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Integrating BIM and FEM Tool for Design of Non-Prismatic Member to Minimize Connection and Bracing

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Abstract*:* *The integration of Building Information Modelling (BIM) and Finite Element Method (FEM) tools is transforming structural engineering design workflows, particularly for complex geometries such as non-prismatic members. Non-prismatic members, characterized by varying cross-sections along their length, are increasingly used in modern structural systems for their material efficiency and aesthetic appeal. However, their design presents challenges in accurately modelling their behaviour and optimizing their performance. This study explores a methodology that seamlessly integrates BIM and FEM tools to enhance the design process of non-prismatic members. The proposed approach leverages the parametric modelling capabilities of BIM to define non-uniform geometries and exports this data to advanced FEM software for structural analysis and optimization. A case study of a real-world project demonstrates the efficiency of the integration in terms of reducing design iteration cycles, improving material utilization, and achieving structural performance targets. The research emphasizes the potential of BIM-FEM integration to bridge the gap between architectural intent and structural feasibility. The findings contribute to the development of a robust workflow for designing non-prismatic members, thereby addressing critical challenges.*

Keywords: Building Information Modelling, BIM, Finite element Method Tool, FEM, Non-Prismatic Member, Structural Optimization, Parametric Design.

I. INTRODUCTION

Structural symbiosis epitomizes the collaboration between structural engineering and BIM methodologies, aimed at transcending traditional boundaries and unlocking new potentials in architectural design and construction. It embodies a paradigm shift from conventional linear workflows to interconnected, data-driven processes, where structural considerations are seamlessly integrated into the BIM framework from conceptualization to completion.

Furthermore, Structural Symbiosis does not exist in isolation but rather intersects with and complements other emerging trends in the architecture, engineering, and construction (AEC) industry. It synergizes with the principles of sustainable design, where BIM-driven analysis enables the optimization of building performance metrics such as energy efficiency, daylighting, and thermal comfort. Moreover, the integration of modular construction techniques and robotic fabrication processes into the BIM workflow facilitates the realization of complex structural geometries with enhanced precision and efficiency. Additionally, the advent of digital twins and immersive technologies augments the capabilities of Structural Symbiosis by providing stakeholders with immersive visualization tools and predictive analytics, fostering greater understanding and engagement throughout the project lifecycle. By embracing collaboration with these interconnected trends, Structural Symbiosis amplifies its transformative impact on the AEC industry

II. HISTORY OF BIM IN STRUCTURAL ENGINEERING

Building Information Modelling (BIM) emerged in the late 20th century as a response to the growing complexity of construction projects. Initially, traditional CAD (Computer-Aided Design) systems were used for drafting designs, but they lacked the ability to integrate different aspects of a project, such as structural, mechanical, and electrical systems, in a single platform. The development of BIM, which gained momentum in the 1990s, allowed for a more holistic approach by enabling the creation of a 3D digital model that encompasses the entire building's lifecycle.

BIM software evolved to include capabilities for structural engineers to perform sophisticated analyses, simulate building performance, and optimize designs. This progress has been instrumental in reducing errors, improving collaboration, and enhancing the sustainability of engineering projects. Today, BIM is an essential tool in structural engineering, with advanced integrations that support the design of non-prismatic members and complex connections.

III. CHALLENGES IN DESIGNING OF NON-PRISMATIC MEMBERS

Designing non-prismatic members presents significant challenges due to their complex geometries and varying cross-sectional profiles. Unlike prismatic members with uniform dimensions, non-prismatic members exhibit non-linear stress distribution and deformation behaviour, making their analysis and design more intricate. Conventional design methods, which rely on simplified assumptions and linear approximations, are often inadequate for addressing these complexities. These methods fail to accurately model the variation in geometry, leading to conservative designs that may overuse materials or compromise structural performance. Furthermore, traditional tools and workflows lack the capability to integrate parametric geometries seamlessly with advanced analysis techniques, creating inefficiencies in the design process. The detailing of connections and bracing systems also becomes problematic, as conventional approaches are not optimized for the unique requirements of non-prismatic members. This often results in increased fabrication and assembly complexities. To overcome these challenges, advanced computational tools and methodologies, such as the integration of BIM and FEM, are essential. These tools provide the precision and adaptability needed to address the non-uniformity in geometry and behaviour, offering sustainable and cost-effective solutions while ensuring structural safety and performance.

IV. METHODOLOGY

The methodology adopted in this study focuses on integrating Building Information Modelling (BIM) and Finite Element Method (FEM) tools to design and optimize non-prismatic members. The process begins with the development of two structural models using BIM software: a traditional truss structure incorporating braces and connections and a single non-prismatic member as its equivalent. Parametric modelling capabilities in BIM are utilized to define the varying geometries of the non-prismatic member accurately. These models are then exported to FEM tools, where advanced computational algorithms are employed to analyse structural behaviour under various loading conditions. Key performance metrics, such as stress distribution, deformation, and material usage, are evaluated to compare the designs. Optimization techniques are applied to the non-prismatic model to refine its performance, focusing on minimizing material usage, simplifying connections, and ensuring structural integrity. The results are validated through iterative simulations to ensure reliability.

To further enhance the workflow, the study utilized automated data exchange between BIM and FEM tools, ensuring a seamless transfer of complex geometrical and material properties for analysis. Custom scripting and parametric algorithms were employed to refine the non-prismatic member's geometry, enabling precise optimization of structural performance under various loading scenarios. The generation of automated fabrication-ready files, such as steel sheet cutting patterns, directly from the BIM model streamlined the manufacturing process, reducing manual errors and improving efficiency. This integration ensured that the design intent was accurately translated into constructible components, facilitating a smoother transition from digital modelling to physical construction.

Through this methodology, the study demonstrates the potential of advanced computational tools to streamline the design process, enhance material efficiency, and improve constructability for complex structural systems.

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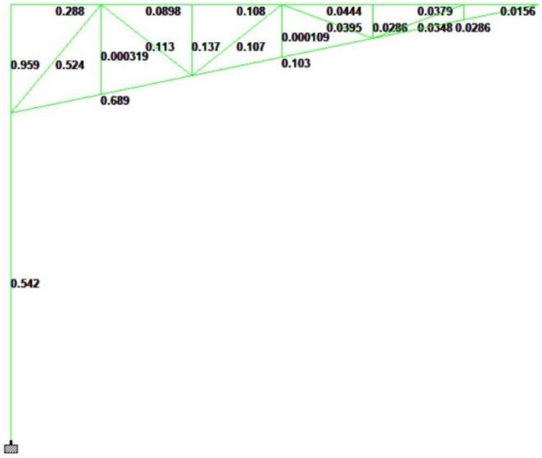

Fig. 1 Convectional Truss System with Multiple Connection

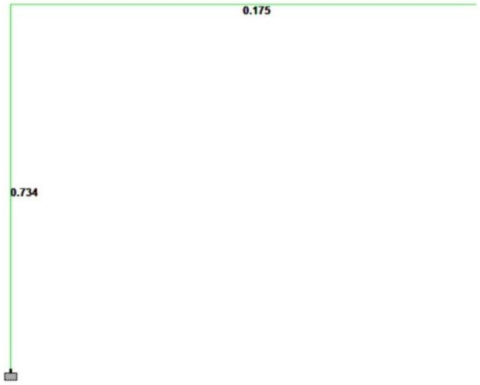

Fig. 2 Equivalent Non Prismatic Member with Unity Ratio Check

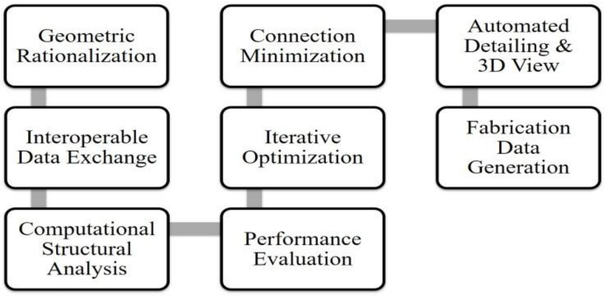

Fig. 3 Hierarchical Process for BIM-based FEM Structural Analysis and Optimization of Non-Prismatic Sections

V. DISCUSSION

The integration of Building Information Modelling (BIM) and Finite Element Method (FEM) tools marks a significant advancement in addressing the challenges associated with designing non-prismatic members. Traditional design methodologies often fall short in accurately modelling the varying cross-sections and complex geometries of non-prismatic members, resulting in over-conservative designs and increased material usage. This study demonstrated the effectiveness of leveraging BIM's parametric modelling capabilities to create precise representations of such members, which were then seamlessly integrated into FEM tools for comprehensive structural analysis and optimization. The proposed workflow led to a substantial reduction in the number of structural connections by approximately 78%

compared to conventional truss structures simplifying assembly processes, reducing potential failure points, and cutting down overall construction costs.

Another key advantage of the integrated approach is the automation of manufacturing-related tasks, such as generating steel sheet cutting files directly from the BIM model. This automation ensures precision, reduces fabrication time, and minimizes material waste, aligning with contemporary goals of sustainability and efficiency in construction. The comparative analysis between a truss system and a non-prismatic member highlighted the potential to achieve similar material consumption while eliminating the need for additional supporting materials. Despite these benefits, successful implementation requires expertise in both BIM and FEM platforms and a collaborative design environment. The findings underline the potential of this approach to bridge the gap between innovative architectural designs and structural feasibility, paving the way for more efficient and sustainable practices in structural engineering.

VI. CONCLUSION

The findings of the study highlight the transformative potential of integrating Building Information Modelling (BIM) and Finite Element Method (FEM) tools in the design of non-prismatic members. By leveraging the parametric modelling capabilities of BIM and the analytical precision of FEM, the study successfully demonstrated a streamlined workflow for replacing traditional truss structures with optimized non-prismatic members. A significant outcome of this integration was the reduction in the number of connections by approximately 78%, which not only simplified fabrication and on-site assembly but also minimized potential points of failure, improving overall structural reliability. Additionally, the use of advanced BIM tools facilitated the automatic generation of precise steel sheet cutting files, enhancing constructability and reducing fabrication time. This automation also contributed to cost savings by improving material efficiency and ensuring that design complexities were translated accurately into manufacturing processes.

Furthermore, the findings underline the sustainability benefits of adopting this integrated approach. While material consumption for the primary member was comparable to the traditional truss, the elimination of bracing and connection materials resulted in reduced material wastage. The methodology also aligns with modern construction practices, where precision, sustainability, and efficiency are paramount.

This workflow provides a robust framework for addressing the challenges associated with non-prismatic members, paving the way for broader adoption in both academic and professional engineering contexts. Future studies can expand on this approach by exploring further automation, optimization techniques, and applications to other complex structural geometries.

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