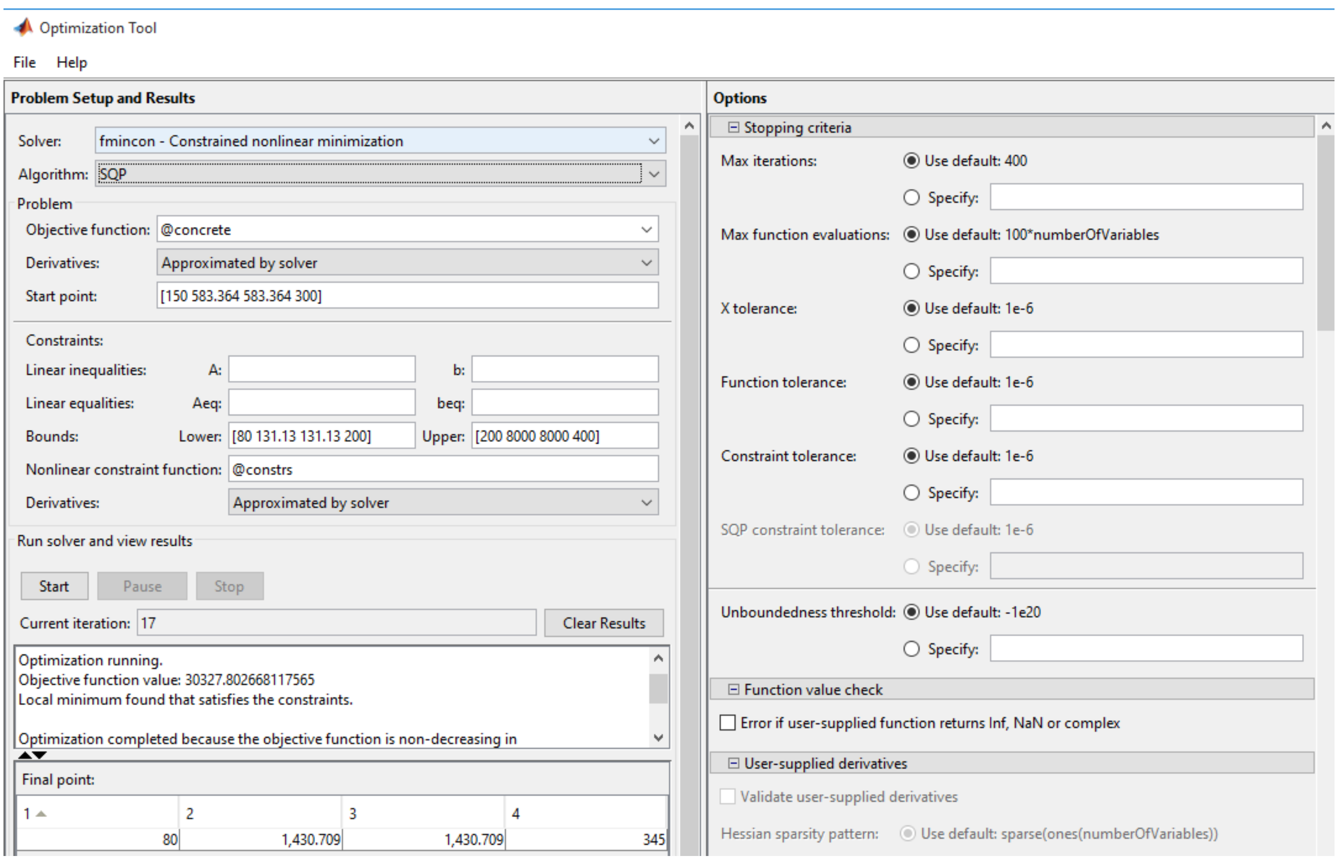

Figure 3.12. graphical user interface of optimization tool box for grouped slabs

3.6.4. Solution for Formulated Optimization Problems Using Evolutionary Solver in Excel Solver

Solutions using the Solver involve preparation of an Excel worksheet, initialization of the Solver and interpretation of the optimum solution. The optimization problem formulated for all structural elements were solved using Evolutionary algorithm embedded in Excel solver through the following steps

1. Creating a spread worksheet which model the problems
2. Specifying the cell which contain the objective function
3. Specifying the design variables
4. Specifying the cells which define the constraints
5. Solving the model i.e. optimizing

3.6.4.1. Solution for Formulated Optimization Problems of Beams

	A	B	C	D	E	F	G	H	I	J	K	L
1	Design Variables											
2	x1= width of beam											
3	x2= depth of beam											
4	x3= area of tensile steel											
5	x4= area of compressive steel											
6	x5 = area of shear reinforcement											
7	x6 = spacing of shear reinforcement											
8	**Minimize** W = 0.075*x1*x2+3.75*x1+0.1605*x3+0.1605*x4+0.321*x1*x5/x6 +0.321*x2*x5/x6-											
9	48.15*x5/x6+0.7246*x3^0.5*x5/x6+1.4482*x5^1.5*/x6+0.000107*x1*x5+0.000107*x2*x5+0.0002414*x3^0.5*x5+0.0004844*x5^1.5											
10	**Obj =**											
11	variable	lower values	required values	upper values								
12	x1	200		350								
13	x2	300		350								
14	x3	1340		8000								
15	x4	335		2000								
16	x5	500		803.04								
17	x6	300		600								

18		**constraint functions**			
19		157.411*10^6 -400.2x2x3 +5884.77x3²/x1 ≤ 0			
20			<=	0	
21		157.411*10^6 -4.0176x1x2+400.2x2x4-20010x4 ≤ 0			
22			<=	0	
23		131.74*10^3-8.64x1x2 ≤ 0			
24			<=	0	
25		131.74*10^3 -234.783x2x5/x6 ≤ 0			
26			<=	0	
27		0.00141x1x2-x3 ≤ 0			
28			<=	0	
29		x3-0.04x1x2-2x1 ≤ 0			
30			<=	0	
31		x4-0.04x1x2-2x1 ≤ 0			
32			<-	0	
33		x6-0.75x2 ≤ 0			
34			<=	0	
35		x6-600 ≤ 0			
36			<=	0	

Figure:3.13. spread work sheet with the specified cells for objective function, design variables and constraints of beams

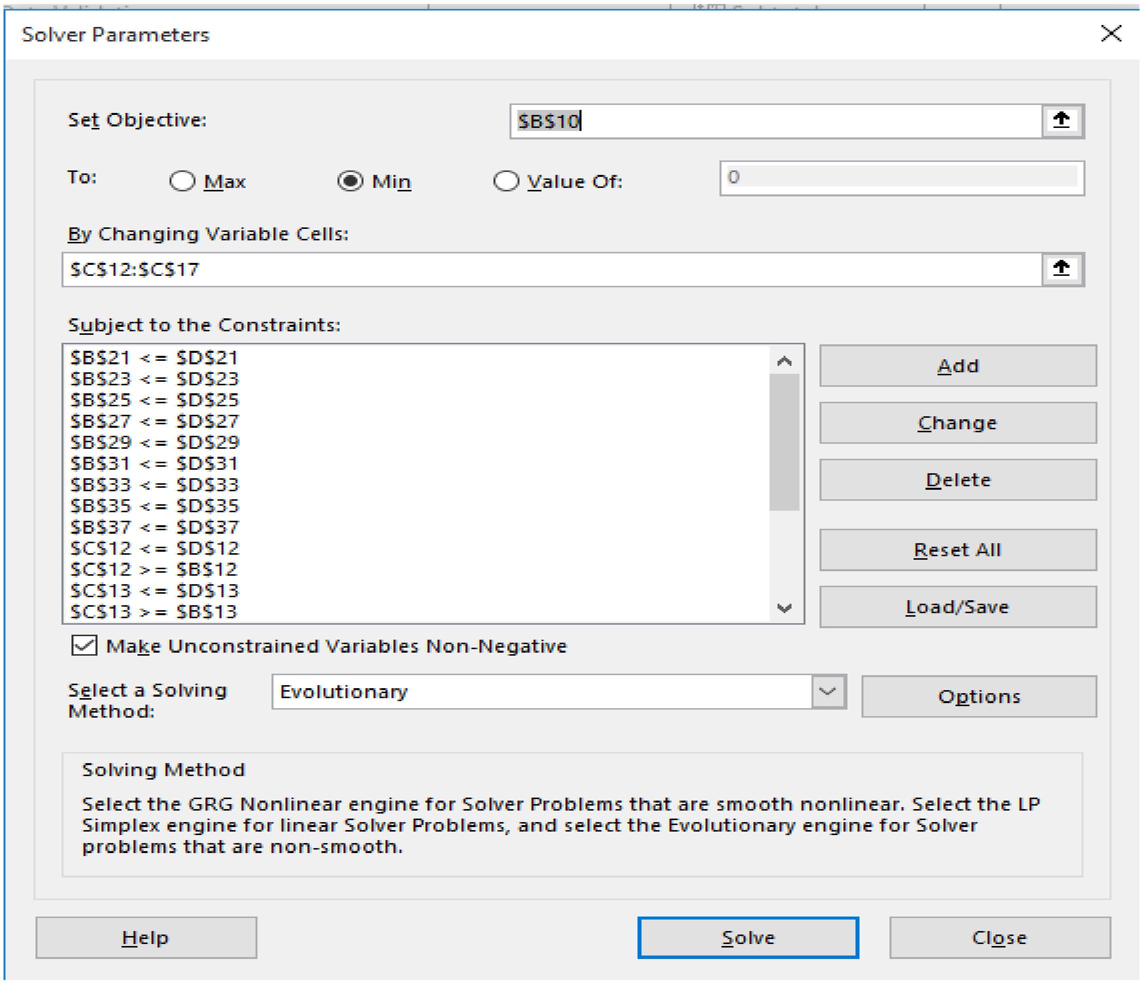

Figure 3.14: Optimization Setup for Evolutionary Algorithm for beams elements

3.6.4.2. Solution for Formulated Optimization Problems of columns

	A	B	C	D	E	F	G	H	I	J
1	Design Variables									
2	x1= width of column									
3	x2= depth of column									
4	x3= area of steel									
5	x4 = area of shear reinforcement									
6	x5 = spacing of shear reinforcement									
7	Min W=	0.075x1x2+3.75x1+0.1605x3+0.321x1x4/x5+0.321x2x4/x5-48.15x4/x5-0.7246x3^0.5x4/x5								
8	Obj=	+2.8018x4^1.5/x5+0.000107x1x4+0.000107x2x4-0.01605x4+0.0002412x3^0.5x4+0.0009356x4^1.5								
9										
10		x1	250		500					
11		x2	350		550					
12		x3	600		12000					
13		x4	28.26		113.04					
14		x5	200		600					

15		constraint function			
16		x1-x2-50 ≤ 0			
17			<=	0	
18		124.73*10^3 -13.68x1x2-684x1-400.2x3 ≤ 0			
19			<=	0	
20		54.36*10^6 -4.0176x1x2^2-200.1x2x3+10005x3 ≤ 0			
21			<=	0	
22		0.002x1x2+0.1x1-x3 ≤ 0			
23			<=	0	
24		x3-0.04x1x2-2x1 ≤ 0			
25			<=	0	
26		28.26 –x4 ≤ 0			
27			<=	0	
28		x5 –x1 ≤ 0			
29			<=	0	
30		x5 – 400 ≤ 0			
31			<=	0	

Figure:3.15. spread work sheet with the specified cells for objective function, design variables and constraints of columns

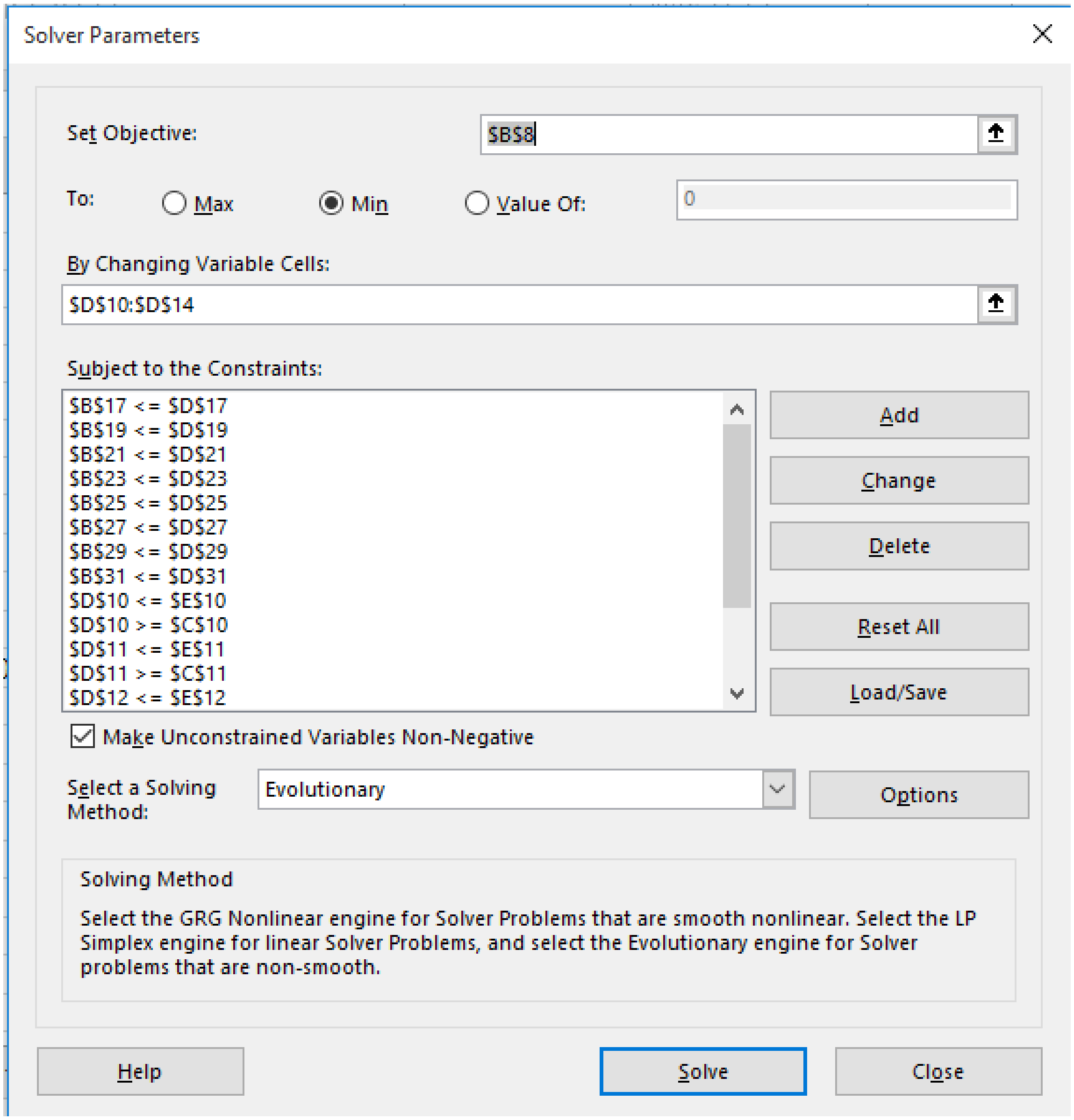

Figure 3.16: Optimization Setup for Evolutionary Algorithm for column elements

3.6.4.3. Solution for Formulated Optimization Problems of slab

	A	B	C	D	E	F	G
1		Design Variables					
2		x1 =depth of slab					
3		x2= area of main reinforcement along longer direction					
4		x3=area of main reinforcement along shorter direction					
5		x4= spacing of reinforcement					
6		W_{slab} = 225*x1+7875+481.5*x2/x4+0.1605*x2+481.5*x3/x4+0.1605*x3					
7		Obj =					
8		variable	lower values	Required values	upper values		
9		x1	80		200		
10		x2	131.13		8000		
11		x3	131.13		8000		
12		x4	200		400		
13		constraints function					
14		$7.2*10^6 -400.2x1x2+7.36x_2^2 \leq 0$					
15			<=	0			
16		$7.2*10^6 -400.2x1x3-7.36x_3^2 \leq 0$					
17			<=	0			
18		$1.41x1-x2 \leq 0$					
19			<=	0			
20		$1.41x1-x3 \leq 0$					
21			<=	0			
22		$x2-40x1 -1400 \leq 0$					
23			<=	0			
24		$x3-40x1 -1400 \leq 0$					
25			<=	0			
26		$x4 -3x1-105 \leq 0$					
27			<=	0			
28		$x4 -400 \leq 0$					
29			<=	0			

Figure:3.17. spread work sheet with the specified cells for objective function, design variables and constraints of floor slabs

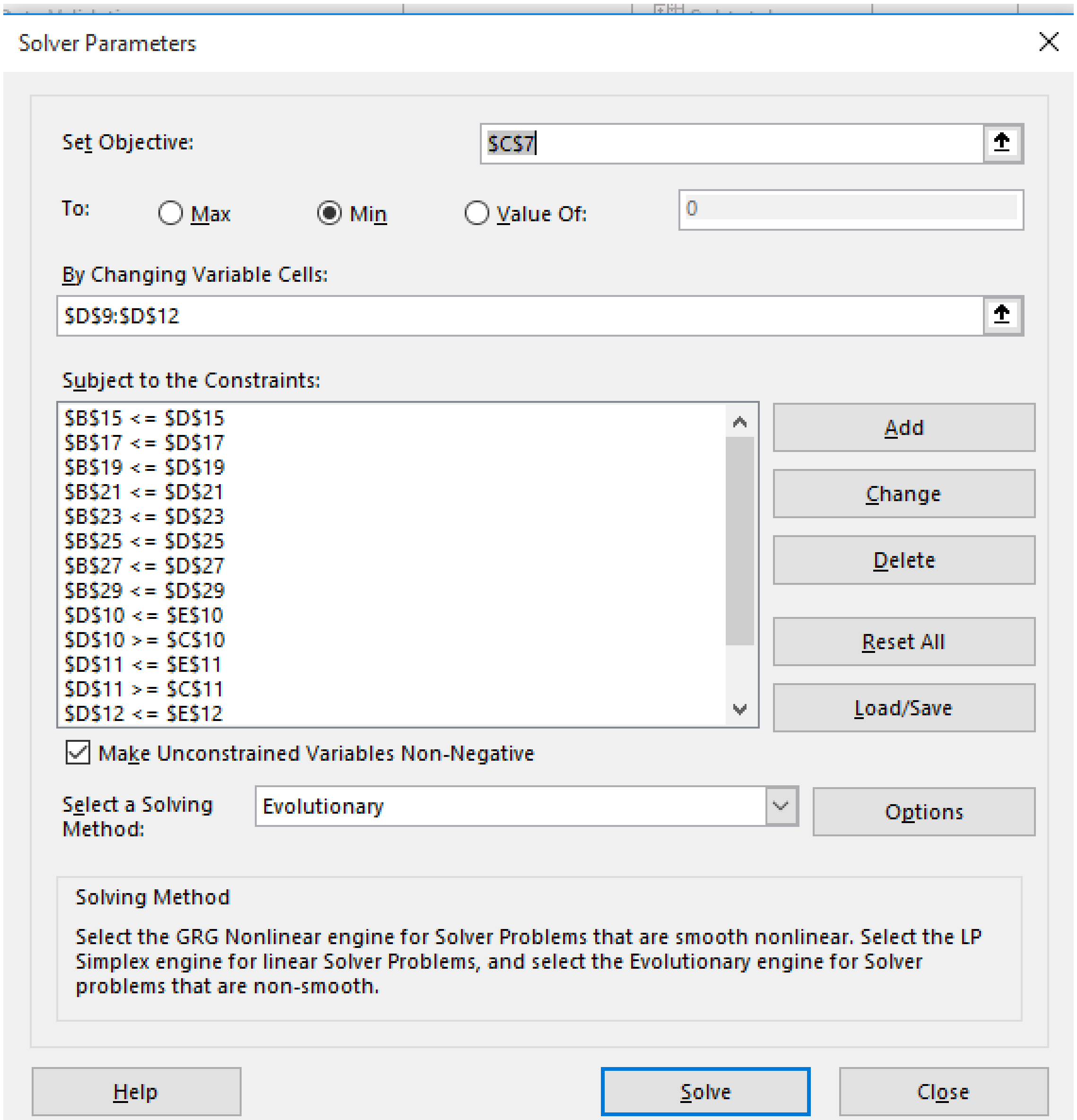

Figure 3.18: Optimization Setup for Evolutionary Algorithm for slabs

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1. General

This chapter presents the results of the optimum design method by optimization tool in MATLAB and evolutionary algorithm in Excel solver in terms of total weight, story drift and story displacement and compare these results with conventional design method (initial design).

4.2. Structural Modelling and Basic Assumptions for the Case Study

Modeling a building involves the modeling and assemblage of its various load carrying elements. The model must ideally represent the mass distribution, strength, stiffness and deformability. Structural modeling is a tool to establish three mathematical models. These three models are a structural model, material model and load model. Structural model consists three basic components such as structural members or components, joints (nodes, connecting edges or surfaces), and boundary conditions (supports and foundations). For designing a new structure, connection details and support conditions shall be made as close to the computational models as possible. Since this study is for structural optimization of an existing structure, structures are modeled as close to the actual as-built structural conditions. Three-dimensional model of building was modeled using commercial software ETABS v9.7.0.

4.3. Loads of the Structure and Load Combinations

The loading on the model buildings have been done according to Ethiopian Building Code Standards for the office building category. In the seismic analysis, the self-weight of the building is a key component. In this study, the self-weight of the structural members is automatically included by the program, ETABS software and therefore, they are not calculated as an additional load. In addition to the self-weight, other assumed dead and live loads were as shown below.

- Dead load on slab for each floor 1.5KN/m^2
- Live load on slab for each floor 2.5KN/m^2
- Live load on roof (assumed as flat roof) 0.5KN/m^2

- dead load on each exterior frame of the floor 16.96KN/m
- dead load on each interior frame of the floor 13.22KN/m
- parapet wall load 4.125KN/m

The live loads and the super imposed dead loads, were assigned as a pressure load to each floor and the super imposed wall loads on beams are assigned as line load. The magnitude of the live loads for the model is considered as the intended purpose of the building floors based on EN 1992-1-1:2013 Code. All restrains are defined so that the stiffness of the building members correctly transfers the vertical and lateral loads and the frames have been modeled as rigid frames. Since the focus of this study is on the determination of the optimized total weight of the whole building under maximum force envelope, nine load combinations were selected in the ETABS analysis as shown below.

Combination 1: 1.35DL+1.5LL

Combination 2: = 0.75(1.35DL+1.5LL) + EQX+

Combination 3: = 0.75(1.35DL+1.5LL) – EQX+

Combination 4: = 0.75(1.35DL+1.5LL) + EQX-

Combination 5: = 0.75(1.35DL+1.5LL) – EQX-

Combination 6: = 0.75(1.35DL+1.5LL) + EQZ+

Combination 7: = 0.75(1.35DL+1.5LL) – EQZ+

Combination 8: = 0.75(1.35DL+1.5LL) + EQZ-

Combination 9: = 0.75(1.35DL+1.5LL) – EQZ-

Combination 10: = DL+EQX

Combination 11: = DL+EQZ

Where DL= dead load, LL = live load,

EQX+ and EQX- are earthquake load in positive and negative X-directions respectively.

EQZ+ and EQZ- are earthquake load in positive and negative Z-directions respectively

Since the building is assumed to be located in high seismic area zone 4 as per EBCS 8, the lateral forces from earthquake are obtained using EBCS 8 based methodology incorporated in ETABS after the assumed dead loads and live loads loaded on the modeled building.

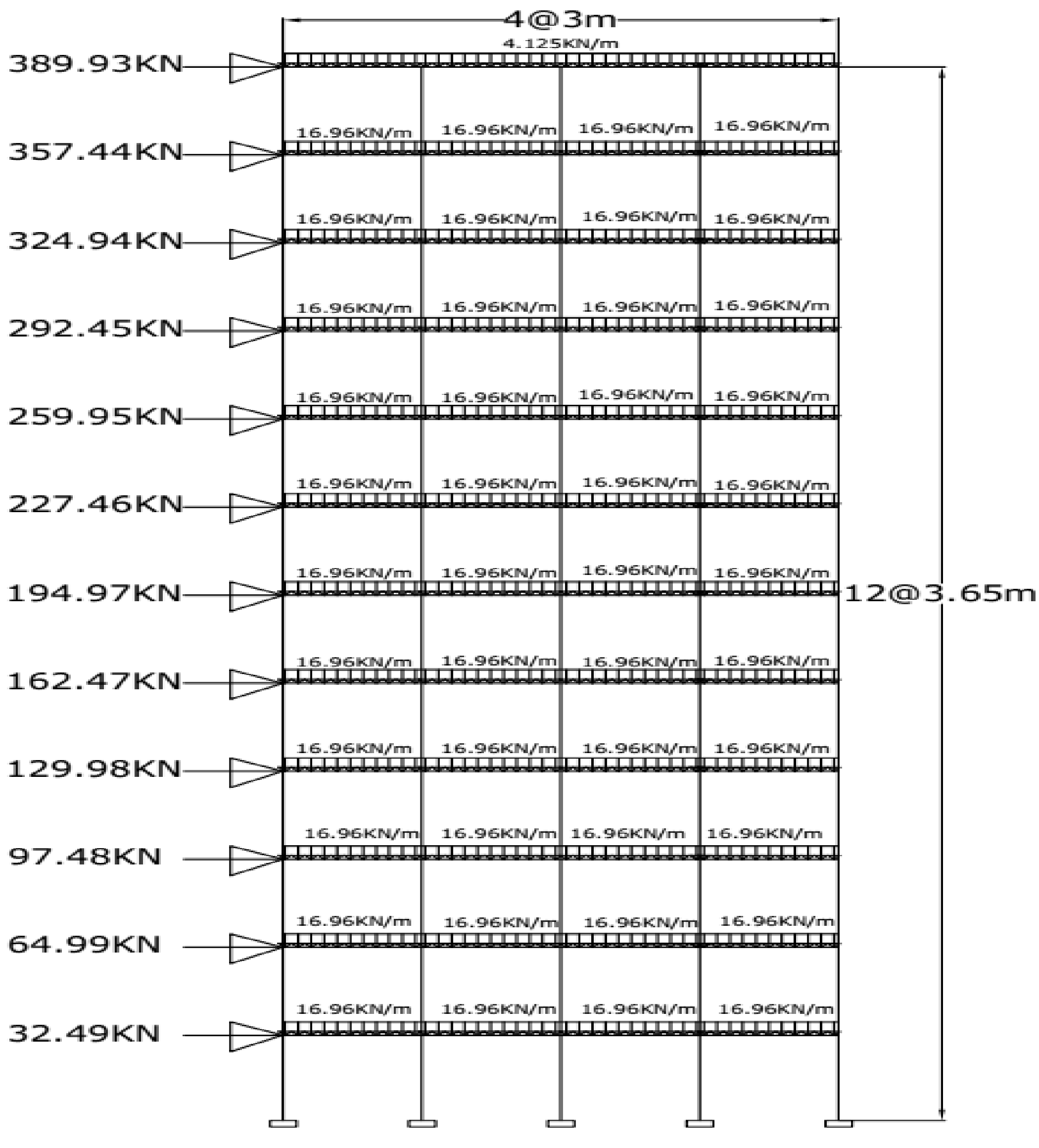

Figure 4.1. Design loading of the case study (Section A-A in Figure 1)

4.4. Structural Analysis and Design Actions for the Case Study

Structural analysis is a process to analyze a structural system to predict its responses and behaviors by using physical laws and mathematical equations. The main objective of structural analysis is to determine internal forces, stresses and deformations of structures under various load effects. In most normal cases analysis will be used to establish the distribution of internal forces and moments, and the complete verification or demonstration of resistance of cross sections is based on these action effects; however, for certain particular elements, the methods of analysis used (e.g. finite element analysis) give stresses, strains and displacements rather than internal forces and moments. In this study equivalent static analysis method (Seismic coefficient method) was used for the analysis of the models of each case under consideration using ETABS program. The governing load combination in this case was found to be COMB 7 which was expected because, the buildings location was assumed to be in high seismic area and thus earthquake load governs. In addition, the building's plan geometry is equal in the X and Y- directions which was therefore the same stiffness in both directions and made the earthquake load to be equal in the directions.

Table 4.1 Beam internal forces

group	**no. of member**	**span moment (KNm)**		**design shear force (KN)**	**support moment (KNm)**
1	2	157.411		131.74	165.99
2	2	147.312		140.5	166.149
3	2	137.588		136.28	160
4	2	128.978		129.07	151.813
5	2	118.768		120.56	140.954
6	2	106.758		110.54	128.108
7	2	92.954		99.04	113.304
8	2	77.292		86.01	96.489
9	2	59.747		71.41	77.635
10	2	40.303		55.29	56.815
11	2	20.408		38.54	35.068

12	2	9.9		25.86	17.124
13	2	149.34		126.05	152.494
14	2	145.714		142.93	158.797
15	2	144.538		141.81	157.81
16	2	138.749		136.87	152.124
17	2	130.427		129.85	143.85
18	2	119.571		120.75	132.999
19	2	106.353		108.1	118.92
20	2	90.895		96.8	104.262
21	2	73.388		82.21	86.711
22	2	53.92		66.08	67.255
23	2	34.788		49.97	47.928
24	2	16.539		29.36	26.963

Table 4.2. Columns internal forces

group	**no. of member**	**axial load (KN)**	**design moment (KNm.)**
1	2	1407.97	353.604
2	2	1336.23	261.62
3	2	1219.44	237.157
4	2	1100.07	228.445
5	2	979.07	214.347
6	2	856.69	196.906
7	2	733.24	157.112
8	2	608.94	141.749
9	2	484.01	123.373
10	2	358.61	102.645
11	2	233.02	75.427
12	2	106.78	56.396
13	2	1712.1	340.946

14	2	1637.1	252.764
15	2	1475.11	255
16	2	1316.76	240.963
17	2	1161.02	226.872
18	2	1007.62	208.266
19	2	856.16	185.806
20	2	706.16	159.569
21	2	557.74	129.77
22	2	410.19	104.831
23	2	263.16	76.333
24	2	117.67	56.528
25	1	1773.56	328.577
26	1	1696.67	243.315
27	1	1533.26	246.385
28	1	1371.35	231.596
29	1	1211.06	218.325
30	1	1052.29	200.663
31	1	894.97	178.185
32	1	738.93	152.933
33	1	584	127.627
34	1	430.01	100.341
35	1	276.6	73.069
36	1	124.73	54.357

4.5. Results of Conventional Design Method

After the case study modeled, sections and materials properties were defined, load cases considered loaded and analyzed using coefficient method in commercial software ETABS v9.7.0. the design actions (shear forces, axial forces and moments) were received as shown in Tables 4.1 and 4.2. Using those design actions, the results were obtained. Tables 4.3,4.4 and 4.5 show the weight of used materials (concrete and steel reinforcements) for beams, columns and slab and story drift and story displacement at each story levels for both directions.

4.5.1. Weight of Structural Elements

Table 4.3. Weight of Structural Elements for the Case Study

Structural Elements	Weight(kg)
Beams	533096.7
Columns	1409026.67
Floor slab	426054.82
Roof slab	41814.31
Total	**2409992.5**

For this conventional design method, maximum material consumptions were obtained for each structural element as shown in Table 4.3.

4.5.2. Story Displacement and Drift for the Whole Structure (Case Study)

Since the lateral loads were applied on both X and Y directions, the story displacement and story drift of the structure were checked for the two directions.

Table 4.4. Story Displacement along X and Y Direction for the Case Study

Along X- Direction					Along Y - Direction				
Floor Level	story height(m)	story displacement(mm)	L/C	Permissible deflection (mm) H/300 [EBCS- 3-	Floor Level	story height(m)	story displacement(mm)	L/C	Permissible deflection (mm) H/300 [EBCS- 3-1995-5.2.2]
roof	43.8	63.34	L/C-10&11	146.0	roof	43.8	64.73	L/C-10&11	146.0
10th FL	40.15	61.67	L/C-10&11	133.8	10th FL	40.15	62.11	L/C-10&11	133.8
9th FL	36.5	58.97	L/C-10&11	121.7	9th FL	36.5	60.44	L/C-10&11	121.7
8th FL	32.85	56.87	L/C-10&11	109.5	8th FL	32.85	58.89	L/C-10&11	109.5
7th FL	29.2	53.61	L/C-10&11	97.3	7th FL	29.2	57.61	L/C-10&11	97.3
6th FL	25.55	52.84	L/C-10&11	85.2	6th FL	25.55	56.87	L/C-10&11	85.2
5th FL	21.9	49.52	L/C-10&11	73.0	5th FL	21.9	53.41	L/C-10&11	73.0
4th FL	18.25	44.06	L/C-10&11	60.8	4th FL	18.25	47.60	L/C-10&11	60.8
3rd FL	14.6	36.79	L/C-10&11	48.7	3rd FL	14.6	39.87	L/C-10&11	48.7
2nd FL	10.95	28.09	L/C-10&11	36.5	2nd FL	10.95	30.67	L/C-10&11	36.5
1st FL	7.3	18.21	L/C-10&11	24.3	1st FL	7.3	20.43	L/C-10&11	24.3
GD FL	3.65	5.26	L/C-10&11	12.2	GD FL	3.65	6.26	L/C-10&11	12.2

Table 4.5. Story Drift along X and Y Direction for the Case Study

Along X- Direction					Along Y - Direction				
Floor Level	story height(m)	L/C	story drift	permissible value [0.004h](mm)	Floor Level	story height(m)	L/C	story drift	permissible value [0.004h](mm)
roof	43.8	L/C-10&11	1.67	14.6	roof	43.8	L/C-10&11	2.62	14.6
10th FL	40.15	L/C-10&11	2.7	14.6	10th FL	40.15	L/C-10&11	1.67	14.6
9th FL	36.5	L/C-10&11	2.1	14.6	9th FL	36.5	L/C-10&11	1.55	14.6
8th FL	32.85	L/C-10&11	3.26	14.6	8th FL	32.85	L/C-10&11	1.28	14.6
7th FL	29.2	L/C-10&11	0.77	14.6	7th FL	29.2	L/C-10&11	0.74	14.6
6th FL	25.55	L/C-10&11	3.32	14.6	6th FL	25.55	L/C-10&11	3.46	14.6
5th FL	21.9	L/C-10&11	5.46	14.6	5th FL	21.9	L/C-10&11	5.81	14.6
4th FL	18.25	L/C-10&11	7.27	14.6	4th FL	18.25	L/C-10&11	7.73	14.6
3rd FL	14.6	L/C-10&11	8.7	14.6	3rd FL	14.6	L/C-10&11	9.2	14.6
2nd FL	10.95	L/C-10&11	9.88	14.6	2nd FL	10.95	L/C-10&11	10.24	14.6
1st FL	7.3	L/C-10&11	12.95	14.6	1st FL	7.3	L/C-10&11	14.17	14.6
GD FL	3.65	L/C-10&11	5.26	14.6	GD FL	3.65	L/C-10&11	6.26	14.6

From Tables 4.3.and 4.4, both story displacement and story drift along Y-direction is greater than that of X-direction for the conventional design method. But, both story displacement and story drift for the two directions were very less than permissible limit recommended by the design code EBCS EN 1992 -1-1-2013 as shown in the Tables. The safety requirements were satisfied but the structure might not be economical. Therefore, update for optimization was conducted.

4.6. Results of Optimum Design Method

Once the conventional/normal design satisfy requirements or convergency, modification of design by optimization procedures was carried out. For the update of design by optimization procedures optimization tool box in MATLAB and Evolutionary algorithm in Excel solver were implemented as optimization methods.

4.6.1. Results of Optimization Tool Box in MATLAB

The design of structure which was formulated as optimization problems were converted into MATLAB language by writing M-file for objective function and constraint functions. Then the optimization ran for the optimum solution of objective function and design variables.

Weight of Structural Elements by Optimization Tool in MATLAB

After the optimization ran, optimum results for the specified objective functions and design variables for each group of structural elements and total weight were obtained as shown in Tables 4.6,4.7 and 4.8

Table 4.6. Optimized Weight of Beams by Optimization tool in MATLAB as Optimizer

Story	Member group	No. of members in group	Design variables values						Optimized weight
			Design variables values						
			width	effective depth	tensile steel area	compressive steel area	shear reinforcement area	spacing of shear reinforcement	
1	1	2	277	297	2662.7	603.2	623.4	206	16931.5
2	2	2	260	316	3239.3	628.1	613.1	222	16896.6
3	3	2	269	304	2153.5	1314.1	617.9	206	16863.9
4	4	2	263	314	2110.3	759.2	663.0	200	16835.5
5	5	2	270	299	2640.7	728.2	709.8	206	16802.8
6	6	2	268	297	3402.1	684.1	611.3	199	16677.0
7	7	2	270	301	1702.4	984.2	670.0	200	16677.0
8	8	2	255	316	2958.9	1621.3	570.7	227	16723.4
9	9	2	248	319	3666.5	467.6	718.3	228	16619.0
10	10	2	247	324	2472.4	1683.9	590.3	219	16570.4
11	11	2	266	310	1506	717.8	622.1	197	16513.0
12	12	2	254	314	2583.1	1471.1	551.1	200	16480.6
1	13	2	264	314	3070	852.8	528.9	232	16903.8
2	14	2	264	314	3287.9	83.4	610.8	219	16891.2
3	15	2	269	300	3161.6	625.9	675.4	207	16887.9
4	16	2	255	317	3221.5	1789.0	487.2	213	16867.7
5	17	2	261	314	2603	1237.7	601.3	222	16840.4
6	18	2	258	327	1626.6	1268.5	550.9	204	16805.6
7	19	2	267	302	2441.5	1324.8	642.2	215	16764.2
8	20	2	248	334	2509.6	690.5	621.2	219	16717.2
9	21	2	262	300	2980.7	1093.6	692.3	200	16665.7
10	22	2	256	313	2406	903.9	758.5	218	16609.8
11	23	2	246	311	3431.4	1914.2	710.6	210	16554.8
12	34	2	249	334	1865	675.3	637.3	229	16501.0
Total									**401600.2**

Table 4.7. Optimized Weight of Columns by Optimization tool in MATLAB as Optimizer

Story	Member group	No. of members in group	Design variables values					optimized weight
			width	effective depth	tensile steel area	shear reinforcement area	spacing of shear reinforcement	
1	1	2	374	531	3159.75	69.5	274	35076
2	2	2	414	460	7096.24	69.7	340	35281.8
3	3	2	401	478	7570.5	62.8	367	35336.8
4	4	2	442	436	5337.6	61.1	240	35356.4
5	5	2	455	426	4546.8	72.54	341	35388.4
6	6	2	464	419	3716.62	69.8	276	35427.8
7	7	2	422	460	5628.23	63.14	234	35518
8	8	2	400	507	1784.1	67.7	267	35553
9	9	2	413	477	5290.4	58.9	307	35642
10	10	2	425	473	1339.1	48.86	259	35703.6
11	11	2	436	455	4011	67.6	318	35770.4
12	12	2	410	476	7153.2	51.1	388	35104
1	13	2	407	487	2587.52	67.8	290	35301.6
2	14	2	444	446	2222.52	71.5	295	35296.6
3	15	2	442	454	1399.07	63.5	311	35328.2
4	16	2	394	512	2448.8	48.7	226	35360
5	17	2	437	452	3142.2	67.5	317	35402.2
6	18	2	424	452	6405.6	76.6	357	35453
7	19	2	409	490	2979.2	66.3	291	35512.4
8	20	2	399	492	6007.2	51.7	315	35802
9	21	2	428	478	7580.1	58	333	35637
10	22	2	428	458	4851.73	64	260	35702
11	23	2	401	491	6060.4	56	312	35747.2
12	24	2	412	474	6650.7	55.1	285	17565.8
1	25	1	374	529	4044.3	63.4	336	17661.5
2	26	1	377	513	7588.98	50.7	368	17658
3	27	1	366	522	8516.8	53	221	17427.2
4	28	1	416	460	7371.08	38.7	238	17443.1
5	29	1	421	481	1617.7	38.3	266	17464.3
6	30	1	419	461	6211.9	66.1	315	17491.3
7	31	1	403	493	4227.67	58.9	357	17521.7
8	32	1	371	518	8383.7	50.2	285	17552.1
9	33	1	410	488	3891.83	36.74	261	17584.9
10	34	1	422	467	5251.84	71.7	262	17617.7
11	35	1	391	501	6711.96	80.45	377	176440
12	36	1	376	524	6531.45	97.2	288	17603.5
Total								**1202732**

Table 4.8. Optimized Weight of Slab by Optimization tool in MATLAB as Optimizer

Element type	Story	Member group	number of members in group	Design variables values				optimized weight
				effective depth	steel area along longer direction	steel area along shorter direction	spacing of reinforcement	
floor slab	2 to 11	1	10	93.00	1337.82	1092.01	351.51	321032.20
roof slab	12	2	1	84.00	1730.96	1520.90	337.78	31507.08
Total								**352539.28**

Results of Story Displacement and Story Drift by Optimization Tool in MATLAB

Table 4.9. Optimized Story Displacement along X and Y-Direction by optimization tool Box in MATLAB

Along X- Direction						Along Y- Direction				
Floor Level	story height(m)	story displacement(mm)	L/C	Permissible deflection (mm) H/300 [EBCS- 3-		Floor Level	story height(m)	story displacement(mm)	L/C	Permissible deflection (mm) H/300 [EBCS- 3-1995-
roof	43.8	51.22	L/C-10&11	146.0		roof	43.8	52.71	L/C-10&11	146.0
10th FL	40.15	47.89	L/C-10&11	133.8		10th FL	40.15	50.33	L/C-10&11	133.8
9th FL	36.5	46.54	L/C-10&11	121.7		9th FL	36.5	48.98	L/C-10&11	121.7
8th FL	32.85	44.56	L/C-10&11	109.5		8th FL	32.85	47.97	L/C-10&11	109.5
7th FL	29.2	43.54	L/C-10&11	97.3		7th FL	29.2	46.78	L/C-10&11	97.3
6th FL	25.55	42.90	L/C-10&11	85.2		6th FL	25.55	46.17	L/C-10&11	85.2
5th FL	21.9	40.21	L/C-10&11	73.0		5th FL	21.9	43.36	L/C-10&11	73.0
4th FL	18.25	35.77	L/C-10&11	60.8		4th FL	18.25	38.65	L/C-10&11	60.8
3rd FL	14.6	29.87	L/C-10&11	48.7		3rd FL	14.6	32.38	L/C-10&11	48.7
2nd FL	10.95	22.81	L/C-10&11	36.5		2nd FL	10.95	24.90	L/C-10&11	36.5
1st FL	7.3	14.79	L/C-10&11	24.3		1st FL	7.3	16.59	L/C-10&11	24.3
GD FL	3.65	4.27	L/C-10&11	12.2		GD FL	3.65	5.08	L/C-10&11	12.2

Table 4.10. Optimized Story Drift along X and Y-Direction by optimization tool Box in MATLAB

Along X- Direction						Along Y- Direction				
Floor Level	story height(m)	L/C	story drift	permissible value [0.004h](mm)		Floor Level	story height(m)	L/C	story drift	permissible value [0.004h](mm)
roof	43.8	L/C-10&11	2.55	14.6		roof	43.8	L/C-10&11	2.38	14.6
10th FL	40.15	L/C-10&11	2.13	14.6		10th FL	40.15	L/C-10&11	1.35	14.6
9th FL	36.5	L/C-10&11	1.98	14.6		9th FL	36.5	L/C-10&11	1.01	14.6
8th FL	32.85	L/C-10&11	1.02	14.6		8th FL	32.85	L/C-10&11	1.19	14.6
7th FL	29.2	L/C-10&11	0.64	14.6		7th FL	29.2	L/C-10&11	0.61	14.6
6th FL	25.55	L/C-10&11	2.69	14.6		6th FL	25.55	L/C-10&11	2.81	14.6
5th FL	21.9	L/C-10&11	4.44	14.6		5th FL	21.9	L/C-10&11	4.71	14.6
4th FL	18.25	L/C-10&11	5.9	14.6		4th FL	18.25	L/C-10&11	6.27	14.6
3rd FL	14.6	L/C-10&11	7.06	14.6		3rd FL	14.6	L/C-10&11	7.48	14.6
2nd FL	10.95	L/C-10&11	8.02	14.6		2nd FL	10.95	L/C-10&11	8.31	14.6
1st FL	7.3	L/C-10&11	10.52	14.6		1st FL	7.3	L/C-10&11	11.51	14.6
GD FL	3.65	L/C-10&11	4.27	14.6		GD FL	3.65	L/C-10&11	5.08	14.6

From the Tables 4.6-4.10, all the comparative parameters (total weight, story displacement and drift for the two directions) were less than that of convectional design method. Again, both story displacement and story drift for Y-direction is greater than that of X- direction as in the case of convectional design method with respective directions.

4.6.2. Results of evolutionary algorithm in Excel solver

Once the spreadsheet developed for the formulated optimization problems, the excel solver was invoked for optimum solution of both objective function and design variables for all structural elements.

Weight of Structural Elements by Evolutionary Algorithm in Excel Solver

After solving the developed spreadsheet with the specified cells for objective and constraint functions for the formulated optimization problems optimum results for the specified design variables for each group of structural elements and total weight were obtained as shown in Tables 4. 11,4.12 and 4.13

Table 4.11. Optimized Weight of Beams by Evolutionary Algorithm in Excel Solver as Optimizer

Story	Member group	No. of members in group	Design variables values						Optimized weight
			width	effective depth	tensile steel area	compressive steel area	shear reinforcement area	spacing of shear reinforcement	
1	1	2	284	305	2734.1	619.4	640.15	211	17385.52
2	2	2	267	325	3325.3	644.73	629.37	228	17344.98
3	3	2	278	312	2211.5	1349.5	634.58	211	17317.9
4	4	2	270	323	2171.7	781.29	682.32	206	17325.7
5	5	2	277	306	2707.6	746.65	727.8	211	17228.6
6	6	2	276	306	3500.5	703.84	629.01	205	17250.46
7	7	2	279	311	1754.8	1014.51	690.71	207	17190.44
8	8	2	261	324	3030.6	1660.62	584.52	233	17128.84
9	9	2	255	329	3771.3	480.96	738.9	235	17094.82
10	10	2	254	333	2540.6	1730.33	606.53	235	17027.52
11	11	2	273	319	1547.4	737.6	639.26	202	16967.16
12	12	2	260	322	2649.7	1509	565.31	205	16905.5
1	13	2	272	323	3157.4	877.02	538.76	238	17384.88
2	14	2	271	322	3375.6	85.76	627.05	225	17341.2
3	15	2	276	308	3246.7	642.84	693.55	213	17342.84
4	16	2	262	326	3306.3	1836.15	500	219	17311.8
5	17	2	268	323	2672.4	1270.71	617.35	228	17289.72
6	18	2	265	336	1670.6	1302.87	565.86	210	17260.72
7	19	2	275	310	2507.4	1360.6	569.6	221	17216.42
8	20	2	255	343	2576.9	709	637.86	225	17165.62
9	21	2	267	308	3059.8	1122.67	710.68	206	17108.08
10	22	2	263	322	2472.2	928.76	779.33	224	17066.04
11	23	2	253	319	3523.7	1760.35	729.74	216	17000
12	34	2	256	343	1915.9	693.44	654.43	235	16943.76
Total									**412598.52**

Table 4.12. Optimized Weight of Columns by Evolutionary Algorithm in Excel Solver as Optimizer

Story	Member group	No. of members in group	Design variables values					optimized weight
			width	effective depth	tensile steel area	shear reinforcement area	spacing of shear reinforcement	
1	1	2	384	545	3243.5	71.3	282	36005.3
2	2	2	425	473	7289	71.5	350	36235
3	3	2	411	491	7774.73	64.5	377	36289.96
4	4	2	454	448	5480.3	62.7	246	36300.8
5	5	2	467	437	4667.1	74.5	350	36324.4
6	6	2	476	430	3815.7	71.7	383	36372.2
7	7	2	433	473	5780.2	64.82	241	36477
8	8	2	411	521	1832.5	69.5	274	36516.6
9	9	2	424	489	5429.8	60.4	315	36532.6
10	10	2	437	486	3222.2	50.2	265	36585.4
11	11	2	448	467	4119.02	69.4	327	36665.2
12	12	2	421	489	7345.3	52.5	398	36730.94
1	13	2	418	501	2656.86	69.7	298	36050.4
2	14	2	456	457	2281.7	73.4	302	36241.86
3	15	2	454	466	1436.6	65.2	320	36243.48
4	16	2	405	526	514.6	50	232	36278
5	17	2	449	464	3626.95	69.3	325	36313.44
6	18	2	436	464	6578.1	78.7	380	36355.2
7	19	2	419	503	3058.52	68	299	36396.8
8	20	2	410	505	6168.01	53	324	36463.08
9	21	2	440	491	778.4	59.56	342	36537
10	22	2	440	471	4980.4	66.56	267	36581.96
11	23	2	412	504	6221.85	57.5	320	36653.12
12	24	2	424	487	6830.4	56.4	293	36713
1	25	1	485	544	4151.95	65.1	346	180334
2	26	1	387	527	7792	52.1	378	18133.93
3	27	1	376	536	8746.1	54.4	228	18133.46
4	28	1	427	472	7298.34	75.7	245	17895.1
5	29	1	433	494	1660.95	39.3	274	17909.5
6	30	1	431	474	6377.6	67.9	323	17930.3
7	31	1	414	506	4340.9	60.44	366	17959.84
8	32	1	381	531	8607.4	51.51	296	17989.07
9	33	1	421	501	3693.3	37.72	268	18023.2
10	34	1	433	480	5392.97	73.6	269	18057.44
11	35	1	402	514	6891.1	82.6	387	18087.92
12	36	1	386	538	6706.6	96.8	296	18113.2
Total								**1252429.7**

Table 4.13. Optimized Weight of slab by Evolutionary Algorithm in Excel Solver as Optimizer

Element type	Story	Member group	No. of members in group	design variables values				optimized weight
				effective depth	steel area along longer direction	steel area along shorter direction	spacing of reinforcement	
floor slab	2 to 11	1	10	95.00	1373.67	1121.28	360.94	329636.0
roof slab	12	2	1	86.00	1776.87	1561.24	346.74	32342.7
Total								**361978.7**

Results of Story Displacement and Story Drift by Evolutionary Algorithm in Excel

Table 4.14. Optimized Story Displacement and along X and Y-Direction by Evolutionary in Excel Solver

Along X-Direction

Floor Level	story height(m)	story displacement(mm)	L/C	Permissible deflection (mm) H/300 [EBCS- 3-1995-5.2.2]
roof	43.8	54.32	L/C-10&11	146.0
10th FL	40.15	51.55	L/C-10&11	133.8
9th FL	36.5	49.76	L/C-10&11	121.7
8th FL	32.85	46.98	L/C-10&11	109.5
7th FL	29.2	45.08	L/C-10&11	97.3
6th FL	25.55	44.43	L/C-10&11	85.2
5th FL	21.9	41.65	L/C-10&11	73.0
4th FL	18.25	37.05	L/C-10&11	60.8
3rd FL	14.6	30.95	L/C-10&11	48.7
2nd FL	10.95	23.62	L/C-10&11	36.5
1st FL	7.3	15.32	L/C-10&11	24.3
GD FL	3.65	4.42	L/C-10&11	12.2

Along Y-Direction

Floor Level	story height(m)	story displacement (mm)	L/C	Permissible deflection (mm) H/300 [EBCS-3-1995-5.2.2]
roof	43.8	55.96	L/C-10&11	146.0
10th FL	40.15	52.88	L/C-10&11	133.8
9th FL	36.5	51.66	L/C-10&11	121.7
8th FL	32.85	49.11	L/C-10&11	109.5
7th FL	29.2	48.44	L/C-10&11	97.3
6th FL	25.55	47.83	L/C-10&11	85.2
5th FL	21.9	44.92	L/C-10&11	73.0
4th FL	18.25	40.04	L/C-10&11	60.8
3rd FL	14.6	35.54	L/C-10&11	48.7
2nd FL	10.95	25.80	L/C-10&11	36.5
1st FL	7.3	17.18	L/C-10&11	24.3
GD FL	3.65	5.26	L/C-10&11	12.2

Table 4.15. Optimized Story Drift and along X and Y-Direction by Evolutionary in Excel Solver

Along X- Direction

Floor Level	story height(m)	L/C	story drift	permissible value [0.004h](mm)
roof	43.8	L/C-10&11	2.47	14.6
10th FL	40.15	L/C-10&11	1.79	14.6
9th FL	36.5	L/C-10&11	2.78	14.6
8th FL	32.85	L/C-10&11	1.9	14.6
7th FL	29.2	L/C-10&11	0.65	14.6
6th FL	25.55	L/C-10&11	2.78	14.6
5th FL	21.9	L/C-10&11	4.6	14.6
4th FL	18.25	L/C-10&11	6.1	14.6
3rd FL	14.6	L/C-10&11	7.33	14.6
2nd FL	10.95	L/C-10&11	8.3	14.6
1st FL	7.3	L/C-10&11	10.9	14.6
GD FL	3.65	L/C-10&11	4.42	14.6

Along Y- Direction

Floor Level	story height(m)	L/C	story drift	permissible value [0.004h](mm)
roof	43.8	L/C-10&11	2.47	14.6
10th FL	40.15	L/C-10&11	1.22	14.6
9th FL	36.5	L/C-10&11	2.09	14.6
8th FL	32.85	L/C-10&11	1.12	14.6
7th FL	29.2	L/C-10&11	0.62	14.6
6th FL	25.55	L/C-10&11	2.91	14.6
5th FL	21.9	L/C-10&11	4.58	14.6
4th FL	18.25	L/C-10&11	5.8	14.6
3rd FL	14.6	L/C-10&11	9.74	14.6
2nd FL	10.95	L/C-10&11	8.62	14.6
1st FL	7.3	L/C-10&11	11.92	14.6
GD FL	3.65	L/C-10&11	5.26	14.6

4.7. Comparison of the Results

In this study, the comparative parameters were total weight of the structure, story displacement and story drift obtained by conventional and optimum design methods. The results of these comparative parameters which were obtained by conventional and optimum methods were compared with one another.

4.7.1. Comparison of Total weights

The cross-sectional dimension for all structural elements were reduced as it shown above. As a result, the total weight of each structural elements (beams, columns, floor slab and roof slab) were reduced as compared to results obtained by conventional design method.

Table 4.16 Weight and Percentage Variation of Design Cases for the case study

Design Cases	Weight (KN)	Percentage Variation of Weight w.r.t Conventional design method
Conventional design method	2409992.5	0
Optimum Design by optimization tool box in MATLAB	2027006.92	18.801
Optimum Design by evolutionary algorithm in excel solver	1956871.48	15.89

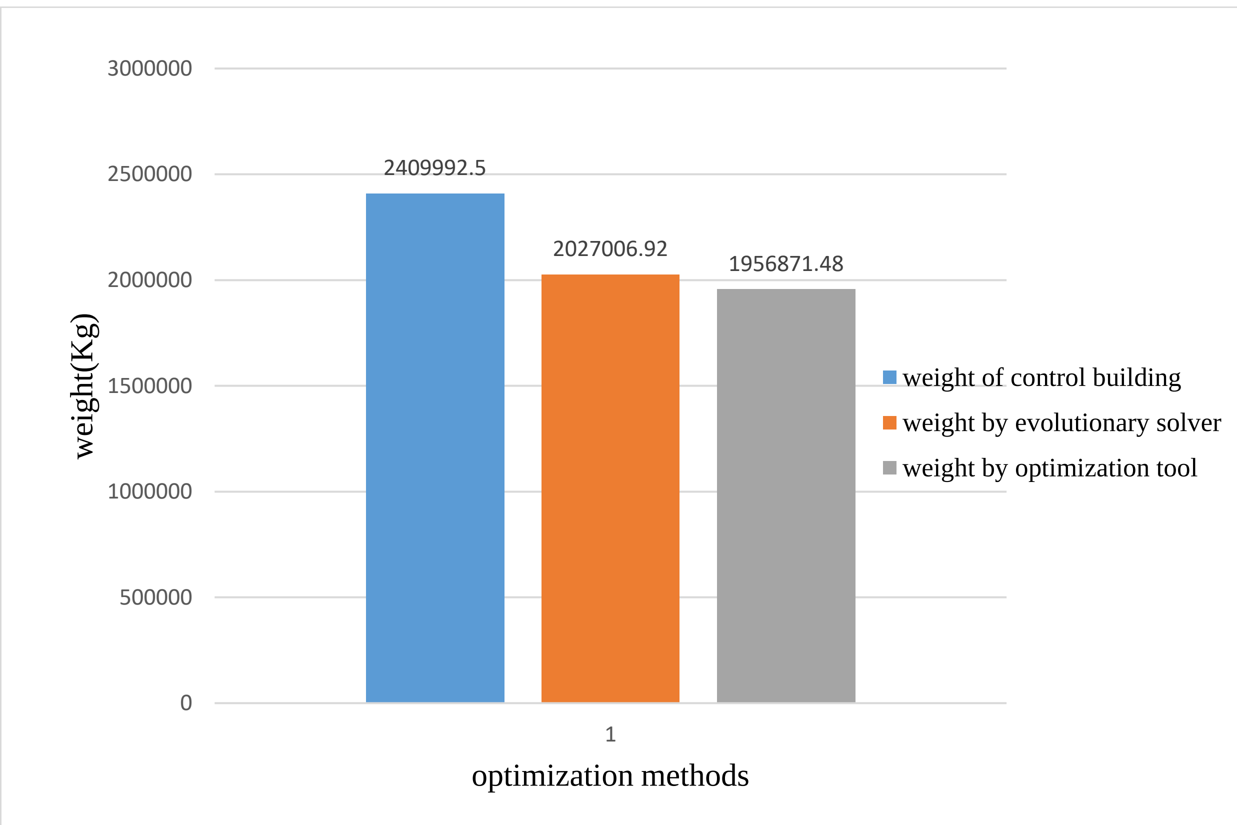

Figure 4.2 graphical representation of weights for cases study and optimization methods

As it can be seen from the figure 4.2, the weight obtained by conventional design method is the greatest as compared to weights obtained by evolutionary algorithm embedded in excel solver and optimization tool box in MATLAB. Also, weight obtained by optimization tool box is the least as compared to others.

Again, as shown in the table 4.16, for weight fluctuation on the three design cases, the weights were decreased by 18.801% and 15.89% for evolutionary algorithm and optimization tool respectively. In fact, the decrease in weight is due to decrease in cross section of structural elements as a result of optimization. Specifically, the decreasing in weight is lower in the column than beams and slab. This can be attributed to the fewer number of design variables in column optimization

4.7.2. Comparison of story displacements and story drifts

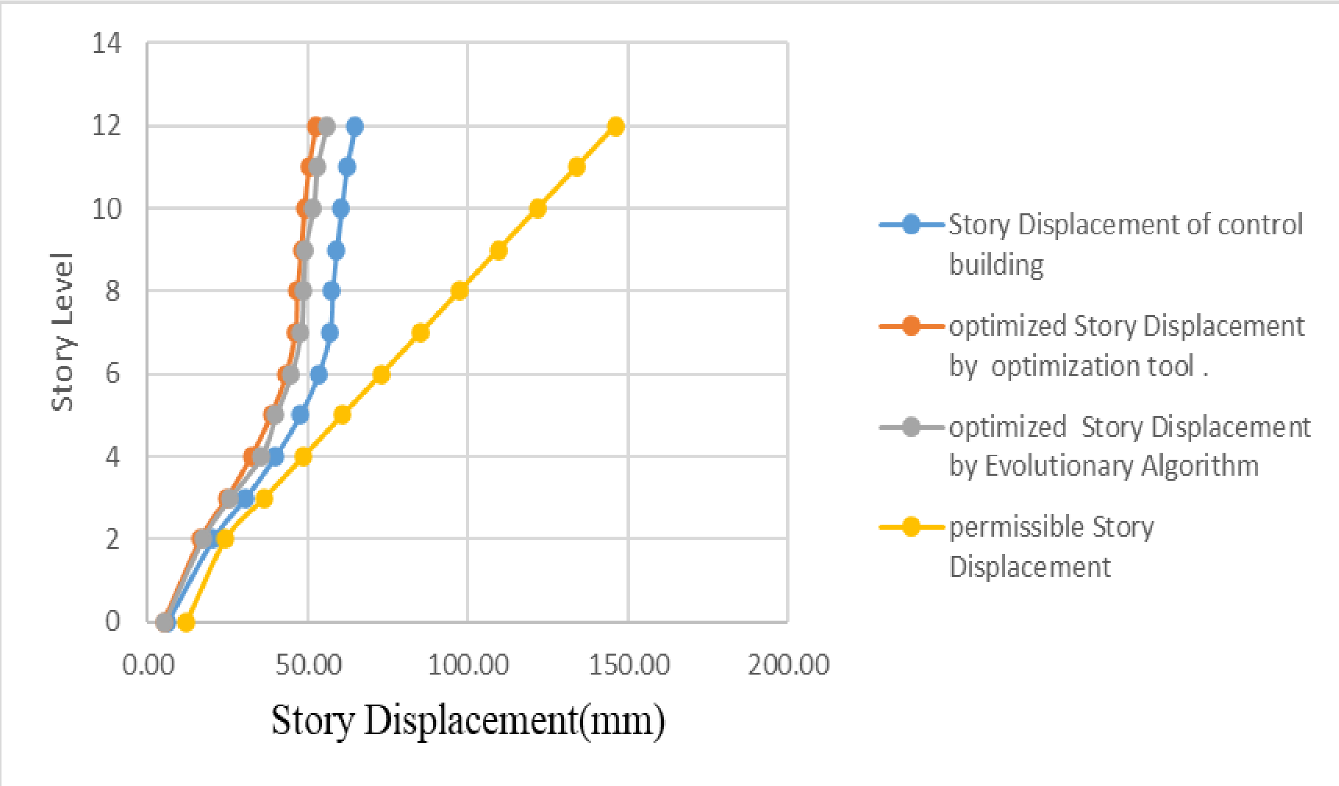

Figure 4.3: Graphical Illustration of Story Levels Versus Story Displacements

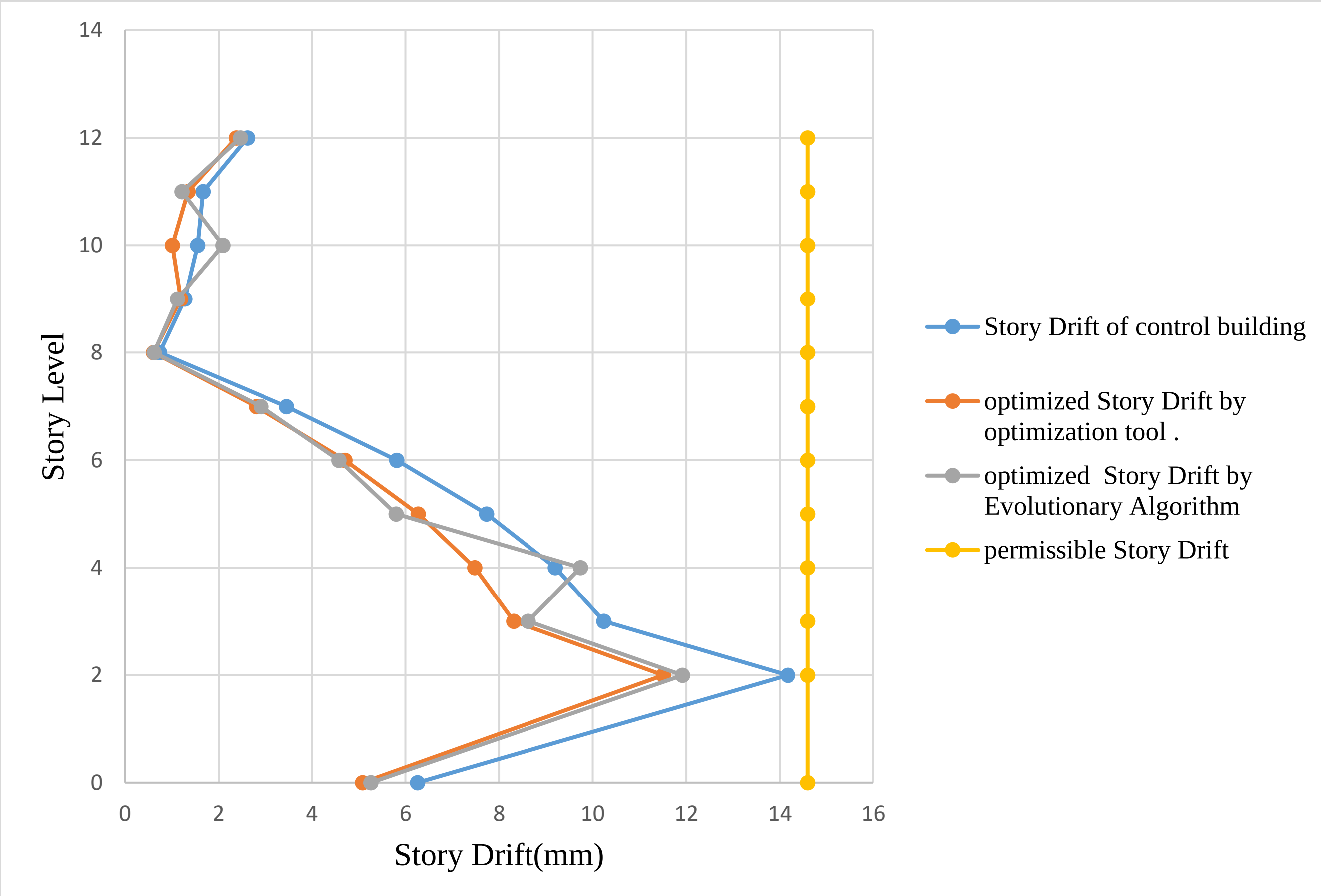

Figure 4.4: Graphical Illustration of Story Levels Versus Story Drift

As it can be seen from figures 4.3 and 4.4, both story displacement and story drift were reduced for the optimization techniques used as optimizers. This reduction was due to reduced vales of lateral loads. Lateral loads at each story level were reduced due to the fact that their magnitudes depend on total weight of structure (the total weight reduced with respect to control building)

Accordingly, the percentage reduction of story displacement and drift by optimization tool box in MATLAB and Evolutionary Algorithm in excel solver were 18.81% and 15.89% respectively with respect to that of conventional design method for both story displacement and drift.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

This chapter summarizes the major conclusions from the previous chapters and makes recommendations based on the obtained results and recommendations for further studies.

5.1. Conclusion

This study was conducted to optimize the total weight of multi-storied reinforced concrete building structure subjected to seismic lateral load in addition to normal use gravity loads using different optimization techniques under multiple design constraints. Mainly, the total weight of structure is the key parameter focused on as it results from the values of design variables predominantly the size of cross-sectional dimensions of structural elements. In addition to this parameter the story drift and story displacement were checked as they are the results of flexural and shear mode contributions, due to the column axial deformations, beam deformations and beam-column joint deformations. The optimization tool box in MATLAB and Evolutionary algorithm embedded in excel solver were used as optimizers for the optimum design of all structural elements (beams, columns and slabs). Multi storied reinforced concrete building structure(G+10) was used as the case study for simulating the applicability of optimization techniques used as optimizers. The building analysis was done by coefficient method commercial software ETABS.

The following conclusions were drawn.

1. The design requirements for the case study was converged by conventional design method.
2. All the formulated constraint functions for all structural elements were satisfied.
3. Both story displacement and drift at each story level were obtained from analysis output and they are within permissible limit specified by the design code.
4. The total weight of the case study was decreased by 18.801% with respect to weight obtained by conventional design method when optimization tool box in MATLAB is used as optimizer.

5. The total weight of the case study was decreased by 15.89% with respect to weight obtained by conventional design method when Evolutionary algorithm embedded in excel solver used as optimizer
6. Percentage reduction of the total weight of the case study by optimization tool box in MATLAB was greater (the difference was 2.911%) than that of Evolutionary algorithm embedded in excel solver.
7. Both story displacement and drift at each story level were small in the optimum design obtained by optimization tool box in MATLAB.

5.2. Recommendation

5.2.1. Recommendation based on results obtained

As the results of comparative parameters obtained by optimizers are less than that of conventional design way, structural design optimization by the application of modern optimization techniques as optimizers must be used in any structural design. All structural elements should be designed by using optimization techniques to reduce time for searching optimum cross-sections.As optimization tool box in MATLAB reduces total weight than Evolutionary algorithm embedded in excel solver, it is better to use optimization tool box in MATLAB rather than Evolutionary algorithm embedded in excel solver.

Generally, the application of modern optimization techniques should be incorporated in the design of reinforced concrete structures.

5.2.2. Recommendations for future work

This section focuses on future work that would be appropriate in further developing the methods and themes presented in this thesis

Increase of scale: The study undertaken is intended to regular RC buildings both in plan and elevation representing medium structures with respect to height. Analysis for response of structure was carried out by coefficient method. For future research, Optimum design of high-rise building structure with irregular both in plan and elevation under multiple design criteria using one of modern optimization techniques such as genetic algorithms, Simulated annealing, Particle swarm optimization, Ant colony optimization. Fuzzy optimization Neural-network-based methods or combination of them with response spectrum method of analysis for structural response to increase the scale of structural optimization.

Inclusion of inter-storey drift constraints: In the work presented, maximum lateral displacement and drift are the only constraints considered. This is a simplification and should be extended to include consideration of inter-storey drift and potentially in conjunction with the introduction of section-size optimization

References

[1] H. Nikzad and S. Yoshitomi, "Practical Design Procedures of 3D Reinforced Concrete Shear Wall-Frame Structure Based on Structural Optimization Method," vol. 12, no. 6, pp. 694–702, 2018.

[2] Ashwini R. Kulkarni and Vijaykumar Bhusare, "Structural optimization of reinforced concrete structures," *Int. J. Eng. Res.*, vol. V5, no. 07, pp. 123–127, 2016.

[3] A. A. A. Aga and F. M. Adam, "Design Optimization of Reinforced Concrete Frames," *Open J. Civ. Eng.*, vol. 05, no. 01, pp. 74–83, 2015.

[4] M. J. Esfandiari, G. S. Urgessa, S. Sheikholarefin, and S. H. D. Manshadi, "Optimum design of 3D reinforced concrete frames using DMPSO algorithm," *Adv. Eng. Softw.*, vol. 115, no. July 2018, pp. 149–160, 2018.

[5] I. Rahmanian, Y. Lucet, and S. Tesfamariam, "Optimal design of reinforced concrete beams: A review," *Comput. Concr.*, vol. 13, no. 4, pp. 457–482, 2014.

[6] C.-T. Ng and H.-F. Lam, "Optimization design of tall buildings under multiple design criteria," *Int. J. Appl. Math. Mech.*, vol. 4, pp. 35–48, 2005.

[7] D. M. Alex and L. Kottalil, "Genetic Algorithm Based Design of a Reinforced Concrete Cantilever Beam," *Int. Res. J. Eng. Technol.*, pp. 1249–1252, 2015.

[8] H. Xiong and M. A. H. Calvo, "High-Rise Residential Reinforced Concrete Building Optimisation," *Open J. Civ. Eng.*, vol. 05, no. 04, pp. 437–450, 2015.

[9] S. M. Thomas and P. A. G, "Optimization of singly reinforced rc beams *1," vol. 5, pp. 199–207, 2017.

[10] S. A. Babiker, F. M. Adam, and A. E. Mohamed, "Design Optimization of Reinforced Concrete Beams Using Concrete Beams Using Artificial Neural Network," *Green Bookee,* vol. 1, no. 8, pp. 7–13, 2012.

[11] A. Kaveh and A. F. Behnam, "Design optimization of reinforced concrete 3D structures considering frequency constraints via a charged system search," *Sci. Iran.*, vol. 20, no. 3,

pp. 387–396, 2013.

[12] O. Access, "We are IntechOpen , the world ' s leading publisher of Open Access books Built by scientists , for scientists TOP 1 %."

[13] S. Rathod, I. Khan, and K. Sangle, "Optimization of Structures using Different Structural System," *Int. J. Eng. Technol.*, vol. 6, no. 5, pp. 1605–1608, 2016.

[14] P. Gare and S. S. Angalekar, "Design of Structural Element Employing Optimization Approach," pp. 13808–13816, 2016.

[15] S. Chutani and J. Singh, "Optimal Design of RC Frames using a Modified Hybrid PSOGSA Algorithm," *Arch. Civ. Eng.*, vol. 63, no. 4, pp. 123–134, 2017.

[16] B. F. A. Mohammad and D. A. Seyan, "Optimum Design of Reinforced Concrete Rectangular Columns Subjected to Axial Compression and Biaxial Bending Moments," vol. 2, no. September, pp. 225–240, 2016.

[17] P. A. Sangave and S. M. Nikate, "A Study on Structural Optimization of Multistoried RCC Buildings," vol. 3, no. 3, pp. 326–353, 2015.

[18] G. Singh and R. S. Bansal, "Cost Optimization of R . C Multistory Building," pp. 1036–1038, 2017.

[19] V. Lakshmi, "Optimized Design of G + 20 Storied Building," vol. 7, no. 4, pp. 418–425, 2016.

[20] R. Kumar, "Optimised Cost Design of Reinforced Concrete Frame," no. 4, pp. 194–199, 2016.

[21] G. Mehta, B. Sharma, and A. Kumar, "Optimization of member size and materials for multistoried RCC buildings using ETABS," *Indian J. Sci. Technol.*, vol. 9, no. 44, 2016.

[22] Z. J. Goo, "Topology Optimization of Building Bracing Schemes," 2013.

[23] D. W. Seo, Y. S. Chun, and K. K. Chang, "Structural Optimum Design of Tall Buildings," no. 1, pp. 0–5.

[24] A. M. Abd, "Diyala University Construction Projects Management," no. September, 2018.

[25] C. Standard, "FINAL DRAFT Ethiopian Building Code Standard 8 : Design of structures for earthquake resistance Part 1 : General rules , seismic actions and rules for buildings," no. August, 2013.

[26] The Mathworks, "Optimization Toolbox TM 4 User ' s Guide," *Order A J. Theory Ordered Sets Its Appl.*, vol. 200, p. 20, 2010.

[27] K. Han, A. Meimand, and P. Neto, "Optimization in Matlab IE 521," pp. 1–38, 2011.

[28] N. Trautmann and M. Gnagi, "On an application of Microsoft Excel's evolutionary solver to the resource-constrained project scheduling problem RCPSP," *IEEE Int. Conf. Ind. Eng. Eng. Manag.*, vol. 2016-Janua, pp. 646–650, 2016.

[29] J. Arora, *Introduction to Optimum Design*. 2012.

[30] U. Development, "EBCS-2 Design of Concrete Structures Final Draft," 2013.

[31] T. S. Ketkukah, I. Abubakar, and S. P. Ejeh, "Optimum Design Sensitivity of Reinforced Concrete Frames," vol. 2, no. 5, pp. 144–158, 2014.

[32] "Design_of_Reinforced_Concrete_Structure_-_Volume_2_-_DR._Mas.pdf." .

[33] T. Izhar and R. Dagar, "Comparison of reinforced concrete member design methods of various countries," *Int. J. Civ. Eng. Technol.*, vol. 9, no. 4, pp. 637–646, 2018.

Appendices

Appendix A: structural Analysis

Common to each of the methods presented in this thesis is the requirement for structural analysis to evaluate the performance of a proposed design. In all cases the analysis of building was done by Seismic Coefficient Method using ETABS Software.

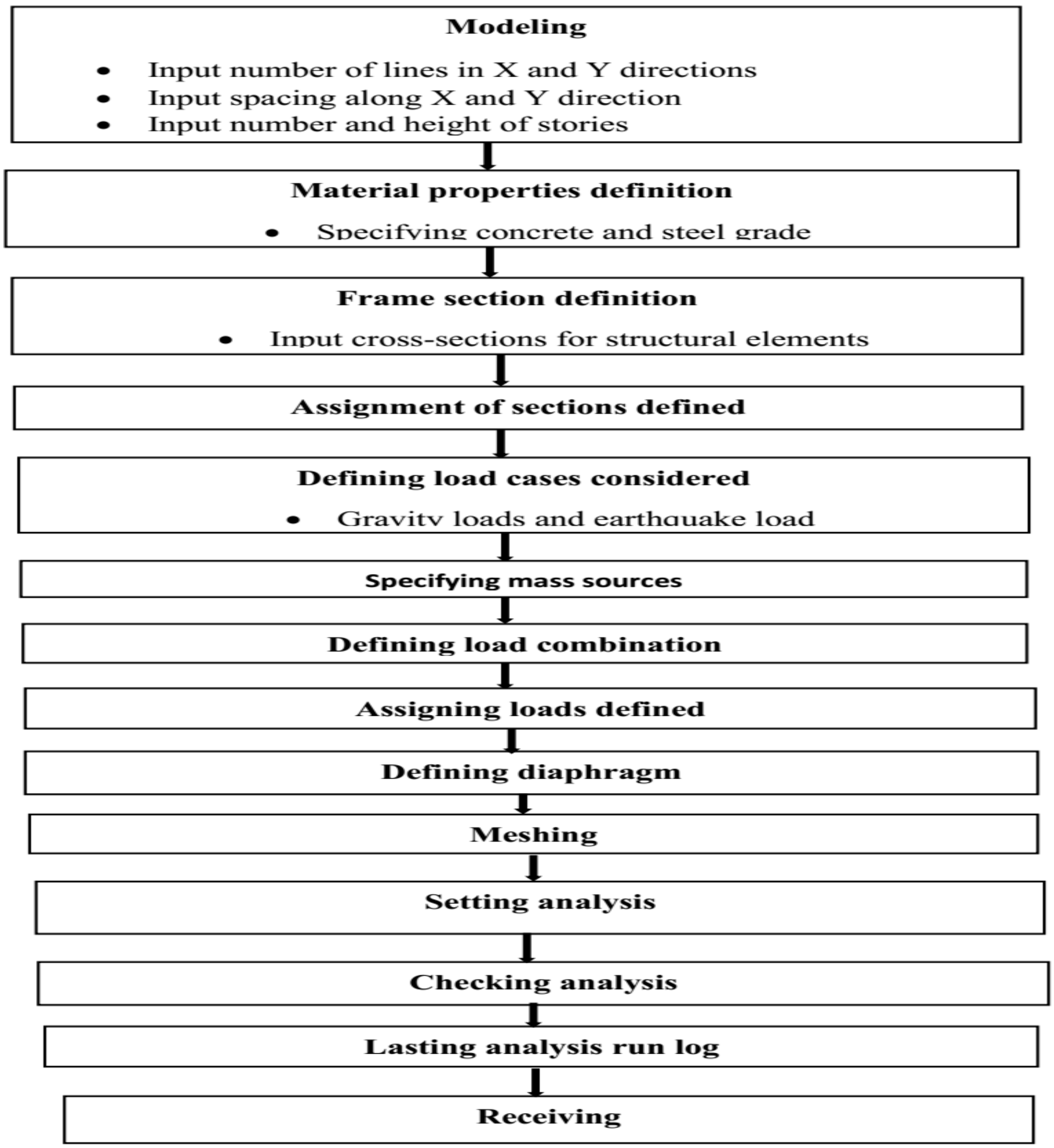

Figure.A.1 Structural Analysis flow chart

Appendix B: Sample for evolutionary algorithm

B.1. Sample for solving formulated optimization problems for grouped beams (group one)

Microsoft Excel 16.0 Answer Report

Worksheet: [excel solver.xlsx] Sheet4

Report Created: 1/17/2020 10:57:24 PM

Result: Solver has converged to the current solution. All Constraints are satisfied.

Solver Engine

Engine: Evolutionary

Solution Time: 28.5 Seconds.

Iterations: 197 Subproblems: 427

Solver Options

Max Time Unlimited, Iterations Unlimited, Precision 0.000001, Use Automatic Scaling

Convergence 0.9, Population Size 200, Random Seed 0, Mutation Rate 0.8, Time w/o Improve 40 sec, Require Bounds

Max Subproblems Unlimited, Max Integer Sols Unlimited, Integer Tolerance 1%, Assume Nonnegative

Objective Cell (Min)

Cell	Name	Original Value	Final Value
C2		11235.24454	8692.755084

Variable Cells

Cell	Name	Original Value	Final Value	Integer
D4	x1 value	350	283.9021765	Contin
D5	x2 value	350	304.6617482	Contin
D6	x3 value	1340	2734.088746	Contin
D7	x4 value	335	619.3649981	Contin
D8	x5 value	600	640.1472229	Contin
D9	x6 value	300	210.9439577	Contin

B.2. Sample for solving formulated optimization problems for grouped columns (group one)

Microsoft Excel 16.0 Answer Report

Worksheet: [column optimization.xlsx] Sheet1

Report Created: 1/16/2020 10:08:01 PM

Result: Solver has converged to the current solution. All Constraints are satisfied.

Solver Engine

Engine: Evolutionary

Solution Time: 15.203 Seconds.

Iterations: 229 Subproblems: 244

Solver Options

Max Time Unlimited, Iterations Unlimited, Precision 0.000001

Convergence 0.9, Population Size 200, Random Seed 0, Mutation Rate 0.8, Time w/o Improve 30 sec

Max Subproblems Unlimited, Max Integer Sols Unlimited, Integer Tolerance 1%, Assume Nonnegative

Objective Cell (Min)

Cell	Name	Original Value	Final Value
C3		23275.41634	18002.64912

Variable Cells

Cell	Name	Original Value	Final Value	Integer
D5	x1 value	500	383.5896025	Contin
D6	x2 value	550	545.0750747	Contin
D7	x3 value	2540	3243.462894	Contin
D8	x4 value	600	712.9282224	Contin
D9	x5 value	300	281.1179808	Contin

B.3. Sample for solving formulated optimization problems for floor slab (group one)

Microsoft Excel 16.0 Answer Report

Worksheet: [slab optimization.xlsx] Sheet1

Report Created: 1/24/2020 7:27:12 AM

Result: Solver has converged to the current solution. All Constraints are satisfied.

Solver Engine

Engine: Evolutionary

Solution Time: 30.907 Seconds.

Iterations: 307 Subproblems: 885

Solver Options

Max Time Unlimited, Iterations Unlimited, Precision 0.000001

Convergence 0.9, Population Size 200, Random Seed 0, Mutation Rate 0.8, Time w/o Improve 30 sec

Max Subproblems Unlimited, Max Integer Sols Unlimited, Integer Tolerance 1%, Assume Nonnegative

Objective Cell (Min)

Cell	Name	Original Value	Final Value
C9		42605.47816	32963.60454

Variable Cells

Cell	Name	Original Value	Final Value	Integer
D11	x1 value	150	94.93253991	Contin
D12	x2 value	583.364	1373.673132	Contin
D13	x3 value	383.364	1121.276087	Contin
D14	x4 value	300	360.9356952	Contin

Appendix C: sample for optimization tool box in MATLAB

The iteration table in the command window shows how MATLAB searched for the minimum value of weight function in the file named constraint. This table is the same whether you use Optimization Tool or the command line. MATLAB reports the minimization as follows:

Ite	F-count	f(x)	Feasibility	Step length	N. of First-order	step optimality
0	7	11293.67	37.50			30.71
1	14	10415.12	0.00	1.00	48.48	37.10
2	22	8998.31	0.00	1.00	59.45	15.40
3	30	8247.66	0.00	1.00	46.35	11.29
4	39	7276.17	0.00	0.7 0	75.66	9.68
5	47	6808.36	0.00	1.00	63.02	2.23
6	57	6751.56	0.00	0.49	24.92	2.05
7	64	6664.21	0.00	1.00	59.32	1.66
8	72	6658.66	0.00	1.00	3.62	1.66
9	83	6651.78	0.27	0.34	3.82	1.64
10	91	6626.90	0.00	1.00	12.87	1.63
11	99	6577.793	0.00	1.00	42.98	1.61
12	112	6550.48	0.00	0.20	24.87	1.60
13	127	6539.10	0.00	0.08	10.67	1.60
14	142	6528.25	0.00	0.08	10.42	1.59
15	158	6520.87	0.04	0.057	7.27	1.59

16	178	6519.04	0.05	0.014	1.85	1.59
17	199	6517.60	0.062	0.097	1.50	1.59
18	221	6516.38	0.07	0.068	1.33	1.587
19	244	6515.25	0.07	0.005	1.282	1.587
20	268	6514.17	0.08	0.0033	1.262	1.586
21	292	6512.86	0.09	0.0033	1.568	1.586
22	316	6511.53	1.019	0.0033	1.594	1.585
23	340	6510.21	1.113	0.0033	1.593	1.584
24	364	6508.89	1.206	0.0033	1.591	1.583
25	388	6507.59	1.297	0.0033	1.589	1.583
26	412	6506.280	1.385	0.0033	1.587	1.582
27	436	6504.98	1.473	0.0033	1.585	1.581
28	460	6503.68	1.557	0.0033	1.583	1.581
29	484	6502.39	1.639	0.0033	1.582	1.580
30	508	6501.11	1.721	0.0033	1.580	1.579
31	532	6499.83	1.801	0.0033	1.578	1.579
32	556	6498.55	1.877	0.0033	1.576	1.578
33	580	6497.280	1.952	0.0033	1.574	1.577
34	604	6496.01	2.024	0.0033	1.573	1.577

The following description applies to the table as displayed

- The first column, labeled Iter, is the iteration number from 0 to 34. fmincon took 34 iterations to converge.

- The second column, labeled F-count, reports the cumulative number of times weight's function was evaluated. The final row shows an F-count of 604, indicating that fmincon evaluated weight's function 604 times in the process of finding a minimum. The third column, labeled f(x), displays the value of the objective function.
- The final value, 6496.01, is the minimum that is reported in the Optimization Tool **Run solver and view results** box, and at the end of the exit message in the command window.
- The fourth column, feasibility, goes from a value of 37.50 at the initial value, to very small, 2.024, at the final iteration. This column shows the value of the constraint function in the constraint at each iteration. Solver stopped prematurely.