A New Analytical Model for Concrete Cover Separation of R/C Beams Strengthened with FRP Laminates

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ABSTRACT

External bonding of fibre reinforced plastic (FRP) laminates to reinforced concrete (RC) beams has been found to be an effective technique for flexural strengthening. The ultimate flexural strength of strengthened RC beams can be improved significantly. However the premature failure modes, such as concrete cover separation, prevent the full flexural capacity from being achieved. The objective of this paper is to establish a simple and accurate design methodology based on the concrete tooth model to predict the load carrying capacity of a FRP laminate strengthened RC beam with concrete cover separation. An analytical expression is developed taking into account the stress concentrations in concrete near the tension rebar closest to the shear crack initiating from cut off point of the FRP laminate. The derivation of the expression involves three major steps: (1) determination of the tensile stress in the FRP laminates assuming a full monolithic action; and (2) obtaining the local stresses and comparison with the concrete strength and (3) prediction of the length of concrete cover separation when the peak load of strengthened beam is reached. The reliability and accuracy of the proposed analytical procedure has been successfully verified by comparing analytical and experimental peak loads of the 52 FRP laminate strengthened beams with concrete cover separation available in the literatures.

KEYWORD

FRP strengthening; debonding; concrete cover separation; concrete tooth model
1. INTRODUCTION

External bonding of fibre reinforced plastic (FRP) laminates is considered as a major retrofitting method for flexural and fatigue strengthening or retrofitting of concrete flexural members. This technique has numerous advantages such as increasing the strength and stiffness of an existing beam while FRP characterizes high strength-to-weight ratio, low maintenance cost and higher corrosion resistance.

Existing experimental observations [1-18] have shown that the application of externally bonded FRP laminates to strengthen RC structures can lead to brittle failures involving debonding of the FRP laminates before the design load is reached. Among the premature debonding failure modes, concrete cover separation, as shown in Fig. 1, is often observed in the experiments. The failure of the concrete cover separation was initiated by the formation of a crack at the end of FRP laminate. The crack was further propagated to the level of the tension reinforcement in the RC part and then progressed horizontally along the level of the steel reinforcement, which results in the separation of the concrete cover. Current models to explain the concrete cover separation of a FRP strengthened beam fall into three broad basis [1]: (1) the derivation of elastic stress concentrations at the FRP laminate end (2) the shear capacity of strengthened beams and (3) the concrete tooth model. However, it has been reported that none of the current models can predict the peak load satisfactorily when concrete cover is separated [1-2]. For practical design, a better model is hence necessary.

The authors are conducting a series of studies with the aim at development of an analytical approach for flexural strengthening of an existing structure with external FRP laminate with predicting debonding failure. The objective of this paper is to establish a simple and accurate design methodology to predict the load carrying capacity of FRP laminates strengthened RC beam failed by concrete cover separation from the cut-off point of laminate end. The concrete tooth model is induced as an analytical tool and the length of concrete cover separation corresponding to the peak load is derived analytically. A proposal for identifying the inherent failure mode of FRP-strengthened beams with respect to the concrete cover separation is developed. The reliability and accuracy of the proposed analytical procedure are then verified by comparing the analytical and experimental peak load of the FRP-strengthened beams compiled in a bending test database.

2. ANALYTICAL MODEL

The experimental observations [5-18] available in the literatures suggest that the failure of the FRP-strengthened beam with concrete cover separation is controlled by two factors. One is the initiation and propagation of concrete cover separation, which consists of two stages; 1) formation of a shear crack at the end of FRP laminate, and 2) propagation of the crack to the level of the tension reinforcement and then progressed horizontally along the level of the steel reinforcement. Another one is the conditions to reach the peak load of FRP-strengthened beam after the concrete cover separation, which are 1) yielding of tension reinforcement at the shear flexure zone, which leads to the reduction of shear resistance of beam, 2) debonding of concrete cover along the entire shear span, which results in a total loss of efficiency of FRP flexural strengthening. The analytical approach should include the prediction of the stress concentrations in substrate concrete near the reinforcing bar above the location of the cut-off point of FRP laminate and the stresses of reinforcing and strengthening reinforcement at a certain distance from the laminate end when the peak load with concrete cover separation is reached. The following assumptions are made for the analysis:

1) The concrete, reinforcement in the substrate concrete part and the FRP laminate follow linear elastic behavior.
2) The concrete section between two adjacent cracks has linear strain distribution in tension (see Fig. 2).
3) The FRP laminate and the substrate are assumed to behave monolithically before the concrete cover separation.

2.1 Concrete Tooth Model

Series of cracks in the concrete cover lead to the formation of concrete blocks with a slit between
that resemble “comb teeth” along the bottom of the RC beam as shown in Fig. 2. The concrete tooth model was developed by assuming that a concrete “tooth” between two adjacent cracks deforms like a cantilever under the action of horizontal shear stresses acting near the cantilever tip, which is caused by the difference in tension stress ($\Delta \sigma_f$) in the FRP laminate [3, 4].

For a single tooth (concrete block) within given tooth spacing $S_{cr}$ as indicated in Fig. 2, the tensile stress $\sigma_A$ at point A generated by the tensile stress of FRP laminate $\sigma_f$ can be determined as follows:

$$\sigma_A = \frac{M_A}{I_A} \left( \frac{S_{cr}}{2} \right)$$  \hspace{1cm} (1)

$$I_A = b S_{cr}^3 / 12$$  \hspace{1cm} (2)

$$M_A = \sigma_f t_f h_f h_0$$  \hspace{1cm} (3)

where $I_A$ denotes the moment of inertia of a tooth as a cantilever, $M_A$ denotes the moment at the base of the tooth, $h_0$ is the net height of concrete cover measured from the bottom side of the reinforcing bar in the substrate concrete to FRP laminate, $b$ is the width of beam and $h_f$ and $t_f$ are the width and thickness of FRP laminate, respectively.

The debonding criteria used in this study is such that when the concrete tensile stress $\sigma_A$ in the tooth closest to the cut-off point of the overlay is greater than the tensile strength of concrete, concrete cover separation failure occurs. Based on Eqs. (1)-(3), the tensile stress in the FRP laminate at the point B (see Fig. 2) required to cause tensile cracking and failure of a tooth can then be determined as

$$\sigma_f = \frac{f_i b S_{cr}^2}{6 h_0 b_f t_f}$$  \hspace{1cm} (4)

where $f_i$ denotes the tensile strength of substrate concrete and can be determined with the following equation based on JSCE Standard Specifications for Concrete Structures [19] as

$$f_i = 0.23 f_c^{2/3}$$  \hspace{1cm} (5)

where $f_c$ denotes the cylinder compressive strength of concrete.

Based on the experimental observations, the concrete cover is separated and propagated towards the center of beam, until it meets one of the shear flexure cracks, at which the reinforcing bar yields due to concrete cover separation, and the peak load is reached. If all the teeth within the length $L_p$ ranging from the FRP laminate end to the shear flexure crack are assumed to have the same tooth spacing $S_{cr}$ and fail simultaneously, the tensile stress of reinforcing bar or FRP laminate at a distance of $L_p$ from the laminate end can be determined from Eq. (4) as

$$\sigma_{sp} = \frac{f_i b S_{cr} L_p}{6 h_0 b_f t_f}$$  \hspace{1cm} (6)

where $L_p$ equals to the distance from the FRP laminate end to the point C of shear crack which causes the shear failure of beam as shown in Fig. 2.

However, the current developed tooth model can not predict the peak load satisfactorily mainly because 1) the debonding length ($L_p$) corresponding to the peak load were calibrated with the test data, which were actually difficult to be measured accurately due to the abruptness of debonding failure and 2) the effect of diagonal shear crack to the tooth spacing ($S_{cr}$) were ignored, which indeed greatly affected the prediction results. Therefore, the determination of $L_p$ analytically and reduction of tooth spacing after the formation of the diagonal shear crack are key considerations in this analysis.
2.2 Concrete Tooth Spacing

Fig. 3.a shows a longitudinal segment of FRP strengthened beam between two adjacent cracks. The bond stress at the reinforcement-concrete interface and the concrete-FRP interface at the stabilized crack stage are assumed to follow a parabolic variation according to [20] and [21]. The free body diagram of the concrete and FRP composite elements with length of $dx$ is shown in Fig. 3.b. Based on the equilibrium of forces acting on the concrete and FRP segment and following the fact that the tensile stress of concrete between to adjacent cracks is not greater than the concrete tensile strength at the stabilized crack stage, the stabilized flexural crack spacing ($S_{\beta}$) of FRP laminate strengthened RC beam is given by

$$S_{\beta} = \frac{3bf_{\beta}A_{\beta}}{\sum O_{r} \tau_{sc} + b_{f} \tau_{FRP}}$$  \hspace{1cm} (7)

where $O_r$ denotes the perimeter of reinforcement in concrete. $k$ is a coefficient to account for strain gradient = $(\epsilon_1 + \epsilon_2)/2\epsilon_1$ according to [22], $\epsilon_1$ and $\epsilon_2$ are the largest; and smallest tensile strains in the effective tension zone as illustrated in Fig. 4. $\tau_{sc}$ and $\tau_{FRP}$ denote the peak bond stress at the reinforcement-concrete interface and the FRP-concrete interface at the stabilized crack stage, which can be calculated as following [23]

$$\tau_{sc} = 1.25 \sqrt{f'_{c}}$$ \hspace{1cm} (8)

$$\tau_{FRP} = 1.25f_{t}$$ \hspace{1cm} (9)

$A_{\beta}$ denotes the effective tension area of concrete. According to An et al. [24], for a certain steel bar, the maximum effective tension area of the reinforced concrete ($A_{\beta,max}$) within which stable crack can develop is,

$$A_{\beta,max} = \frac{A_{r} \cdot f_{yr}}{f_{t}}$$ \hspace{1cm} (10)

where $A_{r}$ and $f_{yr}$ denote the area, the yielding strength of unit tension reinforcement in concrete respectively. In a two-dimensional consideration, the maximum side length of square effective tension zone for reinforcement in substrate ($h_{ct,max}$) can then be calculated as,

$$h_{ct,max} = \sqrt{A_{\beta,max}}$$ \hspace{1cm} (11)

This effective tension zone of steel bar should be limited by the cover thickness of concrete. Moreover, in case of bending, the height of effective tension area should not be higher than the height of area in tension ($h_{ct}$), which is below the neutral axis as shown in Fig. 3.

Eq. (7) predicts the stabilized flexural crack spacing within the constant moment zone. However, the concrete tooth spacing (mainly at the FRP laminate end zone and shear flexural zone) depends not only on the flexural cracking but also on the diagonal shear cracking as illustrated in Fig. 1. Based on experimental observations, it is assumed that the average spacing of concrete teeth after formation of the diagonal shear crack is same as the minimum flexural crack spacing [2-4], which is usually taken as two-thirds of the average flexure crack spacing calculated from Eq. (7).

According to ACI Code 318-02[25], it was suggested that in regions with large shear an small moment, diagonal tension cracks were formed at an average shear force of
where $d_{eff}$ denotes the effective depth of FRP-strengthened beam. Eq. (12) is applied in this study to identify the formation of diagonal shear cracks.

2.3 Sectional Analysis
The tensile stress of reinforcing bar in RC part and FRP laminate can be calculated based on sectional analysis of FRP-strengthened beam as shown in Fig. 5.

(1) FRP laminate
The moment at the section of Point C (see Fig. 2) before concrete cover separation can be expressed as,

$$M_{sp} = \frac{I_f \sigma_{sp}}{(d_f - x_{g1})}$$

where $x_{g1}$, $I_f$ denote the neutral axis depth (see Fig. 4.b) and the transformed moment of inertia of the beam cracked cross section in terms of the FRP laminate, $d_f$ is the efficient depth of FRP laminate.

(2) Reinforcing bar in substrate concrete beam
After the concrete cover separation, the FRP laminate has no contribution to the cross section stiffness. This may lead to the yielding of reinforcing bar in the substrate concrete and the shear resistance of concrete beam is decreased consequently. The beam may fail by diagonal tension failure right after the concrete cover separation if the decreased shear resistance is less than the applied shear force at that moment.

The bending moment which causes the yielding of the reinforcing bar at a distance of $L_p$ from FRP laminate end is calculated as:

$$M_{ru} = \frac{P(d_0 + L_p)}{2} = \frac{I_l f_{ys}}{(d_f - x_{g2})}$$

where $d_0$ and $P$ denote the distance from support to laminate end and the applied load respectively. $x_{g2}$, $d_f$ and $I_l$ denote the neutral axis depth (see Fig. 4.c), effective depth and the transformed moment of inertia of the cracked cross section of the beam in terms of the reinforcing bar respectively.

2.4 Prediction of Peak Load
As discussed above, the peak load can be reached right after the reinforcing bar is yielded at a distance $L_p$ from the FRP laminate. Therefore at the peak load point,

$$M_{sp} = M_{ru}$$

From Eq. (6) and Eqs. (13)-(15), the following relationship can be derived

$$\sigma_{sp} = \frac{f_{fs} S_c L_p}{6 h_d b_f I_f} = \frac{M_{ru}(d_f - x_{g1})}{I_f}$$

The distance $L_p$ necessary for yielding of reinforcing bar can then be determined as

$$L_p = \frac{6 h_d b_f I_f (d_f - x_{g1}) M_{ru}}{f_{fs} S_c I_f}$$

Finally, the peak load at the yielding of reinforcing bar in the substrate concrete $P_{dy}$ can be calculated as
If the reinforcements with high yielding strength are used in the substrate concrete, the calculated value of $L_p$ may be greater than the length of FRP laminate within the shear span $L_a$ (see Fig. 2). In this case, the peak load of FRP strengthened beam is reached with the debonding of FRP laminate along the entire shear span (until Point D in Fig. 2), before the yielding of reinforcements in the shear flexure zone of substrate concrete beam, the length $L_a$ should be used in Eq. (6) and Eq. (18) to predict peak load $P_{da}$ with debonding of FRP laminate along the entire shear span.

3. DESIGN PROPOSAL

A proposal for identifying the inherent failure mode of FRP-strengthened beams with respect to the concrete cover separation is shown in Fig. 6. At the beginning, the tooth spacing is taken as average flexural crack spacing ($S_f$). If the calculated debonding load is greater than the diagonal shear cracking load, which means that the diagonal shear cracks occur before the concrete cover separation, the tooth spacing is then taken as two-thirds of the average flexural crack spacing as discussed previously to calculate again the debonding load. If this newly calculated debonding load is smaller than the diagonal shear cracking load, the concrete cover separation takes place right after the formation of diagonal shear cracks ($P_{dy}=V_{cd}$). The flexure strength $P_f$ of FRP-strengthened beam without concrete cover separation can be predicted using the conventional analysis approach by assuming that the FRP
laminate and substrate beam are monolithic according to the available standard specifications [19]. By comparing the debonding strength with the theoretical flexure strength without concrete cover separation, the peak load \( P_u \) and failure mode of a given strengthened beam can be determined by the minimum strength. The shear failure of FRP-strengthened beam without debonding is not considered in this proposed analysis.

4. VERIFICATION OF PROPOSED MODEL

The proposed analytical model can be applied to predict the strength of FRP-strengthened RC beam with failure of concrete cover separation. In order to verify the applicability and reliability of this analytical approach, a database as in [2] assembled from the published literatures with following selection criteria are presented, 1) failure of beam was due to concrete cover separation 2) sufficient geometric and material parameters were provided.

With the above selection criteria, 52 available test results are included in the present database which provides a solid basis for verifying and assessing the proposed design proposal. All the test data included in this data base were obtained for simply supported rectangular RC beams strengthened with CFRP or GFRP laminate, subjected to four-point bending load. Appendix A gives the RC beam details as well as the reinforcement properties in the RC beam and the geometric and material properties of FRP laminate, respectively. Eq. (5) is adopted to calculate the concrete tensile strength if it is not provided.

Analytical and experimental results in detail are listed in Appendix A (available online at [26] due to space limitation). The effects of several process operations according to flowchart in Fig. 6, e.g. effect of diagonal shear cracks to average tooth spacing, the location at the yielding of tension reinforcement, the failure mode with concrete cover separation are noted as well. All the predicted peak loads \( (P_{CAL}) \) are smaller than corresponding flexural strength \( P_f \), which indicates the correct prediction of failure mode. The comparison between experimental and analytical peak load are shown in Fig. 7. The mean value of ratio between calculated and experimental peak load \( P_{CAL}/P_{EXP} \) is 0.98 with a standard deviation of 0.16 and \( R^2=0.95 \). In total, the analytical values have a satisfactory agreement with the experimental values, which verifies the accuracy of proposed analytical approach, indicating that the proposed prediction method is reliable.

5. CONCLUSIONS

The behaviors of FRP laminate strengthened RC beam failed by concrete cover separation are investigated in this paper. The failure of the concrete cover separation was initiated by the formation of a crack at the edge of FRP laminate caused by its abrupt termination. The crack was further propagated to the level of the tension reinforcement in the substrate concrete beam part and then progressed horizontally along the level of the steel reinforcement and the peak load is reached after the concrete cover separation until 1) the tension reinforcing bar yields or 2) the entire shear span debonds. A simple and easy handling analytical approach is developed based on the considerations in concrete near the reinforcing bar closest to the cut-off point of the FRP laminate. The analysis, based on the tooth model, consists of three stages; the determination of 1) local stress of substrate concrete at the lower face of the reinforcing bar, 2) tensile stress of FRP laminate by assuming the monolithic composite action, and 3) length of concrete cover separation corresponding to the peak load. The peak load of FRP-strengthened beams with concrete cover separation can be predicted by using this analytical approach.

The reliability and accuracy of the proposed analytical procedure have been successfully verified by comparing the analytical and experimental peak load of the FRP-strengthened beams provided in the published literatures.
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REFERENCES