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# BOND BETWEEN CFRP SHEETS AND CONCRETE

Brian Miller[1]
Antonio Nanni[2], Member ASCE

*Abstract*

This paper presents the findings of an experimental program aimed at investigating the strain distribution between Carbon Fiber Reinforced Polymer (CFRP) sheets and concrete. CFRP is used as externally bonded reinforcement for concrete structures to improve flexure and shear strength and confinement of concrete. The effects of bonded length, concrete strength, and number of plies (or stiffness) of CFRP were investigated. From the results, a method for determining the ultimate load was found.

**Keywords:** Composite,CFRP,laminate,sheets, concrete, bond, peeling,externally bonded

*Introduction*

The bond between CFRP sheets and concrete is an issue that is in need of attention. The importance of bond is that it is the means for the transfer of stress between the concrete and CFRP in order to develop composite action. The bond must be characterized by determining the shape of the strain distribution in the CFRP sheet and the factors that affect the strain distribution. Also, the failure mode must be determined.

The main objective of this experimental project was to address the factors affecting the bond between CFRP sheets and concrete. The factors addressed were:

- length of bonded surface
- compressive strength of concrete
- number of plies of CFRP (stiffness)

A series of test specimens was fabricated to address each of the factors. The results of these tests were analyzed in order to determine their effect on strain distribution in the CFRP sheet and failure mode. Also, the results were compared with previous work as described in the literature. From this, a method for predicting the ultimate load was presented.

[1]Department of Civil Engineering, University of Missouri-Rolla, M.S. Student
[2]Department of Civil Engineering, University of Missouri-Rolla, Jones Professor of Civil Engineering

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*Outline of Experiment*

The experimental portion of the investigation consisted of testing 18 specimens. The specimen can be seen in Figure 1. The specimen is a plain concrete beam with an inverted T-shape. The purpose of the T-shape is to increase the flexure capacity while maintaining a manageable specimen size. The beam is simply supported and has a span of 42 in (1067 mm) and a total length of 48 in (1219 mm). A notch was placed at the center of the beam in order to force the beam to crack at midspan. Also, a hinge is placed at the center of the beam. The purpose of the hinge was to cause the distance between the internal compression and tension forces to remain constant. A CFRP strip was bonded to the tension face of the beam. The sheet was 2 in (51 mm) wide and had a fiber thickness of 0.0065 in (0.165 mm). The modulus of elasticity of the fiber is 33000 ksi (228 GPa). A transverse sheet was placed on one side to force failure to occur at the other end. Also, the sheet was left unbonded approximately 2 in (51 mm) on each side of midspan. The design choices were made to ensure that no cracking would occur in the bonded area.

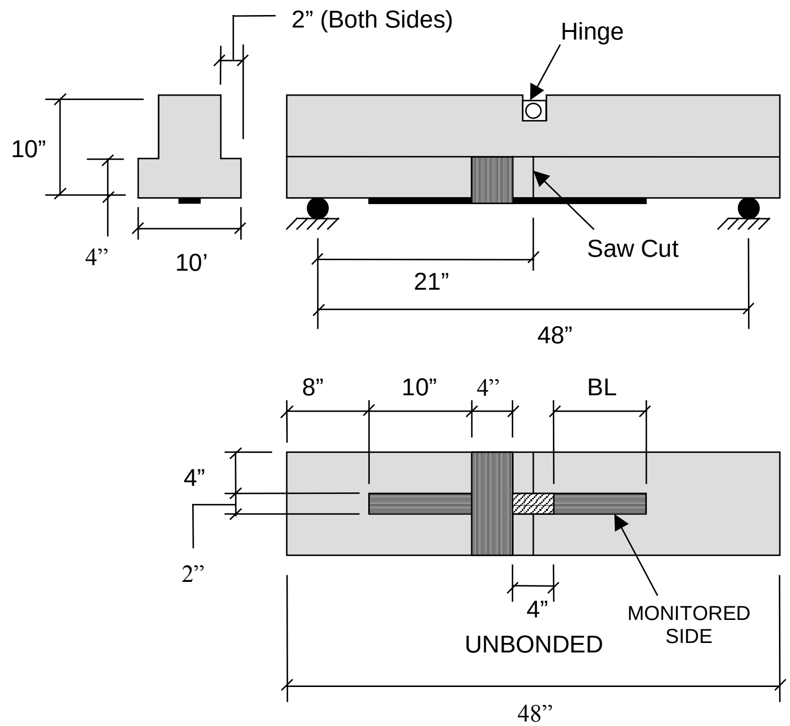


**Figure 1: Test Specimen (1 inch = 25.4 mm)**

There were three series of specimens tested (See Table 1). Each series consisted of six specimens and three different bonded lengths. Either concrete strength or number of plies of CFRP is varied between each series.

Data collection was accomplished by a series of strain gauges located along the length of CFRP sheet. A LVDT was located at midspan to monitor the beam deflection during testing.

**Table 1: Description of Specimens**

| Series Number | Specimen Code | Concrete Class [$f_c'$] (psi) | Number of Plies | Bonded Length (in) | Ultimate Load (lb) |
|---|---|---|---|---|---|
| I | 6-1-4-1 | 6000 [6860] | 1 | 4 | 3720 |
| | 6-1-4-2 | | | | 3990 |
| | 6-1-8-1 | | | 8 | 3560 |
| | 6-1-8-2 | | | | 3190 |
| | 6-1-12-1 | | | 12 | 3830 |
| | 6-1-12-2 | | | | 3390 |
| II | 6-2-4-1 | 6000 [5900] | 2 | 4 | 5930 |
| | 6-2-4-2 | | | | 5140 |
| | 6-2-8-1 | | | 8 | 4630 |
| | 6-2-8-2 | | | | 6260 |
| | 6-2-12-1 | | | 12 | 5590 |
| | 6-2-12-2 | | | | 5080 |
| III | 3-1-4-1 | 3000 [3550] | 1 | 4 | 3300 |
| | 3-1-4-2 | | | | 3120 |
| | 3-1-8-1 | | | 8 | 4450 |
| | 3-1-8-2 | | | | 2920 |
| | 3-1-12-1 | | | 12 | 4770 |
| | 3-1-12-2 | | | | 3450 |

Note: 1 inch = 25.4 mm; 1 psi = 6.89 kPa; 1 lb = 4.45 N

*Results*

The data collected from the strain gauges was used to develop strain-location curves for each of the specimens. The curve is a plot of the strain vs. the distance the strain gauge is located from the midspan of the beam. Each curve is plotted for a given load. Figure 2 is a typical diagram for the 4-inch (102-mm) bonded length, and Figure 3 is typical of the diagrams for lengths above 4 in (102 mm). It can be seen in Figure 3 that peeling occurred in the sheet prior to failure.

The failure mode of the specimens was by peeling of the sheet. The peeling mechanism is described as follows. The effective length of the CFRP sheet takes the entire load to a certain point at which localized peeling occurs causing the effective bond length to shift. This shifting of the effective bond length continues until the CFRP sheet has completely peeled from the concrete. When peeling first occurs, the load decreases slightly and then increases again until it reaches the load at which peeling first occurred and peeling occurs again. Therefore, it seems that a limit exists at which the load cannot surpass.

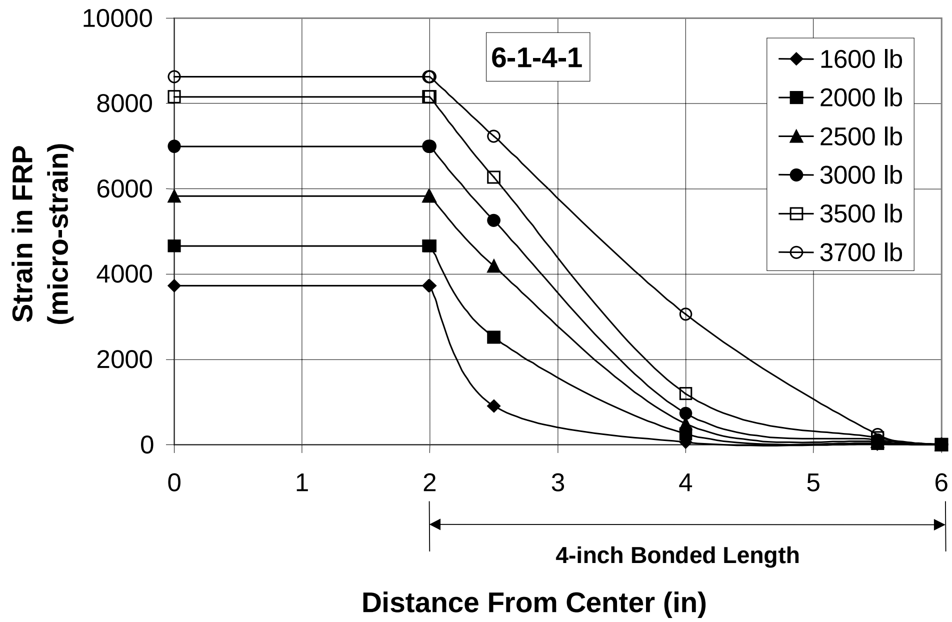


**Figure 2: Strain vs. Location (1 inch = 25.4 mm; 1 lb = 4.45 N)**

*Comparison of Results*

When comparing the results, it was found that the bonded length did not affect the bond strength. In fact, it was found that the bond strength decreases as the bonded length increases for all three series. It was concluded that an effective length exists in which no stress is transferred beyond until peeling occurs. Other researchers have also reported the existence of an effective development length (Maeda et al., 1997; Takahashi et al., 1997; Brosens and Van Gemert, 1997; Tripi et al., 1998).

While it was expected that concrete strength would have an affect on the bond strength, there was no evidence from this investigation. The average cracking load and ultimate load for Sereis I and II along with the compressive strengths are compared in Table 2. The significance of the last column of this table is to show that the concrete strength did have an affect on the cracking load, but it did not affect the ultimate load.

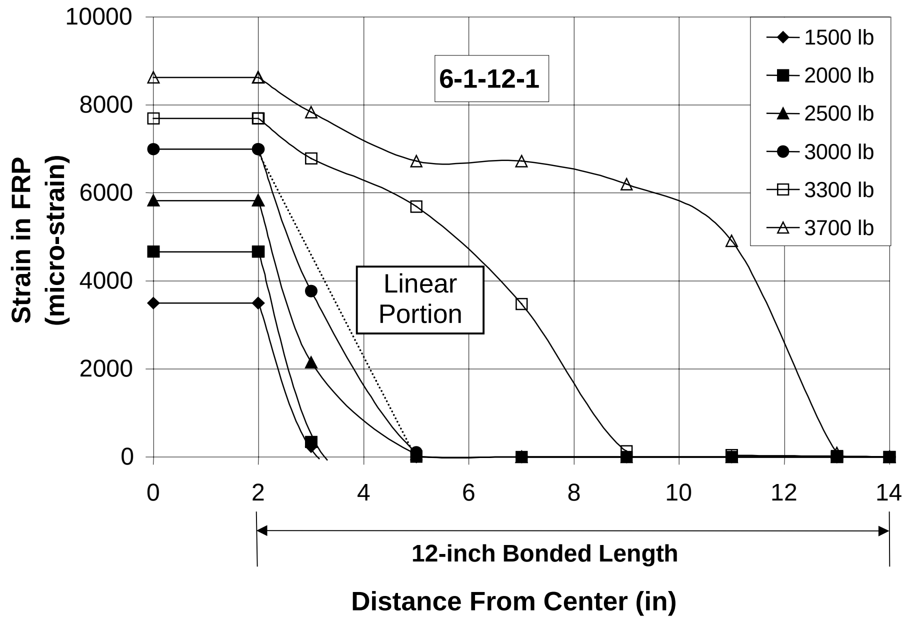


**Figure 3: Strain vs. Location (1 inch = 25.4 mm; 1 lb = 4.45 N)**

The number of plies used to make the CFRP laminate affects the bond strength of the laminate. In order for two plies of CFRP sheet to be as efficient as one ply, the bond strength would have to double. As expected, this does not occur. The average of the ultimate loads are compared in Table 2 in the next to the last column, and it shows that the increase is only 1.5 times Series I as opposed to 2 times.

**Table 2: Comparison of Cracking and Ultimate Load for Series I and III**

| | Series I | Series II | Series III | II/I | III/I |
|---|---|---|---|---|---|
| **$f_c'$ (psi)** | 6860 | 5900 | 3550 | 86% | 52% |
| **$(f_c')^{0.5}$ ((psi)$^{0.5}$)** | 82.8 | 76.8 | 59.6 | 93% | 72% |
| **Cracking Load (lb)** | 3727 | 4013 | 2718 | 108% | 73% |
| **Ultimate Load (lb)** | 3613 | 5438 | 3668 | 151% | 102% |

Note: 1 lb = 4.45 N 1 psi = 6.89 kPa

*Analytical Results*

The first step to finding a model to predict the ultimate load of the specimens is to quantify the effective development length of the sheet. This can be accomplished by utilizing the linear portion of the strain distribution just before peeling occurs (see Figure 3). Maeda et al. (1997) and Brosens and Van Gemert (1997) also reported this linear shape of the strain distribution. Experimentally, an average value of the slope (dε/dx) of the linear portion of the strain location curve was found to be 2225 μ/in (88 μ/mm). Maeda et al. (1997) reported a value of 2799 μ/in (110.2 μ/mm). Using data from this experiment and Maeda et al. (1997), Figure 4 was plotted. A linear approximation was plotted through the data points. The equation of this line is seen in equation (1).

$$L_e = -0.00298(tE_f) + 3.711 \qquad (1)$$

$$L_e = -0.432(tE_f) + 94.3 \qquad (1M)$$

Using this equation for $L_e$, and the following equations that were presented by Maeda et al. (1997), the value of $P_{max}$ can be calculated by equation (2).

$$P_{max} = L_e w \tau \qquad (2)$$

$\tau$ is the average bond stress calculated by equation (3).

$$\tau = E_f t \left( \frac{d\varepsilon}{dx} \right)_{avg} \times 10^{-6} \qquad (3)$$

$L_e$ = Effective Bond Length (in or mm)
$\tau$ = Average bond stress (ksi or GPa)
$t$ = thickness of CFRP sheet (in or mm)
$E_f$ = Modulus of Elasticity (ksi or GPa)
$P_{max}$ = Ultimate load (kips or kN)
$w$ = width of CFRP sheet (in or mm)
$(d\varepsilon/dx)_{avg}$ = average gradient for effective bond length (2225 μ/in or 88 μ/mm)

In Figure 5, the values of the ultimate load are shown for both Maeda et al. (1997) and current data of Series I and II. It can be seen that as the stiffness increased, the ultimate load increases. It also seems that the linear relationship is reasonable until further experiments become available.

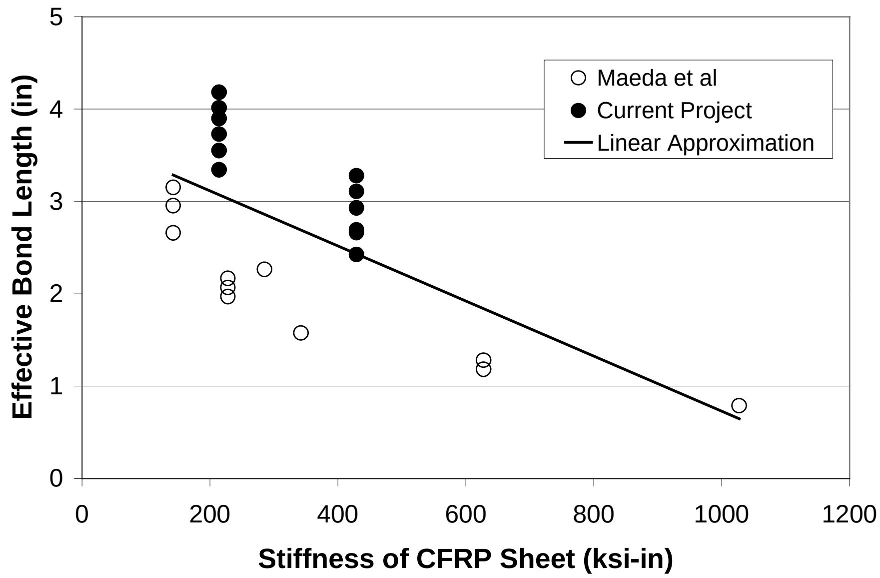


**Figure 4: Effective Bond Length vs. Stiffness of CFRP (1 inch = 25.4 mm; 1ksi-in = 5.71 Gpa-mm)**

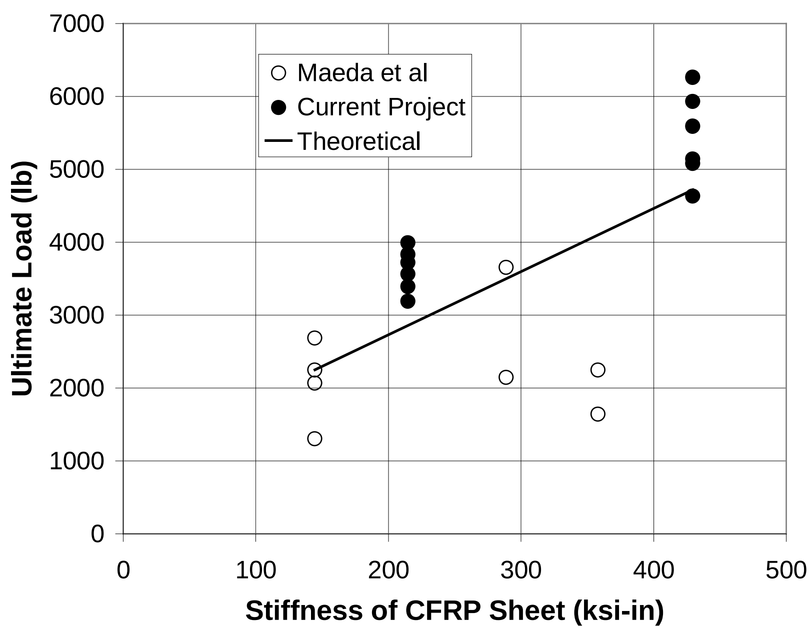


**Figure 5: Comparison of Theoretical Model to Experimental Model (1 lb = 4.45 N; 1ksi-in = 5.71 GPa-mm)**

*Conclusions*

The following conclusions were made from the experimental work of this investigation.

- The bonded length did not have any affect on the ultimate load of the sheet.
- The concrete strength did not affect the ultimate load. In this test performance is controlled. The failure is occurred in the concrete-adhesive interface.
- Increased stiffness did increase the bond strength, but not proportional to the number of plies.

Also, the method for determining the ultimate load of the specimens proposed by Maeda et al. (1997) was modified based on the results presented in this paper. This method proved to be an acceptable method for predicting the ultimate load when failure is controlled by peeling.

*Acknowledgements*

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