FLEXURAL BEHAVIOR OF TIMBER-STEEL COMPOSITE BEAMS USING MECHANICAL FASTENERS FOR HERITAGE AND MULTI-STOREY BUILDING APPLICATIONS

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Abstract - This study evaluates the structural behavior of timber-steel composite beams assembled with mechanical connections: steel nails and self-drilling screws. The study is to enhance the load-bearing capacity of wooden components in wooden muiti-storey buildings and the renovation of heritage architectural structures. Many early 20th-century Asian wooden structures exhibit deficiencies, requiring reinforcement, for which the timber-steel composite structure offers a solution by combining the lightweight and renewable properties of wood with the strength and ductility of steel. Full bending tests have been conducted with flat steel plates or I-shaped steel cores, connected by various types of bolts. I-shaped steel cores and self-drilling screws achieved 4 times greater load-bearing capacity and 3.6 times higher stiffness compared to unreinforced specimens. The study enhances structural stability in both the preservation of ancient wooden structures and the development of Vietnam modern construction infrastructure using wood.

Key words - Timber-steel composite; bending strength; structural retrofitting; multistory timber construction; fastener efficiency; sustainable architecture; heritage conservation

1. Introduction

1.1. Context of timber–steel composite applications in heritage and multistory building

Wood has been employed for centuries for building applications given its lightweight, simplicity of construction, and elevated aesthetic value. However, limitations in load-bearing capacity and long-term stability restrict such materials' challenges in performing independently in major construction projects. In contrast, steel has high strength and ductility but lacks environmental sustainability and does not provide the warm visual feel of wood. The combination of these two materials in composite timber-steel beams is increasingly attracting attention in modern construction projects and architectural heritage preservation.

Traditional wooden architectural structures, notably Temples in the imperial capital of Hue, Hanoi, present considerable challenges for conservation efforts not only in Vietnam but also other Asian countries. These structures require strengthening and reinforcement without harming their historical and aesthetic values. Besides, the expansion of multistory timber buildings call for beams that are readily accessible to install, lightweight, and structurally dependable. Timber-steel composite beams show significant potential in addressing both demands, especially when combined with mechanical fasteners such as steel nails or self-tapping screws.

Unlike adhesive connections, which need surface preparation, regulated cure durations, and a controlled working environment, mechanical connections are simple, replaceable, and easy to maintain durability. Their properties make them ideal for on-site construction, repair, and preservation. Many worldwide studies have shown that the timber-steel composite beam system works well in medium and muiti-storey structures [1], [2].

This study examines the bending performance of timber-steel composite beam specimens that relate to self-tapping screws or nails and are made from two distinct steel configurations: flat plates and I-shaped sections. Their behavior under stress was investigated using full-scale experiments, and its findings were compared against mathematical models. Furthermore, this study builds upon insights from several notable international projects and previous research. These include the Mjøstårnet tower [3] and the "TREET" residential building [4] in Norway, as well as the structural reinforcement work at the Biblioteca Civica di Verona in Italy [5] (see Figure 1). In addition, earlier studies by Le and Tsai [6], and by Dickof et al. [7], have demonstrated the structural behavior and seismic performance of timber-steel hybrid beams. These findings provide a valuable foundation for adapting similar systems to the architectural and construction contexts of Asian countries, including Vietnam.

(a) (b)

Figure 1. *Retrofitting with steel-wood composite beams (a) steel plates along beams; (b) steel profiles at column joints [5]*

These findings support the broader applicability of timber–steel composite systems in both prefabricated timber architecture and heritage retrofitting - particularly in regions like Asia, where minimal, reversible interventions are preferred. For example, historical buildings from the Japanese colonial era often require reinforcement solutions that preserve aesthetics and fit within dimensional constraints. In modern contexts, such as multi-storey timber buildings, similar composite connections serve as critical elements in transferring loads and ensuring frame stability.

1.2. Research Objectives

The aim of this research was to determine the structural performance and utility of timber-steel composite beams for both new construction and old timber structure renovations. The research focuses on the following three objectives:

1. To evaluate structural behavior, conduct full-scale flexural testing on composite beams with two distinct steel types (flat plates and I-shaped sections) and two different mechanical fasteners (steel nails and self-tapping screws). Stiffness, load-bearing ability, and failure modes were all evaluated as significant variables.

2. To evaluate various connection methods by investigating the impact of different fasteners on field application compatibility, installation ease, and structural reaction.

3. To apply research findings to real-world contexts, such as historic restoration and modern timber constructions, using examples like the Mjøstårnet tower.

These objectives aim to support the development of simple, effective timber-steel composite systems that are adaptable to a variety of construction settings.

2. Composite Beam Design and Testing

2.1. Specimen Configuration

The configurations of the four beam types examined in this study can be seen in Table 1. Main test parameters include the variety of fasteners used across every specimen, the assembly technique, and the type of steel reinforcement.

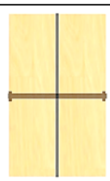
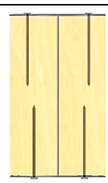
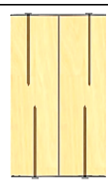
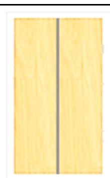
Type A: A bolt-connected timber beam strengthened with a flat steel plate.

Type C: A timber beam strengthened with an I-shaped steel core and fastened with steel nails.

Type D: A timber beam strengthened with an I-shaped steel core and self-tapping screws.

Type F: A timber-only control specimen without steel reinforcing.

Table 1. *Testing Specimens*

	Type A	Type C	Type D	Type F
Fastener Type	Bolt	Nail	Screw	None
Layout				
Description	Horizontal bolts (700mm spacing).	4 rows of vertical nails.	4 rows of vertical screws.	no mechanical connection visible
Section (mmxmm)	82×140	80×144	80×144	78×140

2.2. Materials

All specimens had identical timber dimensions and were constructed using Cryptomeria wood. Regarding timber variability, moisture content was measured and controlled (average 12%). The steel components were prefabricated and precisely aligned to ensure consistent assembly across configurations (Figure 2).

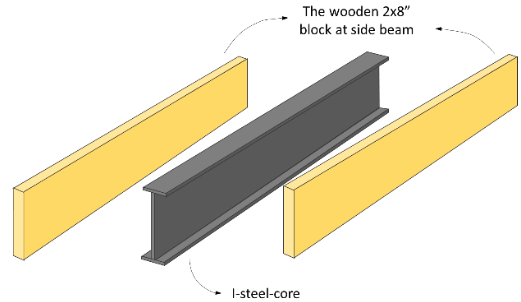


Figure 2. *Wood with I-shape steel*

2.3. Test Setup and Measured Parameters

2.3.1. Experimental Setup and Measured Parameters

Full-scale four-point bending tests were carried out to simulate structural loading conditions. The beams were tested over a span of 2970 mm (Figure 3). Key parameters measured included:

Load-deflection behavior

Load at L/360 deflection (serviceability limit)

Maximum load at failure

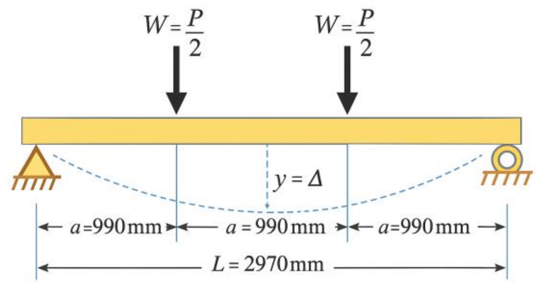


Figure 3. *Four-point bending test setup*

Load and displacement data were recorded throughout the test for each specimen using load cell and Linear variable differential transformer (LVDT), respectively. Visual observations were also conducted to identify typical failure modes, such as connector slip, cracking, or torsional deformation.

2.3.2. Theoretical Calculation Model

Based on the established relationships above, the calculation model for the composite timber-steel beam can be simplified as follows:

The theoretical study of the hybrid timber-steel beam is based on the concept of linear elasticity, intent at assessing the bending stress and deflection of the beam under the action of transverse load. The stress in each material (wood and steel) can be defined according to the values of the utilized moment, modulus of elasticity (E), and moment of inertia (I), with the condition that the stress its own does not exceed the material's bending capacity ($\sigma \leq f$). From thus, the allowable distributed load expressions (q) are determined, considering into account the stiffness of each component. The deflection limitation has been set according to the L/360 recommended in the model. After processing the equivalent equations, the limit load is expressed as a function of the cross-sectional shape and material properties, as follows:

$$q \le \frac{384E_wI_w(1+1+\alpha\times\dfrac{b(h+t)^3-(b-\dfrac{t}{2})h^3}{bh^3}}{1800L^3}$$

• q: Uniform load on the beam (force per unit length).

• L: Length of the beam.

• E_s: Steel Modulus of elasticity, E_w: Timber Modulus of elasticity).

• I= Area moment of inertia of cross section (I_w: Moment of inertia of the timber section, I_s: Transformed moment of inertia of steel section, α represents the relative stiffness factor between steel and timber, while b, h, and t refer to the width and height of the timber section, and the thickness or height of the steel reinforcement, respectively. The use of equivalent transformed sections for analyzing composite timber-steel beams has also been adopted in practical design criteria as shown by Tavoussi et al. [2]. A similar approach using the modular ratio and transformed section concept was also employed by Le and Tsai [6] in their numerical optimization of hybrid wood-steel beams.

The test results were analyzed to evaluate structural stiffness, strength, and deformation behavior. Comparative analyses were made between the different fastener types (bolts, steel nails, self-tapping screws) and steel geometries (flat plates, I-shaped sections) to evaluate their influence on performance. Experimental results were validated against simplified elastic bending theory to evaluate the accuracy of theoretical predictions.

To bridge laboratory outcomes with field applications, the performance of the tested configurations was evaluated in the context of successful timber-steel composite systems, such as those implemented in the Mjøstårnet tower in Norway. This allowed evaluation of the tested configurations' feasibility for use in Vietnamese heritage buildings and modern timber construction domestically grown Cryptomeria wood.

3. Structural Performance and Comparative Analysis

3.1. Failure modes

The results of the flexural tests showed that the configuration of the steel element and the fastener type significantly influenced beam performance (Figure 4). Type D beams, which used I-shaped steel sections and self-tapping screws, demonstrated the highest initial stiffness and best serviceability, closely followed by Type C, which used nails with the same steel shape. Both outperformed Type A (flat steel plates with bolts) and the timber-only Type F this also have been predicted in previous research model (Figure 5).

The failure modes observed during testing were distinct across beam types. Type F failed by tension rupture below and compression crushing above. Type A showed torsion and bolt slippage. Type C had cracking and nail withdrawal. Type D failed predictably in flexure with distributed cracks and minimal slip. These patterns highlight how fasteners influence ductility and failure behavior.

Figure 4. *Cracking in timber lower chord of Type F beam (left) and type D (right)*

3.2. Flexural Behavior and Load-Carrying Capacity

Although Type A had the greatest ultimate load before collapse, it was less stable due to twisting during extreme deformation. Type D, on the other hand, was more stable and exhibited predictable failure behavior. Type F beams, which lack steel reinforcing, fared the worst and failed in a typical bending pattern (Figure 6). We have clarified that the typical bending pattern observed in Type F beams involves tensile rupture in the lower fibers and compression crushing at the top, which aligns with the expected moment–curvature (M–φ) response of unreinforced timber beams.

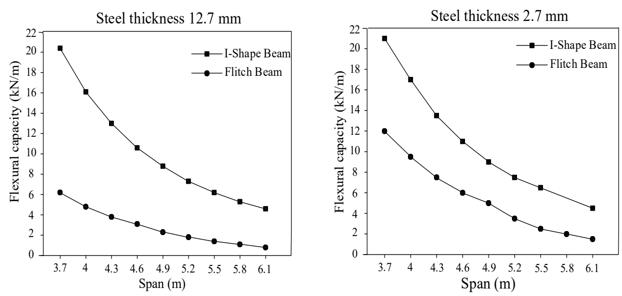


Figure 5. *Load-bearing capacity of the wooden-steel composite beams with various spans [6]*

Experimental data further validate the comparative performance of the beam types. As shown in Table X, Type D beams achieved the highest initial stiffness at 1.99 kN/mm, which is more than 3.6 times the stiffness of the unreinforced Type F beams (0.54 kN/mm). Similarly, at the serviceability limit (L/360), Type D sustained a load of 13.24 kN, markedly outperforming the control specimen and exceeding the performance of other reinforced types. The comparison between theoretical predictions and experimental results is presented in Figure 6. The linear elastic model closely approximates the observed behavior up to the serviceability limit, with minimal deviation. This alignment confirms the model's validity within the elastic range and addresses the applicability of simplified analytical approaches in preliminary design.

This confirms the effectiveness of I-shaped steel reinforcement with self-tapping screws in enhancing both stiffness and load-carrying capacity.

These results confirm the superior performance of I-shaped steel cores with self-tapping screws. All reinforcement types improved stiffness and capacity over the unreinforced beam (Type F). Type A, using bolted flat plates, also showed clear gains and remains a practical solution, especially where alignment and easy assembly are required. Overall, I-shaped steel beams with self-tapping screws (Type D) provided the best stiffness, capacity, and ductility ratio. Their performance under condition settings-controlled failure modes recommends that they are sufficient for both prefabricated construction and historical retrofitting.

Timber-steel composite systems have been previously used in various projects worldwide, demonstrating both structural efficiency and adaptability. Real-world applications of timber-steel composite systems can be observed in landmark projects such as Mjøstårnet and TREET in Norway. In Mjøstårnet - the tallest timber building in the world - composite connections with built-in steel plates and dowels were critical to transferring loads between floors and ensuring structural stability [3]. Similarly, in the TREET project, hybrid structural members enabled long-span performance with reduced deflection, which would have been difficult using timber alone [4].

Compared to these advanced configurations, the timber-steel beams examined here - particularly Type D, using I-shaped steel cores and self-tapping screws - offer a simpler and more accessible solution for small- to medium-scale construction. The suitability of Type D beams for prefabricated and modular construction is confirmed by test data. With the highest initial stiffness (1.99 kN/mm) and serviceability load (13.24 kN), along with predictable flexural failure and minimal slip, Type D offers the strength, consistency, and ease of assembly required in modular systems. These beams exhibited high flexural performance in lab testing and are well suited for prefabrication and modular systems.

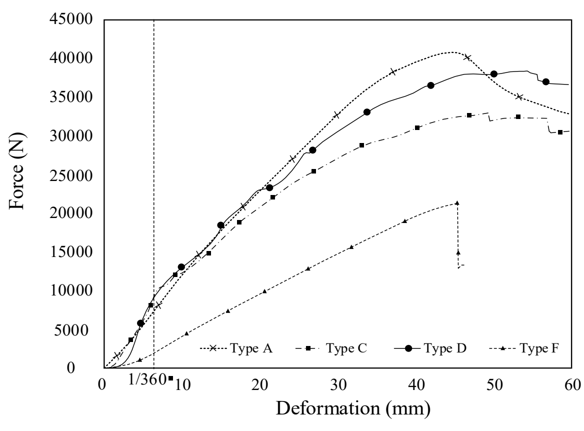


Figure 6. *Load–deflection behavior of beam types*

3.3. From Heritage to modern Multistory case

The practical use of the composite beam in a typical beam–column joint is illustrated in Figure 7. Table 2 presents the four main types of connections commonly used in construction practice - groove plates, round pins and bolts, and brackets - which are typically subjected to compressive, bending, and shear stresses.

Full-scale bending tests conducted in this study, especially on Type D beams (incorporating I-shaped steel cores and internal self-tapping screws), demonstrated significant improvements in flexural stiffness, load-bearing capacity, and ductile failure modes. Despite some construction challenges, these connections exhibited outstanding structural performance. The findings suggest that even relatively simple timber–steel composite systems can achieve adequate strength, reinforcing their potential for broader application in multi-storey timber buildings.

These characteristics also make them attractive for rehabilitation projects in Asia, particularly in Vietnam, where preserving wooden architectural heritage demands reinforcement methods that combine strength, minimal visual impact, and ease of installation. While real-world joints are often more complex, the test results confirm the viability of simplified configurations for practical use.

In the Vietnamese context, these findings are especially relevant to two domains: first, the restoration of historical timber structures - such as temples and communal houses - where internal reinforcement with slim steel cores and mechanical fasteners can enhance structural safety without altering original aesthetics; and second, the advancement of modern mid-rise timber buildings, where lightweight and modular composite systems like Type D can contribute to achieving both structural resilience and environmental sustainability.

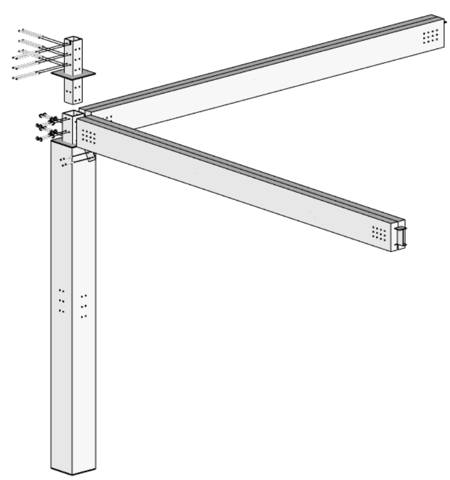
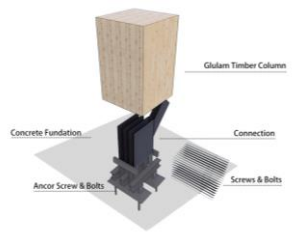
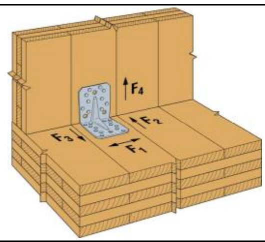


Figure 7. *Application of Composite Beam at Beam–Column Joint*

In addition to validating their structural potential in new construction, Table 2 provides a system of categories for typical timber–steel composite joint configurations across their related structural duties, also offering reference suggestions for deciding on and application of connections in actual construction.

Vietnam has a large collection of historic wooden structures, notably in Hue and Hoi An. The aging process, exposure to the elements, or damage by insects may weaken the structural components of many of these buildings. It is necessary to find options for retrofitting historic structures without compromising the original materials or altering their outward appearance. Type D beams successfully meet these standards due to their mechanical fastening and thin steel core.

Table 2. *Timber–Steel Composite Joint Configurations*

Connection Type	Suggested Figure	Rationale
Base–Column		Shows how steel plates and dowels anchor the base, highlighting vertical load transfer.
Brace–Beam		The only figure showing this lateral bracing detail, critical for in-plane reinforcement.
Slab–Slab		Demonstrates panel-to-panel joining via straps or end screws.
Slab–Wall		Highlights corner connections - key to uplift resistance and structural stability.

Low-rise timber buildings are also becoming increasingly popular as eco-resorts and sustainable design gain popularity. Without sacrificing safety, engineers may achieve greater spans and lower material utilization by using composite beams with straightforward, long-lasting connections.

4. Conclusion

This study reveals that timber-steel composite beams, especially those with I-shaped steel sections and self-tapping screws (Type D), are an achievable and reliable structure. These components demonstrated predictable, flexure-controlled failure mechanisms, improved serviceability, and increased strength. Simple mechanical fasteners make construction, disassembly, and low invasiveness easier than more complicated hybrid systems, which makes them appropriate for both heritage building retrofits and prefabricated new projects. Future studies are recommended to include additional loading conditions such as lateral, shear, and cyclic forces to reflect more realistic service conditions.

This article presents a simplified analytical model that was evaluated through full-scale four-point bending tests, showing good agreement with the experimental results within the elastic range. This addition helps address earlier concerns regarding the lack of a theoretical framework. In addition, the Mjøstårnet project is referenced to help contextualize and illustrate the broader applicability of the experimental findings. The results are particularly significant for places like Vietnam, where traditional timber structures must be strengthened without sacrificing architectural integrity. In conclusion, this study indicates that enhancing timber-steel composite systems is a promising way to offer more adaptable and sustainable building techniques.

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