Strength and Ductility Assessment of Strengthened Reinforced Concrete Beams Using Externally Bonded CFRP with Varied Width and Thickness

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Abstract: Several publications suggest a set of measures for strengthening of reinforced concrete beams and give an estimate of the additional flexural load carrying capacity of strengthened beams with CFRP. Some of these publications offer contradicting conclusions regarding the width of the CFRP sheets and the use of multiple layers. In this study a total of ten under-reinforced beams; nine of which are strengthened with CFRP of different widths and different number of layers; are fitted with electronic strain gauges on the top concrete fiber and on the reinforcing steel and the CFRP material, stains at mid-span were recorded for each load increment and modes of failure reported. The data was analyzed and compared with other researchers findings. It was concluded that the ACI 440 committee guidelines give a about 68%-81% accurate results for 5" wide layers, and completely erroneous results of 1" wide strips.

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1. Introduction

Rehabilitation of reinforced concrete beams using carbon fiber reinforced plastics (CFRP) to deal with increased service loads on bridges is widely acceptable. The recommendations of the ACI committee 440 report 2008; Guide for the Design and Construction of Externally Bonded CFRP Systems for Strengthening Concrete Structures; is usually used to determine the required area of CFRP and estimate the enhanced load carrying capacity of the strengthened beam.

The ACI committee 440 report puts down equations that quantify the area of the CFRP material as the thickness multiplied by the width. There are no guidelines regarding the minimum width of the CFRP material, neither as an absolute value nor as a ratio of the width of the concrete section. Moreover it is implied that to achieve the desired strength multiple layers of CFRP may be used rather than using one layer with the desired thickness.

Thomsen et. al. 2004 analyzed the failure modes or reinforced concrete beams strengthened in flexure with externally bonded CFRP sheets and concluded that CFRP sheet width plays a role in the failure modes reported such that wider sheets with equal cross sections will give better strengthening results by reducing the bond stress between the concrete surface and the CFRP sheets leading to higher flexural beam strength.

McSweeny and Lopz 2005 conducted a pull off tests on CFRP strips of varying widths and thicknesses from concrete blocks of different strengths; they concluded that the concrete strength had limited effect on bond failure load, while changing the width or thickness had significant effect on the bond failure load.

Zhang et. al. 2011 conducted a series of studies with the aim at development of an analytical approach for flexural strengthening of an existing structure with external CFRP laminate with predicting debonding failure and to clarify the main parameters affecting debonding strength of CFRP laminate strengthened RC beam with concrete cover separation, they proposed several effective countermeasures to enhance the performance of strengthening and to avoid the occurrence of concrete cover separation namely; to reduce the width of CFRP laminate, reduce the distance between support and end of CFRP sheet, select CFRP sheets with higher tensile strength, and apply end anchorage system.

Jumaat et. al. 2011review of plate bonded beams concluded that failure modes of flexural strengthened reinforced concrete beams are; premature debonding without showing any ductility, premature shear failure due to insufficient shear reinforcement and delamination (cover separation) at midspan.

The failure modes described by Jumaat et. al. is consistent with the findings of Zhang et. al., but the recommendations of Zhang et. al. to reduce the width of CFRP laminates in order to avoid the occurrence of cover separation is not in line with the recommendations of Thomsen et. al. that wider sheets will give better strengthening results and those of McSweeny and Lopez that the width and thickness of the CFRP sheets had significant effect on the bond failure.

Naeun et. al. 2013 on the other hand had a 5 beam experimental test scheme to evaluate of the width of CFRP sheets has on the behavior of the strengthened beam. They recorded the failure load and recorded the deflection, and concluded that the width of the CFRP sheet had a significant influence on the structural behavior of the strengthened beams.

The objectives of this paper is to determine if the ACI committee 440 report can accurately predict the behavior and provide a reasonable estimate of the increase in load carrying capacity without an appreciable reduction of ductility of beams externally bonded with CFRP sheets as compared to CFRP narrow strips as well as beams externally bonded with single layer CFRP sheets as compared to multiple layers. To achieve this goal a reliable instrumentation plan which includes implanting strain gages at critical sections on reinforcing steel bars, concrete and CFRP sheets and using a data acquisition system to monitor the change in the strains of strengthened reinforced concrete beams was adopted; a total of ten beams 9.25” × 7” were cast, these beams were under-designed in flexure but had enough shear reinforcement, one of these beams will be used as a control specimen, and the other ten beams were strengthened with CFRP. All beams were fitted with electronic strain gages to monitor strain in concrete, steel and CFRP and the deflection at mid-span were measured, data from strain gauges are recorded and analyzed, failure modes reported and relevant conclusions and recommendations drawn.

2. Materials

2.1 Concrete

A total of ten beams were cast with dimensions 9.25” × 7” as shown in Fig. 1; after placement of reinforcement, beams were cast using Portland cement concrete with an average compressive strength at 28 days $f_c' = 5500$ psi. All beams were cast at the same time and from the same concrete batch.

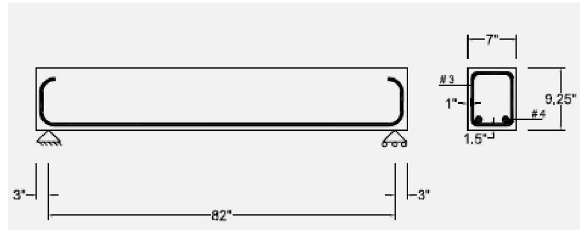


Fig. 1. Longitudinal Section and Cross Section of R.C. Test Beam

2.2 Steel

Two reinforcing steel bars #4 Grade 60, with a minimum specified yield stress f_y = 60000 psi were placed in the tension zone of each beam. Beams were reinforced with #4 representing the under designed case. Shear reinforcing stirrups; #3 Grade 60 deformed bars were placed at three inch interval at both ends and at six inch intervals in the middle third.

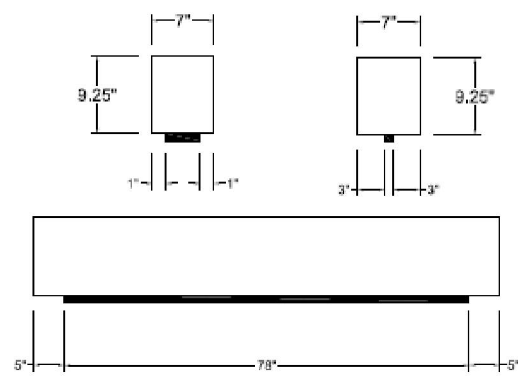


Fig. 2. FRP Position With Respect to Beam Dimensions

2.3. CFRP Composite Materials

A non-woven uniaxial carbon fibers manufactured by Japan’s Mitsubishi Chemical Corporation with the following material properties:

- Tensile strength ≥ 435113 psi
- Modulus of Elasticity = 34083868 psi
- Thickness = 0.067 inch

The Mitsubishi Chemical Corporation also manufactures the two-part epoxy used for adhesion to concrete surfaces. The position of the CFRP sheets with respect to beam dimensions are as shown in Fig. 2.

3. Experimental Setup

3.1. Instrumentation

3.1.1. Strain Measurement

In order to determine the bending strains three uniaxial electronic strain gages were installed on each of the three materials at mid span on each of the eleven reinforced concrete beams.

3.1.2. Deflection Measurements

Deflections were measured at the midspan of each reinforced concrete test beam using a spring loaded dial gage. Deflection values were directly read from the dial gage to the nearest 0.001 inches.

3.2. Test Setup

Each reinforced beam was tested using a four-point loading scheme, where two equally concentrated point loads were symmetrically placed at a distance of one-third the total clear span from each end. Half of the total load was distributed to each of the point loads. At each end, the beam was simply supported allowing for rotation; the load was applied as shown in Fig. 3. Beams were tested with either one layer or five layers of CFRP.

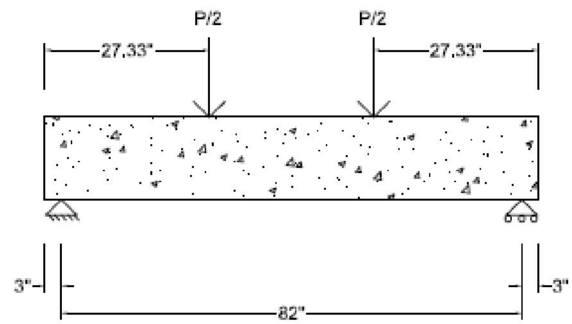


Fig. 3. Experimental Setup

4. Results and Discussion:

Results are reported in Table 1., comparing between the strain change along the beam cross section with increasing load and the ductility change, we notice the following:

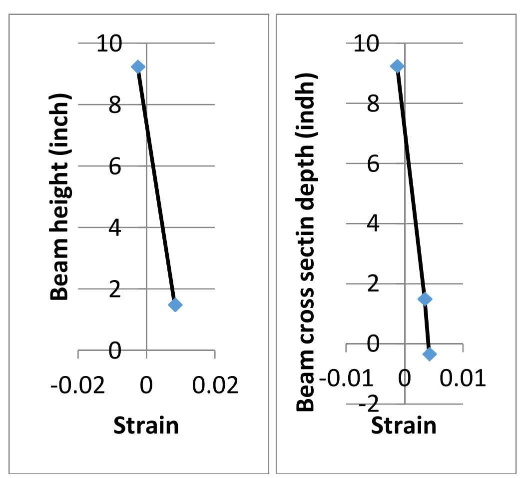
Table 1. The Failure Mode, Ultimate Load and Ductility of tested beams

BEAM	CFRP Width	No. of Lay-ers	Failure Mode	Ulti-mate Load (lbs.)	Ducti-lity $\frac{\varepsilon_u}{\varepsilon_y}$
1	Control beam (No CFRP)		Yielding of steel reinforcing bars	19300	4
2	5”	5	Shear failure at CFRP end	32050	1.3
3	1”	5	CFRP debonding	18986	5
4	1”	5	CFRP debonding	19394	1.7
5	5”	5	Shear failure at CFRP end	29869	1.2
6	1”	5	CFRP debonding	19937	4.7
7	5”	5	Shear failure at CFRP end	31779	2.6
8	5”	1	CFRP rupture	26290	3.65
9	5”	1	CFRP rupture	23862	3.2
10	5”	5	Shear failure at CFRP end	29960	1.35

4.1. The control beam

The theoretically calculated nominal load was calculated to be 12,820 lbs. and the actual ultimate load was found to be 19300 lbs, an average safety factor F.S. = 1.67 . The strain was typical of a reinforced concrete beam as described in text books (Fig.4-a). The beam was under reinforced; therefore, the steel reinforcing bars yielded and reached a strain level above 0.005 at failure while the concrete top fibers strained just below the concrete crushing strain of 0.003. The ductility of the control beam was calculated D.F.= 4.

In Fig.4(a) the strain distribution across the section of Beam-1 just before failure is shown, and in Fig.4(b) the same is shown for Beam-4. We noticed from Table-1 that even though Beam-4 is strengthened with 5 layers of narrow 1” CFRP strips the ultimate load carrying capacity has not improved.

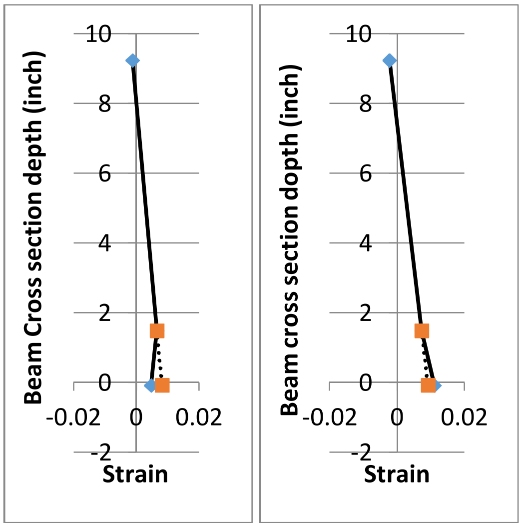


(a) Beam-1 (b) Beam-4

Fig.4 Strain at failure for Beam-1(control beam) and Beam-4

4.2. One Layer of 5” Wide CFRP

The calculated expected load carrying capacity using the equations from ACI 440 for this category is 15653 lbs. an increase of 27% from the design nominal strength of the control beam



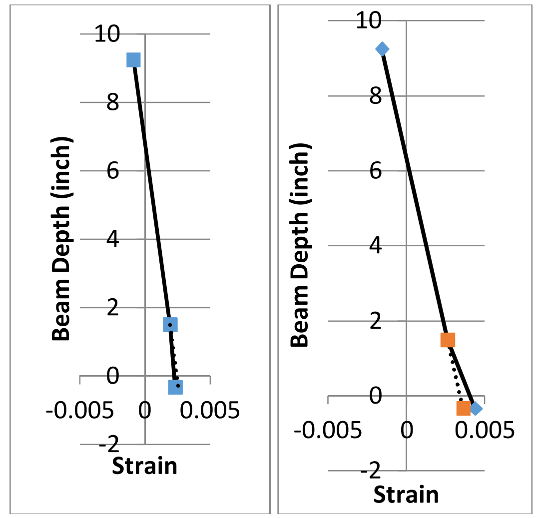
(a) Load = 19000 lbs.(b) Load = 26000 lbs.
Fig.5 Strain across the section of Beam-8

The three beams strengthened with one layer of 5” wide CFRP sheets showed an increase of strength compared to the unstrengthened beam ranging from 23% to 47% with an average increase of strength of about 35% as compared with the failure strength of control beam, i.e. an accuracy of 81%. The strain behavior of this category was manifested by the fact that stress in the CFRP sheet was lagging the linearly expected behavior of the composite construction with the steel and concrete. One step before failure, the strain in the CFRP sheet become linear and then just at failure it started to exceed the linearly expected value signaling the start of debonding or delamination of the CFRP sheet from the reinforced concrete beam as shown in Fig. 5.

4.3. Five Layers of 5” Wide CFRP

The calculated expected load carrying capacity for this category is 23175 lbs. an increase of 88% from the design nominal strength of control beam.

The four beams strengthened with 5 layers of 5” wide CFRP sheets showed an increase of strength compared to the unstrengthened beam ranging from 54% to 66%, i.e., an average increase of strength of about 60% as compared with the failure strength of the control beam, i.e., a 68% accuracy. The strain behavior of this category was manifested by the fact that stress in the CFRP sheet was lagging the linearly expected behavior of the composite construction with the steel and concrete. One step before failure, the strain in the CFRP sheet become linear and then just at failure it started to exceed the linearly expected value signaling the start of debonding or delamination of the CFRP sheet from the reinforced concrete beam as shown in Fig. 6.



(a) Load = 19000 lbs.(b) Load = 31000 lbs.
Fig. 6. Strain across the section of Beam-2

4.4. Five Layers of 1” Wide CFRP

The calculated expected load carrying capacity for this category is 15653 lbs. an increase of 27% from the design nominal strength of the control beam.

The three beams strengthened with 5 layers of 1” wide CFRP strips showed no increase of strength and exhibited exactly the same failure load as the unstrengthened beam. The strain before failure is shown in (Fig. 4), which shows that the strain in the CFRP layer has not fully developed and that at the onset of the failure load of the unstrengthened beam, the CFRP strips suffered debonding resulting of no added strength.

5. Conclusions

- Using single layer of CFRP sheets for strengthening reinforced beams in flexure is an effective method to gain extra strength while the ductility of the beam is within acceptable limits of the ACI 440.
- Multiple layers of CFRP sheets can contribute to additional strength of the beam but will result in more lose of ductility causing it to fall below the acceptable limits of ACI 440.
- Using multiple layers of CFRP strips does not add to the strength of the beam, but might have an adverse effect on its ductility.
- Enough care should be taken to the bonding between the beam and the CFRP material.
- The ACI 440 could estimate the increase of strength of the strengthened reinforced concrete

beams with 5” CFRP sheets by 68%-81% accuracy while the beams strengthened with 1” CFRP strips there were no real increase of strength in contrast to the estimated increase of strength by ACI.

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References

1. Hawileh R.A., Rasheed H.A., Abdalla J.A., and Al-Tamimi A.K., “Behavior of Reinforced Concrete Beams Strengthened with Externally Bonded Hybrid Fiber Reinforced Polymer Systems”, Materials and Design Journal, No. 53, Elsevier, 2014, , pp. 972-982.
2. Naeun K., Young-Hee K., and Hee S.K., “Experimental Study for Evaluating Structural Behavior of RC Beams Strengthened by Different Width of FRP Layers”, IACSIT International Journal of Engineering and Technology, Vol. 5, No. 6, December 2013.
3. Zhang D.W., Ueda T., and Furuuchi H., “Concrete cover separation failure of overlay strengthened reinforced concrete beams”, *Construction and Building Materials*, Vol.26, No. 1, January 2012, pp. 735-745.
4. Zhang D.W., Ueda T., and Furuuchi H., “A new analytical model for concrete cover separation of R/C beams strengthened with FRP laminates”, Proceeding of the Third Asia-Pacific Conference on FRP in Structures, February, 2012.
5. Jumaat M.Z., Rahman M.A., Alam M.A. and Rahman M.M., “Premature failures in plate bonded strengthened RC beams with an emphasis on premature shear: A review”, International Journal of the Physical Sciences Vol. 6(2), 18 January, 2011, pp. 156-168.
6. Chitsazan I., Kobraei M., Jumaat M.Z. and Shafigh P., “An experimental study on the flexural behavior of FRP RC beams and a comparison of the ultimate moment capacity with ACI”, Journal of Civil Engineering and Construction Technology, Vol. 1(2), December 2010, pp. 27-42.
7. McSweeney B.M. and Lopez M.M., “FRP-Concrete Bond Behavior: A Parametric Study Through Pull-Off Testing”, 7th International Symposium on Fiber Reinforced Polymer (FRP) Reinforcement for Reinforced Concrete Structures, ACI SP-230-26, 2005, p.p. 441-460.
8. Thomsen H., Spacone E., Limkatanyu S. and Camata G., “Failure Mode Analyses of Reinforced Concrete Beams Strengthened in Flexure with Externally Bonded Fiber-Reinforced Polymers”, Journal of Composites for Construction (ASCE),Vol. 8, No. 2, April 2004, p.p. 123-132.

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