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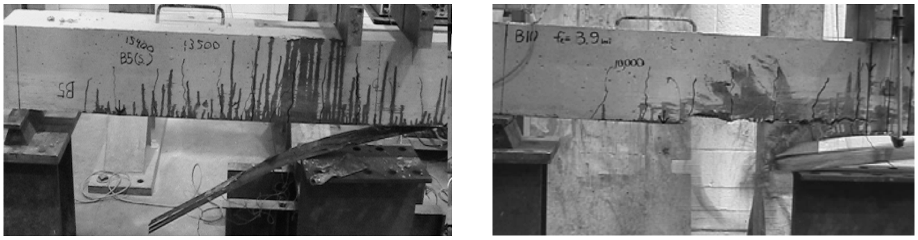
Design guidelines for preventing cover delamination failure

M. So[1], C. Schiller[2] & T. Harmon[1]
[1]*Washington University in St. Louis, Missouri, USA*
[2]*University of Nebraska at Lincoln, Nebraska, USA*

ABSTRACT: R/C beams reinforced with surface mounted fiber reinforced plastic (FRP) can fail prematurely by cover delamination due to separation of the concrete cover beneath the bottom layer of steel reinforcement. Most existing models predict cover delamination failure mode based on stress concentrations that are dependent of the properties of the bond layer. The effect of bond layer properties on cover delamination was studied based on an experimental program. The experimental results demonstrate that bond layer properties do not significantly affect cover delamination. A new model that is independent of bond layer properties is proposed and provides a correlation coefficient of 0.96 with all data available in the literature, including ACI 440 Committee's Bond Group database for R/C beams failed by cover delamination. The model predicts loss of structural integrity in the concrete cover in a manner similar to the ACI detailed shear equation and is essentially a shear/moment interaction equation. In addition, the correlation to the failure load was further improved by including the ratio of stiffness of FRP to the stiffness of the steel reinforcement but didn't improve when the stiffness of FRP alone was used. This paper presents a power-law equation and design guidelines for preventing FRP cover delamination failure.

1 INTRODUCTION

ACI Committee 440-2R identifies two premature failures for FRP mounted R/C members. They are FRP and Cover Delamination as shown in Figures 1(a) and 1(b). FRP Delamination occurs at the FRP/concrete interface and originates at flexural or shear cracks. Delamination proceeds from the origination point toward the support. Cover Delamination initiates at FRP termination points and occurs in the concrete in the plane of the reinforcement and results in separation of concrete cover. Delamination proceeds from the FRP termination point toward the center of the span. This paper focuses on Cover Delamination (CD).



(a) FRP Delamination (b) Cover Delamination

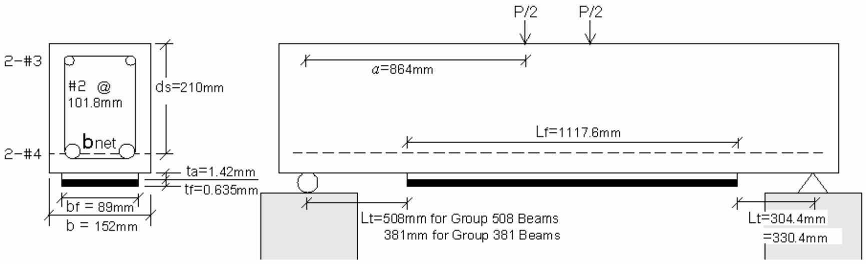
Figure 1. Two premature failure modes identified by ACI Committee 440-2R

Previous studies showed that a soft bond layer increases the FRP Delamination failure load. Therefore, it was decided to study if a softer bond layer would improve Cover Delamination. Many models predict CD failure load based on the stress concentrations at the FRP termination points and thus are dependent upon adhesive flexibility. However, the predicted failure loads based on the stress concentrations did not agree with the experimental loads.

This paper includes an experimental program that was developed to investigate CD, which showed that existing models may be inadequate. Subsequently, a new failure model was identified, and a larger database was created to develop a design equation with which structural engineers can predict CD failure loads.

2 EXPERIMENTAL INVESTIGATION

An experimental program was developed to verify the effect of adhesive flexibility. Twelve 152 mm by 229 mm beams reinforced with FRP strips were tested in four-point bending. Three test variables were studied: the first variable was the adhesive stiffness which was either 2,482MPa or 1.2 MPa; the second parameter was the ratio of shear to bending moment, represented by L_t, the distance from the support to the termination point; the third variable was the concrete strength. Tested beams were grouped by L_t into group 508 and group 381. The elastic modulus of the FRP and steel reinforcements are 124,110MPa and 200,000MPa, respectively.



(a) cross-section (b) longitudinal section

Figure 2. Beam details and test setup.

3 EXPERIMENTAL RESULTS AND DISCUSSION

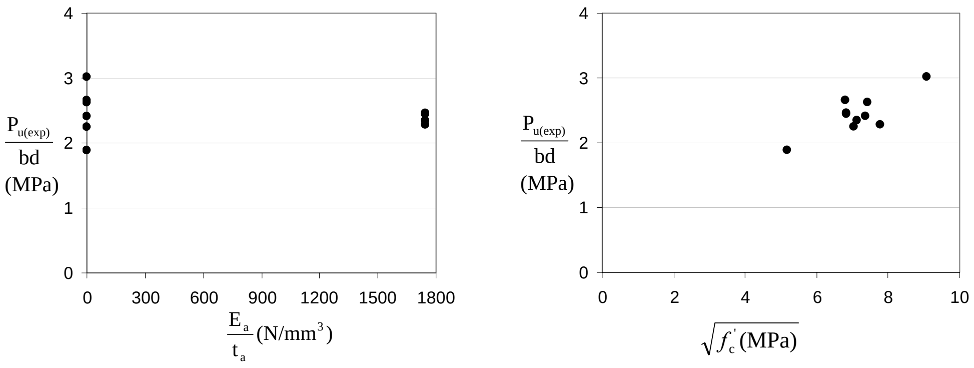
So and Harmon (2008) reported the experiment results summarized in Table 1. Most of the beams failed by CD; two failed for other reasons.

Table 1. Test results.

Group 508 (L_t = 508mm)								
Beam	UB1	B3	B7	UB4	UB2	B2	B4	UB3
E_a, MPa	1.2	1.2	1.2	1.2	2.482	2.482	2.482	2.482
$f_c^{'}$, MPa	83	54	50	55	47	47	51	61
$P_{u\ (exp)}$, kN	93.2	74.8	69.7	81.4	75.5	76.2	72.7	70.6
Failure Mode	CD	CD	CD	CD	CD	CD	CD	CD

Group 381 (L_t = 381mm)				
Beam	B6	B20	B8	B9
E_a, MPa	2.482	1.2	1.2	1.2
$f_c^{'}$, MPa	51	27	46	77
$P_{u\ (exp)}$, kN	78.3	58.2	82.4	89.9
Failure Mode	FRP del.	CD	CD	FRP split

Figure 3 shows the effect of test parameters. In Figure 3(a), the failure load, $P_{u(exp)}$, seems fairly constant while the adhesive modulus, E_a, ranges from 1.2 to 2500MPa. In contrast, Figure 3(b) shows that the concrete strength, $f_c^{'}$, is directly related to the failure load.



(a) effect of adhesive modulus (b) effect of concrete strength

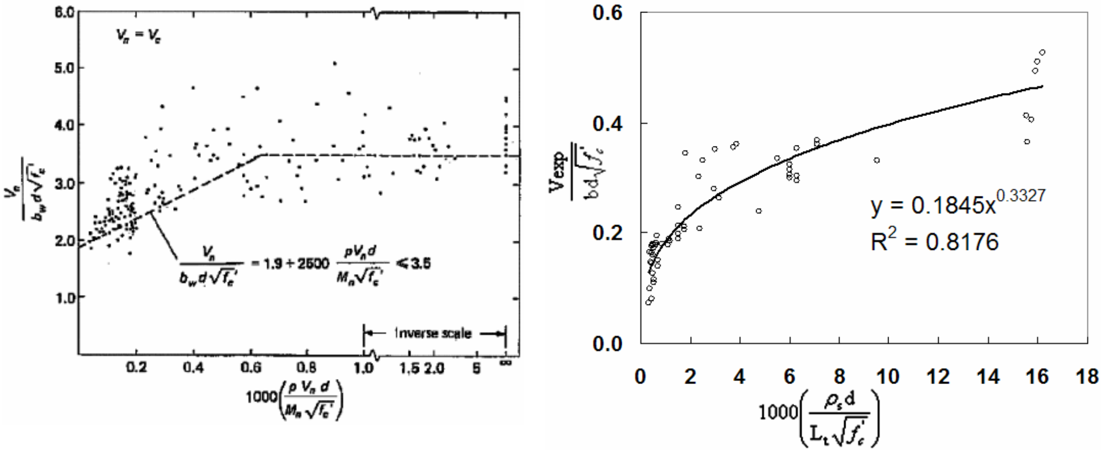
Figure 3. Effect of test parameters on cover delamination failure loads.

4 FAILURE MODEL

Four stages of failure were identified from observations made during the experiment. Stage 1: flexural cracks develop over the span; Stage 2: Diagonal shear cracks develop at the FRP termination point; Stage 3: further shear/flexural cracks develop and the concrete cover loses its integrity; Stage 4: the FRP reinforcement pulls concrete cover away from the beam, and a longitudinal crack is observed before CD failure. In essence, the new failure model evaluates the integrity of concrete cover and assesses the amount of force developed in the FRP reinforcement, which is what causes the concrete cover to separate.

5 DESIGN EQUATION

A new failure model was identified from the experimental observation; however, a larger database was needed to develop a design equation. Therefore, 60 test data (Ahmed et al. 2001; Arduini et al. 1997; Fanning & Kelly 2001; Harmon et al. 2003; Jones et al. 1980; Kaminska et al. 2000; Nguyen et al. 2001; Oehlers 1992; Quantrill et al. 1996; Swamy et al. 1987), including the experimental data reported by So & Harmon (2007), were collected.



(a) derivation of ACI’s detailed shear equation (b) new CD shear equation

Figure 4. Detailed shear equation: adopted from ACI-ASCE Committee 326 Report.

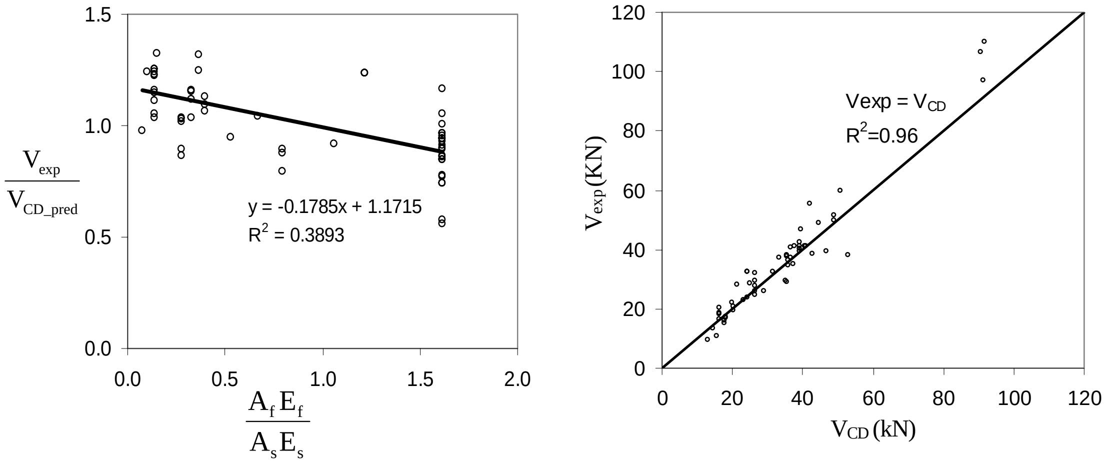
The detailed shear equation of the current ACI standard is a good predictor of the extent of the loss of structural integrity due to combined shear and flexural cracking. Therefore, in building a design equation, the same methodology used to develop the ACI detailed shear equation was adopted. Instead of fitting the data with two linear lines, a power-law equation was used to relate the CD failure load to the concrete strength and V/M ratio at the FRP termination point, which is also L_t (the second parameter of the experimental program).

$$V_{CD\_pred} = 0.1845 \left(\frac{1000\rho_s d}{L_t \sqrt{f_c^{'}}} \right)^{1/3} bd\sqrt{f_c^{'}}\text{, where } L_t = \frac{V_t}{M_t} \tag{1}$$

CD failure would not have occurred in the absence of surface mounted FRP reinforcement even though the concrete cover loses its integrity. The amount of force developed in the FRP reinforcement not only depends on the stiffness of the FRP reinforcement but also on the stiffness of the steel reinforcement. Therefore, the ratio of FRP stiffness to steel stiffness (A_fE_f/A_sE_s) was further related to the experimental failure load as shown in Figure 5(a).

$$V_{CD} = \left[-0.1785\left(\frac{A_f E_f}{A_s E_s} \right) + 1.1715 \right] V_{CD\_pred} \tag{2}$$

$$V_{CD} = \left[-0.1785\left(\frac{A_f E_f}{A_s E_s} \right) + 1.1715 \right] \left[0.1845\left(\frac{1000\rho_s d}{L_t \sqrt{f_c^{'}}} \right)^{1/3} bd\sqrt{f_c^{'}} \right] \tag{3}$$



(a) effect of the FRP stiffness to steel stiffness ratio (b) predicted vs. experimental failure shear force

Figure 5. Design equation, V_{CD}, derivation and correlation with the experimental failure shear force, V_{exp}.

Replacing V_{CD_pred} shown in Equation 2 with Equation 1, Equation 3 yields the improved prediction of the Cover Delamination failure load. Figure 5(b) compares the predicted failure shear force, V_{CD}, calculated by Equation 3, to the experimental failure load, V_{exp}, and shows the correlation factor of 0.96 for 60 studied beams.

6 DESIGN GUIDELINES

The experimental results (Kaminska & Kotynia 2000; Ritchie et al. 1991) of four beams that failed by CD, provided by the ACI 440 Committee's Bond Group, were used to predict the CD failure load. Figure 6 includes the experimental results and failure load predictions of the four beams alongside those of the previously studied beams, and clearly shows that Equation 3 satisfactorily predicts the experimental CD failure shear load. The ACI detailed shear equation limits $M_t d/V_t$ (or d/L_t) to 1.0; the limit of $M_t d/V_t$ in Equation 3 has yet to be set by ACI. Be aware that the studied beams are small in scale (d < 250 mm). The equation may not apply to large R/C members. A full-scale test should be undertaken.

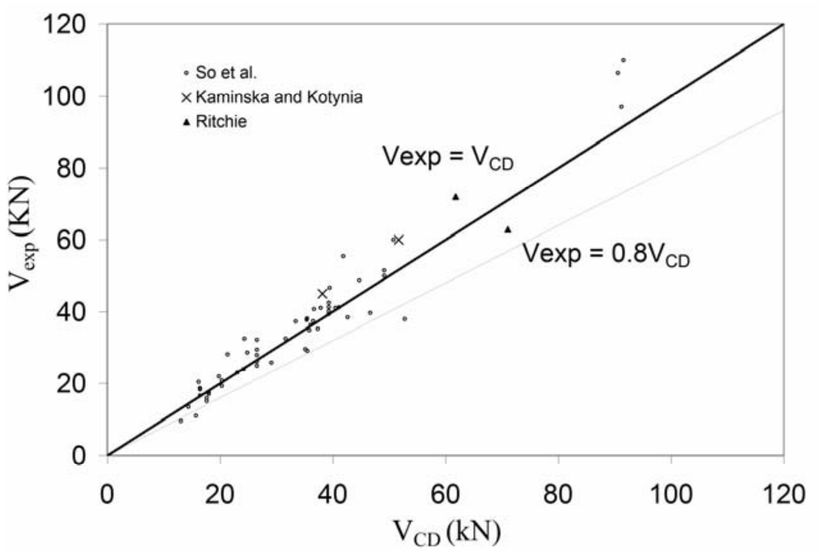


Figure 6. Predicted vs. experimental cover delamination failure loads.

If the equation correctly predicts the observed loads, it would be expected that the relative error between the experimental and predicted loads (Eqn. 4) would be normally distributed about zero. Examine, first, the mean with a *t*-Test, and, then, the distribution with a chi-squared test.

$$relative\ error = V_{\exp} / V_{CD} - 1 \tag{4}$$

For the 63 observations above (mean error of 5.42%, standard deviation of 15.56%), a *t*-Test, with null hypothesis of the average relative error equal to zero and an alternative hypothesis of it not equal to zero, rejects the null hypothesis at the 99% level. Thus the mean of 5.42% suggests that the model is biased toward predicting failure loads less than actual failure loads.

A chi-squared test (χ^2 = 4.88, df = 7), with null hypothesis of experimental values come from a normal distribution with a mean of 5.42% and standard deviation of 15.65% and alternative hypothesis of experimental values come from some other distribution, cannot reject the null hypothesis at even the 40% level. Illustrated in Figure 7, the relative error is normally distributed about 5.42% with a standard deviation of 15.65%.

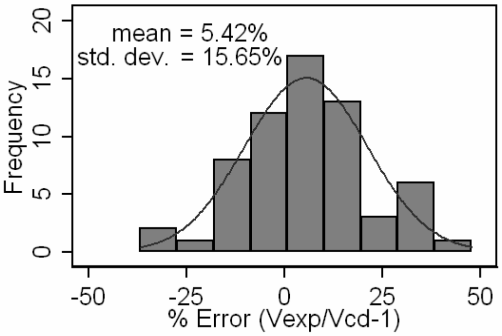


Figure 7. Histogram of relative error with the normal curve superimposed.

Relative error that is normally distributed about a nonzero mean could suggest the model is incomplete. In fact, there is a term which would remedy this. However, it had been unnecessary to include as it is implicitly absorbed by the confidence coefficient. The confidence coefficient is the coefficient added to a model to account for the variability between the predicted and observed values. With it, it may be said that the actual strength will exceed the calculated strength C% of the time. Thus, the equation becomes:

$$V_{C\%} = C_{C\%}(V_{CD}) \tag{5}$$

where $C_{C\%}$ is the confidence coefficient, V_{CD} is the predicted failure load, and $V_{C\%}$ is the maximum load at which it is expected that C% of members will still hold. $C_{C\%}$ is obtained from

$$C_{C\%} = 1 + invNorm(5.42\%, 15.65\%, 1 - C\%) \tag{6}$$

Values of $C_{C\%}$ are provided in Table 2 below. Thus, in Figure 6, it can be said with 95% confidence that the observed failure load will be greater than that indicated by the line $V_{\text{exp}} = 0.8V_{\text{CD}}$.

Table 2. Table of confidence coefficients, $C_{C\%}$.

C%	90.00%	95.00%	99.00%	99.50%	99.90%	99.95%	99.99%
$C_{C\%}$	0.85	0.80	0.69	0.65	0.57	0.54	0.47
	decreasing certainty	......	......	......	......	......	*increasing certainty*

7 CONCLUSIONS

It is concluded that adhesive flexibility does not affect the Cover Delamination (CD) failure load but strength of concrete is directly related to the CD failure load. The ratio of FRP stiffness to steel stiffness also affects the failure load. CD failure load can be predicted by the proposed power-law equation and in accordance with the above suggested design guidelines.

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