JOURNAL SIPIL
Structures, Infrastructure, Planning, Implementation, and Legislation

Study on the Optimization of Concrete and Reinforcement Steel Volume in the Superstructure Work of Multi-Story Buildings

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Article Information
Received: September 04, 2025
Revised: October 22, 2025
Online: October 25, 2025

Keywords
Concrete Volume, Optimization, Reinforced Concrete, Reinforcement Steel, SNI 2847:2013, Superstructure, Sustainability

ABSTRACT

The efficient use of materials in reinforced concrete (RC) superstructures is a critical challenge in modern construction, driven by both economic and environmental considerations. This study investigates the optimization of concrete and reinforcement steel volumes in the superstructure of a multi-story RC building by analyzing project-specific volumetric data. The research employs a quantitative approach, beginning with data collection from structural design documents, followed by structural analysis in accordance with SNI 2847:2013 and SNI 1727:2013, and concluding with optimization strategies based on comparative and algorithmic methods. The results indicate that slabs consume the largest portion of concrete, accounting for 58.93% of the total volume, while beams and columns account for 31.33% and 9.74%, respectively. Reinforcement steel consumption was more balanced, with beams (37.96%) and slabs (36.72%) dominating, and columns contributing 25.32%. These findings are consistent with global trends, where slabs and beams represent the most material-intensive components in RC structures. The study highlights the potential for optimization strategies such as reducing slab thickness, refining reinforcement detailing, or applying algorithm-based approaches like genetic algorithms and MINLP to achieve significant material savings without compromising safety. By integrating empirical volumetric data with computational optimization methods, this research provides both theoretical insights and practical recommendations to improve the structural efficiency, cost-effectiveness, and sustainability of multi-story RC buildings.

***Keywords**: Concrete Volume, Optimization, Reinforced Concrete, Reinforcement Steel, SNI 2847:2013, Superstructure, Sustainability*

DOI: http://doi.org/10.69855/sipil
Available online at website: https://gpijournal.com/index.php/sipil
PUBLISHED BY : G Press Indonesia

INTRODUCTION

The development of structural engineering has increasingly emphasized the efficient use of construction materials, particularly in the design of reinforced concrete (RC) multi-story buildings. Concrete is a material that is widely used in superstructure work because of its high compressive strength and durability; however, its weakness in resisting tensile stresses requires reinforcement with steel bars. This combination forms the basis of reinforced concrete design, which has been standardized in various building codes such as SNI 2847:2013, regulating the structural requirements for buildings in Indonesia (Badan Standardisasi Nasional [BSN], 2013). The integration of concrete and steel reinforcement ensures that structural elements such as slabs, beams, and columns can perform safely under diverse load conditions. Nevertheless, excessive or inefficient use of these materials can result in increased project costs, higher environmental impacts, and unnecessary energy consumption during construction. Thus, the optimization of concrete and reinforcement steel volumes is not only a technical necessity for structural safety but also a key strategy for achieving cost-effectiveness and sustainability in construction projects.

Over the last decade, numerous studies have demonstrated the advantages of optimization strategies in reinforced concrete structures. Research on sustainable building design indicates that by applying energy-efficient and material-optimized structural planning, embodied energy in RC buildings can be reduced by approximately 12% with only minimal cost trade-offs, while the use of higher-strength reinforcement steel substantially reduces carbon emissions (Niu et al., 2024). Similar investigations also reveal that the distribution of material usage across structural components is uneven. For instance, slabs typically account for the largest share of total concrete volume sometimes up to 80% whereas columns consume only 2.5% to 14% of the total (Paya-Zaforteza et al., 2020). This discrepancy highlights the significant potential for optimization, as reducing the thickness or modifying the reinforcement design of slabs may lead to greater savings compared to focusing solely on beams or columns. From an engineering perspective, this suggests that identifying material-intensive elements and implementing optimization techniques at those points can yield meaningful improvements in both cost and sustainability performance.

In terms of methodological advances, optimization in structural engineering has evolved from basic cost-saving calculations to the application of sophisticated algorithms and multi-objective approaches. Studies applying genetic algorithms and nonlinear programming have shown their effectiveness in minimizing both construction costs and environmental footprints, while ensuring compliance with structural safety codes (Lee & Ahn, 2006; Zhang et al., 2023). Low-carbon optimization using genetic algorithms has successfully demonstrated reductions in material usage and emissions, particularly in beams and primary structural components (Zhang et al., 2023). In addition, optimization through multi-integer nonlinear programming (MINLP) has proven capable of delivering cost reductions of up to 25% for beams and nearly 14% for columns in multi-story RC frames (iManager Publications, 2019). These findings confirm that the application of computational optimization techniques can effectively balance the three fundamental objectives of structural design: safety, cost-efficiency, and sustainability.

The incorporation of advanced computational tools has further accelerated progress in structural optimization. With the adoption of cloud computing and evolutionary algorithms, engineers are now able to manage complex, high-dimensional optimization problems in RC structures more efficiently (Chen & Wang, 2022; Li, 2021). In seismic-prone regions, performance-based optimization frameworks using pushover analysis and metaheuristic methods such as the artificial bee colony algorithm have been applied to minimize structural weight while ensuring compliance with seismic performance targets including Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) (Rahimi et al., 2023). These approaches underscore the growing importance of integrating computational intelligence into structural engineering practice, particularly for multi-story and high-rise construction.

Despite the wealth of research in this domain, there remains a gap between theoretical optimization models and their practical implementation in real projects. Most studies emphasize generic optimization frameworks but often overlook the necessity of applying project-specific volumetric data of concrete and reinforcement steel. Detailed construction documentation, such as that used in project planning exercises, provides essential empirical data on material distribution across slabs, beams, and columns. By integrating these actual volumetric figures into optimization analyses, engineers can ensure that their strategies are not only mathematically optimal but also feasible and directly applicable to construction practice. This approach offers the potential to transform optimization from an abstract computational exercise into a practical decision-making tool that delivers tangible savings in material costs, project budgets, and environmental impact.

Within this context, the present study aims to focus on the optimization of concrete and reinforcement steel volumes in the superstructure of multi-story buildings by making use of detailed volumetric data. The objectives are threefold: first, to quantify the distribution of concrete and reinforcement steel in different superstructure components such as slabs, beams, and columns; second, to identify material-intensive elements and evaluate opportunities for reducing material usage without compromising structural safety; and third, to apply optimization strategies including genetic algorithms and MINLP to propose alternative designs that balance performance, cost, and sustainability. By bridging empirical construction data with modern optimization frameworks, this research seeks to contribute both theoretically and practically to the advancement of structural efficiency in reinforced concrete building design.

METHODS

This study adopts a quantitative and analytical approach to evaluate and optimize the volumes of concrete and reinforcement steel used in the superstructure of multi-story reinforced concrete (RC) buildings. The methodology integrates design standards, structural analysis, and computational optimization techniques to ensure that results are both technically sound and practically applicable.

1. Research Design

The study is based on a case project of a two-story reinforced concrete building located in Padang, Indonesia, as documented in the preliminary design and structural calculation report. The research is structured into three sequential stages: (1) data collection and volume quantification, (2) structural analysis using design standards, and (3) optimization of concrete and reinforcement usage.

2. Data Collection and Volume Quantification

Primary data were obtained from the detailed design documentation of the project, which included dimensions of structural elements and reinforcement detailing for columns, beams, and slabs. The volumes of concrete and steel reinforcement were calculated based on these design drawings and schedules of quantities.

a. Concrete volume was derived from the geometric dimensions of each structural element (columns, beams, slabs).
b. Reinforcement volume (weight) was determined by calculating the total length of reinforceme bars multiplied by the unit weight of steel according to bar diameters used.

This process produced a comprehensive inventory of material usage in the superstructure, serving as the baseline for optimization analysis.

3. Structural Analysis

The structural design adhered to the provisions of SNI 2847:2013 – Requirements for Structural Concrete for Buildings (BSN, 2013)" and "SNI 1727:2013 – Minimum Loads for the Design of Buildings and Other Structures. Load calculations considered dead loads, live loads, and additional permanent loads, which were applied to structural elements to obtain bending moments, shear forces, and axial loads. Both manual calculation methods (e.g., moment distribution or Cross method) and computer-assisted structural analysis using SAP2000 were employed to verify the accuracy of results.

The reinforcement design was conducted according to the calculated internal forces, following the strength design method (ultimate strength design). The required area of reinforcement for columns, beams, and slabs was determined and compared against the provided reinforcement in the case project to identify potential over-design or under-design.

4. Optimization Framework

To evaluate efficiency, an optimization framework was developed with the following objectives:

a. Minimization of concrete volume, particularly in slabs which represent the largest portion of material consumption.
b. Reduction of reinforcement steel usage without compromising structural safety and serviceability.
c. Balancing structural safety, cost, and sustainability by proposing alternative configurations.

The optimization approach involved:

a. Comparative analysis between the baseline design and modified design alternatives, where slab thickness, beam dimensions, or reinforcement ratios were adjusted within the limits permitted by SNI 2847:2013.
b. Application of computational optimization techniques, particularly multi-objective methods such as genetic algorithms and nonlinear programming, as demonstrated in prior studies (Lee & Ahn, 2006; Zhang et al., 2023). These methods were used to explore design alternatives and identify optimal solutions with the lowest combined material volume and cost.
c. Evaluation criteria included structural safety (ultimate strength and serviceability checks), material efficiency (percentage reduction in concrete and reinforcement volumes), and cost implications.

5. Validation

The optimized solutions were validated against SNI 2847:2013 requirements to ensure that minimum strength, ductility, and serviceability criteria were maintained. Comparative results were then analyzed to determine the potential material savings and economic benefits relative to the baseline project design.

RESULTS

The analysis of material usage in the superstructure of the studied building project focused on three primary structural components: columns, beams, and slabs. Quantitative data on concrete and reinforcement steel volumes were extracted from the detailed design documentation, providing the basis for subsequent optimization analysis.

1. Concrete Volumes

The total volume of concrete required for each structural component was calculated based on the geometric dimensions of the elements. The results are summarized in Table 1.

Table 1. Concrete Volume Distribution

Structural Element	Volume of Concrete (m^3)	Percentage of Total (%)
Columns	16.85	9.74
Beams	54.20	31.33
Slabs	101.89	58.93
Total	172.94	100.00

The results show that slabs accounted for the largest portion of concrete consumption at nearly 59% of the total volume, followed by beams at 31%, while columns contributed less than 10%. This indicates that optimization efforts targeting slab design offer the greatest potential for material reduction.

2. Reinforcement Steel Volumes

The reinforcement steel requirement was calculated based on reinforcement detailing, bar lengths, and diameters provided in the design.

Table 2. Reinforcement Steel Volume Distribution

Structural Element	Weight of Reinforcement (kg)	Percentage of Total (%)
Columns	6,550	25.32
Beams	9,820	37.96
Slabs	9,480	36.72
Total	25,850	100.00

Unlike concrete, the reinforcement steel was more evenly distributed between beams (38%) and slabs (37%), with columns consuming about 25% of the total reinforcement. This distribution suggests that optimization strategies must consider not only slab thickness but also reinforcement detailing in beams to achieve significant reductions.

3. Comparative Analysis

From the results above, several key findings can be highlighted:

a. Concrete consumption is heavily concentrated in slabs, which account for more than half of the total volume. Therefore, strategies such as reducing slab thickness or applying voided slab systems could provide substantial savings.
b. Reinforcement consumption is shared almost equally between beams and slabs, indicating that optimization in reinforcement detailing (e.g., adjusting bar spacing, using higher strength steel) may be necessary to reduce overall usage.
c. Columns, although critical for structural stability, consume a relatively small proportion of total material. Hence, optimization in columns may yield less significant savings compared to slabs and beams.

4. Implications for Optimization

The distribution of material usage reinforces the importance of focusing optimization efforts on slabs and beams, where most of the concrete and reinforcement steel are consumed. By applying optimization frameworks such as genetic algorithms or nonlinear programming, alternative design solutions can be evaluated to minimize these volumes while maintaining structural safety according to SNI 2847:2013.

DISCUSSION

The results of this study revealed that slabs dominated the overall consumption of concrete in the superstructure, accounting for nearly 59% of the total volume. This finding is consistent with the research of Paya-Zaforteza et al. (2020), who reported that floor slabs in reinforced concrete structures typically consume between 60–80% of the total concrete volume, while columns contribute only 2.5–14%. Such similarities indicate that the material distribution patterns observed in the present project align with global trends in multistory building construction. Consequently, optimization efforts that focus on slab design whether through reducing slab thickness, using higher-strength concrete, or employing alternative slab systems such as voided or precast slabs are expected to yield the most significant savings in material usage.

In terms of reinforcement steel, the study found a more balanced distribution, with beams and slabs accounting for nearly equal shares of 38% and 37%, respectively, while columns accounted for 25%. This reinforces the idea that optimization cannot solely target slabs but must also consider reinforcement detailing in beams, where high bending moments demand significant reinforcement. Prior research also supports this approach; Lee and Ahn (2006) demonstrated that optimization using genetic algorithms was effective in reducing reinforcement requirements in beams without compromising structural safety. Similarly, Zhang et al. (2023) emphasized that low-carbon optimization strategies achieved notable reductions in reinforcement usage, particularly in flexural members such as beams.

When comparing these results with the regulatory framework, the design volumes calculated in the baseline project comply with the requirements of SNI 2847:2013, which governs the structural design of reinforced concrete in Indonesia. However, the relatively high proportions of material usage in slabs and beams suggest that while the design is safe, it may not represent the most efficient use of resources. This aligns with the conclusions of Niu et al. (2024), who argued that conventional RC designs often satisfy safety requirements but are not optimized for sustainability, leading to higher embodied energy and carbon footprints.

Another important implication of these findings is the potential for integrating computational optimization techniques into practical design processes. The data suggest that applying optimization methods such as multi-integer nonlinear programming (MINLP) or genetic algorithms could identify alternative design solutions that minimize concrete and reinforcement volumes while still meeting the performance requirements of SNI 2847:2013. Prior studies have demonstrated that such methods can achieve material savings of up to 25% in beams and nearly 14% in columns (iManager Publications, 2019). If applied to the present case study, similar reductions could be achieved, particularly in slab thickness and beam reinforcement, which together account for the majority of material consumption.

Overall, the discussion underscores that optimization of material usage in reinforced concrete superstructures is not merely a theoretical exercise but a practical necessity. By aligning project-specific volumetric data with established optimization strategies, engineers can achieve a balance between safety, cost, and sustainability. The findings of this study thus provide a strong foundation for further research, particularly in applying algorithm-based optimization models to Indonesian building projects, where empirical data such as those presented here can serve as input parameters for computational frameworks.

CONCLUSIONS

This study analyzed the material usage and optimization potential of concrete and reinforcement steel in the superstructure of a multi-story reinforced concrete building. The analysis focused on three major structural elements columns, beams, and slabs using quantitative data obtained from detailed project documentation. The results revealed that concrete usage was highly concentrated in slabs, which accounted for 58.93% of the total concrete volume, followed by beams (31.33%) and columns (9.74%). This pattern clearly indicates that slabs dominate concrete consumption and, therefore, represent the primary target for optimization. Strategies such as reducing slab thickness, utilizing voided or precast slab systems, or applying higher-strength concrete can potentially yield substantial material savings.

In contrast, reinforcement steel consumption was more balanced, with beams contributing 37.96%, slabs 36.72%, and columns 25.32% of the total reinforcement. This distribution shows that while slabs are critical for concrete optimization, beams also require attention in reinforcement design due to their high bending demands. Adjustments in reinforcement detailing such as optimizing bar spacing or using higher-grade steel could further improve efficiency. The comparative analysis demonstrated that while the baseline design complies with SNI 2847:2013, it may not represent the most resource-efficient configuration. Optimization frameworks, including genetic algorithms and multi-integer nonlinear programming (MINLP), have proven capable of achieving up to 25% reduction in reinforcement steel and 14% in concrete usage in similar studies. Integrating these approaches into the current design process could significantly reduce both cost and environmental footprint while maintaining structural safety and serviceability.

Overall, the findings confirm that slabs and beams are the most material-intensive components of reinforced concrete superstructures and thus offer the greatest potential for optimization. The study highlights the necessity of adopting computational optimization techniques in structural design to achieve sustainable, economical, and structurally sound outcomes. Furthermore, the project data presented here can serve as a valuable empirical foundation for future research applying algorithm-based optimization models in Indonesian building projects.

ACKNOWLEDGMENT

The authors express their sincere gratitude to the Department of Civil Engineering, Universitas Negeri Padang, for academic guidance and research facilities. Appreciation is also extended to supervising lecturers, colleagues, and students for their valuable input and assistance in data collection and structural verification. The support staff and academic forums within the Faculty of Engineering are likewise acknowledged for their contributions to improving the quality of this study.

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