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Advancing Timber for the Future Built Environment

SHEAR PROPERTIES OF ADHESIVE JOINTS FOR I-SHAPED SECTION TIMBER-GLASS COMPOSITE BEAMS

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ABSTRACT: Timber-glass as a novel composite structure, which has gradually attracted attention in timber structure due to its advantages in sustainability, low-carbon footprint, light transmission, and aesthetic appeal. This study mainly presents the bonding performance of the interface for I- shaped section timber-glass composite beams composed of poplar LVL and tempered glass. Multiple adhesive joints were designed and next they were subjected to monotonic shear tests. The parameters included bonding width, bonding length, adhesive layer thickness, and adhesive types. The test results demonstrate that epoxy resin provides better bonding performance than one-component polyurethane. The joints primarily undergo shear failure in the wood, with an average shear strength of approximately 4.16 MPa. When the bonding width increased from 20 mm to 40 mm, the shear load-carrying capacity of the joints increased by approximately 59.36%. Furthermore, the load-carrying capacity slightly increased with the adhesive layer thickness. Specifically, adhesive layer thicknesses of 2 mm and 3 mm resulted in increases of 6.50% and 12.36%, respectively, compared to the 1 mm, which will provide a good reference for the design of I- shaped section timber-glass composite beams.

KEYWORDS: I- shaped beams, Timber-glass composite, Adhesive bonding, Parametric analysis, Shear properties

1 – INTRODUCTION

With the increasing demand for transparent, lightweight load-bearing members in the construction industry, timber-glass composite (TGC) I-beams have gradually gained attention as an innovative structural form, as shown in **Fig.1**. By using high-strength adhesives to bond the timber flanges and glass web, this structural form has the advantage of not only meeting the occupants' needs for natural lighting and aesthetic appeal in buildings but also fully utilizing the tensile strength of timber and the compressive strength of glass. It serves as an alternative to traditional wood I-joists [1-3]. Additionally, compared to concrete or steel, the combination of timber and glass also offers lower environmental burdens and energy consumption, making it a more environmentally friendly and sustainable building material choice.

The existing studies mainly focus on the adhesive joints and mechanical behaviour of TGC [4,5]. The adhesive type is a key parameter that affects the mechanical performance of TGC I-beams. Three different types of adhesives (Acrylate, Silicone and Polyurethane) for timber-glass bond joints were first shear tested by Blyberg et al. [6]. The results showed that the Acrylate (SikaFast 5215) provided the largest strength, both in tension and shear. The mean strength was 3.0 MPa in tension and 4.5 MPa in shear. Then, Blyberg et al. [7] tried to bond timber flange and glass web with these three adhesives to form TGC I-beams. The test results show that the TGC I-beams based on acrylate bonding achieves a higher ultimate bearing capacity, and its bending stiffness is 30% higher than that of comparable traditional I-joists. Recently, Rodacki and Furtak [8] used the extended finite element method to numerically study the crack development of timber-glass composite I-beams, also discussed and analyzed the influence of the adhesive layer material model on the values of deflections and stresses in I-beams with a constant load in elastic work of materials. The simulation results agree well with the experimental results.

Strukelj et al. [9] proposed bonding glass wall directly to a LVL frame with adhesive to form timber-glass composite shear wall, creating a lightweight structural

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element that is both load-bearing and visually interesting. They conducted static-dynamic tests on these walls, with the control parameters being three adhesive types and two bonding lines. The research results indicated that the failure mechanism mainly depends on the adhesive type and adhesive line. Environmental conditions also affect the bonding performance of the joints. In 2019, Unuk et.al. [10] used cold-cured two-component structural adhesive epoxy resin (Mapei Adesilex PG1) to bond timber and glass. Shear tests were conducted under different temperatures and moisture content conditions. The results showed that the shear strength was related to both the environmental temperature and the moisture content, with the main failure mode being timber failure. Next, Unuk et al. [11] developed a novel composite connection consisting of aluminum inserts, two-component structural epoxy resin adhesive, and self-tapping screws. Shear tests were performed on seven sets of these connection specimens to determine the load-bearing capacity and slip modulus. The results found that all the connections primarily exhibited screw failure, while the tempered glass remained undamaged.

The above studies mainly discussed the influence of factors such as adhesive type and environmental conditions on the shear performance of joints and the overall mechanical performance of TGC. However, further research is needed on the geometric dimension optimization of the bonding joints, such as the depth of the glass web into the timber flange and the thickness of the adhesive, in order to provide valuable references for the engineering design of TGC I-beams. Additionally, it is essential to carry out this work before further studying the in-plane mechanical behavior of TGC I-beams under different shear-span ratios.

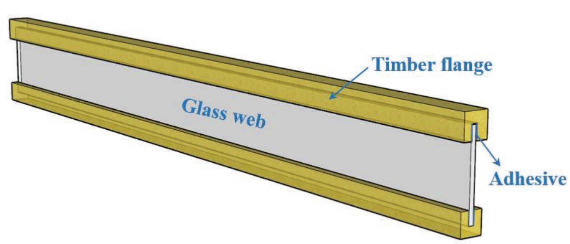

Figure 1: *Structural form of TGC I-beam*

2 – MATERIALS AND METHODS

2.1 EXPERIMENT PROGRAMME

In experiment, the design details of timber-glass adhesive joints are shown in **Fig. 2**. The main material is laminated veneer lumber (LVL), with a nominal length of 150 mm and a cross-section size of 45 mm × 50 mm. The base material is tempered glass, the nominal length is 100 mm, the nominal thickness is 5 mm, and the width is the variable parameter. The main material and the base material are bonded by structural adhesive, and the diagonal part is the bonding zone.

A total of 12 groups of specimens were designed, with 5 replicates in each group. The control parameters are the type of adhesive (epoxy resin and one-component polyurethane), the bonding length between the glass web and LVL (40, 50, 60, 70, and 80 mm), the bonding width of the glass plate (20, 25, 30, 35, and 40 mm), which indicates the depth of the glass web into the LVL flange, and different adhesive layer thicknesses (1, 2, and 3 mm).

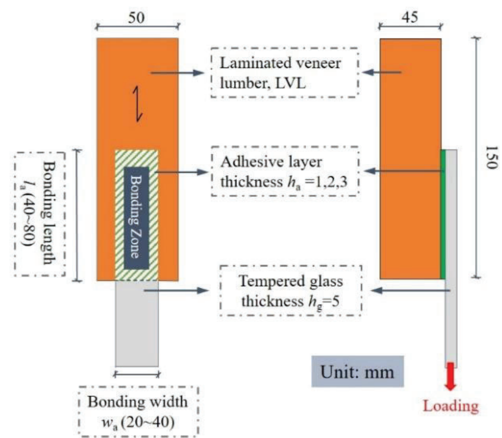

Figure 2: *The design details of adhesive joints*

2.2 MATERIAL PROPERTIES

The LVL is made from domestically sourced fast-growing poplar, with a veneer thickness of 1.9 mm. The average air-dried density and moisture content of 20 poplar LVL samples with dimensions of 20 × 20 × 20 mm³ were measured as 590 kg/m³ and 9.7%, respectively. Ten samples with dimensions of 45 × 45 × 270 mm³ were used to determine the compressive strength parallel to the grain and modulus of elasticity parallel to the grain according to EN 408 [12], with average values of 50.51 MPa and 12,230 MPa, respectively. Additionally, the shear strength parallel to the grain of the poplar LVL was measured, with an average value of 3.01 MPa. All test results, including the average values, standard deviations, and coefficients of variation, are summarized in **Table 1**.

As there is no known difference between the application of adhesives on float, heat strengthened or tempered glass, it was decided to carry out the shear tests with tempered

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glass samples. Glass is an isotropic material with an elastic modulus of 70000 MPa. The glass samples were simply cut, without any processing of the edges or surfaces.

***Table 1：** Material properties of popla LVL*

Properties	Mean	s	Cov (%)
Air-dried density, [kg/m^3]	590	12.61	2.14
Moisture content, [%]	9.66	0.12	1.22
Compressive strength parallel to the grain, [MPa]	50.51	1.17	2.31
Shear strength parallel to the grain, [MPa]	3.01	0.27	8.95
Modulus of elasticity parallel to the grain, [MPa]	12230	1594	15.89%

The chosen epoxy resin was LOCTITE EA 3628 from the company LOCTITE, which is a cold-curing two-component structural bonding epoxy resin of the rapid-setting thixotropic adhesive type. The mixing ratio is 1:1(component A – resin: component B – hardener). It is a bisphenol-based (bisphenol A and bisphenol F) epoxy adhesive. Its advantages include a low density, low viscosity, fast curing speed, and high bonding strength. According to the technical specifications provided by the manufacturer, the recommended construction temperature is between 15°C and 35°C, with an initial curing time of 4 - 8 hours and a curing time of 24 hours.

2.3 SAMPLE PROCESSING

The specimen fabrication process is carried out as follows：Step 1: Surface treatment, including sanding the surface of the polar LVL and wiping the glass web. Step 2: Determining the bonding area, marking and positioning the bonding area, and securing a 2 mm thick fine wire with tape to form a U-shaped region. Step 3: Preparing the adhesive, mixing the epoxy resin adhesive in a 1:1 ratio according to the manufacturer's instructions, weighing it, and stirring thoroughly in a container to ensure uniformity. Since the curing of the adhesive is highly temperature-dependent during the initial stage, air conditioning is used to maintain a temperature above 20°C. The adhesive is then evenly applied to the specimen's surface for bonding. Step 4: Curing the specimen for 7 days to ensure complete curing and to achieve optimal bonding strength. The main processing process is shown in **Fig. 3**.

2.4 TEST SETUP

The single-shear test was conducted at the Modern Timber Structure Laboratory of Nanjing Tech University, using an MTS testing machine for loading. A specialized steel tool was designed for the shear test, with the loading and measurement setup shown in **Fig. 4**. As the shear tools were clamped into the universal testing machine.

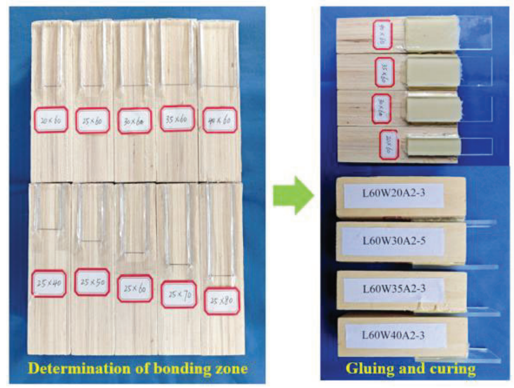

***Figure 3:** Manufacturing process*

The measurements include the applied load, interface slip, and failure mode. The loading was applied at a rate of 1 mm/min until the specimen failed or the adhesive layer was completely peeled off. In addition, a linear variable displacement transformers (LVDT) was arranged on the right side of the test sample to eliminate displacements caused by the deformation of steel components, thereby improving the accuracy of the test results.

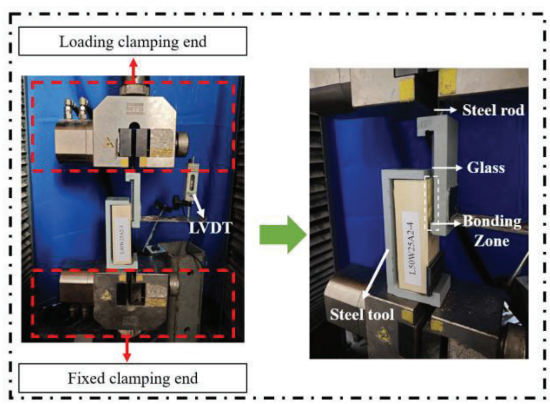

***Figure 4:** Loading and measurement*

3 –RESULTS AND DISCUSSION

3.1 FAILURE MODES

The failure types of shear specimens can be classified into the following: In the plane localized glass failure, timber shear failure,, adhesive shear failure, and out of plane glass failure, as shown in **Fig. 5**. For shear specimens bonded with epoxy resin adhesive, no significant phenomena were observed during the early stages of loading. Upon reaching a certain load, a crisp sound was heard, likely due to slight tilting of the steel tools, which caused stress concentration at the tool's end, resulting in localized crushing of the glass in the plane. As the load increased, noticeable relative slip occurred between the tempered glass and poplar LVL until the maximum load was reached. Afterward, most shear specimens exhibited a mixed failure mode at the adhesive bond zone's ends, characterized by timber shear failure and adhesive layer failure. However, timber shear failure predominated, mainly due to the use of transparent tape to fix the fine iron wire, which resulted in insufficient bonding strength between the adhesive and timber at the bonding edge. Additionally, a few shear specimens experienced out-of-plane failure due to significant deflection of the glass during loading, constrained by the steel tools. These specimens exhibited a sudden drop in bearing capacity after reaching the maximum load, indicating brittle failure.

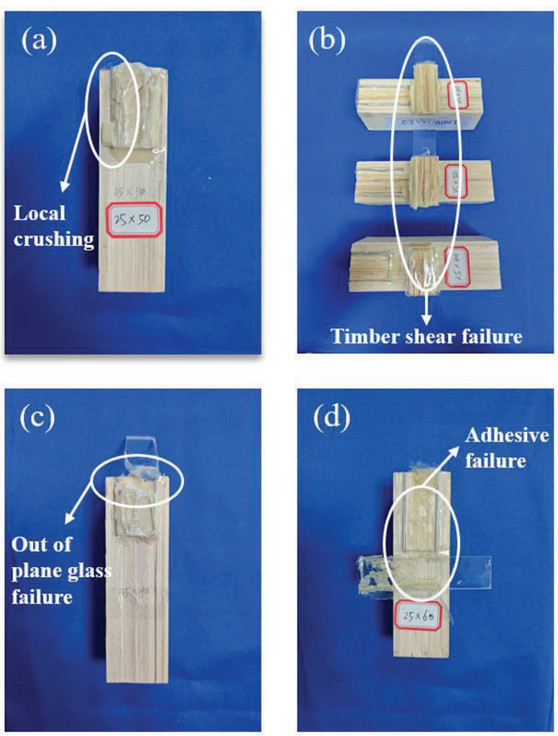

***Figure 5:** Main failure modes for adhesive joints*

For shear specimens bonded with single-component polyurethane adhesive, the phenomena in the early loading phase are consistent with those of shear specimens bonded with epoxy resin adhesive. The difference is that when the maximum load is reached, the failure mode in the adhesive bond zone primarily involves adhesive layer failure. This is mainly due to the relatively low shear strength of the interfacial adhesive. However, the advantage of polyurethane adhesive over epoxy resin is that the specimen's bearing capacity decreases more gradually after reaching the maximum load, maintaining relatively good post-failure bearing capacity.

3.2 LOAD-DISPLACEMENT CURVES

The load-displacement curves measured by each group of shear specimens are shown in **Fig. 6**. It should be noted that the diagram of the shear specimen with epoxy resin adhesive connection only shows the ascending section but not the descending section (Fig. 6a), the peak load corresponds to the largest point in the graph and. Because it is a brittle failure that leads to sudden drop of load, which indicates a generally abrupt energy release. The testing device recorded displacement is a sum of the shear specimen deformation, shear tool deformation and the universal testing machine compliance. The displacement I recorded was also compared to the displacement from the LVDT, which was very close. Therefore, the displacement we eventually used was still from the test device. The average peak load for each group is summarized in **Table 2.**

After the initial stiffening zone, most of load-displacement curves showed almost linear behaviour, few load-displacement curves also had some discontinuities, which happened due to the combination of different failure types. According to the test results, discussions in terms of the effects of adhesive type, Adhesive layer thickness, bonding length and bonding width are made in the following sections.

3.3 SHEAR STRENGTH

The average shear strength (τ), standard deviation (s), and coefficient of variation (Cov) for each group of specimens were calculated, as listed in **Table 2**. The shear strength of the specimens bonded with epoxy resin is significantly higher than that of the one-component polyurethane, approximately 3.02 MPa, making it more suitable for the interface connection of poplar LVL flange and glass web. Although the shear strength of the specimens bonded with one-component polyurethane is lower, the load-carrying capacity shows a slow decline after reaching the peak load, maintaining good post-failure load-carrying capacity with a relatively large slip.

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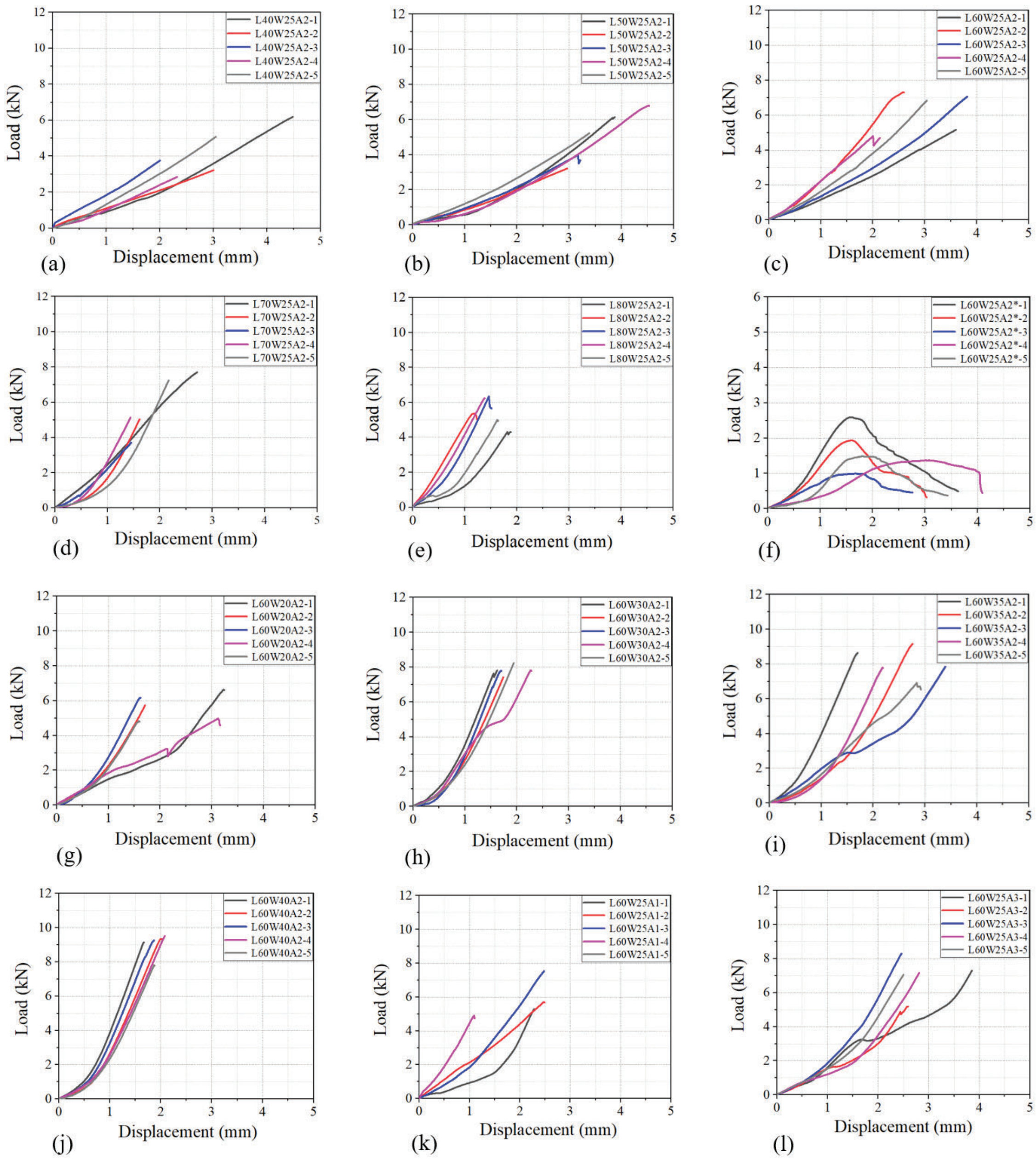

Figure 6: *Load-displacement curves*

The effect of bonding length was compared and discussed. It can be observed that the shear strength remains above 4.0 MPa in the bonding length range of 40 mm to 60 mm, which is higher than the shear strength of polar LVL parallel to the grain, 3.01 MPa. Therefore, this verifies that the phenomenon where the shear specimens ultimately fail primarily due to timber shear failure is reasonable. Furthermore, we also observed that as the bonding length increases, the shear strength slightly decreases. For bonding lengths of 70 mm and 80 mm, the decrease is more pronounced, with shear strengths of only 3.30 MPa and 2.72 MPa, respectively. In fact, the full-length bonding effect was not fully realized. Because during the test, as the load increased, the glass web slightly deflected in the plane. The ends of the bonding region not only experienced shear stress but also some out-of-plane tensile stress, causing premature failure at the ends rather than complete failure of the entire bonding region. This is consistent with the observed failure mode.

Table 2: *Summary of shear test results*

Designations	F_u [kN]	τ [MPa]	s [MPa]	Cov [%]
L40W25A2	4.22	4.22	1.39	32.88
L50W25A2	5.07	4.05	1.18	29.20
L60W25A2	6.23	4.16	0.78	18.68
L70W25A2	5.77	3.30	0.95	28.95
L80W25A2	5.45	2.72	0.43	15.68
L60W25A2*	1.68	1.12	0.41	36.47
L60W20A2	5.66	4.72	0.65	13.73
L60W30A2	7.81	4.34	0.16	3.67
L60W35A2	8.07	3.84	0.41	10.72
L60W40A2	9.02	3.76	0.28	7.64
L60W25A1	5.85	3.90	0.78	20.04
L60W25A3	7.00	4.67	0.75	16.07

Next, the effect of bonding width (this parameter represents the depth of the glass web into the the LVL flange) was compared. Theoretically, bonding width is proportional to peak load, and the shear strength at different bonding widths should remain a constant value. In this study, the shear strength at different bonding widths remained in the range of 3.76 - 4.72 MPa, which is an acceptable range due to experimental error. This also indicates that the adhesive can fully exert its bonding effect when the depth is between 20 mm and 40 mm. When the bonding width increased from 20 mm to 40 mm, the shear load-carrying capacity of the joints increased by approximately 59.36%.

Finally, the effect of adhesive thickness on shear strength was discussed. It can be seen that as the adhesive thickness increases, the shear strength also increases. For example, the shear strengths corresponding to adhesive thicknesses of 1 mm, 2 mm, and 3 mm were 3.90, 4.15, and 4.67 MPa, respectively, representing increases of 6.41% and 19.74%. This indicates that increasing the adhesive thickness is also an effective way to improve the interface shear strength. However, it should be noted that an increase in adhesive thickness also leads to higher costs. Therefore, selecting an appropriate adhesive thickness will not only improve shear strength but also save some economic costs.

Note: F_u dontes average peak load, τ dontes average shear strength, s dontes standard deviations, and Cov dontes coefficients of variation.

4 – CONCLUSION

This paper investigates the interfacial bonding performance between poplar LVL and tempered glass through single-shear tests. The effects of adhesive types and geometric parameters of the interface bonding, including bonding length, bonding width, and adhesive layer thickness, are discussed. The main conclusions are as follows:

For adhesive joints with epoxy resin adhesive from LOCTITE company, the main failure type was timber shear failure. The evaluated epoxy resin adhesive was proved to be suitable for I- shaped timber-glass beams made from fast-growing poplar LVL.

As the bonding width increases, the shear load-carrying capacity also increases, but it has little the impact on shear strength. The load-carrying capacity of adhesive layer thicknesses of 2 mm and 3 mm resulted in increases of 6.50% and 12.36%, respectively, compared to the 1 mm. Correspondingly, the shear strength increased by approximately 19.74% when the thickness increased from 1 mm to 3 mm, and the cost also increases. Therefore, the adhesive layer thickness needs to be determined based on the actual shear strength of the timber to avoid adhesive failure.

Future research should focus on the long-term performance of interface bonding under varying environmental conditions, aiming to provide valuable references for the engineering design of timber-glass composite I-beams.

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