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Shear Performance of Timber-Steel Hybrid Beams: Experimental Investigation

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Abstract

The building sector accounts for approximately 40 % of global CO₂ emissions, setting the demand for efficient and resource-efficient structural systems. Timber structures offer significant sustainability advantages but exhibit mechanical limitations, particularly regarding shear strength and stiffness. Steel-based strengthening therefore represents a promising strategy to improve the structural performance of timber elements while maintaining a high percentage of the renewable material timber.

This study investigates a strengthening approach for timber beams using slender steel profiles that are adhesively bonded into the timber cross-section. Three-point bending tests with a span of 0.74 m were conducted to generate shear-dominated loading conditions. Strengthened beams were compared with timber reference beams of identical geometry using two material combinations: GL 24h with S355 and LVL 48p with S420. The strengthening significantly improves structural performance. The load-carrying capacity increases by 99 % for GL 24h and 77 % for LVL, while the shear stiffness increases by factors of 5.7 and 4.0, respectively. Whereas the timber reference beams fail in a brittle shear mode, the strengthened beams exhibit a more ductile response due to plastic deformation of the steel profiles combined with timber failure. The results demonstrate the high potential of steel-based strengthening for shear-critical timber members.

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1. Introduction

1.1. Motivation

The building sector must significantly reduce CO₂ emissions to contribute to climate change mitigation. Timber structures are an important part of this transition, as timber is a renewable material with a favorable carbon balance, and is increasingly promoted for multi-story and large-span structures (Bundesministerium für Ernährung und Landwirtschaft, 2016; Ministerium für Ernährung, Ländlichen Raum und Verbraucherschutz, 2018). However, the mechanical limitations of timber often require large cross-sections when serviceability and strength requirements govern the design. Structural strengthening of timber members with steel components offers an efficient solution to overcome these limitations. By integrating slender steel profiles into timber cross-sections in a shear-resistant manner, the stiffness and load-carrying capacity can be significantly increased while maintaining a high proportion of renewable material. Previous research at the Karlsruhe Institute of Technology has demonstrated the strong potential of such hybrid beams under bending loads (Haase et al., 2024a). Integrating the steel profile into the timber cross-section protects the steel and the adhesive bond from high temperatures in case of fire. Additionally, in a corrosive environment or with slender steel sections belonging to cross-section class 4, full embedment in the timber cross-section provides corrosion protection and prevents premature failure due to buckling. While externally bonded side plates are easier to apply in existing structures, they do not provide the same structural efficiency in case of fire as the integrated configuration, as the timber cross-section cannot fully protect the bond and the steel profiles.

1.2. Timber-steel-hybrid construction

Timber provides a high strength-to-weight ratio and a favorable environmental profile, while steel offers high stiffness and ductility. When properly connected, hybrid cross-sections can therefore achieve significantly improved structural performance compared to pure timber members.

Mechanical connections are widely used when strengthening timber beams with steel lamellas but often introduce slip, which reduces stiffness and may govern serviceability behavior. Adhesive bonding, in contrast, enables a continuous connection between timber and steel and allows composite action without slip (Haase et al., 2024b). In a recent research project at the Karlsruhe Institute of Technology, adhesively bonded timber-steel hybrid beams were systematically developed and investigated with a focus on bending behavior (Haase et al., 2024a, 2024c). Large-scale four-point bending tests demonstrated substantial increases in bending stiffness and in load-carrying capacity compared to reference timber beams, while plastic deformation of the steel contributed to a more overall ductile structural response. However, shear failure was observed in certain hybrid configurations. While these investigations demonstrated the strengthening potential of hybrid beams under bending-dominated loading, the behavior under dominant shear stresses has not yet been examined in detail. A dedicated investigation of the shear performance is therefore required to fully assess the structural capabilities of timber-steel hybrid systems. Various reinforcement strategies have been developed to improve shear resistance and structural robustness, including inclined self-tapping screws, glued-in rods, and locally embedded steel elements (Dietsch, 2012). In addition, hybrid timber-steel concepts such as flitch beams have been investigated, demonstrating that steel reinforcement can significantly increase stiffness and strength (DeStefano, 2007; Riola-Parada, 2016). Harte et al. provide a review of the state of the art regarding methods for reinforcing timber components (Harte et al., 2015).

1.3. Scope of paper

This study investigates the shear performance of timber beams strengthened with integrated steel profiles in comparison to timber reference beams of identical outer geometry. Two material combinations, GL 24h with S355 and LVL 48p with S420, are examined under shear-dominated loading conditions. The experimental investigation focuses on shear strength, shear stiffness, and failure mechanisms, with particular attention to the transition from brittle timber failure to a more ductile response due to steel strengthening.

2. Materials and Methods

2.1. Materials

The investigated specimens were manufactured using glued laminated timber GL 24h and laminated veneer lumber LVL 48p. The mechanical properties of the timber materials were determined according to DIN EN 408 (DIN, 2012a) in (Haase et al., 2024a). The mean modulus of elasticity was approximately 11,100 MPa (COV = 12.6 %) for GL 24h and 12,600 MPa (COV = 2.1 %) for LVL 48p. The corresponding bending strengths were 35.0 MPa and 51.7 MPa, and the shear strengths 4.86 MPa and 5.99 MPa, respectively. The densities were on average 443 kg/m³ for GL 24h and 493 kg/m³ for LVL 48p.

Two structural steel grades were used: S355 for the regular-strength configuration (RS) and S420 for the high-strength configuration (HS). Tensile tests conducted in (Haase et al., 2024a) according to DIN EN ISO 6892-1 (DIN, 2020) determined mean yield strengths of approximately 380 MPa and 449 MPa, respectively. The modulus of elasticity of steel was assumed as $E = 210,000$ MPa according to Eurocode 3.

The timber and steel components were connected either by adhesive bonding or by punched metal plate fasteners (PMPF) to achieve shear-resistant composite action. Two two-component epoxy adhesives (EP 1 and EP 2) and one polyurethane adhesive (PUR) were used. Tensile tests according to DIN EN ISO 527-2 (DIN, 2012b) showed moduli of elasticity between 5,000 MPa and 6,300 MPa and tensile strengths between 25.6 MPa and 45.5 MPa, depending on the adhesive type. For selected specimens, PMPF were used as an alternative joining technique. The PMPF were pressed into the timber surface and adhesively connected to the steel profile (using EP 2), enabling shear transfer through mechanical interlocking (Haase et al., 2024a, 2024b).

2.2. Test specimen, manufacturing and experimental testing

Test specimen

The tests were conducted in accordance with DIN EN 408 (DIN, 2012a). Due to the expected high shear strength of the hybrid cross-sections, the span was significantly reduced compared to the standard configuration in order to promote shear-dominated behavior. It is acknowledged that the reduced span may introduce additional load-carrying effects in the timber reference specimens, such as arch action. However, to ensure direct comparability between timber reference beams and hybrid beams, the same span and measurement setup were used for all specimens. The test setup and the tested geometry are shown in Fig. 1. Based on the bending tests in (Haase et al., 2024a), a 12 mm thick steel profile was chosen as it best addresses the demands concerning higher bending stiffness, homogenization of local timber defects, and load increase. Other geometries are being validated in ongoing research. Table 1 gives an overview of the test campaign.

Manufacturing

The specimens were manufactured as described in detail in (Haase et al., 2024a). Steel surfaces were prepared by abrasive blasting to SA 2½ (DIN EN ISO 8501-1 (DIN, 2007)) or hot-dip galvanizing (DIN EN ISO 1461 (DIN, 2022)), followed by degreasing with methyl ethyl ketone. Timber elements were planed within 24 h prior to bonding in accordance with DIN EN 14080 (DIN, 2013). The adhesive was applied using a static mixer and distributed with a notched spatula.

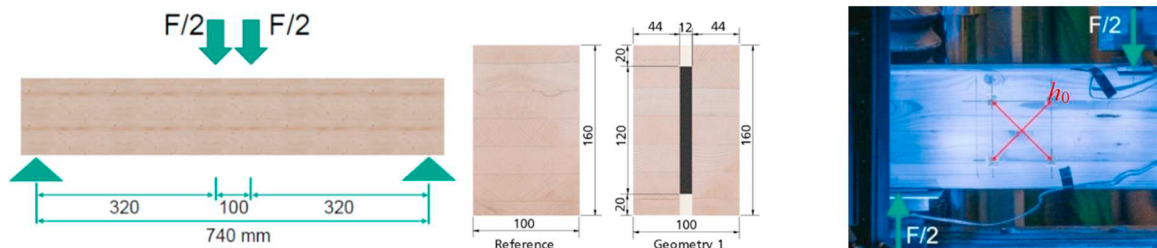


Fig. 1. Test setup, specimen geometry and measuring system

Experimental testing

In the previous four-point bending tests with a span of 2.4 m (Haase et al., 2024a), no shear failure occurred. Therefore, the present study employed a significantly reduced span of 0.74 m to promote shear-dominated behavior. This configuration increases the level of shear stresses relative to bending stresses. Local steel inlets were used at the load introduction points to bridge the gap between the steel profile and the timber surface, ensuring uniform load transfer and preventing local compression failure in the timber. The tests were performed on a servo-hydraulic testing machine under displacement control with a loading rate of 0.25 mm per minute.

In addition to the applied force and actuator displacement, steel strains were recorded between the load introduction points using two strain gauges placed at the top and bottom of the steel profile. A constant shear force is present between the support and the load introduction point. Shear distortion was measured at mid-length of this shear field at both ends of the beam in accordance with DIN EN 408. For this purpose, four measuring points arranged in a square were monitored using digital image correlation (Fig. 1). The shear stiffness GA of the member was determined from the change in length of the diagonals.

Due to the testing setup, an initial section with reduced stiffness was observed for all tests. Since the extent of this effect varied between specimens, the load-deformation curves were not directly comparable in the initial range. To account for this, the stiffness was evaluated within the linear elastic range, and the load-deformation curves were shifted along the x-axis so that the linear regression lines intersect the origin. This normalization enables a direct comparison of the specimens from the onset of linear elastic behavior onward. For the timber reference specimens, the evaluation range was defined between 10 and 50 kN, while for the hybrid specimens a range between 75 and 150 kN was used. Within these intervals, the coefficient of determination was 0.99 or higher for all specimens. Equation (1) presents the evaluation method used to calculate the apparent shear stiffness GA_{app} . A height of $h = 160$ mm was used for all specimens. The same evaluation range was used to determine the stiffness k , defined as the ratio between the change in shear force and the corresponding change in shear deformation obtained from the diagonal measurements.

$$GA_{app} = \left[\frac{3}{2} - \frac{h_0^2}{4h^2} \right] \cdot h_0 \cdot k \quad (1)$$

Table 1. Overview of test campaign with series designation and sample size

Material	EP 1	EP 2	PUR	PMPF	Timber reference
GL 24h + S355	$n = 1$	1 + 1*	1	1 + 1*	9
LVL 48p + S420	2 + 2*	-	1	2	6

*Specimens with a blasted steel surface

3. Results

In the following section, the experimental results are presented. The material combination GL 24h with S355 is referred to as regular-strength, RS, while LVL 48p with S420 is referred to as high-strength, HS.

Due to the limited number of specimens per joining technique, for $n = 1-2$, no statistical comparison between joining methods is performed. As previously shown in (Haase et al., 2024a, 2024b), no significant influence of the joining technique, adhesive or PMPF, nor of the surface preparation, blasted or galvanized, was observed. Therefore, all hybrid specimens with identical material combinations are grouped for discussion in section 4.

In this section, the x-axis of the diagrams shows deformations up to 20 mm and the y-axis shows loads up to 250 kN. The deformation corresponds to the actuator displacement.

3.1. Material combination GL 24h + S355

The load-deformation curves of the timber reference specimens are shown in Fig. 2a. All specimens exhibit linear elastic behavior up to approximately 50 kN. One specimen shows a reduction in stiffness beyond this level, while the

remaining specimens remain linear up to approximately 75 kN. At higher loads, all specimens show a progressive reduction in stiffness followed by pronounced deformation without immediate failure. This behavior indicates a bending compression failure of timber fibers.

Global failure occurs between 9 mm and 15 mm of deformation. Some specimens fail directly by brittle shear failure (Fig. 3) between the support and the load introduction point, while others show bending tension cracking accompanied by minor load drops before final shear failure.

The mean load-carrying capacity is 103.7 kN with a coefficient of variation (COV) of 14.1 %. The shear stiffness evaluated between 10 and 50 kN is $GA_{app} = 1.81 \times 10^7$ N with a COV of 10.8 %.

Fig. 2b and c present the results of the hybrid specimens. Independent of surface preparation (blasted or galvanized) and joining technique (EP 1, EP 2, PUR or PMPF), all specimens show comparable behavior. After the initial setting of the test setup, linear elastic behavior is observed up to approximately 160 kN. Strain gauge measurements indicate that yielding of the steel profile occurs between 120 and 150 kN, which is consistent with the analytical prediction (Haase et al., 2024a) of 133 kN for yielding in the steel edge fiber. Beyond 160 kN, a slight reduction in stiffness is observed. Plastic deformation of the steel develops while the timber remains largely intact. Some specimens fail by bending-dominated failure accompanied by minor load drops. The galvanized specimen with EP 2 and the blasted specimen with PMPF show a further increase in load followed by brittle shear failure within the timber elements (Fig. 3b). Significant plastic deformation of the steel, exceeding 5 mm, is observed after testing (Fig. 3c).

The mean load-carrying capacity of the grouped hybrid specimens is 206.8 kN (COV = 6.7 %). The shear stiffness evaluated between 75 and 150 kN loading is $GA_{app} = 10.3 \times 10^7$ N (COV = 19.5 %).

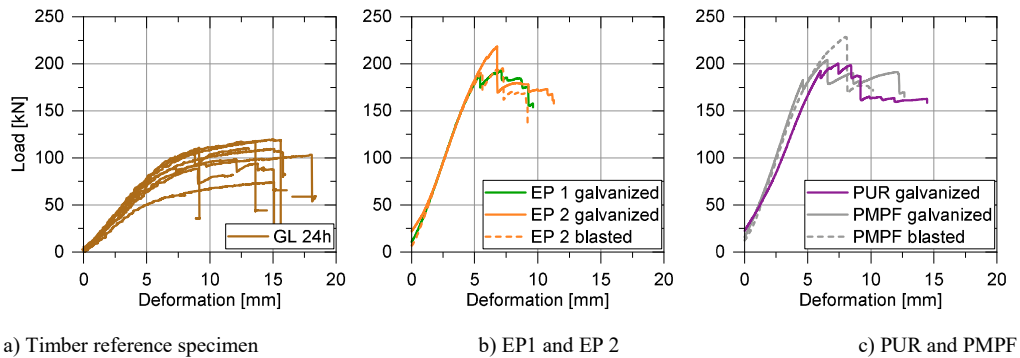


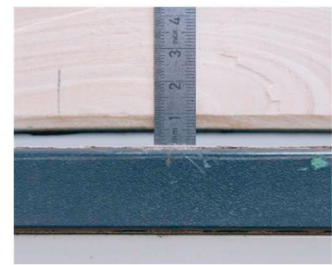
Fig. 2. Results GL 24h + S355



a) Shear failure of a timber reference specimen



b) Shear failure of a PMPF specimen



c) Plastic deformations at midspan after the

Fig. 3. Fracture patterns GL 24h + S355

3.2. Material combination LVL48p + S420

The results of the LVL reference specimens are shown in Fig. 4a. All specimens exhibit similar behavior with linear elastic response up to approximately 90 kN. Beyond this level, a slight reduction in stiffness occurs until failure at a mean load-carrying capacity of 128.0 kN (COV = 3.2 %). The shear stiffness of the LVL specimens is $GA_{app} = 2.0 \times 10^7$ N (COV = 8.1 %).

The hybrid cross-sections are shown in Fig. 4b and c. Regardless of surface preparation and joining technique, all specimens show similar behavior. After initial reduced stiffness, linear elastic behavior is observed up to approximately 175 kN. Strain gauge measurements indicate that yielding of the steel profile occurs at approximately 160 kN. Beyond 180 kN, stiffness decreases as plastic deformation develops, and failure occurs through a combination of shear failure in the timber and bending failure.

Fig. 5b illustrates the fracture pattern of a PMPF specimen. Shear failure is visible near the support, while bending tensile and compressive failure occurs in the central region of the beam. All hybrid beams reach a mean load-carrying capacity of 226.4 kN with a COV of 4.3 %. The shear stiffness determined from DIC evaluation is $GA_{app} = 8.14 \times 10^7$ N (COV = 22.7 %).

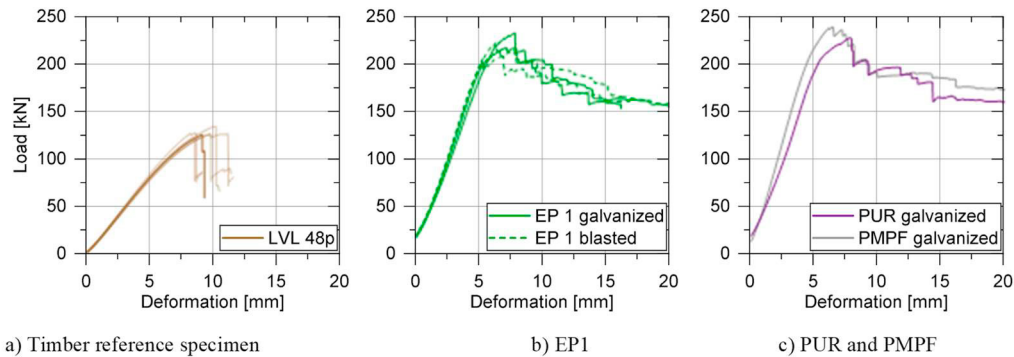
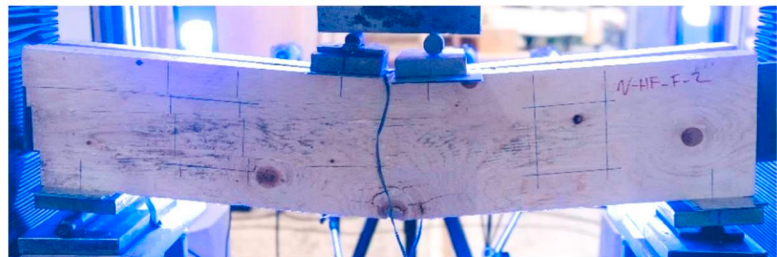


Fig. 4. Results LVL 48p + S420



a) Shear failure of a timber ref. specimen



b) Shear and bending failure of a PMPF specimen

Fig. 5. Fracture patterns LVL 48p + S420

4. Discussion

Result overview

This section compares the different specimen groups and their respective timber reference beams. First, the influence of hybridization is evaluated. Subsequently, the effect of the material combination is discussed. All results are summarized in Fig. 6. No adhesive failure was observed during testing in any specimen, regardless of adhesive type or surface preparation. Failure consistently initiated in the timber, either through shear cracking or bending failure, confirming that the bonded interface was not the limiting element of the system. Accordingly, the adhesive layer did not govern structural behavior under the loading conditions investigated.

Influence of the hybridization

Hybridization increases the load-carrying capacity by 99 % compared to the timber reference beams. In addition, the coefficient of variation decreases from 14.1 % to 6.7 %, indicating homogenization of the cross-section due to the steel profile. The shear stiffness increases by 470 % compared to the pure timber beams. However, the coefficient of variation increases from 10.8 % to 19.5 %. This higher variation is attributed to the DIC-based measurement of shear distortion on the timber surface. In hybrid cross-sections, shear deformations are significantly smaller than in pure timber beams. Consequently, local timber imperfections have a greater relative influence on the calculated shear stiffness.

For the high-strength material combination, hybridization increases the load-carrying capacity by 77 % compared to the timber reference beams. The variation remains at a comparable level, with 3.2 % for timber and 4.3 % for hybrid specimens. Since LVL is highly homogeneous, the timber reference specimens already exhibit low variability. The addition of a steel profile does not further homogenize the cross-section, which explains the comparable variation in load-carrying capacity. The shear stiffness increases by 300 % due to hybridization. However, the coefficient of variation increases from 8.1 % to 22.7 %. As explained above, the shear failure of the timber reference beams (RS and HS) is brittle, with load drops of up to 50 % of the ultimate load. In contrast, the hybrid specimens fail in a ductile manner, with small, incremental load drops.

Compared to conventional shear reinforcement methods for timber beams, such as inclined self-tapping screws or glued-in rods (Dietsch, 2012), the integrated steel profile simultaneously improves shear strength, shear stiffness, and ductility.

Influence of the material combination

The LVL 48p reference specimens show a 23 % higher load-carrying capacity and an 11 % higher shear stiffness compared to the GL 24h specimens. This is consistent with the nominal material properties presented in Section 2.1. While the shear strength of LVL 48p is approximately 23 % higher than that of GL 24h, its bending strength is 48 % higher. As a result, the GL 24h specimens reach bending compression failure prior to shear failure, whereas the LVL specimens remain nearly linear elastic until shear failure occurs. Furthermore, the variation in load-carrying capacity is significantly lower for LVL (3.2 %) compared to GL 24h (14.1 %), reflecting the higher material homogeneity and the uniform failure mode. The difference in shear stiffness variation is comparatively small, 10.8 % for GL 24h and 8.1 % for LVL.

For the hybrid beams, the high-strength material combination increases the load-carrying capacity by 9 % compared to the regular-strength configuration. In contrast, the shear stiffness of the high-strength hybrid beams is 21 % lower than that of the regular-strength hybrid beams.

Since failure consistently occurs in the timber component, full adhesion between timber and steel is assumed for both material combinations. In the RS beams, shear deformation is transferred through a single adhesive layer between steel and timber. In the HS configuration, shear distortion must additionally be transferred through multiple veneer layers and adhesive interfaces within the LVL. The reduced shear stiffness is therefore attributed to the layered structure of the LVL material. Due to the high variation between the specimens, more tests (with a more precise measurement system) would be necessary to assess the influence of the material on the shear stiffness.

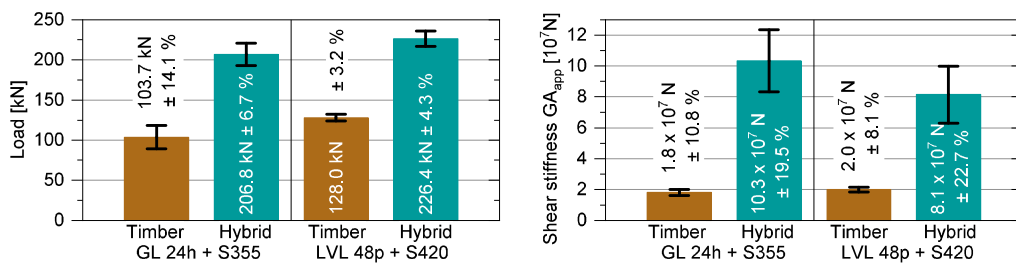


Fig. 6. Comparison of failure load and shear stiffness RS - HS

5. Conclusions

Three-point bending tests with short span length were conducted on hybrid timber-steel beams to investigate their shear strength and stiffness in comparison to timber reference beams of identical geometry. The material combinations GL 24h with S355 (RS) and LVL 48p with S420 (HS) were examined. The main findings are summarized as follows:

- No adhesive failure was observed during testing. All specimens failed as shear or bending failure in the timber cross-section.
- The load-carrying capacity of the hybrid beams is 1.99 times as high for RS and 1.77 times as high for HS compared to the respective timber reference beams.
- For the RS configuration, the coefficient of variation decreases from 14.1 % to 6.7 %, indicating a homogenizing effect of the steel profile.

- For the HS configuration, no further reduction in variation is observed due to the already high material homogeneity of LVL.
- The shear stiffness increases by a factor of 5.7 for RS and by a factor of 4.0 for HS due to hybridization.
- The variation in shear stiffness increases, which is attributed to the measurement method and local timber defects.
- The brittle shear failure of the timber reference beams with load drops of up to 50 % transitions to a more ductile structural response in the hybrid beams due to plastic deformation of the steel prior to failure.

In conclusion, the results demonstrate the significant potential of strengthening timber cross-sections with integrated steel profiles. The substantial increase in load-carrying capacity and shear stiffness expands the structural application range of timber members. In combination with the previously reported bending performance (Haase et al., 2024a), the presented hybrid system offers clear mechanical advantages compared to pure timber structures while maintaining a high proportion of renewable material.

The results presented in this study are part of a broader research campaign on timber-steel hybrid systems. Experimental investigations on the durability behavior are currently being finalized and will be reported in a forthcoming publication. Furthermore, a comprehensive numerical parameter study is underway to extend the experimental findings to a wider range of cross-section geometries, with the aim of developing validated analytical design models for hybrid timber-steel members.

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