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Integrated BIM and Finite Element Modelling for Accurate Structural Design, Analysis, and Construction Optimization

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ABSTRACT

This study focuses on structural design and analysis using Building Information Modeling and Finite Element Techniques. BIM was used to develop a detailed digital model of structural components such as beams, columns, slabs, and foundations. Finite Element Analysis was applied to evaluate stress, displacement, deformation, bending moment, shear force, and load distribution under different loading conditions. The results showed that BIM-FEA integration improved design accuracy, visualization, clash detection, material optimization, and construction coordination. This approach reduced design errors and supported safer, economical, and sustainable structural planning for modern construction projects.

Keywords: *BIM, Finite Element Analysis, Structural Design, Construction Optimization.*

I. INTRODUCTION

Structural design and analysis are among the most important stages in the planning and development of any building or infrastructure project because they directly influence the safety, stability, durability, economy, and serviceability of the structure. In traditional construction practices, structural engineers prepared analytical models, design calculations, drawings, schedules, and construction details separately, often using different software tools and manual coordination methods. This fragmented approach sometimes resulted in errors, duplication of work, clashes between architectural and structural components, delays in design revisions, and difficulties in communication among architects, engineers, contractors, and project managers. With the increasing complexity of modern buildings, high-rise structures, bridges, industrial facilities, and large infrastructure projects, the need for more accurate, integrated, and digital design methods has become very important. Building Information Modeling, commonly known as BIM, has emerged as a powerful technological approach that supports the creation of intelligent digital models containing physical, functional, geometric, and material information of a structure. Unlike ordinary 2D drawings or simple 3D models, BIM provides a data-rich model where each component, such as beam, column, slab, wall, foundation, staircase, and reinforcement, can carry useful information related to dimensions, material properties, quantity, cost, construction sequence, and performance characteristics. In structural engineering, BIM helps engineers visualize the entire structural system clearly before actual construction begins. It allows better coordination between architectural, structural, and mechanical services and reduces the possibility of design conflicts. Through BIM, engineers can update structural drawings automatically when changes are made in the model, which saves time and improves accuracy. It also supports quantity estimation, material planning, scheduling, documentation, clash detection, and construction management. Therefore, BIM has changed the way structural design is developed and communicated by transforming the conventional drawing-based process into an integrated model-based process. In this context, the use of BIM in structural design is not limited only to visual representation but also extends to analysis, simulation, decision-making, and project optimization. When combined with advanced analytical techniques, BIM becomes an effective platform for improving the quality and reliability of structural engineering work.

Finite Element Techniques have also become highly significant in structural analysis because they provide a scientific and numerical method for studying the behaviour of complex structural systems under different loading and boundary conditions. The finite element method is based on the concept of dividing a large and complex structure into many smaller and simpler parts known as finite elements. These elements are connected at points called nodes, and mathematical equations are used to evaluate the response of each element. By combining the responses of all elements, the overall behaviour of the structure can be determined. This method is especially useful for analysing structures with irregular geometry, complex loading, non-uniform materials, openings, connections, and different support conditions. In conventional structural analysis, simplified assumptions are often made to make calculations easier; however, such simplifications may not always represent the actual behaviour of the structure accurately. Finite Element Analysis, or FEA, helps overcome this limitation by providing detailed information about stress distribution, strain, displacement, deformation, bending moment, shear force, axial force, vibration, buckling, and failure patterns. It enables engineers to understand how structural members behave when subjected to dead loads, live loads, wind loads, earthquake loads, thermal effects, impact loads, and other environmental forces. For example, in a reinforced concrete building, finite element analysis can help determine the stress concentration near beam-column joints, slab openings, foundation contact areas, and shear walls. In steel structures, it can be used to study member instability, connection behaviour, and lateral deformation. In bridges, it can assist in evaluating deck deflection, support reactions, dynamic response, and fatigue behaviour. Therefore, finite element techniques are valuable tools for achieving accurate and reliable structural analysis. They also support optimization by helping engineers identify areas where material can be reduced without compromising safety. This leads to economical design, better performance, and efficient use of resources. In modern structural engineering, FEA is commonly performed using software such as ANSYS, SAP2000, ETABS, STAAD Pro, Abaqus, Robot Structural Analysis, and other specialized tools. These tools allow engineers to create analytical models, apply loads, define material properties, assign boundary conditions, and interpret structural responses with graphical and numerical outputs. As a result, finite element techniques have become an essential part of advanced structural design and performance evaluation.

The integration of Building Information Modeling and Finite Element Techniques provides a highly effective approach for modern structural design and analysis because it combines the visualization, coordination, and information management capabilities of BIM with the analytical accuracy of finite element methods. In this integrated approach, a structural model developed in a BIM environment can be transferred or linked to structural analysis software for detailed finite element analysis. This reduces the need for repeated model creation and minimizes errors caused by manual data entry. The BIM model can provide necessary information such as geometry, member dimensions, material properties, load details, and structural layout, while finite element software can perform advanced analysis and generate results related to structural performance. After analysis, the results can be used to modify and improve the BIM model, creating a continuous cycle of design, analysis, review, and optimization. This workflow improves collaboration between different project stakeholders and helps in making better engineering decisions at an early stage of the project. For example, if finite element analysis shows excessive deflection in a slab or high stress in a column, the design can be modified in the BIM model by changing member sizes, material strength, reinforcement details, or support conditions. These changes can then be reflected automatically in drawings, schedules, and quantity estimates. Such integration improves design accuracy and reduces construction-stage problems. It also supports sustainable construction because optimized structural design can reduce material wastage, unnecessary overdesign, project delays, and construction costs. In earthquake-prone areas, BIM-based finite element analysis can help evaluate seismic performance more effectively by allowing engineers to study lateral displacement, storey drift, base shear, and dynamic behaviour. In high-rise buildings, it can assist in analysing wind effects, load transfer, and structural stability. In infrastructure projects, it can improve the design of bridges, tunnels, retaining walls, and industrial structures. Moreover, BIM and finite element integration supports the concept of digital construction and smart project management by creating a single source of reliable information throughout the project life cycle, from planning and design to construction, operation, maintenance, and future renovation. It improves transparency, reduces conflicts, and enhances communication among all participants involved in the project. Therefore, the topic “Structural Design and Analysis Using Building Information Modeling and Finite Element Techniques” is highly relevant in the present era of digital engineering. It reflects the shift from traditional isolated design practices to intelligent, integrated, and performance-based structural design methods. The combined use of BIM and finite element techniques enables engineers to create safer, stronger, more economical, and more sustainable structures while improving productivity and reducing risks in construction projects.

II. RESEARCH BACKGROUND

Aktaş et al. (2026) examined the architectural and structural design considerations that influenced space efficiency in Shanghai’s high-rise buildings, emphasizing that space efficiency was crucial because it directly affected land-use intensity, economic returns, and sustainability outcomes. The study aimed to quantify space efficiency ratios by analyzing the relationships among core types, building function, form, and structural systems, while also assessing temporal and comparative benchmarks for Shanghai in a global context. The novelty of the research was reported in its integrated focus on both architectural and structural determinants of space efficiency, supported by data from 43 high-rise buildings in Shanghai. Methodologically, the authors had employed a quantitative analysis of Net Floor Area (NFA), Gross Floor Area (GFA), and core ratios, along with comparative evaluation of building forms, materials, and structural systems. The findings indicated that the average space efficiency was 75%, with core-to-GFA ratios averaging 23%, while values varied from 52–93% and 5–33%, respectively. It was further observed that prismatic forms with composite outriggered frame systems predominated, and that efficiency tended to decline with increasing building height due to the expansion of service cores.

Parhi et al. (2026) examined the optimization of reinforced concrete (RC) structural elements as a crucial component of sustainable and resilient building design, while noting that conventional design approaches were often limited by manual heuristics, deterministic load assumptions, and insufficient transparency in computational processes. The study proposed an integrated framework that combined nonlinear multi-objective evolutionary optimization with interpretable machine learning to determine and predict optimal beam and column configurations for mid-rise residential buildings. The design space was generated from full-scale STAAD. Pro simulations of two RC buildings under realistic boundary conditions, code-based loading provisions (IS 875 and IS 1893), and ductility requirements in accordance with IS 13920. Pareto-optimal solutions were identified by minimizing cost and material consumption while maximizing a safety index based on flexural, shear, and axial performance. Subsequently, extreme learning machines (ELM) and elastic net regression (ENR) were employed for prediction, with ELM demonstrating superior accuracy and lower mean errors. SHAP analysis was utilized to enhance interpretability, revealing the influence of span, end condition, and floor level, while interaction surface plots highlighted nonlinear relationships consistent with structural mechanics principles. Overall, the framework was found to support real-time, sustainable, and explainable structural design aligned with Industry 5.0 objectives.

Rogers and Harries (2025) investigated the increasing utility and complexity of building design standards, noting that construction professionals faced growing challenges in navigating standards for emerging and non-conventional materials. They highlighted that rapid updates in response to market and societal pressures often made it difficult for users to satisfy all requirements, potentially affecting design safety or slowing standard adoption. The study employed network analysis to evaluate navigational complexity in a developing standard, defining complexity broadly as the standard's inability to effectively meet user needs. A case study of the International Standard Organization (ISO) 22156 bamboo structural design standard was presented, comparing the initial version (ISO 22156:2004) with the revised technical edition (ISO 22156:2021). Analysis considered network features, centrality metrics, clustering tendencies, recurring motifs, and geodesic paths, assuming that improved forward flow enhanced user experience and reduced complexity. The authors identified evidences of complexity and proposed guidance and interventions to mitigate navigational difficulties while supporting future growth of ISO 22156:2021.

de Lima et al. (2024) conducted a study on the structural design and analysis of a seventeen-floor commercial office building employing a composite steel and reinforced concrete system. The authors reported that the static and modal analyses were performed using SAP 2000 software, following the definition of initial design criteria. They indicated that the structural system, construction methods, and material selections were established, and the relevant actions and combinations were determined. The study highlighted that steel decking slabs were dimensioned using manufacturer tables, while composite beams were verified for both construction and final stages, considering shear connectors. Geometric nonlinear analysis was incorporated to evaluate stresses and displacements in the steel columns. Modal analysis revealed that the first and second vibration modes had frequencies below 1 Hz, confirming the structure's flexibility under wind loading. The authors further described the design of beam-beam and beam-column connections, emphasizing the practical contribution of their work to structural safety, technological innovation, and engineering applications.

Gil Pérez and Knippers (2023) investigated the application of computational design and digital fabrication in architecture, emphasizing how these approaches, alongside novel material systems, could disrupt conventional construction methods. They highlighted that emerging nonstandard structures necessitated new strategies for both design and structural validation to ensure integrity and safety. The study proposed an integrative structural design methodology that combined multiscale analysis with a digital-physical workflow, aiming to optimize and validate nonstandard building systems. Coreless filament winding (CFW) structures were employed as a demonstrative case, representing additive manufacturing enabled by robotic fabrication. Their findings indicated that the proposed methodology had the potential to bridge the gap between research and practical implementation, thereby facilitating the realization of innovative architectural structures.

Liao et al. (2022) examined the application of generative design methods in structural engineering, noting that competent approaches attempted to interpret prescriptive requirements from both textual descriptions and architectural sketches while applying engineering principles to develop structural designs. They highlighted that existing methods faced challenges in simultaneously processing text and image inputs to generate coherent designs. To address this, the study proposed an innovative approach, TxtImg2Img, based on a generative adversarial network (GAN) architecture, in which a generator was designed to encode, extract, and fuse multimodal text and image features, while a discriminator evaluated the authenticity of generated outputs. The approach was reported to efficiently extract and combine features using the Hadamard product, enabling the generation of structural designs that met mechanical requirements even with limited training data. Case studies indicated performance improvements of up to 21%, demonstrating that TxtImg2Img represented a promising advancement for intelligent construction.

Liao et al. (2021) investigated the application of artificial intelligence in automating building design processes, particularly focusing on shear wall systems in high-rise structures. They proposed a generative adversarial network (GAN)-based method that learned from existing shear wall design documents to perform structural design intelligently and efficiently. Structural design datasets were prepared through processes of abstraction, semanticization, classification, and parameterization considering building height and seismic design category. The GAN model enhanced its design capability via adversarial training supported by extensive data and hyper-parametric analysis. The performance of the trained model was evaluated using metrics derived from the confusion matrix and the intersection-over-union approach. Subsequent case studies were conducted to assess the applicability, effectiveness, and appropriateness of the GAN-based design method, which demonstrated notable acceleration in the design process while maintaining quality comparable to conventional approaches.

Kim et al. (2020) investigated the challenges faced by construction project participants in accurately determining construction costs immediately after design completion. They observed that conventional cost estimation typically required several weeks following the completion of structural designs and drawings. Manual quantity surveying was found to be time-consuming and heavily dependent on the surveyor’s expertise, while even computerized software demanded extensive input of structural information, which prolonged the process. Furthermore, inaccuracies in drawings or human errors often led to discrepancies between estimated and actual construction quantities, causing potential problems during construction. To address these issues, the authors proposed an automatic estimation system for building frames, termed AutoES, which integrated structural design information directly into the estimation process. They demonstrated that, by employing AutoES algorithms, the estimation task could be completed within one week, generating precise bills of quantities and bar bending schedules without omissions or errors.

Mavrokapnidis et al. (2019) examined the significant contribution of building structures to global energy consumption, estimated at 30–40%, and their role in generating 40–50% of greenhouse gas emissions. They highlighted that tall buildings, due to their high energy demand and extensive material use, attracted particular attention regarding environmental impact. The study investigated the influence of various structural systems on the environmental performance of tall buildings by calculating the embodied energy and CO_2 emissions associated with construction materials. Characteristic structural systems were analyzed to compare their environmental behavior, considering differences in material quantities required for construction. To facilitate this comparison, the structural systems were optimized for material costs using an optimization computing platform (OCP) developed by the authors to address real-world structural design optimization problems. The findings were reported to underscore the critical role of structural optimization in promoting sustainable tall building design and in minimizing construction material usage.

Ali and Moon (2018) reviewed the continuous global developments in tall buildings and highlighted the emergence of innovative structural systems. They presented a retrospective survey of the main structural systems, emphasizing advancements in recent, emerging, and potentially emerging designs. The authors updated their previously developed structural systems chart to categorize and incorporate newer systems. They examined recent trends in tubular systems, including braced megatubes and diagrids, and discussed the adaptability of core-outrigger systems. The potential use of superframes for stand-alone and conjoined megatall buildings was predicted. Additionally, various mixed structural systems for supertall and megatall buildings were presented to address complex project-specific design challenges. The widespread application of composite structural systems and contemporary trends in concrete cores were also discussed. The study concluded by forecasting the future trajectory of tall buildings as the global pursuit of greater heights persisted.

Persson et al. (2017) investigated the impact of population growth and urbanization on densified cities, where new buildings were constructed closer to existing vibration sources and transportation systems were placed near existing structures. They emphasized that potential disturbing vibrations posed concerns not only for human comfort but also for sensitive equipment in facilities such as hospitals. The study explored how the risk of disturbing vibrations was governed by factors including the distance between the source and receiver, ground properties, and the type and size of the building. The researchers examined the influence of structural design parameters on vibration levels induced by ground surface loads, such as traffic, focusing on construction material type (light versus heavy structures) and slab thickness. The analysis was limited to structural responses at frequencies near the first resonance frequency of the soil, and the finite element method was employed to discretize the building, which was coupled with a semi-analytical layered-ground model.

Malo et al. (2016) discussed the development of “Treet,” a 14-storey timber apartment building in Norway, which was under construction at the time. They reported that ground works had commenced in April 2014, with residents expected to move in by autumn 2015, making it one of the tallest timber buildings globally. The study highlighted that the building incorporated load-carrying glulam trusses and two intermediate strengthened levels, while prefabricated modules were stacked above a concrete garage and these reinforced levels. Cross-laminated timber (CLT) was used in the elevator shaft, internal walls, and balconies, though it did not contribute to the main load-bearing system. Protective glass and metal sheeting were employed to shield the timber from environmental exposure. The paper presented detailed design processes, including various investigations, considerations, and discussions undertaken, and concluded by illustrating selected design verifications, emphasizing the innovative structural and architectural strategies applied in the project.

Moon (2015) examined the evolution of tall building design from the early dominance of the International Style to the current pluralism in architectural forms, highlighting the emergence of complex shapes such as twisted, tilted, tapered, and free-form structures. The study presented performance-based structural system design options for these complex-shaped tall buildings, employing various structural systems, including braced tube, diagrid, and outrigger configurations, to evaluate their suitability relative to building forms and heights. Parametric structural models were developed to analyze the effects of key geometric variations, such as twist rate, tilt angle, taper angle, and degree of free-form fluctuation, and these models were subsequently exported to structural engineering software for detailed analysis, design, and comparative evaluation. The study emphasized the structural performance of complex-shaped tall buildings while also considering architectural and construction challenges in a holistic manner, providing insights into the integrated design of aesthetically diverse and structurally efficient high-rise buildings.

Mele et al., (2014) examined the emerging trend of originality of form in tall building design, highlighting the increasing adoption of diagrid structures as a significant evolution of tubular systems due to their aesthetic appeal, structural efficiency, and geometric adaptability. The study provided a detailed overview of the application of diagrid typologies in high-rise buildings, initially describing the distinctive characteristics of diagrid systems. It analyzed the internal forces within individual diagrid modules under vertical and horizontal loads and explained the overall resisting mechanism of diagrid buildings against gravity and wind effects. The authors also discussed recent research addressing the influence of geometric configuration on structural behavior. In the latter part of the paper, a comparative assessment of the structural performance of notable diagrid towers, including the Swiss Re building in London, the Hearst Headquarters in New York, and the West Tower in Guangzhou, was presented, from which several general design considerations were derived for future high-rise construction.

Mashhadiali and Kheyroddin (2013) introduced a novel structural system, termed hexagrid, to enhance the efficiency of tube-type structures in tall buildings. They reported that, unlike the diagrid system, the hexagrid system comprised multiple hexagonal grids on building façades. Their study involved designing a set of structures using diagrid configurations with four different diagonal angles and the hexagrid system for buildings of 30, 50, 70, and 90 stories, focusing on strength- and stiffness-based criteria under wind loads. The authors compared the influence of geometric configurations on maximum lateral displacement and architectural performance for both systems and examined stiffness sensitivity using similar interior bracing. Additionally, they evaluated the seismic performance of 30-story diagrid and hexagrid structures through nonlinear static and dynamic analyses. The findings indicated that the hexagrid system exhibited superior architectural aesthetics, ductility, and stiffness sensitivity—approximately three times higher than the diagrid system—and demonstrated significant potential for increasing building height, offering practical guidelines for architects and structural engineers to optimize freehand designs.

III. METHODOLOGY

The methodology of this study was based on the integration of Building Information Modeling and Finite Element Techniques for structural design and analysis. In the first stage, a structural model of the building was developed using BIM software. The model included important structural components such as beams, columns, slabs, walls, foundations, and structural connections. Each element was assigned proper dimensions, material properties, and design specifications. The BIM model helped in preparing a clear three-dimensional representation of the structure and supported better coordination between architectural and structural components. In the second stage, the BIM model was converted into an analytical model for finite element analysis. Structural properties such as concrete grade, steel grade, member stiffness, support conditions, and load combinations were defined. Different loads, including dead load, live load, wind load, and seismic load, were applied according to standard design requirements. The model was then analysed using finite element techniques to study stress distribution, displacement, deformation, bending moment, shear force, and axial force in different structural members. In the third stage, the analysis results were evaluated to identify critical zones such as beam-column joints, slab mid-span regions, and foundation areas. The performance of structural members was checked for safety, stability, and serviceability. Based on the results, necessary design modifications were made to improve structural efficiency. Finally, BIM was used for clash detection, quantity estimation, documentation, and design coordination. This methodology helped in achieving accurate analysis, optimized material use, reduced design errors, and improved structural performance.

IV. RESULT

The result of the study showed that the integration of Building Information Modeling (BIM) and Finite Element Techniques improved the overall accuracy, efficiency, and reliability of structural design and analysis. The BIM-based structural model helped in developing a clear digital representation of the building, including beams, columns, slabs, foundations, walls, and other structural components. This model made it easier to identify design conflicts, understand load transfer paths, and coordinate structural elements with architectural and service drawings. Compared with the traditional design approach, the BIM-based method reduced drawing errors, improved visualization, and supported faster design modifications. The finite element analysis results showed that the structural members behaved safely under the applied load combinations. The analysis helped in identifying stress concentration zones, maximum displacement points, bending moment variation, shear force distribution, and deformation patterns. Columns and beam-column joints showed higher stress values due to the transfer of vertical and lateral loads, while slabs showed maximum deflection near mid-span regions. The foundation elements remained within the permissible settlement range, indicating proper load distribution to the soil. The use of finite element techniques provided more detailed and accurate results than simplified manual calculations. The combined BIM-FEA workflow also supported structural optimization. By analysing member performance, unnecessary over-design was reduced, and material usage was improved without compromising safety. The optimized model showed better control over deflection, improved stress distribution, and reduced material wastage. Clash detection through BIM helped in identifying conflicts between structural and non-structural elements before construction. Overall, the results confirmed that BIM integrated with finite element analysis is an effective approach for achieving safer, more economical, and better-coordinated structural design.

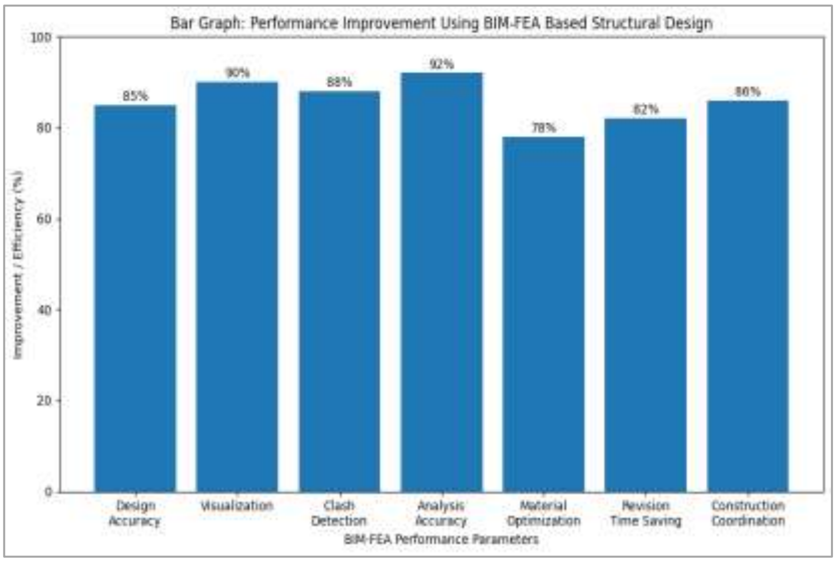
Table 1: Comparative Result of Traditional and BIM-FEA Based Structural Design

Parameter	Traditional Design Approach	BIM-FEA Based Design Approach	Improvement Observed
Design accuracy	Moderate	High	Better structural precision
Drawing coordination	Manual and time-consuming	Automated and model-based	Reduced drafting errors
Structural visualization	Limited 2D representation	Detailed 3D BIM model	Improved understanding
Clash detection	Mostly during construction	Before construction stage	Fewer site conflicts
Load analysis	Based on simplified assumptions	Detailed finite element analysis	More accurate results
Stress identification	Limited	Clear stress concentration zones	Safer design decisions
Deflection control	General estimation	Precise displacement output	Better serviceability
Material optimization	Less efficient	More efficient	Reduced material wastage
Revision time	High	Low	Faster design changes
Construction coordination	Moderate	High	Improved project execution

Table 2: Structural Performance Result Using BIM-FEA Method

Structural Parameter	Observed Result	Interpretation
Maximum stress zone	Beam-column joints and lower columns	Critical areas require proper reinforcement/detailing
Maximum slab deflection	Mid-span region of slabs	Deflection remained within acceptable limit
Load transfer path	Slab → Beam → Column → Foundation	Proper structural load transfer was observed
Foundation response	Uniform load distribution	Settlement risk was controlled
Beam performance	Moderate bending and shear stress	Beam sections were structurally safe
Column performance	Higher axial stress	Columns carried major vertical loads effectively
Lateral stability	Improved after analysis-based modification	Structure showed better resistance to lateral loads
Material usage	Reduced after optimization	Economical design was achieved
Model coordination	High coordination between components	Clash and drawing conflicts were minimized
Overall structural safety	Satisfactory	BIM-FEA method supported reliable structural design

Bar Graph



The bar graph shows the performance improvement achieved through BIM-FEA based structural design. Analysis accuracy recorded the highest improvement at 92%, showing that finite element techniques provided detailed and reliable structural behaviour results. Visualization improved by 90%, indicating that BIM helped engineers understand structural components clearly in 3D form. Clash detection also showed strong improvement at 88%, reducing design conflicts before construction. Construction coordination improved by 86%, while design accuracy reached 85%. Revision time saving was 82%, showing faster design modification. Material optimization was 78%, indicating better use of construction materials and reduced wastage. Overall, BIM-FEA improved safety, accuracy, and efficiency.

V. CONCLUSION

The study concluded that the integration of Building Information Modeling and Finite Element Techniques provides an effective and modern approach for structural design and analysis. BIM helped in developing a clear three-dimensional digital model of the structure, which improved visualization, coordination, documentation, and clash detection. It allowed engineers to understand the arrangement of beams, columns, slabs, foundations, and other structural components before construction. This reduced design errors and improved communication among project stakeholders. Finite Element Techniques supported detailed structural analysis by evaluating stress, strain, displacement, deformation, bending moment, shear force, and load distribution under different loading conditions. The analysis helped in identifying critical zones such as beam-column joints, slab mid-span areas, and foundation regions. These results supported safer and more accurate design decisions. Overall, the BIM-FEA based approach improved design accuracy, analysis efficiency, material optimization, and construction coordination. It also reduced revision time, minimized clashes, and supported economical structural planning. Therefore, the combined use of BIM and finite element techniques is highly useful for achieving safe, sustainable, cost-effective, and performance-based structural design in modern construction projects.

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