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MODELLING THE BOND SLIP BEHAVIOUR OF FRP EXTERNALLY BONDED TO TIMBER

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ABSTRACT: Recent studies and applications have demonstrated that Fibre Reinforced Polymer (FRP) has become a mainstream technology for the strengthening and / or rehabilitation of ageing and deteriorated structures. However, one of the main problems which limit the full utilisation of the FRP material strength is the premature failure due to debonding. This research study presents 1) a review of available FRP-to-timber and FRP-to-concrete bonded interface models, and 2) investigates factors affecting bond strength. A stepwise regression method has then been employed to evaluate the influence of potential factors on the bond strength. The proposed stepwise regression model is based on 195 experimental results of FRP-to-timber bonded interfaces. Results of this stepwise regression analysis are then assessed with results of pull-out tests and satisfactory comparisons are achieved between measured failure loads (R^2=0.59) and the predicted loads (R^2=0.71, P<0.0001).

KEYWORDS: FRP, Bond-slip, Pull-out test, Debonding, Stepwise regression analysis

1 INTRODUCTION

A large number of bridges, highways and other civil infrastructure were built around the world during the last century. Many of these structures have reached the end of their design service life. Moreover, ageing, environmental action and increased service loads, have caused many structures to gradually deteriorate and resulting in significant reduction in load capacity and subsequent safety. Consequently, either entire structures or key components require strengthening, rehabilitation or replacement [1]. Disadvantages associated with traditional rehabilitation or retrofitting methods have led to development of new techniques using new composite materials such as advanced fibre reinforced polymers (FRPs) [1, 2]. External bonding of FRP composites has emerged as an innovative and widespread method for strengthening and retrofitting of infrastructure over the last three decades [3-5]. Although FRPs have a number of advantageous properties such as high Young's modulus, high fatigue performance, high stiffness and strength to weight ratios, superior resistance to corrosion and low weight [4-6], they still have some important limitations.

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 material strength of the FRP [7]. Debonding can be defined as the single most important failure mechanism of retrofitted beams [8, 9] that occurs at much lower FRP strains than its ultimate strain [10]. Debonding directly impacts the total integrity of structure, with the subsequent outcome that the ultimate capacity and desirable ductility of the structure may not achieved.

The bond mechanism between concrete or timber and FRP is complex and is affected by a number of variables. Failure of a fibre reinforced polymer timber/concrete beam can take place in several ways, including but not limited to substrate failure (timber or concrete separation), FRP delamination, FRP/adhesive separation, FRP rupture, cohesion failure (adhesive de-cohesion), adhesive failure, and substrate-to-adhesive interfacial failure. More than one of these modes may be observed, in an actual failure, as indicated in Figure 1. When debonding occurs, the bond stress is transferred over a limited active area, which leads to local shear stress concentrations. Stress concentration may also result from the discontinuity near the ends of FRP [6]. Among the mentioned failure modes, adhesive fails rarely occurs due to its strong characteristic behaviour [3]; however, debonding between adhesive and adherent is often the

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critical failure mode since it has a significant influence on the performance of strengthened structures [8, 9, 11].

Mostofinejad and Shameli [10] reported that several attempts have been made to improve the performance of FRP techniques to eliminate or postpone debonding failure of the FRP attached to concrete. Fracture mechanics-based models have been developed (both theoretically and experimentally) by many researchers to predict the initiation of debonding in retrofitted concrete elements and the peak load that the composite layers can resist before debonding [12, 13]. However, performance of FRP composite bonded externally to timber, considering debonding and failure modes, has not been fully investigated [14] and to date, limited attempts have been made to investigate the bond behaviour of FRP to timber beams. Despite the large number of studies on externally bonded elements, there is a significant knowledge gap about the parameters that influence interfacial behaviour of the bond, particularly the FRP-to-timber bond. Therefore, comprehensive understanding of the behaviour of externally bonded FRP-to-timber is essential.

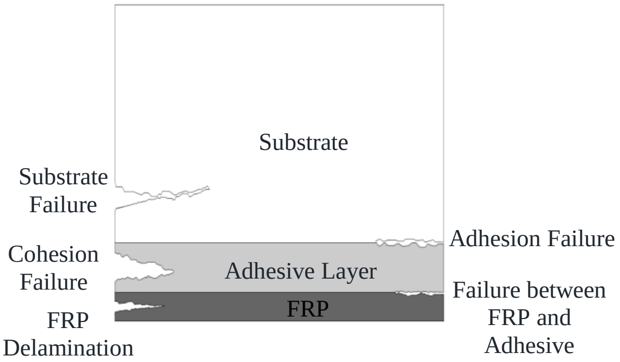

Figure 1 *Debonding modes in externally bonded elements*

This research study firstly, presents a review of available timber bonded interfaces model in the literature and secondly, investigates factors affecting bond strength. A database containing results of 195 experimental results of FRP-to-timber bonded interfaces has been built. A stepwise regression method has been employed to evaluate the influence of potential factors such as bond width, bond length, material properties and geometries on the bond strength. Finally, results of stepwise regression analysis have been assessed by undertaking a comparative analysis with experimental data collected from the literature.

2 TEST METHODS

In order to determine bond-slip relations of FRP-strengthened materials, failure mode, bond strength, force transfer and effective bond length, various bond testing methods have been carried out experimentally; including single shear tests [8, 9, 12, 15, 16], double shear tests [17-20], and modified beam tests as shown in Figure 2 [3, 9]. The test setup for single and double shear pull tests can be configured using two different approaches, such as near-end supported and far-end supported in which the near-end support introduces compressive stress to the bonded surface, whilst far-end support introduces tensile stress to the bonded surface [3, 14]. In the single lap shear test, FRP plates are attached to one side of the substrate and placed on the test rig. Then, the load can be gradually applied either to the plate end or substrate end, depending on the test setup as shown in Figure 2. In this method, FRP and substrate are subjected to uniformly distributed axial stresses [21], while the interface is predominantly subjected to the shear deformations. On the other hand, in the double shear lap test, FRP plates are symmetrically attached on both sides of the substrate. In this method, the loading system is identical to the single shear lap test; however, special consideration must be taken into account to minimise the possibility of the eccentricity of the acting forces in order to avoid error in the results [9, 19].

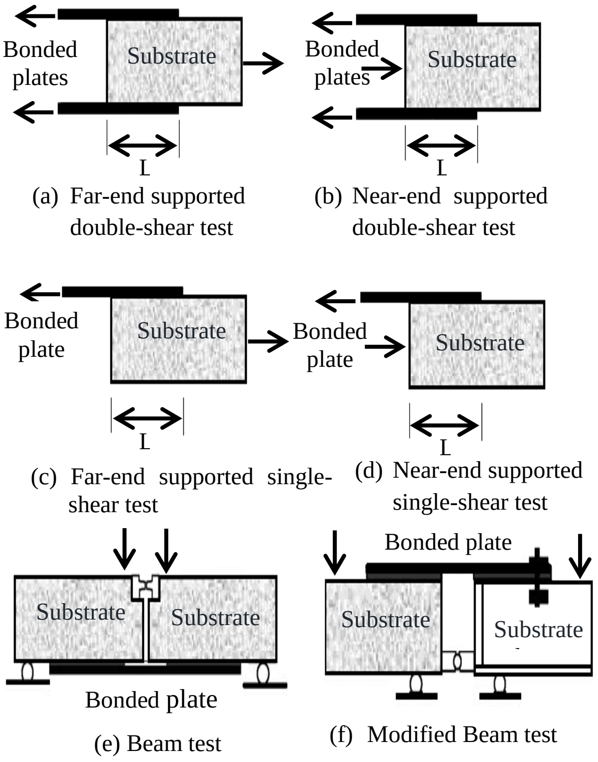

Figure 2 *Bond tests classification [3].*

In order to predict the behaviour of FRP retrofitted beams, results of the pull-out tests may not represent the actual debonding phenomenon; that is because the loading type, boundary conditions, and deflections are different in FRP retrofitted beams from those of the FRP-to-substrate joint under shear force in pull-out tests [22]. The interfacial stress transfer in FRP strengthened RC beams produces high accuracy using bending tests rather than shear tests, since the interface is under both shear and flexural stresses simultaneously; however, such tests require a complex test setup and higher investment [23]. In the beam tests, specimens may consist of two substrate blocks joined by a steel plate on the bottom side or a substrate beam with a notch in the middle as shown in Figure 2. In this method, the shear bond strength can be defined as an average stress along the bond length. Theoretical work has included both the development of empirical models based on simplistic assumptions and regression of experimental data, and fracture mechanics analysis [3].

3 FACTORS AFFECTING BOND STRENGTH

Many factors control the likely occurrence of a debonding failure mode for an FRP strengthened beam. Whilst environmental conditions, surface treatment and moisture content are reported in many publications as the key parameters [24, 25], these factors are outside the scope this study and differing moisture contents, durability and their impacts on the bond strength have not been considered in the preparation of this paper. It is also important to note that debonding mechanisms of FRP retrofitted timber beams may not be analogous to debonding mechanisms of retrofitted concrete beams. One reason is that timber generally behaves as a brittle material under tensile loading, and also its mechanical properties, mainly elastic modulus, are less than concrete. The debonding process may also be influenced by timber characteristics such as knots, grains and defects [14]. Furthermore, unlike timber, concrete is weak in tension. Debonding initiates when the tensile stress at the interface exceeds the bond strength. Therefore, debonding mechanism of retrofitted timber and concrete may not be similar.

Regardless of the effect of environmental conditions, 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 [26] 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. Yao, Teng [11] also stated that concrete failure most often take place in pull-out tests under shear, occurring mostly at a few millimetres from the adhesive layer. Therefore, it can be concluded that the substrate mechanical properties directly impact the bond strength.

Adhesive stiffness and adhesive strength are also amongst factors that impact strongly upon the bond strength. Vallée, Tannert [27] reported that stiffness of adhesive (E_A) as well as the level of plasticity significantly impact the stress–strain state inside bonded joints. A number of studies have been also carried out considering the behaviour of bond [8, 24, 25, 28, 29] and their results have shown that the bond strength is highly dependent to the geometry of the bond and also varies with the FRP width and thickness, and the specimen alignment [8, 11]. Furthermore, it has also been observed that boundary conditions [8] and FRP to substrate width ratio [3] significantly impact on the bond strength. With the increase of an FRP plate width, the interfacial bond strength increases and the ductility of the FRP-concrete interface reduces, leading to a decrease of the interfacial slip during the softening-debonded stage [6]. It has also been reported that when the width of FRP is smaller than that of the width of the substrate, the force transfer from the FRP to the substrate leads to a non-uniform stress distribution across the width of the substrate member resulting a higher shear stress in the adhesive at failure [3].

Bond length is also an important parameter that affects the bond strength; however, effective bond length (also referred to as transfer length or critical anchor length in some literature) must always be taken into consideration, since many experimental studies [8, 11, 28] and fracture mechanics analyses [30] have confirmed that there is no benefit in extending the bond length beyond that where there is no increase the bond strength. Bond strength is typically defined as the maximum load divided by the effective bonded area $(A_e = b_f \times L_e)$; where b_f is FRP width and L_e is effective bond length. From existing experimental and theoretical models, which have been mentioned earlier, the following parameters are accepted as the main factors that impact on the effective bond length (L_e): the interfacial stiffness (k_s); the reinforcing stiffness ($E_f.t_f$); interfacial fracture energy of the adhesive layer (G_f^b); shear-span ratio and span of the beam [7, 31]. In the following sections each of these parameters will be discussed in detail.

Wu and Hemdan [7] concluded that an adhesive with relatively high interfacial stiffness transfers stresses from concrete to FRP rapidly. They also reported that if the interfacial stiffness of the adhesive increases, the effective bonding length decreases; however, for values of interfacial stiffness higher than 160 MPa/mm, interfacial stiffness has no substantial impact on the effective bonding length. Therefore, using an adhesive with low interfacial stiffness increases the effective bonding length and consequently relieves the stress concentration in the FRP that will cause delay in the debonding failure [7, 31].

In addition, increasing in FRP reinforcing stiffness ($E_f.t_f$) will lead to increased effective bond length. The results of experimental investigations conducted by Hadigheh [9] agree that the effective bond length increases for samples with more layers of FRP; however, the joint tends to be more brittle whilst the load carrying capacity increases. To address this concern, Chen and Teng [3] recommended that using FRP plates with higher modulus of elasticity and smaller thickness, achieves high stress in externally bonded joints. Nakaba, Kanakubo [19] and De Lorenzis, Miller [32] also reported that the effective bond length and load carrying capacity of FRP bonded members increases as the FRP stiffness increases. In general, it is recommended that using softer adhesives [3] and higher FRP stiffness [3, 19] can increase the average bond strength.

4 INTERFACE MODELLING METHODS

A number of studies have been carried out experimentally [14, 16, 19] and theoretically [33, 34] to address the behaviour of FRP bonded to timber and concrete substrate due to critical importance of debonding failures in member performance. In addition, extensive models have been developed to predict the behaviour of the bond. However, due to the limited success and applicability of these proposed models, further research in this area is highly desirable from a structural design perspective, to develop models that can properly predict debonding failure loads as well as associated failure criteria for FRP strengthened members.

Lu, Teng [35] has reported that Chen and Teng [3] model (Eq. 1) is the most accurate model amongst the twelve existing FRP-to-concrete bond strength models in literatures. Chen and Teng [3] proposed a semi-empirical design model based on the combination of a fracture mechanics model (with rational simplifications) and regression models. This model was calibrated with a series of single shear and / or double shear pull out tests and is applicable to both externally bonded steel plate and FRP-to-concrete bonded joints. Although this model was initially developed to investigate debonding failure in the concrete, it can also be appropriately used on debonding failure at the adhesive concrete interface [11, 14]. In the proposed model by Chen and Teng [3], one of the main parameters is the width ratio of the bonded plate to the substrate. Chen and Teng [3] concluded that if concrete width (b_c) is greater than that of the bonded plate (b_p), stress distributes non-uniformly across the width of the concrete and consequently, may result in a higher shear stress in the adhesive at failure. By taking into account the above considerations, Chen and Teng [3] developed their model where the ultimate strength of joint, stress in the bonded plate at failure and the effective bond length can be calculated as given in Eqs. (1), (2), (3), respectively.

$$P_u = \alpha\beta_p\beta_L L_e b_p \sqrt{f'_c} \tag{1}$$

$$\sigma_p = \alpha\beta_p\beta_L \sqrt{\frac{E_p\sqrt{f'_c}}{t_p}} \tag{2}$$

$$L_e = \sqrt{\frac{E_p t_p}{\sqrt{f'_c}}} \tag{3}$$

$$\beta_L = 1 \quad \text{if} \quad L \geq L_e \tag{4}$$

$$\beta_L = \sin\frac{\pi L}{2L_e} \quad \text{if} \quad L < L_e$$

$$\beta_p = \sqrt{\frac{2 - b_p / b_c}{1 + b_p / b_c}} \tag{5}$$

Megapascal, Newton and millimetres are the units for the above equations, where P_u and σ_p are the ultimate strength and stress in the bonded plate at failure; L and L_e are the bond length and the effective bond length, respectively. t_p, E_p and b_p are thickness, elastic modulus and width of the bonded plate, respectively. b_c is concrete width and f'_c is the cylinder concrete compressive strength. β_L and βp are dimensionless parameters that are influenced by the bond length and bonded plate-to-concrete width ratio, respectively. A best fit value of α=0.427 was achieved by Chen and Teng [3].

As mentioned earlier, very limited studies have been conducted on FRP-to-timber bond; therefore, reference will be made to concrete although timber is the target substrate material in this study. It is notable to mention that due to numerous studies on FRP-to-concrete joint, from both theoretical and numerical point of views, the principles should largely be transferable to FRP-to-timber bonds [14].

Wan [14] developed a new bond strength model for FRP-to-timber bonds using a regression model and the performance of this model was compared to the experimental peak loads. The model of Wan [14] is given in Eq. (6) and the expression of the effective bond length is calculated using the model derived by Chen and Teng [3].

$$P_u = 0.012\gamma_t\gamma_e b_p L_f{}^{0.28}\sqrt{E_p t_p} \tag{6}$$

The parameter γ_t is related to hardwood and softwood sides, and γ_e is related to the adhesive types. L_f is equal to the bond length of joints when it is less than effective bond length (L_e) or equal to L_e when it is equal to or larger than L_e. *tp*, *Ep* and *bp* are thickness, elastic modulus and width of the bonded plate, respectively. Note that the expression for effective bond length proposed by Chen and Teng [3] has been used in the model proposed by Wan [14]. It is also important to note that the compressive strength of timber was not considered in Eq. (6) because Wan [14] believed that the compressive strengths of softwood, hardwood and glulam used in that research were not significantly different from one another. In this case, the importance of timber properties that have a major factor influencing the failure of the retrofitted beam reported by others [26] has been ignored.

5 STEPWISE REGRESSION ANALYSIS

5.1 STEPWISE REGRESSION METHOD; A BRIEF EXPLANATION

When dealing with a large group of potential independent variables, stepwise regression (SR) can be employed to determine the most significant variables in predicting the dependent variable [36]. Stepwise regression is a robust approach not only for selecting the best subset of independent variables that provides efficient prediction of the dependent variable, but also significantly reduces computing complexity than is required for all possible regressions [37]. The determination of the best subset models can be obtained either by trying out one independent variable into the regression model that produces the highest value of R-Squared if statistical significance of model is kept (Forward selection), or by including all potential independent variables in the regression model and removing those that are least significant (Backward selection). Stepwise regression is a combination of these two methods, selecting variable(s) that has the highest effect on the residual sum of squares; and conversely, removing the variable(s) that has the least significant on the residual sum of squares. In stepwise regression analysis, after each step in which a variable is added or removed, all candidate variables in the model are checked to ensure whether or not their significance has been reduced below the specified tolerance level. If a non-significant variable is then found, it will be removed from the model. It should be noted that stepwise regression analysis consecutively adds or deletes variables while there is no further contribution of independent variables to remain or enter to the model, then variable selection process will be terminated [36, 38].

This study presents the application of SR analysis for finding factors affecting bond strength when the FRP plates are externally attached to timber. The proposed stepwise regression model is based on 195 experimental results of FRP-to-timber bonded interfaces as reported by [14]. The accuracy of the proposed SR analyses is quite satisfactory when compared to experimental results.

5.2 SR MODEL OF FRP-TO-TIMBER BONDED INTERFACES

In the present study, a database was built covering the results of 195 single shear FRP-to-timber joint tests collected from Wan [14]. In the research conducted by Wan [14], the main focus was on bond length and types of adhesive and there were limited variations in parameters such as bond width, FRP-to-timber width ratio, bond stiffness, FRP thickness, compressive strength of timber etc. As such, the SR model for FRP-to-timber joint presented in this study is valid only for the ranges of variables of the experimental database given in Wan [14]. Prior to the modelling phase, the correlation of each potential independent variable on output (dependent variable), which is the ultimate load (P_u), has been determined. The most common measure of correlation in statistics is the Pearson Correlation, which is a measure of the strength of the linear relationship between two sets of data. The symbol for Pearson's correlation is "*r*" with the range from -1 to 1. An *r* of adjacent to 1 and -1 indicates a perfect positive and negative linear relationship between variables, respectively; while an *r* of 0 indicates no linear relationship between variables [39]. Pearson correlation coefficient can be calculated by Eq. 7.

$$r = \frac{\sum xy - n\overline{x}\,\overline{y}}{\left(\sqrt{\sum x^2 - n\overline{x^2}}\right)\left(\sqrt{\sum y^2 - n\overline{y^2}}\right)} \tag{7}$$

where *x* and *y* are independent and dependent variables, respectively. $\overline{x}$ and $\overline{y}$ are mean of x and y values, and *n* is the number of samples. As a result of these analyses, in the stepwise modelling of externally bonded FRP-to-timber joint, timber modulus of elasticity (E_t) and compressive strength (f_t), bond length (L), FRP elastic modulus and tensile strength, FRP stiffness ($E_f t_f$), adhesive elastic modulus (E_A) and tensile strength (t_A) have been considered as the main parameters which impact on the bond strength, as shown in Table 1. It is worth noting that the value of Pearson's Correlation of timber width (b_w), FRP width (b_p), FRP thickness (t_p), FRP to timber width ratio (b_p/b_t) on the ultimate load has been found equal to zero, because these parameters have been constant for all samples. This finding indicates that there is no observable linear relationship between these parameters and the ultimate load for the present database.

The stepwise selection process has been performed using different possible combinations of independent variables including linear; polynomial; exponential model; reciprocal model and nonlinear multiple regression. It is noted that the power of the polynomial is usually either two or three [40]. Models considered for the SR procedure are tabulated in Table 2.

One way to test the model proposed by SR is not to rely on the model's P-value, significance or R-squared, but instead, assess the model against an "independent" data set that was not used to create the model [41]. Thus, a model can be built based on a sample of the dataset available (e.g., 70%) and then, assess the accuracy of the

***Table 1** Pearson's correlation of independent variables on output (P_u)*

	timber compressive strength (f_t)	timber modulus of elasticity (E_t)	bond length (L)	FRP tensile strength	FRP modulus of elasticity	FRP stiffness ($E_f t_f$)	adhesive modulus of elasticity (E_A)	adhesive tensile strength (t_A)
$\mathbf{P_u}$	0.34	0.16	0.81	-0.26	0.26	0.26	0.04	-0.32

Table 2 *models considered for the SR procedure*

Model	**Equation**
Multiple regression model (linear regression)	$Y = b_0 + b_1x_1 + b_2x_2 + ... + b_mx_m + e$
Polynomial Regression	$Y = b_0, + b_1x + b_2x^2 + b_3x^3 + ... + b_mX^m + e$
Nonlinear multiple regression models	$Y = b_0 + b_1x_1b_2x_2b_3x_3b_mX_m + e$
Exponential model	$\text{Ln } Y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + \text{Ln } e$
Reciprocal model	$Y = 1 / (b_0 + b_1x_1 + b_2x_2 + b_3x_3 + ... + bmxm + Le)$

Y = dependent variable, X_i *= independent variable i,* b_0 *= y intercept,* b_i *= the slope for independent variable i, e = random error*

Table 3 *Equations of best subsets for SR analysis of externally bonded FRP-to-timber joint*

Step	**Equation (P_u)**	**R^2**
1	$4.448 + 0.086(L)$	0.65
2	$5.857 + 0.096(L) - 0.474(E_t)$	0.71
3	$5.234 + 0.077(L) - 5.778(E_t) + 1.124(f_t)$	0.78
4	$64.849 + 0.084(L) - 7.005(E_t) + 1.383(f_t) - 0.786(E_f t_f)$	0.82
5	$113.57 + 0.0752(L) - 8.813(E_t) + 1.7013(f_t) - 1.306(E_f t_f) - 0.1689(t_A)$	0.87

Table 4 *Statistical details of best subset for stepwise regression model*

Step Label	**Main parameters**	**Partial R^2**	**Model R^2**	**C(p)**	**F Value**	**Pr > F**
1	Bond length	0.65	0.65	31.58	47.31	<.0001
2	Timber modulus of elasticity	0.06	0.71	24.46	4.81	0.038
3	Timber compressive strength	0.07	0.78	15.58	7.24	0.013
4	FRP stiffness	0.04	0.82	11.08	5.09	0.034
5	Adhesive tensile strength	0.05	0.87	4.81	8.77	0.008

model using the remaining 30% dataset [42]. This method is predominantly valuable when data are collected in different resources. Accordingly, a database including 130 experimental results of the FRP-to-timber joint has been used to create the model (predict) and remaining 65 sets of data have been used to test the measurement accuracy of SR model. Statistical Analysis Software (SAS®) has been employed for the stepwise regression analysis. SAS®, permits choosing the stepwise variable selection option by providing the opportunity to specify the method as “Forward” or “Backward”. In the present study, a fully stepwise analysis has been selected (both Forward and Backward methods) allowing the software to perform a straight multiple regression using all the variables. At the next step, a significance level of a variable must be specified before it can be entered into the model (F-to-enter) prior to analysis, and then to remain in the model after each step of analysis (F-to-remove). Therefore, the options SLENTRY=0.05 and SLSTAY=0.1 have been set as the level of significance for a variable to enter and remain in the model, respectively. Dependent and independent variables have been defined to the model and program, then preceded analysis automatically. It is important to note that when the procedure terminates, all variables added and deleted must be checked, since it is possible that the addition or removal of a few more variables might not lead to improvement to the model. Furthermore, the value of the adjusted R-squared of the model must always be checked, because the adjusted R-squared should increase consistently as the stepwise process works; however, it may sometimes decrease. Hence, variables that tend to reduce the value of adjusted R-squared must be manually removed from the model. Table 3 shows SR equations which have been obtained for the best subsets of FRP-to-timber bonded interface.

R, the multiple correlation coefficient and square root of R^2 (Coefficient of Determination), is the correlation between the independent variable(s) and the predicted values. A model with $R^2=1$ has perfect predictability, and a model has no predictive capability if $R^2=0$. As mentioned earlier, the effect of timber width, FRP width, FRP thickness and FRP-to-timber width ratio cannot be identified based on the current model due to the limited data set that the model is based on. This occurs because Pearson’s Correlation of the above parameters and the ultimate load is zero; noting that these parameters have been constant for all samples. On the other hand, stepwise regression modelling of FRP-to-timber joint illustrates that bond strength can be significantly related to the bond length, as shown in Table 4, with the value of $R^2=0.65$. That is not only because bond length varies in the present database, but also the other parameters, which are mentioned earlier, are suppressed in the SR analysis. It was also found that the timber modulus of elasticity and timber compressive strength have a significantly higher impact on the bond strength, rather than that of adhesive tensile strength. This finding is in agreement with observations made by Crews and Smith [26]. However, the compressive strength of timber was not considered in the research conducted by Wan [14], since it was believed that the compressive strengths of softwood, hardwood and glulam used in that study were not significantly different from one another. Therefore, the importance of this parameter has been ignored in the existing model.

In**Error! Reference source not found.** Table 4, Pr > F labels the P-values indicates whether or not a variable has statistically significant predictive capability in the presence of the other variable. A low P-value (<0.05) demonstrates that the null hypothesis can be rejected. In other words, an independent variable with a low P-value is likely to be a meaningful addition to the model; that is because; changes in the independent variable are associated to changes in the dependent variable. A larger P-value, on the other hand, illustrates that changes in the independent variable are not related with changes in the response, representing that the independent variable is statistically insignificant. Consequently, the P-value for each term investigates the null hypothesis that the coefficient is equal to zero (no effect).It can be seen (Table 4) that bond length, timber modulus of elasticity, timber compressive strength, FRP stiffness and adhesive tensile strength are significant because their P-values are smaller than 0.05.

The F-value can be interpreted as the ratio of the Model Mean Square to the Error Mean Square that investigates whether or not the model as a whole has statistically significant predictive capability. An F-value is often used for comparing statistical models that have been fitted to a data set, with the intention of identifying the model that best fits the dependent variable from which the data were collected. When the model has no predictive capability, the null hypothesis is rejected if the F-value is large and P-value is smaller than 0.05. Consequently, the stepwise regression analysis revealed that amongst parameters which are proposed by the other researchers, bond length, timber modulus of elasticity, timber compressive strength, FRP stiffness and adhesive tensile strength have the major contribution to the bond strength.

5.2.1 Accuracy of the proposed models

Figure 3(a) shows the evaluation of the stepwise regression model of FRP-to-timber bonded interface against experimental results. Wan [14] has proposed an analytical model predicting ultimate load of FRP-to-timber joint (Eq. 6). To determine the accuracy of the proposed stepwise regression model of FRP-to-timber joint, all samples have been validated with the model proposed with Wan [14], as shown in Figure 3(b). It is interesting to mention that the coefficient of determination (R^2) of the stepwise regression analysis signifies that the SR model is even more enhanced when compared with the model proposed by Wan [14] and is a more accurate predictor than the existing bond–slip model. In addition, the average values and correlation coefficient of Wan's [23] model for the bond strength and stepwise regression analysis-to-test bond strength ratios are given in Table 5. It can be seen that SR model performs significantly better than Wan's [23] model. Nevertheless, although the predictor variables of bond length, timber modulus of elasticity and compressive strength, FRP stiffness and adhesive tensile strength are statically significant (P-values < 0.05), in order to consider accurately the effect of the all potential factors, further research is necessary. In addition, a low R-squared of Wan's [23] model indicates that a new bond strength model for FRP-to-timber bonded interface is highly required in order to predict the ultimate load of the bond with superior accuracy.

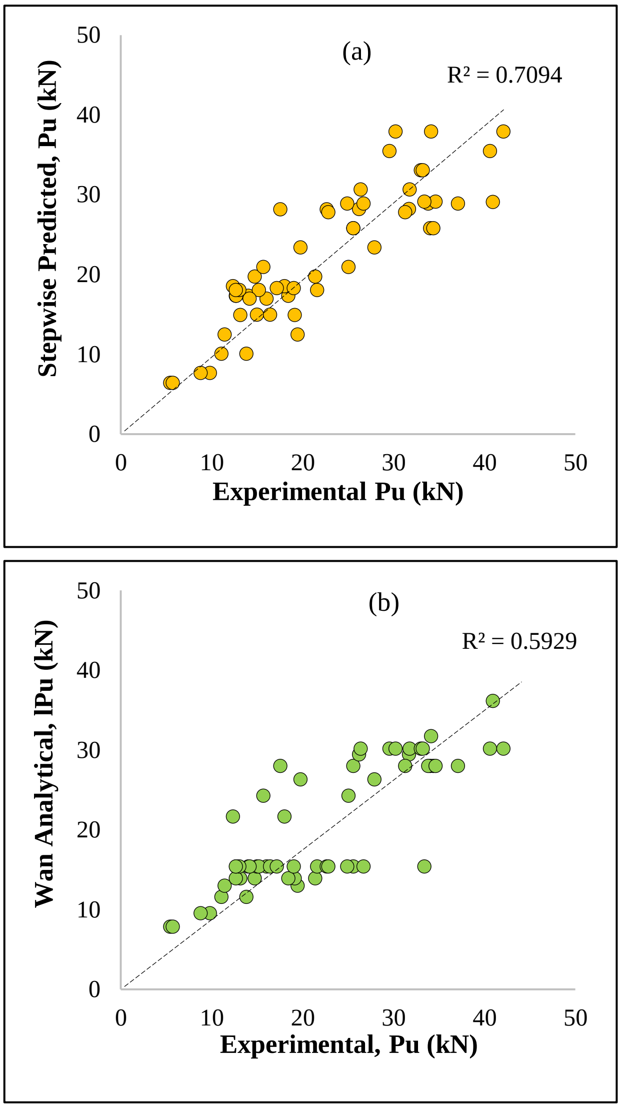

Figure 3 *Wan [14], Pu predicated by: (a) Stepwise Regression Analysis; (b) Wan's Model*

***Table 5** Wan [14] model and stepwise regression analysis-to-test bond strength ratios*

Data set reported	Wan [23] model-to-test bond strength		Stepwise regression analysis-to-test bond strength	
	$P_{u\ analytical}/P_{u\ experimental}$	Correlation coefficient	$P_{u\ analytical}/P_{u\ experimental}$	Correlation coefficient
Wan [14]	1.05	0.77	0.97	0.84

6 Conclusion

This paper provides a review of existing bond-slip models in the literature for externally bonded FRP on concrete and timber. Whilst several research studies have been carried out to improve the performance of FRP techniques to eliminate or postpone debonding failure of the FRP attached to concrete, there are limited studies on FRP-to-timber bond. The findings of such studies have been reviewed with the intention of characterising and identifying potential failure modes of FRP-to-concrete and FRP-timber bond interface. Based on the consequences and considerations obtained in the present study, the main findings can be concluded as:

- Debonding can be defined as the most common failure mode in the externally bonded elements which directly impacts on total integrity of the structure causing devastating damages to the whole structure. In addition, the failure mode of externally bonded joints may occur in different ways, such as substrate failure, FRP delamination, FRP/adhesive separation, FRP rupture, cohesion failure, adhesive failure, and substrate-to-adhesive interfacial failure; although the actual failure may be a mixture of these modes. Consequently, in order to investigate the debonding mechanism, numerous bond testing methods have been carried out experimentally such as single shear and double shear tests as well as modified beam tests. Different factors have been reported in the literatures that affect the interfacial behaviour of the joints. The main parameters, which are repeatedly confirmed in literature, are substrate stiffness and strength, bonded length, adhesive stiffness and strength, FRP stiffness, FRP bonded width and FRP-to-substrate width ratio and interfacial fracture energy.
- This paper presents the application of a stepwise regression analysis for determining the key parameters affecting bond strength when the FRP plates are externally attached to timber, and also to evaluate their influence on the bond strength. The proposed stepwise regression model is based on an average of 195 single shear pull out tests of FRP-to-timber bonded interfaces collected from literature. It is notable that 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. Therefore, the models which work for FRP-to-concrete bond may not work for FRP-to-timber bond.
- This study is a part of an ongoing research project aiming to accurately consider the effect of the all potential parameters affecting bond strength, particularly when FRP is bonded to timber. The present work nevertheless has been performed to address critical variables that will be included in a new FRP-to-timber model in order to predict the ultimate load of the bond with superior accuracy. Further research and development of a new FRP-to-timber bonded joints model will be reported in subsequent publications.

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