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Analysis of externally bonded Carbon Fibre Reinforced Polymers sheet to timber interface

Abbas Vahedian*, Rijun Shrestha, Keith Crews

School of Civil and Environmental Engineering, University of Technology, Sydney, Australia

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ABSTRACT

The performance of FRP composite bonded externally to timber is complex and to date, limited attempts have been made to investigate the bond behaviour of 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. The objective of the present study is to develop a functional and efficient analytical model to accurately predict the behaviour of FRP-to-timber joints. This research study has been performed using 136 FRP-to-timber joints subjected to pull-out tests, and accordingly a new predictive model for determination of the strain distribution profile, slip profile and shear stress along the interface has been established. A comparative analysis of the results of the experimental pull-out tests results and those predicted from the analytical model indicates a satisfactory correlation is achieved between measured and predicted parameters. The assessment results show that the proposed strain model is rather conservative at 80% of the ultimate load, while slightly underestimates strain distribution profile at ultimate load. High correlation was obtained for the proposed shear stress and bond-slip models against the experimental at ultimate load. Finally, significant improvement in prediction has been achieved when results of the proposed analytical models compared with the existing models from the literature, signifying the capability of the new models.

1. Introduction

Recent studies and applications have demonstrated that Fibre Reinforced Polymer (FRP) has become a mainstream technology for the strengthening of ageing and deteriorated structures [1]. FRPs are light, highly resistant to corrosion, cost effective and have superior strength and stiffness properties and its specific strengths remain high at elevated temperatures [2,3]. In particular, FRP composites work well in tension and shear, and therefore it can lead to increase load carrying capacity of structures when used as tensile or shear strengthening. With such strengthening, structures are capable of supporting loads at greater deformations, which is of enormous importance from a structural safety point of view [3–6].

In the retrofitted timber structures, the stress transforms from timber to the FRP composite through the bond generating tensile stresses in FRP. Therefore, bond between the timber and the FRP has a vital role that controls the efficacy of the repair and the selection of the adhesive for bonding of FRP to timber is critical. The adhesive must be capable of bonding with both the FRP and timber and should have adequate strength. Nevertheless, the bond mechanism between timber and FRP is a complex phenomenon and directly impacts on the overall performance of the FRP repair system. Therefore, investigating and predicting the bond behaviour and its effect is vital for the efficient application of FRP bonding technology. Over the last two decades, a number of studies have been carried out experimentally [7–9] and theoretically [10,11] to address the behaviour of FRP bonded to concrete substrates. However, different failure modes when FRP is externally bonded to timber have not been fully investigated and limited attempts have been made to investigate the bond behaviour of FRP to timber beams [12].

In order to obtain the FRP strain distribution, shear stress distribution and bond-slip responses, Silva et al. [13] performed four-point bending test on FRP-to-timber joints through near-surface mounted and externally bonded reinforcement technic. Juvandes and Barbos [14] performed a series of pull-tests and proposed the effective bonding length which was mainly on the basis of the model proposed by [15]. Crews and Smith [16] reported that timber failure has been the main failure mode that occurred in their tests, indicating that the bond behaviour may be controlled by the properties of timber rather than that of the adhesive. Wan [17] has conducted a more extensive study on FRP-to-timber interface in which results of 86 single shear tests are reported. The main focus in Wan's [17] study was on bond length and

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* Corresponding author at: School of Civil and Environmental Engineering, The University of Technology, Sydney (UTS), Sydney 2007, NSW, Australia.
E-mail addresses: abbas.vahedian@student.uts.edu.au (A. Vahedian), Rijun.Shrestha-1@uts.edu.au (R. Shrestha), Keith.Crews@uts.edu.au (K. Crews).

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types of adhesives, and limited variations in parameters such as bond width, FRP-to-timber width ratio, bond stiffness, FRP thickness, compressive strength of timber. Wan [17] concluded that the adhesives used had not been noticeably influenced the ductility of the bonded joints. This finding is in agreement with observations made by Crews and Smith [16].

Wan [17] developed an exponential bond strength model for FRP-to-timber bonds in which the compressive strength of timber was not considered since it was believed that the compressive strengths of softwood, hardwood and glulam used in the study were not significantly different from one another. In addition, Wan [17] calculated the effective bond length using Chen and Teng's [15] model. It is important to note that Chen and Teng's' [15] model was derived based on results of FRP-to-concrete interface. There are some fundamental differences between the failure mechanism in timber and concrete when bonded with FRP. Concrete is weak in tension; whilst timber is often stronger in tension. Debonding initiates when the tensile stress at the interface exceeds the bond strength. Therefore, the models which work for an FRP-to-concrete bond may not work for a FRP-to-timber bond. As a result, the bond-slip model proposed by Wan [17] did not correlate particularly well with the experimental results.

In addition to the experimental investigations, finite element simulation on bond behaviour between FRP and timber has been developed in recent years. Valipour and Crews [18] proposed a novel force-based element for nonlinear analysis of timber beams strengthened with FRP sheet (bar), including bond–slip effects. The formulation takes into account material nonlinearities and preserves the continuity of slip shear (force), without using a predefined force or displacement shape function.

In summary, the research on the bond behaviour of FRP-to-timber is still in its infancy. Further investigations need to be carried out to determine the influence of the various parameters such as FRP width, bond length, thicknesses of FRP sheets, timber material properties and geometries etc. affecting the bond between FRP and timber. Moreover, a new bond strength model of the bond between FRP and timber is essential to be able to accurately predict the ultimate load capacity of timber members repaired/strengthened with FRP.

This paper proposes an efficient and functional analytical interface model to accurately predict the serviceability and ultimate behaviour of FRP-to-timber joints. This study presents results of 136 carbon FRP-to-timber joint with different bond width, bond length and cross-sectional area size. Moreover, two different types of timber, namely Laminated Veneer Lumber (LVL) and hardwood, are utilised. Results of the proposed analytical models for strain profile, shear stress and slip profiles are then assessed with results of pull-out tests and satisfactory comparisons are achieved. Finally, results of the proposed models have been assessed by undertaking a comparative analysis with existing models from the literature.

2. Experimental outline

This study is based on laboratory testing of 136 modified single shear CFRP-to-timber bonded interface, as summarised in Table 1. Two different types of timber, namely Laminated Veneer Lumber (LVL) and hardwood, have been used. The LVL samples were either 320 or 370 mm long with a 110 mm × 65 mm cross section, whilst the overall dimension of hardwood samples were 320 mm long × 110 mm wide × 35 mm deep. To promote and maximise the adhesion capacity of the bond, timber surface was prepared prior to bonding with 300 and 400 grit sandpaper. Surface preparation was performed to remove all contaminants and weak surface layers that can interfere with adhesion, and to develop a surface roughness. The timber surface was then wiped clean with acetone and air blasting following the recommendation of [19]. The surface of FRP sheets was also prepared as per ASTM-D2093-03 [20] and BSI [21] to remove all impurities and potential contaminants such as mould release agents, lubricants, or fingerprints as a result of the production process. One and two plies of unidirectional wet-lay up of carbon FRP (CFRP) with nominal thickness of 0.117 mm (obtained from the product data sheet specified by manufacturer) were externally bonded with an epoxy base to the timber. Structural adhesive – a two-part, solvent free, thixotropic epoxy based impregnating resin/adhesive – has been used for bonding FRP sheets to timber. An aluminium roller was used to remove trapped air, impregnate the fibres, and brush out the excessive epoxy from the specimen. All specimens were stored in the lab for at least 10 days for epoxy curing in the laboratory environment with 20 °C to 22 °C temperature. Strain gauges were attached to the surface of FRP to measure the strain variation of the bond during the experiment. Strain gauges 5 mm in length with 120.3 ± 0.5 Ω resistance were bonded to the CFRP surface for each sample. One strain gauge was placed at the unbonded zone of the FRP sheet, and other strain gauges were distributed on the centre-line of FRP along the bond length as shown in Fig. 1.

Table 1
Detail of the tested specimens.

Timber type	Identification of specimen	FRP Thickness (mm)	Bond Length (mm)	Bond Width (mm)	Number of specimens
Laminated Veneer Lumber	LVL[1] 50[2]-35[3]-01[4]	1 × 0.117	50	35	5
	LVL 100-35-01		100	35	5
	LVL 150-35-01		150	35	5
	LVL 200-35-01		200	35	5
	LVL 50-35-02	2 × 0.117	50	35	5
	LVL 100-35-02		100	35	5
	LVL 150-35-02		150	35	5
	LVL 200-35-02		200	35	5
	LVL 50-45-01	1 × 0.117	50	45	5
	LVL 100-45-01		100	45	5
	LVL 150-45-01		150	45	5
	LVL 200-45-01		200	45	5
	LVL 150-45-02	2 × 0.117	150	45	5
Hardwood	H 50-45-01	1 × 0.117	50	45	5
	H 100-45-01		100	45	5
	H 150-45-01		150	45	5
	H 200-45-01		200	45	5
	H 50-45-02	2 × 0.117	50	45	5
	H 100-45-02		100	45	5
	H 150-45-02		150	45	5
	H 200-45-02		200	45	5
Laminated Veneer Lumber	LVL 50-55-01	1 × 0.117	50	55	5
	LVL 100-55-01		100	55	5
	LVL 150-55-01		150	55	5
	LVL 200-55-01		200	55	5
	LVL 250-55-01		250	55	3
	LVL 150-55-02	2 × 0.117	150	55	5
	LVL 250-55-02	2 × 0.117	250	55	3

[1] Timber type;
[2] Bond length;
[3] Bond width; and
[4] Number CFRP plies.

The bond-slip responses reported in the literature vary from one experiment to the other and a proper bond–slip model has yet to be generally accepted due to various influential parameters and a wide range of values from the experimental results. One of the main reasons for scattered results reported in the literature may be attributed to the test setup, due to unexpected out of plane movements since the interface is subjected to both shear and flexural stresses simultaneously. Furthermore, the timber block may not be cut perfectly and may not be tightly fitted and held in the frame. Therefore, any out of plane movement of timber block can be expected. Thus, to monitor accurately bond behaviour and bond-slip relationships, a modified single shear test setup including: a thick steel basement fixed to strong floor through four prestressed high strength bolts, an angle connected to the steel basement through two lines of steel bolts, as shown in Fig. 2. The timber