WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA

Advancing Timber for the Future Built Environment

OPTIMIZED DESIGN AND STRUCTURAL PERFORMANCE OF STEEL-ENCASED TIMBER COMPOSITE (SETC) BEAMS

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ABSTRACT: Steel-Encased Timber Composite (SETC) beams offer a sustainable and high-performance alternative for structural applications by combining the strength of cold-formed steel (CFS) with the resilience and environmental benefits of timber. This study investigates the influence of key design parameters, including CFS thickness, profile variations, timber grade, and screw spacing, on the structural behavior of SETC beams. Experimental analyses was conducted to evaluate load-bearing capacity, ductility, and failure mechanisms. Results indicate that profile modifications, such as the inclusion of lips and plate reinforcements, significantly enhance structural performance. Additionally, the study highlights the importance of optimized screw spacing and timber grade selection in achieving an effective balance between strength and ductility. The findings provide valuable insights for the optimized design of SETC beams, contributing to the development of efficient, durable, and sustainable composite structural systems.

KEYWORDS: Steel-Encased Timber Composite (SETC), Composite Beams, Cold-Formed Steel (CFS), Composite Action, Structural Optimization.

ABBREVIATIONS:

CFS	Cold Formed Steel
SETC	Steel Encased Timber Composite
STC	Steel Timber Composite
G.SETC	Glued Steel Encased Timber Composite
S.SETC	Screwed Steel Encased Timber Composite

1 – INTRODUCTION AND BACKGROUND

The increasing demand for sustainable, high-performance construction materials has driven the development of composite structural systems that combine timber and steel. Steel-Encased Timber Composite (SETC) beams represent a promising solution by leveraging the compressive strength and lightweight properties of timber with the tensile strength and stiffness of cold-formed steel (CFS). These composite systems enhance load-bearing capacity, improve structural efficiency, and reduce material consumption, making them ideal for modern construction applications. However, their performance is highly dependent on key design parameters, including bonding techniques, material properties, and geometric configurations, which influence load transfer mechanisms and failure modes.

1.1 TIMBER GRADES AND MECHANICAL PROPERTIES

The structural performance of Steel Encased Timber Composite (SETC) beams is significantly influenced by the mechanical properties of timber, which vary depending on species, growth rate, moisture content, and processing methods [1, 2]. Softwoods like spruce and pine are commonly used due to their high strength-to-weight ratio, while hardwoods offer superior density and stiffness [3, 4]. Timber's anisotropic nature results in different mechanical responses in tension, compression,

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https://doi.org/10.52202/080513-0510

and shear, which must be carefully considered in composite applications [5, 6]

The modulus of elasticity, bending strength, and shear capacity of timber determine its load distribution within SETC beams [7]. Studies indicate that incorporating timber in steel composites enhances energy absorption and ductility, reducing the likelihood of brittle failure[8]. However, timber's hygroscopic nature can lead to dimensional instability, necessitating moisture control measures for long-term structural integrity [9]. Proper selection of timber grades ensures optimal performance in composite structures, balancing strength, weight, and sustainability [5, 10].

1.2 CFS SECTION THICKNESS AND PROFILE GEOMETRY

Cold-formed steel (CFS) is widely used in composite construction due to its high strength-to-weight ratio and efficient manufacturability[11]. However, thin-walled CFS sections are prone to local, distortional, and global buckling, which can compromise structural stability under axial and flexural loads ([12-14]. Studies show that the addition of timber significantly restrains buckling effects, improving the performance of CFS elements in composite structures [15-17]

The geometry of CFS sections, including channel (C), lipped-C, and rectangular hollow sections (RHS), influences their mechanical behaviour [18]. For instance, RHS sections provide uniform confinement when timber is inserted, enhancing composite action [19, 20]. Experimental findings reveal that optimized steel thickness and profile selection enhance the ultimate load-bearing capacity of SETC beams while maintaining a lightweight design [21, 22]. Furthermore, improvements in cold-forming techniques have enabled the production of ultra-thin yet high-strength steel profiles suitable for SETC applications [23, 24].

1.3 COMPOSITE ASSEMBLY TECHNIQUES AND COMPOSITE ACTION

Achieving effective composite action between CFS and timber requires precise assembly techniques. Mechanical fasteners, such as screws, bolts, and nails, facilitate load transfer and prevent excessive slip at the interface [24, 25]. Studies show that mechanical fastening increases the flexural capacity of composite beams by 120%–180% compared to timber-only beams [17, 26, 27]. Similarly, SETC beams under compressive loads demonstrate up to 6.7 times higher strength compared to standalone steel sections [18, 28].

Adhesive bonding provides an alternative joining method, offering superior load distribution and enhanced aesthetics [29, 30]. Structural adhesives have been found to improve flexural stiffness by 50%–180% and increase shear connection capacity by approximately 100% compared to bolted configurations [31, 32]. However, adhesive bonding requires meticulous surface preparation and strict environmental controls to ensure long-term durability [33].

1.4 EXPERIMENTAL INVESTIGATIONS OF SETC BEAMS

While numerical modeling has provided valuable insights into the behavior of SETC beams, experimental validation remains essential to accurately assess their structural performance under real-world conditions. Key aspects requiring investigation include slip behavior at the steel-timber interface, load distribution in flexural members, and the long-term durability of different composite interaction techniques [34]. Pushout tests are widely used to evaluate bonding strength and slip resistance, while four-point bending tests provide critical insights into flexural capacity, ductility, and failure mechanisms [32, 35].

Experimental research indicates that timber integration reduces local and global buckling failures in CFS sections, increasing load capacity and ductility [25, 36]. Various composite interaction techniques, including mechanical fastening, and adhesive bonding, have been assessed for feasibility [16, 21, 31]. SETC systems offer potential for extended spans and higher applied loads with minimal material consumption, making them a sustainable and cost-effective solution [19, 20, 25, 37]

1.5 SCOPE AND OBJECTIVES

This study systematically investigates the behavior of SETC beams by analysing:

1. Timber Grade (MGP10 vs. F5): Evaluating its impact across Screwed (S.SETC), and Glued (G.SETC) configurations.
2. CFS Section Properties: Evaluating the influence of section thickness (1.15 mm vs. 1.6 mm) and profile geometry, including C-section (C), lipped C-section (CL), and reinforced C-section with Lip by a plate (CLP), on stiffness, load-bearing capacity, and geometric interlocking.
3. Screw Spacing (100 mm, 150 mm, 200 mm): Investigating its role in load distribution and failure modes.

Through 37 experimental beam tests, this study provides valuable insights into the structural efficiency of SETC beams. The findings aim to optimize composite assembly techniques, promoting more efficient, resilient, and sustainable timber-steel composite structures. By addressing gaps in existing research, this work contributes to advancing SETC technology, balancing structural innovation with practical and ecological considerations for high-performance buildings and retrofitting projects.

2 – EXPERIMENTAL PROGRAM

This study investigates the structural behavior of SETC beams by examining the influence of timber grades, CFS thickness and profiles, and screw spacing in three composite assembly techniques: Screwed, and Glued configurations. The goal is to optimize bonding strength and maximize beam capacity.

2.1 MATERIALS

MGP10 and F5 pine timber was selected due to its widespread use and favorable mechanical properties. Tensile and compression tests were performed following AS/NZS 4063.1, confirming the material's strength characteristics. The mechanical properties of the timber, including tensile strength, modulus of elasticity, and compressive strength, were key factors influencing the overall beam behavior, as shown in Table 1.

CFS sections were fabricated from 1.15 mm and 1.60 mm thick cold-rolled steel sheets, formed into C-sections (C), C-section with Lip (CL), and C-section with Lip and Plate (CLP). Tensile coupon tests were conducted according to AS/NZS 4600:2005 and AS 1391 to determine yield strength, ultimate strength, and strain capacities as shown in Table 1. The CFS thickness and profiles directly affected the beam's stiffness and load-bearing capacity.

TABLE 1: MATERIAL PROPERTIES.

Material	Property	*MGP10*	*F5*
Timber*	Tensile Strength (MPa)	57.55	57.00
	Ultimate Tensile Strain	0.0072	0.0088
	Modulus of Elasticity in Tension (GPa)	9.091	8.65
	Compressive Strength (MPa)	29.77	30.09
	Ultimate Compressive Strain	0.015	0.015
CFS	Yield Strength (MPa)	332.97	
	Ultimate Strength (MPa)	396.50	

Note: *For timbers, parallel to grain values are included.

Specimen Configurations and Screw SpacingThree distinct SETC configurations were tested:

1. Screwed SETC Beams: Coach screws (6 mm diameter, 25 mm length) were inserted at varied spacings to assess the effect of mechanical fastening on load distribution and stiffness.
2. Glued SETC Beams: High-strength liquid nail adhesive was applied to enhance bonding strength between CFS and timber.

A total of 37 specimens were prepared, incorporating various combinations of timber grades, CFS thicknesses, profiles, and composite assembly techniques, as detailed in Table 2. Each specimen type was tested in duplicate, and the average values were taken, except for MGP10 timber specimens, which were tested five times to ensure accuracy. The results showed good agreement between duplicate samples before averaging. Flexural tests were conducted on 2400 mm long specimens.

TABLE 2: DESCRIPTION AND CLASSIFICATION OF SETC SPECIMENS.

Sample	Timber Grade	CFS Thickness and Profile	Assembly Technique	No. In Fig. 0
1a	MGP10	-	-	Figure 1 A
1b	F5	-	-	Figure 1 B
2	-	C – 1.15	-	Figure 1 C
3	-	CL – 1.15	-	Figure 1 D
4	-	CLP – 1.15	-	Figure 1 E
5a	MGP10	C – 1.15	Glued	Figure 1 F
5b	F5	C – 1.15	Glued	Figure 1 G
5c	MGP10	C – 1.60	Glued	Figure 1 H
6a	MGP10	C – 1.15	Screwed @100 mm	Figure 1 I
6a_1	MGP10	C – 1.15	Screwed @150 mm	Figure 1 J
6a_2	MGP10	C – 1.15	Screwed @200 mm	Fig. 1 K
6b	MGP10	C – 1.60	Screwed @150 mm	Fig. 1 L
6c	F5	C – 1.60	Screwed @150 mm	Fig. 1 M
7	MGP10	CL – 1.15	Screwed @150 mm	Fig. 1 N
8a	MGP10	CLP – 1.15	Screwed @150 mm	Fig. 1 O
8b	MGP10	CLP – 1.60	Screwed @150 mm	Fig. 1 P

2.2 SPECIMEN'S PREPARATION

Three typical sets of specimens were fabricated, comprising screwed, and glued SETCs. Comprehensive details regarding the specimens are provided in Table 2, and Figure 1.

The steel sections used were bended CFS C-sections with dimensions of 192.3 mm × 46.15 mm × 1.15 mm and 193.2 mm × 46.6 mm × 1.60 mm, as well as C-sections with lip profiles measuring 192.3 mm × 47.30 mm × 35 mm × 1.15 mm and 193.2 mm × 47.2 mm × 35 mm × 1.60 mm and Steel Plate of 192.3 mm × 1.15 mm and 193.2 mm × 1.60 mm. Specimens were cut and prepared to lengths of 2400 mm for flexural testing. The timber samples measured 2400 mm in length with cross-sectional dimensions of 45 × 90 mm.

https://doi.org/10.52202/080513-0510

Screwed SETC specimens were fabricated by inserting timber into CFS sections and fastening them with 6 mm diameter, 25 mm length coach screws. The screws were placed at varied spacings, 100, 150, and 200 mm, to analyse their influence on beam strength. Pre-drilled holes ensured precise alignment before fastening.

For glued SETC specimens, four lines of high-strength liquid nail adhesive were applied to the CFS section before inserting the timber. The adhesive was selected for its strong bonding properties and durability in various conditions. The specimens were clamped for 24 hours to ensure proper curing.

2.3 TEST SETUP

The 1000 kN capacity test setup operated under supported load control mode. A load cell recorded flexural loads, while three LVDTs (Linear Variable Differential Transformers) measured displacements at midspan and quarter-span locations. Load application was facilitated through a piston with a load cell. A data acquisition system recorded load, displacement, time, and strain data, as shown in Figure 2.

3 – RESULTS AND DISCUSSIONS

The structural performance of CFS and Timber beams varies significantly depending on profile and material configurations. The experimental results highlight the distinct load-bearing behaviors of these materials when used individually and in composite systems. Figure 3 illustrate the load-deflection responses of different CFS and timber beam configurations, providing critical insights into their structural characteristics.

As shown in Figure 3, standalone CFS beams demonstrate significantly lower ultimate load capacities than their composite counterparts. A standard CFS C-section without reinforcement achieves only 8.5 kN, whereas adding a lip profile unexpectedly decreases the peak load to 4.5 kN due to local buckling effects. However, incorporating a steel plate with the lip reinforcement enhances the ultimate load capacity to 12 kN, indicating that plate stiffeners mitigate premature local buckling and improve load resistance.

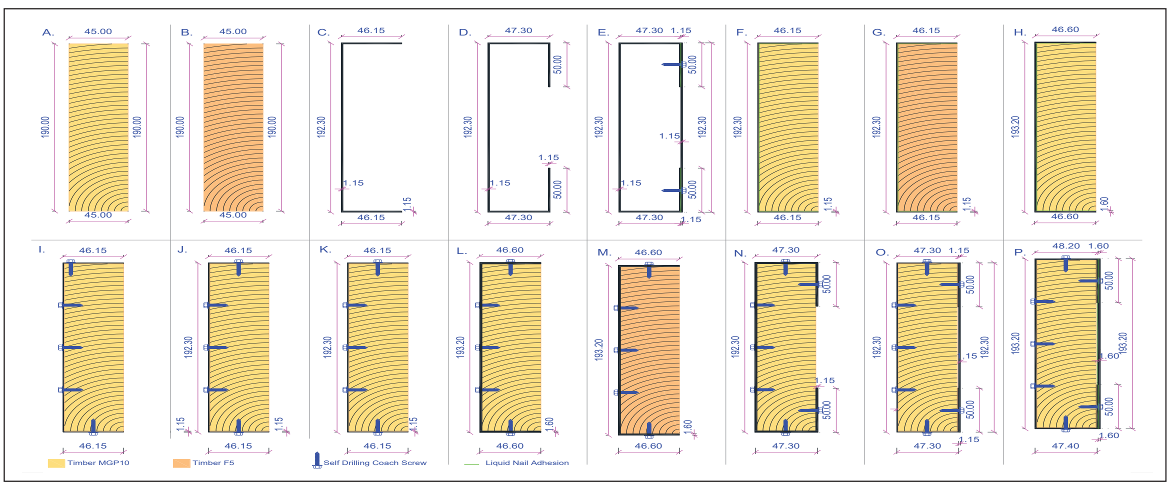

Figure 1. Cross-sectional view of all specimens.

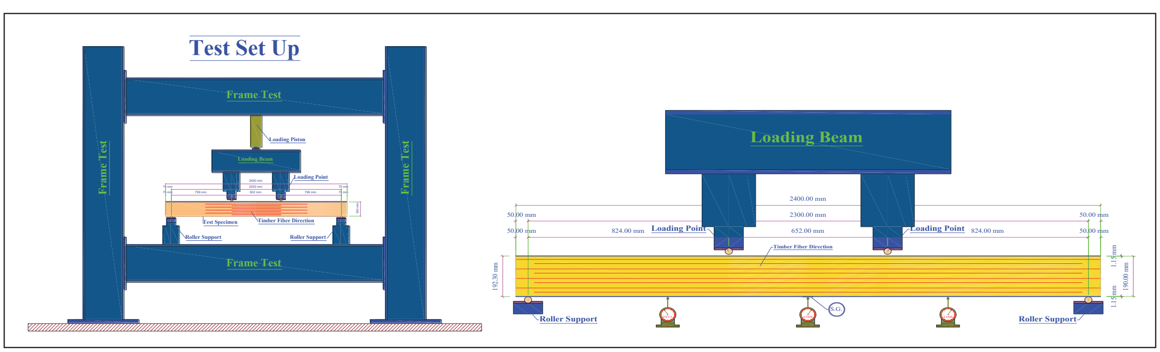

Figure 2. SETC beams test setup, LVDT, and Strain gauge positions.

Similarly, Figure 3 presents the structural response of timber beams of different grades, emphasizing the effect of material strength on performance. The MGP10 timber beam achieves a higher peak load (24.5 kN) compared to the F5 timber beam (18 kN), reflecting the superior mechanical properties of higher-grade timber. Both timber beams exhibit notable post-peak ductility, with a gradual reduction in load, indicative of their energy dissipation capabilities. This characteristic contrasts with the sharp strength degradation observed in some CFS configurations, further reinforcing the necessity of composite action for improved structural efficiency.

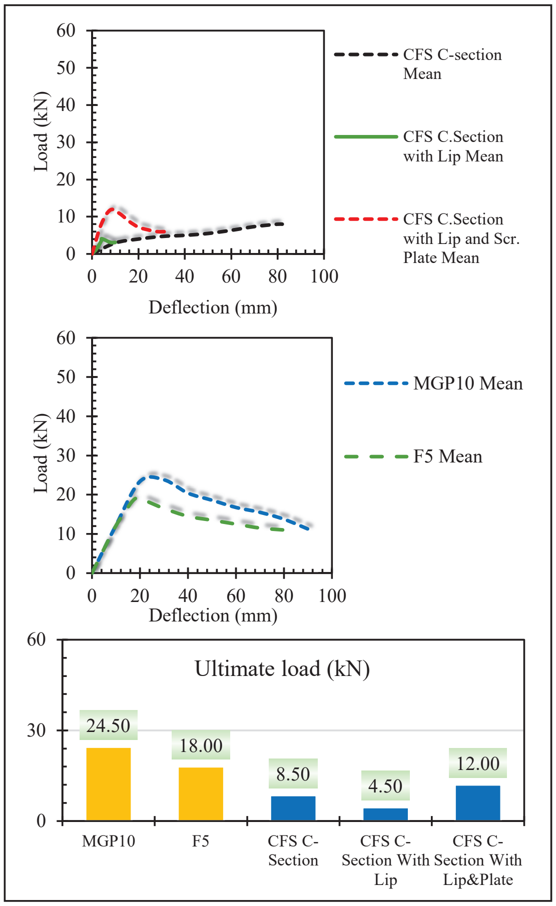

Figure 3. Load VS Deflection of CFS profiles and timber grades.

Enhancing SETC beams through profile optimization, screw placement, and composite reinforcements can significantly improve load-bearing capacity and failure resistance.

3.1 STRUCTURAL PERFORMANCE OF SETC BEAMS

3.1.1 Influence of Assembly Techniques: Screwed vs. Glued

The structural performance of SETC beams varies significantly depending on the assembly technique. Screwed (S.SETC) beams exhibited superior load-bearing capacity and ductility due to the mechanical interlocking between the timber core and steel encasement. Glued (G.SETC) beams, while providing strong initial bonding, showed brittle failure modes under high loads.

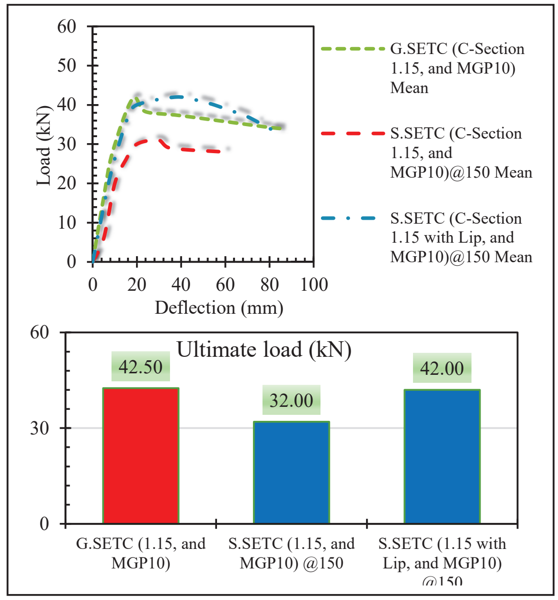

Figure 4. SETC beams by different composite assembly techniques.

Figure 4 presents the load-deflection behavior of different assembly techniques for SETC beams, highlighting their structural response under loading. All beams exhibit an initial elastic phase, followed by yielding, peak load, and subsequent softening, indicating a ductile failure mode. Among the tested configurations, the G.SETC beam C- section profile and S.SETC beam C-setion with lip achieved the highest load capacity (42.5, 42 kN), suggesting superior structural performance. In contrast, the S.SETC without a lip exhibited the lowest peak load (32 kN), indicating that the absence of the lip reduces structural efficiency. Post-peak behavior analysis further revealed that G.SETC beams experienced a more gradual reduction in load, implying better ductility and energy dissipation, while S.SETC beams without a lip displayed a sharper degradation, suggesting a more brittle failure mode. These findings indicate that both the presence of a lip and the type of connectors significantly influence the overall performance of SETC beams, necessitating further investigation into bonding mechanisms and failure modes for optimized design.

https://doi.org/10.52202/080513-0510

3.1.2 Impact of CFS Thickness and Profile Variations

The structural performance of SETC beams is significantly influenced by the CFS thickness and profile variations, including the presence of lips and plate reinforcements. The load-deflection responses in Figure 5 demonstrate that modifying the CFS profile and thickness affects both load capacity and ductility.

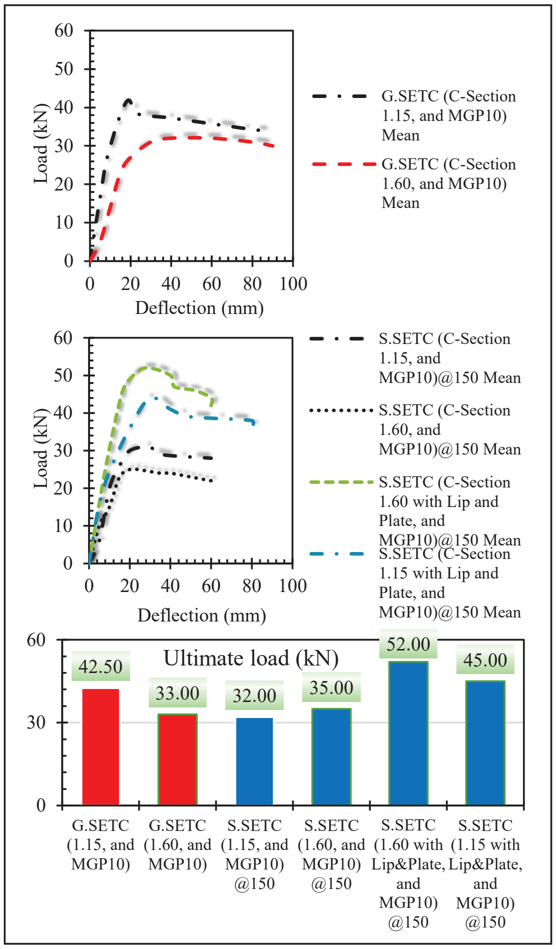

Figure 5. SETC beams, Glued and Screwed, with 1.15 and 1.60 mm thickness of C-section only and C-section with Lip and plate profiles.

Figure 5 presents the performance of Glued (G.SETC) and Screwed (S.SETC) beams with 1.15 mm and 1.60 mm thick C-sections, comparing C-section profiles against those reinforced with lips and plates. The results indicate that increasing CFS thickness alone does not necessarily enhance the ultimate load capacity, as seen in the G.SETC beams, where the 1.15 mm C-section achieved a higher load capacity (42.5 kN) than the 1.60 mm C-section (33 kN). This suggests that beyond a certain thickness, other failure mechanisms, such as timber crushing, may limit load-bearing improvements. In contrast increasing CFS thickness in the S.SETC beam enhance the ultimate load capacity, where the 1.60 mm C-section achieved a higher load capacity (35 kN) than the 1.15 mm C-section (32 kN).

In the S.SETC category, the inclusion of a lip and plate reinforcement significantly enhanced the ultimate strength. The S.SETC (1.60 mm, Lip & Plate) @150 mm connectors recorded the highest ultimate load (52 kN), outperforming the S.SETC (1.15 mm, Lip & Plate) @150 mm connectors (45 kN). This indicates that profile modifications, such as lips and plate reinforcement, contribute more effectively to strength enhancement than increasing thickness alone.

Post-peak behavior analysis shows that beams with reinforced profiles (lip and plate) exhibited a more gradual strength degradation, suggesting improved ductility and energy dissipation. In contrast, C-sections, particularly in S.SETC configurations without a lip, exhibited a sharper decline in load capacity, indicating a more brittle failure mode. These findings highlight that CFS profile design plays a critical role in optimizing SETC beam performance, necessitating further investigation into the interaction between steel thickness, reinforcement profiles, and bonding mechanisms to achieve an optimal balance between strength and ductility.

3.1.3 Effect of Timber Grade

The structural performance of SETC beams is significantly influenced by the timber grade used in the core. The load-deflection responses in Figure 6 illustrate that the mechanical properties of timber directly impact ultimate load capacity, ductility, and failure mode.

Figure 6 presents the performance of Glued (G.SETC) and Screwed (S.SETC) beams using two different timber grades: MGP10 and F5, with a 1.15 mm and 1.60 mm thick C-section. The results demonstrate that beams utilizing higher-grade timber (MGP10) achieved superior load-bearing capacity compared to lower-grade timber (F5). For instance, in G.SETC beams, the MGP10 timber core resulted in an ultimate load of 42.5 kN, whereas the F5 timber core reached only 31.5 kN, indicating that lower-strength timber reduces the composite system's overall capacity.

Similarly, in S.SETC beams (1.60 mm C-section, @150 mm connectors), the use of MGP10 timber achieved a higher ultimate load (35 kN) compared to F5 timber (25 kN). This reinforces the observation that timber grade plays a crucial role in determining the composite action between steel and timber, affecting both load resistance and post-peak behavior.

The post-peak response further highlights that beams with higher-grade timber (MGP10) exhibit better energy dissipation and ductility, whereas beams with lower-grade timber (F5) show a more brittle failure mode with sharper degradation in load capacity. This suggests that in SETC beams, higher timber grades enhance not only strength but also structural resilience, making them more suitable for applications requiring higher load-bearing efficiency and improved failure characteristics.

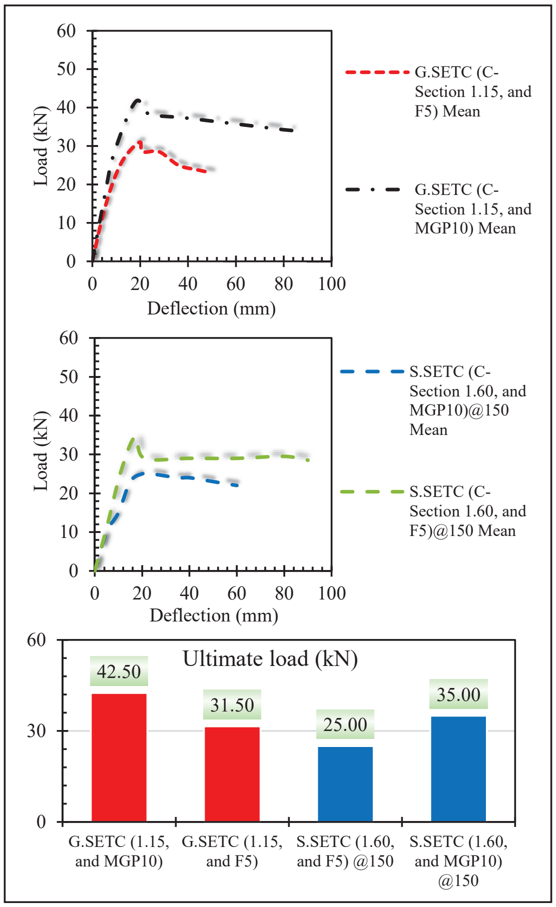

Figure 6. SETC beams, Glued with 1.15 mm and Screwed with 1.60 mm thickness of MGP10 and F5 timber grades.

These findings emphasize the critical role of timber selection in optimizing SETC beam performance, warranting further investigation into the interaction between timber grade, bonding mechanisms, and CFS profiles to enhance the overall strength and durability of composite structures.

3.1.4 Effect of Screw Spacing

The spacing of screws in SETC beams plays a crucial role in determining their structural performance, particularly their load-bearing capacity and ductility. Figure 7 presents the load-deflection behavior of S.SETC beams with varying screw spacings of 100 mm, 150 mm, and 200 mm. The results indicate that all configurations exhibit an initial elastic phase, followed by yielding and peak load, with subsequent softening behavior.

As shown in Figure 7, the ultimate load capacity of the beams remains relatively consistent across different screw spacings, with values of 32 kN, 33 kN, and 33 kN for spacings of 150 mm, 100 mm, and 200 mm, respectively. This suggests that within the tested range, screw spacing has a minimal effect on peak load capacity. However, differences in post-peak behavior indicate variations in ductility and energy dissipation. The S.SETC beam with 150 mm screw spacing demonstrated a more stable load reduction after peak load, indicating improved energy dissipation and reduced brittleness compared to the 100 mm and 200 mm configurations.

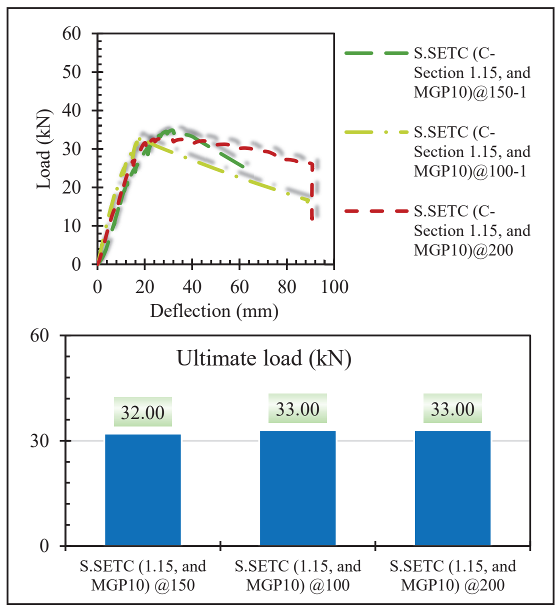

Figure 7. SETC beam, Screwed with different screw spacing.

While the 100 mm screw spacing configuration showed slightly higher load capacity, its post-peak degradation suggests a more sudden loss of strength, potentially due to excessive localized stress concentrations around the fasteners. Conversely, the 200 mm spacing resulted in a more gradual decline in load-bearing capacity, indicating better overall ductility but a slight reduction in stiffness. These findings suggest that while screw spacing does not significantly impact ultimate strength within the tested range, it affects the failure mode and ductility of the beams. Further investigation is necessary to optimize

https://doi.org/10.52202/080513-0510

screw spacing for improved composite action and long-term structural performance.

3.2 OPTIMIZING SETC BEAMS FOR STRUCTURAL EFFICIENCY

The structural efficiency of SETC beams is influenced by assembly techniques, cross-sectional profiles, material properties, and connection configurations. This study highlights that selecting the right combination of these factors is crucial for achieving optimal strength, ductility, and failure resistance.

Among the tested configurations, S.SETC (1.60 mm with Lip & Plate, MGP10) demonstrated the highest load-bearing capacity (52 kN), marking a 112.2% improvement over pure timber (MGP10) and a 57.6% increase over the theoretical sum of MGP10 and CFS C-section, emphasizing the role of mechanical interlocking. G.SETC (1.15 mm, MGP10) reached 42.5 kN, offering a 73.5% improvement over pure timber but failing in a brittle manner under high loads, suggesting adhesive bonding alone lacks long-term stability.

Cross-sectional modifications significantly enhanced structural performance, with lip and plate reinforcements increasing load capacity by 57.6% over theoretical timber-steel combinations. However, excessive steel thickness did not always yield proportional strength gains, as timber crushing became a limiting factor. Additionally, higher-grade timber (MGP10) outperformed lower-grade alternatives (F5), reinforcing the importance of material selection.

Screw spacing influenced ductility and load redistribution, improving post-peak behavior without significantly affecting peak load capacity.

In summary, optimized SETC beams, particularly screwed and reinforced configurations, achieved the highest strength. Future research should refine the steel-timber interface, explore composite solutions, and enhance manufacturing techniques to improve long-term performance.

4 – CONCLUSION

Mechanically fastened SETC beams (S.SETC) with reinforced configurations, such as 1.60 mm steel with lips and plates and MGP10 timber, achieved an ultimate load of 52 kN, marking a 112.2% improvement over pure MGP10 timber and a 57.6% improvement over the theoretical sum of timber and steel . This demonstrates the critical role of mechanical fasteners in enhancing composite action and overall structural efficiency.

Glued assemblies (G.SETC) showed promising initial performance but exhibited brittle failure under high loads, with improvements ranging from +28.6% to +136.1% over pure MGP10 and F5 timber. Their inconsistency and failure under high loads highlight the limitations of adhesive-dependent systems for long-term structural stability.

Cross-sectional reinforcements, such as lips and plates, significantly enhanced load transfer efficiency. However, excessive steel thickness increased the risk of premature timber crushing. Optimized screw spacing improved ductility and post-peak behavior, enhancing energy dissipation without compromising peak capacity.

An integrated design approach that harmonizes connection methods, geometric enhancements, and material properties is essential for maximizing performance. While S.SETC excels in strength.

Future research should focus on refining steel-timber interface treatments, exploring composite configurations, and advancing manufacturing techniques to enhance the viability of SETC without screw or glue as a competitive alternative to conventional systems.

5 – ACKNOWLEDGMENT

The authors sincerely appreciate the financial support provided by the Australian Government and the University of South Australia through the RTP scholarship awarded to the first author. Additionally, the authors extend their gratitude to Aatif Sunasra, Feroz Ali, Sakalalo Vaealiki, and Nasrullah Shafahi for their valuable contributions to the experimental work as part of their Honours Project at the University of South Australia.

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