PUSH-OUT TESTING OF ADHESIVELY BONDED LIGHT GAUGE STEEL AND FRP TO TIMBER CONNECTIONS: AN EXPERIMENTAL STUDY

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ABSTRACT: This study presents an experimental investigation into the shear performance of adhesively bonded interfaces between engineered timber and lightweight construction materials, specifically cold-formed steel and fibre-reinforced polymer (FRP) panels. Seven bond configurations were tested using small-scale push-out specimens to assess the influence of timber species, adhesive type, grain orientation, surface preparation, assembly delay, and interface gap. Radiata Pine Glulam and H2S Laminated Veneer Lumber (LVL) were bonded to steel and FRP using two polyurethane adhesives: Bostik AV515 and SikaBond-145 SuperGrip. All steel-timber specimens were subjected to displacement-controlled pull-out tests using a 300 kN MTS machine, and slip behavior was analyzed through digital image correlation. Results revealed that adhesive type and timber grain orientation significantly affected bond strength and stiffness, with specimens bonded using Sikabond outperforming those with Bostik in terms of shear strength. Glulam consistently showed higher shear capacity than LVL, especially when loaded parallel to the grain. Delayed assembly and interface gaps substantially reduced bond performance. FRP-timber specimens exhibited moderate strength and ductility but highlighted the importance of bonding quality and testing method. This research contributes valuable experimental data to the limited literature on adhesively bonded hybrid timber systems and supports the development of efficient, prefabricated structural elements.

KEYWORDS: Adhesive bond, FRP, Ligh-gauge-steel, Push-out test, Hybrid timber construction

1 – INTRODUCTION

With the rapid advancement of hybrid construction techniques and an increasing push for sustainable and modular building practices [1], the integration of engineered timber with lightweight structural components such as cold-formed steel and fibre-reinforced polymers (FRP) has become an area of growing interest. Hybrid systems that combine the ductility and strength of steel or FRP with the low-carbon, renewable nature of timber are highly attractive for their structural efficiency, aesthetic appeal, and environmental benefits.

One of the most promising applications of such hybrid systems lies in steel-timber composite (STC) floor and beam assemblies [2], where cross-laminated timber (CLT), glulam, or laminated veneer lumber (LVL) are connected to cold-formed or hot-rolled steel elements. Research in this area has explored various connector systems, including mechanical fasteners (e.g., bolts, screws) and demountable shear connectors, with a growing interest in alternative bonding strategies that improve constructability and vibration/acoustic performance [3–5]. Notably, the study of semi-rigid connections using extended end plates in composite joints with CLT has demonstrated significant promise for achieving strength and de-constructability in modular timber buildings [6].

The cyclic behaviour and long-term performance of mechanical connectors in STC systems have been the focus of several experimental and numerical studies. For instance, the response of bolt and screw connectors under repeated loading has highlighted critical failure modes and energy dissipation characteristics relevant to seismic applications [3–5]. However, mechanical fasteners are

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prone to issues such as local crushing, slippage, and time-dependent deformation, which may reduce the effectiveness of the composite action over time [7].

Studies on long-term behaviour have revealed substantial creep and moisture-related deformation in both timber and connections. Research into the dimensional stability of CLT under sorption/desorption isotherms has shown that timber can experience significant strain fluctuations due to changes in humidity, affecting both structural performance and durability [8]. Furthermore, the long-term tensile behaviour of engineered wood has demonstrated nonlinear strain development in the parallel-to-grain direction, underscoring the importance of robust bonding and connector strategies in hybrid systems [9]. To address these challenges, adhesive bonding has emerged as a potential solution for developing continuous, slip-resistant interfaces in STC systems. While mechanical connectors often exhibit a progressive loss of stiffness due to cyclic or long-term effects, glued interfaces—when properly detailed and protected—may offer improved load transfer, reduced vibration sensitivity, and enhanced durability. Prior research has also shown that dynamic response and vibration characteristics of STC floors are highly influenced by connector stiffness and interface damping [10,11].

Despite these developments, the behaviour of adhesively bonded timber-to-steel or timber-to-FRP connections remains relatively underexplored in structural engineering literature. Most current work has focused on mechanical connector performance or numerical simulation of long-term effects, leaving a gap in experimental data for bonded hybrid connections [2,9].

2 – PROJECT DESCRIPTION

This study aims to experimentally investigate the shear transfer capacity and bond performance of adhesively bonded interfaces between engineered timber products—namely Radiata Pine Glulam (GLT) and H2S Laminated Veneer Lumber (LVL)—and lightweight materials such as cold-formed steel and FRP panels. To address the current gap in the literature, a detailed push-out testing program was designed to evaluate the behaviour of these hybrid connections under shear loading. The test campaign examines the influence of timber species, adhesive type, grain orientation, interface preparation, and assembly timing on the load transfer efficiency and slip characteristics of the bonded joints. The findings aim to advance the understanding of adhesively bonded hybrid construction systems that combine the benefits of lightweight prefabrication with robust and sustainable structural performance. The research is particularly motivated by applications in composite lightweight flooring systems, such as those employed in hybrid timber flooring systems [12–15], where reliable bonding between dissimilar materials is essential for effective composite action and serviceability. Adhesive bonding offers several practical and structural advantages over mechanical fastening, such as uniform stress distribution, reduced thermal bridging, improved aesthetics, and potential for automation in prefabrication. However, despite its widespread use in timber-FRP applications, limited experimental data exist for timber-to-steel or timber-to-FRP bonded joints, particularly under push-out loading conditions that simulate in-plane shear. This study addresses this knowledge gap by performing a comprehensive experimental program involving small-scale push-out tests. The aim is to assess the effects of various parameters on the interface behaviour, including: adhesive type, timber species and grain orientation, adhesive application time, presence of interface gaps, surface preparation, and material combination (e.g., steel vs. FRP). The experimental results are intended to inform future design and modelling of hybrid timber connections and to serve as a reference for adhesive selection and interface detailing in modular and prefabricated structural systems.

Table 1. Material Properties of Materials Used for Testing

Mechanical Properties (MPa)	Bending (f'_b)	Tension (f'_t)	Shear (f'_s)	Compression (f'_c)	Elastic Modulus (E)	Shear Modulus (G)
Radiata Pine (GL10)	22	11	3.7	26	10000	670
LVL E13.2 H2S	44	37	4.1	35	12200	600

3 – EXPERIMENTAL SETUP

2.1 Materials and Prototype Configurations

The test specimens were fabricated using two commonly available engineered timber products in the Australian construction market: Radiata Pine Glulam (GL10) and LVL E13.2 (H2S treated). These materials were selected due to their favourable structural properties, consistent quality, and compatibility with lightweight construction systems. Their respective mechanical properties, including bending, tension, shear, compression strengths,

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and elastic/shear moduli, were sourced from suppliers and are summarised in Table 1. Two structural adhesives were used to create the bonded interfaces:

- Bostik AV515, a high-performance polyurethane adhesive with a tensile strength of 10 MPa and shear strength of 7 MPa.
- SikaBond-145 SuperGrip, another polyurethane adhesive with slightly lower mechanical properties but enhanced elasticity for accommodating minor material movements.

The steel component consisted of cold-rolled mild steel sheets with thickness of 0.8 mm was utilized. The steel had a yield strength of at least 300 MPa and an elastic modulus of approximately 195 GPa, based on manufacturer data.

A total of seven unique configurations, listed in Table 2, were tested. Variables included grain orientation (parallel or perpendicular), adhesive type, gap thickness at the interface, and application time before clamping. Most configurations were tested with at least two to seven repetitions to ensure statistical reliability.

Table 2. Laboratory Specimen Overview and Properties

ID	Timber Species	Adhesive	Loading Direction to Grains	Number of Repeats	Application Time	Interface Gap
GLBPART0	Radiata Pine	Bostik	Parallel	7	0 Minutes	0mm
GLBPERT0	Radiata Pine	Bostik	Perpendicular	2	0 Minutes	0mm
LVBPART0	LVL	Bostik	Parallel	2	0 Minutes	0mm
LVBPERT0	LVL	Bostik	Perpendicular	2	0 Minutes	0mm
GLSPART0	Radiata Pine	Sikabond	Parallel	2	0 Minutes	0mm
GLBPART5	Radiata Pine	Bostik	Parallel	2	5 Minutes	0mm
GLBPART0.15	Radiata Pine	Bostik	Parallel	5	0 Minutes	1.5mm

2.2 Sample Preparation

Timber members were sawn from full-length structural stock (Radiata Pine: 168 × 55 × 2700 mm; LVL: 200 × 63 × 2400 mm) into smaller blocks with final dimensions of 50 × 50 × 150 mm. Prior to adhesive application, steel surfaces were sanded to remove any surface oxidation or oils and to promote mechanical interlocking. Adhesive was applied manually across the entire bond area, after which the samples were clamped and left to cure under room temperature conditions for a minimum of 24 hours. All samples were labelled and monitored to ensure consistent fabrication tolerances and alignment. Steel plates used in the tests were 150 × 50 mm, with two pre-drilled 10 mm diameter holes for attachment to the testing rig. The assembled specimens were fixed to the grips of the universal testing machine (UTM) using 6 × 110 mm bolts to enable axial tension without eccentricity.

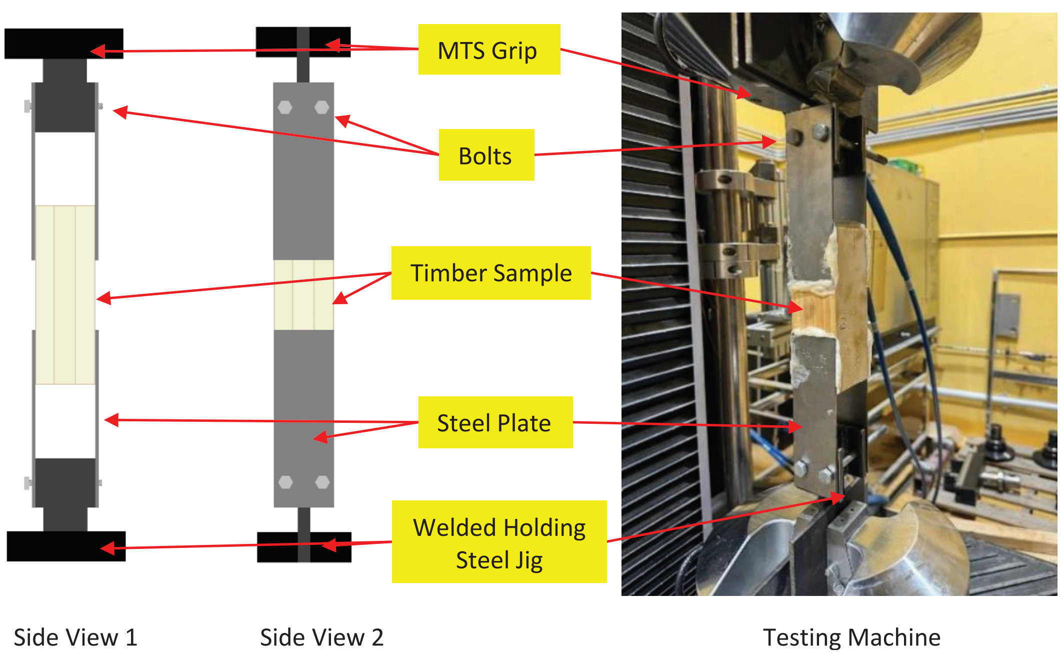

Figure 1. Timber Steel Adhesive Pull Out Testing Setup

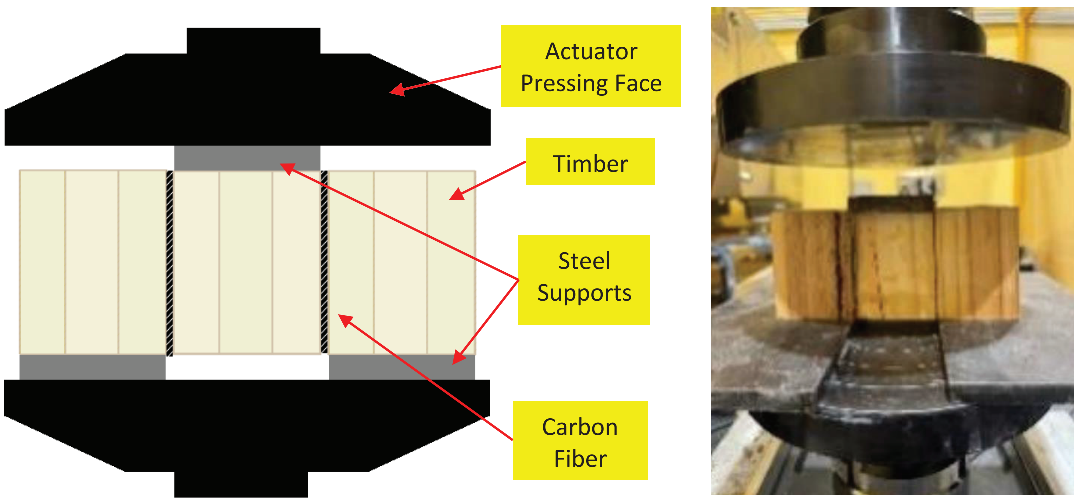

Figure 2. Carbon Fiber Adhesive Shear Testing Setup

2.3 Push-Out Test Setup (Timber–Steel Interface)

As shown in Figure 1, The push-out tests were conducted using a 300 kN MTS Model 45 universal testing machine, capable of applying precise displacement-controlled loading. The steel plates bonded to the timber specimens were clamped into the testing machine grips, and a tensile load was applied at a constant rate of 0.4 mm/min. The test continued until 60% post-peak load drop, which was defined as the failure criterion. While the MTS machine recorded the global displacement of the test assembly, this included deformation of the grips and fixtures. Therefore, to accurately capture interface slip behaviour, the tests were recorded with high-resolution digital cameras positioned perpendicular to the interface. These videos were later processed using Digital Image Correlation (DIC) software (GOM Correlate) to extract relative displacement between the timber and steel components throughout the loading process.

2.4 Testing of Timber–FRP Interface

For the carbon fibre reinforced polymer (CFRP) specimens, a different testing configuration was employed to accommodate the flexible nature of the FRP layers (see Figure 2). The specimens were assembled by gluing three timber blocks with two intermediate CFRP panels forming the interface. Once the adhesive had fully cured, the middle timber block was loaded in compression using the UTM while the two outer blocks were restrained, allowing shear stress to develop across both CFRP interfaces. This setup enabled accurate observation of interfacial shear deformation and failure under simulated push-out loading conditions.

5 – RESULTS

5.1 Steel-timber Specimens

The load-slip curves for the tested specimens are presented in Figure 4 to Figure 6. Solid lines indicate the average values, while dashed lines represent individual test repeats. All specimens exhibited a brittle failure mode. Shows the GLBPART0 'baseline' sample test results. These tests used Radiata Pine as a timber material, Bostik AV515 adhesive between timber and steel applied parallel to the grain. In total there were 7 repeats with 0 minutes in delay before applied the adhesive and 0mm of gap between the steel timber interfaces.

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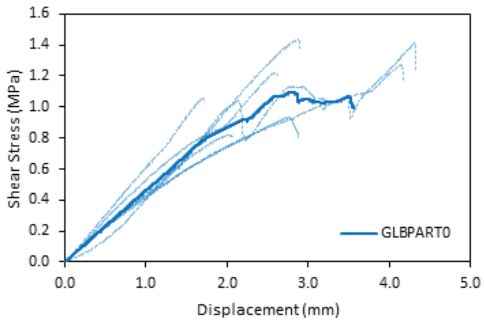


Figure 3. Glulam with Parallel Orientated Grain (GLBPART0) 'Baseline' Average Shear Stress and Displacement Relationship

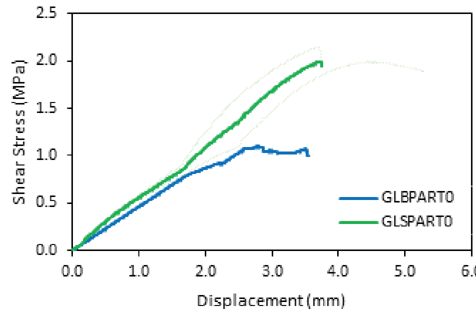


Figure 5. Sikabond145 (GLSPART0) and 'Baseline' (GLBPART0) Average Shear Stress and Displacement Relationship

Figure 4 shows the comparative performance of GLBPART0 and LVBPART0 samples. The LVL samples demonstrated slightly higher stiffness (~21%), while the Glulam specimens had an average ultimate stress of 2.75 MPa, which was approximately 15% greater than LVL.

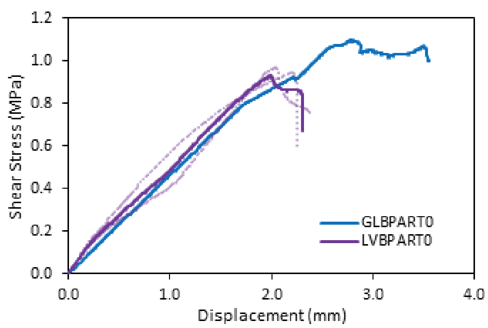
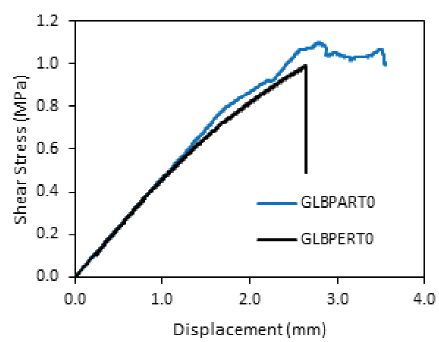


Figure 4. LVL with Parallel Orientated Grain (LVBPART0) and Baseline (GLBPART0) Average Shear Stress and Displacement Relationship

For specimens made using different adhesives but the same Glulam timber, those with Sikabond 145 outperformed the Bostik counterparts. Both Sikabond specimens exhibited a bilinear load-slip curve, with secondary stiffness being on average 17% higher than initial stiffness, as seen in Figure 5. The average initial stiffness and peak shear strength of the Sikabond specimens were 8% and 45% higher, respectively, than those with Bostik adhesive.

Both GLBPART0 and GLSPART0 samples followed a similar trend when shear stress was less than 0.80 MPa. However, after this point, the GLBPART0 specimens started to fail, with a sharp decrease in stiffness, while GLSPART0 specimens demonstrated increased stiffness and began to fail at approximately 1.98 MPa. The GLSPART0 specimen showed the highest maximum shear stress of 4.98 MPa and a displacement capacity of 3.80 mm.

Figure 6 illustrates the effect of grain direction on bond behaviour. Glulam samples with perpendicular grain orientation showed almost the same stiffness as those with parallel grain orientation, though the ultimate shear strength was slightly lower by approximately 10%. In contrast, LVL specimens with perpendicular grain orientation exhibited significantly lower stiffness and ultimate shear strength, with reductions of 47% and 43%, respectively.



a) Glulam

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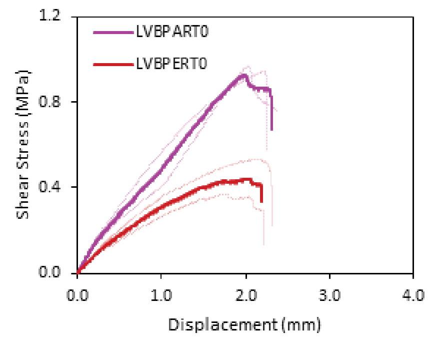
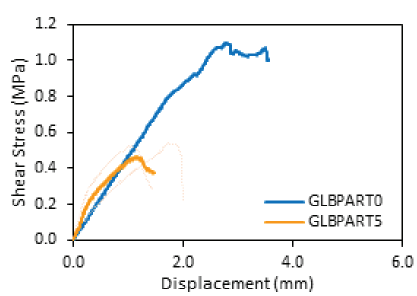


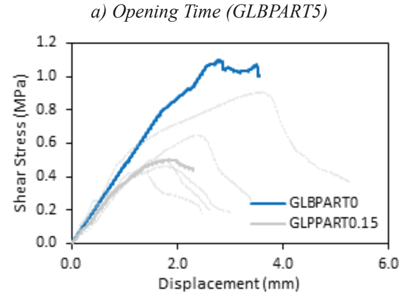
b) LVL

Figure 6. Glulam (GLBPERT0) and LVL with Perpendicular Orientated Grain (LVBPERT0) Compared to 'Baseline' (GLBPART0) Shear Stress and Displacement Relationship

To investigate the impact of defects on bond connection performance, two potential scenarios were considered: late assembly of the specimen (GLBPART0) and a specimen with a 15mm air gap (GLBPART0.15). Exposing the adhesive to air for 5 minutes before bonding the timber to steel had a significant negative effect on the sample's performance, as shown in Figure 7 (a). While the average stiffness remained nearly the same, the ultimate shear strength was reduced by 58% to 0.46 MPa. The presence of an air gap proved even more detrimental, leading to a 59% and 17% reduction in both capacity and stiffness respectively. This underscores the importance of eliminating air gaps and ensuring a tight assembly to achieve a fully effective bond connection.



a) Opening Time (GLBPART5)



b) Gap (GLBPART0.15)

Figure 7. 5 Minute Exposed BostikAV515 (GLBPART5) and 1.5mm interface gap (GLBPART0.15) compared to Baseline (GLBPART0) Average Shear Stress and Displacement Relationship

Overall, specimens bonded with Sikabond adhesive outperformed in both stiffness and strength. The effect of grain direction in laminated veneer timber (LVL) was more pronounced compared to that of Glulam. Late assembly had a minor impact on the initial stiffness, which would be negligible where shear forces are small in composite beams, such as at mid-span. However, the presence of gaps proved far more detrimental, significantly reducing the bond capacity required to develop composite action. A summary of the average initial stiffness, shear strength, and failure slip is shown in Figure 59.

To summarize, the bar chart in Figure 8 compares the stiffness of various specimens under three ranges of load application: k0.1-0.6, k0.1-0.4, and k0.4-0.6, where each range represents a specific portion of the load-displacement curve. The k0.1-0.6 range corresponds to the overall stiffness from 10% to 60% of the ultimate load, reflecting the general performance of the specimens. The k0.1-0.4 range represents stiffness at lower loads, capturing the elastic behaviour, while k0.4-0.6 focuses on the stiffness closer to higher loads, revealing potential material softening or nonlinear effects.

GLBPART5 (5-minute opening time) exhibits the highest stiffness in the k0.1-0.6 range, approximately 90% greater than the next closest sample, LVBPART0. This trend suggests that the extended opening time during adhesive application allows for better bonding and overall structural performance. In the k0.1-0.4 range, its stiffness remains high, but the difference with other specimens is less pronounced, indicating consistent performance across different load levels. Under the k0.4-0.6 range, its stiffness advantage is still evident, highlighting its superior performance even at higher load levels suggesting a better stiffness performance for curing while exposed to air.

GLBPART0 (Glulam Parallel Average) and LVBPART0 (LVL Parallel Average) show relatively similar stiffness across all ranges, with GLBPART0 slightly outperforming LVBPART0 by 10-15%. This indicates that both materials perform well in parallel configurations, with glulam providing a marginal advantage. Samples with Sikabond glue (GLSPART0) demonstrate stiffness values 5-10% lower than GLBPART0, suggesting that glue type impacts performance, though not as significantly as other factors like material orientation or bonding conditions.

The stiffness of glulam in a perpendicular configuration (GLBPERT0) is significantly lower—30-40% less than its parallel counterpart (GLBPART0) across all ranges.

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This reduction reflects the weaker shear resistance of glulam when loaded perpendicular to the grain. Similar to GLBPERT0, LVL in a perpendicular configuration (LVBPERT0) shows lower stiffness, about 20-30% less than LVBPART0 (LVL Parallel). However, LVBPERT0 slightly outperforms GLBPERT0 by 5-10%, likely due to the uniformity and engineered properties of LVL.

GLBPART0.15 (1.5mm gap) shows the lowest stiffness across all ranges, with a reduction of 50-70% compared to the best-performing sample (GLBPART5) in the k0.1-0.6 range. This seems to be because the 5-minute bond time had a much weaker but stiffer bond compared to the other samples. The presence of a 1.5mm gap significantly compromises bonding quality and stiffness, demonstrating the critical importance of tight bonding interfaces.

Trends and Key Insights:

In overall, Parallel specimens (GLBPART0 and LVBPART0) consistently outperform perpendicular ones (GLBPERT0 and LVBPERT0) by 30-40%, emphasizing the importance of material orientation. Samples with presence of air gap, such as GLBPART5, exhibit significantly better stiffness compared to those with gaps (GLBPART005), demonstrating the importance of precise adhesive application. The performance difference between Sikabond (GLSPART0) and Bostik (GLBPART0) is minimal (~5-10%), indicating that glue selection plays a secondary role compared to other factors. Stiffness in the k0.4-0.6 range reveals the capacity of specimens to sustain higher loads without significant softening, with GLBPART5 and GLBPART0 performing best.

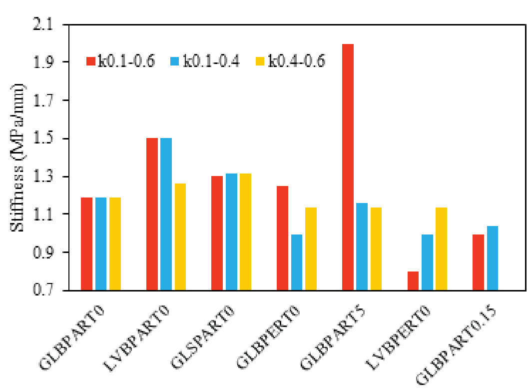

Figure 8. 5 Comparison of specimen stiffness during each loading stage

During testing, it was observed that in the early phase of each test, there were sudden jumps in the stiffness of the samples. Upon further investigation, this was found to be caused by the bolts securing the samples engaging at different times. Small inaccuracies in sample manufacturing led to asymmetrical bolt engagement, where one bolt would engage first, and full initial stiffness was only achieved after the MTS tensioned the sample, allowing the second bolt to engage. Some inconsistencies between samples developed during the gluing and clamping process. Despite taking care, without a dedicated jig, it was difficult to ensure consistent assembly timing across samples. Prolonged durations between gluing and clamping likely weakened the bond between the steel and timber surfaces, which could have reduced the sample's shear capacity. Furthermore, on several occasions, the steel was slightly displaced while adjusting the clamps, breaking part of the bond that had already formed between the steel and timber. This movement likely contributed to a reduction in the final shear capacity of the samples. Moreover, maintaining a consistent thickness of the adhesive layer proved challenging. If the clamps were applied too tightly, excess adhesive would seep out from the sides of the steel interface. Conversely, if the clamping pressure was insufficient, the bond between the two layers was suboptimal.

5.2 Failure Modes

For all the samples where the steel was adhered to the timber parallel to the grain, the adhesive failed, leaving both the timber and steel intact as shown in Figure 9. There was only one exception where both the glue and timber failed simultaneously. These results suggest that in the parallel orientation, the weakest material is typically the adhesive, although in some weaker samples, the timber may also be a point of failure. An example of this failure mode is depicted in Figure 9.

Figure 9. Steel Adhered Parallel to Grain Failure Mode, Glulam 4 (top) and all other samples (bottom)

For the samples where the timber was bonded to the steel on the perpendicular face (LVLPERT0 and GLPERT), the timber failed by cracking along the grain direction and perpendicular to the direction of force, as shown in Figure 10. In this orientation, the tensile strength between parallel grains was less than the shear capacity of the adhesive, leading to the timber's failure.

5.3 Carbon Fibre Testing

Three different carbon fibre timber composites were tested using a shear compression test. The results of this testing are presented in Table 3. Both force and displacement measurements were recorded by the MTS machine, so the stiffness values represent the entire composite material, not just the timber-carbon fibre interface. Some of the displacement recorded by the MTS could have been caused by the compression of timber fibres, meaning the actual slip at the carbon fibre joint might have been less than what was measured.

Figure 10. Steel Adhered Perpendicular to Grain Failure Mode

Table 3. Timber Carbon Fiber Composite Shear Compression Testing Results

	Shear Area (mm^2)	**Maximum Stress (MPa)**	**Ultimate Strain (%)**	**K (10-60%)**	**K (10-40%)**	**K (40-60%)**
S.01	7590	2.17*	2.35	15.25	12.39	24.68
S.02	7700	4.16	2.84	12.53	20.29	15.50
S.03	7344	4.06	3.42	33.45	27.87	44.05
Ave	7545	3.98	2.82	20.41	20.18	28.08

*Note that test 1 has a lower maximum stress as it failed in bending, not shear.

When considering Sample 1, the average maximum stress capacity of the carbon fibre samples is 3.98 MPa. If Sample 1 is excluded (since it failed in bending rather than shear), the average shear capacity rises to 4.61 MPa. The ultimate strains experienced by the samples were relatively consistent, with an average of 2.82% and a maximum deviation of 0.53%. Due to several sharp drops in shear stress over the course of each test, it is difficult to discern any clear trends in stiffness from the fixed K values in Table 3. However, the graph in Figure. 11 better illustrates the stiffness performance. Sample 1, which failed in bending, showed a smooth exponential increase in shear stress until failure at 2.17 MPa. The other two samples, which failed in shear, displayed an exponential build-up in shear stress, but both experienced sharp drops—at 2.14 MPa for Sample 2 and at 3.25 MPa for Sample 3—before building back up to their maximum capacities. Near the peak stress, all three samples (especially Samples 1 and 3, and to a lesser extent Sample 2) exhibited several sharp drops followed by gradual increases in shear stress. Both Samples 1 and 3 had ductile failure modes, while Sample 2 showed a more brittle failure.

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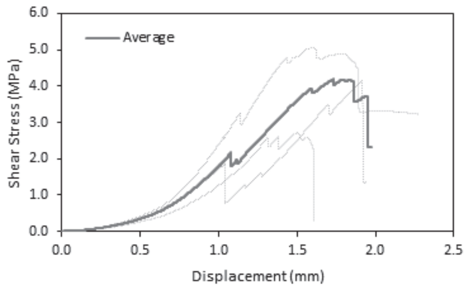

Figure. 11. Carbon Fibre Samples Shear Stress and Displacement Relationship

6 – CONCLUSION

This experimental study evaluated the shear performance of adhesively bonded interfaces between timber and lightweight construction materials, focusing on small-scale push-out tests of timber–steel and timber–FRP specimens. The results demonstrate that:

- Grain orientation significantly affects bond strength, with parallel orientation yielding greater stiffness and shear capacity than perpendicular configurations, particularly in Glulam specimens.
- Adhesive selection plays a crucial role: SikaBond-145 exhibited superior performance over Bostik AV515 in both peak shear stress and ductility, especially under increasing slip conditions.
- Manufacturing precision is critical. Delays in clamping after adhesive application and the presence of even small interface gaps led to substantial reductions in shear capacity and stiffness, underscoring the importance of tight tolerances during assembly.
- Material choice influences performance. Glulam generally outperformed LVL, and the difference was more pronounced when the loading was applied perpendicular to the grain.
- Carbon fibre–timber interfaces demonstrated moderate strength and relatively ductile behaviour, although the testing configuration introduced some complexity in interpreting interface slip.

These findings highlight the importance of adhesive bonding quality and interface detailing for achieving reliable shear transfer in hybrid timber systems. The data generated offers practical guidance for the design of glued interfaces in prefabricated timber–steel and timber–FRP elements. Future work will focus on scaling up the testing to full-scale composite beams, investigating long-term durability under environmental exposure, and modelling the interface behaviour for integration into structural design frameworks.

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