JIMMA UNIVERSITY

JIMMA INSTITUTE OF TECHNOLOGY

FACULTY OF CIVIL AND ENVIRONMENTAL ENGINEERING

STRUCTURAL ENGINEERING STREAM

Weight Optimization of Reinforced Concrete Mat foundation

A Case study on Addis Ababa Housing Condominium

A Research Thesis Submitted to School of Graduate Studies of Jimma University in Partial Fulfilment of the Requirement for the Degree of Masters of Science in Structural Engineering

FRAOL TAMIRU

FEBRUARY, 2022

JIMMA, ETHIOPIA

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BY

FRAOL TAMIRU

ADVISOR – ENGR. ELMER C. AGON, Asso. Prof.

CO-ADVISOR – ENGR. YEHAMLESHET MENBERU, MSc

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JIMMA, ETHIOPIA

DECLARATION

I declare that this research titled “Weight Optimization of Reinforced Concrete Mat foundation a case study on Addis Ababa Housing Condominium” is an authentic record of my work and has not been submitted before for degree to any other university.

Name	**Signature**
I. Student – Fraol Tamiru	___________________________
II. Advisor – Engr Elmer C. Agon, Asso. Prof.	___________________________
III. Co-Advisor – Engr Yehamleshet Menberu, MSc	___________________________

ABSTRACT

With the advancement of construction technology and increase in the land scarcity in the cities due to urbanization, the demand of high-rise buildings is at highest priority in real estate projects. The construction of this buildings takes highest investment economies and the designs must concern not only for the serviceability and durability but also the economic advantages. The design of these reinforced concrete structures is performed by conventional methods following the paradigm "estimate-analysis-*check" making the design process time consuming and having a larger design margin making it safe but uneconomical. This leads to the optimization concept for having the best performance within the available resources.*

In this research, a case study of uniform flat plate mat foundation of 3B+G+21 building of the Addis Ababa Housing Condominium project was carried out mainly because the project is currently under review and will be implemented in large scale soon. The research mainly focused on the minimization of weight of the reinforced concrete Mat foundation while satisfying the limitations and specifications described by ES EN 1992-1-1-2015 design code. Structural optimization problems were formulated with inclusion of weight minimization as objective function, design constraints and design variables. The design variables were taken as the area of the reinforcement and the cross-sections of the structural members. The design constraints were formulated based on the design book of ES EN. For the study, MATLAB optimization toolbox software was used for the optimization process. The case study mat has been designed in SAFE Foundation software which were validated in ABAQUS software for accepting the loads for the optimization process.

The optimization process was carried out and was able to reduce the total structural weight of the mat foundation by 18.7% while having structural members of 22.24% and 16.58% reduction for beam and slab respectively as compared to the original design. In conclusion, the optimized design is more economical than the conventional design due to the weight reduction the consumption of materials has been reduced and it's better to consider a more optimized design by satisfying the safety constraints for future use.

Keywords: Structural optimization, Structural weight, Mat foundation

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ACRONYMS

ACI	American Concrete Institute
Asc	Area of Longitudinal compression reinforcement
Ast	Area of Longitudinal tensile reinforcement
Av	Area of Shear reinforcement
Bb	Width of beam
CDPM	Concrete Damage Plasticity Model
CEA	Complete ABAQUS Environment
Ceq	Equality Constraint
Db	Effective Depth of beam
Ds	Effective Depth of slab
ES EN	Ethiopian Standards in Euro Norms
FEA	Finite element analysis
Lb	Centre to centre length of beam
RC	Reinforced concrete
S	Spacing of shear reinforcement
SLS	Serviceability limit state
SSI	Soil-structure interaction
Vbc	Volume of concrete in a beam
Vbs	Volume of reinforcing steel in a beam
Vv	Volume of stirrups in a beam
Vsc	Volume of concrete in a slab
Vss	Volume of main and secondary reinforcing steel in both direction of slab
ULS	Ultimate limit state

CHAPTER ONE

INTRODUCTION

1.1 Background of the study

Construction of buildings dates back to the old ancestors of mankind built for different purposes, in recent years the lack of space in major cities tall buildings are in demand for this reason development of new technologies and methodologies must be developed and implemented. The main requirement of present-day engineering designs are safety and economy. Safety is guaranteed by design parameter constraints and the economy can be achieved by minimization of cost functions. The design parameter constraints are fulfilled by following the design codes and standards in this case Ethiopian building codes of standards in Euro-norms and for the economy we will be using optimization methodologies. The most frequently used geotechnical structure in low bearing capacity soils and high-rise building is Mat foundation. According to the standard ES EN 2: Design of Concrete Structure – Part 1 : general rules for building states that structures must satisfy ultimate limit state (ULS) and serviceability limit state (SLS) conditions. Mat foundation must be designed to withstand structural failure (bending failure, shear failure and design constraints of a concrete design code) and geotechnical failure (bearing failure, sliding failure and settlement) and also equilibrium caused by combined failure in ground and structure by overturning due to eccentricity. In this study, structural failure and geotechnical failure by bearing failure has been consider and no equilibrium case since the mat foundation has symmetrical shape which omitted the situation.

Mat foundations are parts of shallow foundation type which are thick concrete slab placed on the ground as the foundation of the structure, used for their best ability to transferring of loads simultaneously to the ground which has a week bearing capacity to support the coming load. Mat foundation will transfer the load uniformly and prevents sudden settlements of the structure.

Recently, various methods and algorithms are being developed for the optimization of structures. Optimization is getting best result under given circumstances to achieve the goal of minimizing effort and maximize desired benefit in this case minimize the over cost and maximize the performance of the mat foundation. For nonlinear problem there are different solving techniques and for this case optimization of nonlinear programming was done using MATLAB toolbox software.

1.2 Statement of the problem

The increasing demand of high rising building due to land scarcity and designing of the structures with the conventional methodology based on the design books and codes that follows the “estimate – analysis – check” view which leads to larger designs only to satisfy the strength and durability rather makes it uneconomical. This design approach increases the focus to stability and being in safe zones rather choosing a better economical sections and approaches. Due to the increase cost of construction materials and economical views, the increase demand for optimized projects of reinforced concrete structures is at highest level.

In this research, 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 are from the requirements of newly revised Ethiopian Building Codes of Standard including section capacity (Moment and shear capacity), Minimum and Maximum requirements of reinforcement bar. There are some reasons for choosing weight function optimization rather than cost functions: since the study is planning to reduce the cost of the structure by reducing the dimensions not on material and labour cost since those are varied based on location and time due to inflation is hard to estimate and validate.

1.3 Objective of the study

1.3.1 General objective

The general objective of this thesis was to optimize and compare design of mat foundation for safe and economical design using MATLAB Toolbox.

1.3.2 Specific objective

- To model and study the performance of already designed mat foundation using ABAQUS software
- To optimize weight of the design by reducing the cross-sectional area of mat beam and slab and reinforcement using MATLAB optimization tool box using fmincon
- To compare the optimized design with original weight of concrete and reinforcement

1.4 Research questions

The research addressed in this study are following questions:

1. How to optimize the weight of Mat Foundation (concrete and rebar) for satisfaction requirements stated under the design code?
2. What are the percentage difference of the reduced or optimized structure versus the originally designed structure?

1.5 Significance of the study

Now days, the rapid growth building construction and need of structural stable and economical designs, Mat foundation are used for high rising buildings and also small buildings with low bearing capacity soils for transferring loads from above uniformly which makes it a core area of study since it is the fundamental part of structural engineering and the size and scale of the projects within the country is boosting with scarce resources and capital optimized structures come in handy. This will make the designed structure economical by minimizing the total material usage as a structure is built under constraints. Simple mathematical expression for objective function and constraints have been developed and solved using MATLAB optimization tool box. Through that process best optimization tool was proposed for design engineers based on the optimum solution obtained from software solutions. Therefore, the study of optimized design of Mat foundation is critical and lay a methodology of optimization techniques for sub-structures and also this material can be used for future students and researchers conducting studies on optimization of Mat foundations and helps the government saving additional costs required on this and similar projects proposed and to be launched soon.

1.6 Scope and limitation of the study

The study is an attempt to optimize the uniform flat plate mat Foundation of 3B+G+21 Addis Ababa Housing Condominium Apartment designed in the city where soil test conducted on site having bearing capacity of 550KPa and the design have been done on conventional methodology for adequate transfer of the lateral load. Also, the research deals with the optimization of mat foundation and limited to studying the lateral loadings and their effect without soil structure interaction and also limited to the weight reduction optimization process by MATLAB Toolbox optimization and the 3D analysis has been carried out by ABAQUS software. The material nonlinearity for concrete and reinforcement grades for yield strength capacity are not design constraints.

CHAPTER TWO

RELATED LITERATURE REVIEW

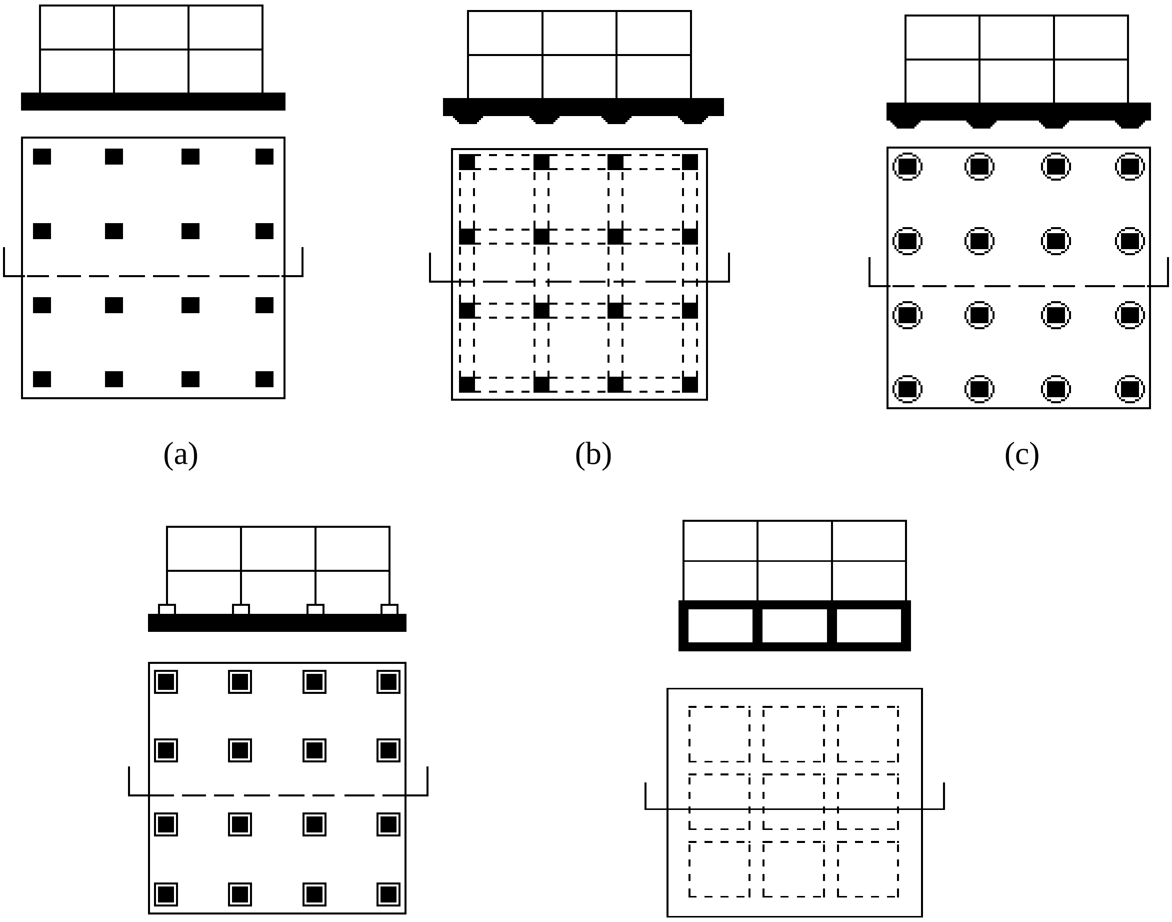
2.1 General

In this chapter, development of commonly used optimization problem formulas, previous studies on the concepts of optimization of reinforced concrete structures and review on optimization techniques using MATLAB tool box and also reviews on the concept of Mat foundation design and methodologies. Optimization is a process of finding a minimum or maximum value of a function subjected to constraints helping to find the maximum desirable benefit from the available resources. The basic requirements for an effective structural design are that the response of the structure should be acceptable as per various specifications from design books and limitations. There can be variety of feasible designs but it’s essential to choose the best from the candidates. The best designs could be in terms of minimum cost, minimum weight or maximum performance or a combination of those (S. M. Thomas and P. A. G, 2017).

2.2 Design of Mat foundation

Mat foundation is a large rigid slab covering the entire area under the structure supporting several columns and walls to transfer the load to the soil strata uniformly (Venkatramaiah, C., 1993). It’s preferred for soils with low bearing capacity. Under some conditions, if a spread footing would cover more than half the building area Mat foundation is more economical. There are several types of mat foundations used currently. Some of the common are listed below:

a. Flat plate, uniform mat thickness
b. Flat plate thickened under column
c. Beam and slab, columns are located at the intersection of the beams
d. Flat plates with pedestals
e. Slab with walls as a part of the mat



(a) (b) (c)

(d) (e)

Figure 2.1 Types of Mat foundation

Now days due to advanced aesthetic design in construction it difficult to provide a regular spacing of columns and isolated footings or combined footings hence the overlapping and failure of soil, its common to design mat foundations which reduces the cost, effort of excavation and prevent sliding of adjacent footing. In the paper analysis and design of raft foundation, superstructural analysis was done in ETABS 13 and foundation was done in SAFE foundation V12. The area of steel obtained for moment obtained from the envelop combination was the same as the strip method and the punching shear ratio is less than 1 also for the deflection there is allowable deflection within the limit making the design safe. (Zia-abe D. S. Punekar et at.,2017)

There are several important structural design parameters to address while modelling and designing of mat foundations those includes dimensions of the mat, soil bearing capacity, and structural loads. By using those parameters feed into the Finite element software analysing all the elements giving solutions and make sure none of the critical cases have not been missed (David B. Lorenz, 1989).

Mat foundation is a large rigid concrete slab rests directly on soil or rock which covers the entire area under the structure and supports all the columns and the walls. This type of foundation is best suitable when the allowable bearing capacity of the soil pressure is low or the load is very heavy in a case when spread footings cover more than half of the plan area. And it's also a better choice for soil strata which are likely to have considerable differential settlements (Venkatramaiah C., 1993).

Design of Mat foundations are as inverted continuous flat slab floor supported without any upward deflection at the columns and walls. In the analysis of Mat foundations, it is assumed that the soil pressure acting against the slab is uniformly distributed and equal to the total load from all columns. Mat slabs have uniform thickness throughout the entire area for relatively small loads but for larger column loads, the slab under the column is thickened to provide sufficient strength for negative moment and shear (Peck, R.B. et al., 1974).

Mat foundations are reinforced structures used to transfer structural loads to the underlying soil and are well suited in reduction of differential settlement. In the study on analysis of mat foundation finite element has been used for the analysis. The mat foundation was analysed as an inverted flat slab by flat plate analysis and FEA. The result from plate analysis were similar to the FEA. Hence the direct design method analysis overestimates the moment making the sections larger certainly making the design safe when compared to the FEA method but making it an economical. (Rashed C. 2012)

A very commonly used type of foundation this time is Mat foundation having many advantages in adopting this type of foundation which includes the compensation of loadings, utilization of underground space, lowering foundation settlements and increase in safety factor of the bearing capacity for the foundation. In foundation design differential settlement affects the whole structure in worst case it will lead to structural failure threatening the inhibitors within the building. Therefore, designing of foundation needs to follow strict attention and evaluation (C-M Ma and Y-Y Chen, 2019).

2.3 Nonlinear analysis

Study on the Analysis of Mat Foundation using finite element and direct design method shows that the FE analysis gives a more economical sections rather than the direct method which is based on higher safety standards making it safe but not economical (Rashedul H. Chowdhury et al. 2013).

Finite element analysis using ABAQUS software was performed to investigate the behaviour of post tensioned concrete beams attempting to examine the concrete damage plasticity model in ABAQUS as well as the effect of an external post tensioning steel rod system. In the paper, the finite element analysis has been done with some assumptions including perfect bond of steel and concrete. The simulated tensile deformation result from FE analysis and experimental results are similar to actual crack patterns in tests and analytical responses such as strength and deflections are in good agreement with the measured responses from the experimental testes (Swoo-Heon Lee, et al., 2020).

A novel biaxial constitutive model and a non-linear model using updated algorithm have been implemented in ABAQUS software for simulating the reinforced concrete shear walls. An optimization algorithm based on the discrete Fréchet distance is proposed to quantify and minimize the difference between test results and FE simulation results of the load-displacement curves. The comparison shows the proposed model with optimization method predicts high accuracy simulation results (Jia-Ji Wang, et al., 2021).

Research on shear behaviour of reinforced concrete beams done to investigate the effect of the orientation of stirrups on the shear capacity of RC structure as a shear span to depth ratio varies and for the analysis using general purpose finite element package, ABAQUS software. the shear capacity of the RC beam obtained from the numerical analysis gives a good agreement with the experimental result. The results have been compared to analytically calculated values by using shear provisions of ACI 318-14 and EN-2 (Chalachew B. Hunegnawand Temesgen W. Aure, 2021).

2.4 Structural optimization

The use modern numerical techniques of optimized design of structures dated back to 1960. Schmit is the most widely referenced beginning of method in this field. During the decade of 1960s, study of the application of optimization technique has been used for Varity of structures

(Schmit, 1960). At the time the problems where relatively simple but through time the problems become sophisticated.

A review on design optimization of reinforced concrete beams was presented and have been discussed that the optimal design of concrete beam either individually or as part of frame have been addressed using various optimization techniques depending on the formulation of the problems. It was explained that the objective of optimization (minimization of weight, cost) the design variables and constraints vary depending on the problems arise therefore methodologies differ for each problems providing the optimal design (I. Rahmanian, 2014).

Optimization of T-beam have been studied for both minimization of cost and weight under geometrical constraints, shear and moment capacity for deflection have been considered. Optimal solutions for minimum cost and weight were compared showing results were affected significantly by the optimal size. Cost is significantly affected since the size reduction leads to lesser material uses making is economical too (Fedghouche Ferhat, 2018).

Optimization is a methodology of getting the best result under given circumstances to achieve the goals of minimizing effort and maximize desired benefit in this case minimize the over cost and maximize the performance of the mat foundation. For nonlinear problem there are different solving techniques, since there is no define way to solve all problems, in this problem from mathematical programming or optimization technique, nonlinear programming will be used using MATLAB software using optimization tool box for solving.

Optimization can include a wide range of problem with the aim of searching for certain optimality. Therefore, there are many ways of classification of optimization problems and techniques differ from problem to problem. A unified approach is not possible and complexity depends on the function forms of its objective functions and constraints.

Mathematically it’s possible to write most optimization problems in the generic forms as:

$$\begin{aligned} &\text{Minimize} && f_i(x), && (i=1, 2, ..., M), && (2.1)\\ &\text{Subjected to} && \phi j(x) = 0 && (j=1, 2, ..., J), \\ & && \Psi k(x) \leq 0, && (k=1, 2, ..., K) \\ & && X = (X_1, X_2, \dots X_n)^T \end{aligned}$$

Where: - $fi(x)$, $\phi j(x)$ and $\Psi k(x)$ are functions of the design vector.

- Xi of X are called design or decision variables, and they can be real continuous, discrete or the mixed of these two.
- The functions fi(x) where i=1, 2,..., M are called the objective functions (cost function/ energy function), in the case of M=1,there is only a single objective and in the case of M>1, there are multi objectives.
- The equalities for ϕj and inequalities of Ψk are called constraints. It is worth pointing out that we can also write the inequalities in the other way ≥0 for Ψk, and we can also formulate the objectives as maximization problem.

2.4.1 Design variables

Design variable also called control variable is under control of the designer and can impact the solution of the optimization problem. Combination of different variables represents different designs. The main aim of the design optimization is to find the best combinations of design variables that can give best solution for the intended objective and also maintains the required constraints. Design variables have lower limit and upper limit specifying the minimum value and maximum values.

2.4.2 Objective function

Objective functions define the objective of the optimization process. It’s a numeric value that is formulated from sets of design variables whose values is either be minimized or maximized over the set of alternatives/ constraints. In our case minimization of weight or size of the mat foundation.

2.4.3 Design constraints

Design constraints are values limiting the function which is either equality or inequality mathematical forms. This can be the resources available, time available or permeable limits of such design within design codes.

2.5 Classification of Optimization

The classification of optimization is not well established and there are some confusions in literature especially about the use of terminologies. Here we can use the most widely used terminologies. If we try to classify optimization problems according to the number of objectives, then there are two categories: single objective $M = 1$ and multi-objective $M > 1$. Multi-objective optimization is also referred to as multicriteria or even multi-attributes optimization in literature. Most real-world optimization problems are multi-objective. Similarly, we can classify optimization as constrained and unconstrained. If there are no constraints at all J=K=0 it called an unconstraint optimization problem. And if there is inequality in either or both J & K the optimization problem is called inequality constraint and if the if J=0 & K≥ 1 the problem is called equality constraint. Here is a diagram of the classification of optimization problem (Xin-She Yang, 2010).

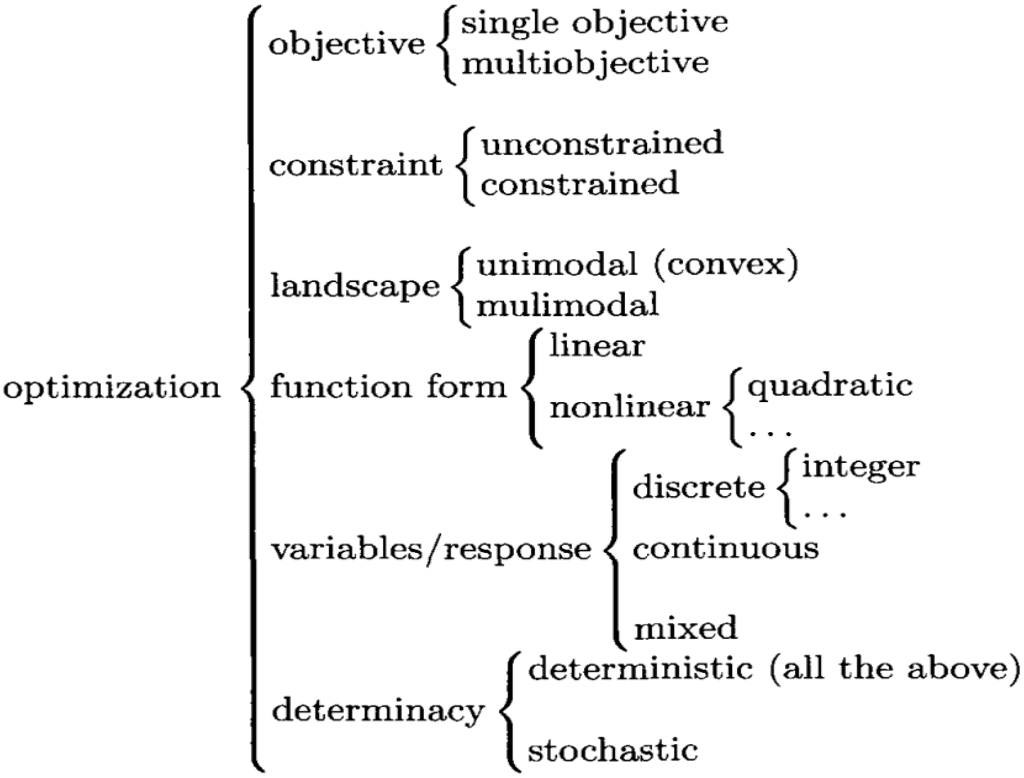


Figure 2.2 Classification of Optimization problems

Generally, the optimization problem focusses on weight reduction it’s a single objective problem with different inequality constraints depends on the values for different variable constraints bound under the code of standards. Therefore, for this research study the optimization problem is single objective inequality constrained nonlinear optimization problem.

2.6 Optimization Techniques

Optimization problems are defined by its objective functions and their constraints, a suitable method is chosen to find the best solution for the problems arise and wide ranges of method are available as per the design functional forms. If the functional forms are all linear it can be taken as a linear optimization problem where as if any of the constraints or objectives are nonlinear the optimization technique will be nonlinear optimization problem. In Reinforced concrete structure design nonlinearity is common due to the objective functions and constraints are nonlinear. Therefore, nonlinear optimization method is taken for solving the RC problems.

2.6.1 Optimization Tool Box in MATLAB

MATLAB’s Optimization Toolbox is an integrated part in MATLAB software which provides functions for solving linear and nonlinear programming, mixed-integer linear programming, quadratic programming, and nonlinear least square problems (Optimization toolbox user guide, 2010).

Based on types of optimization problems, there are several functions of MATLAB Optimization Toolbox. Those are:

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.

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 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.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 General

Structural optimization is a procedure of improving a preliminary design done by a designer according to the design codes and design criteria stated (Structural Strength, stability durability and comfort). While improving the design, limitations are being considered for each elements cross section and capacity for performing the intended purpose while reducing the unnecessary parts for better economical usages. There are plenty numbers of optimization techniques and software for performing optimization and are different for different types of problems faced. Those includes Optimization Toolbox 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 achieve the objective of the study, the methodology describes in brief on how to execute the works, what tools are being used and the methods to execute the task for the mat foundation which is a reinforced concrete structure. The use of optimization technique was based on the nature of optimization problems and depends 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 ES EN 1992-1-1:2015, Structural use of concrete in buildings.

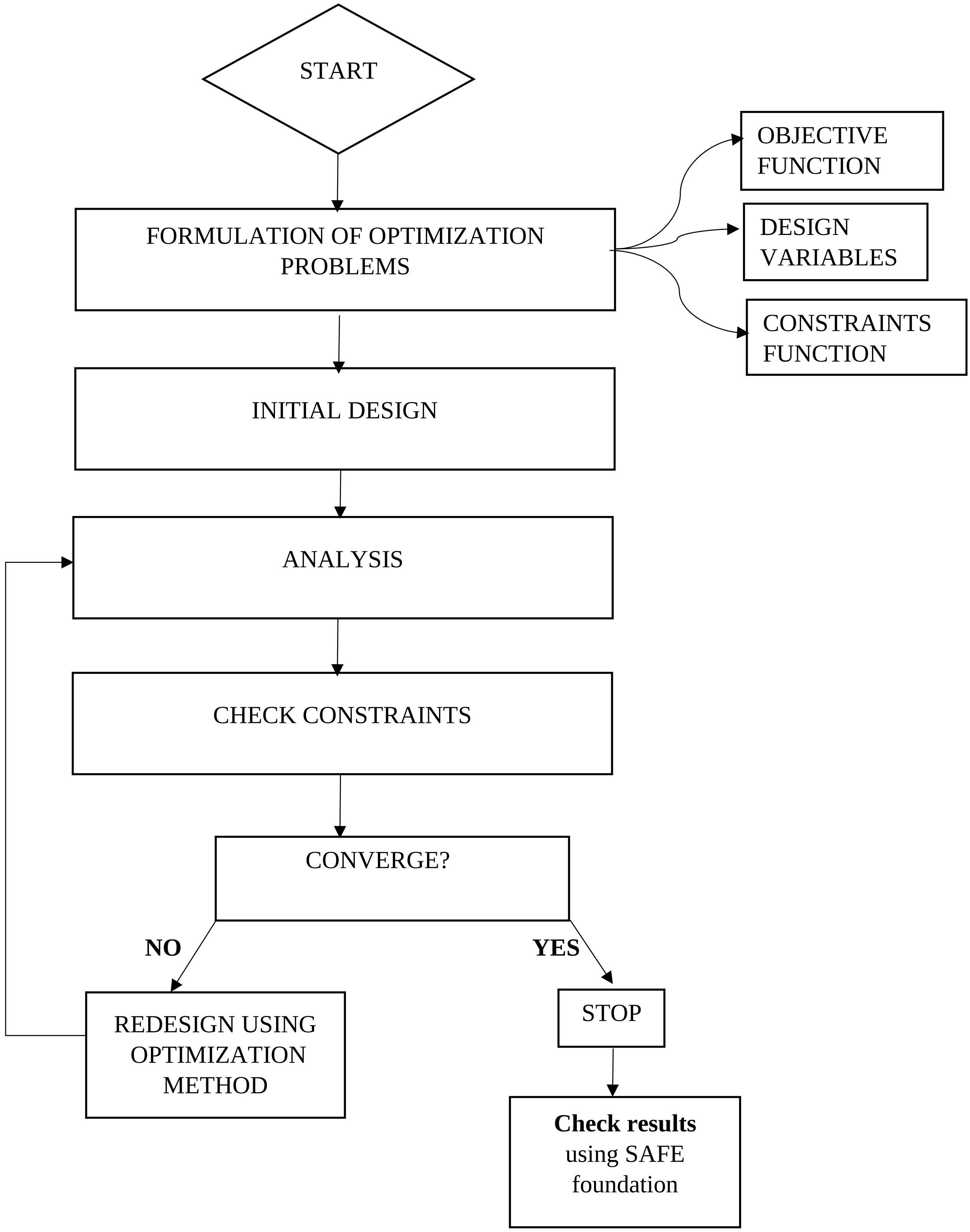


Figure 3.1 Optimization methodology flow chart

3.2 Formulation of the optimization problem

Identification of design variables for structural systems, an objective function that must be minimized, and design restrictions that must be placed on the systems are all required for the formulation of the optimum design issue (A. A. A. Aga and F. M. Adam, 2015). The general form of optimization problem is as follows:

- Constant parameters
- Objective function
- Design variables
- Design constraints

3.2.1 Constant parameters

In this study, mat foundation system is used for this specific project. The mat foundation provides adequate bearing capacity and to transfer the loads over large foot print of the building area. The mat foundation reduces differential settlement and is preferable for compressible soils. The foundation was dimensioned in such a way that the allowable soil bearing capacity is not exceeded. The allowable bearing capacity of the soil for economical shallow foundation system is 550kpa with allowable settlement of 50mm. This bearing capacity of soil should be achieved by replacing and properly compacting suitable selected soil to appropriate depth soil under the foundation in case of a soil with a lower bearing capacity than 550kpa. The concrete grade of the concrete is C25/30 type of concrete of cylindrical strength of 25MPa or a cubic strength of 30MPa and the steel yield strength of 466MPa which satisfies the requirement in the Ethiopian Building Code of Standards ES EN-1-1:2015 valid yield strength range from 400 to 600MPa.

3.2.2 Design variables

An important first step in the formulation of an optimization problem is to identify the design variables. For the present formulation, cross sectional dimensions and reinforcement areas (tensile, compressive and shear reinforcement) for beams and slabs are taken as design variables. Specifically, for beams there exist six design variables: the width, Bb, the effective depth, db, the longitudinal tensile reinforcing steel area, Ast, the longitudinal compression reinforcing steel area, Asc, shear reinforcement area, Av. and spacing of shear reinforcements, Sv. For slab, there exist three design variables: effective depth of slab, ds, area of reinforcement (longitudinal and lateral reinforcements in both directions) and spacing of reinforcement in both directions.

3.2.3 Design variable boundaries

In designing an optimization methodology, it must be clearly stated for the minimum and maximum boundaries of each design variables to satisfy their limits under the design codes and considerations. The upper and lower bounds state the feasible solution ranges to consider for the optimum design needed. The following bounds are considered in the modelling of the equation for the optimization problem in this research.

Depth - $D_{min} \leq D \leq D_{max}$ for overall depth of the Beams and the Mat slab

Width - $B_{min} \leq B \leq B_{max}$ for overall depth of the Beams

Reinforcement -$As_{min} \leq As \leq As_{max}$ for main tensile reinforcement for the Beam and Mat slab

Shear Rebar- $As_{min} \leq As \leq As_{max}$ for main tensile & compressive reinforcement for the Beam

Spacing of shear reinforcement - $S_{min} \leq S \leq S_{max}$ for spacing of shear reinforcement

3.2.3.1 Minimum and Maximum Cross- sectional Dimensions of Structural Elements

Minimum width of beams should not be greater than minimum width of column for the safe transfer of the load. According to ES EN 1992-1-1:2015, section 5.3.1, the width of primary seismic beams shall be not less than 200mm and the Maximum allowable width of the beam is limited to the thickness of the beam section $b_{max} = h$. In general, in rectangular reinforced concrete structure beams the ratio of overall depth ‘D’ to width ‘b’ ranges from 1.5 to 2 and for heavy loads it can range up to 3. In most cases beam sections are restricted by the Architects for aesthetics purpose for super structure, the substructures are not restricted by the architect since they don’t disturb the aesthetics and the structural engineer is the one who is responsible for the cross-sectional area needed to provide adequate strength and stability to transfer and support the upcoming loads from superstructure and shall design it to withstand the moments and deflections.

$D_{min} = d + \phi_{min}/2 + \phi_t$ + concrete cover

d = effective span/20 for continuous beams of highly stressed concrete (ES EN 1992-1-1:2013, section 7.4).

The maximum depth and width of the beam dependent on the designer whether it supports the upcoming load.

3.2.4 Objective Function

The main objective of this optimization process is to design a structure capable of supporting the applied loads while having a minimum possible size to save economy within the design constraints stated under the design codes. In this paper, the objective function of the optimization is structural weight function and it is expressed in terms of beam and mat slab weight. The total weight of reinforced concrete building can be expressed as:

Minimize $W = W_{beam} + W_{mat\ slab}$ ……………………………..(3.1)

Where W_{beam} = Weight of beam

$W_{mat\ slab}$ = Weight of mat slab

These weights can be calculated in the following formulations as:

$W_{beam} = \sum_{i=1}^{Ns}[(\gamma c(\mathrm{Vbc} - \mathrm{Vbs} - \mathrm{Vv}) + \gamma s(Vbs + Vv))]$…………(3.2)

$W_{mat\ slab} = [\gamma c(Vsc - Vss) + \gamma sVss]$………………………………….(3.3)

Where

γc, γs: are unit weight of concrete and steel respectively

Vbc: volume of concrete in a beam

Vbs: volume of reinforcing steel in a beam

Vv: volume of stirrups in a beam

Vsc: volume of concrete in a slab

Vss: volume of main and secondary reinforcing steel in both direction of slab

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

Where Agb = gross cross-sectional area of beam &

Lb = Centre to centre length of beam

$V_{bc} = B_b D_b L_b = B_b(d_b + d') L_b$ ………………………………………….…(3.4)

Where B_b and d_b are width and effective depth of beam and d′ is concrete cover (to centre of reinforcing steel bars)

$V_{bs} = As\ L_{bbars}$

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

Lbbars = length of beam longitudinal reinforcing steel bars.

Since As= Ast +Asc where Ast and Asc areas of tensile and compressive steel respectively, Vbs can be rewritten as:

Vbs = (Ast +Asc) Lbbars ……………………………………(3.5)

Vv =Av Lv ns

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

Lv = length of one stirrup.

ns = number of stirrups in one beam.

$Lv = 2(Bb + db + d') - 8(d' - \Phi/2 - \phi t)$,

Φ= diameter of longitudinal bar and ϕt = diameter of stirrups and $\Phi = (4/\pi)^{1/2} As^{1/2} = 1.128 As^{1/2}$, $\phi t = 1.128 Av^{1/2}$

$$Ns = \frac{length\ of\ beam}{spacing} + 1$$

$$Vv = Av[\,2(Bb + db + d') - 8(d' - \Phi/2 - \phi t)]\ (\frac{length\ of\ beam}{spacing} + 1)$$

$$Vv = Av[\,2(Bb + db + d') - 8(d' - 0.564As1/2 - 1.128Av1/2)](\frac{length\ of\ beam}{spacing} + 1) \text{ …………..(3.6)}$$

Vsc = LWh= LW (ds + d') ………………………………..(3.7)

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

$$Vss = AsL(\frac{L2}{S} + L) + A_{ss}W\ (\frac{W2}{S} + W) \text{…………………(3.8)}$$

Where ASL = cross section area of reinforcement bars parallel to span length of slab

ASW = cross section area of reinforcement bars parallel to span width of slab

3.2.5 Design Constraints

Constraints are the functional and structural requirements of the structural optimization expressed as equality or inequality equations. For the optimization problem the design constraints are of two types: Structural optimization such as code requirements and serviceability criteria and size limitations. In our case, the structural constraints are in accordance with ES EN 1992-1-1:2015 code for Mat slab constraints and Beam constraints categorized as geometric constraints. The mathematical expression contains only inequality constraints as in the design book stated the lower limit and upper limits ranges where equality constraints are not usually found in the case of structural optimizations.

3.2.5.1 Beam Constraints

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

i. Flexural Capacity

The applied bending moment shall be lower than the moment resistance capacity of the cross section. The applied bending moment includes the self-weight of the section which imposed a nonlinear constraint to the optimization. In this study the Beams are all double reinforced rectangular sections.

Double reinforced rectangular sections

Double reinforced sections are those having reinforcement in the tensile and compression zones. If the required area of tension steel exceeds the maximum area of recommended by the code the compression reinforcement is provided. The compression reinforcement also reduces the long-term deflection and beam ductility. The ultimate limit state is shown for the rectangular section with compression reinforcement below.

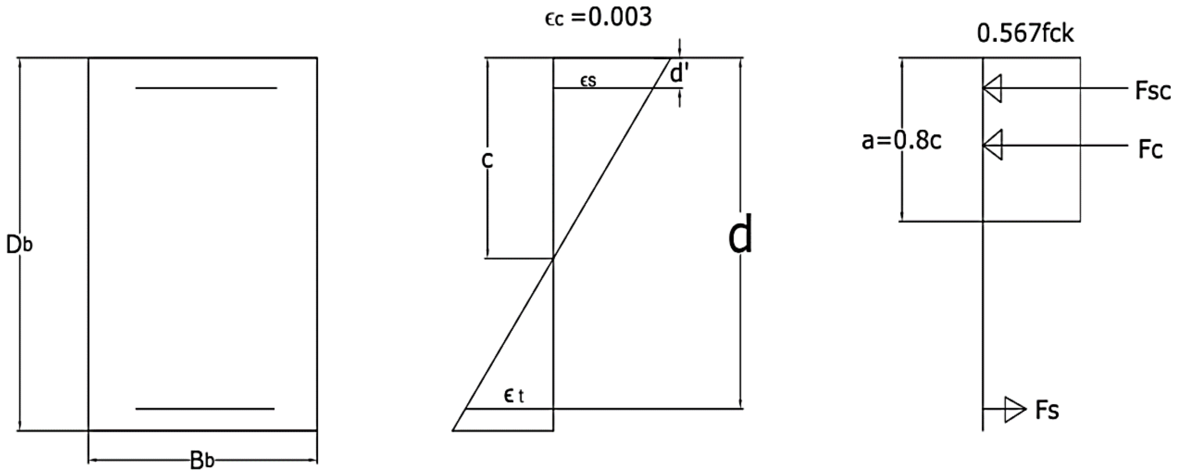


Figure 3.2 Double reinforced concrete cross section and resistive forces

From the section property by taking moments about centre of tensile reinforcement:

Muc =Fc (db- a/2) +Fsc (db- d’), Fc=0.567fck aBb ,Fsc=0.87fykAsc

a= 0.8c, Asc is area of compression reinforcements

a is the depth of stress block and c is the depth of neutral axis from top outer most surface of beam. 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 ES EN 1992-1-1:2015 $\frac{c}{d} \leq 0.8(\delta - 0.44)$, where δ = % moment redistribution,

$= \frac{Moment\ after\ redistribution}{Original\ moment}$, when no moment is redistributed, δ = 1

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

Mu=0.1674fckBbdb2 +0.87fyk Asc (db- d’)

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

Md ≤ Mu =0.1674fckBbdb2 +0.87fyk Asc (db- d’)

Md - 0.1674fckBbdb2 - 0.87fykAsc (db- d’) ≤ 0 …………………………………….(3.9)

ii. Shear Strength Requirement

For reinforced concrete members with vertical shear reinforcement, the shear resistance, VRd,s should be taken to be the lesser, either (ES EN 1992-1-1-2015 section 6.2.3).

$$VRd;s = \frac{Av}{s} zfyd \cot\theta \quad \text{or} \quad VRd;max = \alpha cbzvfcd /(\cot\theta + \tan\theta)$$

where VRd,s is the design value of the shear force that can be sustained by the yielding shear reinforcement; VRd, max is the design value of the maximum shear force that can be sustained by the member, limited by compression strut crushing; VRd, max is the design value of the maximum shear force that can be sustained by the member, limited by crushing of the compression struts; VRd, max is the design value of the maximum shear force that can be sustained by the member, limited by fyd is the yield strength of the shear reinforcement; is the angle of the inclined struts; b is the width of the member; fcd is the design compressive cylinder strength of concrete after 28 days; and c is a coefficient that accounts for the effect of normal stresses on the shear strength. The recommended value of αc is as follows:

Table 3.1 Recommended value of αc

1	for non-pre stressed structures
$(1 + \sigma cp/fcd)$	for $0 < \sigma cp \leq 0.25$ fcd
1.25	for 0.25 fcd $< \sigma cp \leq 0.5$ fcd
$2.5 (1 - \sigma cp/fcd)$	for 0.5 fcd $< \sigma cp < 1.0$ fcd

σcp is the mean compressive stress in the concrete caused by the design axial force. v is a coefficient that accounts for the rise in fragility and decrease in shear transmission by aggregate interlock as compressive concrete strength increases. It is taken to be 0.6 for fck ≤ 60 MPa. 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, VRd;max is given by:

$$VRd;max = \alpha cbzvfcd = Bb*0.9db*0.6*fcd = 0.54\ Bbdbfcd$$

$$VRd;s = \frac{Av}{s} zfyd = \frac{Av}{s} 0.9dfyd$$

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

$Vd \leq VRd;max = 0.54\ B_b d_b fcd$

$Vd - 0.54\ Bbdbfcd \leq 0$ ……………………………………………………(3.10)

$Vd - \frac{Av}{s}\ 0.9dfyd \leq 0$ ……………………………………………..……(3.11)

iii. Minimum and Maximum limits of Area of reinforcement

According to ES EN 1992-1-1:2015, section 9.2 for longitudinal reinforcement minimum reinforcement area for tension reinforcement should not be taken as less than $A_{s,min}$

$As, \min = 0.26 \frac{fctm}{fyk}\ B_b d_d$ But not less than $0.0013 B_b d_b$

The cross-sectional area of tension or compression reinforcement should not exceed 0.04Ac outside lap locations.

Therefore, for the minimum tensile reinforcement:

$0.26 \frac{fctm}{fyk} B_b d_d - Ast \leq 0$ or $0.0013 B_b d_b - Ast \leq 0$……………………….(3.12)

For minimum compression reinforcement:

$0.26 \frac{fctm}{fyk} B_b d_d - Act \leq 0$ or $0.0013 B_b d_b - Act \leq 0$……………………….(3.12)

For maximum reinforcing steel area:

$As,max = 0.04Ac = 0.04Bb\ (db + d')$

For tension reinforcement,

$Ast - 0.04Bb\ (db + d') \leq 0$ --(3.13)

For compression steel,

$Asc - 0.04Bb\ (db + d') \leq 0$ --(3.14)

iv. Shear Reinforcement Spacing Constraints

The transverse spacing of the legs in a series of shear links should not exceed St,max

$St,max = 0.75d \leq 600$ mm

$Sv - 0.75d \leq 0$…………………………………………………….(3.15)

$Sv - 600mm \leq 0$ …………………………………………………….(3.16)

3.2.5.2 Mat Slab Constraints

i. Flexural Resistance

The slab of the case study building in this research is a two-way slab since the ratio of longer side to shorter side is less than two. Bending will occur in two directions in a dish-like shape in the case of two-way slabs. As a result, for two-way slabs, the reinforcement against bending is assessed in both short and long directions. A rectangular stress distribution is shown in figure below:

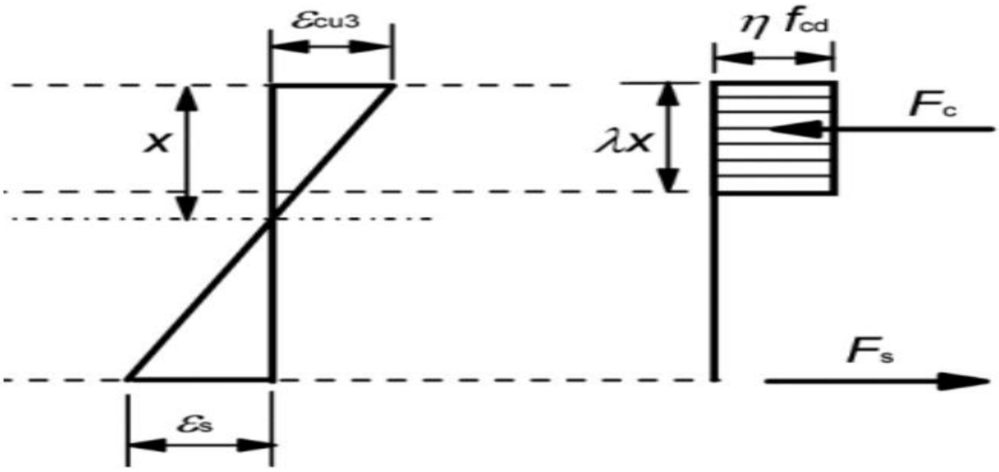


Figure 3.3 Rectangular Stress Distribution

The factor λ defining the effective height of the compression zone and the factor η defining the effective strength and the values:

$\lambda = 0.8$, $\eta = 1.0$ for $fck \leq 50$ MPa &

$\lambda = 0.8 - (fck - 50)/400$, $\eta = 1.0 - (fck - 50)/200$ for $50 < fck \leq 90$ MPa.

Therefore, for this study since the $fck \leq 50$ MPa we take $\lambda = 0.8$ and $\eta = 1.0$

ii. 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:

$$Mul = Fs\ (d - \lambda x/2) = 0.87fykAsl(\ d - \frac{0.87fykAsl}{1.6fcdb})$$

Where b is per meter length and Asl is area of reinforcement along longer direction.

Moment due to external actions, Medl which is along the longer side should not be greater than the section capacity, Mul.

$$M_{edl} \leq Mul = Fs\,(d - \lambda x/2) = 0.87fykAsl(\, d - \frac{0.87fykAsl}{1.6fcdb})$$

$M_{edl} - 0.87fykAsl(\, d - \frac{0.87fykAsl}{1.6fcdb}) \leq 0$……………………………………………..(3.17)

iii. 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:

$$Mus = Fs\,(d - \lambda x/2) = 0.87fykAss(\, d - \frac{0.87fykAss}{1.6fcdb})$$

Where b is per meter length and Ass is area of reinforcement along shorter direction.

Moment due to external actions, Meds which is along the longer side should not be greater than the section capacity, Mus.

$$M_{eds} \leq Mus = Fs\,(d - \lambda x/2) = 0.87fykAss(\, d - \frac{0.87fykAss}{1.6fcdb})$$

$M_{eds} - 0.87fykAss(\, d - \frac{0.87fykAss}{1.6fcdb}) \leq 0$……………………………………………..(3.18)

iv. Minimum And Maximum 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(fctm/fyk) bds or 0.0013bds where b is width per meter or length per meter and ds is effective depth of slab.

$0.26\frac{fctm}{fyk}bd - Ass \leq 0$ or $0.0013bd - Ass \leq 0$……………………….(3.19)

For the maximum areas of reinforcing steel constraint:

$As - 0.04B\,(ds + d') \leq 0$……………………………………….…..…(3.20)

v. Reinforcement spacing

The spacing of bars should not exceed Smax,slabs.

The recommended value of Smax,slabs. is:

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

Based on the mentioned specification for the maximum spacing of bars, constraints on spacing can be set out as shown below in equations 3.21 and 3.22.

$S - 3h \leq 0,\ S - 3(d + d') \leq 0$ …………………………………………………….(3.21)

$S - 400 \leq 0$ ……………………………………………………………………(3.22)

3.3 Description of the case study

In this case study a Mat foundation have been selected for optimization which is taken from a structural design for Addis Ababa Housing of 40/60 condominium which is a 3B+G+21 building designed for residential purpose only to be built in Addis Ababa. The super structural design has been made using ETABS and the sub-structure have been designed using SAFE Foundation software's. From the ETABS analysis the final factored loads from the base of the column have been taken to analysis on the SAFE Foundation software. The characteristic strength of the concrete is taken as C25/30 with a cubic strength of 30MPa and yield strength of main bars are taken to be 466MPa for all sections of the slab and the beams.

Table 3.2 Case study Mat slab dimension and details

Parameters	Values
Plan dimension	47.6*30.1m
Beam size (width*depth)	1m*2.4m
Mat slab thickness	1.2m

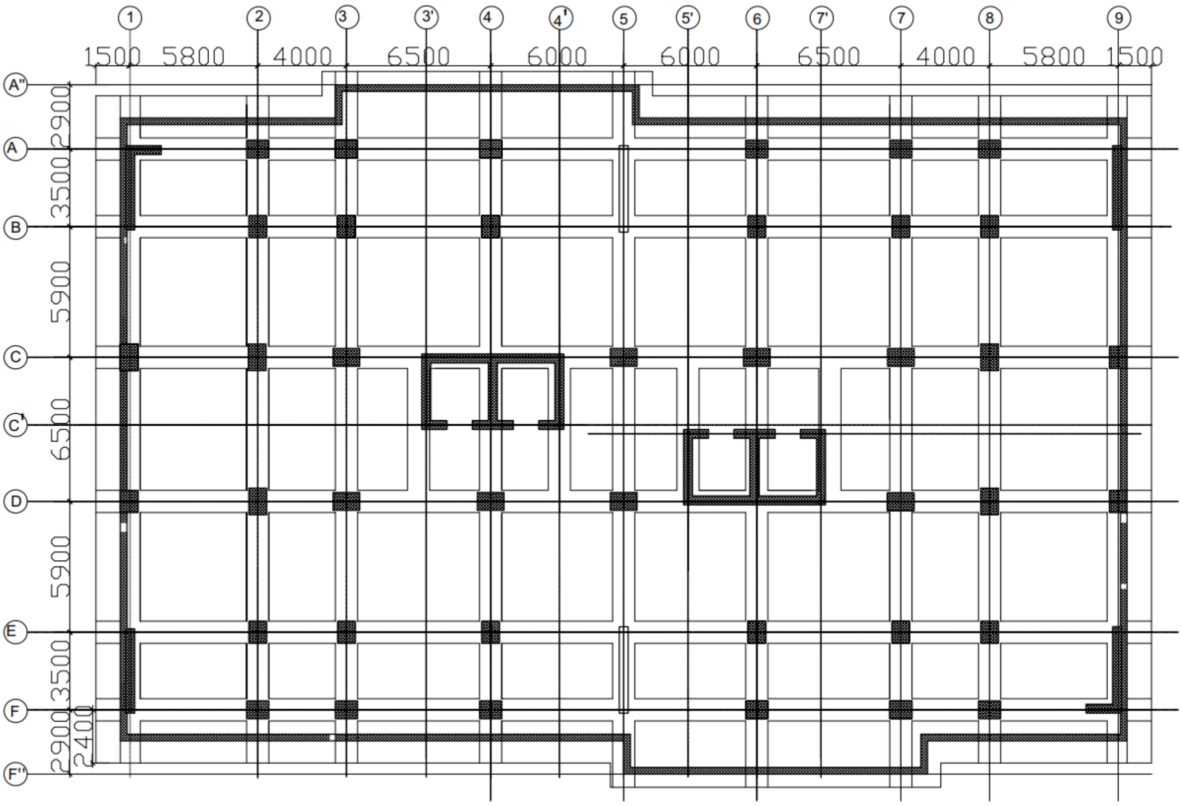


Figure 3.4 Plan view of the case study mat slab

3.3.1 Design strength of concrete and reinforced steel

Concrete

Design of reinforced concrete in Eurocode2 is based on the characteristic cylindrical strength rather than cubic strength, the value of the design compressive strength of concrete is defined as:

$fcd = \alpha ccfck/\gamma c$ $\gamma c=1.5$

αcc is the coefficient taking account of long-term effects on the compressive strength and of unfavourable effects resulting from the way the load is applied and equal to 0.85

The value of the design tensile strength, fctd is defined as fctd = αctfctk, 0.05/ γc

αct is coefficient taking account of long-term effects on the tensile strength and of unfavourable effects, resulting from the way the load is applied and equal to 0.85.

Reinforcement steel

In ES-EN 1992-1-1-2015 section 3.2.2, characteristic strength of reinforcing steel ranges from 400-600 MPa. In this study, 466MPa yield strength is taken for both the longitudinal reinforcement and shear reinforcement.

$fyd = fyk/\gamma s$, $\gamma s = 1.15$

Concrete cover

The concrete cover is the distance between the surfaces of the reinforcement close to the nearest concrete surface which is exposed to external atmosphere. The minimum nominal cover for foundation for this case study has been taken 50mm.

The loads from the original design have been taken from the SAFE Foundation software and the load display are shown in the figure below and the moment and shear forces are tabulated in the Appendix A.2.

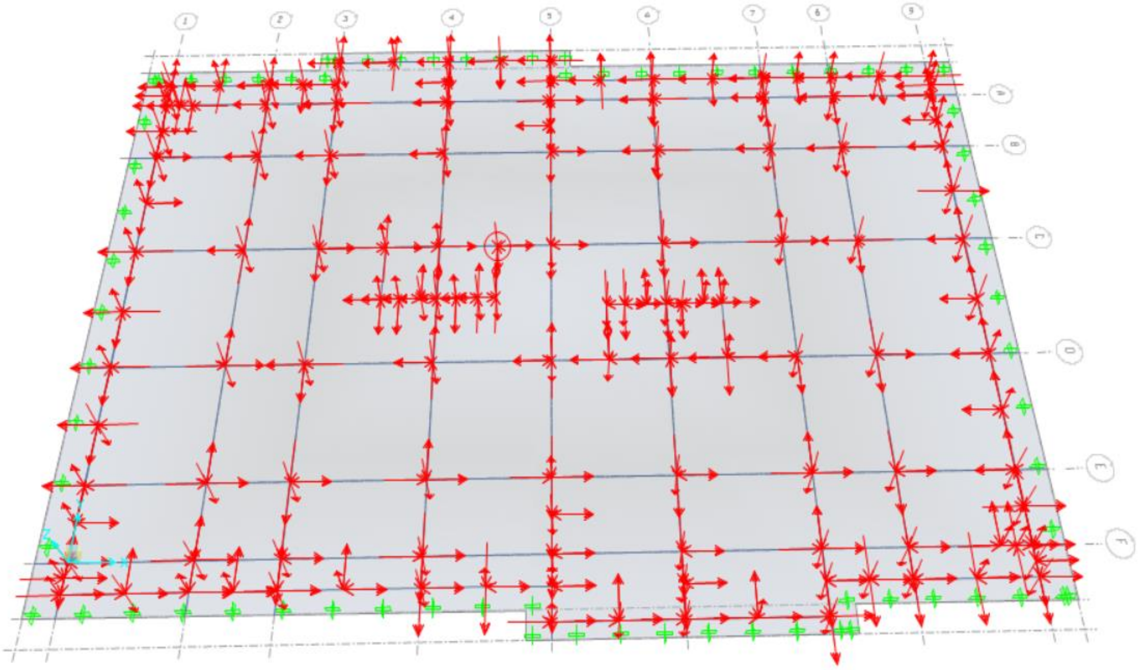


Figure 3.5 Load display form SAFE Foundation software

3.4 Nonlinear Finite Element software

In this study, Nonlinear finite element software called ABAQUS 6.14-5 is used for the analysis of the Mat foundation. The software ABAQUS includes Abaqus CEA, Abaqus viewer, Abaqus standard and Abaqus explicit.

Abaqus CEA is a Complete Abaqus Environment providing an interface for creating, modelling, analysis, and evaluation of result.

Abaqus Viewer provides a graphical display of FE models and results.

Abaqus standard is a solver of a wide range of linear and nonlinear problems including static, dynamic, thermal, electrical, and electromagnetic responses of models.

Abaqus Explicit solve using explicit time integration for nonlinear transient dynamic analysis.

In this study, Abaqus standard has been used for the nonlinear analysis of mat foundation

3.4.1 Modelling of Mat foundation

Modelling and analysis of the mat foundation are described below:

3.4.1.1 Parts (Geometry)

I. Mat Slab and Beam

Mat foundation which has been already designed for 3B+G+21 building contains a beam and slab part of which the slab thickness is 1.2m and the beams are all 2.4m in depth and has been modelled in 3D modelling space as deformable type with solid and extrusion base feature. The mat foundation is shown in the fig below:

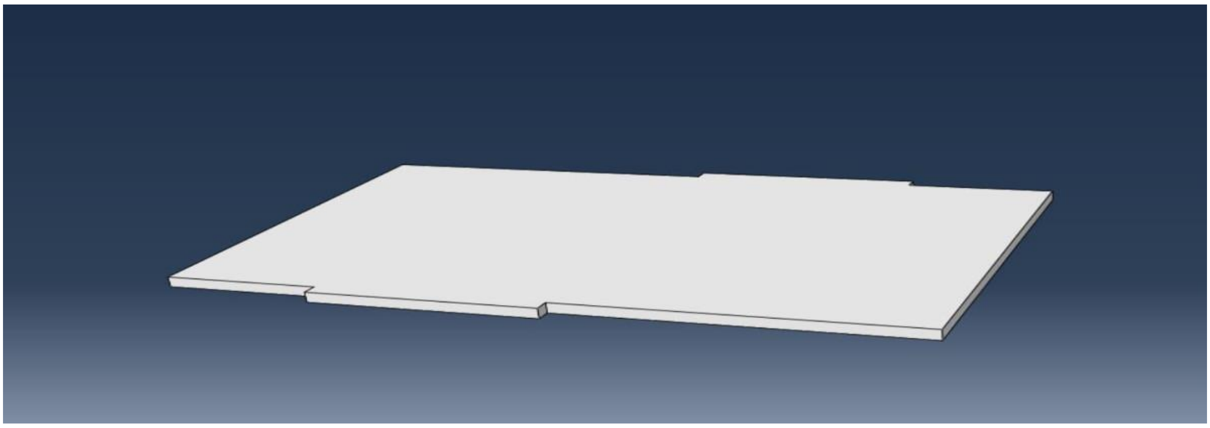


Figure 3.6 Mat foundation model in ABAQUS

II. **Longitudinal Reinforcement Bars**

Longitudinal reinforcement bars were modelled on 3D modelling space as deformable type with wire and planar base feature. The dimensions vary as the length varies. The reinforcement bar is shown in the fig below:

Figure 3.7 Longitudinal Reinforcement Bar

III. Stirrups

Stirrups were modelled on 3D modelling space as deformable type with wire and planar base feature. The dimensions vary as the length varies and it’s shown in figure below:

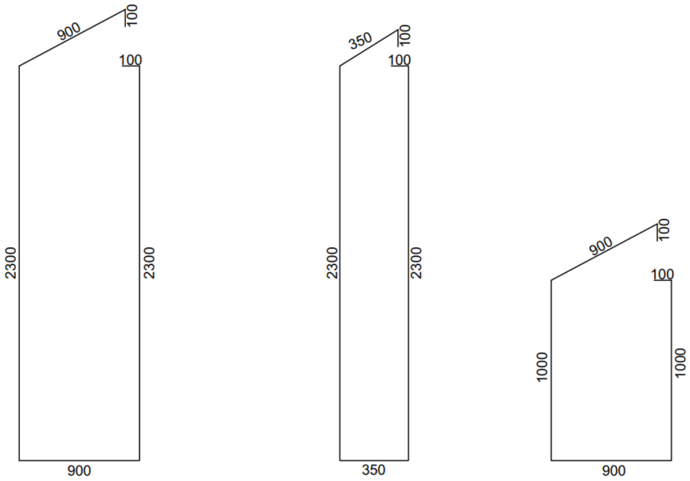


Figure 3.8 Stirrups

IV. Loading plate and support plate

For loading plate steel plates were used at the top of the beams where the columns are in contact with the beam and support plates were used under the mat slab for supporting the plate. Since the plates are not study variables, they have same width and length of the column resting at the points and have thickness of 25mm. the parts where face partitioned for the purpose of support, loading and boundary condition.

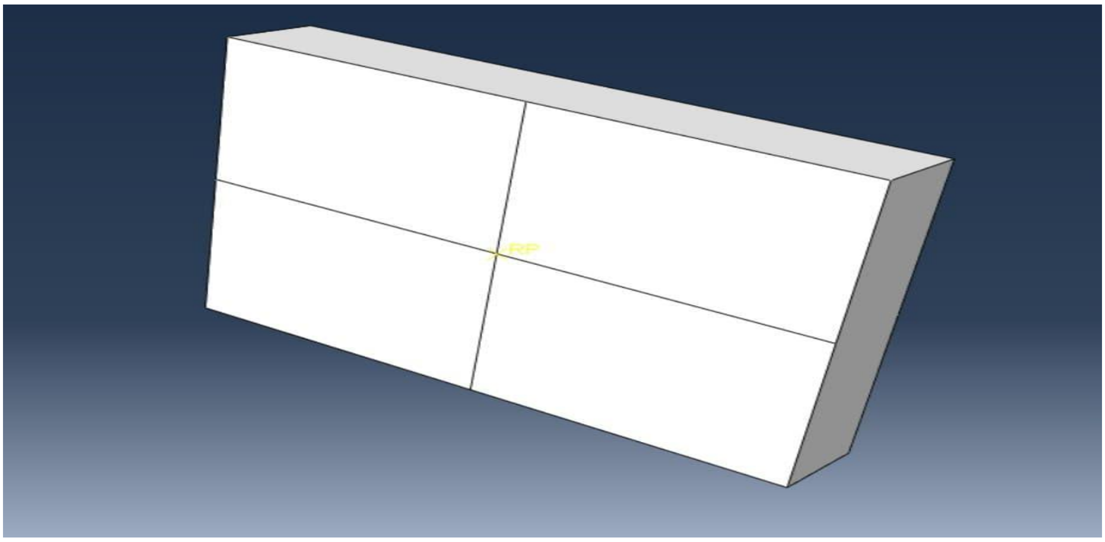


Figure 3.9 Loading plate and Support plate

3.4.1.2 Material property

Concrete

(B. Alfarah a,2017) states that due to micro cracking concrete shows nonlinear stress-strain response which generates failure modes. Stress strain behaviour in tension is characterized by sudden softening go along with reduction in unloading stiffness and in compression failure begins mostly from outside and is more complex involving in crushing and inclined slipping. Stress-strain behaviour involves ductile hardening followed by softening and reduction in the unloading stiffness. Concrete damage plasticity model has shown good performance in capturing concrete behaviour in which it has been tested on practical structures (Houls and Giang D Nguyen, 2007). The unloading response of the concrete specimen is found to be diminished when it is unloaded from any position on the strain-softening branch of the stress-strain curves: the material's elastic stiffness seems to be compromised (or degraded). Between tension and compression testing, the deterioration of elastic stiffness differs substantially. In any instance, the impact becomes more severe as the temperature rises. The degraded response of concrete is characterized by two independent uniaxial damage variables dt and dc which are assumed to be functions of the plastic strain, temperature, and field variables. The uniaxial degradation variables are increasing functions of the equivalent plastic strains. They can take values ranging from zero, for the undamaged material to one for the fully damaged material. If Eo is the initial (undamaged) elastic stiffness of the material, the stress-strain relations under uniaxial tension and compression loading are, respectively: (Abaqus Theory, 2013).

$\sigma_t = (1-d_t)Eo(\varepsilon_t - \varepsilon_t^{pl})$

$\sigma c = (1-dc)Eo(\varepsilon_t - \varepsilon_t^{pl})$

The parameters, which were used in the ABAQUS was discussed in the table 3.3.

Table 3.3 Concrete parameter

Characteristic and cubic strength of concrete $f_{ck}/f_{ck,cube}$ (MPa)	25/30
Modulus of Elasticity (MPa)	31000
Dilation Angle	31 (default)
Eccentricity	0.1 (default)
fb_0/fc_0	1.16 (default)
Constant, Kc	0.6667 (default)
Viscosity	0 (default)
Poisson ratio	0.2 (ES EN 1992-1-1:2013)

Uniaxial compressive strength of concrete

Characteristic and cubic strength of concrete used in this study was 25/30 MPa. In ES EN 1992-1-1: 2015 provides uniaxial compressive stress-strain diagram for nonlinear analysis was used.

$$\frac{\sigma c}{fcm} = \frac{k\eta - \eta 2}{1+(k-2)\eta}$$

Where $\eta = \frac{\varepsilon c}{\varepsilon c1}$, $k = \frac{1.05Ecm|\varepsilon c1|}{fcm}$

where εc1 -peak strain at peak stress Ecm -secant modulus of elasticity of concrete

ε_{cu1} – nominal ultimate strain f_{cm} – mean compressive strength at 28th day

Equation has been provided in ES EN 1992-1-1:2015, Table 3.1 for ε_{c1}, Ecm, f_{cm} and ε_{cu1} which is listed below.

f_{cm} =fck + 8(MPa) Eqn 3-4

$Ecm = 22[(fcm)/10]^{0.3}$ Eqn 3-5

$E_{c1}(\%0) = 0.7fcm^{0.31} \leq 2.8$ Eqn 3-6

ε_{cu1} (%0) =3.5

$0 < |\varepsilon_{cu}| < 3.5$ has been considered. Using the above noted compressive strength each point of the curve for C25/30MPa is presented figure 3.10.

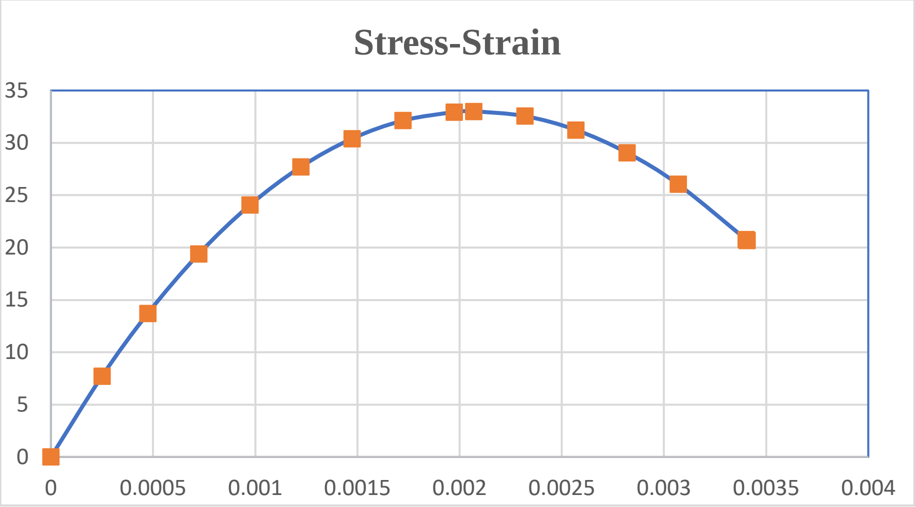


Figure 3.10 Compressive stress-strain diagram for C25/30 Concrete

However, the input data which was used for ABAQUS is compressive stress- crushing strain which was calculated by deducting elastic strain from total strain.

Compressive damage variables (dc)

Based on (B. Alfarah a et al., 2017) proposed methodology and equation the damage variable has been prepared.

$$dc= 1- \frac{1}{2+ac} [\ 2(1+ac) \exp(-bc\varepsilon_c^{ch})-ac \exp(-2bc\varepsilon_c^{ch})]$$

where ε_c^{ch} is compressive crushing strain (inelastic strain).

$$Ac=7.873,\ bc= \frac{1.97\ (fck+8)leq}{Gch}$$

where fck is the cylindrical compressive strength of concrete

leq is the characteristic length of the element

Gch is crushing energies

$$Gch =(\frac{ftm}{ftm})^2\ Gf$$

$$fcm\ (MPa) = 0.073fcm^{0.18}$$

The compressive damage variable crushing strain is shown below in figure calculated using the above equations.

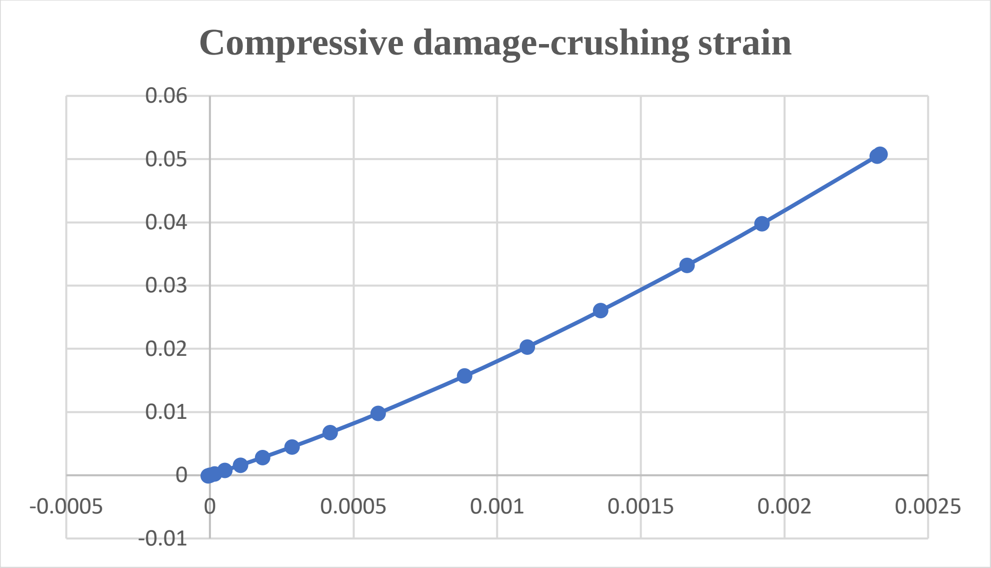


Figure 3.11 compressive damage – crushing strain diagram of concrete

Concrete Tensile strength

For tensile behaviour equation given on Hordijk (Lantsoght et al., 2016), the ratio of tensile stress (w) for crack width ‘w’, and maximum tensile strength ftm is given below:

$$\frac{\sigma t(w)}{ftm}[1+\left(c1\left(\frac{w}{wc}\right)^{3}\right]e^{-c1\left(\frac{w}{wc}\right)} \; -\frac{w}{wc}(1+c1^{3})e^{-c1}$$

In equation 3-8, c1=3, c2=6.93 (Lantsoght, et al., 2016) and wc is the critical crack opening. The equation 3-12 shows that σt(0)=ftm and σt(wc)=0. Therefore, wc can be considered as the fracture crack opening (B. Alfarah a et al., 2017).

Wc $=\frac{5.14Gf}{ftm}$ ftm = 0.3016fck$^{2/3}$

The exact crack spacing was not examined in this suggested approach, but a single crack per element was assumed. The assumption is acceptable for global-purpose simulation, according to Alfarah et al. Following this assumption, the strain in terms of crack opening may be calculated using the kinematic relation below in the descending portion of the tensile stress-strain curve. (B. Alfarah a el al., 2017).

εt = εtm + $\frac{W}{leq}$

The tensile stress-strain of concrete was calculated, tabulated, and displayed in appendix A using the method described above. Figure below, on the other hand, depicts the stress-cracking strain that was utilized as input data for the program. By subtracting elastic strain from total strain, cracking strain was determined.

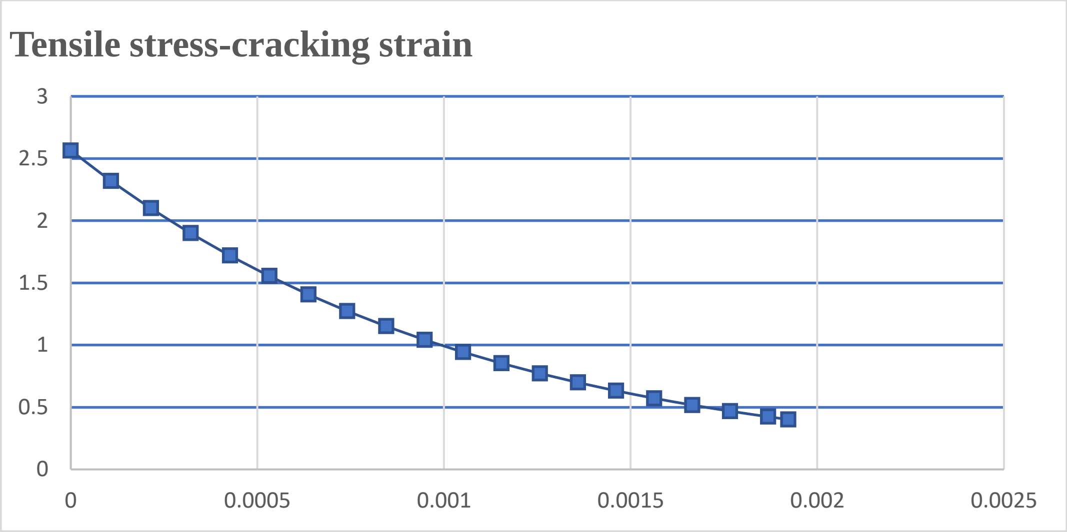


Figure 3.12 Concrete tensile stress- cracking strain diagram

Tensile damage variables

As discussed in compressive damage variable the method used is applied here for tensile damage variables described below:

$$dc= 1- \frac{1}{2+at} [2(1+ac) \exp(-bc\varepsilon_c^{ck})-ac \exp(-2bc\varepsilon_c^{ck})]$$

Where: εt^{ck} is tensile cracking strain (inelastic strain).

$$a_t = 1,\ bt = \frac{0.453 fck^{0.667}}{Gf} leq$$

Using the above equations, the tensile damage variables were calculated and tabulated. The table is presented in appendix A but the tensile damage variables- cracking strain is shown in figure below.

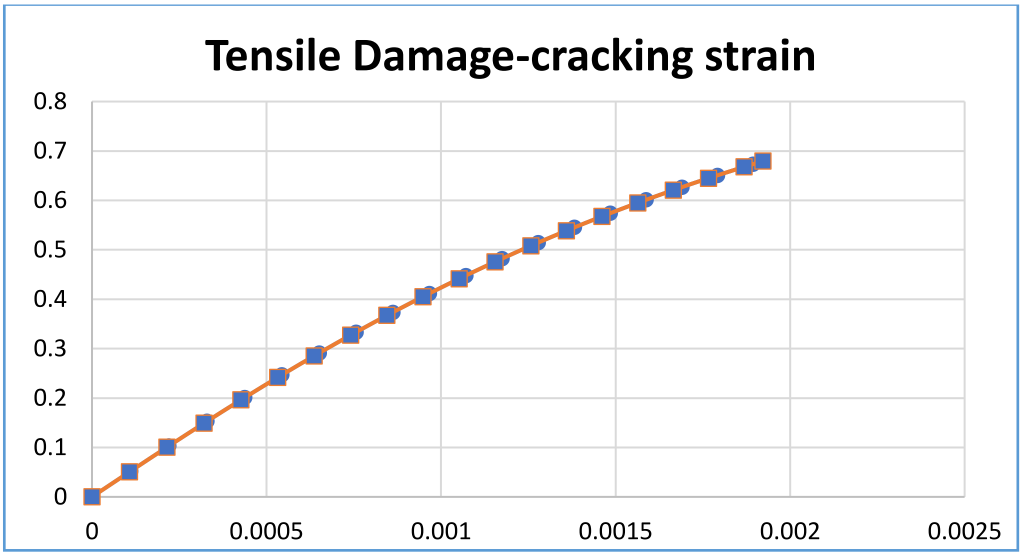


Figure 3.13 Tensile damage- cracking strain diagram of concrete

Reinforcing steel

Youngu's modulus Es=221Gpa and a Poisson ratio of 0.3 were used for all the following steels. The 3.8.2 data for steel was derived from a study by Christina Claeson1 and Kent Gylltoff (Christina Claeson1 and Kent Gylltoff, 1998), as stated at the beginning of this section. Steel reinforcement was provided using deformed Swedish type Ks40S bars. Figure and table show the mechanical characteristics of the steel reinforcement.

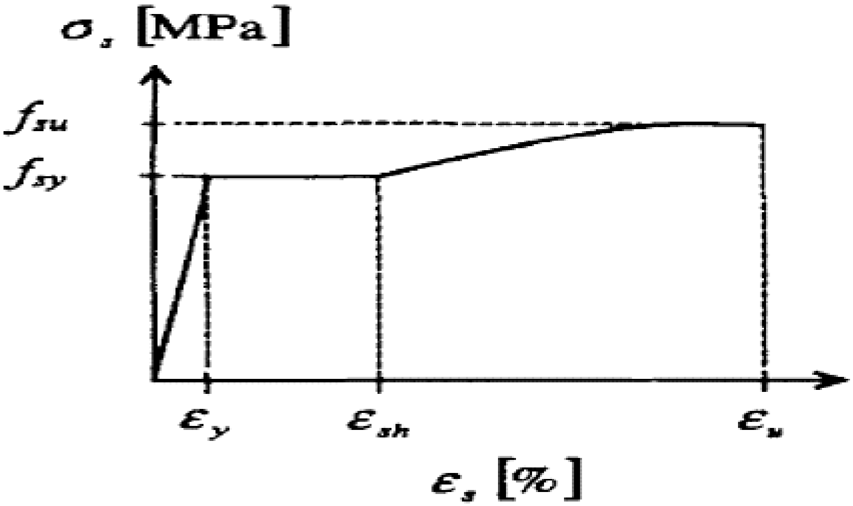


Figure 3.14 Mechanical property of reinforcement bars.

Table 3.4 Mechanical property of reinforcement bars

Type	As (mm)2	fsy (MPa)	fsu (MPa)	ε_{sh} %	ε_u %	Es (GPa)
Ks40S	50	466	620	4.0	12	221

Input data used for the software was true stress-logarithmic plastic strain. The following equation was used to calculate real stress and logarithmic plastic strain from nominal stress and nominal strain:

σ_{true} = σnom (1+εnom)

ε_{ln}^{pl} ln(1+εnom) - $\frac{\sigma true}{E}$

Using nominal stress and strain, true stress and logarithmic plastic strain was computed and tabulated in appendix A but the diagram is shown in figure 3.15.

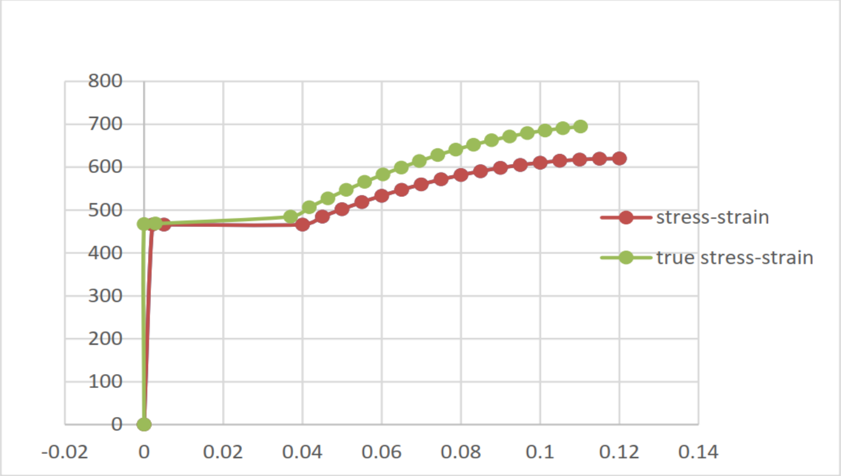


Figure 3.15 Stress-strain and true stress-logarithmic plastic strain of reinforcing steel

3.4.1.3 Part Assembly and their Interaction

After defining the material properties, profiles and sections were created and designed for the individual parts; for all parts, instances were created and assembled to their relative position. Dependent instance was used for all parts.

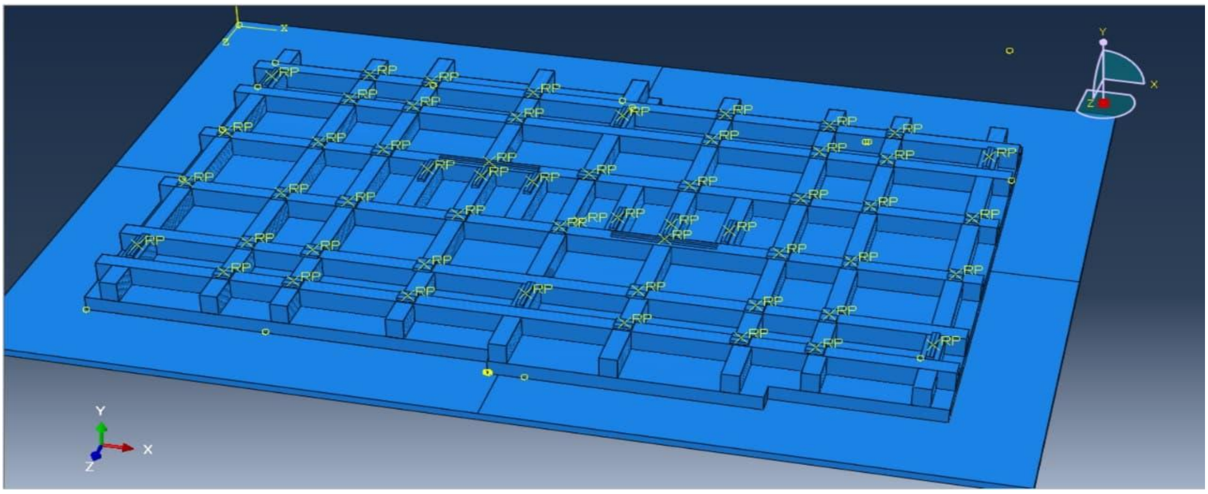


Figure 3.16 Assembled Mat Foundation with its beam using ABAQUS

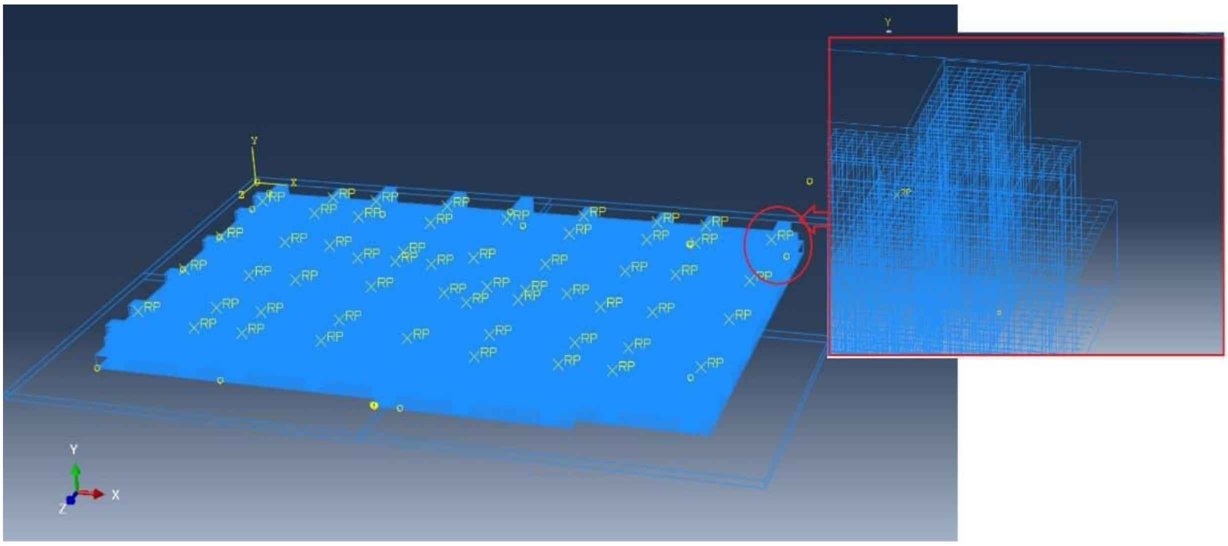


Figure 3.17 Assembled longitudinal bars, stirrups and loading plates

In the model reinforcement bars are embedded region constraints was used by considering the reinforcement bars as embedded parts and the concrete as a host. However, for the loading plates the connection was surface to surface contact interaction has been used in which the steel plate as a master and the concrete beams as slave. This constraint makes the steel plate act as discrete rigid object and prevents local deformation due to applied loading and supporting reaction on its surface.

3.4.1.4 Meshing

Meshing is the critical part of finite element analysis which helps reduce the number of degrees of freedom from infinite to finite. Meshing is dividing the parts into small but finite parts where each piece represents an element. The accuracy of the finite element analysis is increases as the elements gets finer (smaller) in which the analysis is interpolated to give the most accurate solution of the main structure.

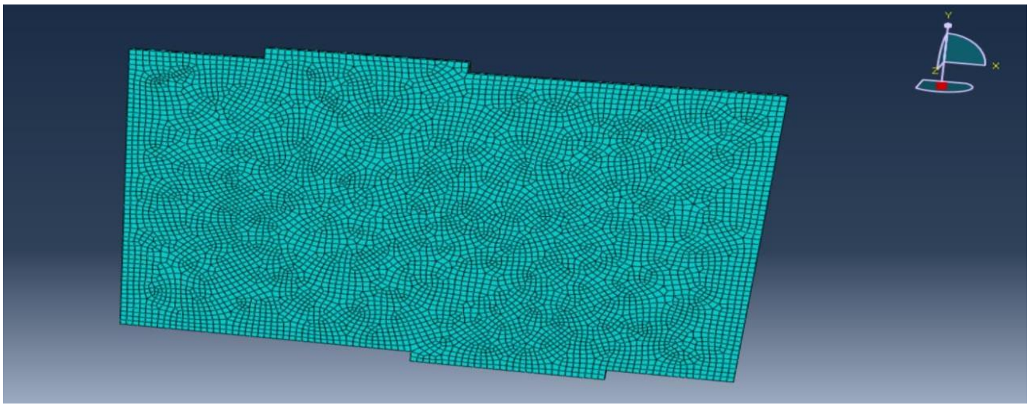


Figure 3.18 Meshing of parts

3.5 Validation

This validation was done to check the workability of the software ABAQUS with reinforced concrete design by remodelling the existing mat foundation, which have been done originally in a commercially used Safe Foundation software, for the loading purposes later to be used in the formulation of objective function and design constraints in MATLAB optimization toolbox.

3.5.1 Reference experiment

Validation of the software was done by comparing the result of previously done experimental research on beams by T. Tejaswini on the paper Analysis of RCC beams using Abaqus.

T. Tejaswini, 2015 conducted a study on RCC Beam dimension of 1200 x 200 x 100 of M30 grade concrete with under, balanced and over reinforced sections and Finite Element Analysis (FEA) have also been performed using ABAQUS. In the validation experiment it has been used the balanced reinforcement which has been casted with 2- ø12, 2- ø8 bars at bottom and 2- ø8 hanger bars and ø8@ 135c/c stirrups are provided.

In the experimental study of the RCC beam it has been calculated the deflection vs load applied and it has been shown in table 3.5.

Table 3.5 Load and corresponding deflection for a balanced section

Load (KN)	Deflection
20	1.25
40	2.35
60	3.56
80	4.65
88.8 (Ultimate)	5.2

In T, Tejaswini research the experimental study Vs ABAQUS result were 88.8KN and 78.4KN respectively.

3.6 Optimization

3.6.1 Load on the mat foundation slab and beam sections

In designing reinforced concrete structure, the most effected panels are the longest span to span length of slabs and beams in our case study the longest beam length is 6.5m located from 9.8-16.3m and 28.3-34.8m in the longer span direction and the largest spans of slabs are 5.5x4.8m length and width respectively. Loads on beams and slab panels are listed below:

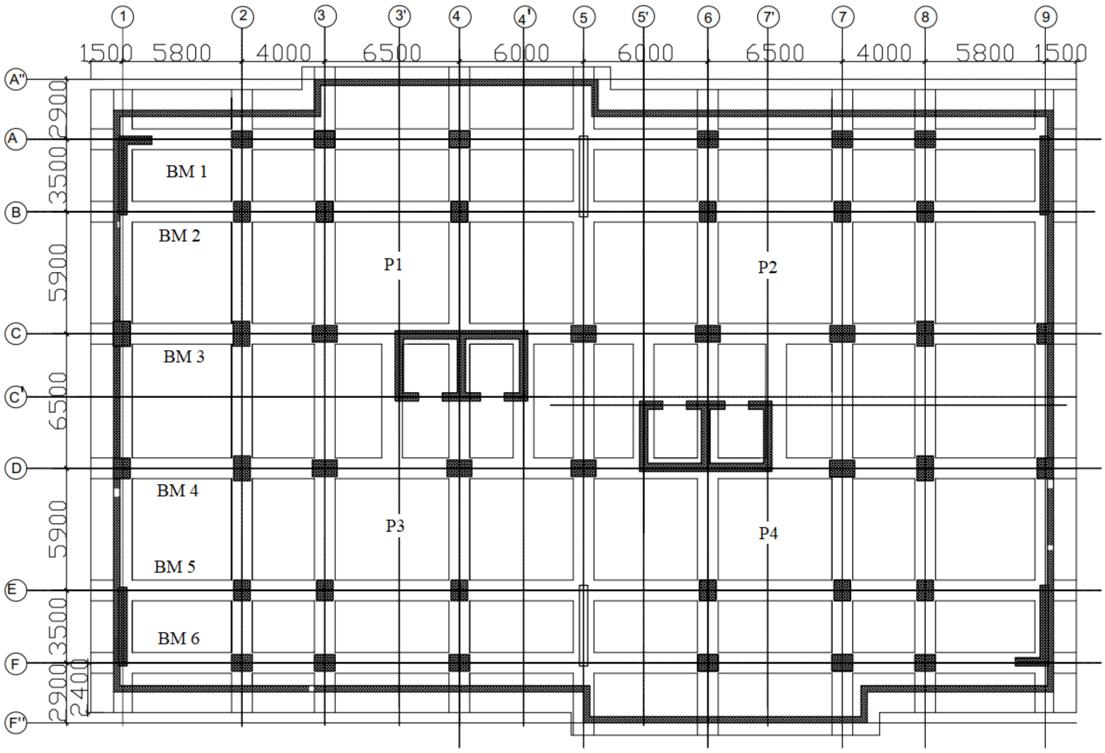


Figure 3.19 Slab panels and beam of the longest spans layout

Table 3.6 Maximum Moment and Shear forces on beams

Beam (m)	Location (m)	Max Moment (KN-m)	Max Shear (KN)
BM1- 1x2.4	11.3	4814.8794	2404.137
BM1 -1x2.4	29.8	2784.8389	2063.477
BM2 -1x2.4	11.3	6579.4204	3365.518
BM2 -1x2.4	29.8	6394.4141	3287.823
BM3 -1x2.4	11.3	4879.9702	3179.692
BM3 -1x2.4	29.8	4358.5957	1756.984
BM4 -1x2.4	14.9	4898.1938	3045.455
BM4 -1x2.4	29.8	6420.3164	3168.539
BM5- 1x2.4	11.3	4828.21	3090.264
BM5 -1x2.4	36.3	6149.9312	3329.831
BM6 -1x2.4	11.3	2688.9763	1971.231
BM6 - 1x2.4	36.3	4692.1733	2403.912

Table 3.7 Maximum top and bottom moment on slab

Panel	Direction	Max Top Moment (KN-m)	Max Bottom Moment (KN-m)
P1	Short	-745.2195	605.0936
P1	Long	-310.6944	1394.8662
P2	Short	-716.6424	451.8846
P2	Long	-554.434	1166.4778
P3	Short	-709.3483	1228.3608
P3	Long	-535.1248	1780.8226
P4	Short	-766.4835	1385.411
P4	Long	-567.7619	1518.9607

3.6.2 Initialization values for design variables

To start the algorithm, it needs a feasible starting point. If the point provided is not feasible, then using linear programming solution can be found. This feasible point is the initial value for design variables. For the purpose of this study, the upper values for decision variables (cross-sectional dimensions of structural elements) are taken from the case study under consideration and the initial values have been used as per ES EN 1992-1-1-2015. Accordingly, the initial lower and upper bound values of the cross-sectional dimensions of the structure is given bellow in the table. The quantities initial value (x0), lower bound (LB) and upper bound (UB) are arguments in fmincon in MATLAB solver and the quantities are given in the following table.

Table 3.8 Initial, Lower and Upper bound values for the design variable

Structural Element	Design variable	Initial Value (mm)	Lower bound (mm)	Upper bound (mm)
Beam	Width	800	800	1000
	Effective Depth	1000	500	2400
	Stirrup Spacing	100	100	600
	Ast (mm^2)	0	0	6328
	Asc (mm^2)	0	0	6328
	Av (mm^2)	0	0	3660
Slab	Effective depth	500	500	1200
	Spacing	100	100	400
	As (top) (mm^2)	0	0	1667
	As (bottom) (mm^2)	0	0	1667

3.6.3 Formulation of 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 beam and slab.

3.6.3.1 Solution for formulated optimization problems using MATLAB Optimization toolbox

The optimization problems formulated for beams and slab were solved by using optimization tool box in MATLAB. Beams where targeted for the longest spans having higher bending moments and shear forces and for the slab was targeted for the longest span to span length having the maximum moment. The formulated optimization problems were solved through the following seps.

1. Creating M-file for objective and constraint functions

2. Running optimization for obtaining optimum solution for design variables

For this case study objective functions and constraints for the beams and for the slab functions having same objective with different constraints are stated below.

M file for objective function for beams

An m-file is a text file with the extension “.m” containing MATLAB commands which can be created in any text editor, or using the built in MATLAB editor. For the objective function of beams is written in M-file as shown below.

function f=beam(x)

```
f=8.25*Bb*db+0.495*Bb-1.925*Ast-1.925*Asc-3.85*Av*Bb/S-3.85*Av*db/S
+(0.639*Av)/S-(29.057Av^1.5/S-0.7*Av*Bb-0.7*Av*db-27.97*Av-3.158*Av^1.5;
```

```
f=8.25*x(1)*x(2)+0.495*x(1)-1.925*x(3)-1.925*x(4)-3.85*x(5)*x(1)/x(6)-3.85*x(5)*x(1))/
x(6)+(0.639*x(5))/x(6)-(29.057x(5)^1.5)/x(6)-0.7*x(5)*x(1)-0.7*x(5)*x(2)-27.97*x(5)-
3.158*x(5)^1.5;
```

M-file for constraint functions for beams

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 beam is written in M-file as shown below.

Function [c, *ceq*]=constraint(x)

```
c(1)=Md*10^3-4.175* Bb*db^2-466*db*Asc+27.96*Asc;
```

```
c(2)= Vd*10^3-7.646*Bb*db;
c(3)= Vd*10^3-(364.5Av*db/S+(18.78 *Av/S);
c(4)= 0.00145*Bb*db-Asc;
c(5)= 0.00145*Bb*db-Ast;
c(6)= 0.0013*Bb*db-Asc;
c(7)= 0.0013*Bb*db-Ast;
c(8)= Asc-0.04*Bb*db-0.0024*Bb;
c(9)= Ast-0.04*Bb*db-0.0024*Bb;
c(10)= S-0.75*x(2);
c(11)= S -600;
ceq = [];
```

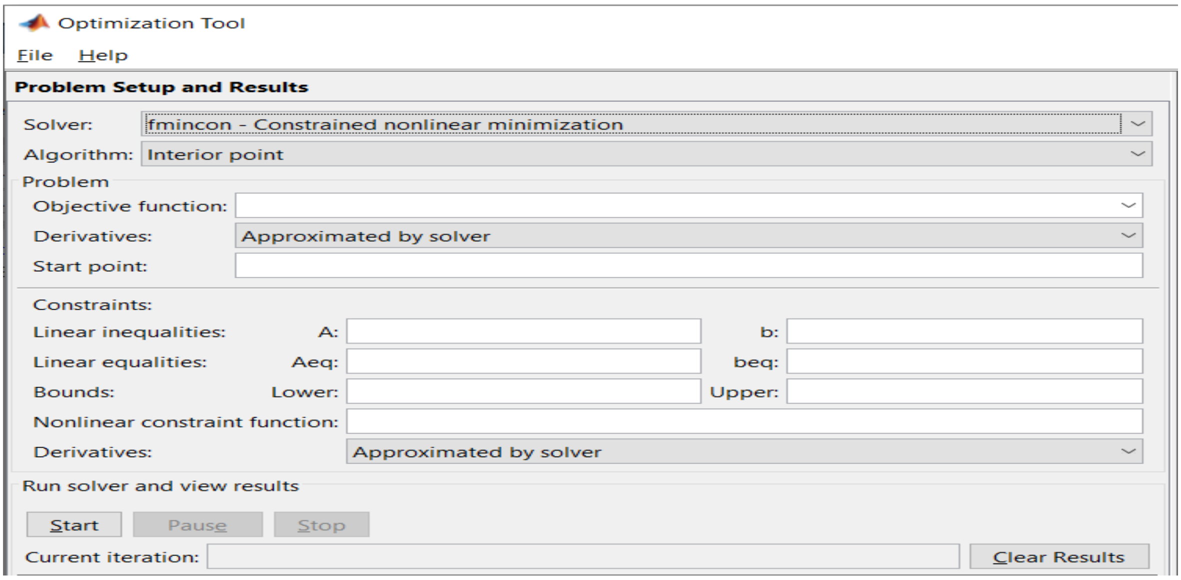
Therefore, the constraint function for beam is:

```
c(1)=6579.42*10^3-4.175* x(1)*x(2)^2-466*x(2)*x(4)+27.96*x(4);
c(2)= 3365.518*10^3-7.646*x(1)*x(2);
c(3)= 3365.518*10^3-(364.5x(5)*x(2))/x(6)+(18.78 *x(5))/x(6);
c(4)= 0.00145*x(1)*x(2)-x(3);
c(5)= 0.00145*x(1)*x(2)-x(4);
c(6)= 0.0013*x(1)*x(2)-x(3);
c(7)= 0.0013*x(1)*x(2)-x(4);
c(8)= x(3)-0.04*x(1)*x(2)-0.0024*x(1);
c(9)= x(4)-0.04*x(1)*x(2)-0.0024*x(1);
c(10)= x(6)-0.75*x(2);
c(11)= x(6)-600;
ceq = [];
```

The constraint function for the beam were written by selecting the longest beam section ranging from 9.8-16.3m and 28.3-34.8m which is 6.5m long beam having the maximum shear force and bending moment.

Running the optimization in Optimization toolbox

By crating m. file for objective function and for the constraints as a script file separate files then by opening the optimization tool box app from the selectable apps available we can insert the values.



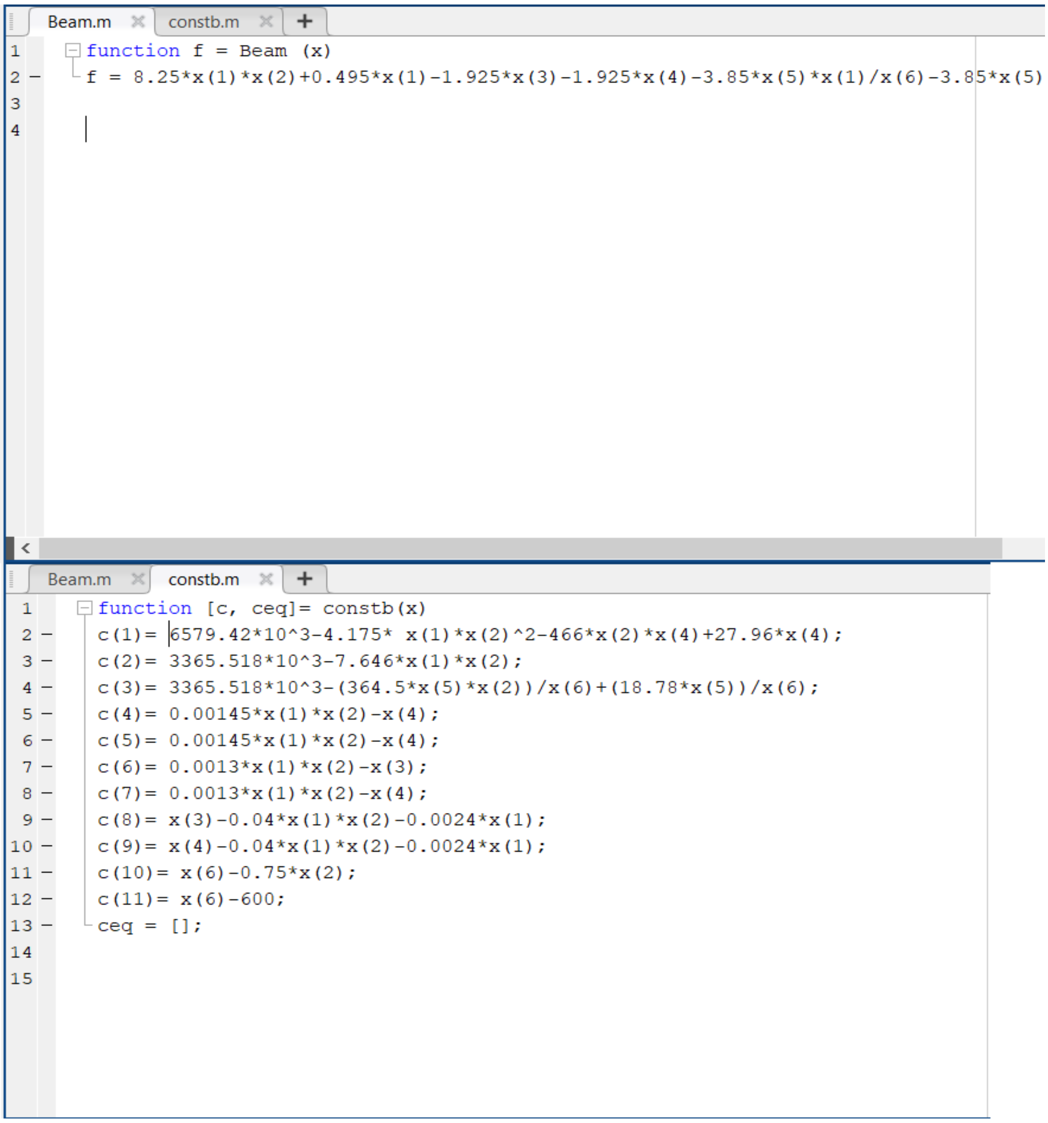
Solver: fmincon - Constrained nonlinear minimization

Algorithm: Interior point

Derivatives: Approximated by solver

Derivatives: Approximated by solver

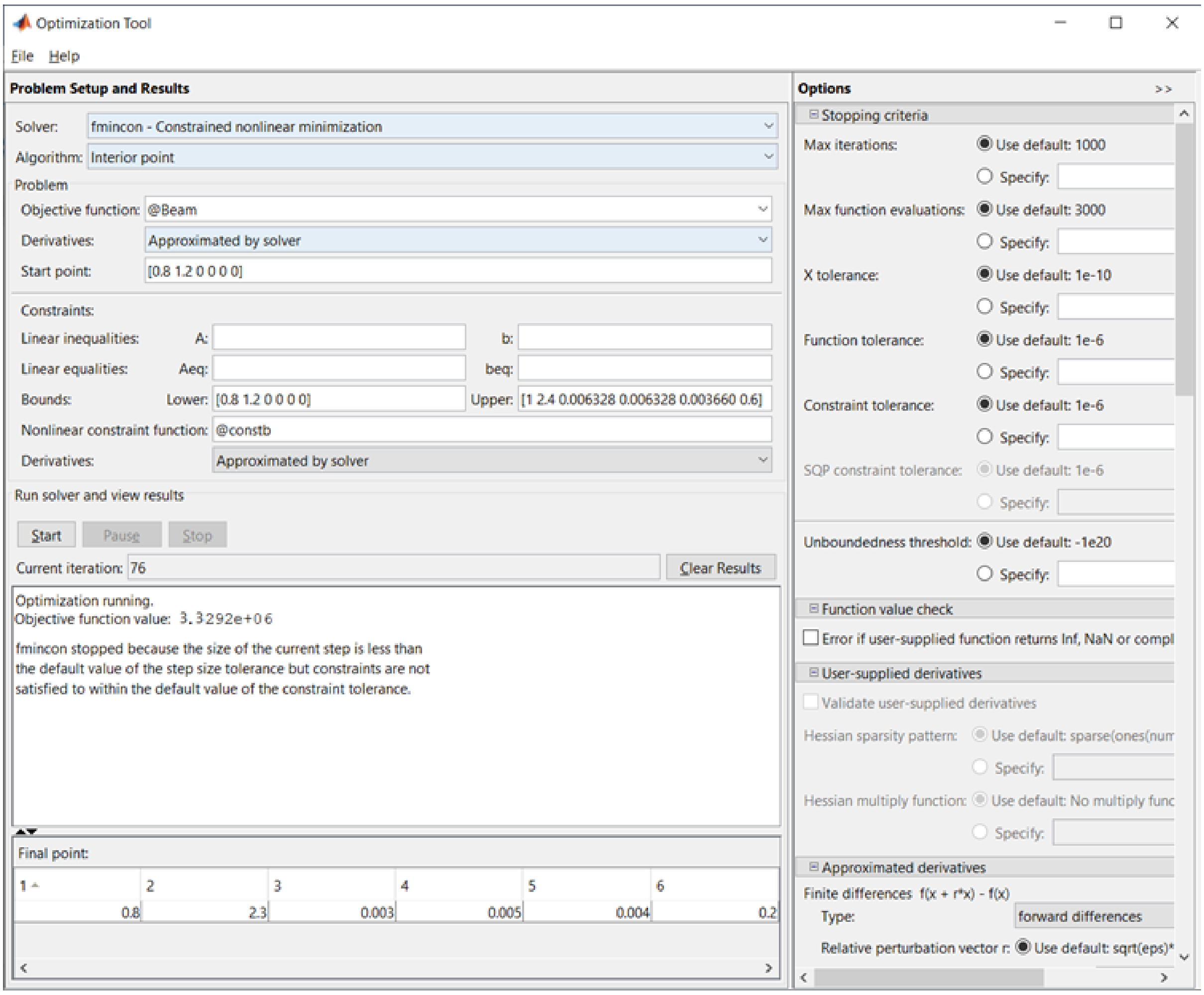
Figure 3.20 MATLAB optimization tool box window



```
function f = Beam (x)
f = 8.25*x(1)*x(2)+0.495*x(1)-1.925*x(3)-1.925*x(4)-3.85*x(5)*x(1)/x(6)-3.85*x(5)
```

```
function [c, ceq]= constb(x)
c(1)= 6579.42*10^3-4.175* x(1)*x(2)^2-466*x(2)*x(4)+27.96*x(4);
c(2)= 3365.518*10^3-7.646*x(1)*x(2);
c(3)= 3365.518*10^3-(364.5*x(5)*x(2))/x(6)+(18.78*x(5))/x(6);
c(4)= 0.00145*x(1)*x(2)-x(4);
c(5)= 0.00145*x(1)*x(2)-x(4);
c(6)= 0.0013*x(1)*x(2)-x(3);
c(7)= 0.0013*x(1)*x(2)-x(4);
c(8)= x(3)-0.04*x(1)*x(2)-0.0024*x(1);
c(9)= x(4)-0.04*x(1)*x(2)-0.0024*x(1);
c(10)= x(6)-0.75*x(2);
c(11)= x(6)-600;
ceq = [];
```

Figure 3.21 m. files for objective function and constraints for beam



Solver: fmincon - Constrained nonlinear minimization
Algorithm: Interior point
Problem
Objective function: @Beam
Derivatives: Approximated by solver
Start point: [0.8 1.2 0 0 0 0]
Constraints:
Linear inequalities: A: b:
Linear equalities: Aeq: beq:
Bounds: Lower: [0.8 1.2 0 0 0 0] Upper: [1 2.4 0.006328 0.006328 0.003660 0.6]
Nonlinear constraint function: @constb
Derivatives: Approximated by solver
Run solver and view results
Current iteration: 76

```
Optimization running.
Objective function value: 3.3292e+06
fmincon stopped because the size of the current step is less than
the default value of the step size tolerance but constraints are not
satisfied to within the default value of the constraint tolerance.
```

Final point:

1	2	3	4	5	6
0.8	2.3	0.003	0.005	0.004	0.2

Stopping criteria
Max iterations: ● Use default: 1000 ○ Specify:
Max function evaluations: ● Use default: 3000 ○ Specify:
X tolerance: ● Use default: 1e-10 ○ Specify:
Function tolerance: ● Use default: 1e-6 ○ Specify:
Constraint tolerance: ● Use default: 1e-6 ○ Specify:
SQP constraint tolerance: ○ Use default: 1e-6 ○ Specify:
Unboundedness threshold: ● Use default: -1e20 ○ Specify:
Function value check
☐ Error if user-supplied function returns Inf, NaN or compl
User-supplied derivatives
☐ Validate user-supplied derivatives
Hessian sparsity pattern: ○ Use default: sparse(ones(num ○ Specify:
Hessian multiply function: ○ Use default: No multiply func ○ Specify:
Approximated derivatives
Finite differences f(x + r*x) - f(x)
Type: forward differences
Relative perturbation vector r: ● Use default: sqrt(eps)*

Figure 3.22 Graphical user interface of optimization toolbox for beam

M file for objective function for Slab

The objective function of slab is written in M-file as shown below.

function f=slab(x)

f= 39.6*ds+1.99+(10.587*Asl/S)-1.925Asl-(38.705*Ass/S)-8.064*Ass;

f= 39.6*x(1)+1.99+(10.587*x(2)/x(4))-1.925x(2)-(38.705*x(3)/x(4))-8.064*x(3);

M-file for constraint functions for Maximum Top slab

Function [c, *ceq*]=constraint(x)

c(1)= Medl-405.42*Asl*ds-7254.828*Asl;

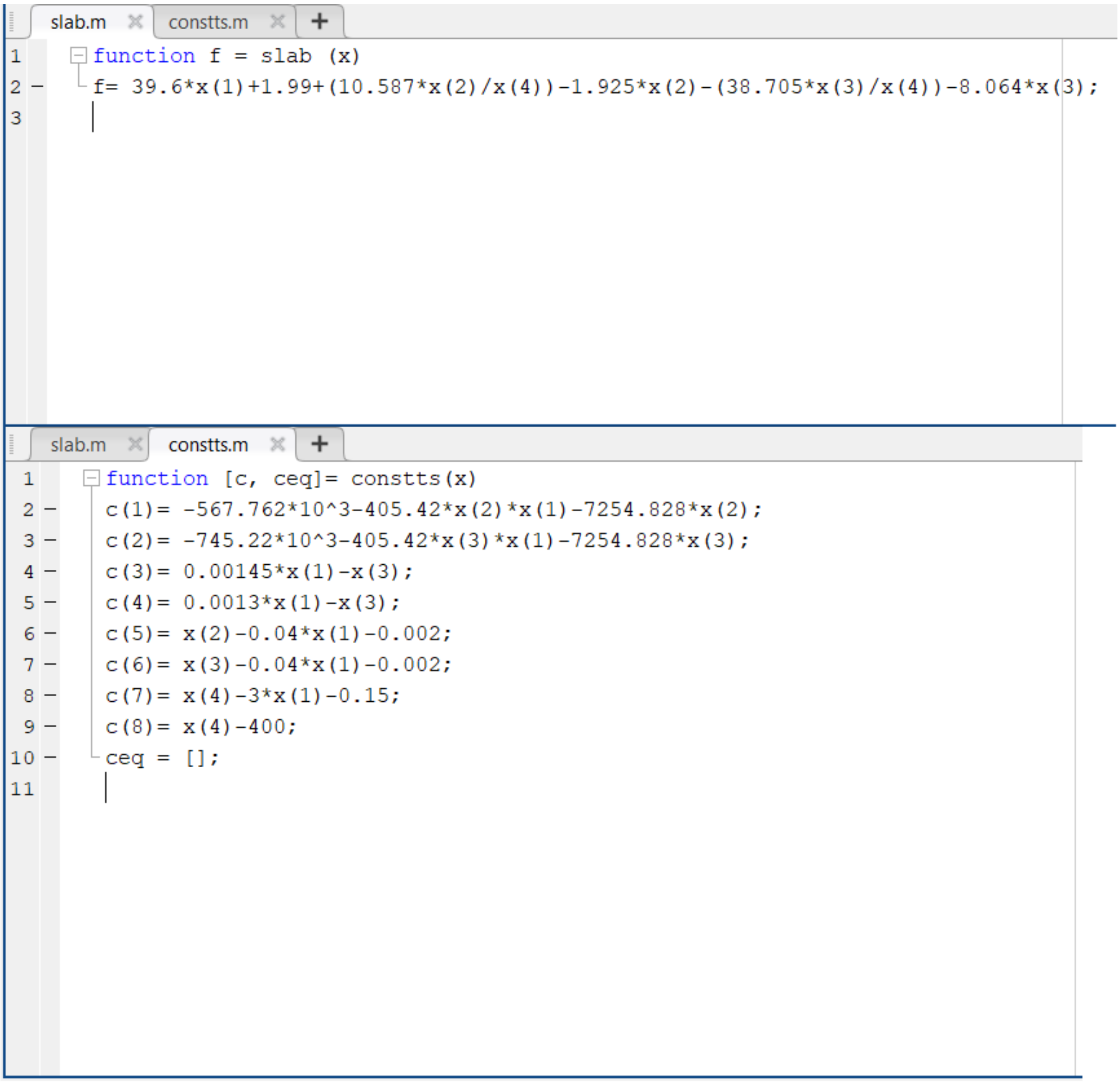
c(2)= Meds-405.42*Ass*ds-7254.828*Ass;

c(3)= 0.00145*ds-Ass;

```
c(4)= 0.0013*ds-Ass;
c(5)= Asl-0.04*ds-0.002;
c(6)= Ass-0.04*ds-0.002;
c(7)= S-3*ds-0.15;
c(8)= S-400;
ceq = [];
```

Therefore, constraint functions are:

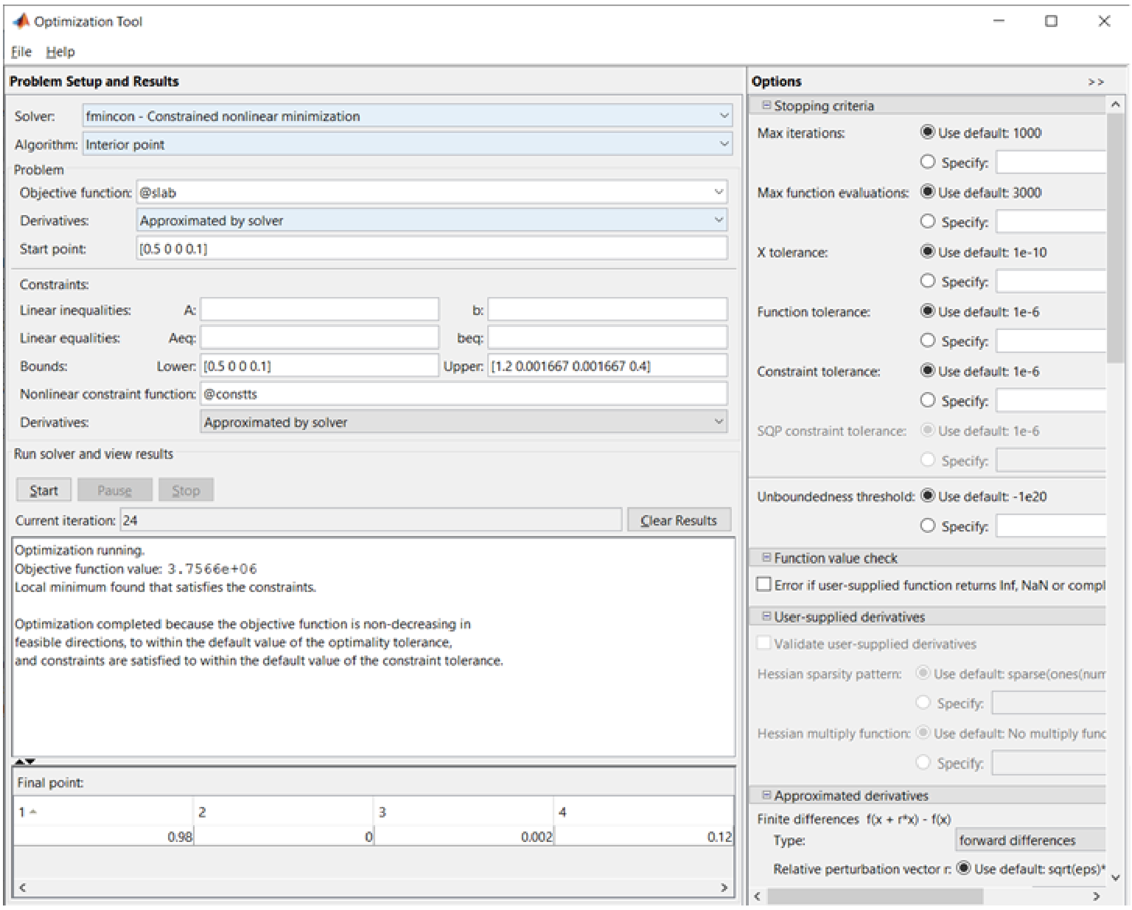
```
c(1)= -567.762*10^3-405.42*x(2)*x(1)-7254.828*x(2);
c(2)= -745.22*10^3-405.42*x(3)x(1)-7254.828*x(3);
c(3)= 0.00145*x(1)-x(3);
c(4)= 0.0013*x(1)-x(3);
c(5)= x(2)-0.04*x(1)-0.002;
c(6)= x(3)-0.04*x(1)-0.002;
c(7)= x(4)-3*x(1)-0.15;
c(8)= x(4)-400;
ceq = [];
```



```
function f = slab (x)
f= 39.6*x(1)+1.99+(10.587*x(2)/x(4))-1.925*x(2)-(38.705*x(3)/x(4))-8.064*x(3);
```

```
function [c, ceq]= constts(x)
c(1)= -567.762*10^3-405.42*x(2)*x(1)-7254.828*x(2);
c(2)= -745.22*10^3-405.42*x(3)*x(1)-7254.828*x(3);
c(3)= 0.00145*x(1)-x(3);
c(4)= 0.0013*x(1)-x(3);
c(5)= x(2)-0.04*x(1)-0.002;
c(6)= x(3)-0.04*x(1)-0.002;
c(7)= x(4)-3*x(1)-0.15;
c(8)= x(4)-400;
ceq = [];
```

Figure 3.23 m. files for objective function and constraints for top slab



Solver: fmincon - Constrained nonlinear minimization
Algorithm: Interior point

Problem
Objective function: @slab
Derivatives: Approximated by solver
Start point: [0.5 0 0 0.1]

Constraints:
Linear inequalities: A: b:
Linear equalities: Aeq: beq:
Bounds: Lower: [0.5 0 0 0.1] Upper: [1.2 0.001667 0.001667 0.4]
Nonlinear constraint function: @constts
Derivatives: Approximated by solver

Run solver and view results
Current iteration: 24

```
Optimization running.
Objective function value: 3.7566e+06
Local minimum found that satisfies the constraints.

Optimization completed because the objective function is non-decreasing in
feasible directions, to within the default value of the optimality tolerance,
and constraints are satisfied to within the default value of the constraint tolerance.
```

Final point:

1	2	3	4
0.98	0	0.002	0.12

Stopping criteria
Max iterations: ● Use default: 1000 ○ Specify:
Max function evaluations: ● Use default: 3000 ○ Specify:
X tolerance: ● Use default: 1e-10 ○ Specify:
Function tolerance: ● Use default: 1e-6 ○ Specify:
Constraint tolerance: ● Use default: 1e-6 ○ Specify:
SQP constraint tolerance: ● Use default: 1e-6 ○ Specify:
Unboundedness threshold: ● Use default: -1e20 ○ Specify:

Function value check
☐ Error if user-supplied function returns Inf, NaN or compl

User-supplied derivatives
☐ Validate user-supplied derivatives
Hessian sparsity pattern: ● Use default: sparse(ones(num ○ Specify:
Hessian multiply function: ● Use default: No multiply func ○ Specify:

Approximated derivatives
Finite differences f(x + r*x) - f(x)
Type: forward differences
Relative perturbation vector r: ● Use default: sqrt(eps)*

Figure 3.24 Graphical user interface of optimization toolbox for top slab

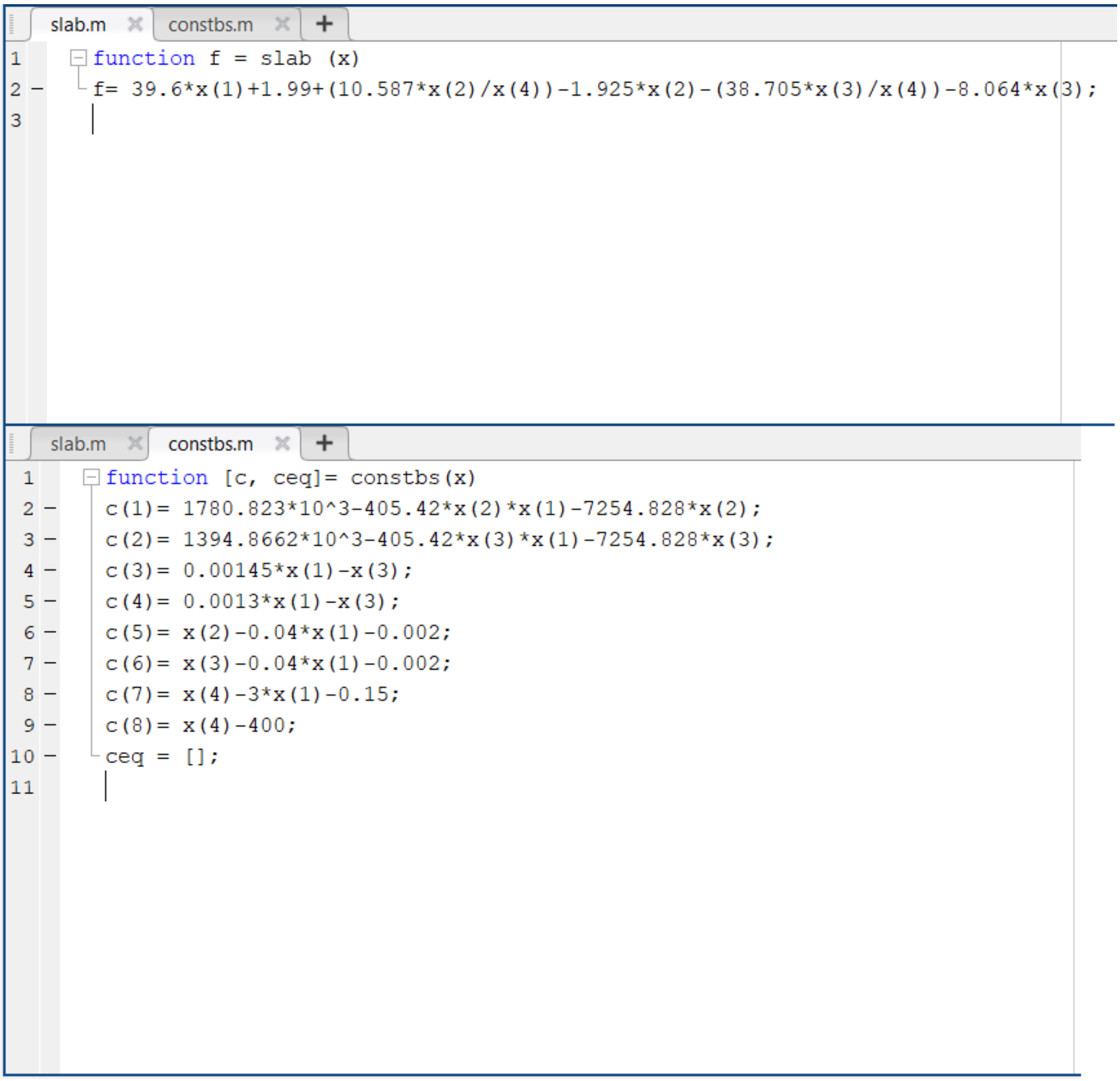
M-file for constraint functions for Maximum Bottom slab

Function [c, *ceq*]=constraint(x)

```
c(1)= 1780.823*10^3-405.42*x(2)x(1)-7254.828*x(2);

c(2)= 1394.8662*10^3-405.42*x(3)*x(1)-7254.828*x(3);

c(3)= 0.00145*x(1)-x(3);

c(4)= 0.0013*x(1)-x(3);

c(5)= x(2)-0.04*x(1)-0.002;

c(6)= x(3)-0.04*x(1)-0.002;

c(7)= x(4)-3*x(1)-0.15;

c(8)= x(4)-400;

ceq = [];
```

Running the optimization

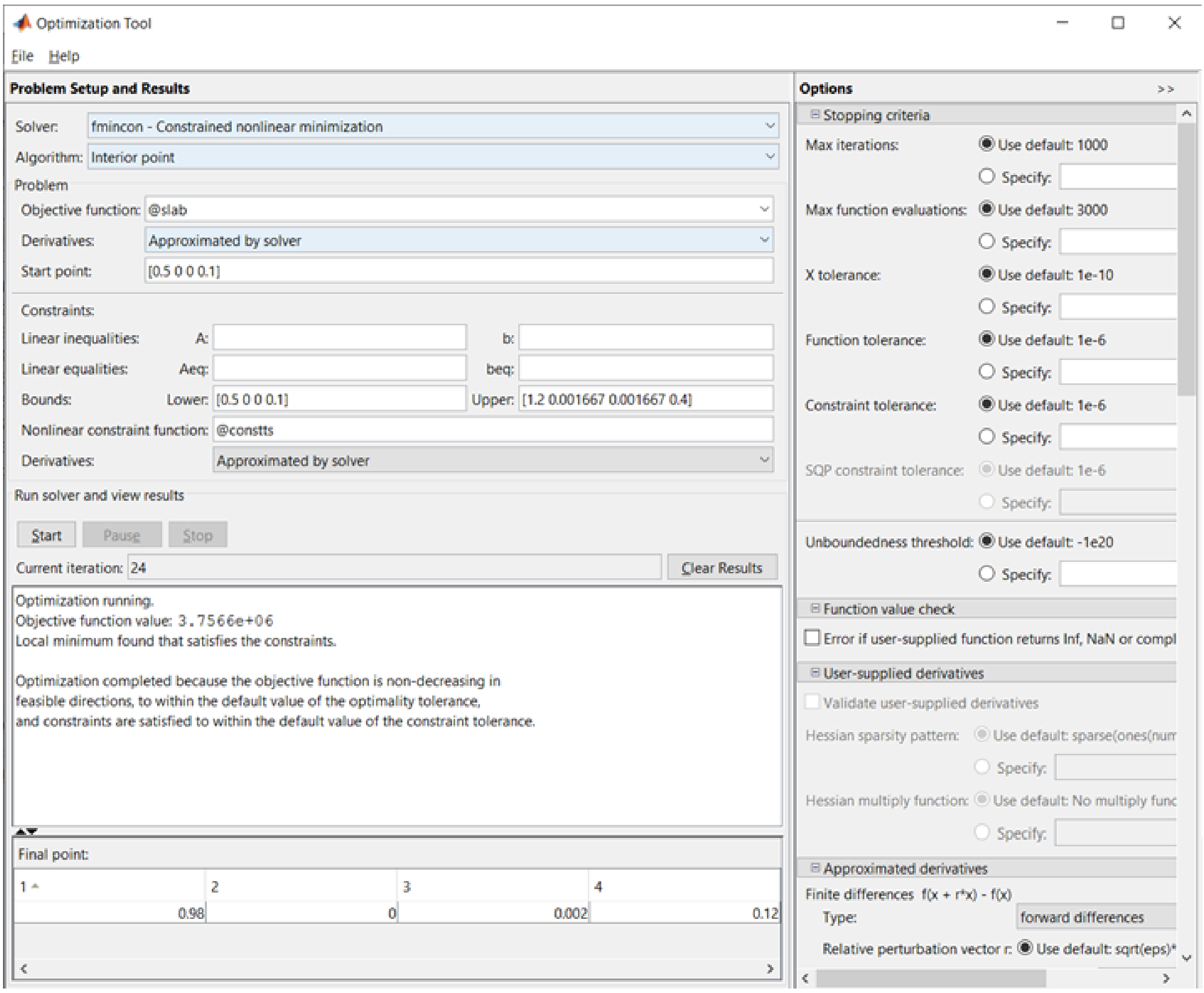
The optimization may be conducted in two ways: using the Optimization Tool or using command line methods. The optimization tool was utilized in this study to find the best value for design variables and goal functions. As a result, the M-files for the objective function and constraint functions for all grouped beams were constructed and run for the best solution, as shown below.



```
function f = slab (x)
f= 39.6*x(1)+1.99+(10.587*x(2)/x(4))-1.925*x(2)-(38.705*x(3)/x(4))-8.064*x(3);
```

```
function [c, ceq]= constbs(x)
c(1)= 1780.823*10^3-405.42*x(2)*x(1)-7254.828*x(2);
c(2)= 1394.8662*10^3-405.42*x(3)*x(1)-7254.828*x(3);
c(3)= 0.00145*x(1)-x(3);
c(4)= 0.0013*x(1)-x(3);
c(5)= x(2)-0.04*x(1)-0.002;
c(6)= x(3)-0.04*x(1)-0.002;
c(7)= x(4)-3*x(1)-0.15;
c(8)= x(4)-400;
ceq = [];
```

Figure 3.25 m. files for objective function and constraints for bottom slab



Solver: fmincon - Constrained nonlinear minimization
Algorithm: Interior point
Objective function: @slab
Derivatives: Approximated by solver
Start point: [0.5 0 0 0.1]
Linear inequalities: A: b:
Linear equalities: Aeq: beq:
Bounds: Lower: [0.5 0 0 0.1] Upper: [1.2 0.001667 0.001667 0.4]
Nonlinear constraint function: @constts
Derivatives: Approximated by solver
Current iteration: 24

```
Optimization running.
Objective function value: 3.7566e+06
Local minimum found that satisfies the constraints.

Optimization completed because the objective function is non-decreasing in
feasible directions, to within the default value of the optimality tolerance,
and constraints are satisfied to within the default value of the constraint tolerance.
```

Final point:

1	2	3	4
0.98	0	0.002	0.12

Max iterations: ● Use default: 1000 ○ Specify:
Max function evaluations: ● Use default: 3000 ○ Specify:
X tolerance: ● Use default: 1e-10 ○ Specify:
Function tolerance: ● Use default: 1e-6 ○ Specify:
Constraint tolerance: ● Use default: 1e-6 ○ Specify:
SQP constraint tolerance: ○ Use default: 1e-6 ○ Specify:
Unboundedness threshold: ● Use default: -1e20 ○ Specify:
☐ Error if user-supplied function returns Inf, NaN or compl
☐ Validate user-supplied derivatives
Hessian sparsity pattern: ○ Use default: sparse(ones(num ○ Specify:
Hessian multiply function: ○ Use default: No multiply func ○ Specify:
Finite differences f(x + r*x) - f(x)
Type: forward differences
Relative perturbation vector r: ● Use default: sqrt(eps)*

Figure 3.26 Graphical user interface of optimization toolbox for bottom slab

By changing the ultimate moment and shear force in the design constraint functions based on different types of soil bearing capacities it's possible to generate an optimized mat foundation. To illustrate this concept, bearing capacity of 450KPa was taken and the foundation was analysed. The design made in the conventional method were tabulated below:

Table 3.9 Design result of conventional design based on 450KPa soil bearing capacity

Conventional design of mat foundation with bearing capacity of 450KPa	
Beam section	1.2m X 2.5m
Mat slab section	1.8m
Maximum moment in beam	4924.6914 KNm
Maximum shear in beam	2989.884 KN
Maximum moment in slab top short	-1533.7656 KNm
Maximum moment in slab top long	-1410.5824 KNm
Maximum moment in slab bottom short	2760.2886 KNm
Maximum moment in slab bottom long	3746.6743 KNm

CHAPTER FOUR

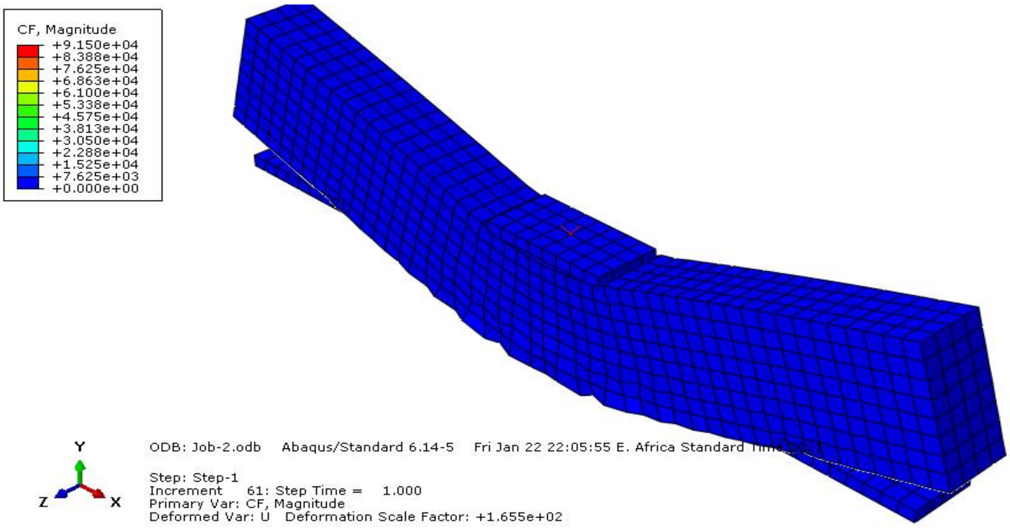
RESULT AND DISCUSSION

4.1 General

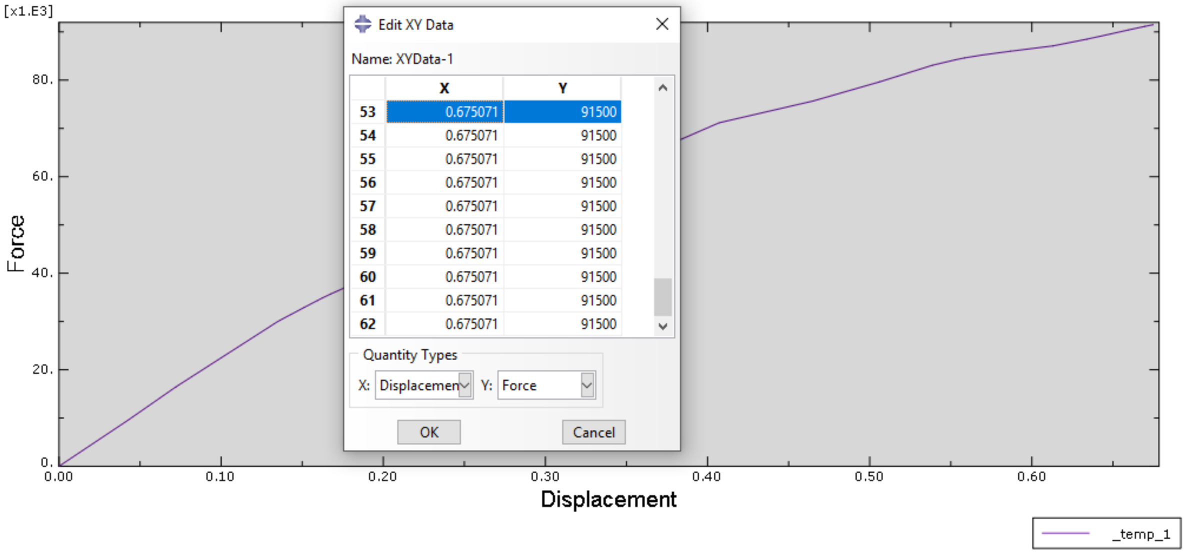
In this chapter, result from the original Mat Foundation design and optimized design from MATLAB optimization tool box are discussed in terms of total weight and compare these results.

4.2 Validation result of ABAQUS Vs experiment

The balanced reinforced beam has been analysed in ABAQUS and has been found that the ultimate load carrying capacity of the modelled beam was found to be 91.5KN which is 97.05% of the result Vs experimental result. Moreover, the load-displacement curve of the FEAc result matched with the load-displacement curve of the experimental result. This indicates that FEA result well conformed to the experimental result.



```
ODB: Job-2.odb    Abaqus/Standard 6.14-5    Fri Jan 22 22:05:55 E. Africa Standard Time

Step: Step-1
Increment     61: Step Time =    1.000
Primary Var: CF, Magnitude
Deformed Var: U   Deformation Scale Factor: +1.655e+02
```



Name: XYData-1

	X	Y
53	0.675071	91500
54	0.675071	91500
55	0.675071	91500
56	0.675071	91500
57	0.675071	91500
58	0.675071	91500
59	0.675071	91500
60	0.675071	91500
61	0.675071	91500
62	0.675071	91500

Quantity Types

X: Displacement Y: Force

Figure 4.1 Graphical representation of Validation beam load Vs Displacement in ABAQUS

Table 4.1 Validation ABAQUS VS Experimental

Abaqus		Experiment	
Disp.	Load	Disp.	Load
0	0	0	0
0.042259	4.47168	0.118065	3.60375
0.135163	7.039	0.248393	5.1123
0.143073	9.452	0.378722	6.87228
0.159313	10.3288	0.50905	8.38082
0.162433	14.8749	0.639378	11.1465
0.175895	17.9387	0.769706	14.1636
0.188132	20.8145	0.900034	16.175
0.19967	25.5856	1.46479	23.2149
0.206682	27.6528	1.59512	25.4777
0.2239	40.3305	2.11643	37.2947
0.240138	46.7455	2.24676	39.5575
0.248901	47.9899	2.37709	41.066
0.249125	48.0217	2.50741	43.3289
0.249576	48.0853	2.63774	44.8374
0.249917	48.133	2.76807	47.3517
0.25121	48.3118	2.8984	50.3688
0.252371	48.4727	3.02873	52.883
0.256681	49.0757	3.15906	54.3916
0.260512	49.6179	3.28938	55.6487
0.274658	51.6447	3.41971	56.403
0.287023	53.4575	3.55004	57.4086
0.330944	60.1038	3.68037	58.6658
0.349848	62.9851	3.8107	60.1743

0.368532	65.6062	3.94102	61.18
0.384743	67.8893	4.07135	62.6886
0.46518	75.6804	4.20168	64.9514
0.506423	79.6712	4.33201	66.7114
0.552787	84.2048	4.46234	68.4713
0.558472	84.6033	4.59267	70.2313
0.586919	85.9887	4.72299	71.4884
0.612981	87.0881	4.85332	72.7456
0.648696	89.5701	4.98365	74.2541
0.65932	90.3803	5.11398	75.0084
0.674938	91.4907	5.24431	76.0141
0.675071	91.5	5.37463	76.5169
0.675071	91.5	5.50496	77.0198
0.675071	91.5	5.63529	78.2769
0.675071	91.5	5.93939	79.534
0.675071	91.5	6.02627	78.7798

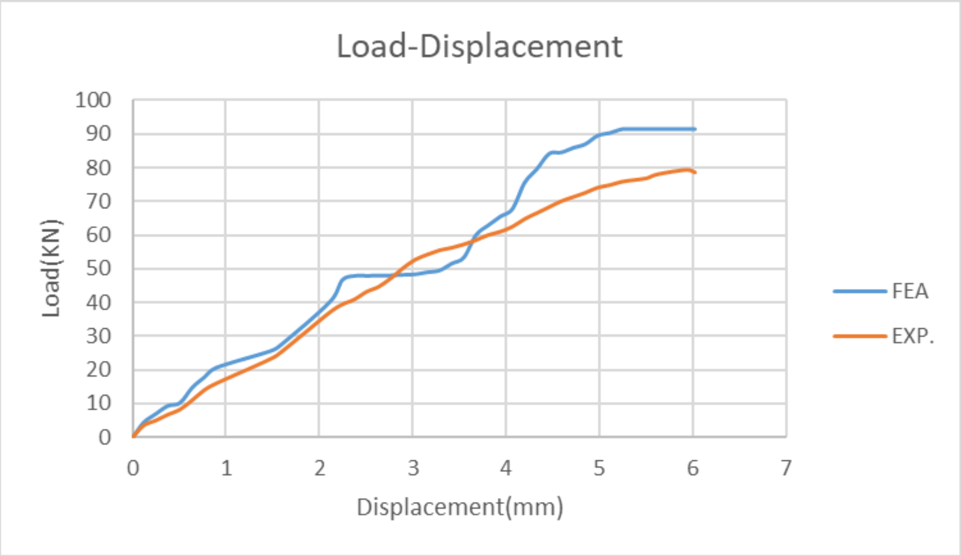


Figure 4.2 Load Vs Displacement curve of FEA and Experimental

4.3 Result of the original Mat Foundation design

The original mat foundation design has been modelled initially in SAFE Foundation, a commercial software, it has been remodelled in ABAQUS to study how the design performs by defining sections and material properties getting the moments and shear forces for further optimization process. From the original design the weight of the Mat slab and beam are taken. Having Mat surface area of 1465.54m^2 and section of 1m beam width, 2.4m depth of beam and slab depth of 1.2m and reinforcement of Mat slab with diameter 20mm bar spaced centre to centre of 150mm top and bottom. The results are tabulated below in the table 4.2:

Table 4.2 Weight of the original Mat foundation design

Structural Element		Weight (Kg)
Beam	Concrete	4,147,200
	Reinforcement	222,328
Slab	Concrete	4,396,620
	Reinforcement	122,442
Total concrete weight		8,543,820
Total Rebar weight		344,770
Total Structural weight		8,815,739

4.4 Result of the Optimized Mat Foundation design

Here the optimized Mat foundation weight is given from the result obtained from the MATLAB optimization toolbox. Having the Mat surface area of 1465.54m2 and section of 0.8m beam width, 2.3m beam depth and 1m Mat slab depth and rounding the numbers for the purpose of workability area of reinforcement of Mat slab having diameter 16mm bar centre to centre 120mm on the top and diameter 20mm bar centre to centre 170mm on the bottom area. The results are tabulated in the table 4.3:

Table 4.3 Weight of the optimized Mat foundation design

Structural Element		Weight (Kg)
Beam	Concrete	3,180,903
	Reinforcement	216,864
Slab	Concrete	3,666,781
	Reinforcement	102,913
Total concrete weight		6,847,684
Total Rebar weight		319,777
Total Structural weight		7,167,461

4.5 Comparison of the results

Here the parameter for comparison is based on weight. The result original design done by conventional methods and the optimized design done by optimization toolbox in MATLAB will be compared.

4.5.1 Comparison of Total weight

As shown above, the cross-sectional dimensions of all structural elements, Mat slab depth, beam depth and width and also area of reinforcement bars have been reduced compared to the conventional design done for the original Mat foundation. Hence showing a reduction of weight of the project making it an economical design satisfying the necessary conditions.

Table 4.4 Weight and percentage variation of original design and optimized design

Design		Element	Weight	Percentage difference w.r.t original design
Beam	Concrete	Original design	4,147,200	-
		Optimized design	3,180,903	23.3%
	Rebar	Original design	222,328	-
		Optimized design	216,864	2.46%
Slab	Concrete	Original design	4,396,620	-
		Optimized design	3,666,781	16.6%
	Rebar	Original design	122,442	-
		Optimized design	102,913	15.95%
Total weight		Original design	8,815,739	-
		Optimized design	7,167,461	18.7%

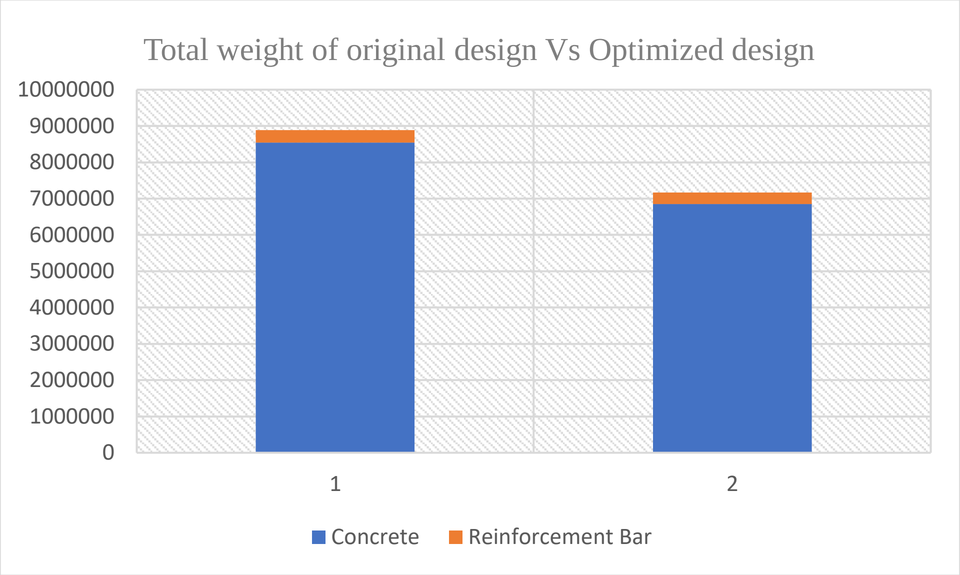


Figure 4.3 Graphical representation of total weight of case study design and optimized design

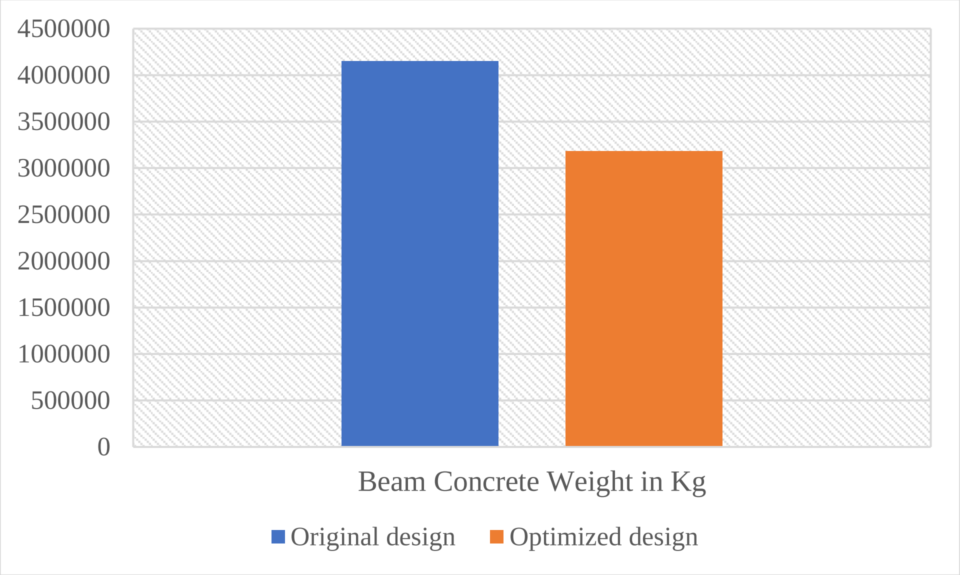


Figure 4.4 Graphical representation of Beam weight of case study design Vs optimized design

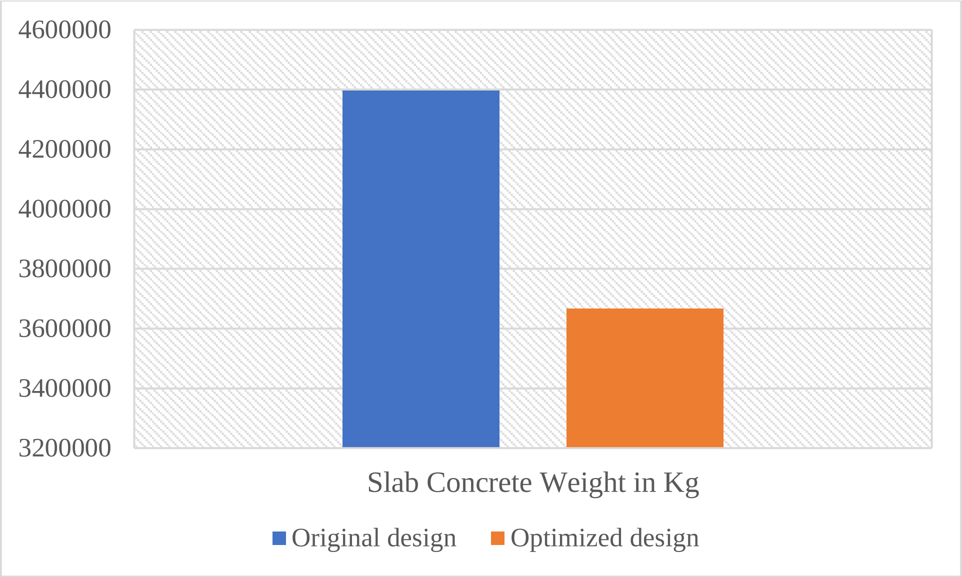


Figure 4.5 Graphical representation of Beam weight of case study design Vs optimized design

As shown above figure 4.1, the case study mat foundation done in conventional methods has higher weight value than the optimized design using MATLAB optimization toolbox making the design uneconomical. While structural elements, beam weight decrease by 22.24% and Mat slab weight decreased by 16.58%, reducing the total weight of the optimized design up to 18.7% making the design more economical and preferable the projects constructed ahead.

4.6 Result of the Optimized Mat Foundation design based on 450KPa bearing capacity

Having the Mat surface area of 1465.54m2 and section of 1.2m beam width, 2.5m beam depth and 1.8m Mat slab depth and rounding the numbers for the purpose of workability area of reinforcement of Mat, the weight of original design by conventional method and optimized sectional design using MATLAB optimization Toolbox result is shown in table 4.5:

Table 4.5 Weight and percentage variation of original design and optimized design

Structural Element		Weight (Kg) Conventional	Weight (Kg) Optimized	% Difference w.r.t conventional design
Beam	Concrete	4,320,000	3,337,239	22.75%
	Reinforcement	231,595	225,574	2.6%
Slab	Concrete	6,594,930	5,488,504	16.78%
	Reinforcement	183,669	154,466	15.9%
Total concrete weight		10,914,930	8,825,743	19.14%

Total Rebar weight	415,264	380,040	8.48%
Total Structural weight	11,330,194	9,205,783	18.75%

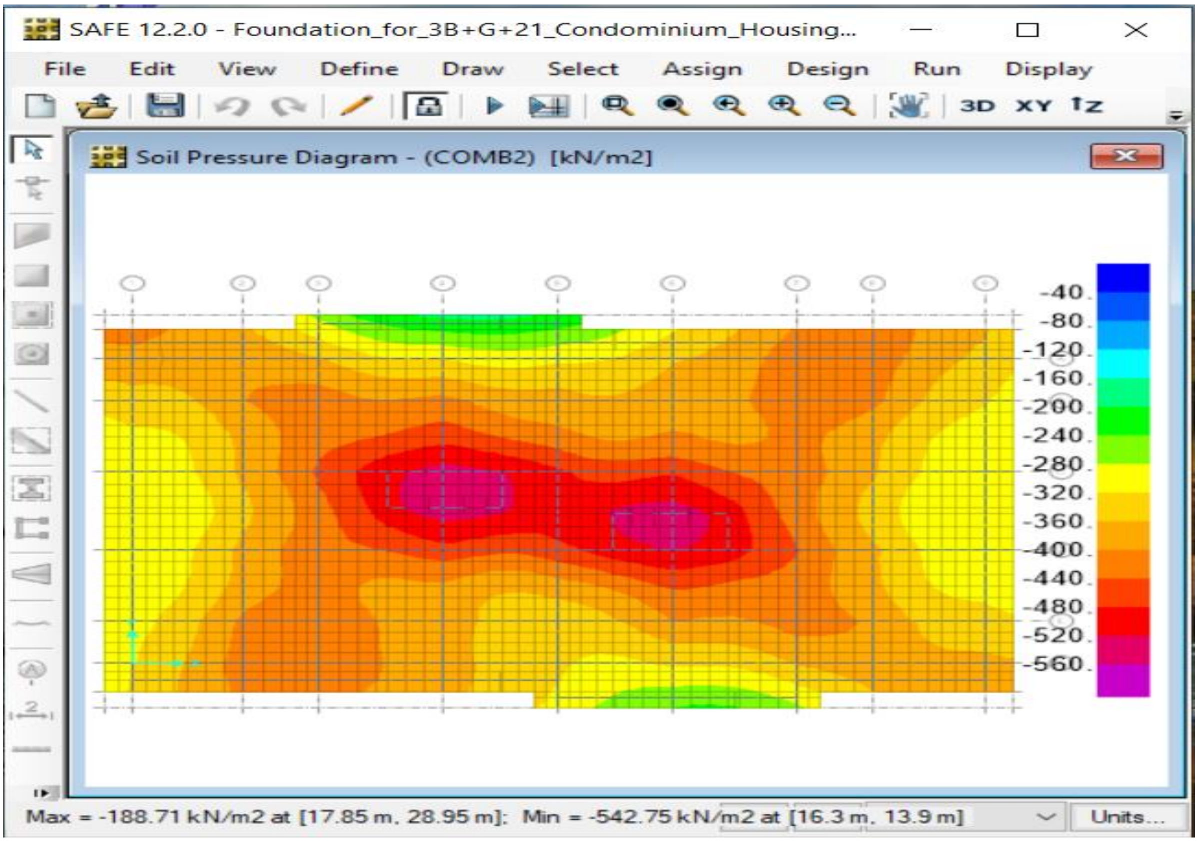
4.7 Verification of result using SAFE Foundation

Using the commercially used software SAFE Foundation V12 the optimized result has been designed to verify if the solution gives the best optimized result and compare the originally designed foundation to the optimized solution. The model and analysis are done following the methods as follow:

- Define material properties
- Define section dimensions
- Define loads onto the Mat
- Defining stripes (1m) horizontally and vertically.
- Analyse

4.7.1 Result from original design using SAFE Foundation

The original Mat foundation design having beam width of 1m, beam depth of 2.4m and slab thickness of 1.2m and soil bearing capacity of 550KPA. The analysis shown in the figure below shows the soil pressure diagram showing the maximum pressure of 542.75KPA.



Max = -188.71 kN/m2 at [17.85 m, 28.95 m]; Min = -542.75 kN/m2 at [16.3 m, 13.9 m]

Figure 4.6 Soil pressure diagram of original design on SAFE Foundation

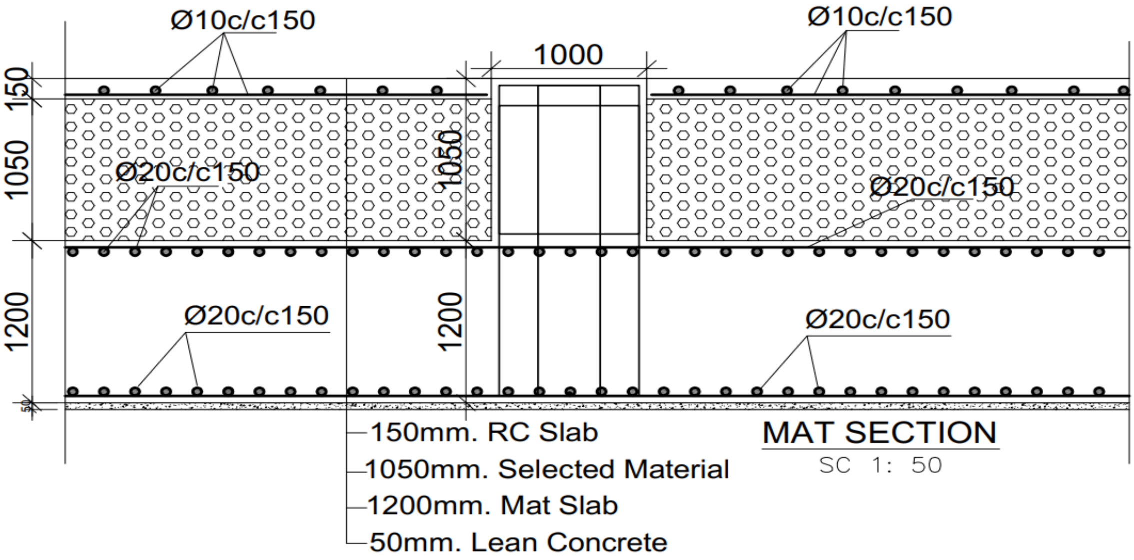
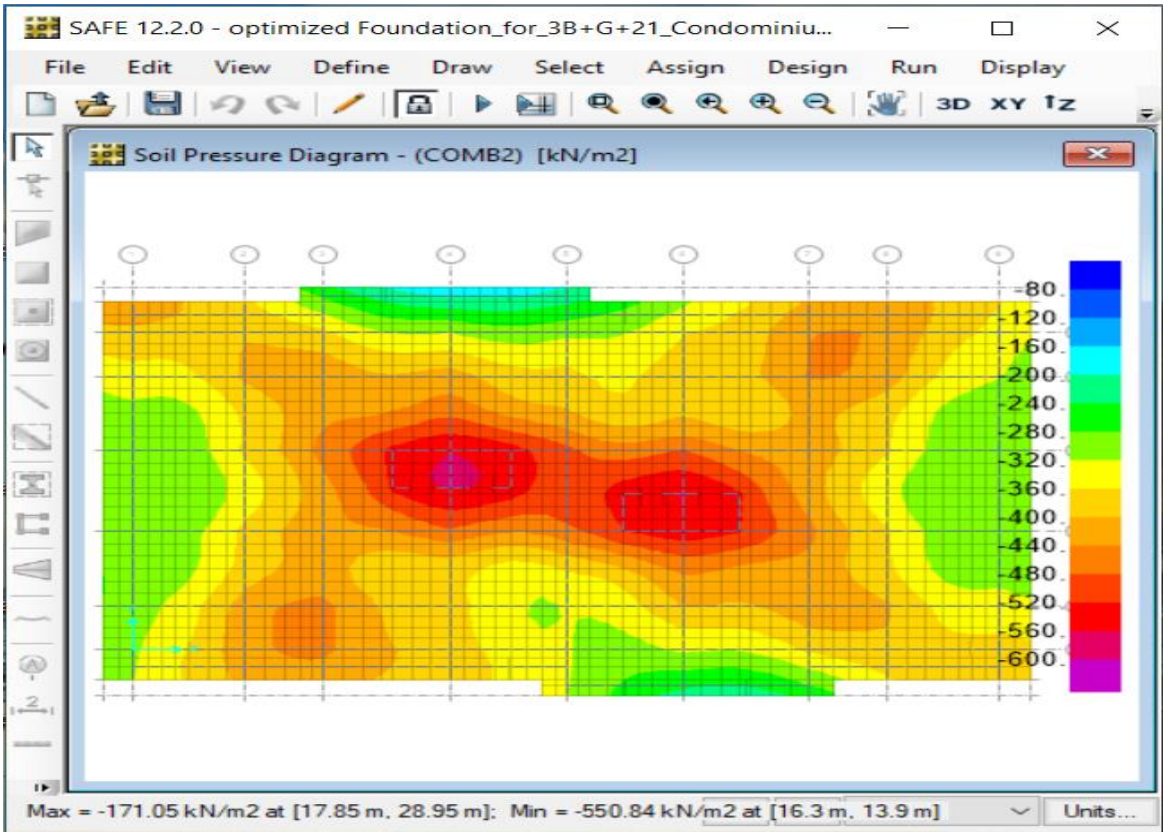


Figure 4.7 Structural design drawing of the original Mat foundation design

4.7.2 Result from optimized design using SAFE Foundation

In the optimized Mat foundation having beam width of 0.8m, beam depth of 2.3m and slab thickness of 1m and soil bearing capacity of 550KPA. The analysis shown in the figure below shows the soil pressure diagram showing the maximum pressure of 550.84KPA and also the punching shear ratio calculated in the SAFE was 0.79.



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Max = -171.05 kN/m2 at [17.85 m, 28.95 m]; Min = -550.84 kN/m2 at [16.3 m, 13.9 m]
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Figure 4.8 Soil pressure diagram of optimized design on SAFE Foundation

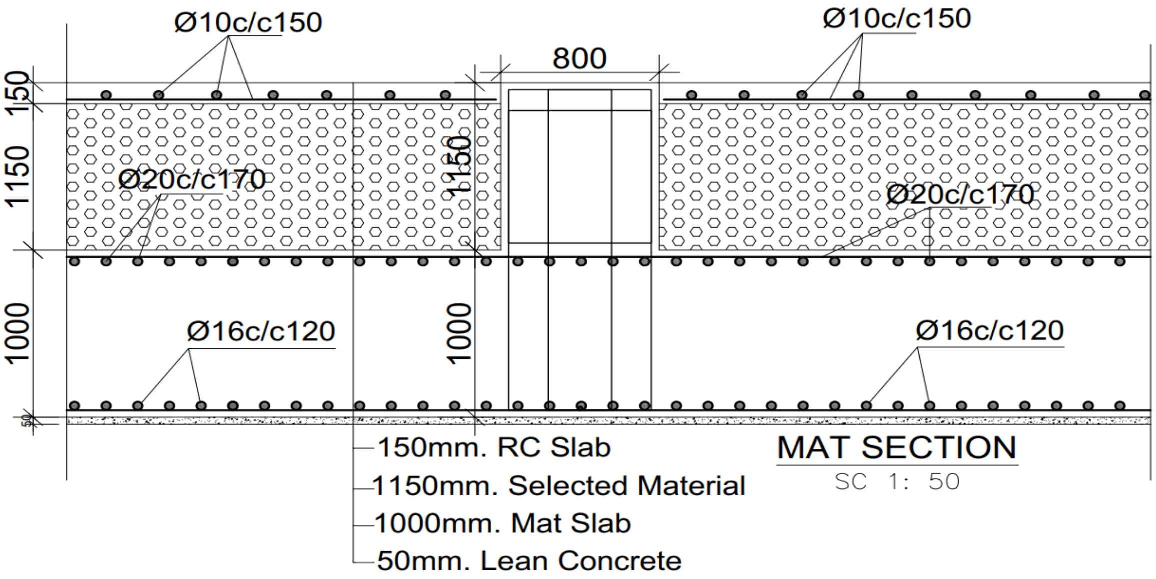

Figure 4.9 Structural design drawing of the optimized Mat foundation design

In the figure 4.8 the structural members adequately transfer the load coming from the superstructure without any failures pushing the limits to the ultimate capacity of 550 KPA of soil pressure which is the ultimate bearing capacity of the given soil bearing capacity done in laboratory soil test and also the punching shear ratio calculated in the SAFE was 0.87 which is less than 1 which makes it safe and performs well.

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 by considering multiple constraints to optimize the total weight of Mat foundation, a case study on 3B+G+21 Addis Ababa condominium housing project which is one of the large-scale projects planned to be executed in the near future. 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. MATLAB Optimization toolbox were used for the optimization analysis for structural elements (Mat beam and slab) using the ultimate moment and shear capacities from the case study done by a commercial analysis software SAFE analysis verified by ABAQUS.

The following conclusions were drawn:

- When optimization toolbox in MATLAB is used to optimize the total weight of the case study, the weight has decreased by 18.7 % while having structural members of 22.24% and 16.58% reduction for beam and slab respectively with respect to the weight obtained by conventional design method.
- Significant weight reduction on concrete of beam about 23.3% and the slab concrete about 16.6% and reinforcement bar of 15.95% but for the beam reinforcement was about 2.46% showing minimum reduction showing the design was at its capacity.
- The soil pressure on the original design was 542.75KPA where the Optimized design reached the ultimate capacity of 550KPa showing the optimized design have been pushed to the maximum limit.
- The punching shear ratio of the original design was 0.79 while the optimized design was 0.87 showing that the optimized structural member adequately transfers the loads to the ground without structural failure due to punching in which both designs where within the safe limit.
- By changing the ultimate moment and shear values in the constraint functions based on bearing capacity 450KPa, 18.75% weight reduction obtained w.r.t optimized design done for bearing capacity of 550KPa .

5.2 Recommendation

The following recommendations are suggested for future researches, which are not covered in the present study.

- For better optimized Mat Foundation design the soil-structure interaction shall be studied since design of foundation is based on the type of soil and it is essential to determine the best suited type of foundation design.
- Design and study the performance of mat foundation by considering different grade of concrete strength and steel capacity and propose an economical section with better capacity.
- There are different methodologies available to optimize reinforced concrete designs, select methods that suits the optimization problems and compare for the better solutions having best economical section and capacity.
- Verify the performance of optimized design by performing experimental investigation in laboratories by studying the tensile and compressive strength of members.
- In practical implementation, pushing the soil to its ultimate bearing capacity is risky due to different factors therefore other measurements have to be considered like using subsurface drainage perforated pipes.

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APPENDIX A
LOADS FROM SAFE MODEL OF THE ORIGINAL DESIGN

TABLE A.1 Concrete Slab Design Summary 01 - Flexural and Shear Data

TABLE: Concrete Slab Design Summary 01 - Flexural and Shear Data					
Strip	**SpanID**	**Location**	**FTopMoment**	**FBotMoment**	**VForce**
SA6	Span 1	Start	-0.1343	547.045	330.691
SA6	Span 1	Middle	-13.8402	604.1533	39.85
SA6	Span 1	End	-0.1832	910.1267	476.537
SA6	Span 2	Start	-188.4598	910.1267	476.537
SA6	Span 2	Middle	-188.4598	352.2479	735.942
SA6	Span 2	End	-4.4238	1228.3608	355.18
SA6	Span 3	Start	-174.1984	1228.3608	814.549
SA6	Span 3	Middle	-709.3483	0.5917	914.111
SA6	Span 3	End	-240.6817	1016.1155	661.382
SA6	Span 4	Start	-238.5712	1016.1155	1074.428
SA6	Span 4	Middle	-715.2907	13.4885	867.631
SA6	Span 4	End	-310.3186	902.987	1207.63
SA6	Span 5	Start	-280.4253	902.987	1207.63
SA6	Span 5	Middle	-766.4835	0.299	665.447
SA6	Span 5	End	-355.4912	1385.411	918.048
SA6	Span 6	Start	-115.3407	1385.411	1410.872
SA6	Span 6	Middle	-508.6405	673.6854	746.733
SA6	Span 6	End	-508.6405	1221.1801	260.476
SA6	Span 7	Start	-1.1653	1221.1801	797.027
SA6	Span 7	Middle	-221.8417	873.8387	347.199
SA6	Span 7	End	-124.4645	829.3794	76.625
SB3	Span 1	Start	-0.3631	507.183	659.301
SB3	Span 1	Middle	-258.5328	439.1104	98.296
SB3	Span 1	End	-218.6671	1338.8312	664.32
SB3	Span 2	Start	-0.4534	1338.8312	1208.046
SB3	Span 2	Middle	0	635.2172	53.159
SB3	Span 2	End	0	1294.8662	569.904

SB3	Span 3	Start	-210.1536	1394.8662	930.877
SB3	Span 3	Middle	-310.6944	133.4392	834.607
SB3	Span 3	End	-300.1927	1032.88	1178.012
SB3	Span 4	Start	-99.8307	1032.88	1178.012
SB3	Span 4	Middle	-269.5794	13.7323	333.58
SB3	Span 4	End	-1.8479	861.4501	507.334
SB3	Span 5	Start	-525.1332	861.4501	843.248
SB3	Span 5	Middle	-541.3324	13.8889	499.688
SB3	Span 5	End	-337.2499	1166.4778	964.793
SB3	Span 6	Start	-399.6544	1166.4778	1305.704
SB3	Span 6	Middle	-554.434	29.6286	815.878
SB3	Span 6	End	-362.2061	1099.205	1303.019
SB3	Span 7	Start	-96.047	1099.205	1303.019
SB3	Span 7	Middle	-282.3283	869.7185	258.184
SB3	Span 7	End	-282.3283	1049.4982	164.727
SB3	Span 8	Start	-554.2616	1049.4982	658.519
SB3	Span 8	Middle	-533.8922	525.7196	426.255
SB3	Span 8	End	-0.1509	857.2291	218.864

TABLE A.2 Concrete Beam Design - Flexural and Shear Data

Concrete Beam Design - Flexural and Shear Data							
Line	**Location**	**Moment**	**VForce**	**Line**	**Location**	**Moment**	**VForce**
BM1	0	72.6156	154.738	BM1	23.2	0	830.852
BM1	0.75	369.8372	422.704	BM1	23.8	442.2766	1084.39
BM1	1.5	686.8651	720.852	BM1	24.4	0	1084.39
BM1	2.25	63.4171	720.852	BM1	25	0	852.813
BM1	2.96667	0	453.858	BM1	25.85	0	527.027
BM1	3.68333	0	173.725	BM1	26.7	0	379.739
BM1	4.4	0	587.472	BM1	27.475	0	841.056
BM1	5.36667	313.1012	1173.557	BM1	28.25	0	1366.39
BM1	6.33333	2038.2112	1990.088	BM1	29.025	1185.6444	2063.477

BM1	7.3	4128.2373	1990.088	BM1	29.8	2784.8389	2063.477
BM1	8.3	2934.28	1193.957	BM1	30.76667	702.4129	2045.356
BM1	9.3	2415.4041	458.085	BM1	31.73333	0	1202.671
BM1	10.1	2925.458	1072.361	BM1	32.7	0	543.874
BM1	10.7	3762.5693	1753.85	BM1	33.3	0	467.794
BM1	11.3	4814.8794	2404.137	BM1	34.3	0	1153.729
BM1	12.3	2121.793	2404.137	BM1	35.3	400.1925	1998.106
BM1	13.3	3.0204	1394.035	BM1	36.3	2724.9836	1998.106
BM1	14.3	0	643.795	BM1	36.9	1985.345	1232.731
BM1	14.9	0	392.746	BM1	37.5	1354.1744	687.061
BM1	15.86667	0	1088.573	BM1	38.3	1020.3499	432.684
BM1	16.83333	889.394	1971.798	BM1	39.3	1645.4213	1219.206
BM1	17.8	2877.7959	1980.798	BM1	40.3	2864.6272	1611.13
BM1	18.575	1342.677	1980.798	BM1	41.26667	1145.9169	1611.13
BM1	19.35	0	1279.16	BM1	42.23333	0	855.309
BM1	20.125	0	776.857	BM1	43.2	0	251.598
BM1	20.9	0	387.898	BM1	46.1	965.0286	625.427
BM1	21.75	0	322.331	BM1	46.85	495.9582	625.427
BM1	22.6	0	612.158	BM1	47.6	90.3204	225.591

Concrete Beam Design - Flexural and Shear Data							
Line	**Location**	**Moment**	**VForce**	**Line**	**Location**	**Moment**	**VForce**
BM2	0	73.9745	167.215	BM2	23.2	0	799.128
BM2	0.75	317.4003	498.818	BM2	23.8	0	799.128
BM2	1.5	691.5139	1041.837	BM2	24.4	0	741.746
BM2	2.25	0	1041.837	BM2	25	0	482.958
BM2	2.96667	0	668.54	BM2	25.85	0	364.821
BM2	3.68333	0	255.434	BM2	26.7	0	898.424
BM2	4.4	0	847.565	BM2	27.475	0	1493.513
BM2	5.36667	0	1729.636	BM2	28.25	1094.8657	2233.919
BM2	6.33333	1955.1146	2950.385	BM2	29.025	3846.3511	3287.823
BM2	7.3	5261.1094	2950.385	BM2	29.8	3394.4141	3287.823

BM2	8.3	3394.2986	1866.811	BM2	30.76667	3235.0232	2972.933
BM2	9.3	2932.228	636.292	BM2	31.73333	157.2197	1691.613
BM2	10.1	3819.6294	1539.997	BM2	32.7	0	733.971
BM2	10.7	5065.6929	2522.88	BM2	33.3	0	707.57
BM2	11.3	5379.4204	3365.518	BM2	34.3	0	1725.545
BM2	12.3	2736.7808	3365.518	BM2	35.3	1643.6257	3080.382
BM2	13.3	0	1957.028	BM2	36.3	5030.8989	3080.382
BM2	14.3	0	906.721	BM2	36.9	3612.4075	2364.152
BM2	14.9	0	556.729	BM2	37.5	2414.9114	1422.64
BM2	15.86667	0	1501.107	BM2	38.3	1572.1991	552.126
BM2	16.83333	1762.4927	2735.123	BM2	39.3	2026.1526	1869.368
BM2	17.8	4593.4707	3093.605	BM2	40.3	3895.5208	2825.452
BM2	18.575	2195.927	3093.605	BM2	41.26667	787.5793	2825.452
BM2	19.35	0	2090.969	BM2	42.23333	0	1639.875
BM2	20.125	0	1382.414	BM2	43.2	0	784.7
BM2	20.9	0	808.769	BM2	46.1	781.186	290.759
BM2	21.75	0	289.667	BM2	46.85	380.5763	700.34
BM2	22.6	0	542.233	BM2	47.6	95.0382	1074.097

Concrete Beam Design - Flexural and Shear Data							
Line	**Location**	**Moment**	**VForce**	**Line**	**Location**	**Moment**	**VForce**
BM3	0	95.0382	248.819	BM3	23.2	0	2828.97
BM3	0.75	63.1156	775.72	BM3	23.8	0	2828.97
BM3	1.5	353.1603	1628.385	BM3	24.4	0	1145.121
BM3	2.25	934.9502	1628.385	BM3	25	0	1069.867
BM3	2.96667	0	1094.172	BM3	25.85	1325.9716	2697.758
BM3	3.68333	0	600.52	BM3	26.7	3619.0662	2697.758
BM3	4.4	0	568.805	BM3	27.475	1892.75	1173.289
BM3	5.36667	0	1470.663	BM3	28.25	2108.5132	834.252
BM3	6.33333	0	2701.164	BM3	29.025	2900.9812	1756.984
BM3	7.3	0	2701.164	BM3	29.8	4358.5957	1756.984
BM3	8.3	2770.5422	1825.292	BM3	30.76667	2857.0759	1553.296

BM3	9.3	1052.8959	740.562	BM3	31.73333	2478.3311	909.692
BM3	10.1	876.2693	1693.465	BM3	32.7	4074.9922	2999.288
BM3	10.7	1892.634	2732.307	BM3	33.3	3275.4197	2999.288
BM3	11.3	3240.5862	3179.692	BM3	34.3	702.8326	1513.352
BM3	12.3	4279.9702	3179.692	BM3	35.3	282.9864	1661.232
BM3	13.3	0	1695.262	BM3	36.3	1898.311	2528.377
BM3	14.3	0	617.797	BM3	36.9	348.4527	2528.377
BM3	14.9	0	818.881	BM3	37.5	0	1569.581
BM3	15.86667	517.0086	1757.025	BM3	38.3	0	662.925
BM3	16.83333	3470.7236	3007.762	BM3	39.3	0	1828.388
BM3	17.8	3378.2275	3157.737	BM3	40.3	1484.5371	2620.528
BM3	18.575	3888.4209	3157.737	BM3	41.26667	0	2620.528
BM3	19.35	701.968	2090.335	BM3	42.23333	0	1419.119
BM3	20.125	0	1282.018	BM3	43.2	0	537.223
BM3	20.9	0	567.684	BM3	46.1	960.0372	613.659
BM3	21.75	0	1046.606	BM3	46.85	370.5528	1104.23
BM3	22.6	0	1603.691	BM3	47.6	73.971	1638.074

Concrete Beam Design - Flexural and Shear Data

Line	**Location**	**Moment**	**VForce**	**Line**	**Location**	**Moment**	**VForce**
BM4	0	73.1277	259.028	BM4	23.2	0	1154.16
BM4	0.75	363.2524	808.128	BM4	23.8	0	2879.362
BM4	1.5	969.3486	1656.438	BM4	24.4	0	2879.362
BM4	2.25	0	1656.438	BM4	25	0	1947.027
BM4	2.96667	0	1108.301	BM4	25.85	0	1080.722
BM4	3.68333	0	610.61	BM4	26.7	0	557.604
BM4	4.4	0	547.043	BM4	27.475	0	1281.429
BM4	5.36667	0	1432.309	BM4	28.25	771.1515	2097.15
BM4	6.33333	0	2638.878	BM4	29.025	3950.8416	3168.539
BM4	7.3	1539.7615	2638.878	BM4	29.8	6420.3164	3168.539
BM4	8.3	0	1840.988	BM4	30.76667	3506.1323	3014.673
BM4	9.3	0	665.754	BM4	31.73333	490.7888	1767.675

BM4	10.1	0	1579.308	BM4	32.7	0	838.248
BM4	10.7	289.7137	2545.826	BM4	33.3	0	569.226
BM4	11.3	1806.6143	2545.826	BM4	34.3	0	1615.058
BM4	12.3	125.2189	1687.252	BM4	35.3	1108.6503	3046.458
BM4	13.3	501.5182	1529.855	BM4	36.3	4351.1816	3046.458
BM4	14.3	3070.9209	3045.455	BM4	36.9	2778.3748	2621.345
BM4	14.9	4808.1938	3045.455	BM4	37.5	1486.0627	1623.287
BM4	15.86667	2372.175	921.418	BM4	38.3	316.6129	705.89
BM4	16.83333	2777.2473	1605.936	BM4	39.3	704.9335	1767.183
BM4	17.8	4329.6519	1790.369	BM4	40.3	2380.8416	2599.291
BM4	18.575	2872.6162	1790.369	BM4	41.26667	0	2599.291
BM4	19.35	2128.1301	838.485	BM4	42.23333	0	1408.417
BM4	20.125	1979.9324	1231.686	BM4	43.2	0	1684.528
BM4	20.9	4047.5427	2763.631	BM4	46.1	989.0264	1684.528
BM4	21.75	1698.4565	2763.631	BM4	46.85	375.9979	817.371
BM4	22.6	0	1093.621	BM4	47.6	69.0685	261.821

Concrete Beam Design - Flexural and Shear Data

Line	**Location**	**Moment**	**VForce**	**Line**	**Location**	**Moment**	**VForce**
BM5	0	105.0317	185.545	BM5	23.2	649.9258	1392.115
BM5	0.75	408.5561	541.297	BM5	23.8	1485.1948	1452.564
BM5	1.5	814.5287	1085.923	BM5	24.4	515.4133	1452.564
BM5	2.25	0	1085.923	BM5	25	0	1097.802
BM5	2.96667	0	709.383	BM5	25.85	0	662.114
BM5	3.68333	0	295.731	BM5	26.7	0	540.283
BM5	4.4	0	789.677	BM5	27.475	0	1182.859
BM5	5.36667	0	1651.377	BM5	28.25	0	1945.486
BM5	6.33333	697.3499	2844.461	BM5	29.025	1485.609	2990.113
BM5	7.3	3801.3679	2844.461	BM5	29.8	3802.9465	2990.113
BM5	8.3	1924.9812	1876.387	BM5	30.76667	957.0699	2783.013
BM5	9.3	1402.7032	557.599	BM5	31.73333	0	1525.554
BM5	10.1	2222.98	1432.299	BM5	32.7	0	570.645

BM5	10.7	3401.252	2378.263	BM5	33.3	0	892.065
BM5	11.3	4828.21	3090.264	BM5	34.3	0	1934.332
BM5	12.3	1392.0735	3090.264	BM5	35.3	2308.3628	3329.831
BM5	13.3	0	1727.467	BM5	36.3	6149.9312	3329.831
BM5	14.3	0	700.904	BM5	36.9	4652.5171	2495.69
BM5	14.9	0	761.077	BM5	37.5	3457.2366	1521.457
BM5	15.86667	0	1738.537	BM5	38.3	2621.0415	625.025
BM5	16.83333	2688.3987	3047.1	BM5	39.3	3170.0017	1869.192
BM5	17.8	5888.8506	3178.93	BM5	40.3	5039.1934	2969.159
BM5	18.575	3425.1794	3178.93	BM5	41.26667	1740.4032	2969.159
BM5	19.35	839.3829	2084.724	BM5	42.23333	0	1743.397
BM5	20.125	0	1291.027	BM5	43.2	0	854.038
BM5	20.9	0	628.149	BM5	46.1	755.8152	1076.964
BM5	21.75	0	595.315	BM5	46.85	360.9893	526.434
BM5	22.6	0	1035.898	BM5	47.6	87.4316	177.777

Concrete Beam Design - Flexural and Shear Data							
Line	**Location**	**Moment**	**VForce**	**Line**	**Location**	**Moment**	**VForce**
BM6	0	100.6418	240.5	BM6	23.2	299.6552	1425.055
BM6	0.75	543.9094	665.131	BM6	23.8	1188.2219	1425.055
BM6	1.5	1042.7578	665.131	BM6	24.4	394.1645	1323.429
BM6	2.25	383.4478	321.308	BM6	25	0	1000.168
BM6	2.96667	117.4351	232.015	BM6	25.85	0	639.139
BM6	3.68333	0	813.355	BM6	26.7	0	249.688
BM6	4.4	0	813.355	BM6	27.475	0	699.907
BM6	5.36667	0	285.987	BM6	28.25	0	1230.007
BM6	6.33333	0	841.938	BM6	29.025	568.035	1942.767
BM6	7.3	1089.9308	1605.928	BM6	29.8	2073.6794	1942.767
BM6	8.3	2805.5825	1605.928	BM6	30.76667	232.5797	1893.897
BM6	9.3	1591.6952	1213.887	BM6	31.73333	0	1021.925
BM6	10.1	969.1935	423.814	BM6	32.7	0	346.51
BM6	10.7	1304.5452	697.845	BM6	33.3	0	669.987

BM6	11.3	1943.8497	1241.878	BM6	34.3	0	1408.088
BM6	12.3	2688.9763	1971.231	BM6	35.3	1982.2833	2403.912
BM6	13.3	386.0539	1971.231	BM6	36.3	4692.1733	2403.912
BM6	14.3	0	1130.903	BM6	36.9	3653.2021	1731.619
BM6	14.9	0	447.96	BM6	37.5	2843.6355	1055.802
BM6	15.86667	0	560.038	BM6	38.3	2376.0083	446.832
BM6	16.83333	0	1219.102	BM6	39.3	2916.9509	1199.374
BM6	17.8	522.2141	2068.166	BM6	40.3	4116.3247	2000.871
BM6	18.575	2598.4333	2068.166	BM6	41.26667	0	1177.176
BM6	19.35	1046.4784	2002.522	BM6	42.23333	0	497
BM6	20.125	0	1290.426	BM6	43.2	119.6548	784.451
BM6	20.9	0	746.665	BM6	46.1	800.4507	784.451
BM6	21.75	0	261.246	BM6	46.85	442.0038	477.929
BM6	22.6	0	719.667	BM6	47.6	88.957	176.427

APPENDIX B
MATERIAL PROPERTIES

B.1 Concrete Properties

Table B.1 Concrete properties

C-30			
Compression			
Ϭc	ein	dc	epl
15.19998722	0		
21.45086476	9.14195E-05		
26.72372722	0.000180841		
31.00522546	0.000300452		
34.2817663	0.000450669		
36.53950688	0.000631912		
37.76434896	0.000844611		
38	0.00100463	0	0
37.46904943	0.0012708	0.02631	0.00124
35.86627915	0.00156961	0.03405	0.00153
33.1766019	0.001901522	0.04322	0.00186
29.38464592	0.002267001	0.05397	0.00222
22.58865097	0.002807225	0.07092	0.00275
22.4735262	0.00281564	0.0712	0.00276

C-30			
Tension			
Ϭt	εcr	dt	εcr
2.896468154	0	0	0
2.620832766	0.000108394	0.05611099	0.000108394
2.371427553	0.00021599	0.111125953	0.00021599
2.145756384	0.000322862	0.164572899	0.000322862
1.941560666	0.000429081	0.216122779	0.000429081
1.75679674	0.000534707	0.265556052	0.000534707
1.589615426	0.000639799	0.31273694	0.000639799
1.438343518	0.000744406	0.357593517	0.000744406
1.301467035	0.000848574	0.40010228	0.000848574
1.177616072	0.000952346	0.440276166	0.000952346
1.065551086	0.001055758	0.478155215	0.001055758
0.964150493	0.001158847	0.513799306	0.001158847
0.872399443	0.001261641	0.547282494	0.001261641
0.789379659	0.001364169	0.578688596	0.001364169
0.714260253	0.001466457	0.608107764	0.001466457
0.646289403	0.001568527	0.635633829	0.001568527
0.584786835	0.0016704	0.661362248	0.0016704
0.52913701	0.001772094	0.685388538	0.001772094
0.478782966	0.001873628	0.707807082	0.001873628
0.456896099	0.001921086	0.71777107	0.001921086

B.2 Steel Properties

Table B.2 Steel properties

fy	εt	Ϭtrue	εpl
0	0		
466	0.00211	466.983	0
466	0.005	468.33	0.00287
466	0.04	484.64	0.03703
484.64844	0.045	506.458	0.04173
502.09375	0.05	527.198	0.0464
518.33594	0.055	546.844	0.05107
533.375	0.06	565.378	0.05571
547.21094	0.065	582.78	0.06034
559.84375	0.07	599.033	0.06495
571.27344	0.075	614.119	0.06954
581.5	0.08	628.02	0.07412
590.52344	0.085	640.718	0.07868
598.34375	0.09	652.195	0.08323
604.96094	0.095	662.432	0.08776
610.375	0.1	671.413	0.09227
614.58594	0.105	679.117	0.09677
617.59375	0.11	685.529	0.10126
619.39844	0.115	690.629	0.10573
620	0.12	694.4	0.11019

B.3 Validation ABAQUS VS Experimental

Table B.3 Validation ABAQUS VS Experimental

Abaqus		Experiment	
Disp.	Load	Disp.	Load
0	0	0	0
0.042259	4.47168	0.118065	3.60375
0.135163	7.039	0.248393	5.1123
0.143073	9.452	0.378722	6.87228
0.159313	10.3288	0.50905	8.38082
0.162433	14.8749	0.639378	11.1465
0.175895	17.9387	0.769706	14.1636
0.188132	20.8145	0.900034	16.175
0.19967	25.5856	1.46479	23.2149
0.206682	27.6528	1.59512	25.4777
0.2239	40.3305	2.11643	37.2947
0.240138	46.7455	2.24676	39.5575
0.248901	47.9899	2.37709	41.066

0.249125	48.0217	2.50741	43.3289
0.249576	48.0853	2.63774	44.8374
0.249917	48.133	2.76807	47.3517
0.25121	48.3118	2.8984	50.3688
0.252371	48.4727	3.02873	52.883
0.256681	49.0757	3.15906	54.3916
0.260512	49.6179	3.28938	55.6487
0.274658	51.6447	3.41971	56.403
0.287023	53.4575	3.55004	57.4086
0.330944	60.1038	3.68037	58.6658
0.349848	62.9851	3.8107	60.1743
0.368532	65.6062	3.94102	61.18
0.384743	67.8893	4.07135	62.6886
0.46518	75.6804	4.20168	64.9514
0.506423	79.6712	4.33201	66.7114
0.552787	84.2048	4.46234	68.4713
0.558472	84.6033	4.59267	70.2313
0.586919	85.9887	4.72299	71.4884
0.612981	87.0881	4.85332	72.7456
0.648696	89.5701	4.98365	74.2541
0.65932	90.3803	5.11398	75.0084
0.674938	91.4907	5.24431	76.0141
0.675071	91.5	5.37463	76.5169
0.675071	91.5	5.50496	77.0198
0.675071	91.5	5.63529	78.2769
0.675071	91.5	5.93939	79.534
0.675071	91.5	6.02627	78.7798

APPENDIX C
LOADS FROM SAFE MODEL OF THE OPTIMIZED DESIGN

Table Concrete beam design flexural and shear data of optimized model

TABLE: Concrete Beam Design 01 - Flexural And Shear Data							
Line	**Location**	**FTopMoment**	**FTopArea**	**FBotMoment**	**FBotArea**	**VForce**	**VArea**
Text	m	kN-m	mm2	kN-m	mm2	kN	mm2/m
BM1	0	0	0	67.5605	0	150.732	640
BM1	0.75	0	0	349.7585	347.615	413.099	640
BM1	1.5	0	0	659.583	670.885	709.118	814.468
BM1	2.25	-312.3839	215.135	42.9362	0	709.118	814.468
BM1	2.96667	-845.2275	770.531	0	0	448.049	640
BM1	3.68333	-997.3287	930.673	0	0	160.959	640
BM1	4.4	-881.9749	809.156	0	0	562.372	645.921
BM1	5.36667	-195.6352	0	194.1591	0	1135.238	1303.894
BM1	6.33333	0	0	1834.1584	1784.884	1948.521	2238.001
BM1	7.3	0	0	3862.4956	3996.577	1948.521	2238.001
BM1	8.3	0	0	2674.6926	2686.468	1187.803	1364.268
BM1	9.3	0	0	2163.6609	2133.394	450.125	640
BM1	10.1	0	0	2665.4846	2679.568	1059.408	1216.799
BM1	10.7	0	0	3495.0784	3591.466	1746.14	2005.554
BM1	11.3	0	0	4542.7622	4764.933	2357.108	2707.29
BM1	12.3	0	0	1921.1703	1889.289	2357.108	2707.29
BM1	13.3	-585.7817	505.897	0	0	1350.333	1550.944
BM1	14.3	-1384.3018	1362.855	0	0	616.655	708.268
BM1	14.9	-1445.9135	1428.312	0	0	391.144	640
BM1	15.86667	-1007.2254	972.633	0	0	1071.105	1230.233
BM1	16.83333	0	0	843.9944	842.204	1950.702	2240.506
BM1	17.8	0	0	2810.8223	2978.309	1950.702	2240.506
BM1	18.575	0	0	1301.7448	1357.557	1947.197	2236.481
BM1	19.35	-355.9315	409.139	0	0	1243.831	1428.619
BM1	20.125	-1115.4055	1217.406	0	0	749.489	860.837
BM1	20.9	-1427.3716	1552.253	0	0	370.24	640
BM1	21.75	-1455.8373	1582.435	0	0	318.655	640
BM1	22.6	-1039.1367	1142.266	0	0	601.001	690.289
BM1	23.2	-360.7548	442.052	0	0	816.934	938.301
BM1	23.8	0	0	483.537	581.667	1060.944	1218.563
BM1	24.4	-669.1497	801.705	0	0	1060.944	1218.563
BM1	25	-1630.1725	1810.455	0	0	832.519	956.202
BM1	25.85	-2330.2983	2544.598	0	0	515.073	640
BM1	26.7	-2394.2869	2613.612	0	0	366.294	640
BM1	27.475	-2042.8064	2216.222	0	0	816.099	937.342
BM1	28.25	-1053.2578	1144.188	0	0	1332.73	1530.727
BM1	29.025	0	0	1222.8474	1283.324	2032.051	2333.941
BM1	29.8	0	0	2797.6868	2972.948	2032.051	2333.941

BM1	30.76667	-56.2235	0	743.2501	757.6	2017.925	2317.717
BM1	31.73333	-1812.9678	1848.81	0	0	1177.288	1352.191
BM1	32.7	-2561.8745	2639.717	0	0	533.224	640
BM1	33.3	-2589.4653	2669.685	0	0	450.047	640
BM1	34.3	-2021.1992	2040.473	0	0	1119.304	1285.592
BM1	35.3	-385.6685	293.888	381.5413	281.489	1958.182	2249.098
BM1	36.3	0	0	2639.4363	2667.96	1958.182	2249.098
BM1	36.9	0	0	1900.1379	1868.908	1232.164	1415.219
BM1	37.5	0	0	1263.1769	1193.38	683.339	784.859
BM1	38.3	0	0	912.4658	825.497	421.023	640
BM1	39.3	0	0	1505.8408	1453.929	1203.927	1382.788
BM1	40.3	0	0	2709.7681	2750.978	1583.52	1818.774
BM1	41.26667	0	0	1026.553	954.835	1583.52	1818.774
BM1	42.23333	-637.0843	573.027	0	0	831.997	955.603
BM1	43.2	-1005.8351	971.138	0	0	246.441	640
BM1	43.91667	-829.219	785.261	0	0	745.022	855.706
BM1	44.6	-933.5771	934.01	0	0	745.022	855.706
BM1	44.63333	-933.5607	933.993	62.5388	0	213.47	640
BM1	45.35	0	0	299.6003	275.048	301.468	640
BM1	46.1	0	0	932.505	948.135	614.432	705.715
BM1	46.85	0	0	471.6809	465.504	614.432	705.715
BM1	47.6	0	0	83.2851	0	220.925	640
BM2	0	0	0	71.355	0	163.849	640
BM2	0.75	0	0	308.1717	323.161	491.281	640
BM2	1.5	0	0	676.6321	707.408	1023.821	1175.924
BM2	2.25	-1105.0945	1056.551	0	0	1023.821	1175.924
BM2	2.96667	-2140.252	2165.8	0	0	656.984	754.589
BM2	3.68333	-2593.4226	2659.608	0	0	255.268	640
BM2	4.4	-2453.1868	2507.405	0	0	816.2	937.458
BM2	5.36667	-1502.5072	1489.792	0	0	1680.448	1930.102
BM2	6.33333	0	0	1780.8652	1794.189	2899.323	3330.059
BM2	7.3	0	0	4992.646	5331.795	2899.323	3330.059
BM2	8.3	0	0	3131.0588	3246.969	1861.587	2138.152
BM2	9.3	0	0	2638.0979	2713.735	627.616	720.858
BM2	10.1	0	0	3505.1365	3665.142	1526.422	1753.194
BM2	10.7	0	0	4741.9941	5050.815	2517.848	2891.91
BM2	11.3	0	0	6252.7026	5495.622	3306.077	3797.242
BM2	12.3	0	0	2503.1807	2597.007	3306.077	3797.242
BM2	13.3	-1406.3018	1423.731	0	0	1899.769	2182.007
BM2	14.3	-2522.1221	2623.194	0	0	870.942	1000.333
BM2	14.9	-2605.2966	2713.468	0	0	553.36	640
BM2	15.86667	-1746.7091	1790.486	0	0	1478.12	1697.716
BM2	16.83333	0	0	1680.0142	1722.372	2710.84	3113.573
BM2	17.8	0	0	4493.939	4801.112	3042.647	3494.675
BM2	18.575	0	0	2135.8877	2202.217	3042.647	3494.675
BM2	19.35	-1004.9515	992.853	0	0	2035.264	2337.632

BM2	20.125	-2521.1528	2609.035	0	0	1337.104	1535.749
BM2	20.9	-3100.0339	3144.541	0	0	778.167	893.775
BM2	21.75	-3334.1199	3152.551	0	0	275.395	640
BM2	22.6	-2940.1023	3052.632	0	0	529.997	640
BM2	23.2	-2065.1667	2096.293	0	0	783.035	899.366
BM2	23.8	-1077.8965	1039.372	0	0	783.035	899.366
BM2	24.4	-1833.7498	1853.785	0	0	731.825	840.548
BM2	25	-2502.5828	2585.948	0	0	476.833	640
BM2	25.85	-2787.3101	2905.727	0	0	344.947	640
BM2	26.7	-2494.1055	2586.975	0	0	862.839	991.026
BM2	27.475	-1602.2167	1635.959	0	0	1443.942	1658.46
BM2	28.25	0	0	1016.7756	1022.899	2174.943	2498.062
BM2	29.025	0	0	3652.6577	3871.882	3235.369	3716.029
BM2	29.8	0	0	5160.0684	5228.496	3235.369	3716.029
BM2	30.76667	0	0	3033.6292	3197.51	2940.286	3377.107
BM2	31.73333	-1105.4896	1119.127	64.157	0	1658.315	1904.681
BM2	32.7	-2328.0776	2421.96	0	0	719.288	826.149
BM2	33.3	-2344.4434	2439.641	0	0	684.266	785.923
BM2	34.3	-1634.824	1676.069	0	0	1681.028	1930.769
BM2	35.3	0	0	1501.729	1533.89	3032.621	3483.161
BM2	36.3	0	0	4821.541	5159.957	3032.621	3483.161
BM2	36.9	0	0	3407.009	3574.954	2357.553	2707.802
BM2	37.5	0	0	2221.7012	2284.519	1408.79	1618.086
BM2	38.3	0	0	1402.5234	1410.493	543.818	640
BM2	39.3	0	0	1897.1588	1938.963	1862.679	2139.407
BM2	40.3	0	0	3759.8379	3971.992	2779.454	3192.381
BM2	41.26667	-60.8966	0	735.1032	724.995	2779.454	3192.381
BM2	42.23333	-2143.6428	2217.711	0	0	1596.116	1833.242
BM2	43.2	-2903.4932	3039.875	0	0	758.574	871.271
BM2	43.91667	-3015.2708	3162.145	0	0	285.97	640
BM2	44.63333	-2426.1133	2518.328	0	0	684.385	786.06
BM2	45.35	-1249.9349	1255.644	0	0	1051.964	1208.248
BM2	46.1	0	0	766.7386	795.706	1051.964	1208.248
BM2	46.85	0	0	371.5627	382.982	526.901	640
BM2	47.6	0	0	92.2861	0	179.155	640
BM3	0	0	0	60.4744	0	246.347	640
BM3	0.75	0	0	349.9428	380.171	771.64	886.279
BM3	1.5	0	0	928.6732	985.18	1597.136	1834.414
BM3	2.25	-1287.1567	1249.91	0	0	1597.136	1834.414
BM3	2.96667	-2684.6001	2757.992	0	0	1067.669	1226.286
BM3	3.68333	-3269.2761	3122.564	0	0	585.385	672.353
BM3	4.4	-3335.0046	3165.31	0	0	550.929	640
BM3	5.36667	-2962.4888	3068.968	0	0	1433.594	1646.574
BM3	6.33333	-1039.3751	1008.219	0	0	2660.464	3055.714
BM3	7.3	0	0	2697.5723	2776.514	2660.464	3055.714
BM3	8.3	0	0	941.3153	900.363	1822.777	2093.577

BM3	9.3	0	0	736.0895	686.316	725.769	833.593
BM3	10.1	0	0	1717.9908	1725.427	1673.014	1921.564
BM3	10.7	0	0	3047.0566	3162.189	2719.68	3123.728
BM3	11.3	0	0	4678.8647	4981.774	3137.026	3603.076
BM3	12.3	0	0	1353.4393	1362.419	3137.026	3603.076
BM3	13.3	-1412.5477	1417.665	0	0	1655.611	1901.576
BM3	14.3	-2012.6492	2058.546	0	0	600.101	689.255
BM3	14.9	-1924.0261	1960.688	0	0	797.505	915.986
BM3	15.86667	-643.309	600.54	398.5929	340.972	1716.565	1971.585
BM3	16.83333	0	0	3230.7507	3369.478	2966.903	3407.678
BM3	17.8	0	0	5598.7563	5422.746	3109.183	3571.096
BM3	18.575	0	0	3660.6309	3830.157	3109.183	3571.096
BM3	19.35	-688.9246	614.918	621.2039	549.349	2037.455	2340.148
BM3	20.125	-2748.4866	2811.068	0	0	1241.284	1425.695
BM3	20.9	-3552.2029	3135.781	0	0	544.783	640
BM3	21.75	-3562.6216	3169.158	0	0	1027.577	1180.238
BM3	22.6	-3549.564	3183.259	0	0	1872.341	2150.504
BM3	23.2	-2493.5842	2526.09	0	0	2797.559	3213.177
BM3	23.8	-815.0486	733.617	0	0	2797.559	3213.177
BM3	24.4	-1422.7858	1352.992	0	0	1183.312	1359.11
BM3	25	-1266.7281	1192.537	0	0	1015.441	1166.3
BM3	25.85	0	0	1228.8381	1162.248	2625.08	3015.074
BM3	26.7	0	0	3460.1565	3577.544	2625.08	3015.074
BM3	27.475	0	0	1695.3376	1699.482	1157.125	1329.032
BM3	28.25	0	0	1877.1823	1896.029	812.797	933.55
BM3	29.025	0	0	2605.0007	2683.862	1723.894	1980.003
BM3	29.8	0	0	4027.72	4264.545	1723.894	1980.003
BM3	30.76667	0	0	2569.9673	2659.487	1530.134	1757.458
BM3	31.73333	0	0	2203.1606	2262.63	890.793	1023.134
BM3	32.7	0	0	4785.7534	5134.445	2937.597	3374.019
BM3	33.3	0	0	3023.1948	3168.596	2937.597	3374.019
BM3	34.3	0	0	525.824	498.375	1465.893	1683.672
BM3	35.3	0	0	176.9735	0	1672.475	1920.945
BM3	36.3	0	0	1849.4484	1898.596	2503.131	2875.007
BM3	36.9	0	0	342.9839	301.944	2503.131	2875.007
BM3	37.5	-670.1829	644.41	0	0	1541.165	1770.127
BM3	38.3	-1184.4878	1185.548	0	0	642.881	738.39
BM3	39.3	-573.5004	542.549	0	0	1827.538	2099.044
BM3	40.3	0	0	1534.8949	1554.098	2581.204	2964.679
BM3	41.26667	-1702.4564	1745.162	0	0	2581.204	2964.679
BM3	42.23333	-3430.646	3118.921	0	0	1384.05	1589.671
BM3	43.2	-3434.7393	3148.477	0	0	521.476	640
BM3	43.91667	-3385.4087	3110.94	0	0	596.584	685.216
BM3	44.63333	-2909.7903	3044.969	0	0	1075.909	1235.75
BM3	45.35	-1427.1752	1445.95	0	0	1605.165	1843.635
BM3	46.1	0	0	954.5664	998.776	1605.165	1843.635

BM3	46.85	0	0	367.9367	385.124	782.173	898.376
BM3	47.6	0	0	71.3033	0	250.66	640
BM4	0	0	0	70.4861	0	256.584	640
BM4	0.75	0	0	360.5829	377.06	804.26	923.744
BM4	1.5	0	0	963.7776	1008.056	1623.9	1865.154
BM4	2.25	-1423.4536	1437.202	0	0	1623.9	1865.154
BM4	2.96667	-2902.6936	3031.605	0	0	1080.343	1240.843
BM4	3.68333	-3571.1428	3160.249	0	0	593.984	682.229
BM4	4.4	-3512.1226	3143.89	0	0	530.623	640
BM4	5.36667	-3099.1865	3074.728	0	0	1396.475	1603.941
BM4	6.33333	-1656.3647	1682.833	0	0	2598.801	2984.89
BM4	7.3	0	0	1588.4489	1586.694	2598.801	2984.89
BM4	8.3	-563.2073	503.331	0	0	1840.142	2113.521
BM4	9.3	-1206.9825	1177.725	0	0	645.524	741.426
BM4	10.1	-690.5633	633.854	0	0	1550.613	1780.979
BM4	10.7	0	0	285.9036	208.265	2520.302	2894.729
BM4	11.3	0	0	1797.2145	1800.044	2520.302	2894.729
BM4	12.3	0	0	70.6885	0	1698.487	1950.822
BM4	13.3	-50.3114	0	337.3241	254.207	1481.418	1701.504
BM4	14.3	0	0	2829.3743	2908.815	2982.315	3425.381
BM4	14.9	0	0	4618.7637	4899.043	2982.315	3425.381
BM4	15.86667	0	0	2105.3325	2117.807	903.131	1037.304
BM4	16.83333	0	0	2490.1521	2533.732	1581.06	1815.949
BM4	17.8	0	0	4002.5271	4198.207	1758.755	2020.044
BM4	18.575	0	0	2576.3416	2611.136	1758.755	2020.044
BM4	19.35	0	0	1890.67	1870.658	818.797	940.44
BM4	20.125	0	0	1769.6069	1741.646	1213.046	1393.261
BM4	20.9	0	0	3855.4285	3976.491	2691.895	3091.814
BM4	21.75	0	0	1567.3182	1479.78	2691.895	3091.814
BM4	22.6	-767.745	634.074	0	0	1040.08	1194.599
BM4	23.2	-855.5438	723.792	0	0	1191.664	1368.703
BM4	23.8	-238.2715	0	0	0	2845.46	3268.194
BM4	24.4	-1949.6183	1912.72	0	0	2845.46	3268.194
BM4	25	-3097.4041	3159.716	0	0	1912.976	2197.176
BM4	25.85	-3019.6479	3071.867	0	0	1058.919	1216.236
BM4	26.7	-3134.5881	3161.562	0	0	537.091	640
BM4	27.475	-2613.8525	2638.578	0	0	1242.845	1427.487
BM4	28.25	-603.9449	498.133	678.3784	580.752	2046.202	2350.194
BM4	29.025	0	0	3713.9885	3861.952	3121.764	3585.547
BM4	29.8	0	0	5536.1553	5411.239	3121.764	3585.547
BM4	30.76667	0	0	3263.8457	3378.779	2971.355	3412.792
BM4	31.73333	-701.6324	635.137	377.8464	291.466	1724.769	1981.008
BM4	32.7	-2026.115	2045.817	0	0	814.354	935.338
BM4	33.3	-2160.6455	2195.112	0	0	554.389	640
BM4	34.3	-1606.2567	1600.876	0	0	1578.444	1812.944
BM4	35.3	0	0	1005.0604	976.984	3006.371	3453.01

BM4	36.3	0	0	4193.3018	4420.182	3006.371	3453.01
BM4	36.9	0	0	2628.2642	2690.739	2608.396	2995.911
BM4	37.5	0	0	1354.1908	1326.313	1603.078	1841.238
BM4	38.3	0	0	417.3971	344.574	691.445	794.169
BM4	39.3	0	0	631.4235	571.349	1764.186	2026.282
BM4	40.3	0	0	2341.5188	2391.739	2560.351	2940.728
BM4	41.26667	-1261.2473	1258.889	0	0	2560.351	2940.728
BM4	42.23333	-3106.1868	3248.085	0	0	1373.39	1577.427
BM4	43.2	-3530.5952	3127.787	0	0	512.492	640
BM4	43.91667	-3544.3713	3132.241	0	0	613.203	704.304
BM4	44.63333	-2733.9465	2843.142	0	0	1102.751	1266.58
BM4	45.35	-1308.0535	1310.509	0	0	1651.896	1897.309
BM4	46.1	0	0	982.5906	1027.474	1651.896	1897.309
BM4	46.85	0	0	372.5328	389.115	813.41	934.254
BM4	47.6	0	0	66.281	0	259.328	640
BM5	0	0	0	102.141	0	182.15	640
BM5	0.75	0	0	398.8369	406.299	533.83	640
BM5	1.5	0	0	799.2093	824.712	1063.155	1221.102
BM5	2.25	-1259.9935	1255.61	0	0	1063.155	1221.102
BM5	2.96667	-2465.5149	2546.347	0	0	692.901	795.841
BM5	3.68333	-3075.6638	3080.639	0	0	290.575	640
BM5	4.4	-3064.1187	3086.43	0	0	763.535	876.969
BM5	5.36667	-2214.0422	2266.892	0	0	1607.394	1846.196
BM5	6.33333	-132.0375	0	654.5009	596.417	2798.147	3213.852
BM5	7.3	0	0	3677.134	3827.864	2798.147	3213.852
BM5	8.3	0	0	1807.509	1788.686	1869.625	2147.385
BM5	9.3	0	0	1251.5511	1176.116	549.088	640
BM5	10.1	0	0	2050.7776	2019.922	1418.119	1628.801
BM5	10.7	0	0	3219.0403	3283.186	2371.269	2723.554
BM5	11.3	0	0	4641.8013	4874.004	3043.158	3495.262
BM5	12.3	0	0	1275.7208	1195.251	3043.158	3495.262
BM5	13.3	-1969.6335	1915.492	0	0	1683.933	1934.106
BM5	14.3	-2722.7471	2725.027	0	0	679.112	780.004
BM5	14.9	-2698.3042	2698.362	0	0	743.76	854.256
BM5	15.86667	-1504.1215	1405.988	0	0	1701.793	1954.618
BM5	16.83333	0	0	2524.7722	2495.481	3010.264	3457.482
BM5	17.8	0	0	5683.6245	6032.981	3134.67	3600.37
BM5	18.575	0	0	3254.2551	3282.791	3134.67	3600.37
BM5	19.35	-71.904	0	762.9756	597.99	2034.655	2336.932
BM5	20.125	-1568.7178	1446.962	0	0	1251.272	1437.166
BM5	20.9	-2118.6428	2034.974	0	0	603.33	692.963
BM5	21.75	-2116.0796	2032.208	0	0	587.54	674.828
BM5	22.6	-1220.838	1072.355	0	0	1018.683	1170.023
BM5	23.2	0	0	659.8406	476.483	1373.388	1577.425
BM5	23.8	0	0	1483.8735	1348.18	1426.552	1638.487
BM5	24.4	-238.9432	0	535.1392	348.767	1426.552	1638.487

BM5	25	-1722.3018	1612.563	0	0	1073.362	1232.825
BM5	25.85	-2860.5105	2848.087	0	0	647.189	743.338
BM5	26.7	-3022.9431	3028.619	0	0	521.559	640
BM5	27.475	-2618.7349	2586.487	0	0	1148.475	1319.097
BM5	28.25	-1375.9891	1250.615	0	0	1899.788	2182.029
BM5	29.025	0	0	1476.8959	1360.262	2948.387	3386.412
BM5	29.8	0	0	3761.896	3850.094	2948.387	3386.412
BM5	30.76667	-33.678	0	941.8339	803.636	2755.319	3164.661
BM5	31.73333	-2271.5254	2232.509	0	0	1499.801	1722.618
BM5	32.7	-3071.1384	3108.87	0	0	565.036	648.981
BM5	33.3	-2994.1138	3024.305	0	0	858.042	985.517
BM5	34.3	-1838.905	1776.956	0	0	1878.683	2157.788
BM5	35.3	0	0	2121.5015	2098.604	3271.756	3757.822
BM5	36.3	0	0	5468.2554	5278.252	3271.756	3757.822
BM5	36.9	0	0	4373.6064	4563.669	2491.081	2861.167
BM5	37.5	0	0	3183.7434	3244.643	1508.49	1732.598
BM5	38.3	0	0	2363.5339	2356.773	617.014	708.68
BM5	39.3	0	0	2934.1812	2994.137	1863.382	2140.214
BM5	40.3	0	0	4797.563	5073.995	2918.561	3352.154
BM5	41.26667	0	0	1589.5603	1569.152	2918.561	3352.154
BM5	42.23333	-1668.1377	1667.716	0	0	1694.749	1946.528
BM5	43.2	-2601.8584	2679.763	0	0	823.415	945.746
BM5	43.91667	-2740.7671	2830.934	0	0	266.604	640
BM5	44.63333	-2250.7786	2304.201	0	0	679.201	780.106
BM5	45.35	-1159.8925	1142.025	0	0	1057.414	1214.508
BM5	46.1	0	0	739.8184	759.283	1057.414	1214.508
BM5	46.85	0	0	350.8811	353.196	518.583	640
BM5	47.6	0	0	84.5747	0	174.256	640
BM6	0	0	0	93.2587	0	235.634	640
BM6	0.75	0	0	518.5558	508.649	653.698	750.814
BM6	1.5	0	0	1008.829	1022.752	653.698	750.814
BM6	2.25	0	0	338.8325	306.869	313.76	640
BM6	2.96667	-965.2118	954.373	92.2146	0	226.613	640
BM6	3	-965.2292	954.392	0	0	800.497	919.422
BM6	3.68333	-830.9333	754.812	0	0	800.497	919.422
BM6	4.4	-1032.9093	967.552	0	0	281.827	640
BM6	5.36667	-685.9186	584.007	0	0	819.605	941.37
BM6	6.33333	0	0	976.5811	843.417	1579.034	1813.622
BM6	7.3	0	0	2657.1453	2624.806	1579.034	1813.622
BM6	8.3	0	0	1458.9396	1333.527	1198.206	1376.216
BM6	9.3	0	0	864.1209	693.403	411.961	640
BM6	10.1	0	0	1217.8177	1045.847	694.009	797.114
BM6	10.7	0	0	1861.7178	1722.133	1241.075	1425.455
BM6	11.3	0	0	2606.363	2527.959	1931.904	2218.916
BM6	12.3	-418.4703	190.679	368.6044	0	1931.904	2218.916
BM6	13.3	-2061.6677	1936.179	0	0	1097.214	1260.22

BM6	14.3	-2638.6035	2565.196	0	0	431.03	640
BM6	14.9	-2601.1895	2524.402	0	0	548.479	640
BM6	15.86667	-1872.5129	1738.905	0	0	1192.761	1369.962
BM6	16.83333	-157.4581	0	565.4637	355.908	2039.701	2342.728
BM6	17.8	0	0	2613.1653	2537.877	2039.701	2342.728
BM6	18.575	0	0	1082.8265	894.093	1974.631	2267.99
BM6	19.35	-1078.0643	882.18	0	0	1260.399	1447.649
BM6	20.125	-1981.3264	1841.865	0	0	725.416	833.186
BM6	20.9	-2240.9678	2117.447	0	0	251.551	640
BM6	21.75	-2051.9255	1913.176	0	0	704.365	809.008
BM6	22.6	-1202.3192	1001.149	0	0	1073.562	1233.055
BM6	23.2	-104.5599	0	368.6835	0	1401.667	1609.905
BM6	23.8	0	0	1238.8752	1042.659	1401.667	1609.905
BM6	24.4	0	0	456.6032	217.944	1303.787	1497.483
BM6	25	-941.1787	729.648	0	0	980.969	1126.706
BM6	25.85	-1723.23	1562.656	0	0	626.873	720.004
BM6	26.7	-1906.5023	1754.986	0	0	238.255	640
BM6	27.475	-1721.8546	1556.736	0	0	677.177	777.782
BM6	28.25	-1033.5171	817.454	0	0	1198.235	1376.25
BM6	29.025	0	0	583.3074	338.014	1912.249	2196.341
BM6	29.8	0	0	2065.3005	1914.862	1912.249	2196.341
BM6	30.76667	-133.9723	0	239.1125	0	1874.204	2152.644
BM6	31.73333	-1351.8251	1153.179	0	0	1005.788	1155.212
BM6	32.7	-1703.8634	1535.412	0	0	346.051	640
BM6	33.3	-1622.7726	1448.596	0	0	641.746	737.087
BM6	34.3	-767.0548	542.397	0	0	1363.32	1565.861
BM6	35.3	0	0	1799.391	1645.937	2355.85	2705.845
BM6	36.3	0	0	4435.4326	4551.968	2355.85	2705.845
BM6	36.9	0	0	3400.2029	3392.702	1725.383	1981.713
BM6	37.5	0	0	2596.4126	2515.619	1044.354	1199.508
BM6	38.3	0	0	2133.6968	2031.947	440.369	640
BM6	39.3	0	0	2663.8652	2620.026	1191.738	1368.787
BM6	40.3	0	0	3855.6028	3935.63	1960.292	2251.521
BM6	41.26667	0	0	1818.7299	1731.47	1960.292	2251.521
BM6	42.23333	-236.8635	0	162.0737	0	1139.973	1309.332
BM6	43.2	-925.0295	843.551	0	0	559.326	642.422
BM6	43.91667	-1032.5118	956.879	0	0	170.879	640
BM6	44.63333	-862.578	788.717	0	0	489.423	640
BM6	45.35	-283.6637	196.284	97.5241	0	770.796	885.308
BM6	46.1	0	0	770.4312	780.151	770.796	885.308
BM6	46.85	0	0	419.6728	413.526	467.678	640
BM6	47.6	0	0	83.3495	0	172.124	640

APPENDIX D
LOADS FROM SAFE MODEL DESIGN BASED ON BEARING CAPACITY 450KPa

Table Maximum moment and shear force on beam

Beam (m)	Location (m)	Max Moment (KN-m)	Max Shear (KN)
BM1- 1x2.4	11.3	4139.6797	2090.569
BM1 -1x2.4	29.8	1763.6329	1963.097
BM2 -1x2.4	11.3	4924.6914	2920.726
BM2 -1x2.4	29.8	4130.21	2989.884
BM3 -1x2.4	11.3	3880.7688	2701.812
BM3 -1x2.4	29.8	3569.4629	1821.19
BM4 -1x2.4	14.9	3344.4429	2729.206
BM4 -1x2.4	29.8	4351.7407	2750.167
BM5- 1x2.4	11.3	3497.0583	2645.761
BM5 -1x2.4	36.3	4547.8242	2881.505
BM6 -1x2.4	11.3	2049.5161	1743.577
BM6 - 1x2.4	36.3	3924.1221	2104.402

Table Maximum top and bottom moment of mat slab

Panel	Direction	Max Top Moment (KN-m)	Max Bottom Moment (KN-m)
P1	Short	-1029.491	270.9785
P1	Long	-539.6213	3445.5005
P2	Short	-1174.3625	724.4664
P2	Long	-1410.5824	1564.056
P3	Short	-1205.8719	1700.2184
P3	Long	-895.3745	3742.6743
P4	Short	-1533.7656	2760.2886
P4	Long	-1392.7419	3174.835