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TIMBER TYPE EFFECT ON BOND STRENGTH OF FRP EXTERNALLY BONDED TIMBER

Abbas Vahedian[1], Rijun Shrestha[1], Keith Crews[1]

ABSTRACT: The performance of FRP composite bonded externally to timber is complex and limited attempts have been made to-date to investigate the bond behaviour of the FRP to timber interface. Furthermore, analytical solutions to determine the interface behaviour of FRP to timber have not been fully investigated and are not covered in current standards. This study investigates the influence of timber type and timber mechanical properties on the bond strength of FRP-to-timber joints. Two different types of timber (LVL and hardwood) have been used and results of experimental tests showed that with the increase of timber tensile strength and modulus of elasticity, the interfacial bond strength increases; however, the failure mode can be brittle. Specimens made from LVL exhibited more ductile behaviour failing gradually; while joints made from hardwood failed suddenly in a brittle manner. It was also observed that the local slip between FRP and timber was higher for joints fabricated from LVL compared to hardwood. Therefore, to achieve a satisfactory bonded joint, the effectiveness of timber mechanical properties is required to be accurately considered.

KEYWORDS: Bond strength, Timber, Hardwood, LVL, Pull out test

INTRODUCTION

Timber has been extensively used in construction for many centuries now. In addition to timber being one of only a few environmentally sustainable construction materials, due to a number of advantageous properties such as aesthetics, strength-to-weight ratio, fire performance and acoustic properties, there has been an increase in the use of timber in modern structures lately [1]. Timber structures may need to be repaired and/or strengthened as due to a number of factors, such as, degradation of the timber due to biological and/or physical hazards, loss of strength or damage due to overloading or to meet increased load demands due to change in functionality or to meet new code requirements.

Recent studies and applications have demonstrated that fibre reinforced polymer (FRP) has become a mainstream technology for the strengthening of ageing and deteriorated structures [2]. FRPs are light, highly resistant to corrosion, cost effective and have superior strength and stiffness properties [3]. However, one of the most common problems associated with the use the externally bonded FRP sheets is the premature failure due to debonding, which limits the full utilisation of the strength of FRP. Debonding has been identified as the single most important failure mechanism of retrofitted beams [4] that occurs at much lower FRP strains than its ultimate strain. Debonding directly impacts the total integrity of structure, with the subsequent outcome that the ultimate capacity and desirable ductility of the structure may not be achieved. Therefore, for the safe and economic design of externally bonded FRP systems, particularly when FRP is attached to timber, a sound understanding of the behaviour of FRP-to-timber interface needs to be developed.

Failure in a timber beam repaired or strengthened with FRP can occur in several ways, including but not limited to timber failure, FRP rupture, FRP delamination, FRP/adhesive separation, cohesion failure (adhesive de-cohesion), and timber-to-adhesive interfacial failure. More than one of these modes may be observed in an actual failure. When debonding occurs, the stress shifts over a partial active area leading to local shear stress concentrations. Discontinuity near the ends of FRP is another reason of stress concentration [5]. Many parameters control the failure mode for a reinforced timber element, since the interaction between timber and

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[1] Abbas Vahedian, The University of Technology Sydney Australia abbas.vahedian@student.uts.edu.au

Dr Rijun Shrestha, The University of Technology Sydney Australia. Rijun.Shrestha-1@uts.edu.au

Professor Keith Crews, The University of Technology Sydney Australia. Keith.Crews@uts.edu.au

FRP is relatively complex and is influenced by several variables.

The bond strength of FRP-to-timber joint depends on the environmental conditions, surface treatment, timber moisture content, geometry of the bond, boundary conditions and specimen alignment. In addition, experimental tests results revealed that bond length [6, 7], bond width and bond stiffness [8], significantly affect the bond strength of FRP-to-timber interface. Moreover, the bond strength depends significantly on the strength of the substrate material. Existing experimental investigations have suggested that the main failure mode associated to the externally bonded FRP joints is substrate failure under shear. Crews and Smith [9] reported that timber failure was the main failure mode that occurred in their tests. Wan [10] has conducted a more extensive study on FRP-to-timber interface and correspondingly developed a bond strength model for FRP-to-timber bond. However, the mechanical properties of timber were not considered in Wan's [10] study, since it was believed that softwood, hardwood and glulam used in the research were not significantly different from one another. As such, the importance of timber properties that have a major impact on the failure mode and failure load of the retrofitted beam reported by others [9, 11] has been ignored in the model proposed by Wan [10]. Consequently, further understanding of the effect of timber mechanical properties is essential.

This research study mainly focuses on the effect of timber mechanical properties on the bond strength. Results of current experimental tests indicated that the ultimate bond strength has been related to the timber tensile strength. Specimens fabricated from timber with higher tensile strength reached higher level of load; however, these samples exhibited a brittle behaviour with sudden debonding failure.

DETAILS OF RESEARCH PROJECT

In this study, 136 FRP-to-timber joints were subjected to pull-out tests. Two different types of timber, namely Laminated Veneer Lumber (LVL) made out of softwood and kiln dried hardwood sawn timber, were used to fabricate the joint specimens. The timber pieces used in the tests were selected to be as free as possible from naturally occurring "defects" such as knots, checks, etc. The LVL samples were either 320 or 370 mm long with a 110 mm x 65 mm cross section. All hardwood samples were 320 mm long, x 110 mm wide and 35 mm deep. One and two plies of unidirectional carbon FRP (referred as FRP here onwards) with the nominal thickness of 0.117 mm were externally bonded with an epoxy base (Sikadur®330) to the timber using a wet lay-up process. In the LVL series, FRP was applied in three different bond widths namely, 35 mm, 45 mm, and 55 mm with five different bond lengths (50 mm, 100 mm, 150 mm, 200 mm and 250 mm). In case of the hardwood series, only one bond width (45 mm) and bond lengths of 50 mm, 100 mm, 150 mm and 200 mm for the FRP were tested. FRPs with 250 mm bond length were attached to timber block with 370 mm long whilst the rest FRPs were bonded to timber block with 320 mm long either in in the samples made from LVL or hardwood. Strain gauges were attached to the FRP surface to measure the strain variation of the bond during the experiment. The pull-out test setup was such that the timber block was restrained in a steel rig and load was applied to the free end of the FRP. The slip between timber and CFRP was measured with a single LVDT which was mounted on the surface of timber block as shown in Figure 1.

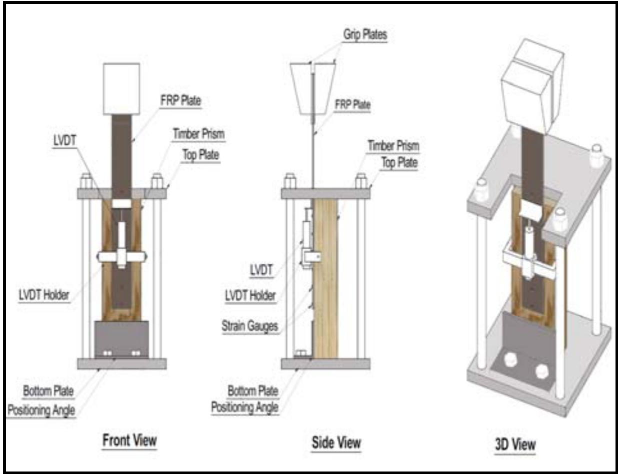

Figure 1, *Single shear test setup*

Tensile and compressive properties as well as modulus of elasticity of the timber were determined based on 28 tests on timber (14 LVL and 14 hardwoods) samples from the same batch as for the pull-out test specimens as per BS EN 408:2010 [12]. Tensile strength and elastic modulus of FRP was determined based on tensile tests on six FRP coupons as per ASTM D3039/D3039M Standard [13]. The epoxy adhesive was not tested; however, as per manufacture's product data sheet [14], the values of elastic modulus and tensile strength of Sikadur®-330 were 4.5GPa and 30MPa, respectively. The mean values of material test results are tabulated in Table 1.

Table 1 *Material Properties of timber, FRP and adhesive*

Material	**Tensile Strength MPa (CoV)**	**Modulus of Elasticity, GPa (CoV)**	**Compressive Strength MPa (CoV)**
Hardwood	67.53 (8.7)	19.75 (8.6)	64.93 (4.5)
LVL	44.31 15.6)	16.18 (5.1)	56.26 (1.8)
FRP	2497 (6.5)	228.89 (10.2)	--
Sikadur®-330	30	4.5	--

CoV: co-efficient of variation

DISCUSSION

Results of pull out tests showed that the main failure occurred predominately in timber, as shown in Figure 2, occurring generally a few millimetres away from the adhesive layer. Failure occurred at the loaded end and propagated to the far end of the bonded FRP; however, the interface failed rapidly in specimens with the bond length shorter than the effective bond length in both LVL or Hardwood series. On the other hand, an ultimate load plateau was observed in the most of samples with the bond length longer than the effective bond length.

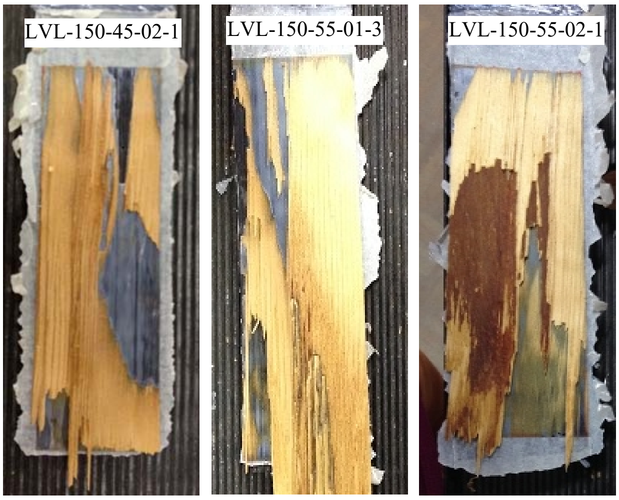

Figure 2, *The main failure mode, timber attached to the FRP*

Figure 3 shows bond slip behaviour of specimens made from LVL and hardwood with identical bond geometry. During the first stage, increase in the load is accompanied with a slight increase in the global slip. In this stage the load-slip curves show almost linear behaviour. With a continuous increase in the applied load, the response becomes nonlinear up to ultimate load and the load approximately fluctuates near a constant load. This trend denotes that the debonding occurred in the interface. At this point, the ultimate load that can be carried by the FRP plate is attained and simultaneously, the effective bond zone shifts away from the loaded end FRP. Therefore, the ultimate load (P_u) remains almost constant and the joint failed in a ductile manner; failing gradually. As can be seen in Figure 3, the bond slip in specimen fabricated from LVL is higher than that of sample made from hardwood for identical loads. Such observations can be attributed to the difference in stiffness of the interface. The elastic modulus of hardwood was approximately 1.22 times higher than that of LVL (Table 2) that leads higher stiffener in the bond. Therefore, the higher elastic modulus, the lower slip can be expected being occurred. A larger slip is evident from the relatively constant load level (9.5kN, refer to Figure 3) in the specimen made from LVL. Unlike samples made from LVL, in specimens made from hardwood, whilst the ultimate load is being reached there is not a distinct load-slip plateau. The joints then failed suddenly in a brittle manner without prior indication warning that collapse is imminent.

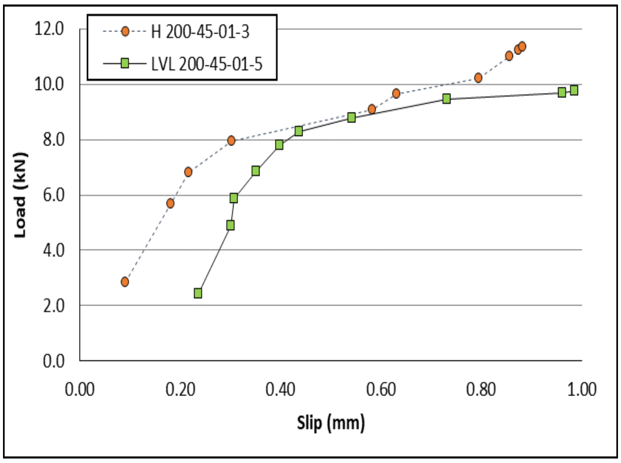

Figure 3*, Relationship between local bond slip and timber type*

The tensile and compressive strength of the hardwood timber used in the present study are approximately similar; while LVL samples are stronger in compression. The mean tensile strengths of LVL and hardwood samples were 44.3 MPa and 67.5 MPa, respectively, while their mean compressive strengths were 56.3 MPa and 64.9 MPa, respectively. A higher ultimate load was recorded for specimens made from hardwood compared to specimens made from LVL as shown in Figure 4. It is noted that all bond characteristics in samples shown in Figure 4 are identical, except for the timber type. As can be seen, specimens made from hardwood exhibited approximately 6.5% to 8.5% higher load compared with the same samples made from LVL. Consequently, higher tensile strength of timber improves the bond strength. This finding is in agreement with observations made by Crews and Smith [9] in which the bond behaviour may be controlled by the properties of timber rather than that of the adhesive.

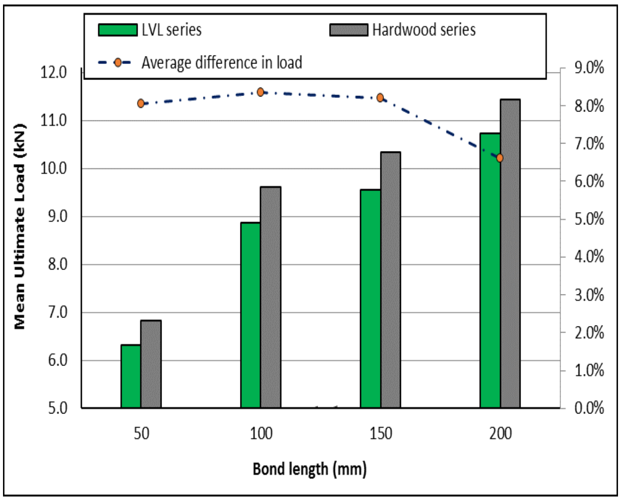

Figure 4*, Relationship between ultimate applied load and timber type*

Figure 5 shows the strain distribution profiles along bonded length at various load level associated with samples considered in Figure 3. As can be seen, there is a bilinear tendency in the strain distribution with a transition point occurring at the limit of the initial transfer area. The bilinear trend in strain distribution is different from the theoretical relationship between the FRP sheet strain and the distance from the loaded end since it is expected to be uniform for completely homogeneous material. This phenomenon may be due to material heterogeneity or stress concentration in the FRP plate and timber at a meso-scale [5, 15]. In addition, the maximum strain in specimen made from LVL was higher than the maximum strain in the joints made from Hardwood; even though joint with LVL substrate failed at 9.69kN and specimen made from Hardwood reached an ultimate load of 11.39kN. This difference has been observed in majority of samples. This observation can be related to the tensile strength of substrate; in which due to lower tensile strength of LVL more ductile tendency with higher strain can be expected being occurred in the interface resulting a higher shear stress in the bond at failure.

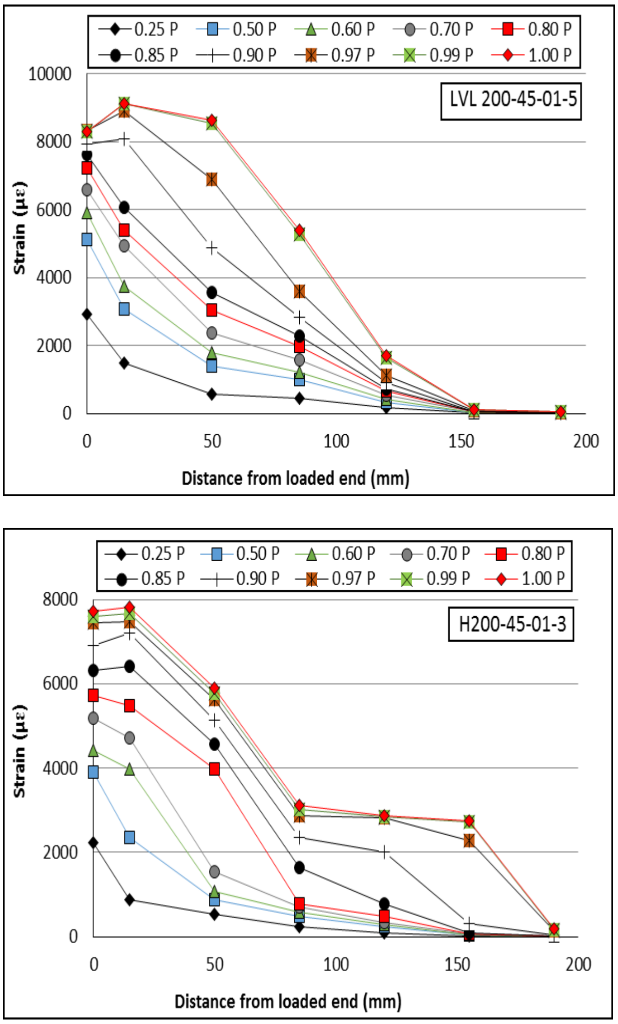

***Figure 5**, Relationship between CFRP strain, distance from the loaded end and timber type*

The average shear stress between two consecutive gauge positions and thus the shear stress distribution can be determined as follows [16]:

$$\tau_{i-j} = \frac{t_f \times E_f \times (\varepsilon_i - \varepsilon_j)}{\Delta l_{i-j}} \qquad (1)$$

In Eq. (1), (ε_i) and (ε_j) are two strain gauges at positions i and j, and Δl_{i-j} is the distance between these two gauges. E_f and t_f are elastic modulus and thickness of the laminate, respectively. Figure 6 illustrates the evaluation of shear stress in different part of the bond as a function of the relative load associated with Figure 3 and Figure 5. The shear stress in the region near the bearing end reaches a peak (P_{max}) and then begins to decrease abruptly, while simultaneously the shear stress in the adjacent region is beginning to increase. It is important to note that the decrease of the shear stress signifies failure in one region, while ascending shear stress in the adjacent region indicates that the load is being transferred there and accordingly the effective bond zone is being shifted inward along the bond length and away from the loaded end of the FRP. This phenomenon was constantly observed such that the region of high stress transferred from one area to the adjacent area until total bond failure occurred. Whilst higher ultimate load was achieved for specimens made from Hardwood, Figure 6 shows that shear stress in the specimen made from LVL is higher than that of samples made from Hardwood. This observation can be attributed to the stiffness of the bond and dissimilar interfacial material properties, since the joint made from LVL has lower modulus of elasticity which results lower stiffness of the interface. Therefore, it can be found that a higher shear stress can be achieved in the bond at failure.

Furthermore, in the previous study conducted by the authors [7] it was concluded that timber tensile strength directly impacts on the effective bond length in which the effective bond length increased when this parameter is increased. In addition, since the effective bond length has a major influence on the bond strength, it can be emphasis that timber tensile strength has a major contribution in the bond strength, bond behaviour and failure model of FRP bonded to timber. Therefore, timber mechanical properties must be considered for determining the bond strength when FRP is bonded to timber.

The most critical parameters affecting bond strength has been considered in previous study [6]; in which the ultimate bond strength has been mostly related to bond width, bond stiffness, timber strength and the bond length. Considering above factors, a novel theoretical model has been developed through stepwise regression (SR) analysis. Statistical Analysis Software (SAS®) was used for the stepwise regression analysis. More information about stepwise regression analysis can be found in [7]. A simple analytical formula but with a superior accuracy has been derived covering those critical variables that influence on the bond strength as follows:

$$P_u = \gamma_t \cdot \sqrt{L_e . f_{ut} . E_f t_f . \left(\frac{b_f}{b_t}\right)^3} \tag{2}$$

The units for the above equation are: Megapascals, Newtons, and millimetres, where, b_f, E_f and t_f are the FRP width, elastic modulus and thickness of FRP sheet, respectively. f_{ut} and b_t refer to the ultimate tensile strength and width of the timber prism, respectively. L_e is the effective bond length. The latter parameter γ_t is related to the timber types, in which γ_t is equal to 0.1 and 0.08 for LVL and hardwood, respectively. Figure 7 shows the evaluation of the stepwise regression model of FRP-to-timber bonded interface against experimental results. The coefficient of determination (R^2) of the stepwise regression analysis signifies that the SR model is an accurate predictor for determining the bond strength of FRP bonded to timber.

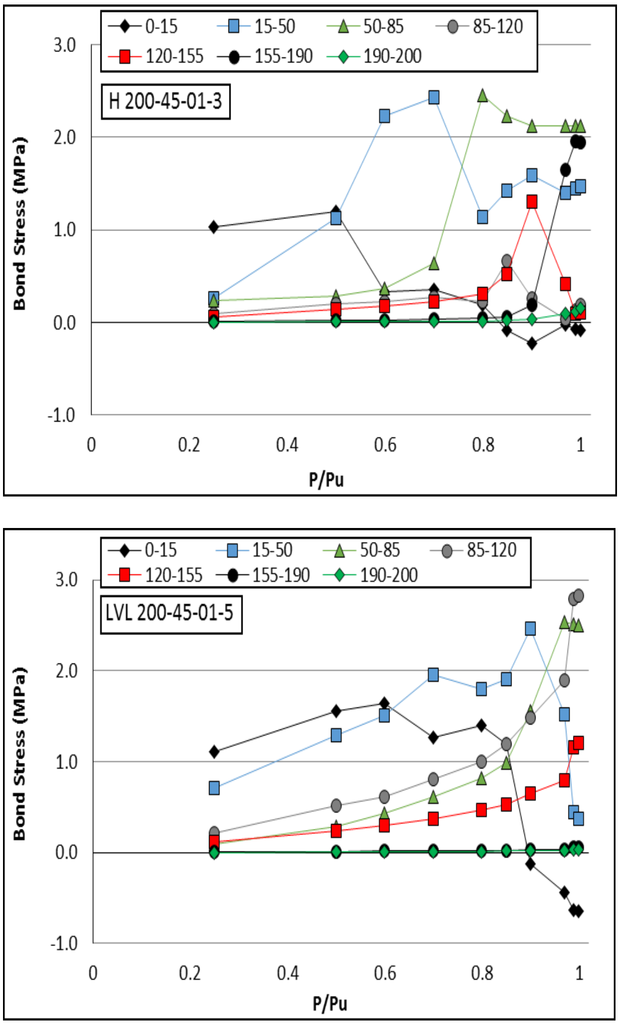

Figure 6 *Shear stress as function of relative load level for selected specimens.*

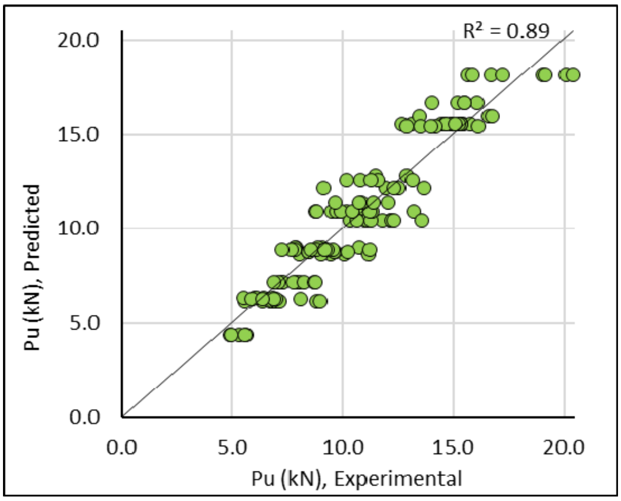

Figure 7, *Comparison of predicted bond strength against experimental results*

CONCLUSION

In this paper, the influence of timber tensile strength and modulus of elasticity on the bond strength, local slip and bond stress have been investigated when FRP sheets are externally bonded to timber. It was observed that with increase of timber tensile strength and modulus of elasticity, the interfacial bond strength increases whilst the interfacial slip decreases during the softening-debonded stage. Furthermore, samples made from hardwood failed suddenly in a brittle manner; whilst joints made LVL exhibited more ductile behaviour failing gradually. The ductile behaviour of the joints was more distinguished where the bond length was longer than the effective bond length. In addition, it was observed that shear stress in the samples fabricated from LVL was higher than that of specimens made from hardwood.

An analytical model with a higher accuracy for FRP-to-timber joints has been presented to predict the bond strength of FRP-to-timber joint covering all parameters affecting the interface. The proposed model is a function of bond stiffness, timber tensile strength, FRP to timber width ratio and bond length. A good correlation was obtained between the proposed model results and experimental results.

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