PREMATURE BOND FAILURE IN FRP STRENGTHENED RC BEAMS

Priyam SAXENA [1] Houssam TOUTANJI [1] John GILBERT [2]

[1] Dept. of Civil and Environmental Engineering, University of Alabama in Huntsville, USA
[2] Dept. of Mechanical and Aerospace Engineering, University of Alabama in Huntsville, USA

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1 INTRODUCTION

FRP application is a very effective way to repair and strengthen structures that have become structurally inefficient over their life span. This paper concerns with the understanding of the debonding failure mechanism in FRP strengthened reinforced concrete beam. It is very important to predict the limit at which FRP shall debond from the beam in order to arrest premature failures. Premature debonding failure, where the composite action between concrete and FRP is lost, prevents the strengthened beam from reaching its ultimate flexure capacity, and therefore must be included in the design considerations. Currently existing models lack the thoroughness of bond predictability. This is mainly due to development of any particular model on the basis of a smaller amount of tested data usually from the researcher itself. Moreover, external conditions are forced upon the experimental setup sometimes in order to stimulate a specific failure mode. Hence, there is a need to review the existing work when applied to an extensive database of strengthened beams.

FRP strengthened reinforced concrete (RC) beams fail in six different failure modes broadly divided into two groups according to the European Code *fib* [1]: (a) those where full composite action between concrete and FRP is maintained (flexural failure) and (b) those where the composite action is lost (premature debonding). The American Concrete Institute (ACI) 440 [2] also differentiates between various failure-modes in a similar manner. Further, the premature debonding failure could be classified into two broad categories, (i) those starting from the plate end, and (ii) those starting at the mid span of the strengthened beam, as shown in Figure 1. The plate end failures are more commonly reported than those starting from the mid span [3, 4]. Amongst the different failure modes, there has been little research in terms of mid span debonding and fewer strength models are developed for predicting such failures. Many studies [4–7] suggest that conducting a simple shear test on the FRP bonded to concrete substrate can simulate this type of failure mode.

(a) (b)

Fig. 1 Premature Debonding Modes: (a) Plate End and (b) Mid Span

To verify this concept experimental work was collected from existing literature consisting of an extensive database of 351 concrete prisms bonded to FRP and tested in direct shear tests. Further, a database of 163 beams tested in bending was also collected. Various models were applied to these databases and the behavior of each model was analyzed.

2 METHODOLOGY

The idea behind developing a new model is to take into account both the modes of premature failure, i.e. plate end and mid span, and the bond behavior of FRP-concrete bond by conducting direct shear tests. The experimental setup for conducting a direct shear test is simple and could be altered for testing different parameters. The model derived through FRP-concrete bond analysis, along with beam theory is then applied to the experimental data of beams tested in three-point and four-point bending tests. The method by which the FRP sheets/plates were bonded to the concrete beam substrate was also categorized into wet lay-up and pultruded lay-up as given in [2].

2.1 Shear Tests

Shear tests are useful for predicting bond failure between FRP and concrete where FRP sheets/plates are used for shear strengthening of RC beams. It is also able to simulate the failure mechanism when the FRP sheets/plates are bonded to the soffit of the beam and the failure starts near the mid span of the beam propagating towards the plate end. This is defined as the mid span debonding failure mode. Hence, a model based on shear tests conducted on concrete prisms, could be a basis for generating a debonding strength model for a reinforced concrete beam strengthened with FRP sheets/plates.

Numerous models are available in literature to predict the bond strength of FRP-to-concrete bonded specimens. The models studied herein are given by Chen and Teng [5], Zhao [7], Khalifa et al. [7], Lu et al. [9], Sato [10], Iso [10], Izumo [10], and Dai et al. [11]. To verify the various models, following conditions were subjected on all the concrete prisms in order to be included in the database:

1. It had a rectangular cross-section,
2. It was subjected to either single or double shear test,
3. It was bonded with carbon, glass, or aramid fiber only,
4. It was not preloaded or precracked,
5. It did not have any form of external anchorage between the concrete and FRP sheet or plate, and
6. It was not devised or subjected to any physical condition in order to induce a particular failure mode.

The predicted bond strength was calculated for each specimen of the database, as defined by all the models and the experimental to predicted bond strength ratios were calculated. Table 1 lists various statistical parameters obtained from the analysis.

Table 1 Experimental to Predicted Bond Strength Ratios

	Models	Average	St. Dev.	COV	% Unsafe Design
1	Chen and Teng [5]	1.167	0.327	28%	30%
2	Chen and Teng Modified [5]	1.581	0.443	28%	2.5%
3	Zhao [7]	1.305	0.429	33%	22%
4	Khalifa et al. [8]	1.253	0.426	34%	28%
5	Lu et al. [9]	1.221	0.359	29%	26%
6	Sato [10]	0.780	0.389	50%	80%
7	Iso [10]	1.086	0.355	33%	42%
8	Izumo [10]	0.739	0.456	62%	73%
9	Dai et al. [11]	0.673	0.199	29%	94%

Chen and Teng [5] based their model on the nonlinear fracture mechanics (NLFM) solution for predicting bond strength and effective bond length, given as:

$$P_u = 0.315\beta_p\beta_L\sqrt{f_c^{'}}b_f L_e \tag{1}$$

where

$$L_e = \sqrt{\frac{E_f t_f}{\sqrt{f_c^{'}}}}, \quad \beta_p = \sqrt{\frac{2 - b_f / b_c}{1 + b_f / b_c}} \quad \text{and} \quad \beta_L = \begin{cases} 1 & if \quad L \geq L_e \\ \sin\dfrac{\pi L}{2L_e} & if \quad L < L_e \end{cases} \tag{2}$$

The modified model of Chen and Teng (Equation 1) gave an average experimental-to-predicted bond strength ratio of 1.581, which implies that the predicted bond strengths are in the safe range. But it is also interesting to note that the percent unsafe design was only 2.5%, making it the safest prediction model as shown in Figure 2. This model was designed to calculate bond strength on the basis of ultimate strength design. Hence, high average strength is obtained.

Zhao [7] conducted an experimental study of 12 concrete prisms bonded with multiple layers of FRP sheets and proposed a simple bilinear relationship between the variation of fracture energy and concrete strength, given as

$$G_f = \begin{cases} 0.014 f_c' & 0 \le f_c' \le 46.2 \text{ MPa} \\ 0.65 & f_c' \ge 46.2 \text{ MPa} \end{cases} \tag{3}$$

Further, the ultimate debonding load between the FRP-to-concrete bond was defined in terms of the interfacial fracture energy and the stiffness of FRP, as given by Taljsten [12].

$$P_u = b_f \sqrt{2 G_f t_f E_f} \tag{4}$$

Of the listed interfacial fracture energy based model Zhao's model gave an average bond strength ratio of 1.314 and 21% unsafe design as shown in Figure 3. While most of the specimens lie in the safe zone for Zhao's model, they are highly scattered.

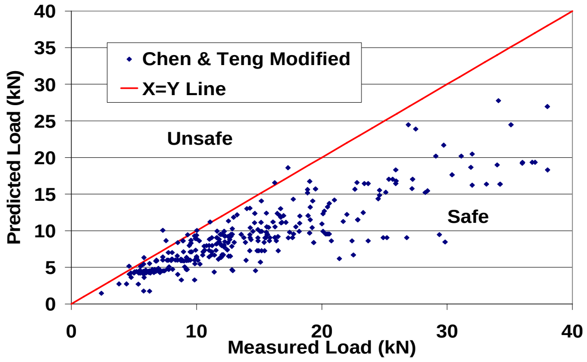

Fig. 2 Chen and Teng's Modified Model

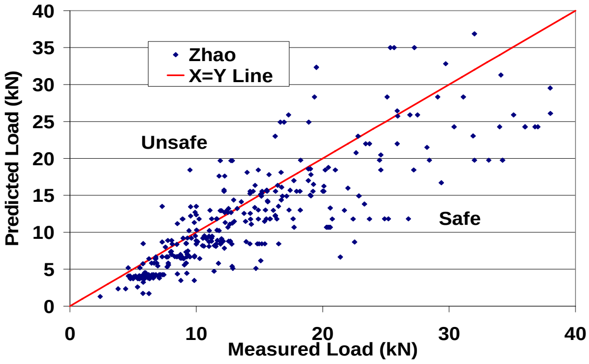

Fig. 3 Zhao's Model

Lu et al.'s [9] model is dependent on several parameters that require long calculations. It gave an average experimental-to-predicted ratio of 1.22 with a 26% unsafe design as shown in Figure 4. Dai et al.'s [11] model overestimated the bond strength and also had the highest percentage of unsafe design. The average is found to be 0.673 and 94% of the data failed earlier than predicted, as shown in Fig. 5.

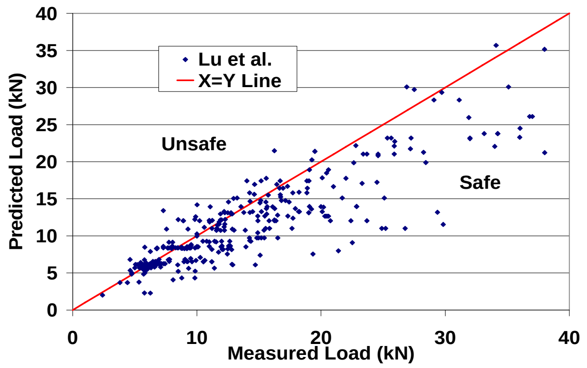

Fig. 4 Lu et al.'s Model

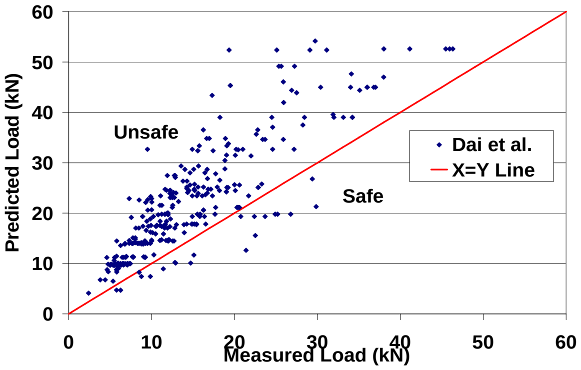

Fig. 5 Dai et al.'s Model

The models overestimating the bond strength were usually found to have a very high percentage of unsafe design and had largely scattered results. Empirical models underestimate the bond strength and have a scattered load prediction. It was also found that the underestimation of bond strength is mainly the reason for attaining a low percentage unsafe design (<10%) for some of these models.

2.2 Bending Tests

To understand the debonding mechanism of FRP sheets/plates from the concrete substrate of a strengthened RC beam, a database was created by reviewing various experimental studies. The beams failing in failure mode other than premature debonding were not included in the database. The details of both the databases are listed in [13]. The database was further divided into four categories based on the failure mode and the sheet lay-up process. The number of beams falling in each category was as follows: plate end wet lay-up = 67, plate end pultruded plate = 73, mid span wet lay-up = 22, and mid span pultruded plate = 1. This clearly shows that plate end debonding is more commonly occurring failure mode than mid span debonding.

Various models readily available in different studies were collected to predict the bond strength of FRP bonded concrete beams. One approach to prevent premature debonding is to limit the debonding strain in FRP to a certain value. Models by European Code *fib* bulletin 14 [1] approaches 1 and 2, Zhao [7], Teng et al. [4, 14], and Hassanen and Raoof [15] were based on this approach. For these models the ultimate debonding moment was calculated using beam theory and linear strain distribution. Other models were based on the shear capacity of the strengthened beam and/or on an interaction between the shear and flexural capacity of the beam. These included models by Matthys [16], Jansze [17], Ahmed et al. [18], Oehlers [19], Smith and Teng [20], Ziraba et al. [21], El Mihilmy and Tedesco [22], and Colotti and Spadea [23]. A simple model proposed by Naaman [24] based on the moment capacity of the unstrengthened beam is also discussed. The following conditions were subjected on all the beams in order to be included in the database:

1. The beam was simply supported with a rectangular cross-section,
2. The beam was subjected to either three-point or four-point bending,
3. The beam was under-reinforced before the application of FRP,
4. The beam was not preloaded or precracked,
5. The beam did not have any form of external anchorage,
6. The beam was bonded with FRP only on the tension face,
7. The beam failed in either mid-span or plate end debonding only, and
8. The beam was not devised or subjected to any physical condition in order to induce a particular failure mode.

Many researchers express the debonding of FRP-concrete interface in terms of strain in the fiber at the time of debond, commonly known as the debonding strain. The debonding strain could be expressed in the following form as derived from Equation (4). It was found on comparison of various existing models that models based on strain provide better estimation of debonding load than the models based on shear capacity.

$$\varepsilon_{db} = \frac{P_u}{b_f t_f E_f} = \sqrt{\frac{2G_f}{t_f E_f}} \tag{5}$$

The predicted ultimate debonding moment was calculated for each specimen of the database, as defined by all the models and the experimental to predicted bond strength ratios were calculated. It was used to analyze the behavior of each model with respect to the failure mode as well as the method of bonding of the FRP sheet/plate to the beam. Table 2 below lists various statistical parameters obtained for all the failure modes grouped together. The rationale of this comparison is simply to observe the predictability of the model for debonding in general and to examine whether or not the model could be used comprehensively.

fib Bulletin 14 [1] approach 1 based the model on the maximum axial tensile force in FRP. The debonding strain is given as

$$\varepsilon_{db} = \alpha c_1 k_c \beta_p \sqrt{\frac{f_{ct}}{E_f t_f}} \times \begin{cases} 1 & for \quad L \geq L_e \\ \dfrac{L}{L_e}\left(2 - \dfrac{L}{L_e}\right) & for \quad L < L_e \end{cases} \tag{6}$$

where, $L_e = \sqrt{\dfrac{E_f t_f}{c_2 f_{ct}}}$ (mm), $\beta_p = 1.06\sqrt{\dfrac{2 - b_f / b_c}{1 + b_f / 400}} \geq 1.0$, $b_f / b_c \geq 0.33$, $\alpha = 0.9$, c_1 = 0.64, c_2 = 2.0 (7)

fib Bulletin 14 [1] approach 2 was based on bond stress at the plate end in the FRP, which gave the debonding strain as

$$\varepsilon_{db} = c_1 \sqrt{\frac{\sqrt{f_{ct} f_c^{'}}}{E_f t_f}} \times \begin{cases} 1 & for \quad L \geq L_e \\ \dfrac{L}{L_e}\left(2 - \dfrac{L}{L_e}\right) & for \quad L < L_e \end{cases} \tag{8}$$

where $$L_e = c_2\sqrt{\frac{E_f t_f}{\sqrt{f_{ct} f_c'}}} \text{ (mm)}, \quad c_1 = 0.23, \text{ and } c_2 = 1.44 \tag{9}$$

Table 2 Experimental to Predicted Bond Strength Ratios for All Bond Failures.

	Models	Average	St. Dev.	COV	% Unsafe Design
1	Proposed Model	1.09	0.22	20 %	23 %
3	*fib* Approach 1 [1]	1.735	0.405	23 %	5 %
4	*fib* Approach 2 [1]	2.081	0.591	28 %	3.5 %
5	Teng et al. [4]	2.004	0.542	27 %	3 %
2	Zhao [7]	1.260	0.269	21 %	11 %
6	Teng et al. [14]	1.613	0.336	21 %	2 %
7	Hassanen and Raoof [15] (lower bound)	0.776	0.278	36 %	78 %
8	Hassanen and Raoof [15] (upper bound)	0.543	0.205	38 %	99 %
9	Matthys [16]	0.858	0.285	33 %	80 %
10	Jansze [17]	1.080	1.22	113 %	62 %
11	Ahmed et al. [18]	0.946	2.124	225 %	74 %
12	Oehlers [19]	1.290	0.518	40 %	30 %
13	Smith and Teng [20]	1.326	0.357	27 %	19 %
14	Ziraba et al. I [21]	2.585	2.940	114 %	36 %
15	Ziraba et al. II [21]	1.129	0.506	45 %	42 %
16	El-Mihilmy & Tedesco [22]	0.372	0.269	72 %	97 %
17	Colotti and Spadea [23]	0.824	0.304	37 %	81 %
18	Naaman [24]	1.307	0.384	29 %	14 %

Strain models by *fib* Bulletin 14 [1] and Teng et al. [4, 14] limit the debonding strain to very low values and hence tend to underestimate the bond strength. High averages in the range of 1.6~2.1 are obtained for all failures types individually and combined. Overly conservative estimate of bond strength is the prime reason for very low percentage of unsafe design (2~6%) obtained for these models. However, these models are slightly better for predicting mid span debonding as compared to plate end. It was interesting to note that for all above mentioned models the predicted debonding strain was in the limit of 0.3%~0.5% and hence similar behavior was obtained when the beam theory was applied to these models. The experimental moment is plotted against the predicted moment as shown in Figures 6 and 7. Teng et al. [14] proposed the following equation to predict the interfacial crack-induced debonding strain of the FRP plate at the critical section,

$$\varepsilon_{db} = 0.171\beta_p(4.32-\alpha)f_{ct}\sqrt{\frac{1}{E_f t_f}} \tag{10}$$

where $$\beta_p = \sqrt{\frac{2.25 - b_f/b_c}{1.25 + b_f/b_c}}, \text{ and } \alpha = \left(\frac{10.53}{\sqrt{f_{ct}^3}} - \frac{2}{3}\right)^{-1} \tag{11}$$

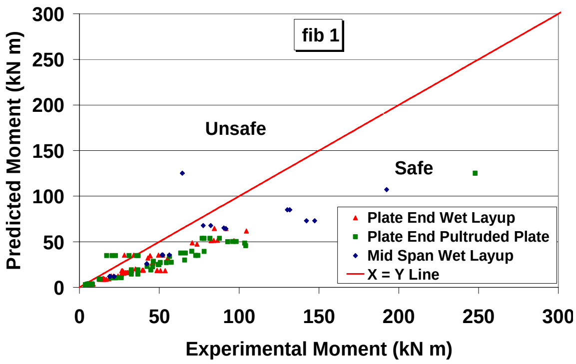

Fig. 6 fib's Approach 1 Model

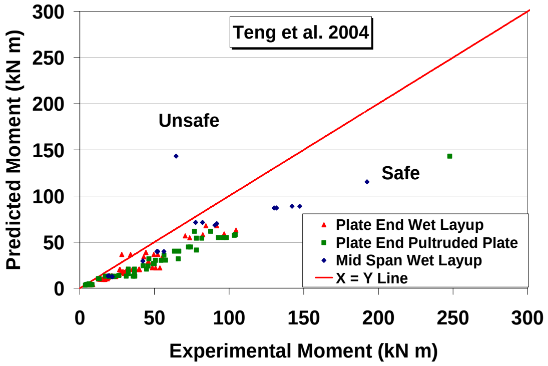

Fig. 7 Teng et al.'s Model

Zhao [7] studied the plate end failure in FRP strengthened RC beams and proposed two separate models for wet lay-up and pultruded plated beams, based on a limit on concrete compressive strength.

For wet lay-up beams
$$\varepsilon_{db} = \begin{cases} 0.35 f_c'(t_f E_f)^{-0.65} & \text{for} \quad f_c' \le 31.5\text{MPa} \\ 11.1(t_f E_f)^{-0.65} & \text{for} \quad f_c' \ge 31.5\text{MPa} \end{cases} \qquad (12)$$

For pultruded plated beams
$$\varepsilon_{db} = \begin{cases} 0.08 f_c'(t_f E_f)^{-0.5} & \text{for} \quad f_c' \le 31.5\text{MPa} \\ 2.51(t_f E_f)^{-0.5} & \text{for} \quad f_c' \ge 31.5\text{MPa} \end{cases} \qquad (13)$$

Zhao's model (Figure 8) gave an average experimental-to-predicted bond strength ratio of 1.387 and percentage unsafe design of 5% for wet lay-up plate end failure. It also predicted an average of 1.17 for pultruded plate end failure with a 16% unsafe design probability. It was the lowest obtained average ratio among the different failure modes using Zhao's model.

Naaman [24] used a simple approach to directly predict ultimate moment of a beam strengthened with FRP in terms of moment capacity of the unstrengthened beam and an increment of 20% of the nominal moment of the unstrengthened beam assuming maximum steel reinforcement ratio $\rho_{\max}$ as defined by ACI 318 [25].

$$M_{u,str} = M_{unstr} + 0.2M_{\rho\max} \qquad (14)$$

Naaman's model is one of the simple models, which provide reliable results for both mid span and plate end debonding as shown in Figure 9. An average experimental-to-predicted bond strength ratio of 1.3 is obtained for plate end failure and 1.09 for mid span debonding. Also a consistency is seen in the percentage unsafe design which ranges from 13~15% for different failure modes.

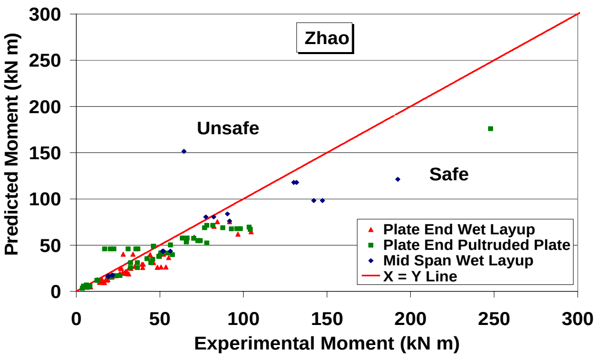

Fig. 8 Zhao's Model

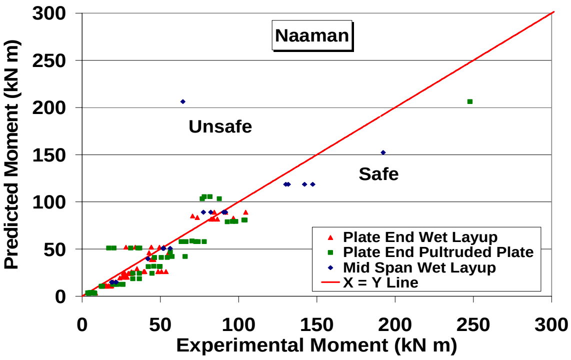

Fig. 9 Naaman's Model

Both lower and upper bound for the models proposed by Hassanen and Raoof [15], are unsafe in predictions with average experimental-to-predicted bond strength ratios ranging from 0.3~0.8. The pattern is similar for different lay ups and failure modes and a large scatter was obtained, as shown in Figure 10. Matthys' [16] model also overestimates the bond strength (average experimental-to-predicted ratio of 0.858) and with high percentage of unsafe design (80%), shown in Figure 11.

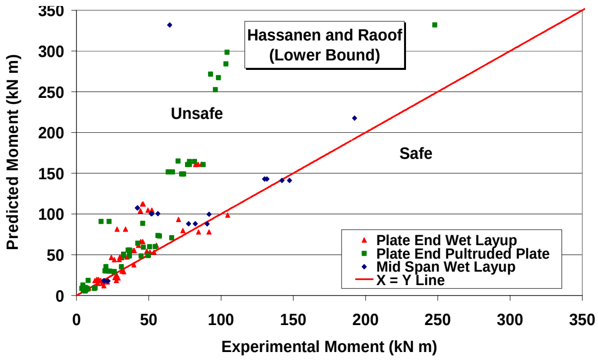

Fig. 10 Hassanen and Raoof's Model

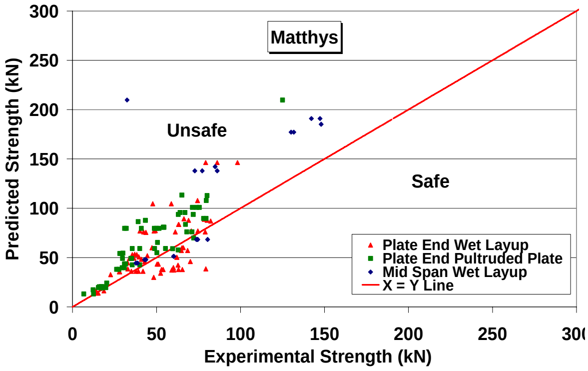

Fig. 11 Matthys' Model

For plate end failure, the models by Jansze [17] (Figure 12) and Ahmed et al. [18] (Figure 13) reverse their behavior for wet lay up and pultruded plated beams. While for plate end wet lay-up failure mode, Jansze's model underestimates the bond strength, and it overestimates the bond strength for pultruded plated beams. Ahmed et al.'s model overestimates the bond strength for plate end wet lay-up failure mode but underestimates the bond strength for pultruded plated beams. Thus, these models are not consistent in predicting the bond strength.

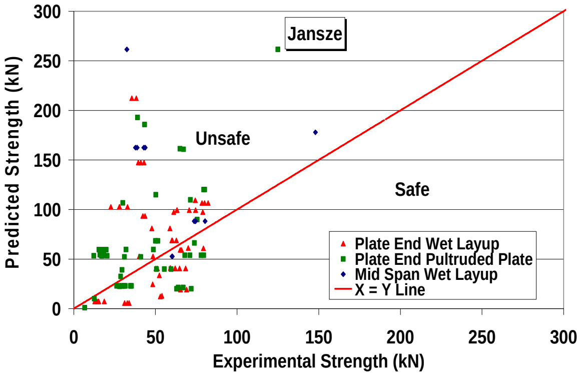

Fig. 12 Jansze's Model

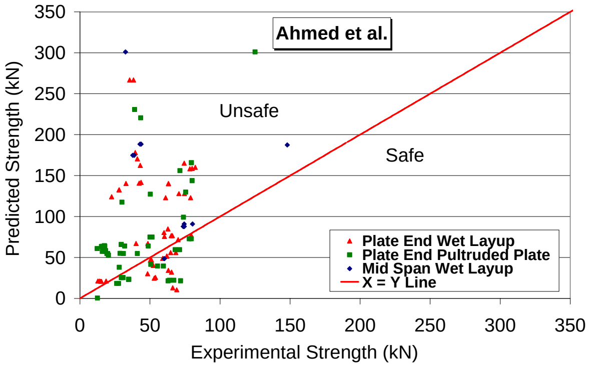

Fig. 13 Ahmed et al.'s Model

Oehlers' [19] noted that the shear capacity of the concrete in the RC beam alone controls the shear force at the plate end $V_{db,s}$, without the contribution from the steel shear reinforcement. He proposed a model based on interaction between the flexural and shear capacity of the beam.

$$\frac{M_{db,end}}{M_{db,f}} + \frac{V_{db,end}}{V_{db,s}} \leq 1.17 \tag{15}$$

where,

$$M_{db,f} = \frac{E_c I_{cr} f_{ct}}{0.901 E_f t_f}, \; V_{db,s} = V_c = \left[1.4 - \left(\frac{d}{2000}\right)\right] b_c d \left[\rho_s f_c^{'}\right]^{1/3}, \; 1.4 - \left(\frac{d}{2000}\right) \geq 1.1 \tag{16}$$

Oehlers' model (Figure 14) predicts conservative estimates of bond strength and therefore most of the specimens are within the safe range. Higher average is obtained for wet lay-up plate end failure at 2.039, but the percentage unsafe design is 0%. A similar pattern of lower percentage unsafe design with high experimental-to-predicted average ratios is seen for all the failure modes.

Smith and Teng [20] compared several plate end debonding models and derived a simple model based on the comparative study, given below. The model (Figure 15) is best suited for pultruded plated beam in plate end failure.

$$V_{db} = 1.5\left[1.4 - \left(\frac{d}{2000}\right)\right] b_c d \left[\rho_s f_c^{'}\right]^{1/3} \tag{17}$$

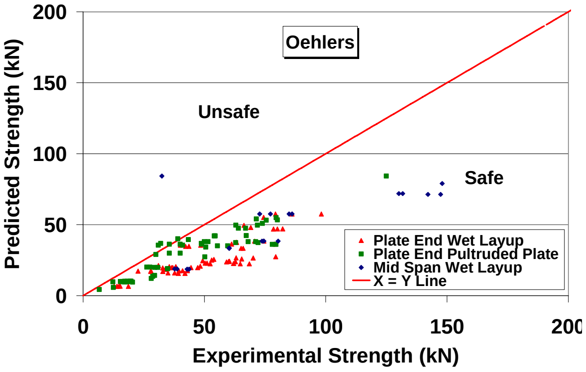

Fig. 14 Oehlers' Model

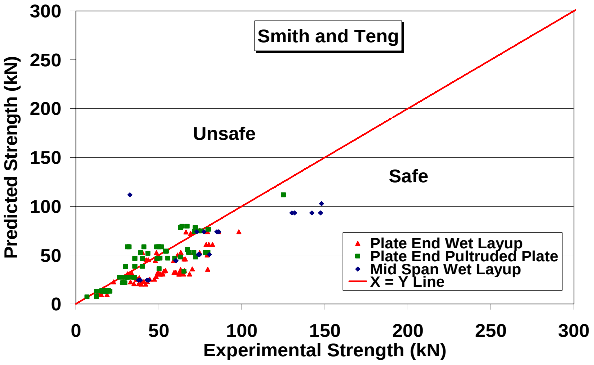

Fig. 15 Smith and Teng's Model

2.3 Debonding Strain

To calculate the actual debonding strain in FRP strengthened RC beams, a MATLAB program was developed. As the debonding strain is defined to be the strain in FRP at the time of failure of the experimental specimen, the following approach was used to calculate it. Failure in the beam was subjected to three conditions:

- When the actual strain in concrete exceeds the ultimate strain (ε_{cu} = 0.003), or
- If the calculated moment exceeds the experimentally obtained moment, or
- If the strain in the fiber exceeds the ultimate rupture strain given by the manufacturer.

If any one of the above-defined conditions was met, the program was designed to calculate no further and the debonding strain was obtained as the strain in the fiber at that instant. The value of neutral depth was iterated sufficiently to obtain the correct value. Beam theory was applied to calculate ultimate moment of the strengthened beam, which was compared with the experimentally obtained moment. The strain in FRP, tension steel and compression steel were obtained using linear strain distribution for the calculated value of concrete strain. The first estimate of neutral axis depth of a doubly reinforced concrete beam was obtained by equating the first moment of area of each component. The neutral axis depth '*c*' was given by c = kd, where

$$k = \sqrt{\left[\rho_s^{'}\left(n_s^{'}-1\right)+\rho_s n_s+\rho_f n_f\right]^2+2\left[\rho_s^{'}\left(n_s^{'}-1\right)\frac{d^{'}}{d}+\rho_s n_s+\rho_f n_f\frac{h}{d}\right]}-\left[\rho_s^{'}\left(n_s^{'}-1\right)+\rho_s n_s+\rho_f n_f\right] \tag{18}$$

The stress in each component was calculated by multiplying the obtained strain with the modulus of elasticity. A limit of 0.003 was placed on the ultimate strain in concrete, while the stresses in tension and compression steel were limited to their yield stress values. Iterations were performed on the neutral axis depth to obtain the correct value using

$$c = \frac{A_s f_s + A_f f_{fe} - A_s^{'} f_s^{'}}{0.85 f_c^{'} \beta_1 b_c} \tag{19}$$

where,

$$0.65 \le \beta_1 = 1.09 - 0.008 f_c^{'} \le 0.85 \tag{20}$$

Finally, the ultimate moment was calculated as given by ACI 440 [2]. An additional strength reduction factor of 0.85 was applied to the flexural contribution of FRP alone. This additional reduction factor is meant to account for lower reliability of the FRP reinforcement, as compared to the internal steel reinforcement. The obtained strain was then compared with parameters of Equation (5).

3 RESULTS

A regression analysis was performed on the database of the beams and the following results were obtained for different failure modes and plate/sheet lay-up processes. The debonding strain was restricted to the value of ultimate rupture strain of the fiber, as reported by the manufacturer. The limiting strain expressions are given as follows:

For plate end wet lay-up

$$\varepsilon_{db} = \begin{cases} 0.0855 f_c^{'} (n t_f E_f)^{-0.5} \le \varepsilon_{fu} & \text{for} \quad f_c^{'} < 31.5 \text{ MPa} \\ 2.694 (n t_f E_f)^{-0.5} \le \varepsilon_{fu} & \text{for} \quad f_c^{'} \ge 31.5 \text{ MPa} \end{cases} \tag{21}$$

For plate-end pultruded lay-up

$$\varepsilon_{db} = \begin{cases} 0.0989 f_c^{'} (n t_f E_f)^{-0.5} \le \varepsilon_{fu} & \text{for} \quad f_c^{'} < 31.5 \text{ MPa} \\ 3.1174 (n t_f E_f)^{-0.5} \le \varepsilon_{fu} & \text{for} \quad f_c^{'} \ge 31.5 \text{ MPa} \end{cases} \tag{22}$$

For mid-span wet lay-up

$$\varepsilon_{db} = \begin{cases} 0.13 f_c^{'} (n t_f E_f)^{-0.5} \le \varepsilon_{fu} & \text{for} \quad f_c^{'} < 31.5 \text{ MPa} \\ 4.1 (n t_f E_f)^{-0.5} \le \varepsilon_{fu} & \text{for} \quad f_c^{'} \ge 31.5 \text{ MPa} \end{cases} \tag{23}$$

Though many of the previously discussed models predict the debonding strength conservatively, almost all of these models are overly conservative. Due to such a high level of conservativeness, the model usually tends to design the beam safely and thus a low percentage unsafe design is obtained. But there is always a need for balancing the efficiency of the design to the conservativeness of the approach. A very conservative model shall predict low levels of bond strength and as a result a lot of material would go to waste in such a design. Economy is a crucial aspect for the design of FRP strengthened beams keeping in mind the high cost of the materials.

The following graph (Figure 16) was obtained between the predicted versus experimental moment when the proposed model was applied to the database.

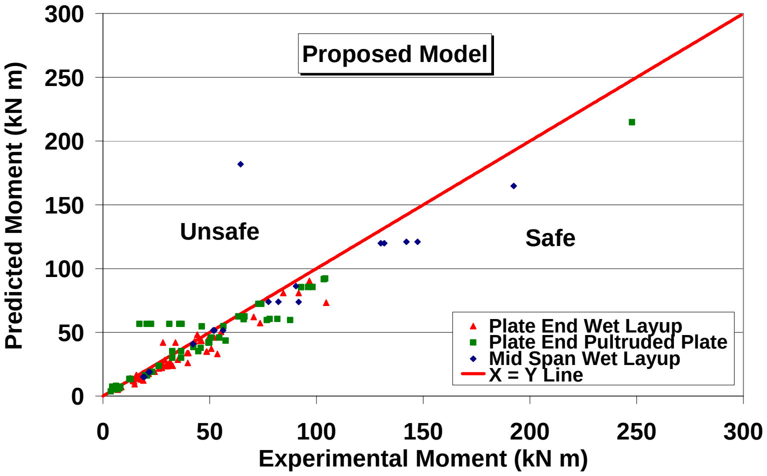

Fig. 16 Experimental vs. Predicted Moment using the Proposed Model.

4 CONCLUSIONS

Bond analysis is crucial for the advancement of newer innovative materials like FRP. It is important to ensure the effective use of this technology by providing safe design and cutting costs.

- The proposed model was verified against the database and the results were found to be satisfactory. Further verification of the model should be undertaken as new experimental results become available.
- The proposed model ensures simplicity and generalization for design purposes. It also warrants a balanced design with reasonable average bond strength ratio and percentage unsafe design.
- Of all the models discussed above, there is a pattern in the results which indicates that the trend of predictability is similar for mid-span and plate-end modes of the debonding failure.
- Limiting the debonding strain helps in preventing debonding but the results are highly conservative. The observed debonding behavior is similar when the debonding strain limit ranges from 0.25% to 0.7%.
- Zhao's model provides better results and safe predictions for pultruded plate end failures. Predictions of bond strength are slightly higher for the wet lay-up beams, but shall ensure safety when used for design purposes. Although Zhao's model was based on plate end failures, it is found to produce satisfactory results for mid span debonding too.
- Naaman's model provides reliable results for both mid span and plate end debonding. However, this model does not consider any of the geometric and material properties of the strengthening plate.

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