

Optimizing Structural and Architectural Design of Columns in Multi-Storey Buildings

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Abstract Multi-story structures are becoming a popular option in modern development due to the fast urbanization and rising demand for residential and commercial spaces. The most popular construction method for these kinds of buildings is reinforced cement concrete (RCC) framed construction. But since materials, mostly steel and concrete, account for about 70% of the entire cost of RC buildings, it is necessary to establish sustainable and economical design techniques. The goal of this study is to optimize a ten-story commercial building's design in order to utilize less material while still meeting design codes' standards for serviceability and safety. The study investigates important factors that affect structural efficiency, such as material qualities, column orientation, geometry of structural grid, and column placement patterns. Case studies with different column grid configurations were examined to determine how these parameters influence the amounts of concrete and steel required for a safe design. The material requirements were determined by designing and evaluating each architectural plan. The column grid was strategically modified in each case to investigate the effect of a particular parameter on achieving design optimization. Moving columns toward the centre band of the building plan, keeping peripheral columns, aligning columns perpendicular to longer spans, and increasing the size of the peripheral columns with columns of shorter depth concentrated near the central band are all crucial design optimization strategies identified by this

study. Higher-grade steel was also used, which improved structural strength while using less material in comparison with increasing the grade of concrete. These changes resulted in material savings of up to 2.58% for steel and 1.52% for concrete. The results offer useful suggestions for column grid architectural planning, emphasizing techniques that reduce the number of columns and maximize material usage. This study emphasizes how effective structural grid planning can lead to environmentally friendly and sustainable building methods. The study supports the larger objective of sustainable infrastructure development by optimizing design parameters, which helps building multi-story structures that are both economical and ecologically conscious.

Keywords Multi-Storey Buildings, Structural Optimization, Reinforced Concrete (RCC), Cost-Effective Design, CYPECAD, Economical Design, Column Placement, Sustainable Construction

1. Introduction

Multi-story building construction has increased due to urbanization and the rising need for residential and commercial spaces. Compared to low-rise buildings, these structures have lower construction costs and can house

more people per unit space. Reinforced cement concrete (RCC) is used in most of these types of projects in India. Optimizing the usage of steel and concrete is essential for cost-effectiveness without sacrificing quality or design requirements because their quantities vary greatly. The goal of optimization in construction is to maximize efficiency in a number of areas, such as the use of materials, time, and space. In addition to cutting expenses, structural optimization aims to improve functionality. An RCC multi-story building's structural materials usually account for a major percentage of its overall cost, therefore an optimised planning of column layout can have a big influence on overall costs.

By examining elements such as column placement, orientation, material grades, and geometric patterns of column layout, this study seeks to maximize the efficiency of structural design. The analysis compares and assesses the amounts of concrete and steel for various cases of column layout using CYPECAD, a powerful structural design program. The case studies offer insights into how to create structural designs that are both economical and effective.

Not many studies have been conducted on the optimization of the structural and architectural design of columns in multi-story structures in order to improve overall structural performance, material utilization, and cost effectiveness (Figure 1). A summary of pertinent research that sheds light on optimization strategies and procedures in structural engineering along with their limitations are discussed in this section.

In multi-story buildings, optimizing column design improves safety, cost-effectiveness, and structural integrity. Important tactics to improve load-carrying capacity, particularly in medium-to-lower stories, include multi-constraint optimization, taking stiffness and axial load ratios into account [1]. Adding slabs and walls increases

lateral load resistance, which is essential for the stability of high-rise buildings [2]. Performance and economy are increased by the choice of materials and structural systems, such as steel frameworks with optimal bracing and beam-column connections [3]. Structural integrity is strengthened by modular techniques that use concrete-filled steel tubular (CFST) columns and laminated double beams [4]. Strength and usable area are balanced when structural grids are set, such as when columns are spaced 7.5 x 6.7 m for low-rise structures [5]. FRP wrapping is one seismic retrofitting approach that improves ductility and earthquake resilience [6]. Column layouts are further improved by advanced automated optimization, which takes structural and architectural limitations into account [7]. When combined, these methods guarantee multi-story building designs that are safe, effective, and long-lasting. However, a holistic approach that integrates all aspects of column positioning, orientation, geometry and dimensions in optimising structural design with due consideration to deflection, moment and load carrying capacity resulting in reduced concrete and steel for a safe design is missing in the literature. Furthermore, some specific investigations in these areas are discussed with specific limitations.

1.1. Methods of Optimization for RCC Structures

In their 2015 study, Prakash A. Sangave et al. [8] optimized reinforced cement concrete (RCC) structures utilizing ETABS software and the Seismic Coefficient and Response Spectrum Methods. In order to reduce the amount of reinforcement area per square foot, they conducted research on G+10 RCC frames using dual systems. They showed cost savings by using less material while preserving structural integrity by adjusting column sizes, orientations, and reinforcement placements. However, the investigation was on optimisation for lateral seismic loading and not for predominant gravity load cases.

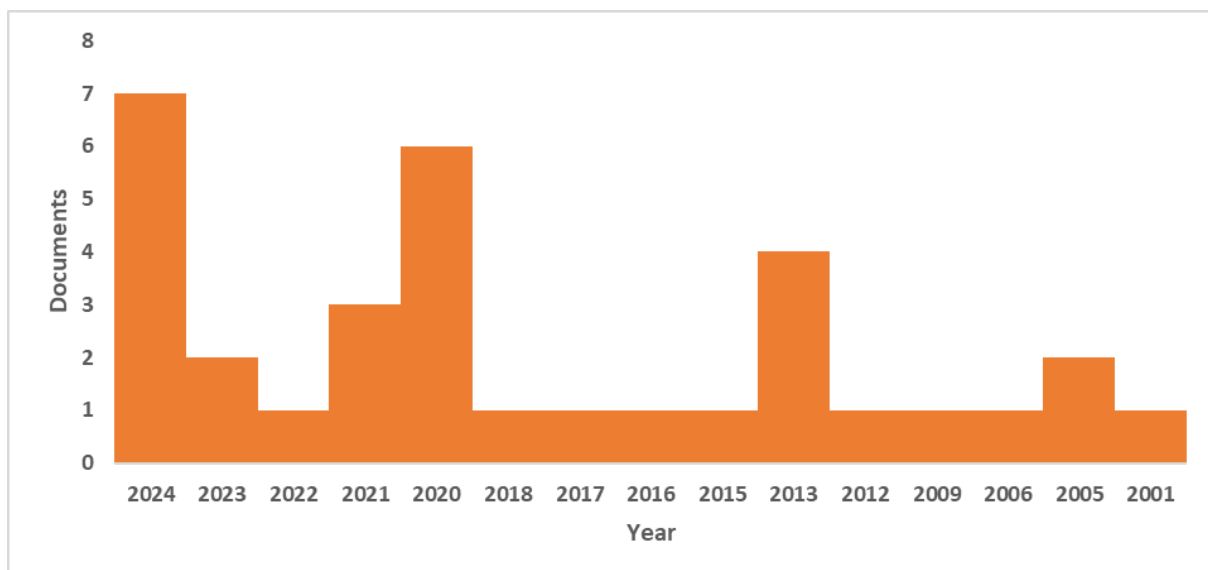


Figure 1. Research documents on optimal design for reinforced concrete tall buildings (from 2001 to 2024) as per scopus database

1.2. Stiffness Optimization for Cost-Effective Design

In order to get the best stiffness correlations between structural elements, Andres Guerra et al. [9] investigated optimization in RC structures. They demonstrated cost savings of up to 23% when compared to conventional approaches using MATLAB for analysis. In order to obtain optimal designs, their studies highlighted the significance of variable stiffness in structural elements, particularly in multi-bay and multi-story frames. However, the layout of column placement along with its influence on design optimisation had not been explored.

1.3. Cost-Effective Column Design for Multi-Story Structures

Mallikarjun et al. [10] used ETABS to optimize the design of columns in multi-story residential constructions. In order to use less steel, their study concentrated on lowering the size of columns on upper levels and aligning columns along longer spans. They emphasized that building costs can be considerably decreased by optimizing column design through the use of materials. The study did not investigate the influence of geometry, layout and orientation of columns in optimising the design.

1.4. Optimizing Structures through Material Variations

Gurjeet Singh et al. [11] investigated cost optimization in STAAD Pro by altering structural component sizes and material grades. They discovered that using Fe-500 steel in conjunction with higher-grade concrete for columns increases cost effectiveness. Seismic forces and building costs were further reduced by utilizing lightweight materials, such as Siporex bricks, and reducing column sizes floor-wise. This investigation is limited to establishing influence of material grade and column size and does not attempt to investigate influence of layout and orientation of columns.

1.5. Optimizing Column Layout Automatically

A methodology for optimizing column layouts in framed reinforced concrete buildings was proposed by Pezhman Sharafi [12]. Sharafi created a mathematical model that connected variations in column layout to cost components (concrete, steel, and formwork) using Ant Colony Optimization (ACO). In preliminary designs, this automated method greatly increased cost-efficiency. Even though, this investigation is a close attempt to attain layout optimisation, it still falls short in capturing the influence of column orientation, size and material grades on achieving optimisation.

1.6. Multi-Story Building Design Assisted by Software

Santhosh Kumar D et al. [13] highlighted the benefits of

developing G+4 residential buildings with CYPECAD. The software reduced labor and material costs by facilitating effective structural component planning, analysis, and optimization. The software's capacity to expedite design procedures and guarantee adherence to safety regulations was highlighted by the study. The investigation barely touches upon the optimisation capabilities that are in-built in the software and does not provide recommendations that could be adopted at planning stage for optimising the design.

1.7. Column Spacing's Effect on Price

Using STAAD Pro, Markandeya Raju Ponnada [14] examined how column spacing affected the price of multi-story buildings. They refined column configurations to reduce the amount of steel and concrete used by examining various aspect ratios and panel sizes. By optimizing column space and design, their studies showed significant cost reductions. However, the investigation does not dwell upon further optimisation that could have been possible by reorienting the columns and material properties along with optimising the layout.

1.8. Using Genetic Algorithms for Structural Improvement

The TOSCA tool, which uses genetic algorithms (GA) for structure optimization, was presented by Corrado Chisari et al. [15]. They demonstrated GA's adaptability in improving seismic retrofitting plans and other engineering uses. This method demonstrated its potential in structural engineering by offering strong answers to challenging optimization issues. However, a practical and simple guideline that a design engineer or architect can adopt while planning the structures was not provided.

1.9. Structure for Optimizing Tall Buildings

In 2012, S. Bobby et al. [16] put forth a thorough methodology for tall building optimization. Their research focused on performance-based design (PBD), which combines the specification of structural systems with aerodynamic shape optimization. For improved aerodynamic performance and material efficiency, they adjusted external geometries using computational methods like CFD analysis. The investigation is limited to the shape optimisation for lateral loads.

1.10. Research Gap

Despite several investigations being made in optimizing the design of high rise structures, the study of literature reveals that there is a lacuna in specifications or recommendations that can be readily adopted by design engineers during planning of tall structures.

The key limitations based on literature survey is presented in Table 1.

Table 1. Key limitations based on literature survey

Theme	Literature Sources	Key Limitation
Column Layout and Orientation Optimization	Prakash A. Sangave et al. [8] Mallikarjun et al. [10] Markandeya Raju Ponnada [14]	Insufficient attention is paid to the methodical examination of column placement, geometrical patterns, and spacing for optimization.
Material and Structural Member Optimization	Andres Guerra et al. [9] Gurjeet Singh et al. [11] Geeta Mehta et al. [18]	Focuses on member sizes and material modifications but does not thoroughly examine column-specific optimizations.
Software-Aided Optimization	Santhosh Kumar D et al. [13] Pezhman Sharafi [12]	Inadequate evaluation of the efficiency of automated tools and software for column positioning and optimization.
Advanced Algorithms and Theoretical Models	Corrado Chisari et al. [15] S. Bobby et al. [16]	A focus on theoretical optimization models for column efficiency that have little practical applications.
Structural Analysis for High-Rise Buildings	T. Sasidhar et al. [17]	Emphasizes general structural analysis rather than a thorough examination of geometrical patterns or column orientation.

- Column Positioning: Insufficient attention is paid to the best possible column positioning for both cost and performance.
- Geometric Patterns: The implications of layout on cost and stability have not been sufficiently studied.
- Column Orientation: Understudied effect on performance and load distribution.
- Column Dimensions: Insufficient research on size optimization in a systematic manner.
- Design Tools: Limited study of software efficacy in column optimization.

2. Materials and Methods

The details such as architectural plan with the material and geometrical properties of a multi-storey residential apartment structure taken for case study are described in this section. A flow chart of the logical sequence of steps followed in the methodology adopted is depicted in Figure 2. The objective of this investigation is to establish practical guidelines for design engineers to achieve design optimization using special column layouts, orientation, geometry and material grades.

2.1. Case Study

A ten-story building was taken into consideration in this study. The plinth level was 1.5 meters from the base, and the typical floor height was 3.0 meters, for a total construction height of 30 meters. The models are assigned with geometrical, material, and structural attributes. A conventional plan with these details is presented in Figure 3 having the specifications as follows.

Column size (mm): 230x600, 230x750, 230x900, 300x900, 600x230, 750x230, 790x230, 900x230 and 900x300, Beam size (mm): 230x450 and grade of concrete and steel: M25 and Fe-415. These dimensions and grade of materials are selected based on minimum requirement of design by designing the conventional structure shown in Figure 3 in accordance with limit state method of design.

The column layout is planned in such a way that there is a uniform distribution of columns over the plan area in conventional structure.

Modifications are then made to the conventional structure for following cases to optimise the column positioning in the structure. M25 grade of concrete and Fe 415 grade of steel are adopted for Case A to Case D as presented in Figure 4 to Figure 12. All 10 floors are identical.

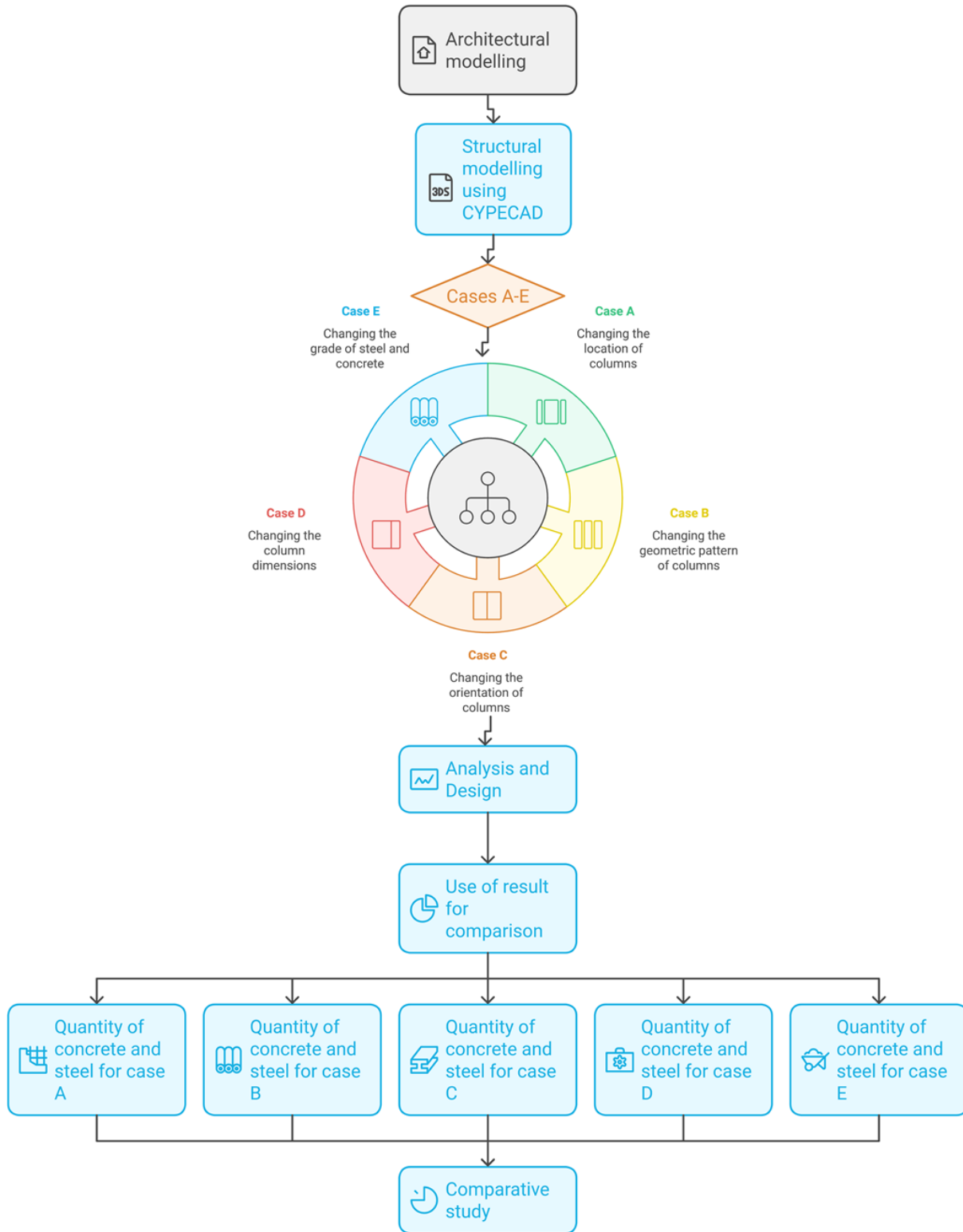


Figure 2. Methodology

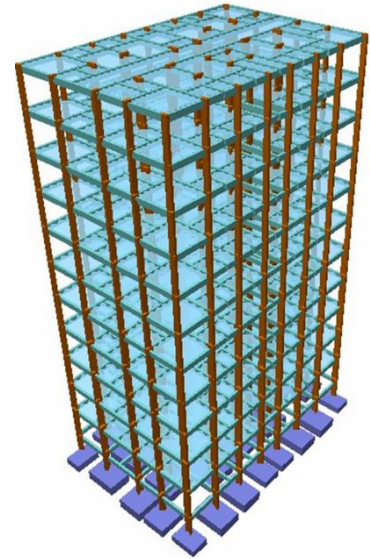


Figure 3. Plan and 3D of Conventional Structure

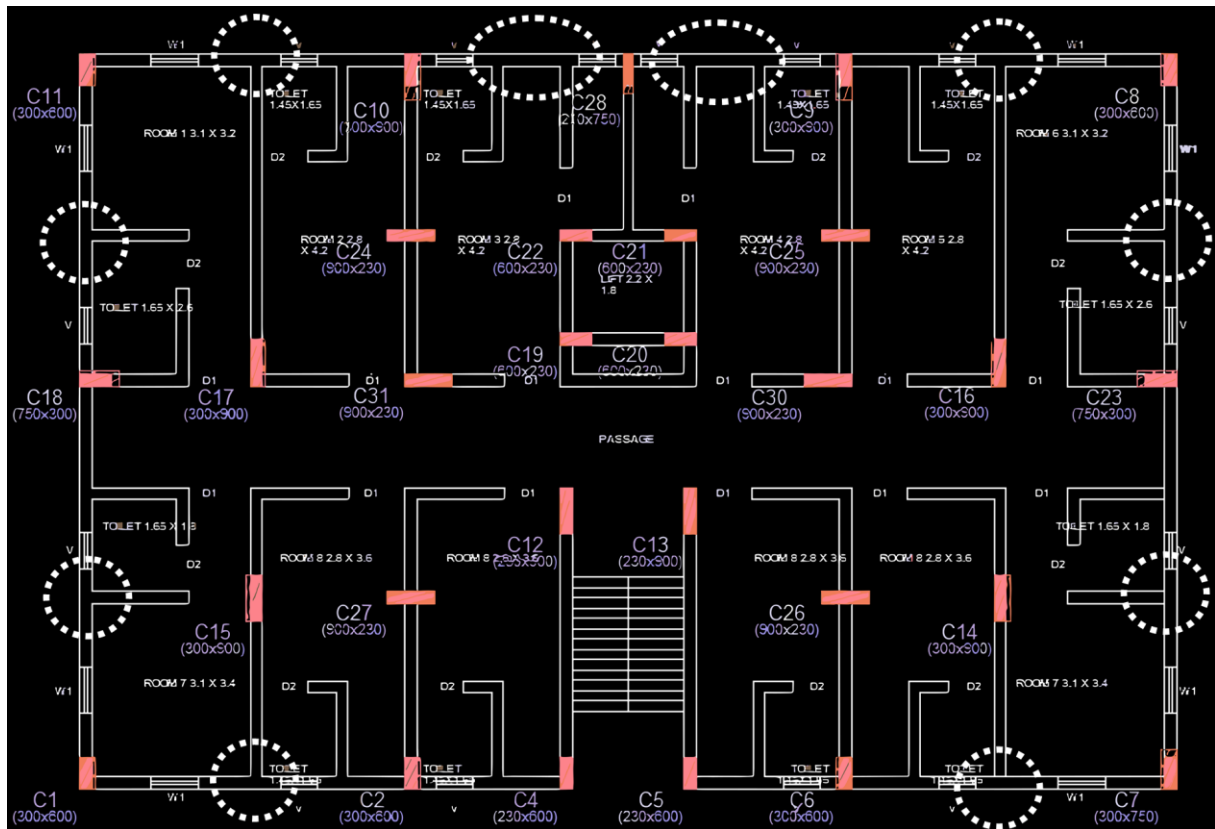


Figure 4. Plan of Case A1 (dotted circles showing removed columns when compared with conventional structure)

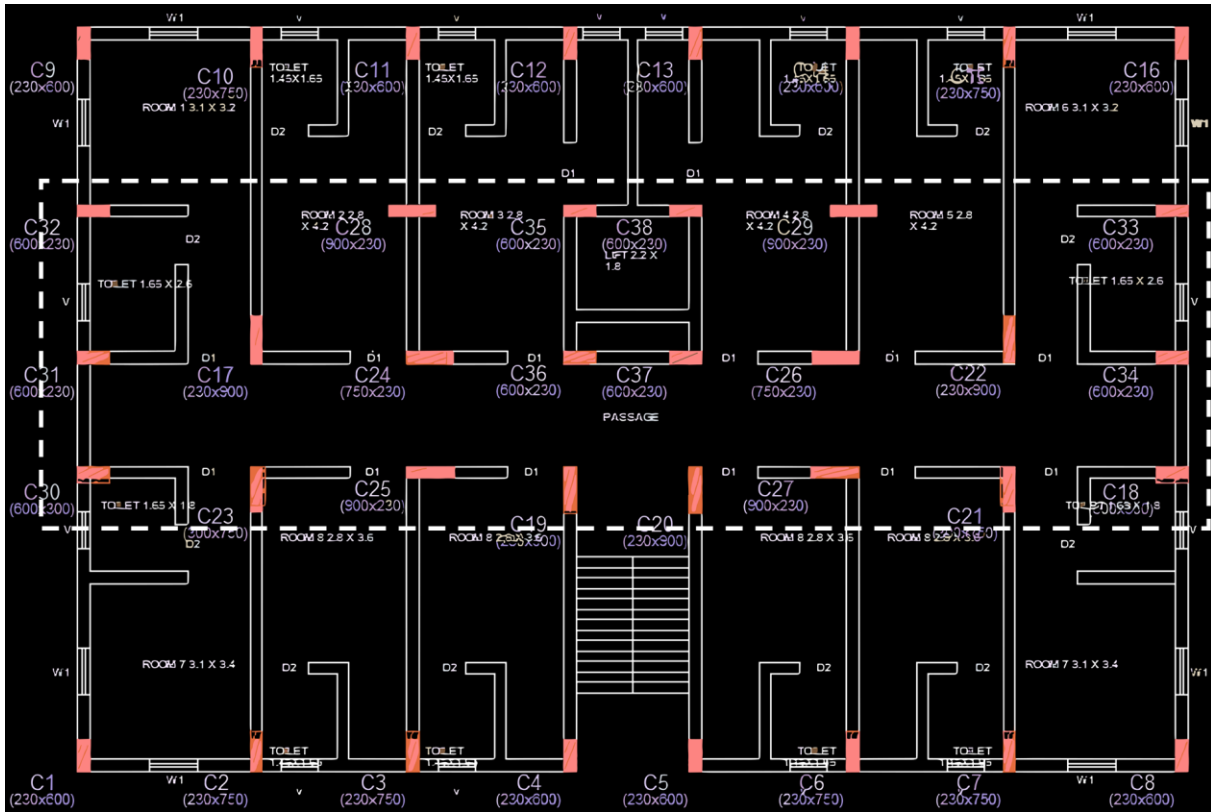


Figure 5. Plan of Case A2 (Dotted line showing columns shifted near to central passage)

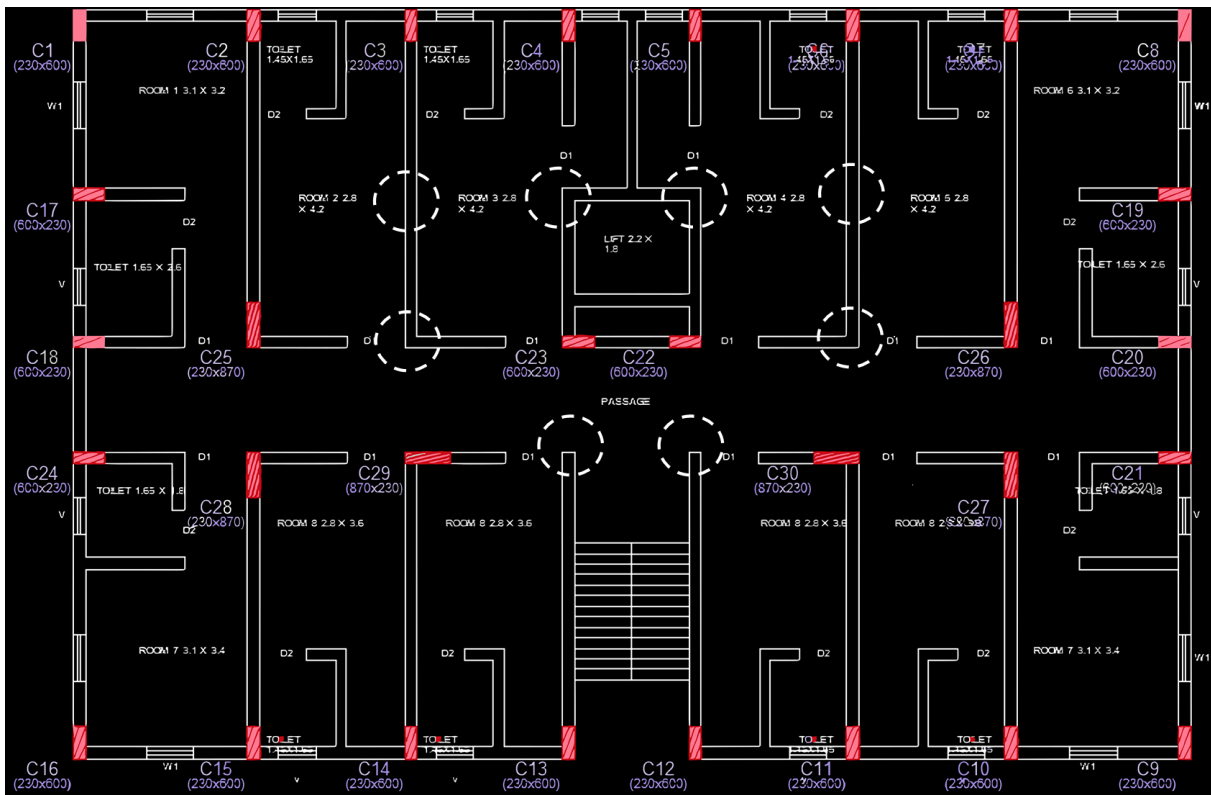


Figure 6. Plan of Case B1 (Dotted circles showing central 8 columns removed with reference to conventional structure)

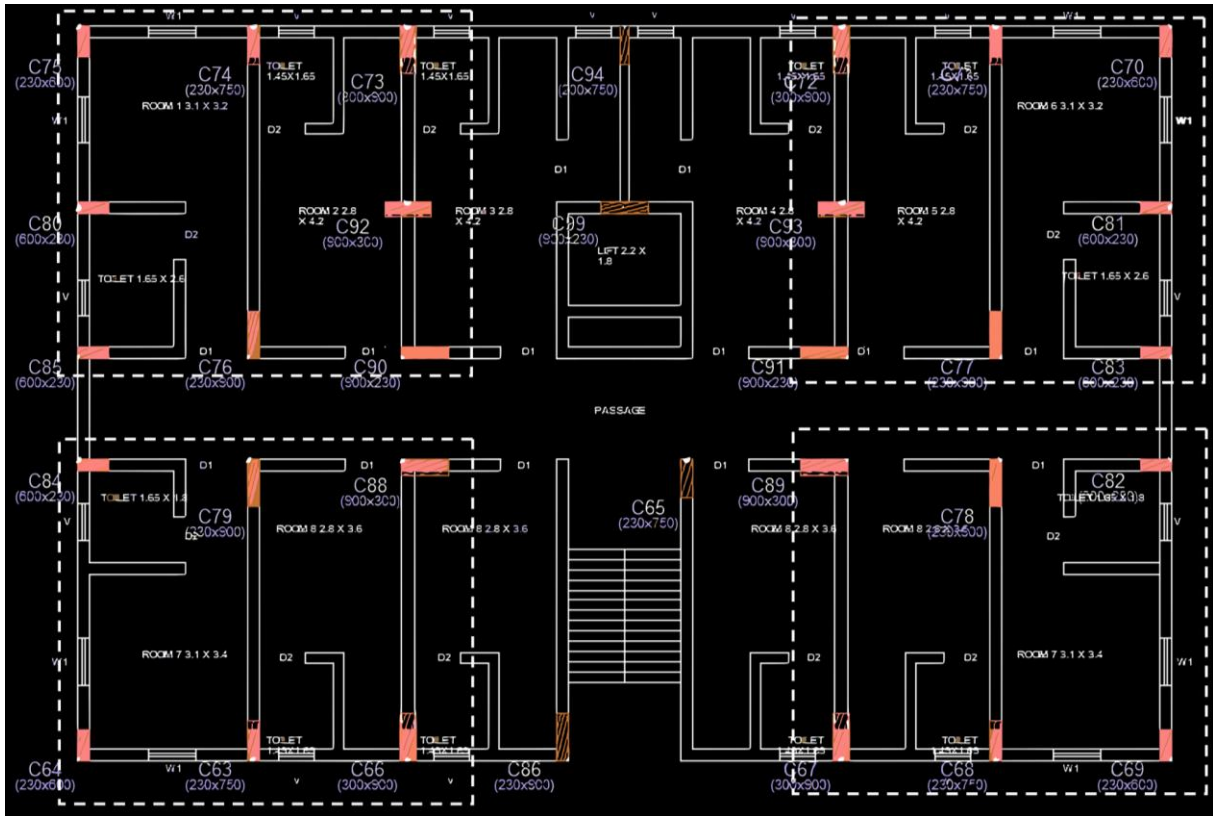


Figure 7. Plan of Case B2 (Dotted boxes showing square pattern of column arrangement at boundaries)

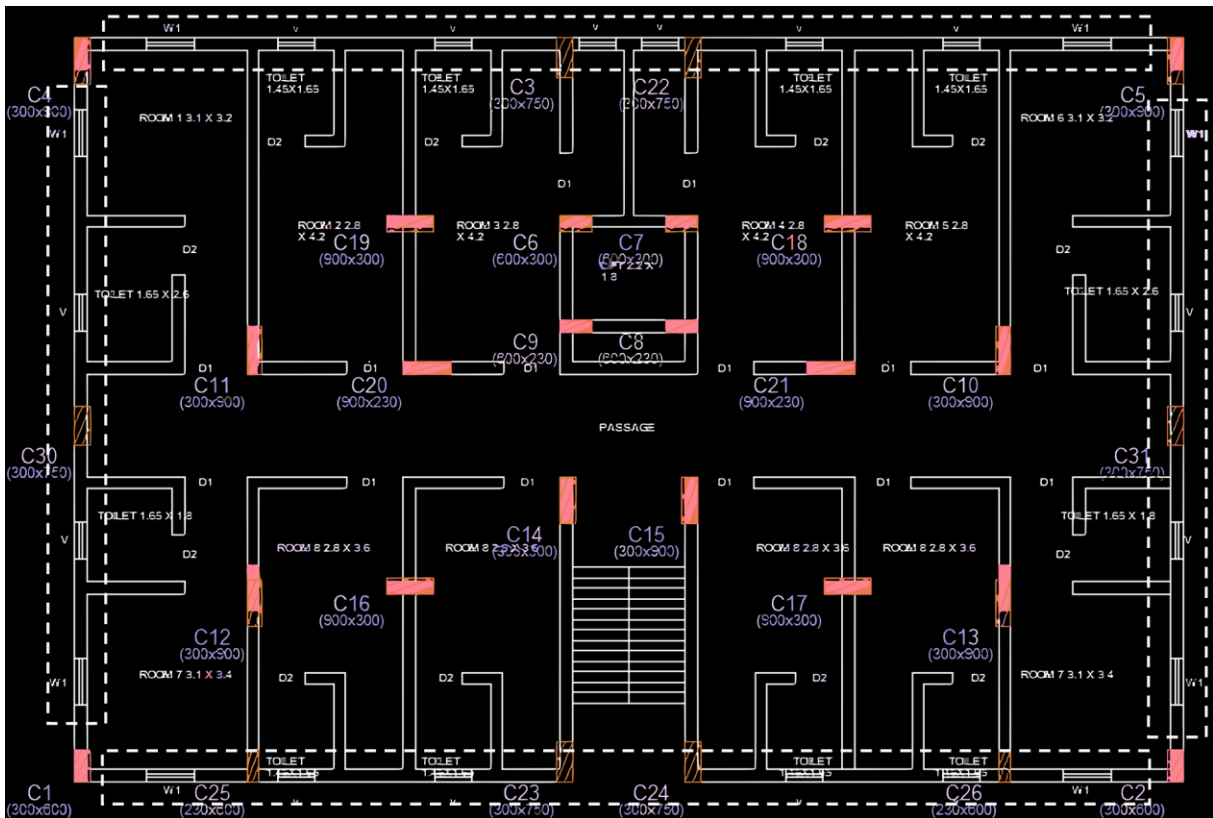


Figure 8. Plan of Case B3 (Dotted boxes showing removal of peripheral columns)

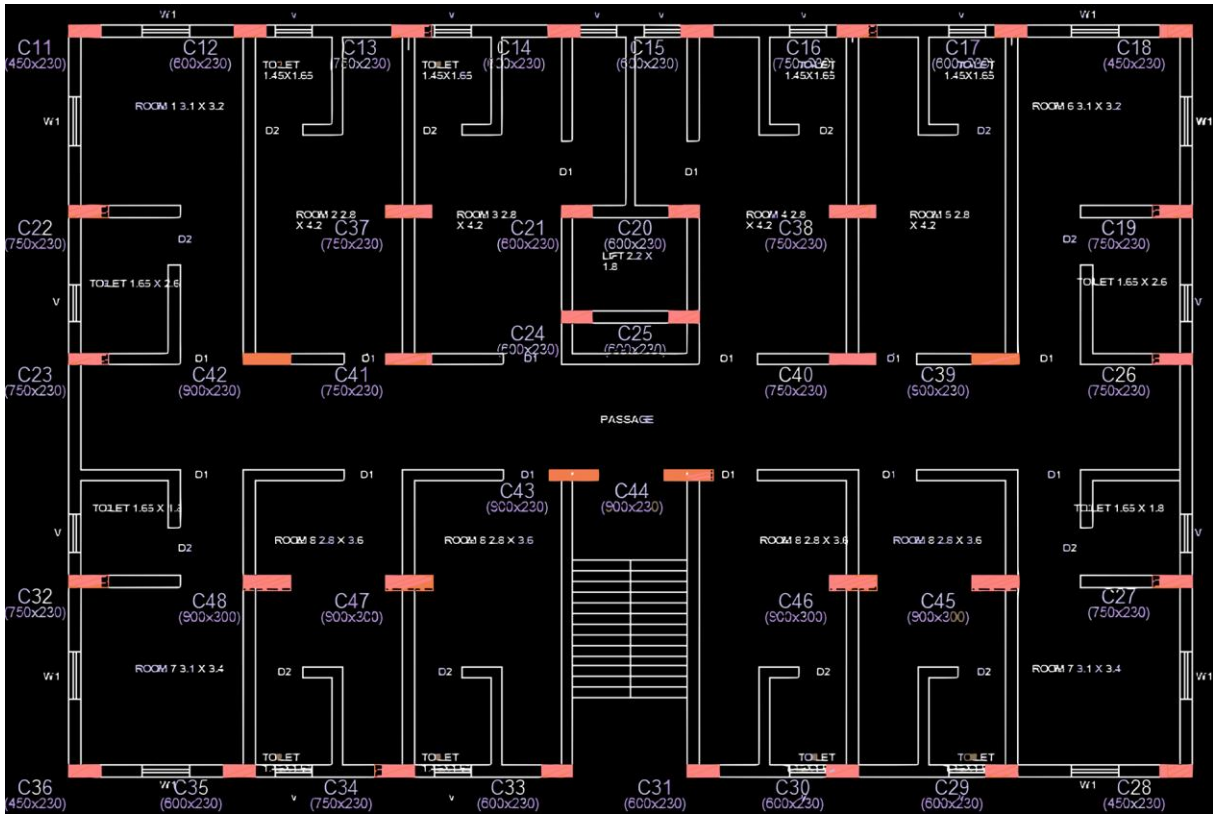


Figure 9. Plan of Case C1 (longer dimension of column is along the longer direction of building)

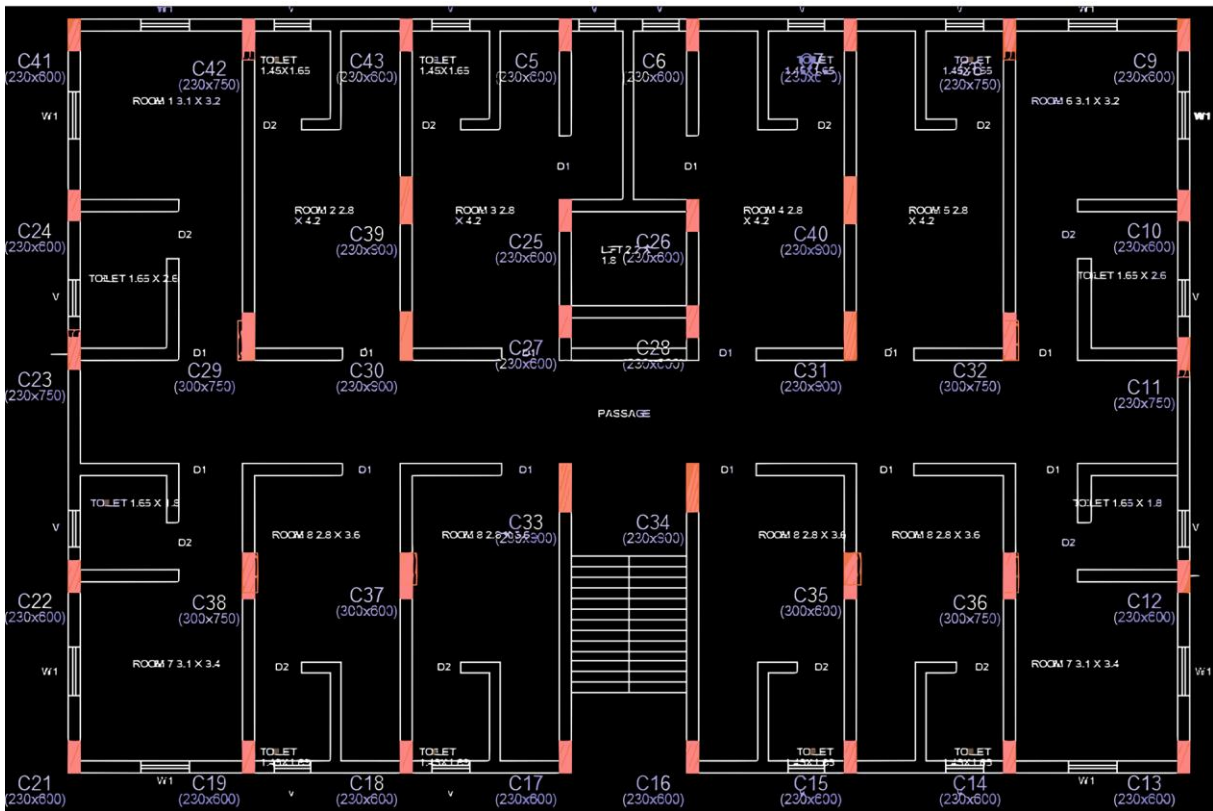


Figure 10. Plan of Case C2 (longer dimension of column is along the shorter direction of building)

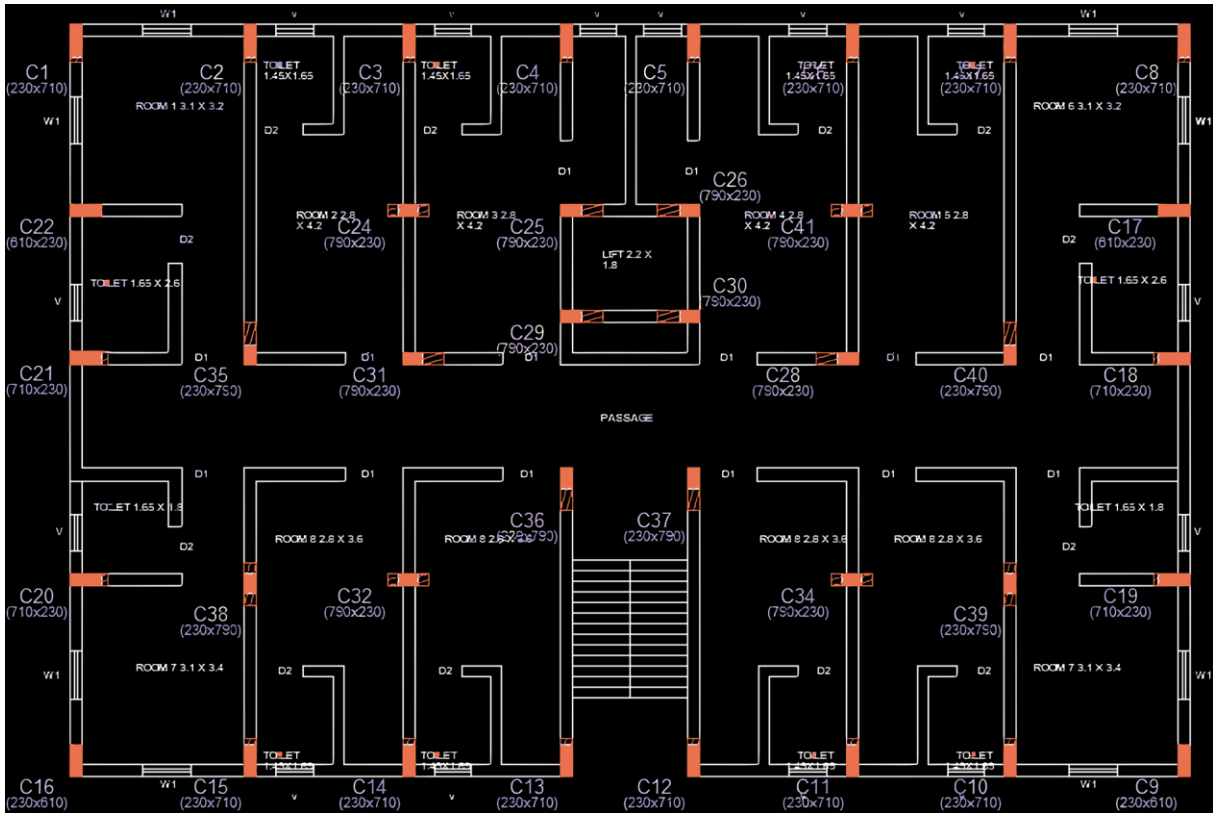


Figure 11. Plan of Case D1 (Central columns are of larger depth than peripheral columns)

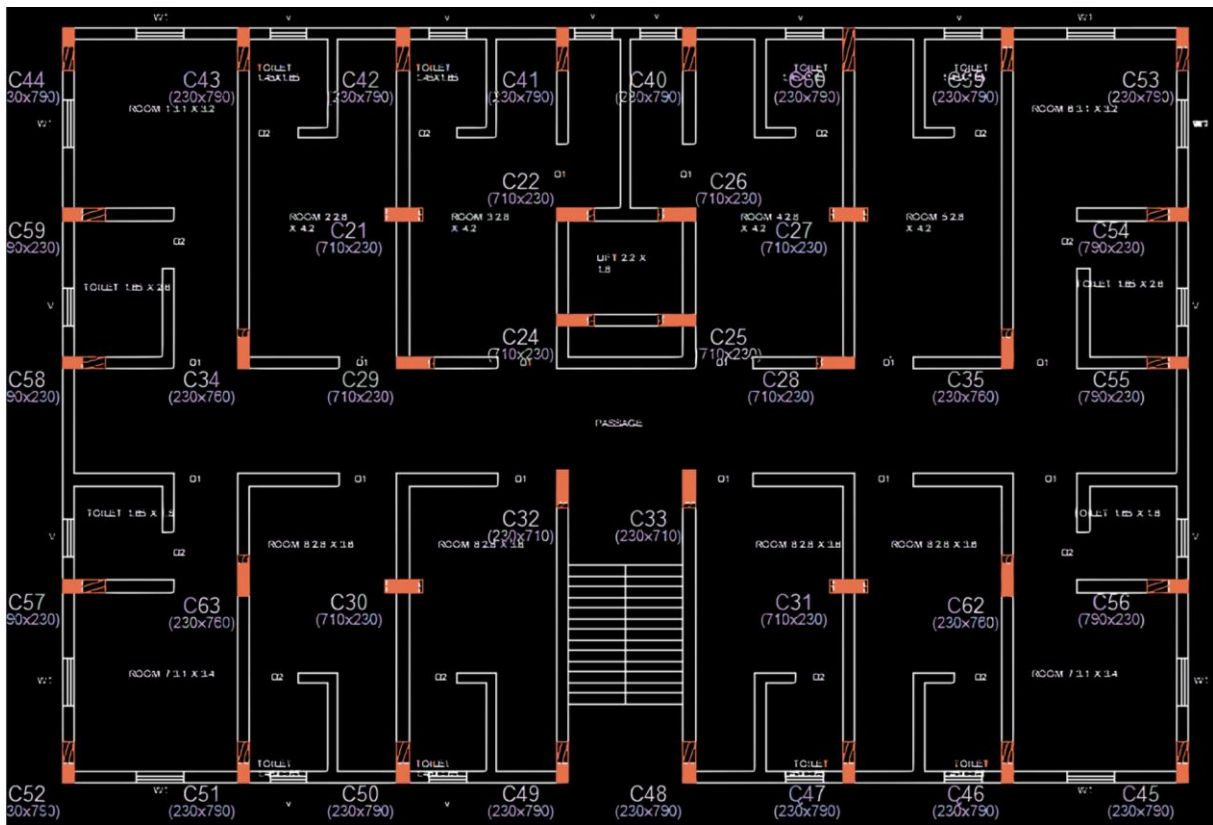


Figure 12. Plan of Case D2 (Peripheral columns are of larger depth than central columns)

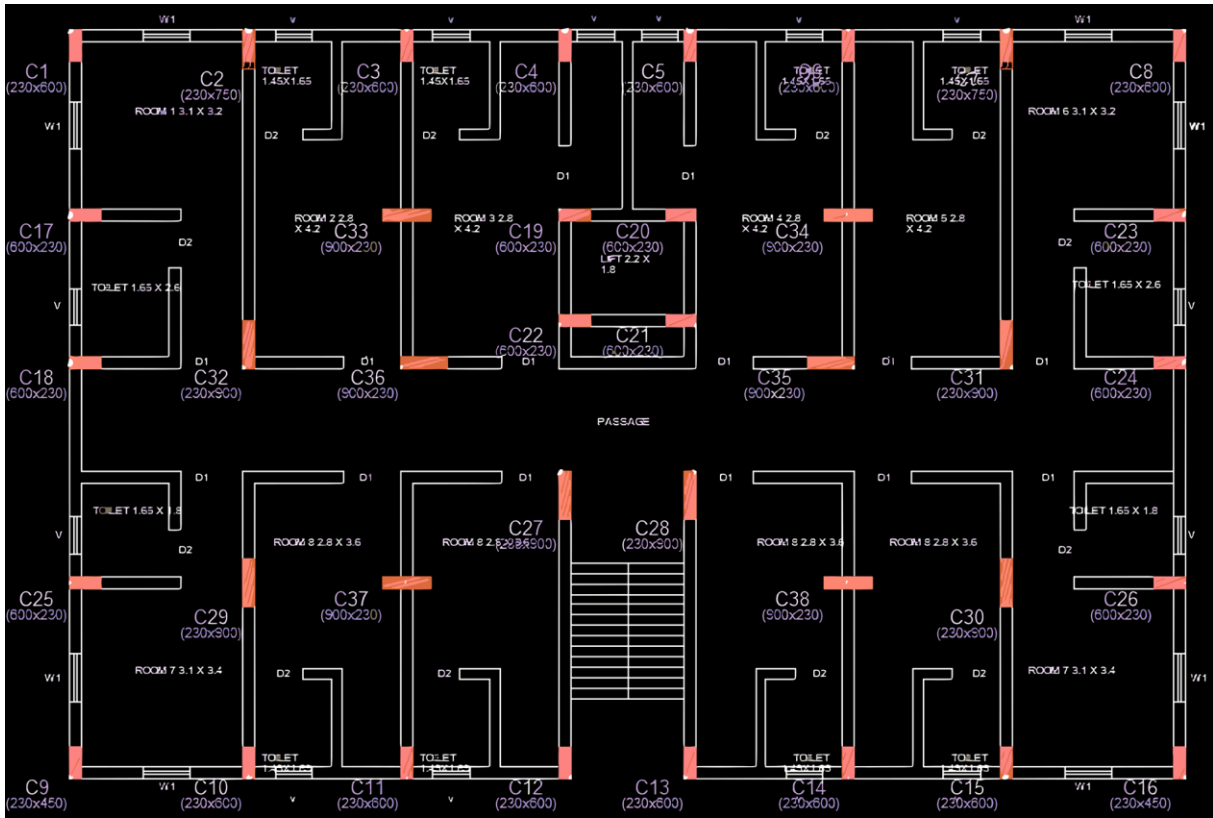


Figure 14. Plan of Case E2 (Steel Fe-500, Concrete – M25)

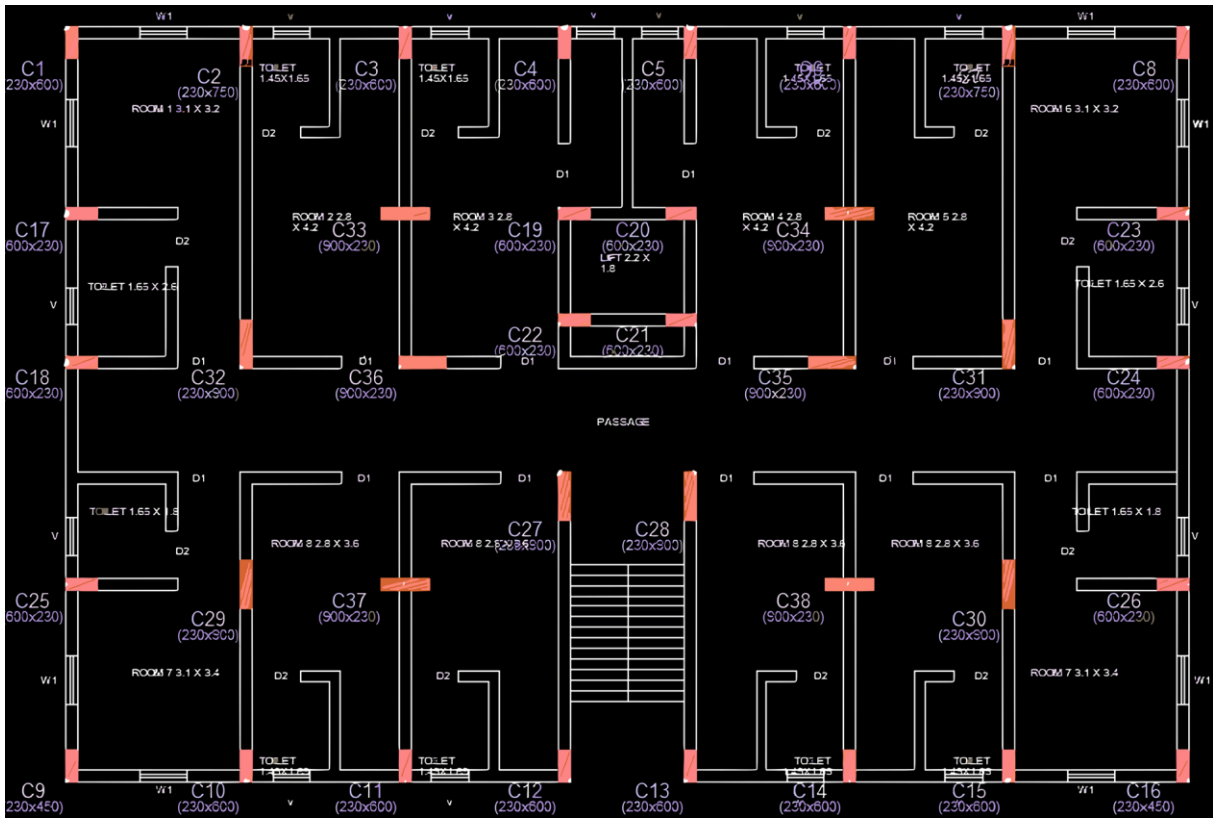


Figure 15. Plan of Case E3 (Steel Fe-415, Concrete – M30)

3. Results and Discussion

Various cases as discussed in the materials and methods section were considered to understand the influence of parameters such as column location, pattern of positioning, orientation, size of columns and grade of material on achieving design optimization. Optimizing the design simply means that the quantity of steel and concrete after design must be minimal without compromising on structural safety and serviceability following the standards of IS 456:2000.

3.1. Maximum Deflection

The maximum deflection in vertical direction is the first parameter that is evaluated for each case. The deflection was found to be maximum at the 10th floor and the same for all the cases were considered for comparison amongst cases A to D as presented in Figure 16.

Cases E1 to E3 correspond to grade of concrete and steel influencing the optimization. The effect of grade of concrete on deflection is presented in Figure 17.

It is evident that minimum deflection is achieved by following column positioning as presented in case B2 (Figure 7) and case E2 (Figure 14). Case E3 has a larger deflection even if the concrete is of better quality because of the fact that the contribution of steel of higher grade is more predominant than the quality of concrete which is also evident from case E2 having the least deflection. However, a comprehensive understanding of the best practices in column placement and material combination can be decided only after taking into consideration the quantity of steel and concrete required after design. The results on deflection only provide an insight on parameters that could result in reducing deflection if it is a requirement for the designers. All the cases are designed to have permissible deflection as per the provisions of IS 456:2000, hence all the designs are safe.

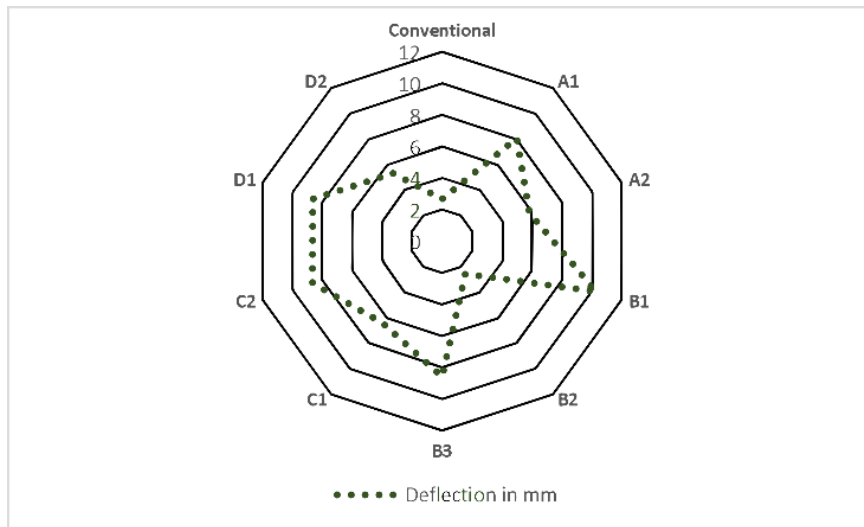


Figure 16. Deflection at 10th floor

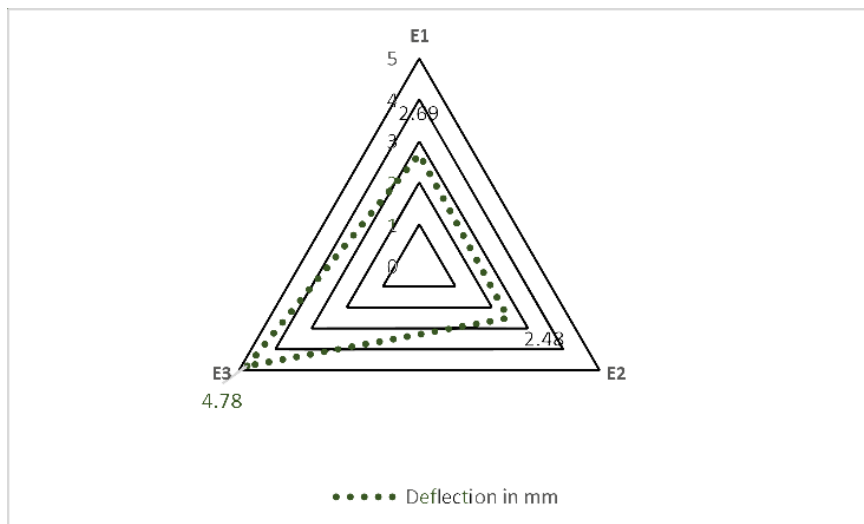


Figure 17. Influence of grade of material on deflection

3.2. Moment and Axial Load for Typical Columns

To study the moment and axial loads acting at each column for different cases, a total of 50 columns which are commonly used in different cases are considered as shown in Figure 18. Graphs of moments and axial load are plotted for a comparative study (Figure 19 to Figure 24).

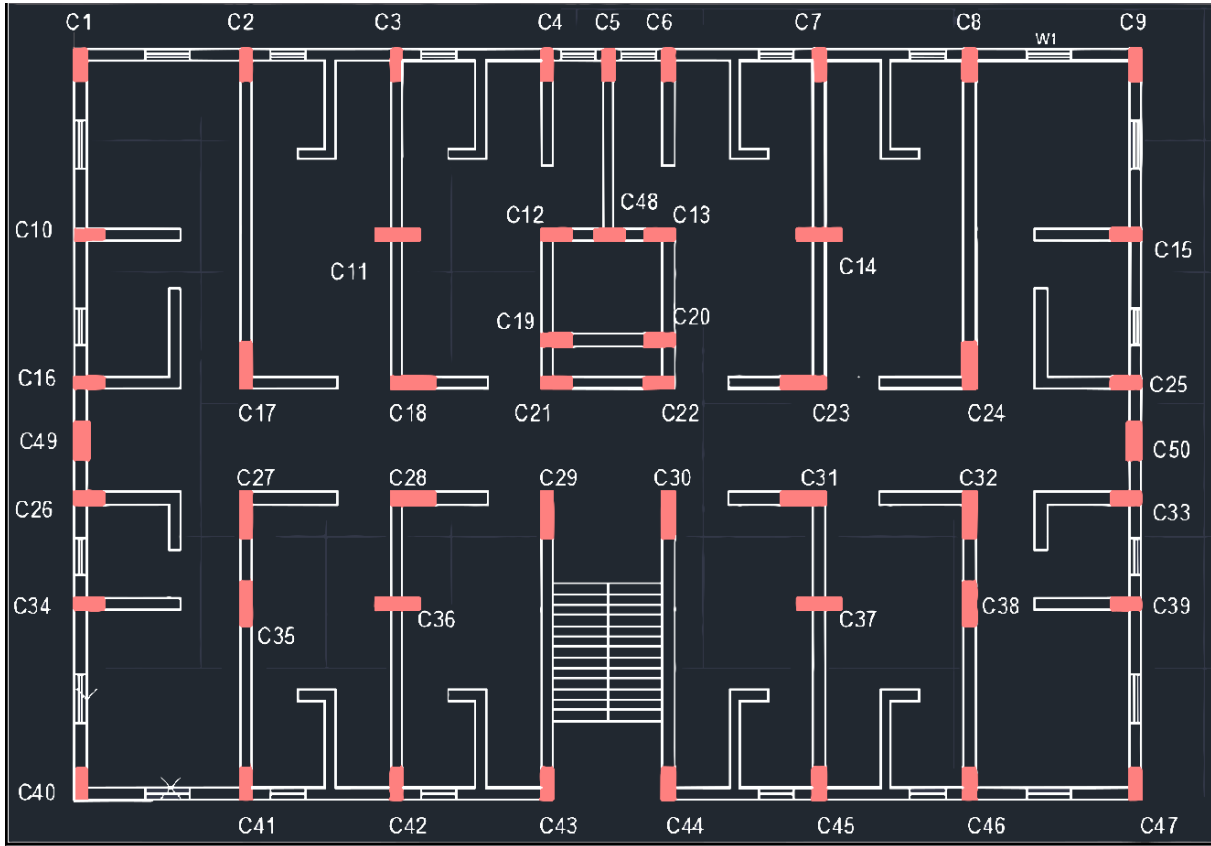


Figure 18. Plan showing typical 50 columns

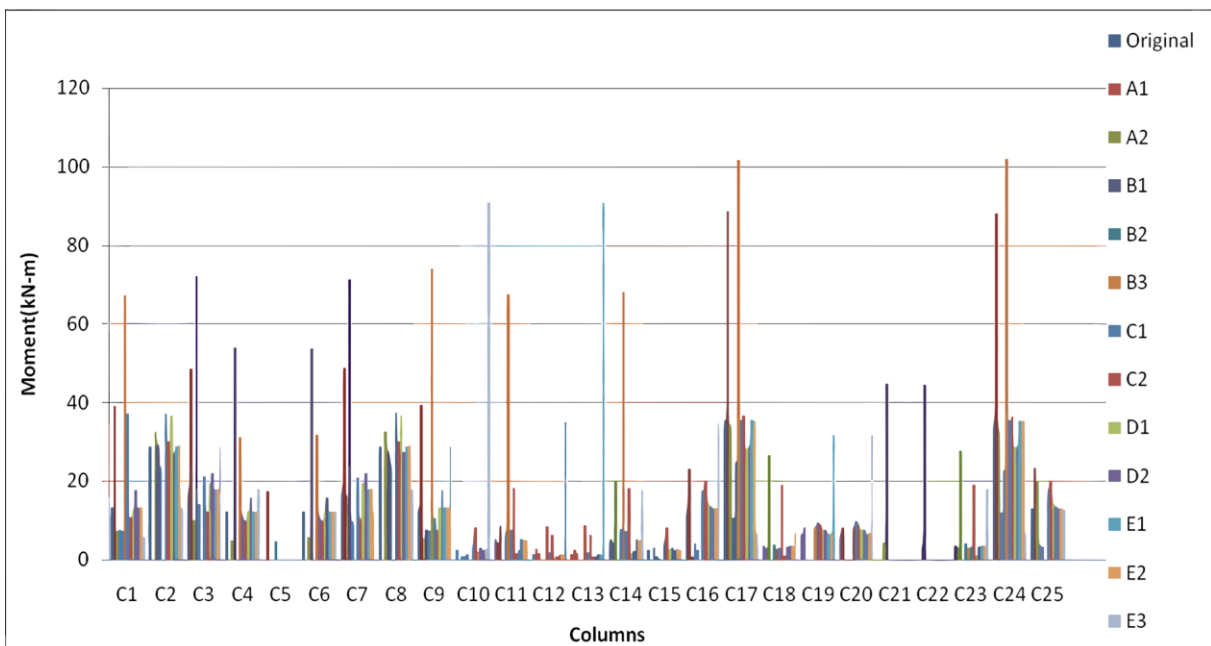


Figure 19. Moment about minor axis for first 25 columns of Ground floor

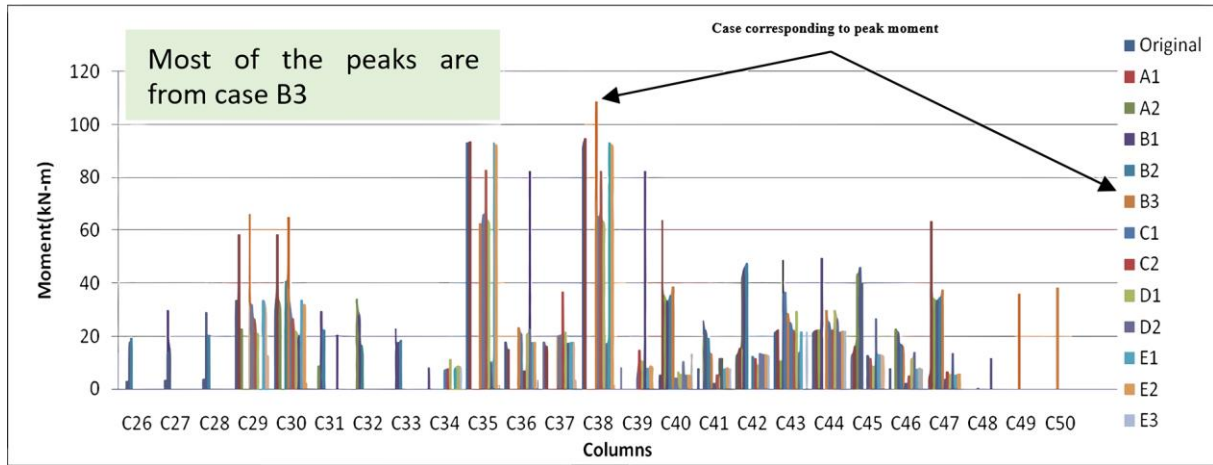


Figure 20. Moment about minor axis for next 25 columns of Ground floor

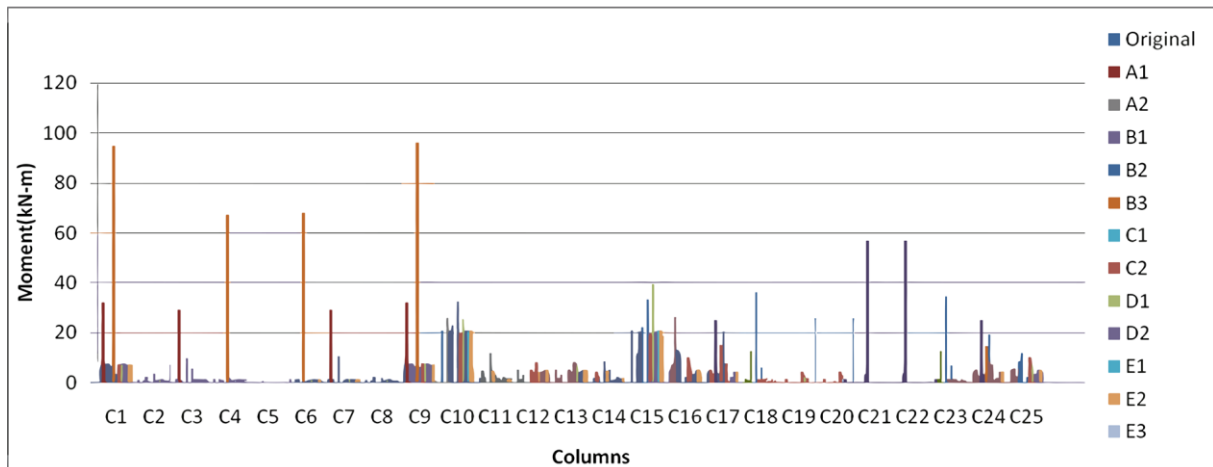


Figure 21. Moment about major axis for first 25 columns of Ground floor

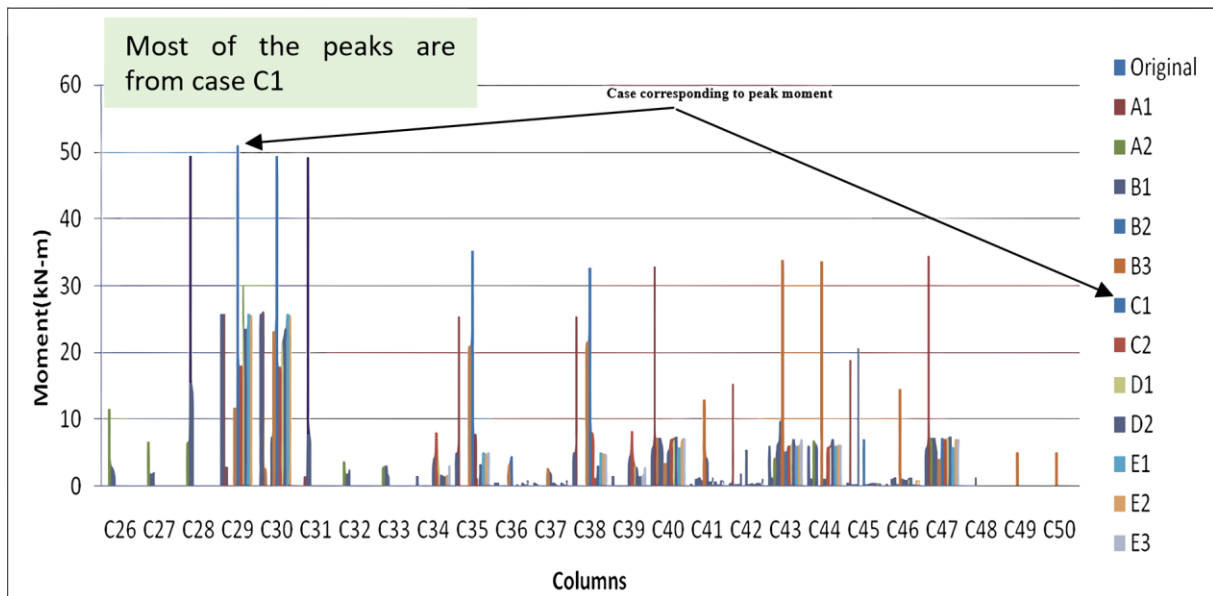


Figure 22. Moment about major axis for the next 25 columns of Ground floor

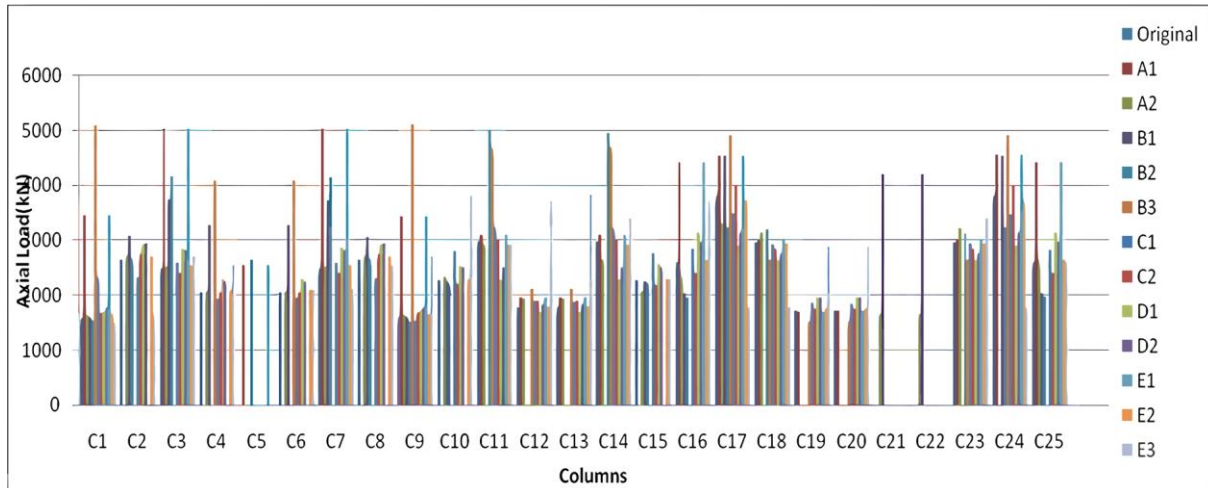


Figure 23. Axial load for first 25 columns of Ground floor

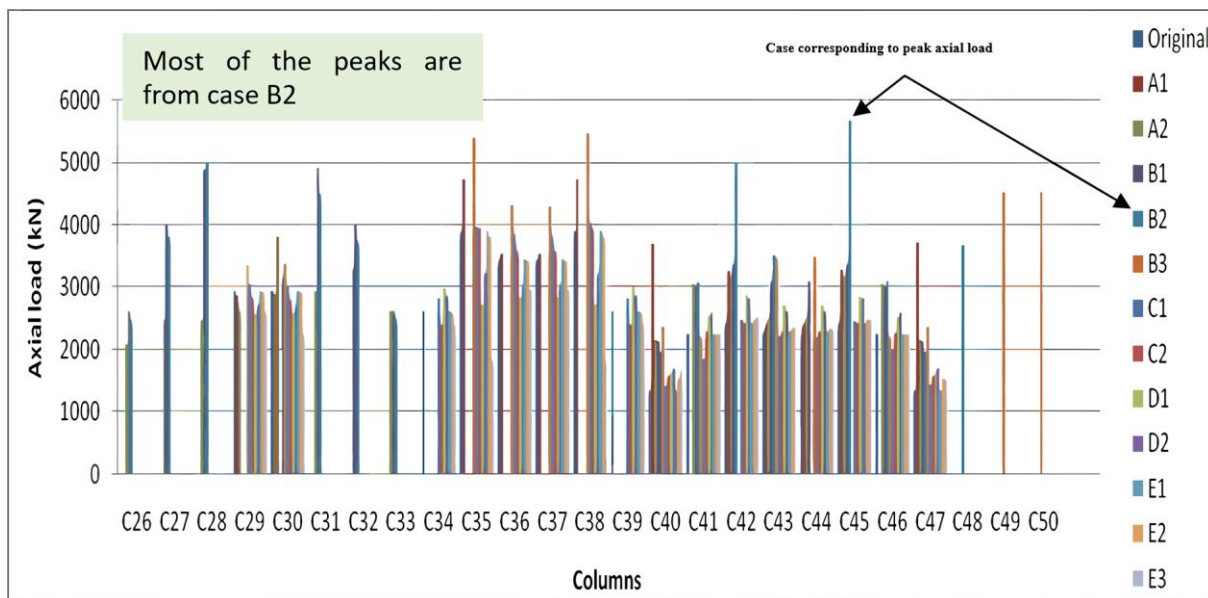


Figure 24. Axial load for next 25 columns of Ground floor

3.3. Concrete and Steel Quantity

After the design of building to satisfy limit state of collapse and limit state of serviceability for all cases the steel and concrete quantity is evaluated in kg per m² and are presented in Figure 25 and Figure 26.

3.4. Discussion

The following inferences can be drawn from the results of the investigation.

Cases B2, B3 and C1 show multiple columns subjected to peak moments and axial loads (Figure 20, Figure 22, and Figure 24). However, case B2 showed minimum deflection (Figure 16). Therefore, in general cases B3 and C1 may be avoided by designers. A detailed discussion on individual cases is presented further in this section.

Removing the alternate columns in the periphery (CASE A1) resulted in the increase in the quantities of both

concrete and steel by 5.63% and 15.1% respectively. There was an increase in deformation by 62.73%. The number of columns was reduced from 38 to 29.

Shifting the columns near passage (CASE A2) resulted in the increase in the quantity of concrete by 1.52% and decrease in the quantity of steel by 2.58%. There was an increase in the deformation by 1.18%.

Removing the central 8 columns (CASE B1) resulted in the decrease in the quantity of concrete by 1.52% and increase in the quantity of steel by 9.88%. There was an increase in the deformation by 74.87%. The number of columns was reduced to 30.

Following a box pattern (CASE B2) at the boundaries resulted in the increase in the quantities of concrete and steel by 14.02% and 13.53% respectively. There was an increase in the deformation by 0.17%. 4 extra columns were added near the lift and staircase. The number of columns was reduced to 32.

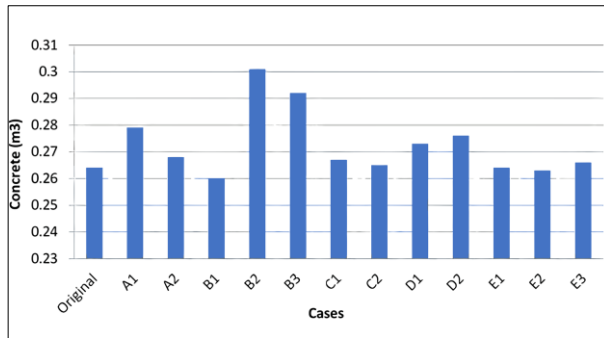


Figure 25. Concrete quantity per m² after design

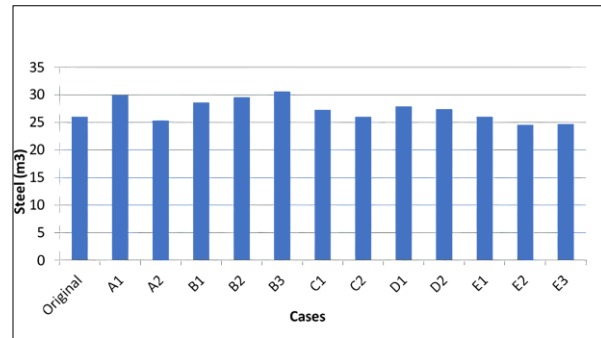


Figure 26. Steel quantity per m² after design

When all other columns except the edge columns at the periphery were removed (CASE B3), there was an increase in the quantities of both concrete and steel by 10.6% and 17.6% respectively. There was an increase in the deformation by 63.07%. 5 extra columns were added in the periphery. The number of columns was reduced to 28.

Orienting all columns in the longitudinal direction (CASE C1) resulted in the increase in the quantities of both concrete and steel by 1.13% and 4.68% respectively. There was an increase in deformation by 4.22%.

Orienting all columns in the transversal direction (CASE C2) resulted in the increase in the quantity of concrete by 0.38% and decrease in the quantity of steel by 0.04%. There was a decrease in the deformation by 4.05%.

When the dimensions of peripheral columns were kept 230 x 700 and that of inner columns were kept 230 x 775 (CASE D1), the quantities of both concrete and steel increased by 3.4% and 7.07% respectively. There was an increase in deformation by 49.75%.

When the dimensions of peripheral columns were kept 230 x 775 and that of inner columns were kept 230 x 700, the quantities of both concrete and steel increased by 4.55% and 5.23% respectively. There was a decrease in the deformation by 5.06%. In this case 4 inner columns failed. Hence their dimensions were increased to 230 x 750.

When the grade of steel was increased from Fe-415 to Fe-500 (CASE E2), the quantities of both concrete and steel decreased by 0.38% and 5.73% respectively. There was a decrease in deformation by 4.72%.

When the grade of concrete was increased from M25 to M30 (CASE E3), the quantities of both concrete and steel increased by 0.76% and 5.15% respectively. There was a decrease in deformation by 14.84%.

From the discussion it is evident that CASE A2 represents the optimum design based on quantity of steel and concrete required. It can be inferred that for a rectangular plan of a high raised structure the optimum positioning of column is attained by maintaining higher density of columns in the central band parallel to the longest side of the plan along with peripheral columns. This observation is also supported by comparing cases B1, B2 and B3 amongst which case B1 is the optimum case and it represents presence of peripheral columns and central band

of columns. Observing cases C1, C2 D1 and D2, it is clear that orienting columns perpendicular to the major axis of the building plan and having larger columns at periphery optimizes the design. Cases E1, E2 and E3 show that increasing grade steel should be preferred over increasing grade of concrete to attain optimal design.

4. Conclusions

In order to optimize the design, the study identified certain factors pertaining to column orientation and location. When planning a structure, engineers and architects may take into account the following factors (Percentage of the conventional structure).

1. Column Positioning: An optimum structural design was achieved by moving columns close to central band parallel to longest side of the building plan which reduces steel quantity by 2.58%. For a multistoried structure with rectangular plan, optimization is attained by maintaining higher density of columns in the central band parallel to the longest side of the plan.

2. Periphery Columns: The structure's efficiency was increased by maintaining the periphery columns. Removing alternate columns on the periphery resulted in increase in the quantities of both concrete and steel by 5.63% and 15.1% respectively which indicates the importance of peripheral columns in design optimization. Designers may choose a configuration of column placements such that the peripheral columns are maintained with more number of columns placed in the vicinity of core of the building plan.

3. Column Orientation: For better optimization, align columns perpendicular to the larger span. In case of a rectangular plan a decrease in the quantity of steel by up to 0.04% may be expected.

4. Inner Column Dimensions: Design optimization was aided by increasing the outer columns' dimensions relative to the inner columns.

5. Material Selection: By using higher-grade steel, the structure was further optimized by using less concrete and steel. Use of higher grade of steel is preferred over using high grade concrete. The quantities of both concrete and steel decreased by 0.38% and 5.73% respectively with the use of higher grade of steel.

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