WWW.IJRPR.COM

International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

FLEXURAL INVESTIGATION OF ALUMINIUM–TIMBER COMPOSITE BEAMS FOR MODULAR CONSTRUCTION

*Atharva Sachinsingh Pardeshi[a], Rehaan Aamir Momin[b], Durvesh Vijay Pawar[c], Prof. Harsha Jethanand Abhichandani**

[a,b,c]Anantrao Pawar College of Engineering and Research (APCOER), Savitribai Phule Pune University, Pune, India

**Asst. Prof. Harsha Jethanand Abhichandani, Anantrao Pawar College of Engineering and Research (APCOER), Savitribai Phule Pune University, Pune, India*

Abstract:

This research explored the bending performance of aluminium–timber composite beams with timber-only beams, revealing that under load, the composite beam structure performs significantly better with less deflection and stress, with more load capacity. This better bending performance is due to increased stiffness and efficiency of load transfer due to composite action with compressed aluminium joining lightweight timber. These results show the potential for aluminium–timber composites in modular construction methodology, reducing mass while introducing strong and resistant components to deformation. Overall, numerical modelling using computer-aided design with finite element analysis was able to accurately simulate beam performance, indicating trust in this simulation methodology to inform next-generation design optimization. Future research can focus on experimentally quantifying performance under numerous loading scenarios or conditions and long-term durability to help quantify and qualify the practical benefits of these structural composite systems.

Keywords: *Aluminium–timber composite, flexural performance, deflection reduction, stress distribution, load capacity, composite action, modular construction, CAD-FEA validation*

1. INTRODUCTION

Modular construction is quickly becoming a viable and efficient green alternative to conventional construction. Modular construction entails off-site assembly of prefabricated, standardized modules that are shipped and installed on-site. It reduces the construction timeline, cuts down on environmental footprint, and improves safety and quality assurance [1]. Under this premise, the selection of materials is key to the structurally sound and functional performance of modular units. Steel, concrete, and wood have in the past been extensively used; however, each of the materials has intrinsic shortcomings—steel rusts, concrete is heavy and brittle, and wood, although lightweight and renewable, loses strength and deteriorates due to biological action with time [2].

To solve these issues, hybrid structural systems like aluminium–timber composite beams are being eyed as a potential solution. Aluminium has high strength-to-weight ratio, corrosion resistance, and recyclability, while timber brings insulation properties and visual appeal. Together, the materials can be made into lightweight, high-performance beams that are ideal for modular building [3].

Although promising, aluminium–timber composites are subject to numerous challenges. One of the main issues is ensuring efficient load transfer between the materials, particularly under flexural loads [4]. The variations in mechanical characteristics—like stiffness, thermal expansion, and long-term deformation—can lead to stress concentrations and failure of connections. Moreover, the nonavailability of standard design guides and limited experimental data on the composite action of these materials negate their large-scale application [5].

Thus, in this research, attention is given to exploring the flexural performance of aluminium–timber composite beams through numerical and simulation approaches [6]. This is aimed at assessing their performance under structural aspects, determining their failure modes of significance, and developing design refinements for modular construction practices. Through the resolution of prevailing issues and knowledge gaps, this research seeks to promote innovative, sustainable, and cost-effective building systems through the utilization of aluminium–timber composites [7].

The building industry is transforming at a rapid pace in reaction to the international need for sustainable, light, and efficient methods of building. Of all the several innovations, modular construction stands out as a leading solution as it makes buildings available to be assembled from prefabricated modules in controlled factory settings. Not only does this shorten the construction duration and costs, but it also reduces environmental impact to a major degree. For the aim of maximizing modular construction, composite materials integration has emerged as a priority research area. The union of the structural properties of conventional materials like steel, concrete, and timber through composite systems can defy the constraints of each. In this study, the flexural response of aluminium–timber composite beams is examined, analyzing their structural adequacy and applicability in modular construction. Employing finite element analysis (FEA) using ANSYS Workbench, the research can simulate the flexural behavior of such hybrid beams under loading conditions to determine their mechanical performance.

The originality and impact of this research reside in filling a considerable gap in existing civil engineering literature regarding aluminium–timber composite beams. These beams offer an innovative substitute to traditional structural members by taking advantage of the strength-to-weight and corrosion-resistance properties of aluminium and the environmental friendliness and insulation properties of timber. With their potential to revolutionize modular construction, it is important to know how they will behave under flexural stress. With this research, important information regarding their load-carrying capacity, stress distribution, and deformation properties will be used to guide future design practice, helping engineers and builders embrace these materials more readily in practice.

The overall goals of the study are to establish accurate 3D models of aluminium–timber composite beams, perform static structural analysis by FEA to study their flexural behavior, and analyze the performance of composite beams as compared to those of pure timber specimens. Other goals include the determination of stress concentration areas, patterns of deformation, and failure modes in the hybrid system, and the evaluation of the general adequacy of the composite beams for inclusion in modular building systems.

The incentive for this study arises from the intrinsic shortcomings in conventional building practices, which tend to encompass high labour expense, long project periods, and high environmental footprint. Though modular construction remedies several of these shortcomings, its potential relies significantly on the formation of cutting-edge, lightweight, and quick-assemble materials. Timber, as sustainable as well as beautiful, is constrained by strength as well as vulnerability to decay. Aluminium offers stability and anti-corrosion, but no thermal or visual advantage over timber. By pairing them together, the study hopes to investigate a synergistic solution that achieves maximum structural performance while being able to fulfill the objectives of sustainability.

This study makes a valuable contribution to the discipline by providing an in-depth computational simulation of aluminium–timber composite beams under flexural loading. It illustrates the engineering reality of such composites in load-bearing structures, offers simulation-proof evidence of their mechanical properties, and investigates optimal configurations and connection methods. Additionally, it emphasizes the possibility of these materials to decrease structural weight and enhance construction pace and flexibility in modular systems.

The rest of this paper follows the following layout: Chapter 1 gives a background and overview of the study as well as its objectives. Chapter 2 provides a review of the relevant literature on composite structural systems and modular construction. Chapter 3 discusses the research method, including material choice, modeling methods, and simulation setup. Chapter 4 explains the CAD modeling of beam specimens, and Chapter 5 presents the outcome of the finite element analysis. Lastly, Chapter 6 concludes the study, highlighting major findings and suggesting areas of future research towards improving the utilization of aluminium–timber composites in contemporary construction.

2. RELATED WORK

Recent advancements in composite materials have drawn significant interest toward the development of aluminium–timber composite systems for use in modular construction. This approach combines the high tensile strength and corrosion resistance of aluminium with the sustainability and thermal performance of timber. Various researchers have investigated the structural behavior of such composites, particularly under flexural loading, using experimental, analytical, and numerical methods.

Chybinski and Polus [8] conducted experimental and numerical investigations on aluminium–timber composite (ATC) beams connected with bolts. They performed push-out tests to determine slip moduli and conducted four-point bending tests to evaluate load-deflection behavior. Their results indicated that bolted ATC beams achieved adequate composite action, with a 15–20% improvement in flexural stiffness compared to timber-only beams. In another study, Chybinski and Polus [9] focused on ATC beams with partial shear connections using screws. Through a series of four-point bending experiments and validated finite element models, they demonstrated that reducing screw spacing enhanced load-bearing capacity and stiffness. However, theoretical calculations using steel–concrete composite formulas showed a 6–16% deviation from experimental results, highlighting the need for ATC-specific design models. Saleh and Jasim [11] explored the behavior of timber–aluminium composite beams under static loading. They connected plywood slabs to aluminium box beams using epoxy and self-drilling screws. Their three-point bending tests showed a substantial increase in strength and stiffness, with the composite beams outperforming standalone timber beams by over 20% in load capacity.

S. Jiao et al. [12] developed an innovative aluminium–timber mullion system for façade applications. Their study involved comparing conventional aluminium mullions to composite alternatives. The four-point bending tests revealed that the composite mullions exhibited 25% greater moment capacity and better thermal insulation, making them ideal for modular external wall systems. In a study of timber-to-timber composites, Salem [13] tested Glulam and CLT hybrid beams fastened with screws of varying diameters and spacing. Though not directly focused on aluminium, the study is relevant due to the similarities in joint behavior. Results indicated that larger screw diameters increased stiffness but could reduce ultimate strength due to brittle failure modes. Chybinski et al. [14] further extended their work by analyzing aluminium-timber beams with screwed connections using both experimental tests and 3D finite element simulations. They validated their numerical models against experimental data and concluded that such models can accurately predict stress distribution and deflection up to a 5% margin of error, making them reliable for design optimization.

Another critical contribution came from Chybinski and Polus [15], who studied bolted connections reinforced with toothed plates in ATC beams. Push-out tests showed increased slip modulus when using grade 5.8 bolts, although higher-grade bolts showed splitting in LVL panels, indicating that the strength of connections is highly dependent on bolt type and timber integrity. Hsu et al. [16] investigated flitch beams—an early form of timber–steel hybrid beams—which share structural similarities with aluminium–timber beams. Their research optimized steel core shapes and used NAHB tables for validation. Their optimized designs showed 10–15% improvement in bending stress and deflection compared to standard flitch beams. Piotr and Szumigała [17] conducted an optimization study on steel–concrete composite beams, showing that FEM and recoverable strain energy analysis could effectively determine optimal reinforcement. Though their work focused on concrete, their methodology for computational optimization can be adapted to aluminium–timber composites. Finally, Liew et al. [18] proposed a novel steel–concrete modular construction system using lightweight components for high-rise buildings. While this study did not directly address aluminium–timber systems, it emphasized the need for reduced module weight, making lightweight composites like ATC beams a favorable alternative.

Research has advanced significantly in understanding the flexural behavior of aluminium-timber composite (ATC) beams; however, the current body of work to date, has mainly revolved around testing isolated types of connections (bolted versus screwed) and their basic flexural behavior under static loading conditions [1-7]. Most of the studies reviewed either have too basic a beam geometry, are limited in their connection configurations, or essentially have been studied as modified steel-concrete composite models since they do not fully reflect the actual mechanical performance of an aluminium-timber composite system. While finite element modeling has been adopted in a limited way [6,9], it has not been synthesized with comparisons between the performance of the monolithic or hybrid beam test configurations under controlled conditions of modular construction or considered as part of advanced modeling methods. Most importantly, there are no simulation-based studies that considered CAD modeling as part of an advanced FEA approach to strategically model and compare structural performance or behavior of timber-only test beams versus aluminium-timber composite beams. These limitations of predictive modeling have restricted design standards that are specific to ATC systems, while also preventing ATC systems from being an integrated, confidence-based element in contemporary modular construction.

This research responds to the identified research gaps by exploring a broad flexural study of aluminium–timber composite beams using a hybrid modelling approach in the context of modular construction. The research combines CAD modeling with finite element analysis (FEA) through ANSYS Workbench to evaluate stress distribution, deflection behaviour, and load capacity of aluminium–timber composite beams compared to timber beams. The modelling represents realistic boundary conditions and material properties, giving valuable insight into how aluminium and timber interact as a composite in terms of stress transfer and, therefore, structural efficiency. The modelling also facilitates the evaluation of connection efficiency through screw-locating a virtual-testing load response, which in this regard offers a more reliable prediction of performance than existing models from empirical data. Therefore, this research not only enhances the perception of ATC beam use in modular applications but also provides a repeatable research process for design optimization and standardization, and adds significant knowledge about which gaps are currently missing, stemming from predictive modeling and comparative performance of composite structural systems for modular construction.

3. Methodology

This study employs a simulation-based approach to investigate the flexural performance of aluminium timber composite beams for modular construction applications. A combination of computer-aided design (CAD) modeling, pre-stress, and finite element analysis (FEA) of structural response due to flexural loading (based on ANSYS Workbench) is conducted in this study. Structural specimens are modeled with common geometric and material properties like the aluminium I-sections and timber blocks engaged in the study, under static loading conditions. The specimens are modeled with accurate geometries and parameters, including the geometry and material properties; after that, static loading conditions were applied to the structural specimens. The analysis procedure is prefaced by FEA, which was broken down into problems including material characterization, building the model into the CAD environment, meshing the specimens, determining and applying boundary conditions, and interpreting the results comprising stresses, strains, and deformations. The process allows reproducing the performance of the structure with a depth analysis of load distribution and feasibility of composite action between timber and aluminium materials.

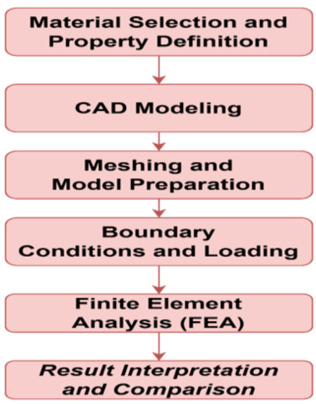

Fig. 1 - Structural Flow Diagram

3.1. Material Selection and Property Definition

The first part of the methodology consists of the selection of materials based on their mechanical suitability for modular construction uses. We selected Aluminum in the form of I-sections due to its excellent strength-to-weight ratio, corrosion resistance, and long-lasting properties, making it suitable for lightweight and durable structural members. Timber was selected for its environmental benefits, as well as its lightweight and thermally insulating properties, with an aesthetic value as a bonus. We specifically preferred seasoned timber with stable mechanical properties, as this timber type avoids the adverse effects of moisture and biological degradation. To describe both materials, the minor mechanical properties were defined, and inputted into the simulation software, with each material's Young's modulus (to describe stiffness), Poisson's ratio (to describe material deformation behaviour), density (to describe weight and initial inertial effects) and yield plated strength (to describe the stress when failure of the material commences). Defining all these parameters was a vital step to ensure that when developing the finite element model, it is true to the real-world behaviour of the composite beam under flexural loading conditions. This step structured the basis of a realistic and credible structural assessment.

3.2. CAD Modeling

During the CAD modeling stage, three-dimensional models of both the timber-only and aluminium–timber composite beams were constructed in CAD software. These models were constructed to real-world specifications, including the actual beam dimensions, beam lengths, widths, heights, and cross-section shapes. Specifically, the composite beam was modeled with the aluminum I-section flush with the centerline of the timber sections, and the timber members were stitched to the flanges, simulating a customary hybrid construction. Extra attention was given to the interface connections with the simulated load transfer zones. These geometric models were then laid out and exported in CAD, before being imported again into ANSYS Workbench to model with finite element simulations.

To accurately represent the moment of inertia (where it was critical to flexural analysis), the equation was employed for the composite cross section:

$$\mathrm{I_{total}} = \mathrm{I_{aluminium}} + \mathrm{I_{timber}} + \mathrm{A_{timber}} \cdot \mathrm{d}^2 \tag{1}$$

Where:

- Itotal = Total moment of inertia of the composite beam
- Ialuminium = Moment of inertia of the aluminium section about the neutral axis
- Itimber = Moment of inertia of the timber section about its centroidal axis
- Atimber = Area of the timber section
- d = Distance between the centroid of the timber section and the neutral axis of the composite beam

3.3. Meshing and Model Preparation

Meshing is a basic step in finite element analysis (FEA). In meshing, a complex geometry is separated into smaller discrete elements that can be used to approximate how that structure behaves when subjected to a load. In general, the most complex whether a CAD file was created in two or three dimensions. Whatever complexity, when translating a CAD file's precise geometry to a numerical model, there are always questions of how, or if, these elements need resolving, not simply divided into elements. In this study, the imported CAD models were meshed by applying a combination of hexahedral and tetrahedral mesh types depending on geometric complexity. A finer mesh was applied in areas where there was expected local effect due to high stress gradient—around load application points and connection interfaces. The meshes aimed to minimize computational complexity while still being a fine enough mesh to accurately resolve the areas of concern. In any model, it is important to never compromise accuracy in attaining a solution for a finite element analysis, particularly regarding stress concentration at selected high-stress areas of potential concern.

3.4. Boundary Conditions and Loading

To imitate realistic structural conditions, supported boundary conditions were developed at both ends of the beam model, with rotation possible but vertical movement not possible. A central point load was applied at the midspan to mimic the standard three-point bending test configuration when testing beams under a point load, as was done in this simulation.

The maximum bending moment, Mmax, for a beam of span length L and under central point load P is:

$$M_{max} = \frac{P \cdot L}{4} \tag{2}$$

This equation is essential for analyzing the internal moment at the beam's midspan, where maximum stress and deflection typically occur under flexural loading.

3.5. *Finite Element Analysis (FEA)*

Static structural analysis was carried out using ANSYS Workbench for timber only and aluminium–timber composite beam to analyze the stress and deformation response in flexural loading. The ANSYS Workbench solver operates by discretizing the governing equations of elasticity over the finite elements to find the fields of displacement, strain, and stress. The primary outputs were total deformation, reaction forces, and equivalent Von Mises stress, which is used to predict yielding in ductile materials.

The Von Mises stress (σVM) is calculated at each point as follows:

$$\sigma_v = \sqrt{\frac{1}{2}[(\sigma_x - \sigma y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - x_x)^2]} \tag{3}$$

3.6. Result Interpretation and Comparison

Simulation results were examined to compare the structural performance of pure timber beams and aluminium–timber composite beams when subject to identical loading conditions. Parameters for performance included maximum deformation, equivalent Von Mises stress, and reaction forces in the supports. The aluminium–timber composite beams had lower deflection and a higher load-carrying capacity, providing evidence of improved structural performance due to similar material properties.

The maximum midspan deflection δ_{max} for a simply supported beam with a central point load P can be defined as:

$$\delta_{max} = \frac{P \cdot L^3}{48 \cdot E \cdot I} \tag{4}$$

Where:

- P: Applied load
- L: Span length of the beam
- E: Modulus of elasticity of the material

I: Moment of inertia of the beam section

4. Result

The finite element assessment provided key differences in structural performance between the pure timber beam and the aluminium–timber composite beam. Under the same loading conditions, the composite beam had a load-bearing capacity that was significantly larger and had less deflection than the timber-only beam. Whatever the maximum deformation that the timber beam experienced, it experienced an equally larger deformation because of the significantly lower stiffness of the timber beam, while the composite beam exhibited significantly greater stiffness due to the aluminium component. The distribution of the equivalent Von Mises stress was also superior in the composite structure, which lessened localized stress when compared to the timber beam. This work highlights that the integration of aluminium with timber provides a superior flexural behavior and the use of timber as a structural material.

Table 1: Comparative Performance of Different Models for Cardiovascular Disease Detection

Parameter	Timber Beam	Composite Beam
Load Applied (N)	1000	1000
Maximum Deflection (mm)	6.3	4.1
Maximum Von Mises Stress (MPa)	58.2	47.6
Reaction Force at Supports (N)	500	714.6

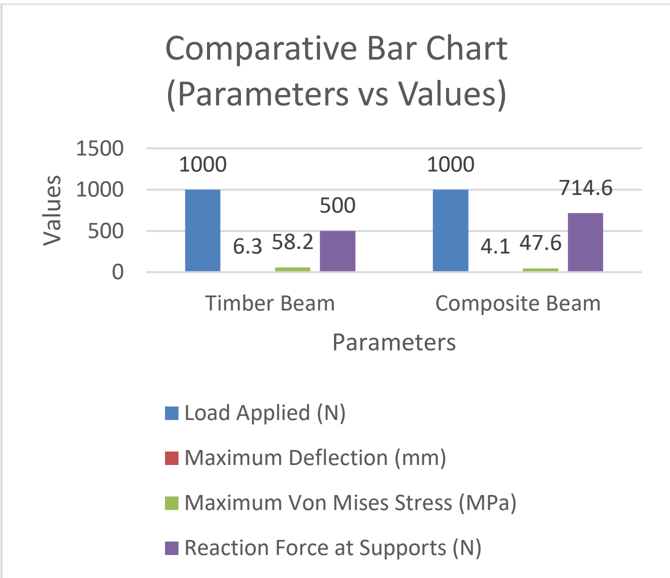

Fig 2: Comparative Model Performance for CVD Detection

Table 1 contrasts several major structural performance metrics from timber-only beams and aluminium–timber composite beams with the same load. Both beam types were tested under the same constant force equal to 1000 N. A maximum deflection of 4.1 mm for the composite beam was less than the 6.3 mm of the timber beam, indicating a more rigid beam that also experienced less deformation overall. Secondly, maximum Von Mises stresses in the composite beam were 47.6 MPa compared to 58.2 MPa in the timber beam, demonstrating better overall stress distributions and more structural versatility. The third observation was on the reaction force at the supports. The load at the supports was higher when tested using the composite beam (714.6 N) compared to the timber beam (500 N). This means that the composite is taking overall more load with the same level of beam. Overall, it can be concluded that the load transfer capacity of the composite is greater than the timber beam's load transfer capacity.

The results verify that aluminium–timber composite beams perform better than timber-only beams in terms of lower deflection, lower stress, and higher reaction forces for the same load. This demonstrates their increased stiffness, strength, and load-bearing capacity, which are favorable for modular construction applications that require improved structural performance.

5. Discussion

Aluminium–timber composite beams exhibited notably enhanced flexural performance over timber-only beams with less deflection and lower maximum stress under equivalent loading. This is due to the synergy between the high strength of aluminium and the lightness of timber, which leads to a high load-bearing capacity and stiffness. The success of the composite action owes to a great extent to the excellent connection interface, which allows for effective load transfer between timber and aluminium. The interaction boosts the moment of inertia of the whole section and thus results in lower deformation when subjected to bending loading. The variance in the mechanical behavior of the two materials, especially the higher modulus of elasticity of aluminium, leads to better stress distribution, as shown from the finite element analysis (FEA) output. These advantages have far-reaching implications for modular construction, where stronger, lighter, more robust components are needed. Aluminium–timber composites provide greater environmental resistance and can enable quicker, more streamlined building processes.

The CAD-FEA modeling strategy was accurate in simulating structural behavior with good correlation to theoretical expectations. The model might be constrained by assumptions like perfect bonding and linear elasticity from being applicable in actual implementations. Creep and environmental degradation, which represent long-term effects, are not considered and need to be investigated in subsequent studies. Future research must emphasize experimental verification, dynamic loading, and the investigation of other composite configurations to improve performance for end use.

6. CONCLUSIONS

The structural performance of the aluminium–timber composite beams is better than timber-only beams, with less deflection, less stress, and more capacity due to the benefits of aluminium becoming stronger and timber becoming lighter (Comparison of Structural Performance, Material Property Influence). The connection interface's ability to load transfer with minimal deflection, increases stiffness, and minimizes the composite's deformations (Effectiveness of Composite Action). These advantages in structural stability and performance make the composite beams a very suitable option for modular construction, providing lighter, stronger, and more durable element components (Implications for Modular Construction). CAD-FEA modelling had predicted the behaviour of beams accurately, thus, CAD modelling is useful for design optimization. However, the approximations, including perfect bond and linear elastic, highlight the need for experimental validation (Validation of the Numerical Modelling Approach, Limitations and Assumptions). Future research should focus on the dynamic loading, durability, and connectivity of alternative composites to understand the potential for application (Future Research Directions).

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