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Modelling of Factors Affecting Bond Strength of Fibre Reinforced Polymer Externally Bonded to Timber and Concrete

Abbas Vahedian, Rijun Shrestha, Keith Crews

***Abstract*—**In recent years, fibre reinforced polymers as applications of strengthening materials have received significant attention by civil engineers and environmentalists because of their excellent characteristics. Currently, these composites have become a mainstream technology for strengthening of infrastructures such as steel, concrete and more recently, timber and masonry structures. However, debonding is identified as the main problem which limit the full utilisation of the FRP material. In this paper, a preliminary analysis of factors affecting bond strength of FRP-to-concrete and timber bonded interface has been conducted. A novel theoretical method through regression analysis has been established to evaluate these factors. Results of proposed model are then assessed with results of pull-out tests and satisfactory comparisons are achieved between measured failure loads ($R^2 = 0.83$, $P < 0.0001$) and the predicted loads ($R^2 = 0.78$, $P < 0.0001$).

***Keywords*—**Debonding, FRP, pull-out test, stepwise regression analysis.

I. Introduction

THE requirement for lightweight, resistant, sustainable and cost-effective structures has been increasingly demanded worldwide due to the reduction in raw material supplies and energy sources. The efficient and sustainable use of materials in building design and construction has received significant attention by civil engineers and environmentalists. There are large numbers of timber structures worldwide that have reached the end of their design service life. Moreover, ageing, inappropriate maintenance, surface degradation due to insect and fungal attack, environmental action, and increased service loads have caused many structures to gradually deteriorate and result in significant reduction in load capacity and subsequent safety. However, one of the main concerns of engineers is to evaluate the integrity of existing structures which were designed based on older codes and standard. Consequently, those structures might not satisfy the requirements of new codes. Therefore, in such structures, the deficient members and joints require strengthening to upgrade their structural integrity in order to the higher loading demands due to change in code requirements or change in functionality [1].

Recent applications have demonstrated that fibre composites can effectively and economically be used for new structures, as well as in the strengthening and retrofitting of existing civil infrastructure [2]. Although FRPs are light, highly resistant to corrosion, cost effective and have superior strength and stiffness properties [3]-[5], they still have some important limitations. Debonding can be defined as one of the main concerns associated with the use the externally bonded FRP sheets that not only impacts directly the total integrity of structure, but also limits the full utilisation of the material strength of the FRP [6], [7].

In the current research study, a preliminary analysis has been conducted to investigate potential parameters affecting bond strength when FRP is externally bonded to concrete and timber. To evaluate the influence of these factors on the bond strength, stepwise regression method as a robust method has been employed and results of this analysis are then assessed with experimental data collected from the literature. Stepwise regression analysis revealed that to consider accurately the effect of the all potential factors affecting bond strength, particularly when FRP bonded to timber, further research is necessary due to the limited data sets available.

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II. Interface Modelling Methods

Despite the large number of studies which have been carried out experimentally [8], [9] and theoretically [10], [11] to address the behaviour externally bonded elements using FRP composites, there is a significant knowledge gap to gain a comprehensive understanding of potential parameters such as bond width, bond length, material properties and geometries that influence bond strength. Although several attempts have been made to eliminate or postpone debonding failure of externally bonded FRP elements, due to the limited success and applicability of the proposed models, further research in this area is highly desirable. The proposed models in the literature can be divided into three main categories including 1) empirical models based directly on the regression of test data, 2) fracture mechanics models based on the behaviour of bond stress-slip and 3), design proposals in which some simple assumptions are usually required to be made [12], [13].

A. Empirical-Based Models

Empirical-based models are mainly dependent on the results of experimental tests where the bond relationships are predominantly determined from a regression analysis of the interface parameters. The formulation of these models is quite simple and straightforward, although their outcomes show high variability from one experiment to another. This appears to be due to the fact that the bond parameters are derived for specific experimental conditions including composition of the materials (substrate, FRP and adhesive properties), test setup, local stress concentrations and equipment. These conditions are not equivalent for all experiments and the assumptions and data used to derive the model require verification. Due to these variations, a number of interface laws based on the test shape and bond parameters have been proposed. Hiroyuki and Wu [14] and Tanaka [15] conducted a series of experimental tests based on which they derived (1) and (2), respectively.

$$\tau_u = 5.88 L_f^{-0.669} \tag{1}$$

$$\tau_u = 6.13 - \ln L \tag{2}$$

A model developed by Maeda et al. [16] in which the average bond shear stress at failure (τ_u) and effective bond length (L_e) can be calculated using (3) and (4), respectively.

$$\tau_u = 110.2 \times 10^{-6} E_f t_f \tag{3}$$

$$L_e = e^{6.13 - 0.580 \ln E_f t_f} \tag{4}$$

where t_f (mm) is the bond thickness and E_p is elastic modulus of the bonded plate. Note that E_p is in MPa and GPa in (3) and (4), respectively. They showed that the effective bond length (L_e) is exponentially related to the FRP stiffness, and the ultimate bond strength can be determined by multiplying the effective bond area ($A_e = b_f \times L_e$) by bond shear stress (τ_u) [12]. This model is clearly unreliable if $L<L_e$.

B. Fracture Mechanics Based Models

Failure of brittle materials can be determined by the interfacial fracture energy which is the area beneath the bond stress-slip response. This theory applies to polymers since adhesive joints usually fail by the initiation and propagation of flaws; however, greater emphasis must be placed on the expansion of a plastic area around the tip of the increasing crack. Two of the main characteristics of fracture mechanics models are that, for a given joint, the fracture energy, (G_f) is geometry-independent, and applicable equally to interfacial failures as it is to cohesive failures as long as the failure mode is noted [17]. Mier [18] distinguished three common separate fracture modes-of-loading in classical fracture mechanics as depicted in Fig. 1: tensile or the opening (mode I) (a), in-plane shear or sliding (mode II) (b), and out-of-plane shear or tearing (mode III) (c). Most cracks tend to propagate in Mode I which is the lowest energy fracture mode for isotropic materials. This mode has been usually used to assess adhesive toughness, adhesion and durability, and surface preparation techniques for investigating fracture toughness, K_{If}, and fracture energy, G_{If}. Crack propagation predominantly occurs under Mode I. Mode II, however, leads to the sliding of the crack surfaces. In the third mode, loads are applied to the crack in a way that causes the two crack surfaces to tear apart. In adhesive joints, most interest focuses on the first two modes, whilst the other mode appears less frequently but is nevertheless of great importance [17], [18]. Custódio et al. [17] reported that the brittle fracture energy of the bondline, G_f, considering linear elastic fracture mechanics (LEFM), can be determined for a given adhesive layer thickness t_a based on (5):

$$G_f = \frac{\tau_v^{\,2} t_a}{2G_a} \tag{5}$$

where τ_v and G_a are the adhesive shear resistance and the adhesive shear modulus, respectively. This model was initially developed by Gustafsson [19] for timber pull-out behaviour, and is currently the ideal model for calculating the pull-out load of rods bonded into timber [17]. A nonlinear fracture mechanics model (NLFM) was developed by Holzenkämpfer [20] considering the bond strength between concrete and steel plate. Niedermeier [21] and Blaschko et al. [22] modified the proposed model in which the ultimate bond strength (P_u), effective bond length (L_e) and fracture energy (G_f) can be derived by (6), (7) and (8), respectively.

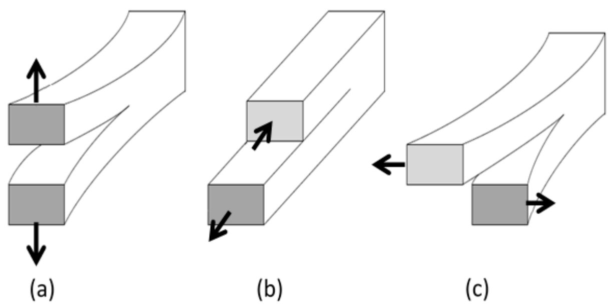

Fig. 1 Three fracture modes: (a) tensile or the opening (mode I), (b) in-plane shear or sliding (mode II) and (c) out-of-plane shear or tearing (mode III) [18]

$$P_u = 0.78 b_p \sqrt{2G_f E_p t_p} \quad \text{if} \quad L \geq L_e \tag{6}$$

$$P_u = 0.78 b_p \sqrt{2G_f E_p t_p}\,\frac{L}{L_e}\left(2 - \frac{L}{L_e}\right) \quad \text{if} \quad L < L_e$$

$$L_e = \sqrt{\frac{E_p t_p}{4 f_{ctm}}} \tag{7}$$

$$G_f = c_f k_p^{\,2} f_{ctm} \tag{8}$$

In the above equations, c_f is a constant that can be determined using a linear regression analysis of the results of double shear or similar tests; f_{ctm} (MPa) is the average surface tensile strength of concrete. The value of f_{ctm} can be determined using the results of pull-out test in accordance with DIN1048 [23]; and k_p is geometrical factor (see (9)) which is related to the width of the concrete (b_c) and width of the bonded plate (b_p)

$$k_p = \sqrt{1.125 \frac{2 - b_p / b_c}{1 + b_p / 400}} \tag{9}$$

III. Stepwise Regression Analysis

A. Stepwise Regression Method; A Brief Explanation

When the number of independent variables is high, stepwise regression (SR) as a robust approach can be used to determine the best combination of independent variables in predicting the dependent variable [24]. Stepwise regression serves to be the best subset model that provides efficient prediction of the dependent variable with significantly less computing complexity than is required for all possible regressions [25]. The best subset models can be obtained either by adding one independent variable into the regression model that produces the maximum value of R-Squared if statistical significance of model is kept (forward selection), or by including full model in the regression model and then eliminating those that are least significant (backward selection). Stepwise regression is a combination of forward and backward selections, selecting variable(s), without a termination rule, that has the highest impact on the residual sum of squares; and conversely, removing the variable(s) whose deletion increases the residual sum of squares. In stepwise regression analysis, the seclection of each variable may be forward, backward or a combination of them. Therefore, after each step when a variable is added or removed, all previously included variables in the model are checked to ensure whether their significance has been met the minimum specified tolerance level. If a non-significant variable is then found, the selection procedure changes to backward elimination removing non-significant variable from the model. It is important to note that SR analysis consecutively adds or deletes variables until all remaining variables meet the minimum criterion, then variable selection process will be terminated [24].

This study presents the application of SR analysis for finding parameters affecting the ultimate load when the FRP sheets are externally bonded to concrete and timber. The proposed stepwise regression model is based on results of 446 single/double pull out tests of FRP-to-concrete collected from literature [10], [12], [26]-[30] and average of 195 experimental results of externally bonded FRP-to-timber joints as reported by [13]. A satisfactory correlation is achieved when proposed SR model compared against bond strength model proposed by Chen and Teng [12] indicating that the proposed SR model and Chen and Teng [12] models are in reasonably close agreement.

B. SR Model of FRP-to-Concrete Bonded Interfaces

In this study, prior to the modelling phase, the correlation of each potential independent variable on the ultimate load (P_u) (dependent variable) has been determined. Pearson Correlation is the most common measure of correlation in statistics which linearly measures the strength relationship between two sets of data. Pearson's correlation (with symbol "r") has the range from -1 to 1; in which 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 [31]. Pearson correlation coefficient can be expressed as:

$$r = \frac{\sum xy - n\overline{x}\,\overline{y}}{\left(\sqrt{\sum x^2 - n\overline{x^2}}\right)\left(\sqrt{\sum y^2 - n\overline{y^2}}\right)} \tag{10}$$

In (10), x is independent variable, y is dependent variable and n is the number of samples. $\overline{x}$ and $\overline{y}$ are the mean of x and y values. Correlation coefficient analysis of potential independent variables on the ultimate load indicated that FRP-to-concrete width ratio (b_f/b_c), FRP stiffness ($E_f.t_f$), FRP elastic modulus, FRP thickness (t_f) and width (b_f) as well as concrete compressive strength (f'_c) and concrete elastic modulus (E_c) and bond length (L) are the most significant independent variables affecting the bond strength, as shown in Table I. As result of this analysis, the above parameters have been used in the stepwise modelling of FRP-to-concrete bonded interface.

Fig. 2 shows distributions of the dataset in terms of the identified key parameters. As can be seen in Fig. 2, a wide range of values for each parameter is available in the test data and hence, a trustworthy criterion for theoretical models can be expected. 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 as tabulated in Table II. It is noted that the power of the polynomial is usually either two or three [32]. Table III shows SR equations which have been obtained for the best subsets of FRP-to-concrete 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.

Many studies [2], [12], [30], [33] have shown that the bond strength depends on FRP-to-concrete width ratio, concrete strength, geometry of the bond, FRP width and thickness, FRP stiffness and bond length. The results of SR analysis of FRP-to-concrete bonded interface, however, showed that two-third of the bond strength (Model R^2=0.67) alone have been associated with FRP width and FRP to concrete width ratio within the regression line. Following this, bond strength also depends on FRP stiffness and bond length, as shown in Table IV.

P-values (labelled as Pr > F), in Table IV, indicates whether a variable has statistically significant predictive capability in the presence of the other variable. An independent variable with a low P-value (<0.05) is likely to be a meaningful addition to the model; on the other hand, a larger P-value, 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 IV) that FRP width, FRP-to-concrete width ratio, FRP stiffness and bond length are highly significant because their P-values are smaller than 0.0001 (<0.05).

TABLE I
PEARSON'S CORRELATION OF INDEPENDENT VARIABLES ON OUTPUT (P_U)

	Concrete compressive strength	Concrete elastic modulus	FRP to concrete width ratio	Bond length	FRP thickness	FRP width	FRP elastic modulus	FRP stiffness
P_u	0.12	-0.09	0.17	0.45	0.20	0.70	0.04	0.29

TABLE II
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

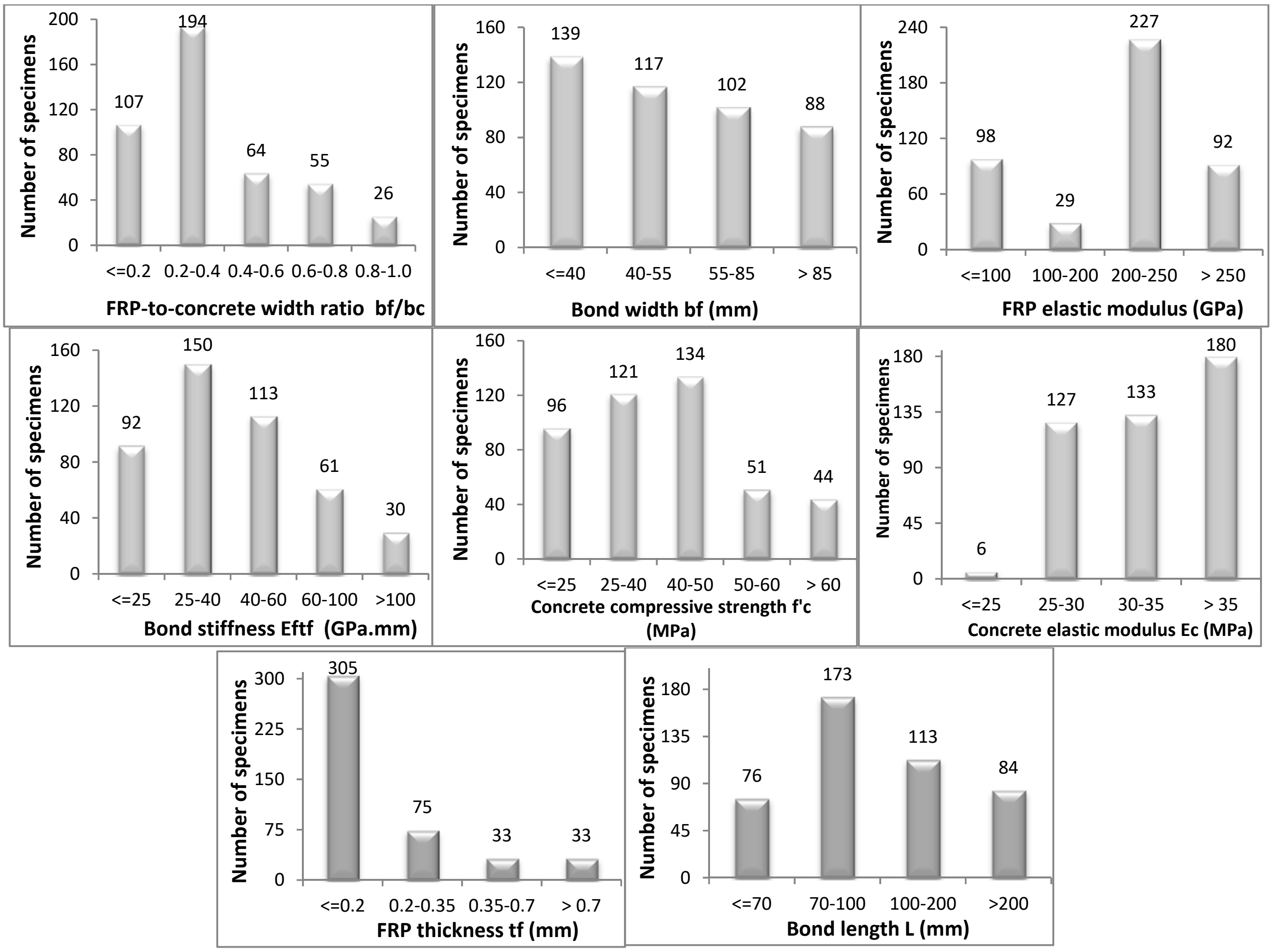

Fig. 2 Distributions of the data set in terms of main factors

In Table IV, the F-value is the ratio of the Model Mean Square (MMS) to the Error Mean Square (EMS). The F-value investigates whether the model as a whole has statistically significant predictive capability. 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 SR analysis of FRP-to-concrete joints revealed that FRP width and stiffness, bond length as well as FRP to concrete width ratio have the major contribution to the bond strength.

C. Accuracy of the Proposed Models

The evaluation of the stepwise regression formulation presented above (Table III, step 4) against experimental tests has been shown in Fig. 3 (a). Lu et al. [34] stated that the model proposed by Chen and Teng [12] (10) is the most accurate model amongst the existing FRP-to-concrete bond strength models. Therefore, to accurately consider the proposed SR model, total data sets have been validated with the Chen and Teng [12] model, as shown in Fig. 3 (b). In addition, the average values and correlation coefficient of Chen and Teng [12] model for the bond strength formula (10) and stepwise regression analysis-to-test bond strength ratios are tabulated in Table V. It was observed that the proposed SR model and the model of Chen and Teng [12] are in reasonably close agreement.

TABLE III
EQUATIONS OF BEST SUBSETS FOR SR ANALYSIS OF EXTERNALLY BONDED FRP-TO-CONCRETE JOINT

Step	Equation (P_u)	R^2
1	$0.8997 + 0.2155\ (b_f)$	0.49
2	$2.8037 + 0.3369\ (b_f) - 23.2969\ (b_f / b_c)$	0.67
3	$-3.1685 + 0.3359\ (b_f) - 20.3063\ (b_f / b_c) + 0.1127\ (E_f t_f)$	0.77
4	$-4.50784 + 0.3144\ (b_f) - 19.44067\ (b_f / b_c) + 0.10303\ (E_f t_f) + 0.0188\ (L)$	0.81

TABLE IV
STATISTICAL DETAILS OF BEST SUBSET FOR SR MODEL

Step Label	Main parameters	Partial R^2	Model R^2	C(p)	F Value	Pr > F
1	FRP width	0.49	0.49	715.44	359.85	<.0001
2	FRP to concrete width ratio	0.18	0.67	338.14	201.05	<.0001
3	FRP stiffness	0.11	0.77	110.00	179.63	<.0001
4	Bond length	0.04	0.81	25.14	82.45	<.0001

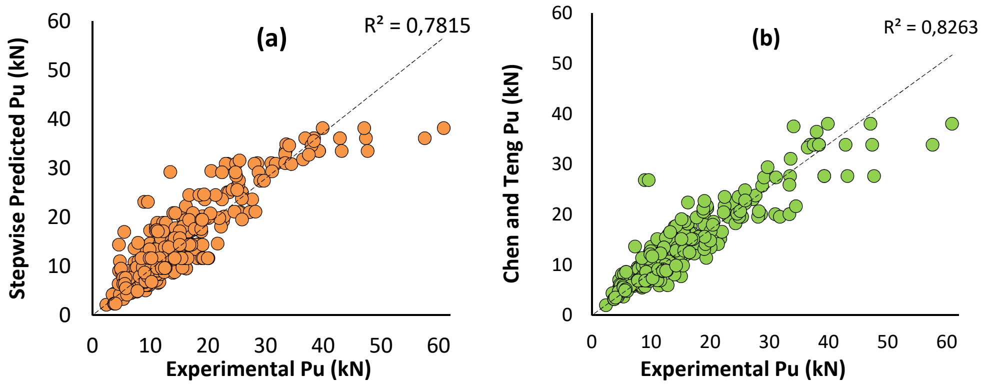

Fig. 3 Concrete pull-out tests (446 specimens), P_u predicated by: (a) Stepwise Regression Analysis; (b) Chen and Tengs' Model

TABLE V
CHEN AND TENG [12] MODEL AND STEPWISE REGRESSION ANALYSIS-TO-TEST BOND STRENGTH RATIOS

Data sets reported	Chen and Teng [12] 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
Concrete pull-out tests	0.94	0.91	1.01	0.88
Ren [27]	1.09	0.89	1.12	0.84
Ueda et al. [26]	0.92	0.97	0.93	0.94
Wu et al. [28]	0.95	0.94	1.01	0.79
Zhou [29]	0.90	0.93	1.00	0.84
Yao et al. [30]	0.97	0.97	1.09	0.88
Dai et al. [10]	0.91	0.84	1.20	0.81
Saxena [35]	0.91	0.84	0.86	0.86

D. 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 [13]. In the research conducted by Wan [13], 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 [13].

Prior to the modelling phase, correlation of each potential independent variable on the ultimate load (P_u) has been determined using Pearson's Correlation method (10). 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 VI. 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.

TABLE VI
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)
P_u	0.34	0.16	0.81	-0.26	0.26	0.26	0.04	-0.32

TABLE VII
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

It is noted that the entire process of stepwise regression analysis for FRP-to-timber joint is quite similar to that for the FRP-to-concrete bonded interface; however, different independent variables need to be entered to the model, as listed in Table VI. Again, a fully stepwise analysis has been selected allowing the software to perform a straight multiple regression using all the variables. Similar to the previous SR analysis, 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. Stepwise regression analysis of FRP-to-timber joint has been performed in order to achieve the best subset of variable for the model. Table VII shows SR equations which have been obtained for the best subsets of FRP-to-timber bonded interface.

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 VIII, with the value of R2=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 [36]. However, the compressive strength of timber was not considered in the research conducted by Wan [13], 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.

E. Accuracy of the Proposed Models

Fig. 4 (a) shows the evaluation of the stepwise regression model of FRP-to-timber bonded interface against experimental results. Wan [13] has proposed an analytical model predicting ultimate load of FRP-to-timber joint (15). 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 [13], as shown in Fig. 4 (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 [13] 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 IX. 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.

TABLE VIII
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

TABLE IX
WAN [13] 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 [13]	1.05	0.77	0.97	0.84

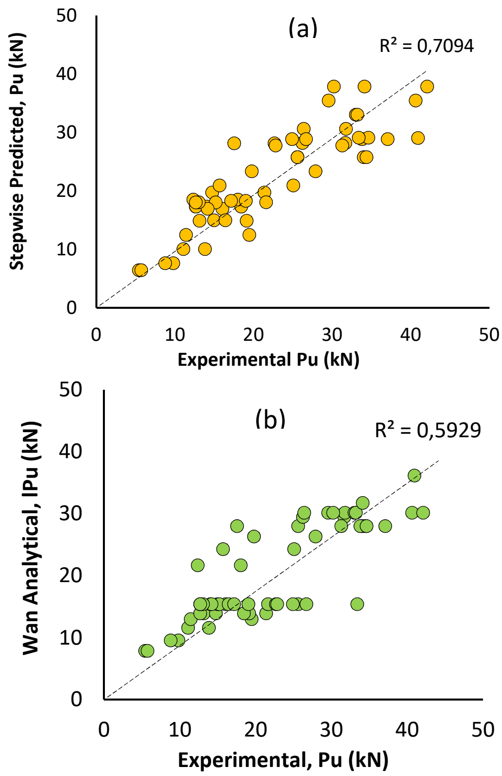

Fig. 4 Wan [13], Pu predicated by: (a) Stepwise Regression Analysis; (b) Wan's Model

IV. 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 concrete and timber, and also to evaluate their influence on the bond strength. The proposed stepwise regression model is based on 446 experimental results of FRP-to-concrete and 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.
- Good correlation could be obtained for the proposed SR models against both the experimental results and existing models such as Chen and Teng [12] model. Stepwise regression analysis revealed that FRP width, FRP-to-concrete width ratio, FRP stiffness and bond length are the key parameters which affect the bond strength of FRP-concrete bond.

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REFERENCES

[1] Shrestha, R., *Behaviour of RC beam-column connections retrofitted with FRP strips*, in *Faculty of Engineering and Information Technology*. 2009, University of Technology Sydney.
[2] Hollaway, L.C. and J.-G. Teng, *Strengthening and rehabilitation of civil infrastructures using fibre-reinforced polymer (FRP) composites*. 2008, North America by CRC Press: Elsevier Reference Monographs.
[3] D'Ambrisi, A., F. Focacci, and R. Luciano, *Experimental investigation on flexural behavior of timber beams repaired with CFRP plates.* Composite Structures, 2014. 108: p. 720-728.
[4] Juvandes, L. and R. Barbosa, *Bond Analysis of Timber Structures Strengthened with FRP Systems.* Strain, 2012. 48(2): p. 124-135.
[5] Valipour, H.R. and K. Crews, *Efficient finite element modelling of timber beams strengthened with bonded fibre reinforced polymers.* Construction and Building Materials, 2011. 25(8): p. 3291-3300.
[6] Khelifa, M. and A. Celzard, *Numerical analysis of flexural strengthening of timber beams reinforced with CFRP strips.* Composite Structures, 2014. 111: p. 393-400.
[7] Wu, Z. and S. Hemdan. *Debonding in FRP Strengthened Flexural Members with Different Shear-Span Ratios*. in *Proceeding of the 7th International Symposium on Fiber Reinforced Composite Reinforcement for Concrete Structures*. 2005. Michigan, USA.
[8] Cao, S., et al., *ESPI measurement of bond-slip relationships of FRP-concrete interface.* Journal of Composites for Construction, 2007. 11(2): p. 149-160.
[9] Mazzotti, C., M. Savoia, and B. Ferracuti, *An experimental study on delamination of FRP plates bonded to concrete.* Construction and Building Materials, 2008. 22(7): p. 1409-1421.
[10] Dai, J., T. Ueda, and Y. Sato, *Unified analytical approaches for determining shear bond characteristics of FRP-concrete interfaces through pullout tests.* Journal of Advanced Concrete Technology, 2006. 4(1): p. 133-145.
[11] Ferracuti, B., M. Savoia, and C. Mazzotti, *Interface law for FRP–concrete delamination.* Composite structures, 2007. 80(4): p. 523-531.
[12] Chen, J. and J. Teng, *Anchorage strength models for FRP and steel plates bonded to concrete.* Journal of Structural Engineering, 2001. 127(7): p. 784-791.
[13] Wan, J., *An investigation of FRP-to-timber bonded interfaces*, in *Civil Engineering*. 2014, The University of Hong Kong Pokfulam, Hong Kong.
[14] Hiroyuki, Y. and Z. Wu, *Analysis of debonding fracture properties of CFS strengthened member subject to tension*, in *Non-Metallic (FRP) Reinforcement for Concrete Structures, Proceedings of the Third Symposium*. 1997: Sapporo, Japan. p. 287–294.
[15] Tanaka, T., *Shear resisting mechanism of reinforced concrete beams with CFS as shear reinforcement*. 1996, Hokkaido University: Japan.
[16] Maeda, T., et al. *A study on bond mechanism of carbon fiber sheet*. in *Non-Metallic (FRP) Reinforcement for Concrete Structures, Proceedings of the Third Symposium*. 1997. Sapporo, Japan.
[17] Custódio, J., J. Broughton, and H. Cruz, *A review of factors influencing the durability of structural bonded timber joints.* International journal of adhesion and adhesives, 2009. 29(2): p. 173-185.
[18] Mier, J.G.V., *Concrete fracture: a multiscale approach*. 2012: CRC press.
[19] Gustafsson, P., *Analysis of generalized Volkersen-joints in terms of non-linear fracture mechanics*. 1987, Paris. p. 139-150.
[20] Holzenkämpfer, P., *Ingenieurmodelle des Verbunds geklebter Bewehrung für Betonbauteile* in *Institut für Baustoffe, Massivbau und Brandschutz*. 1994, Technische Universität Braunschweig: Braunschweig, Germany.
[21] Niedermeier, R., *Stellungnahme zur richtlinie für das verkleben von betonbauteilen durch ankleben von stahllaschen–entwurf märz 1996*, in *Schreiben 1390 vom 30.10. 1996 des Lehrstuhls für Massivbau*. 1996: Technische Universität München, Munich, Germany (in German).
[22] Blaschko, M., R. Niedermeier, and K. Zilch. *Bond failure modes of flexural members strengthened with FRP*. in *Fiber Compos. in Infrastruct, 2nd International Conference on Composites in Infrastructure*. 1996.
[23] DIN1048, *Augsgabe 6.91,*, in *Teil 2: Prüfverfahren für Beton, Festbeton in Bauwerken und Bauteilen.* 1991, Deutsches Institut für Normung, e.V. Beuth Verlag, Berlin (in German).
[24] Cevik, A., et al., *Soft computing based formulation for strength enhancement of CFRP confined concrete cylinders.* Advances in Engineering Software, 2010. 41(4): p. 527-536.
[25] Campbell, M.J., *Statistics at square two: understanding modern statistical applications in medicine*. 2006: BMJ Books/Blackwell.
[26] Ueda, T., Y. Sato, and Y. Asano, *Experimental study on bond strength of continuous carbon fiber sheet.* ACI Special Publication, 1999. 188.
[27] Ren, H., *Study on basic theories and long time behavior of concrete structures strengthened by fiber reinforced polymers*. 2003, Dalian University of Technology: Dalian, China.
[28] Wu, Z., et al., *Experimental/analytical study on interfacial fracture energy and fracture propagation along FRP-concrete interface.* ACI Special Publications, 2001. 201: p. 133-152.
[29] Zhou, Y., *Analytical and experimental study on the strength and ductility of FRP-reinforced high strength concrete beam*. 2009, Dalian University of Technology, Dalian, China.
[30] Yao, J., J. Teng, and J. Chen, *Experimental study on FRP-to-concrete bonded joints.* Composites Part B: Engineering, 2005. 36(2): p. 99-113.
[31] Reddy, M.V., *Statistical Methods in Psychiatry Research and SPSS.* 2014: CRC Press.
[32] Lawrence, K.D., R.K. Klimberg, and S.M. Lawrence, *Fundamentals of forecasting using excel*. 2009: Industrial Press Inc.
[33] Coronado, C., *Characterization, modeling and size effect of concrete-epoxy interfaces*, in *Department of Civil and Environmental Engineering*. 2006, The Pennsylvania State University.
[34] Lu, X., et al., *Bond–slip models for FRP sheets/plates bonded to concrete.* Engineering structures, 2005. 27(6): p. 920-937.
[35] Saxena, P., *Interfacial bond behavior between FRP and concrete substrate*, in *Civil and Environmental Engineering*. 2006, The University of Alabama in Huntsville, Huntsville, Alabama.
[36] Crews, K. and S.T. Smith. *Tests on FRP-strengthened timber joints*. in *Proceedings, 3rd International Conference on FRP Composites in Civil Engineering, CICE 2006*. 2006.