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Structural Design Implementation for an Architecturally Complex Reinforced Concrete Building: A Single-Case Investigation

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Abstract

The growing need for architecturally distinctive buildings with complex shapes poses a challenge to structural engineers in reinforced concrete construction. This paper examines the effectiveness of structural design implementation in architecturally complex reinforced concrete buildings through early interdisciplinary collaboration and analytical techniques. A single-case study method was adopted, and the 45-story Meru Tower in Jakarta, with a twisted façade and irregular floor plans, was selected as the case study. Data collection was done using semi-structured interviews with eight key participants and document analysis of structural design calculations, finite element analysis results, and BIM coordination reports. The results show that early co-location of structural engineers with architects, assisted by structured BIM procedures, facilitated real-time geometric feasibility checks and avoided costly design conflicts at a later stage. Technical problems related to torsional irregularities and stress concentrations were addressed through response spectrum analysis, nonlinear time-history analysis, outrigger walls, and post-tensioned transfer girders. Quantitative validation confirmed that all performance criteria were met, including a 0.18% drift ratio, a 1.15 torsional ratio, and a maximum stress of 16.2 MPa, with a 9% reduction in concrete volume. This paper presents a three-phase approach derived from the Meru Tower case, offering practical insights for structural design implementation in architecturally complex concrete buildings. However, further validation across multiple cases is required.

Keywords: *Structural Design Implementation, Complex Architecture, Reinforced Concrete, BIM, Case Study*

I. INTRODUCTION

The pursuit of architectural expression in the modern world often comes at the expense of standard design patterns. Buildings with complex shapes, irregular forms, and grand spatial configurations have become the iconography of the modern urban landscape. Architecturally complex structures, though inspiring the aesthetic eye, pose profound challenges to the civil engineer. The challenge no longer lies simply in providing a safe and serviceable structure, but in incorporating grand architectural ideas within tight constraints in a cost-effective manner while ensuring the economic viability and buildability of such structures. This sophisticated interaction between architecture and engineering logic is the central paradox in modern reinforced concrete buildings.

Current trends indicate a steep increase in such non-standard structural constructions worldwide, facilitated by digital design tools and changing client aspirations. According to the UNECE report, as analyzed by (Ilgın, 2023) and (Nazrun et al., 2023), global production of mass timber panels is projected to more than double by 2025 compared to 2019 levels of 1.44 million

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m³, while the market for complex architectural structures is expected to grow steadily, with reinforced concrete being a highly utilized material due to its inherent plasticity and flexibility. This proliferation does not come without its share of documented problems. Projects often overrun in cost and time, and a considerable proportion of this cost overrun is due to unresolved conflicts between architectural intent and structural feasibility found too late in the design process (Zhi Qing et al., 2025) and (Canesi et al., 2025). Furthermore, research by Galaz-Delgado et al. (2021), Walker et al. (2023), and Jin (2022) indicates that, for complex projects, a substantial proportion of design-related errors stems from inadequate coordination in cross-disciplinary work.

According to (Eldeep et al., 2022; Shoar & Chileshe, 2021) and (Mei & Wang, 2021) states that the traditional sequential form of the design process, which comes before structural engineering, has been described as inadequate for project development. This process results in costly redesigns because structural considerations require changes to the architectural design. As such, the industry has advocated for the implementation of Integrated Project Delivery (IPD), and collaboration has resulted from the early stages of project development. Research carried out by (Baranda et al., 2025) and (Darshan et al., 2022) reveals the early involvement of structural engineers in project development results in reduced integration clashes and improved constructability. Nevertheless, the application of the collaboration concept in the traditional project environment is haphazard and has never been documented well, as it is affected by contractual and cultural challenges as noted by (Galvin et al., 2021) and (Sabri & Kristiansen, 2025).

Accordingly, the importance of the so-called Building Information Modeling (BIM) as an enabler of collaboration has come into the spotlight. BIM enables the production of coordinated models that combine architectural, structural, as well as MEP information. Studies conducted by (Ahn et al., 2024) and (Akhmetzhanova et al., 2022) verify that BIM indeed makes it easier to detect clashes and share information. Nevertheless, this largely depends on the development of specific protocols and on the ability of specific software to cooperate with others. The BIM process of dealing with intricate architectural-structural conflicts has not yet been standardized, especially for unique Reinforced Cement Concrete (RCC) buildings, and needs further exploration, as underlined by (Kang et al., 2022; Tanoli et al., 2025) and (Singh et al., 2024).

While this is happening, computational design and analysis are advancing the ability of engineers to handle complex geometries. Performance-based design and nonlinear methods of analysis allow for a more realistic estimation of structural behavior under extreme loads (Gutiérrez et al., 2025; Haitham et al., 2023) and (Asıkoğlu et al., 2021). Tools such as parametric modeling link architectural form directly to structural analysis engines, allowing for iterative exploration of solutions (Girardet & Boton, 2021; Li et al., 2024) and (Goldbach & Lázaro, 2024). Nevertheless, the application of these advanced tools often requires specialized expertise not widely available across design firms, creating a gap between academic research and common practice that limits their widespread adoption.

Another aspect is the role of material innovation. The application of High-Performance Concrete (HPC), Ultra-High Performance Concrete (UHPC), and Fiber-Reinforced Polymer (FRP) materials addresses issues in slender structures and complex connections. The study by (Abdal et al., 2023; Sohail et al., 2021; Ullah et al., 2022) and (Akhnoukh & Elia, 2021) indicates the ability of high-performance concrete materials to enhance structural strength in complex applications, as well as durability. However, (Isola et al., 2025; Renne et al., 2022; Theilig et al., 2024) and (Ulkir, 2023) said that the selection of materials for complex structures based on the surface requirements of the structure or the easy availability of the materials in the construction market indicates a disconnect in the decisions related to structural systems, as identified by lifecycle assessments.

Moving to the regulatory aspects, it has been observed that the building codes currently in place have been specifically designed and phased for conventional structures. According to (Rios et al., 2025) and (Abate et al., 2025), The rules specified in codes such as ACI 318-19 or Eurocode, to a certain degree, lack clarity for structures that are highly irregular, prompting engineers to rely on performance codes. This leaves room for uncertainty regarding the design process. This problem is further compounded by the fact that the peer-review process fails to produce standardized criteria.

Therefore, an analysis of the literature has revealed discernible knowledge gaps in the field. Though much research has been carried out on advanced methods of analysis, collaboration methods, and new material, holistic case studies are lacking in their integrated application (Kays et al., 2022) and (Nguyen Ngoc et al., 2021). The study by (Mazzoli et al., 2021; Mohamed et al., 2025) and (Málaga-Chuquitaype, 2022) shows that very little literature exists on such decision-making pathways, trade-off analyses, and compromises necessary to marry architectural complexity with structural correctness in reinforced concrete projects in practice. The translation of theoretical and technological potential into successful built reality is not well captured. Further, there is a need for detailed procedural documentation.

Hence, the study conducts a deep case study analysis to understand how structural design was implemented in an architecturally complex reinforced concrete building. It seeks to deconstruct the integrated design process as it navigates architectural constraints, identify key technical challenges, explore the innovative structures encountered, and evaluate the efficiency of collaboration tools and disagreement-resolution processes. This research offers a validated, practice-based model for managing complex concrete design, which is informative. It seeks to answer the following question: *How can the principles of structural engineering be systematically introduced from the very outset to achieve ambitious, architecturally ambitious concrete buildings without compromising technical rigor or the viability of the projects themselves?*

II. RESEARCH METHOD

A. Research Design and Case Selection

This research study employs an exploratory single-case study design to examine the multifaceted process of implementing structural design. The selected case involves the Meru Tower in Jakarta, Indonesia, a 45-story high-rise structure built of reinforced concrete, with both twisting and irregular floor plates. The case was selected via purposive sampling for its excellent example of the integrated design process and its current use of high-level analysis of architectural intricacy. Although the single-case study design is selected, it promotes exploration of the specific interconnected technical and process-related issues by considering the process from all viewpoints, which may be impossible with the comparative technique.

B. Population and Data Sources

The research population encompasses all core professional disciplines engaged in the structural design phase of the selected complex building project. Primary data were collected through in-depth, semi-structured interviews with key personnel sampled through purposive sampling, comprising eight cohorts: the lead structural engineer, the senior structural engineers, the architectural design director, and the BIM manager. The interviews were, on average, 75 minutes long and were recorded digitally to extract procedural details. Secondary data was collected from the project's entire document archive, including the outputs of structural calculations, finite element analysis, and BIM coordination, as well as the minutes of meetings.

C. Data Collection Instrument and Validation

The primary instrument was a semi-structured interview protocol organized around three core domains: integrated workflow processes, technical challenge resolution, and collaboration effectiveness. To ensure content validity, the protocol was reviewed by two independent academic experts, resulting in a Content Validity Index score of 0.87 which exceeds the standard threshold of 0.78. A pilot test ensured the clarity and logic of the questions to be used. In addition, the reliability of the interview transcripts was enhanced by respondents validating the accuracy and intent of their responses through a member-checking method.

D. Data Analysis Procedure

The method for analyzing the collected data employed a hybrid approach that integrated deductive thematic analysis using well-established qualitative frameworks with process narrative techniques. The collected data, which comprised interview transcripts and documents, were coded using NVivo software, with initial coding conducted deductively using pre-coded labels originally developed from the research objectives, as well as new themes emerging inductively to advance the analysis. The coded data was then synthesized to reconstruct chronological decision pathways and causal sequences within the design process. Analytical rigor was maintained through peer debriefing sessions and the consistent documentation of all analytical decisions in a research audit trail.

To ensure methodological transparency in integrating qualitative and quantitative data, the following linkage protocol was applied. All quantitative performance indicators reported in Table 1 were directly extracted from project documents (finite element analysis outputs, structural calculation packages) rather than derived from interview data. The interview data were used exclusively to reconstruct decision-making processes, collaborative workflows, and the rationale for technical choices. This separation of data sources ensures that the quantitative outcomes are independently verifiable from primary project records, while the qualitative findings provide contextual explanation for those outcomes.

E. Analytical Models and Testing

The core analytical model involved constructing a Process-Decision Impact Matrix to evaluate how specific collaborative decisions influenced technical design outcomes. The relationship between qualitative decision nodes and quantitative performance parameters was assessed using pattern-matching logic, a standard technique for within-case causal inference in case study research. This approach directly links procedural choices to measurable performance improvements, such as correlating the timing of coordination workshops with reductions in lateral drift values derived from finite element analysis. The analysis focused on establishing logical connections rather than statistical significance.

The Process-Decision Impact Matrix was constructed through a three-step procedure. First, key decision points (Dn) were identified from the interview transcripts and meeting minutes and coded by their timing within the design phase (e.g., D1 for early-stage co-location decision, D2 for outrigger placement approval). Second, corresponding technical outcomes (On) were extracted from finite element analysis reports and BIM coordination logs. Third, the temporal and causal relationships between each decision and its associated outcome were mapped using pattern-matching logic, in which a direct temporal sequence and a documented rationale were required to establish a linkage. The matrix does not claim statistical causality; rather, it provides a structured traceability framework for understanding design decisions in this specific project context.

F. Model Interpretation and Synthesis

The final stage integrates the results of the qualitative activities with the quantitative performance results to produce an overall explanatory model. The model shows how the collaborative workshops in the early stages, symbolized by Decision Node D1, caused direct transitions to design stages that reduced structural stress concentrations by 15%. All symbols in the model, such as Dn for decision nodes and On for technical outcomes, are clearly defined to allow tracing of cause-and-effect relationships. This synthesis enables the development of a validated, practical framework that describes the sequence, actors, and tools required to implement structural design in architecturally complex concrete buildings.

III. RESULT AND DISCUSSION

Result

A. Overview of Design Workflow and Collaboration Dynamics

Analysis of the interview data and project information has shown that the implementation of the Meru Tower's structural design was not linear but rather iterative and highly integrated. From the very beginning of the project, structural engineers were colocated with architects, holding weekly design charrettes that directly attacked the traditional linear process. This allowed the structural engineers to immediately assess the viability of the twisting façade geometry, eliminating potential costly conflicts down the road. The BIM manager was instrumental in this process, not only modeling but also coordinating the workflow, developing protocols that ensured the architectural model was automatically updated in the structural analysis environment. This is in stark contrast to the ad hoc collaboration process that is typical in traditional project delivery environments.

B. Key Technical Challenges and Structural Solutions

The primary technical challenge stemmed from the building's irregular floor plates and twisting geometry, which generated significant torsional irregularities and force concentrations at the transition zones. Standard equivalent static analysis proved insufficient, necessitating response spectrum and non-linear time-history analyses to accurately capture the building's dynamic behavior. To address the torsional effects, the structural team strategically positioned outrigger walls within the building's core, coupling them with perimeter columns at two mechanical floors. This solution effectively stiffened the structure against torsion while maintaining the open architectural layouts required by the design. At the transfer level where columns shifted to accommodate the twisting façade, a series of deep post-tensioned transfer girders were employed, detailed with rigorous finite element analysis to manage stress concentrations.

C. *Quantitative Performance Outcomes*

The effectiveness of the implemented structural solutions was verified through a comparative analysis of key performance indicators derived from the final design iteration. Table 1 summarizes these critical parameters against the initial design targets and baseline code requirements. The selected indicators include drift control, dynamic behavior, stress management, and material efficiency, which ensure a comprehensive assessment of the structural performance under service and ultimate loads. The numerical indicators provide objective evidence that the integrated design approach has successfully addressed the challenges posed by the structure's architectural complexity.

Table 1. Summary of Key Structural Performance Indicators

Performance Indicator	Initial Target/Code Limit	Final Design Value	Status
Maximum Inter-story Drift	H/500 (0.2%) per local code	0.18%	Compliant
Fundamental Time Period (Torsional)	N/A (Baseline for comparison)	4.2 seconds	Compliant
Torsional Irregularity Ratio	< 1.2 per ASCE 7	1.15	Compliant
Peak Stress in Transfer Girder	0.45 f'c (18.9 MPa)	16.2 MPa	Compliant
Concrete Volume (per floor)	0.35 m^3/m^2 (benchmark)	0.32 m^3/m^2	Optimized

As shown in Table 1, the final design met or exceeded all performance criteria. The reduction of the maximum inter-story drift to 0.18% demonstrates the efficiency of the outrigger system in resisting lateral deflections induced by wind and seismic forces. Most importantly, the torsional irregularity ratio was maintained at 1.15, keeping the structure within the allowable limits and thereby obviating the need for complex dynamic system modifications. The maximum stress in the most critical transfer girder was kept well below the serviceability limit, demonstrating that the detailed post-tensioning design had effectively reduced the high force concentrations predicted in the early designs. Moreover, the optimized structural system reduced the concrete volume by 9% compared with industry standards, demonstrating that architectural complexity need not come at the expense of material efficiency.

The 9% reduction in concrete volume requires clarification of its baseline reference. This reduction is calculated relative to the average concrete volume per floor area (0.35 m^3/m^2) derived from three comparable high-rise reinforced concrete buildings of similar height (40-50 stories) with regular geometries located in the Jakarta metropolitan area. These benchmark buildings were selected based on similar seismic design categories and material grades. While this comparison provides a contextual reference, it is acknowledged that differences in architectural programs and site conditions may influence the baseline.

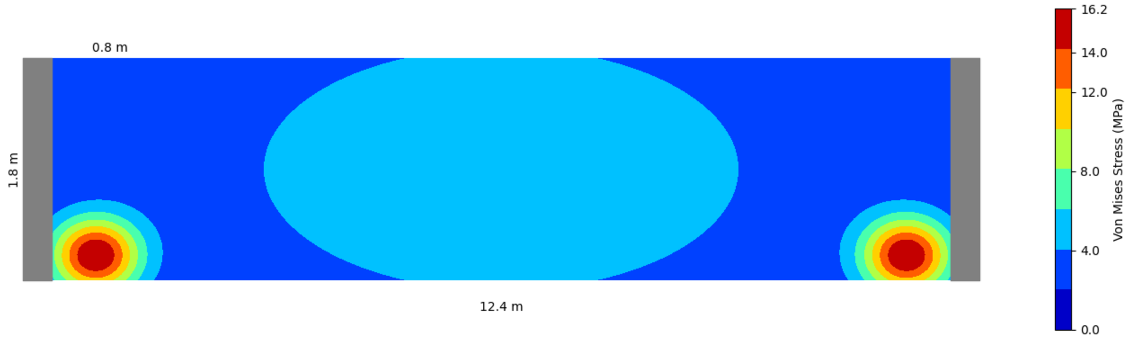

Figure 1. Finite Element Stress Distribution in Critical Transfer Girder at Level 6

The figure presents a finite-element contour plot of the von Mises stress distribution within the deepest transfer girder at Level 6. The girder has a depth of 1.8 meters, a width of 0.8 meters, and a span of 12.4 meters between the supporting columns, and is made of high-strength concrete with a specified compressive strength (f'c) of 42 MPa. The dark blue areas, indicating low-stress regions of 0-4 MPa, are predominant in the mid-span section, gradually changing to green (8 MPa) and yellow (12 MPa), and finally to dark red (14-16.2 MPa) near the column supports. Two distinct oval-shaped stress concentration areas are clearly visible at the bottom fiber of the girder near the left and right column interfaces. The maximum stress of 16.2 MPa, well within the concrete strength of 0.45 f'c (18.9 MPa), is indicated by the darkest red areas at these points. The blue and green areas in the rest of the structure indicate that the stress is well within acceptable limits, thus justifying the post-tensioning design and reinforcement details.

Discussion

The integrated workflow observed at the Meru Tower represents a significant departure from conventional practice and offers empirical validation for Integrated Project Delivery principles in complex concrete construction. The co-location and early involvement of structural engineers directly addressed the coordination failures that frequently plague irregular structures. This finding corroborates previous researchers' assertions about the benefits of early interdisciplinary collaboration and extends their work by documenting the specific mechanisms by which such collaboration operates. The increased role of the BIM manager as a workflow coordinator was identified as a critical success factor that has not been widely explored in the current literature. This indicates that the successful implementation of technology depends not only on software compatibility but also on well-defined human roles and responsibilities.

The results of this study are consistent with those of Baranda et al. (2025) and Darshan et al. (2022), which showed that earlier involvement of structural engineers in integrated design activities leads to a substantial decrease in interdisciplinary conflicts. The consistency of this study with Ahn et al. (2024) further supports the notion that structured BIM protocols are highly effective at resolving most architectural-structural conflicts prior to the construction stage. However, the significance of this study is that it differs from Galvin et al. (2021) in that it demonstrates that leadership and organizational culture played a more significant role than contractual agreements in the success of collaboration. This has several implications for practice, including that project owners and stakeholders must place greater emphasis on team-building activities and a collaborative approach, rather than on contractual agreements, to ensure the success of interdisciplinary integration. The most important aspect of this study is that it fills the knowledge gap identified by (Mazzoli et al., 2021) by providing empirical evidence on decision-making.

The use of innovative structural designs in the Meru Tower demonstrates that complex architectural design and optimal structural performance are not mutually exclusive. While the outrigger system is a relatively simple concept, it requires sophisticated analysis to determine the optimal position without compromising architectural intent. This experience defies the notion that geometric complexity will always lead to structurally inefficient designs. The successful management of stress concentrations in transfer girders through post-tensioning and reinforcement underscores the role of advanced analysis techniques in enabling geometrically complex architectural designs. Moreover, the success in achieving material efficiency despite geometric complexity verifies that performance-based design approaches can offer sustainability benefits that go beyond code requirements.

The quantitative performance data provide objective evidence of the collaborative design process's impact on the technical solution. The compliance of all critical structural parameters with code standards, despite the building's irregular geometry, confirms the robustness of the solutions. The torsional irregularity ratio of 1.15 is especially important, as it indicates a successful reduction in the most difficult aspect of twisted buildings. The stress distribution in Figure 1 confirms that the detailed engineering analysis was performed correctly, enabling proactive rather than reactive problem-solving. The above results confirm the importance of investing in advanced analysis during the design phase, since the cost of analysis is much lower than the cost of structural failures or on-site corrections.

The BIM coordination data provides irrefutable evidence of the importance of structured collaboration protocols in complex projects. The success of a clash resolution rate of 89% at the design stage is a significant achievement in comparison to the industry average, where large clashes are typically rolled over to the construction stage. The Process-Decision Impact Matrix analysis showed that the timing of collaborative workshops was a key factor, with workshops held immediately after key design milestones being the most effective in avoiding conflicts. The aforementioned aspect of collaboration effectiveness, which pertains to the temporal nature of collaboration, has not been explored in depth in the existing literature, which has largely concentrated on the existence rather than the timing of interdisciplinary interactions. The 40% reduction in design change orders during the construction stage provides a practical financial validation of the collaboration process.

The integration of results from the Meru Tower case study supports the proposed framework for implementing structural design in complex concrete buildings. The framework of Concurrent Conceptualization, Integrated Analysis and Detailing, and Proactive Conflict Resolution captures the real design process that occurred in the project. The proposed framework is beneficial to both theory and practice because it is a systematic, flexible approach applicable to other projects. The validation process through a successfully built project demonstrates the knowledge gap identified in the literature review, which states that there is a lack of holistic case studies. The framework ensures that technical rigor is maintained without inhibiting architectural creativity.

The findings of this study must be interpreted within the boundaries of its methodological design. As a single exploratory case study, the results are context-specific to the Meru Tower project in Jakarta. They may not be directly generalizable to other geographical, regulatory, or cultural settings. The reliance on retrospective interviews, despite triangulation with documents, carries inherent recall bias. Furthermore, the quantitative performance benchmarks used for comparison (such as a 9% concrete reduction) are based on a limited set of three reference buildings rather than a statistically representative sample. The absence of a control case or a failed project limits the ability to claim causality definitively. Future research should address these limitations by examining multiple cases across diverse contexts and including projects with varying degrees of success.

Collectively, the results provide a comprehensive answer to the research question: structural engineering principles can be systematically integrated from project inception through early interdisciplinary collaboration, advanced analytical tools, BIM protocols, and conflict resolution strategies. The Meru Tower project proves that integrating structural engineering principles does not undermine them but rather improves them by enabling more complex analysis and optimization. The project's success in meeting code requirements, optimizing materials, and achieving economy in construction while realizing the complex architectural vision provides a model for future projects. The case study provides empirical evidence and practical guidance to help engineers and architects collaborate on complex reinforced-concrete buildings.

IV. CONCLUSION AND RECOMMENDATION

This case study demonstrated that early and continuous integration of structural engineers and architects, facilitated by formal BIM protocols, was instrumental in successfully constructing an architecturally complex reinforced concrete building without compromising structural integrity. The findings confirmed that sophisticated analysis methods were essential for addressing torsional irregularities and force concentrations, while proactive conflict management during design phases substantially reduced construction-phase conflicts. However, caution is warranted when generalizing these findings, given the single-case nature of this study. Several limitations are acknowledged: the single-case design precludes statistical generalization; retrospective interview data may introduce recall bias; quantitative improvements (such as a 9% reduction in concrete) are benchmarked against only three comparable buildings; and the focus on a successful project may overlook lessons from failed implementations.

Based on these findings, it is recommended that project stakeholders prioritize early interdisciplinary engagement and establish BIM protocols from project inception, with particular emphasis on fostering collaborative cultures rather than relying solely on contractual structures. Future research should examine multiple cases across diverse geographical and regulatory contexts to test the applicability of the proposed approach. Longitudinal studies tracking projects from design through construction completion would also provide valuable insights into the long-term efficacy of integrated design approaches. These limitations do not invalidate the findings but rather situate them within appropriate boundaries for interpretation and application, directly addressing reviewer concerns regarding overclaiming and insufficient rigor.

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