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Experimental Investigation on the Effect of Bond Thickness on the Interface Behaviour of Fibre Reinforced Polymer Sheet Bonded to Timber

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Abstract**—**The bond mechanism between timber and fibre reinforced polymer (FRP) is relatively complex and is influenced by a number of variables including bond thickness, bond width, bond length, material properties, and geometries. This study investigates the influence of bond thickness on the behaviour of interface, failure mode, and bond strength of externally bonded FRP-to-timber interface. In the present study, 106 single shear joint specimens have been investigated. Experiment results showed that higher layers of FRP increase the ultimate load carrying capacity of interface; conversely, such increase led to decrease the slip of interface. Moreover, samples with more layers of FRPs may fail in a brittle manner without noticeable warning that collapse is imminent.

Keywords**—**FRP, single shear test, bond thickness, bond strength.

I. INTRODUCTION

IN the last two decades, FRP composite materials have 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]. These composites have lately become a mainstream technology for strengthening of infrastructures such as steel, concrete, masonry structures and more recently, in structural timber and glass beams [3], [4]. FRP is a powerful and viable alternative to steel when considered as a retrofitting material for timber structures. As a composite strengthening material, externally bonded FRP has valuable advantages and in some cases, is the only reasonable and applicable material that can be used for retrofitting, particularly in places where it is impossible to gain access for heavy machinery.

A number of studies have been carried out experimentally [5]-[8] and theoretically [9], [10] to address the behaviour of FRP bonded to concrete and steel substrates. However, performance of FRP composite bonded externally to timber has not been fully investigated and to date, limited attempts have been made to investigate the behaviour of FRP-to-timber joints. The research on the bond behaviour of FRP-to-timber is still in its infancy. Further investigations need to be carried out to investigate the behaviour of FRP and timber. 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 interfaces needs to be developed and consequently, further understanding of the bond is essential.

Many factors impact on bond strength and failure mode of FRP bonded to timber. The most significant independent variables affecting bond strength and bond behaviour of FRP-to-timber joints are bond length, bond width, bond thickness, timber modulus of elasticity and tensile strength, FRP-to-timber width ratio, bond stiffness and geometries of the interface. The bond length, bond width, timber mechanical properties and their influence on the bond strength have been already considered by the authors [11]-[13]. This study focuses on the influence of bond thickness and bond stiffness on the bond strength, bond stress, and local slip for externally bonded interface. Results of experimental tests revealed that bond thickness has a major impact on the behaviour of interface. It was found that higher layers of FRP increase the ultimate load carrying capacity of adhesively bonded FRP sheets to timber. This outcome also signifies that the thicker interface exhibits higher ultimate shear stress during applied load although the thicker may fail suddenly in a brittle manner. Therefore, when strength criteria govern the design for the strengthening of timber structures, increase in FRP layers leads to higher load carrying capacity. Higher thickness, however, also leads to more brittle failure.

II. DETAILS OF RESEARCH PROJECT

Hundred six single shear joint specimens were fabricated and tested and the effect of bond thickness on the interface behaviour is discussed herein. One and two plies of unidirectional wet-lay up of carbon FRP (MBRACE^{TM}) with the nominal thickness of 0.117 mm were externally bonded with an epoxy base (Sikadur$^{®}$330) to the timber. Two different types of timber were used, namely Laminated Veneer Lumber (LVL) (using softwood species) and hardwood sawn timber. The LVL samples consisted of 320 and 370 mm long with a 110 mm x 65 mm cross section, and the overall dimension of hardwood samples were 320 mm long x 110 mm wide x 35 mm deep. The hardwood samples contained bond width of 45 mm and bond lengths of 50 mm, 100 mm, 150 mm and 200 mm. However, in the LVL series, three different bond widths

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with five different bond lengths (50 mm, 100 mm, 150 mm, 200 mm and 250 mm) have been fabricated and tested. Strain gauges were attached to the FRP surface to measure the strain variation of the bond during the experiment. The specimens used for this series are listed in Table I.

Compressive and tensile tests for timber and tensile tests for FRP coupons were conducted as per the respective standards [14], [15] to establish the measure mechanical properties of the timber and FRP. The average tensile strength and modulus of elasticity of LVL were determined to be 44 MPa and 16 GPa, respectively, whereas such mechanical properties for hardwood were 67 MPa and 20 GPa. From the tensile tests on FRP, the values of mean tensile strength and modulus of elasticity were determined to be 2497 MPa and 229 GPa, respectively. A modified single shear test setup was adopted (as shown in Fig. 1) to accurately monitor bond behaviour of FRP-timber joint. 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 FRP was measured by one LVDT which was mounted on the surface of timber block. The pull-out tests have been performed using a universal testing machine. More details of the samples tests can be found in the previous studies conducted by the authors [11], [16].

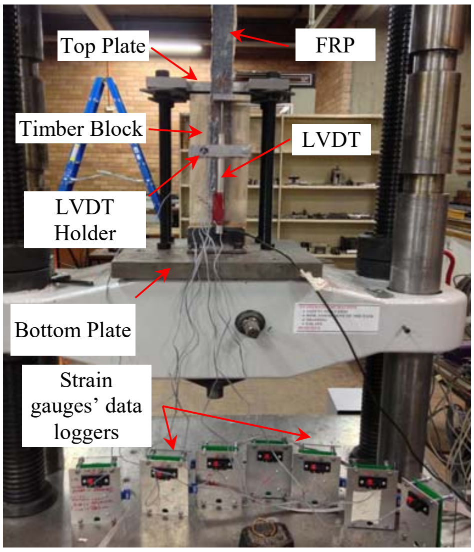

Fig. 1 Modified single shear test setup

III. BEHAVIOUR AND FAILURE MODES

Almost all of the specimens exhibited timber splitting, and failure at timber-adhesive interface. The joints made from LVL either with one or two layers of FRP failed in more ductile behaviour, especially for higher FRP-to-timber width ratio. However, unstable and brittle failure is observed for hardwood specimens. The brittle failure of joints was more eminent when two layers of FRP were bonded to the hardwood. This observation was mainly due to higher tensile strength of substrate as well as higher stiffness of interface while the area of interface remained unchanged, therefore the local bond ductility decreases. FRP and adhesive delamination rarely observed in the sample made from hardwood; however, LVL specimens exhibited mixture of different failure modes and partial FRP rupture was also observed in the LVL series. It is important to note that when FRP delamination was observed, a very small amount of fibre was peeled off from the laminate or a thin layer of the FRP resin matrix was transferred from the adherent and remained on the adhesive. Increasing bond thickness of interface will change failure mode of the joint from ductile to more brittle manner. The last column of I summarises failure modes of specimens investigated in this series.

IV. LOAD-SLIP RESPONSE, STRAIN AND STRESS DISTRIBUTIONS

Fig. 2 shows the load versus slip at the loaded end for selected samples. It was observed that the load-slip has a similar pattern when one and two layers of FRP were bonded either to LVL or hardwood and the load-slip relationship was reasonably linear prior to the initiation of debonding. However, the ultimate load was approximately 1.5 times for the samples with two layers of FRP compared to samples with one layer of FRP. In addition, with the increase of bond thickness, the global slip corresponding to the ultimate load stages decreased. Such finding distinctly indicates that the greater number of FRP plies, the load carrying capacity increases and tendency of interface to fail in a brittle manner also increases. Thus, it can be concluded that when strength criteria are essential to be met for strengthening of timber structures, increase in the bond thickness may lead to higher load carrying capacity. For further investigation, the strain distribution profile and shear stress along interface are studied for when one and two layers of FRP were bonded to the timber.

Fig. 3 illustrates the strain distribution profiles along bonded length at various load levels for one and two plies FRP-to-timber joints. Comparison of specimens with identical bond geometries except bond thickness revealed that at the same level of applied load the strain in samples with two plies of FRP experienced lower strain. The main reason for this behaviour of interface can be explained based on strain distribution profile (Fig. 3), in which apparently the effective bonded zone for samples with thicker bond is higher, hence the stress distributed between adherents (FRP and timber) and adhesive over the longer interface toward the free end of the FRP. The maximum strain occurred at the loaded end, indicating that most of the applied load is carried by the FRP near the loaded end, whilst when the bond length was long enough, strain gauges close to the free end exhibited a small amount of strain even at the final stages of loading. It is clear that the effective bond length for specimens with more FRP layers is longer.

The average shear stress between two consecutive gauge positions, and thus, the shear stress distribution can be determined as follows [17]:

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

In (1), (ε_i) and (ε_j) are the 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. Further considering the effect of bond thickness on the shear stress distribution, Figs. 4 (a) and (b) illustrates that shear stress increased by increase in FRP layers. The average shear stress between two consecutive gauges shown in Figs. 4 (a) and (b) has been determined from (1). Proceeding in this way, interface shear stress is certainly higher for the specimens with two layers of FRP; however, it is not valid to express that shear stress in such specimens must be double of those samples made by one layer of FRP. The main reason for that can be attributed to distribution of the applied load and consequently shear stress, over a larger area of the interface. While the stiffness ($E_f.t_f$) of the interface doubled for the thicker application, it can be expected that a larger and deeper surface of the bond get involved in the interfacial stress transferring, and thus, the stress distributes more uniformly along the interface. Therefore, the interface fails at higher load level. Figs. 4 (c) and (d) shows the evaluation of shear stress distribution along the bonded length as a function of the relative load. The decrease of the shear stress signifies failure in one region, while ascending of shear stress in the adjacent region illustrates that the load is being transferred. It is clear that shear stress in different part of the joint is higher when specimens with two layers of FRP compared with those made from one ply of FRP. Besides, in the majority of specimens, it was observed that initial debonding occurred approximately at 60-65% of the ultimate applied load for both bond thicknesses. It is important to note that, the bond strength for specimens with one layer of FRP was relatively lower than those samples made with two layers of FRP. Therefore, a thin bond cannot sufficiently restrain the initiated debonding, since the main purpose in FRP strengthening system which is binding the emerged debonding on the substrate and preventing them from further growth during the initial stages of loading cannot be achieved.

V. BOND STRENGTH RELATIONSHIP

The relationship between bond strength and bond thickness obtained from the experiments is shown in Fig. 5. The bond strength of interface significantly increased by application of thicker bond line. It can be seen that specimens made from LVL and two layers of FRP exhibited higher bond strength (up to 50%) than that of samples where only one ply of FRP was bonded to the LVL. The bond strength increased by 18% when bond thickness increased by double for the joints made from hardwood with relatively shorter bond length. On the other hands, the ultimate load carrying capacity of interface increased between 40% to 42% when two layers of FRP with bond length equal or longer than effective bond length were bonded to the surface of hardwood.

TABLE I

RESULTS OF SELECTED BOND THICKNESS SERIES TESTS

Identification	Timber			FRP					Pu (kN)							
	L_t (mm)	b_t (mm)	d_t (mm)	type	t_f (mm)	L_f (mm)	B_f (mm)	b_f / b_t	Individual					Average	CoV (%)	Failure modes
50[4]-35[5]-01[6]-1~5[7]	320	110	65	LVL	0.117	50	35	0.32	5.33	4.92	5.62	5.57	4.93	5.27	6.41	TS-FT
150-35-01-1~5	320	110	65	LVL	0.117	150	35	0.32	7.86	7.27	8.03	7.32	7.78	7.66	4.44	TS-AD-FT-FR
200-35-01-1~5	320	110	65	LVL	0.117	200	35	0.32	8.25	7.12	8.70	8.75	6.90	7.94	11.08	TS-AD-FT-FR
150-35-02-1~5	320	110	65	LVL	0.234	150	35	0.32	12.15	10.99	11.80	11.14	11.29	11.47	4.22	TS-FT
200-35-02-1~5	320	110	65	LVL	0.234	200	35	0.32	13.57	10.34	12.21	12.32	10.66	11.82	11.19	TS-AD-FT-AD
150-45-01-1~5	320	110	65	LVL	0.117	150	45	0.41	9.48	9.83	10.15	8.77	13.18	10.28	16.51	TS-FT-FD-AD
150-45-02-1~5	320	110	65	LVL	0.234	150	45	0.41	16.61	13.44	16.75	11.46	12.89	14.23	16.51	TS-FT
150-55-01-1~5	320	110	65	LVL	0.117	150	55	0.50	14.48	14.90	15.42	13.08	12.66	14.11	8.40	TS-AD-FT-FR
150-55-02-1~5	320	110	65	LVL	0.234	150	55	0.50	16.72	15.65	15.85	17.22	19.04	16.90	8.04	TS-FT-FD-AD
250-55-01-1~3	370	110	65	LVL	0.117	250	55	0.50	15.32	15.22	15.11			15.21	0.70	TS-AD-FT-FR
250-55-02-1~3	370	110	65	LVL	0.234	250	55	0.50	19.16	20.10	20.40			19.88	3.27	TS-FT-FD
150-45-01-1~5	320	110	35	Hardwood	0.117	150	45	0.41	11.32	8.82	11.24	9.91	10.41	10.34	10.01	TS-FT-FD
200-45-01-1~5	320	110	35	Hardwood	0.117	200	45	0.41	9.63	10.87	11.39	12.03	10.76	10.94	8.13	TS-FT
150-45-02-1~5	320	110	35	Hardwood	0.234	150	45	0.41	14.22	13.53	16.13	13.97	12.89	14.15	8.60	TS-AD-FT
200-45-02-1~5	320	110	35	Hardwood	0.234	200	45	0.41	15.49	14.04	15.20	16.05	15.50	15.26	4.89	TS-FT-FD

Note: TS= Timber splitting; AD= Adhesive delamination; FD= FRP Delamination; FR= FRP Rupture; FT = Failure at timber-adhesive interface (very thin layer of timber attached

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[4] Bond length
[5] Bond width
[6] Number of FRP layer
[7] Number of specimen

The main reason for unstable enhancement of bond strength when thicker bond line was attached to hardwood can be expressed as: in high-strength timber specimens, when the bond length is not long enough, the applied load is not able to be efficiently distributed along the interface. Therefore, failure occurs at lower load level. However, substrate with lower tensile strength showed more efficient compatibility with adhesive and FRP in which constant increase was observed in the bond strength when bond thickness increased. It is important to state that the concept of optimum bond thickness needs to be considered in studying the interfacial behaviour of FRP-to-timber joints. That is because, with a thicker interface, the risk of flaw in the adhesive is higher which may lead to stress concentrations in the interface. In addition, adhesives are designed to cure in thin layer and application of thick layers can change physical properties of the epoxy when epoxy cured. From the chemical point of view, thicker bond can lead to more polymerisation shrinkage, and thus, internal stress.

Fig. 5 (c) illustrates the relationship between bond thickness and bond strength obtained from experimental tests, in which the bond length was constant, 150 mm, and bond width varied. When one and two layers of FRP were bonded to surface of LVL, it was observed that the higher improvement of the bond strength (50 %) was associated to joints with lower FRP-to-timber width ratio. The main reason can be defined as when FRP width is relatively shorter than width of timber, increase on bond thickness leads to further increase in the effective bond length which results enhancement of effective bonded area. The average effective bond lengths for one and two layers of FRP with 35 mm bond width were 126 mm and 137 mm, respectively. Therefore, more efficient use of interface can be expected to be achieved leading to further improvement of bond strength. However, when the bond length was 150 mm and FRP-to-timber width ratio was high, increasing thickness of FRP only improves the stiffness of interface and does not impact on the effective bonded zone, since the effective bond length was already reached even when one layer of FRP was used. Thus, the bond strength improved by around 20 %.

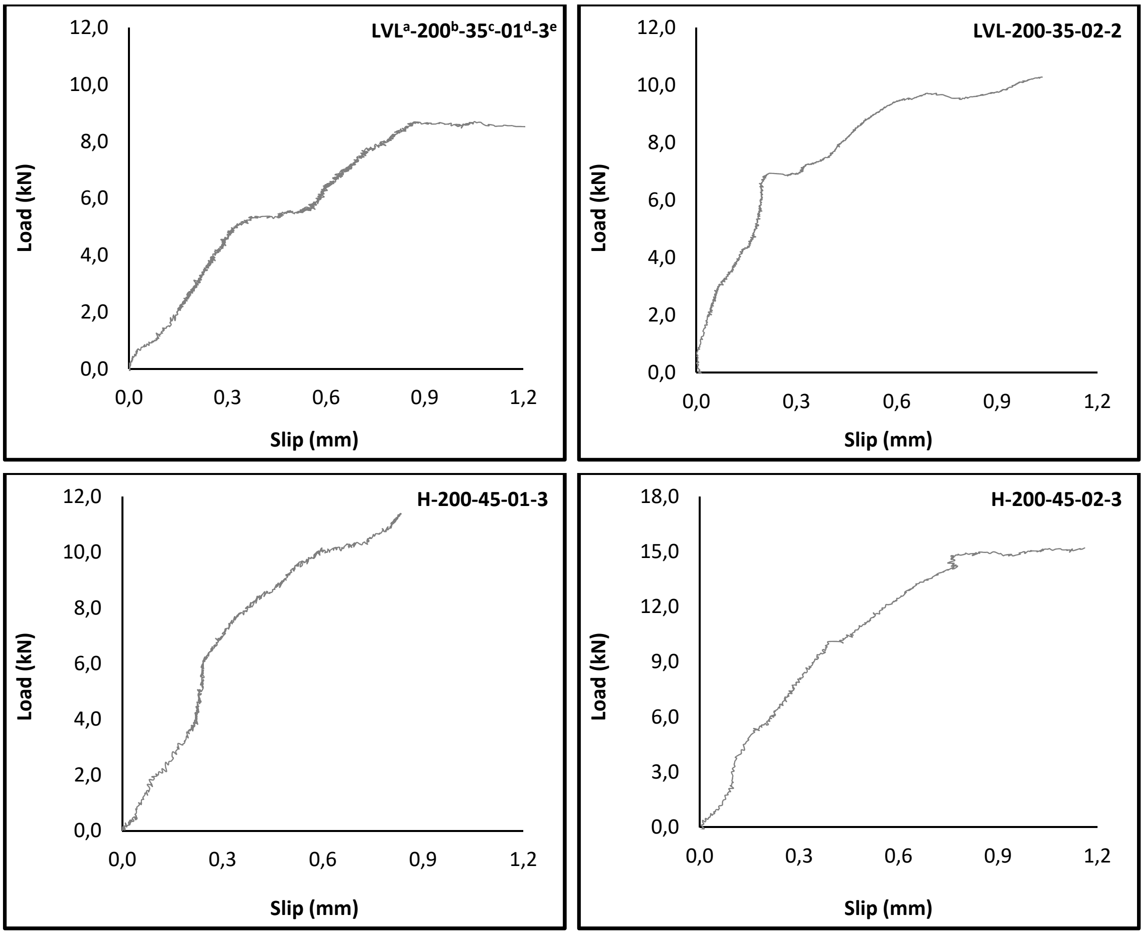


Fig. 2 Load-slip response related to bond thickness series

VI. Conclusion

The influence of bond thickness affecting bond strength and the interfacial behaviour of the adhesively bonded joints are investigated through several experiments. Experimental results showed that bond thickness has a major impact on the behaviour of interface. With the increase of bond thickness, the interfacial bond strength increased; conversely, such increase led to decrease the slip of interface. Lower slip of interface indicates that with a greater number of FRP plies, the joint tends to be more brittle while the load carrying capacity increased. The brittle failure was more noticeable in the joints made form hardwood. The maximum shear stress also increased by increase in FRP layers. Thus, it can be concluded that, when strength criteria govern the design for the strengthening of timber structures, increase in FRP layers leads to higher load carrying capacity. Higher thickness leads to more brittle failure, such that, thinner interface may be more appropriate when a ductile behaviour is expected from the FRP-strengthened system.

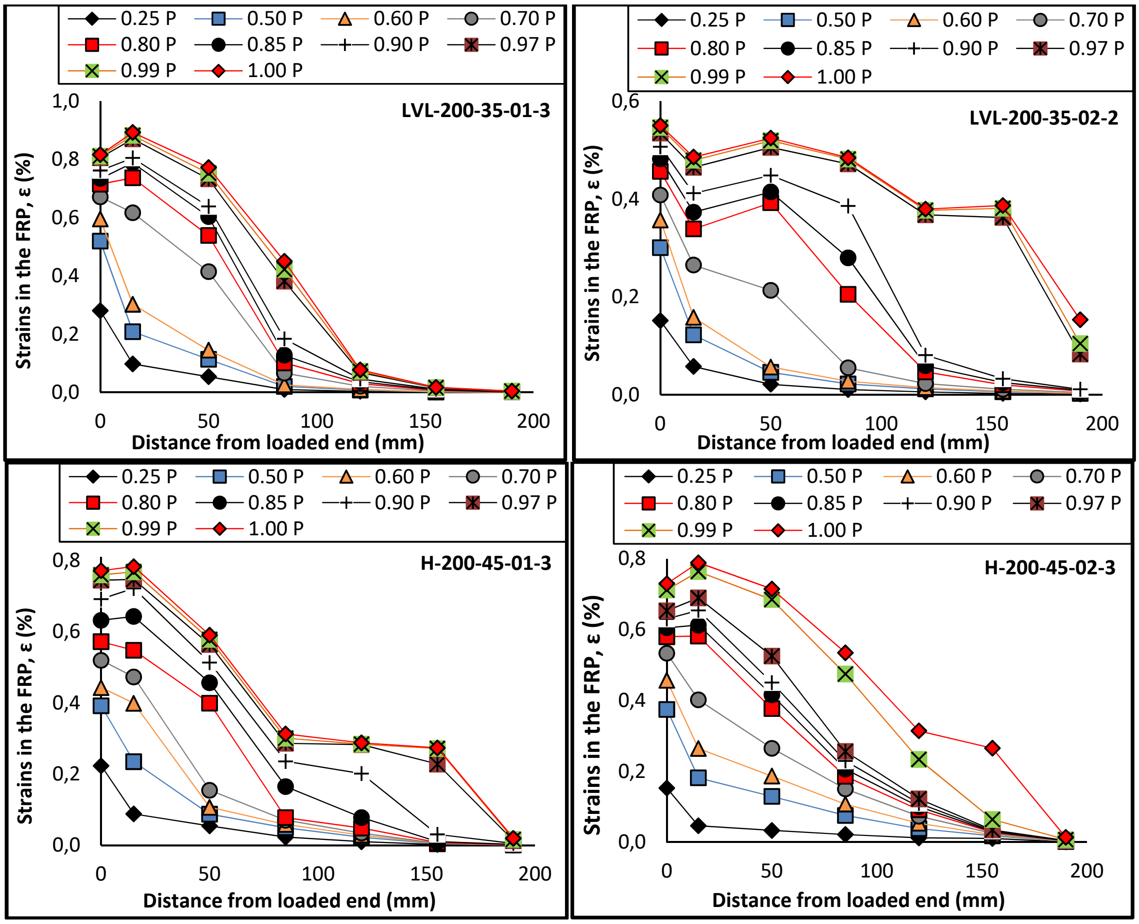
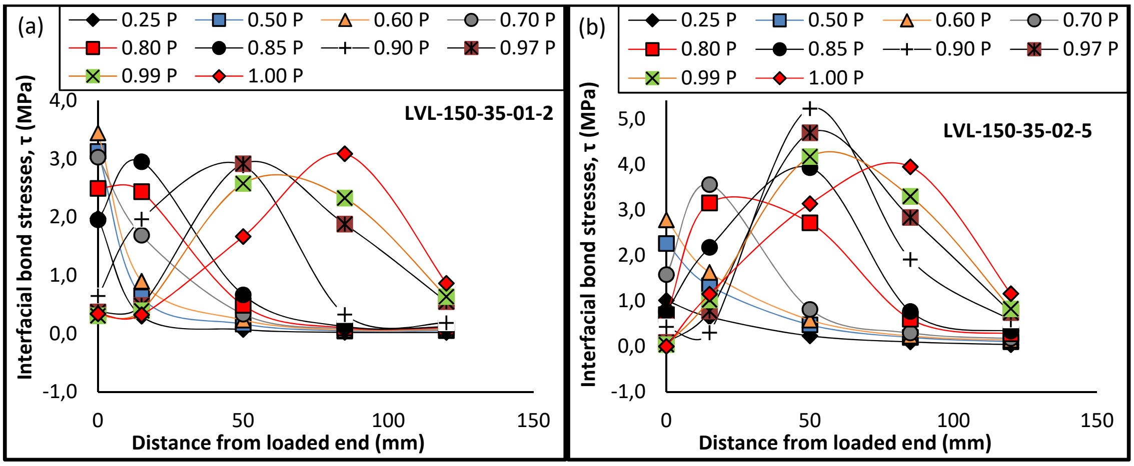


Fig. 3 Relationship between FRP strain and distance from the loaded end related to bond thickness series



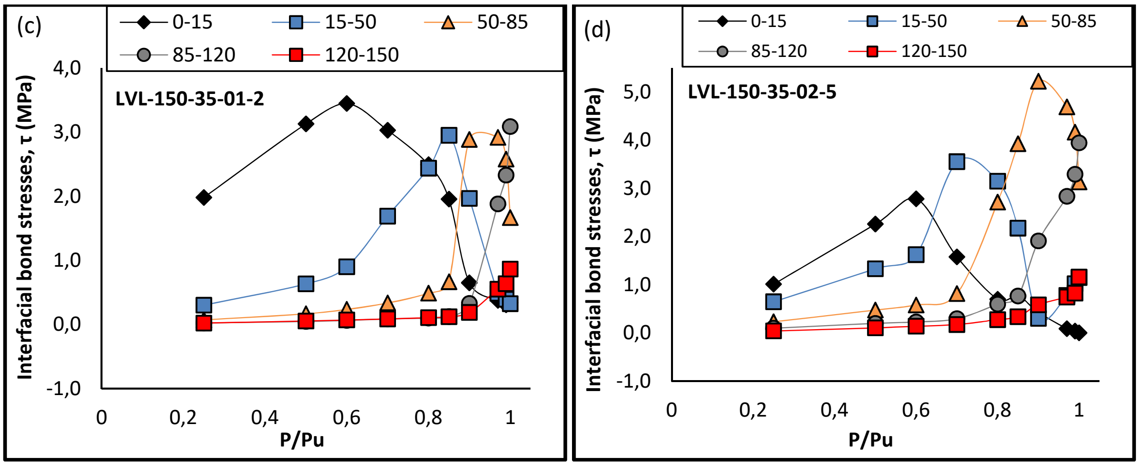


Fig. 4 Relationship between bond stress and bond thickness

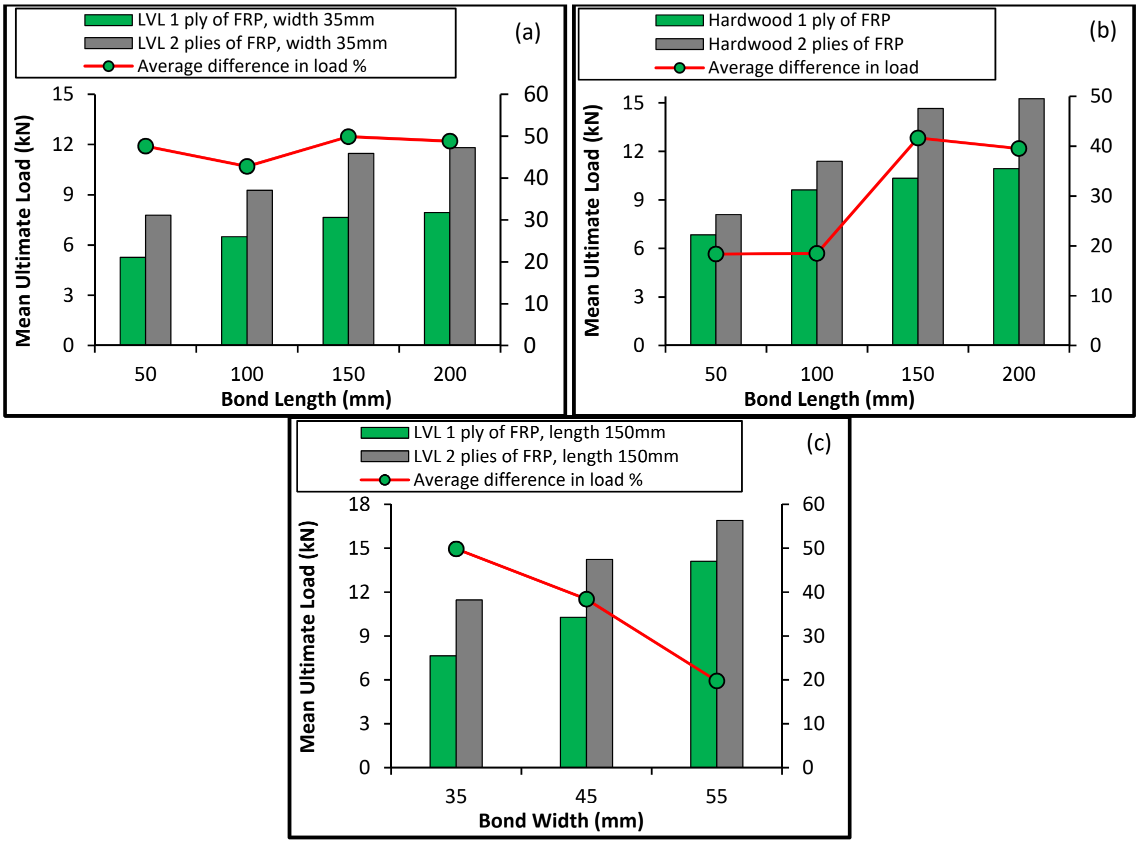


Fig. 5 Relationship between bond strength and bond thickness

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