Optimizing Skyscraper Design with Protostructures: A BS 8110 Analysis

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Abstract

The increasing demand for land-efficient construction due to urbanization has led to the proliferation of high-rise buildings, necessitating advanced design methodologies. This study explores the analysis and modeling of a 33-storey reinforced concrete building using ProtaStructure in compliance with BS 8110, the British Standard for structural use of concrete. The structure, designed for mixed-use purposes, incorporates key elements such as beams, flat slabs, and shear walls, supported by a raft foundation. The foundation was chosen for its ability to uniformly distribute heavy loads and minimize differential settlement, enhancing overall stability. ProtaStructure was employed for its capability to handle complex geometries, dynamic load scenarios, and multi-material systems. The software facilitated finite element analysis (FEA), allowing detailed evaluation of deflections, shears, and moments under various load conditions, including dead loads, live loads, wind forces. The design adhered to BS 8110 guidelines, ensuring compliance with safety and serviceability standards. The results revealed that the maximum axial load was 10105.982 kN, with peripheral columns bearing proportionally lower loads due to loadsharing mechanisms. Maximum deflection of the superstructure under service conditions were 0.000364 m (0.364 mm), well below the allowable span/250 limit. The raft foundation performed effectively, with a maximum soil bearing pressure of 26.441 kN/m², safely within the soil's bearing capacity of 125 kN/m². The raft thickness of 0.9 meters optimized material was used while ensuring stability. The study demonstrates how effectively ProtaStructure streamlines the design processes for high-rise buildings, reducing errors, and achieving cost-effective solutions. Exploring modern codes like Eurocode 2, incorporating sustainability measures, and conducting advanced soil-structure interaction studies can enhanced design precision. Further integration of ProtaStructure with Building Information Modeling (BIM) platforms and comparative studies with alternative software tools are also suggested to expand its applicability. This research underscores the synergy between traditional design standards like BS 8110 and contemporary structural analysis tools like Protastructure software in delivering robust and efficient solutions for modern high-rise buildings.

Keywords: *High-rise building, Skyscraper, Design, Modelling, ProtaStructure, BS8110, 33storey.*

1.1 Background of the Study

The continuous urbanization and increasing land scarcity have driven the need for high-rise buildings to maximize land use and accommodate growing populations. High-rise buildings, defined as structures significantly taller than their surroundings, require meticulous planning, analysis, and design due to the complex forces they encounter, including lateral loads from wind and seismic activity, as well as vertical loads from their own weight and occupants (Ali & Moon, 2007). Among these, the design and analysis of a 33-storey building are particularly challenging because the structural demands increase significantly with height.

ProtaStructure has emerged as a versatile tool for high-rise building design due to its ability to handle complex geometries, multi-material systems, and dynamic loads. Its seamless integration of analysis, design, and detailing functions reduces the potential for errors and accelerates project timelines (Prota Engineering, 2022). This paper explores how ProtaStructure's advanced features can be leveraged to design and model the 33-storey building, ensuring compliance with BS 8110.

The foundation selected type for the building is a raft foundation, chosen for its ability to distribute high loads uniformly and accommodate varying soil conditions. Raft foundations are particularly suited for high-rise buildings on moderately compressible soils, as they reduce differential settlement and enhance structural stability (Oyenuga, 2001). This design decision aligns with the principles of BS 8110, which emphasizes load transfer efficiency and safety in foundation design.

The objective of this research is to evaluate the structural performance of the building, including its load distribution, deflection patterns, and stability under various loading conditions. Special attention is given to the raft foundation, as it is the critical element in transferring loads from the superstructure to the subsoil. The results aim to provide insights into the applicability of ProtaStructure for similar high-rise projects and demonstrate the continued relevance of BS 8110 in modern structural engineering practices.

This study focuses on the analysis and modeling of a 33-storey tall building using ProtaStructure, a robust structural analysis and design software, in compliance with BS 8110. BS 8110, the British Standard for structural use of concrete, has been widely adopted in various regions for its comprehensive guidelines on design principles, material specifications, and safety requirements (British Standards Institution [BSI], 1997). Despite the global shift toward Eurocodes, BS 8110 remains relevant in regions where it continues to be the governing standard or for legacy projects.

2. Literature Review

2.1 High-Rise Buildings and Their Structural Considerations

High-rise buildings are a defining feature of modern cities, and their design has evolved to address the increasing demand for vertical expansion due to urbanization. These buildings are characterized by complex structural systems that must withstand a variety of forces, including gravity, wind, and seismic loads. The challenges in designing high-rise buildings lie not only in their height but also in the complexity of load distribution, material selection, and foundation design (Poulos, 2016). High-rise buildings must balance structural safety, serviceability, and aesthetic appeal, making the design process multifaceted and highly specialized.

High-rise buildings typically employ a combination of structural elements such as shear walls, beams, slabs, and foundations. The choice of materials, particularly reinforced concrete, is dictated by both economic factors and the need to provide sufficient strength and stability (Gambhir, 2006). Reinforced concrete is commonly used in high-rise construction due to its durability, ease of use, and ability to withstand dynamic and static loads. The integration of advanced tools like finite element analysis (FEA) software has significantly improved the design and analysis process for these structures, enabling engineers to account for complex load scenarios and optimize material usage (Ren et al., 2019).

2.2 Loads Affecting High-Rise Buildings

The design of high-rise buildings is influenced by various loads, including dead loads, live loads, wind loads, and, in some cases, seismic loads. Each of these forces affects the building's structural integrity and must be accurately modeled and analyzed to ensure safety and performance.

Dead Loads: These are the constant, non-variable loads that come from the weight of the building’s own structure, including floors, beams, walls, and other fixed components (American Concrete Institute, 2019). Dead loads typically form the baseline of a building’s load distribution.

Live Loads: These loads result from the use and occupancy of the building, including furniture, equipment, and human occupancy. For high-rise buildings, live loads can be significant, especially in mixed-use developments where the building is designed to accommodate commercial, residential, and office spaces (Islam, 2024). Live loads are dynamic and can fluctuate depending on the building's usage, requiring engineers to account for various scenarios in the design process.

Wind Loads: As high-rise buildings become taller, wind forces play a significant role in their structural design. Wind pressure increases with height, leading to the development of specific design guidelines for tall buildings. The effects of wind loads are dynamic and can cause the building to sway, which can impact both the safety and comfort of occupants. As noted by Zheng et al. (2021), wind load calculations for high-rise buildings are crucial for determining the stability of the structure and ensuring that the building can withstand extreme weather conditions.

Seismic Loads: In regions prone to earthquakes, seismic loads must also be considered. While not as universally impactful as wind loads, seismic forces can be critical for high-rise buildings, particularly in areas with significant tectonic activity. Structural systems, such as shear walls and braced frames, are used to resist lateral forces caused by seismic motion (Atlaoui, 2024).

2.3 BS 8110 Standard Codes and Their Application

BS 8110 is a British Standard that provides comprehensive guidelines for the design and construction of reinforced concrete structures. It is particularly relevant for high-rise buildings, where the design of structural elements such as beams, columns, slabs, and foundations are critical. BS 8110 has been widely adopted in the UK and other regions influenced by British design codes, offering a well-established framework for ensuring that buildings meet safety, stability, and serviceability requirements.

Structural Design Principles: BS 8110 outlines the principles for designing reinforced concrete elements, considering factors such as material strength, durability, and the structural capacity to resist various loads (British Standards Institution, 1997). The code provides guidelines for the calculation of bending moments, shear forces, and axial loads in reinforced concrete structures, which are essential for ensuring that the building can withstand the forces it will be subjected to during its lifespan (Arya, 2009).

Load Analysis: BS 8110 also includes specifications for analyzing loads, including the calculation of dead, live, wind, and other environmental loads. It stipulates the methods for determining load combinations and factors that ensure the building's safety under extreme conditions (British Standards Institution, 1997). The code is particularly useful for high-rise buildings as it offers clear methodologies for handling complex load scenarios, such as dynamic wind loads and the effects of thermal expansion and contraction.

Serviceability and Deflection Limits: In addition to safety, BS 8110 emphasizes the importance of serviceability in high-rise buildings. Serviceability refers to the building’s ability to perform as intended without excessive deflections, vibrations, or other issues that might affect the comfort and usability of the structure. According to the code, the maximum deflection for floors should not exceed a span-to-deflection ratio of 1/250 (British Standards Institution, 1997). This ensures that the building remains stable and comfortable for its occupants under regular use.

3. Methodology

The methodology adopted for this study involves a systematic approach to the design and analysis of a 33-storey building using ProtaStructure software, adhering to BS 8110 guidelines. The approach encompasses building modeling, load analysis, and foundation design, with an emphasis on ensuring safety, efficiency, and compliance with design standards.

3.1 Building Overview

Modelling of the Structure

The 33-storey building was thoroughly designed with the structural elements including beams, columns and slab place in proper position with the help of AutoCAD. The architectural designs/drawings are attached to this document. The arrangement of the floor for all storeys were made same to facilitate the ease of the computation and analysis in the Protastructure software.

Specifications

The 33-storey building is modeled as a mixed-use structure with a total height of approximately 105 meters. Each floor has a typical plan area of 168.83 square meters, consisting of office spaces. The structural system incorporates reinforced concrete (RC) components for the beams, columns, and slabs, designed to resist both vertical and lateral loads.

Structural Components

The structural design includes a central reinforced concrete core housing elevators and staircases, functioning as the primary lateral load-resisting system. The floor system uses flat slabs for ease of construction and optimized material usage, supported by columns spaced appropriately to ensure stability. Shear walls are introduced at critical locations to enhance lateral stiffness and stability, as recommended by BS 8110 for high-rise structures (BSI, 1997). The Plan view of the Structural Component is shown in Figure 3.1

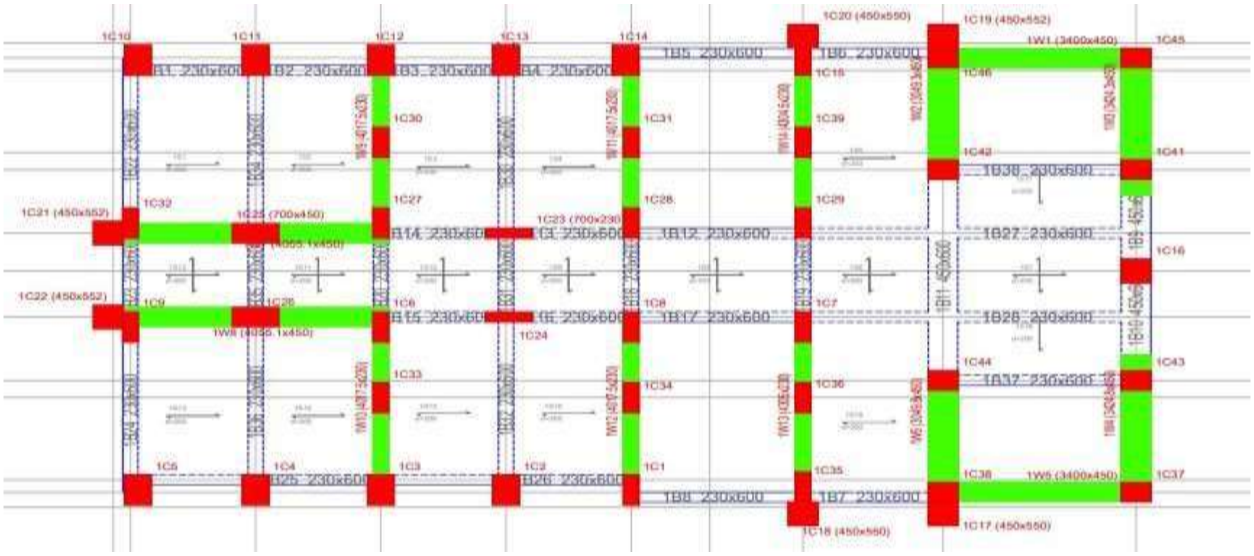


Fig. 3. 1: General Arrangement of Typical Storey Floor

As seen in fig 3.1, the notation is as follows

1B1 = Storey 1 Beam No. 1

1B2 = Storey 1 Beam No. 2

2B1 = Storey 2 Beam No. 1

1C1 = Storey 1 Column No. 1

1W1 = Storey 1 Shear Wall No. 1 5W3

= Storey 5 Shear Wall No. 3

3.2 Software and Design Standards

ProtaStructure Software

ProtaStructure was selected for its capability to model and analyze multi-story buildings efficiently. The software enables 3D visualization of the building, allowing detailed representation of structural elements. It supports the application of various loading scenarios, including static, dynamic, and environmental loads (Prota Engineering, 2022). ProtaStructure's built-in compliance with BS 8110 ensures that the designs meet safety and serviceability requirements.

BS 8110 Guidelines

BS 8110 provides a robust framework for the structural use of concrete, covering areas such as material specifications, load combinations, and limit state design principles. This standard ensures that the design achieves an acceptable level of safety under ultimate and serviceability conditions

(BSI, 1997). It is particularly relevant for this study due to its detailed provisions for reinforced concrete design, including member sizing, detailing of reinforcement, and crack control measures.

3.3 Analysis and Design Approach

Load Considerations

Dead Loads (DL): These include the self-weight of the structural elements, floor finishes, and permanent fixtures. Dead loads are calculated based on material densities and element dimensions as per BS 8110 guidelines (BSI, 1997).

Live Loads (LL): Variable loads such as furniture, occupants, and equipment are applied according to building usage, with load factors derived from BS 8110 recommendations.

Wind Loads: Wind pressure is calculated using regional wind speed data and applied to the structure as lateral forces. The software performs dynamic wind load analysis, accounting for building height and shape.

Seismic Loads: Although seismic activity in the region is moderate, the building is designed to withstand potential earthquake forces, with load combinations specified in BS 8110.

Raft Foundation Design

The raft foundation is designed to distribute the building's load evenly over a large area, minimizing stress concentrations on the underlying soil. ProtaStructure facilitates soil-structure interaction analysis to ensure that the foundation is adequate under both static and dynamic loads. The Slab of the Raft foundation has a total area of 290.55 square meters having 4m spread across all sides of the floor layout. Tha Raft foundation Layout is shown in Fig 3.2

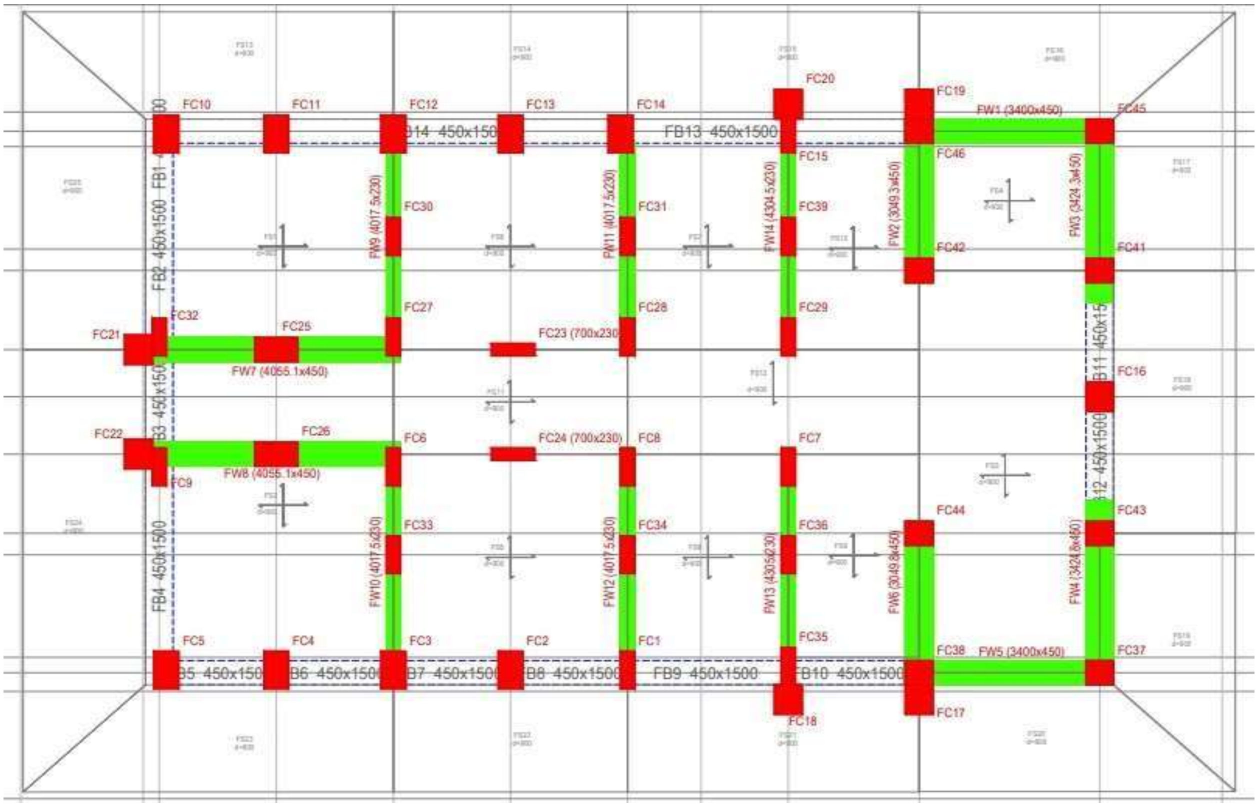


Fig. 3. 2: Raft Foundation Layout The following are considered the design of Raft foundation:

- Soil bearing capacity which can be obtained from geotechnical investigations.
- Differential settlement, controlled by designing an appropriate raft thickness and reinforcement layout.
- Load balancing to prevent tilting or uneven deformation of the foundation slab (Mosley et al., 1999).

Structural Analysis

Static and dynamic analysis is performed to evaluate the building's behavior under various loading conditions. The analysis process involves:

- Modeling: Creating a detailed 3D model in ProtaStructure, assigning materials, and defining element properties. The 3D Model of the structure can be seen in Fig. 2.2
- Load Application: Applying all relevant loads and combinations as per BS 8110.
- Analysis Execution: Running finite element analysis (FEA) to determine deflections, stresses, and moments.
- Design Optimization: Adjusting member sizes and reinforcement to achieve an efficient and code-compliant design (Prota Engineering, 2022).

4. Results and Discussion

4.1 Structural Behavior

Load Distribution

The analysis revealed that the structural components effectively distribute vertical and lateral loads throughout the building. The columns and core walls bear most of the axial loads, while the beams and slabs transfer loads horizontally. Lateral loads from wind and seismic forces are primarily resisted by the shear walls and the central core, ensuring stability and minimizing lateral drift.

ProtaStructure's finite element analysis (FEA) demonstrated that the structural elements are within safe stress limits as per BS 8110, with appropriate safety factors applied. The maximum axial load in the structure was calculated at 10105.982 kN, while peripheral columns experienced reduced loads due to load-sharing mechanisms (BSI, 1997). Table 3.1 shows the Axial load of the building analysis in all stories. The axial load on the structure increases downwards, thus storey 1 experienced the supports the highest magnitude of axial load in the structure. The axial Load on the Storey 1 is shown in Fig 4.1.

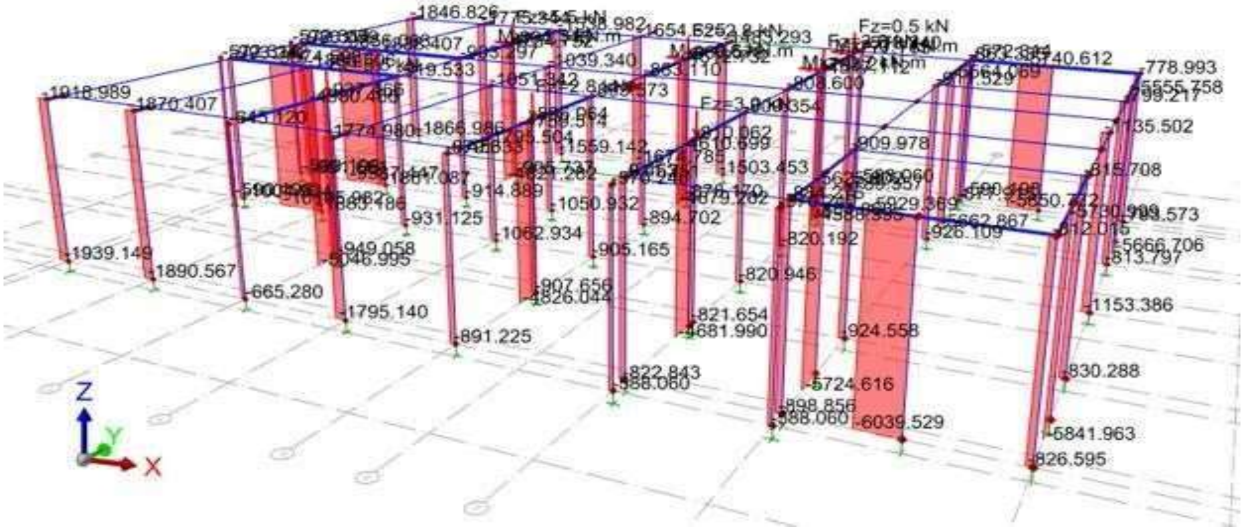
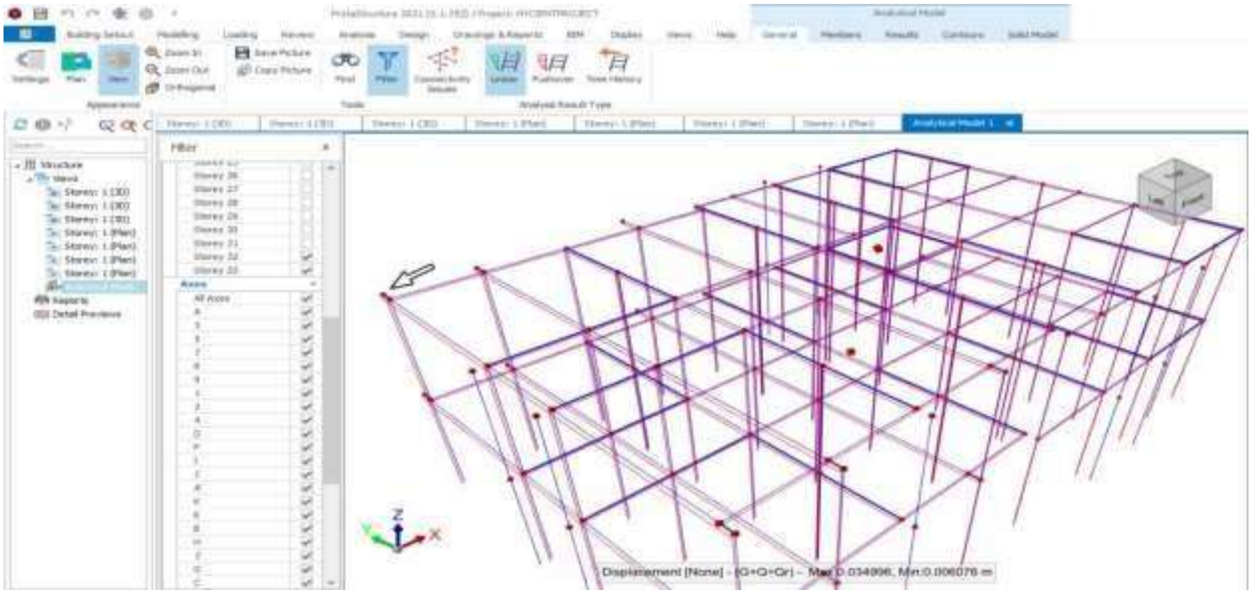


Fig. 4. 1: **Axial Load on the Storey 1**

Deflections and Stresses

Vertical deflection in the slabs and beams was found to be within acceptable limits. The minimum deflection in the structure is 0.000364 m while the maximum deflection under service load conditions was 0.034996 m, which is well below the allowable limit of span/250, as stipulated by BS 8110. The maximum deflection occurred at the top left corner of the topmost storey (Storey 33) where beams 33B1 (beam no. 1 at storey 33(, 33B22, slab 33S1, and column 33C10 are situated. For clarity of image, the deflection of the storey 32 and 33 is shown in Figure 4.2 with an arrow pointing at the point of maximum deflection.



Displacement [None] - (G+Q+Gr) - Max:0.034896, Min:0.006076 m

Fig. 4. 2: Deflection at Storey 32 and 33

The figure 3.2 depicts the deflection at storey 32 and 33 where the frame in blue color indicate the initial position of the structure and the frame in orange color indicate the position of the structure after deflection.

Stress analysis of the beams and columns confirmed that the reinforcement provided is adequate for resisting bending moments and shear forces. The critical bending moment for primary beams was calculated as 136.7 kNm and the maximum bending moment at shear walls results to 510.82 kNm, while shear forces peaked at 167.122 kN, necessitating shear reinforcement detailing in line with BS 8110 guidelines (BSI, 1997). Fig. 4.3 and 4.4 shows the moment and shear in storey 3 respectively for the typical frame layout.

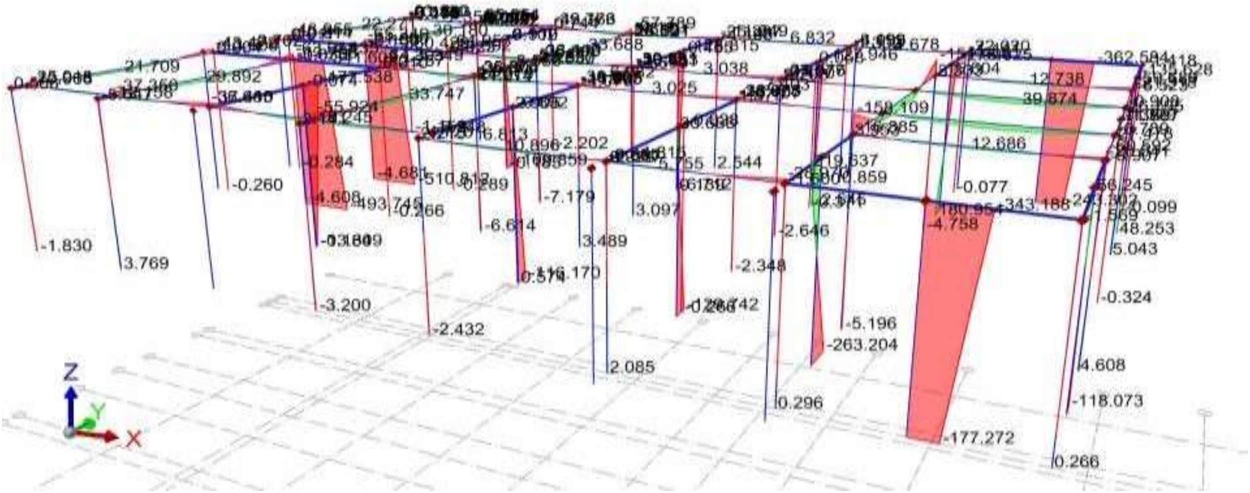


Fig. 4. 3: Bending Moment Diagram in x direction at storey 3

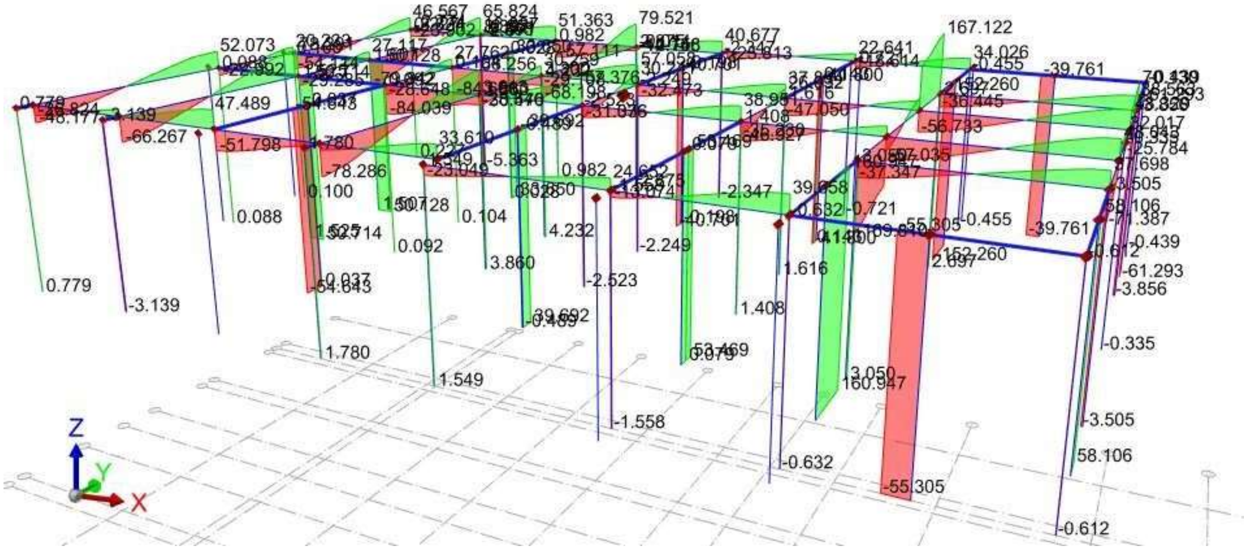


Fig. 4. 4: Shear Force Diagram in x direction at storey 3

4.2 Foundation Performance

Pressure Distribution

The raft foundation successfully distributes the building's load evenly across the soil. ProtaStructure's soil-structure interaction analysis showed that the maximum bearing pressure on the soil was 26.441 kN/m², which is within the soil's safe bearing capacity of 125 kN/m². This indicates that the raft design is efficient and ensures no excessive stress concentrations (Tomlinson & Woodward, 2001). **Deflection Analysis**

deflection calculations indicate that the maximum deflection is 5.11 mm which fall within the tolerable limit (L/d ratio) specified by BS 8110, ensuring that the superstructure remains stable and free from significant distortion.

Optimization

To enhance the foundation's performance, the raft thickness was optimized at 0.9 meters with an upstand beam of 1.5 meters, balancing material efficiency with structural safety. Reinforcement detailing in the raft was carried out to resist bending moments induced by uneven loading.

4.3 Comparative Analysis

Using ProtaStructure for this analysis provided numerous advantages over manual methods and other traditional software tools. One of the most significant benefits was time efficiency, as the software automated repetitive calculations and offered integrated load combinations, which greatly reduced the time spent on modeling and analysis. This allowed for faster iteration and design optimization, contributing to a more efficient workflow. Additionally, the accuracy of ProtaStructure's finite element analysis ensured a detailed and precise representation of stress and deformation patterns, which is essential for complex structural designs.

When compared to manual calculations, the use of ProtaStructure streamlined the design process considerably. Manually designing a 33-storey building would have been time-consuming and prone to errors, especially when handling complex load combinations and checking for deflections. ProtaStructure mitigated these challenges by ensuring consistency and precision throughout the process. The software also allowed for quick design adjustments, which is crucial for optimizing materials and structural performance. This level of efficiency and accuracy would be difficult to achieve with manual methods alone.

ProtaStructure also addressed several key challenges in the design of high-rise buildings. One of the primary difficulties was the need to accurately account for dynamic wind loads and seismic forces, which are critical for ensuring safety in high-rise structures. ProtaStructure’s dynamic analysis capabilities provided a reliable way to model and address these forces, ensuring compliance with the safety requirements outlined in BS 8110. The software's ability to incorporate these complex forces into the design process further validated its usefulness in creating safe and efficient high-rise buildings.

5. Conclusion and Recommendation

5.1 Conclusion

The analysis and modeling of the 33-storey building have led to several key findings. The study successfully incorporated reinforced concrete structural elements and a raft foundation, and the design process was efficiently managed using ProtaStructure software. The software ensured that the design adhered to the BS 8110 guidelines, guaranteeing that all structural elements were capable of performing within the required safety margins. This comprehensive approach allowed for a thorough assessment of the building's performance under various load combinations, confirming that all elements, including shear walls, columns, and slabs, functioned effectively within acceptable limits.

In terms of load distribution, the shear walls played a crucial role in resisting lateral forces, while the columns and slabs efficiently distributed vertical loads. The raft foundation, designed to provide uniform load distribution, helped minimize differential settlement, keeping it well within tolerable limits. These findings were aligned with the guidelines outlined by Tomlinson & Woodward (2001), which emphasizes the importance of controlling settlement in high-rise structures. The ProtaStructure software also demonstrated its value by providing time-efficient and accurate modeling, ensuring that the design process was both reliable and effective.

BS 8110's continued relevance was highlighted throughout the analysis, particularly in regions that adhere to traditional codes for reinforced concrete design. Its comprehensive provisions, which cover critical aspects like member sizing, crack control, and safety factors, remain invaluable for ensuring structural integrity. The iterative design process resulted in an optimized solution, balancing material efficiency with safety and serviceability. For example, the raft foundation's 0.9 meter thickness represented an ideal compromise between cost-effectiveness and performance, and the reinforcement detailing satisfied both strength and durability requirements.

5.2 Recommendations

To further improve the design of high-rise buildings, the adoption of more advanced design codes like Eurocode 2 is recommended. While BS 8110 remains practical, Eurocode 2 offers enhanced safety provisions and efficiency, particularly for taller and more complex structures. The code includes advanced guidelines for seismic and fire-resistant designs, which are becoming increasingly important in urban high-rise buildings. By adopting these modern provisions, designs can better address the challenges posed by evolving safety standards and environmental factors.

Another area for improvement lies in soil-structure interaction modeling. Future studies should focus on more detailed geotechnical analysis using advanced tools or coupled modeling techniques. These approaches could provide a more accurate assessment of foundation performance, especially in regions with challenging soil conditions or those prone to seismic activity. In addition, sustainability should be prioritized by integrating environmentally friendly construction practices. The use of high-performance concrete or recycled materials could optimize designs, and ProtaStructure's ability to accommodate these materials should be leveraged for future projects.

Dynamic load considerations and alternative foundation systems also present opportunities for refinement. For regions with significant seismic activity or high wind speeds, simulations using time-history or response spectrum analysis could further improve lateral load resistance. Additionally, while the raft foundation performed well, exploring alternative foundation systems, such as piled rafts or combined footings, may offer better performance in specific soil conditions or under varying load demands. The integration of Building Information Modeling (BIM) into future projects would also streamline coordination and improve project management, enhancing visualization, clash detection, and lifecycle analysis. Finally, conducting further research comparing ProtaStructure with other software tools like ETABS or STAAD.Pro could help identify its strengths and limitations in high-rise building design.

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