The Effect of Width, Multiple Layers and Strength of FRP Sheets on Strength and Ductility of Strengthened Reinforced Concrete Beams in Flexure

*Khair Al-Deen Bsisu [1), Shad Srgand [2) and Ryan Ball [3)

[1) Assistant Professor, The University of Jordan, Faculty of Engineering and Technology, Civil Engineering Department, Amman, Jordan, Research Scholar at Ohio University, Athens, Ohio, USA.
E-Mail: k.bsisu@ju.edu.jo
[2) Graduate Chair Professor of Civil Engineering, Ohio University, Russ College of Engineering and Technology, Associate Director, Ohio Research Institute for Transportation and the Environment.
[3) M.Sc. Civil Engineering Graduate, Ohio University, Russ College of Engineering and Technology.

ABSTRACT

In this study, a total of eleven under-reinforced beams, ten of which strengthened with FRP of different widths and different numbers of layers, are fitted with electronic strain gauges on the top concrete fiber, the reinforcing steel and the FRP material. Strains and deflection at mid-span were recorded for each load increment. The data was reported and analyzed, as well as ductility requirements and expected failure mode. It was concluded that the use of single layer FRP wide sheets would increase the strength with a negligible reduction of ductility. Using multiple layers of wide FRP sheets yielded more increase of strength but reduced ductility of the beams. Multiple narrow strips of FRP will not add to the strength, but will reduce the deflection by reducing ductility.

KEYWORDS: Fiber reinforced plastics, Flexural strength, Ductility, Strength of FRP material, Reinforced concrete, Strain.

INTRODUCTION

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

The ACI Committee 440 report puts down an equation that quantifies the area of the FRP material as the thickness multiplied by the width. There are no

guidelines regarding the minimum width of the FRP 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 FRP may be used rather than using one layer with the desired thickness.

Ductility of the strengthened members should also be checked. The ACI Committee 440 report states that adequate ductility is achieved if the strain in reinforcing bars at concrete crushing or failure of FRP is at least 0.005.

In his six-beam experimental testing scheme, Siddiqui (2009) used three beams for flexural experimental testing and the rest for shear tests. For the flexural experiment, he used one beam as a control beam and strengthened the other two with a single FRP

sheet bonded at the bottom. He added an end anchorage to the FRP sheet at both ends for one of the beams. Beams were tested to failure using a four-point load. The outcomes of his research were that the beam fitted with an end anchorage of the FRP sheet failed by crushing of concrete, while the other one failed by debonding. The ultimate load increased by 22.5% and 29.4%, respectively.

Thomsen et al. (2004) analyzed the failure modes or reinforced concrete beams strengthened in flexure with externally bonded FRP sheets and concluded that FRP 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 FRP sheets leading to higher flexural beam strength.

McSweeny and Lopez (2005) conducted pull-off tests on FRP strips of varying widths and thicknesses from concrete blocks of different strengths. They concluded that the concrete strength had a limited effect on bond failure load, while changing the width or thickness had a significant effect on the bond failure load.

Zhang et al. (2011) conducted a series of studies with the aim of developing an analytical approach for flexural strengthening of an existing structure with external FRP laminate for predicting debonding failure and clarifying the main parameters affecting debonding strength of an FRP 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 FRP laminate, reduce the distance between support and end of FRP sheet, select FRP sheets with higher tensile strength and apply an end anchorage system.

Jumaat et al. (2011) review 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.

Another series of tests on reinforced concrete beams were carried out by Chajes et al. (1994) using a four-point load to determine the improvement of a beam's flexural capacity using externally bonded FRP composites. They prepared a total of fourteen beams and investigated the use of aramid, E-glass and graphite fibers. Tests showed that the externally bonded FRP resulted in a 36% to 57% increase in the flexural capacity and a 45% to 53% increase in the flexural stiffness. Beams retrofitted with E-glass and graphite failed due to rupturing of the fibers; while beams retrofitted with aramid failed as a result of concrete crushing in compression at the top fibers of the beam cross-section.

Sharif et al. (1994) investigated the effect of FRP plates on retrofitting initially loaded concrete beams. Ten reinforced concrete beams were cast and tested. Beams were under-reinforced (the reinforcement ratio was 0.0098) and loaded to 85% of their ultimate flexural capacity using a four-point load, then repaired with FRP plates of varying thicknesses. Furthermore, to determine the effect on ductility, different repair and anchoring schemes were applied. The results indicated an overall increase in the flexural strength of the retrofitted beams. On the other hand, ductility was inversely proportional to the plate thickness; beams retrofitted with thin plates failed due to plate rupture, while beams retrofitted with thick plates had a premature failure due to plate separation at the ends leading to a local shear failure in concrete.

The objective of this paper is to investigate the ACI Committee 440 report regarding load carrying capacity and ductility of beams externally bonded with FRP sheets as compared to FRP narrow strips as well as beams externally bonded with single layer FRP sheets as compared to multiple layers and the effect of the strength of the FRP material on strength and ductility. To achieve this goal, a reliable instrumentation plan was used which includes implanting strain gauges at critical sections on reinforcing steel bars, concrete and FRP sheets and using a data acquisition system to

monitor the change in the strains of strengthened reinforced concrete beams.

For this purpose, a total of eleven beams (9.25 in. × 7 in.) 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 FRP from different manufacturers. All beams were fitted with electronic strain gauges to monitor strain in concrete, steel and FRP, and the deflection at mid-span was measured.

MATERIALS
Concrete
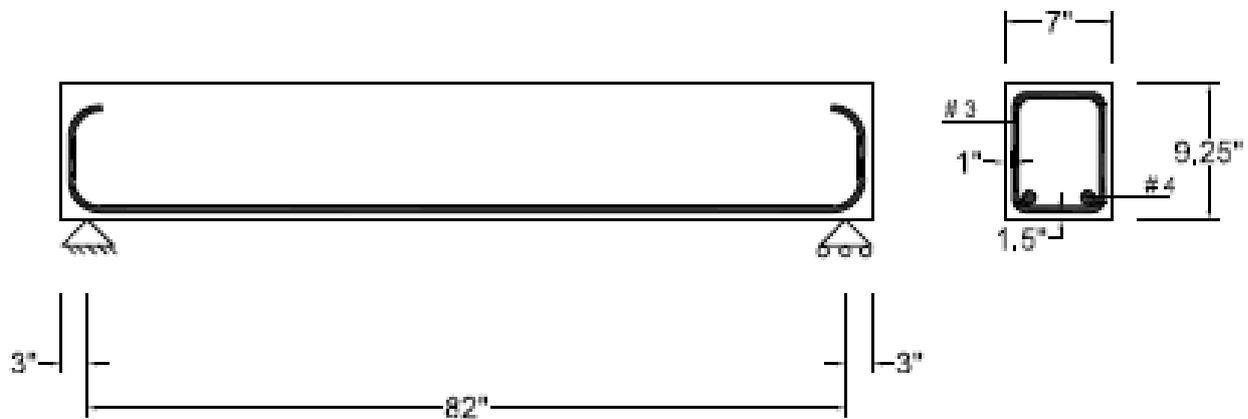
A total of eleven beams with dimensions (9.25×7×88 in.) were cast as shown if Fig. 1. After placement of reinforcement, beams were cast using Portland cement concrete with an average compressive strength at 28 days of $f_c' = 5500$ psi. All beams were cast at the same time and from the same batch.

Steel

Two reinforcing steel bars #4 Grade 60, with a minimum specified yield stress of $f_y = 60000$ psi, were placed in the tension zone of each beam. Eleven beams were reinforced with #4 representing the under-designed case.

Shear reinforcing stirrups; #3 Grade 60 deformed bars were placed at three inch intervals at both ends and at six inch intervals in the middle.

Figure (1): Longitudinal Section and Cross-section of R.C. Test Beam

Composite Materials
CFRP-1: Non-woven uniaxial carbon fibers manufactured by Japan's Mitsubishi Chemical Corporation with the following material properties:

- Tensile strength ≥ 3000 MPa = 435113 psi;
- Modulus of Elasticity = 235 GPa = 34083868 psi;
- Thickness = 0.17 mm = 0.067 inch.

The Mitsubishi Chemical Corporation also manufactured the two-part epoxy used for adhesion to concrete surfaces.

CFRP-2: Carbon fiber fabric similar to CFRP-1, but manufactured by Fabric Development, Inc. in Quaker Town, Pennsylvania. It consisted of carbon fibers in uniaxial direction. The properties of CFRP-2 carbon fiber are:

- Tensile strength = 500000 psi;
- Modulus of Elasticity = 33.0×10^6 psi;
- Thickness = 0.072 inch.

Magnolia Plastics, Inc. in Chamblee, Georgia supplied the two-part epoxy system used.

FCV Plates: A rigid vinyl ester resin system containing 55% carbon fibers by volume, manufactured by DFI Pultruded Composites, Inc. in

Erlanger, Kentucky. The carbon fibers were oriented in a uniaxial direction and their properties of FCV are:

- Tensile strength = 200000 psi;
- Modulus of Elasticity = 18.3×10^6 psi;
- Thickness = 0.08 inch.

The adhesive used to bond FCV plates to the concrete surfaces was the same as the one used for CFRP-2 sheets, manufactured by Magnolia Plastics, Inc.

Ten of the eleven reinforced beams were retrofitted with one of the three FRP composites described above.

The positions of the FRP sheets with respect to beam dimensions are as shown in Fig. 2.
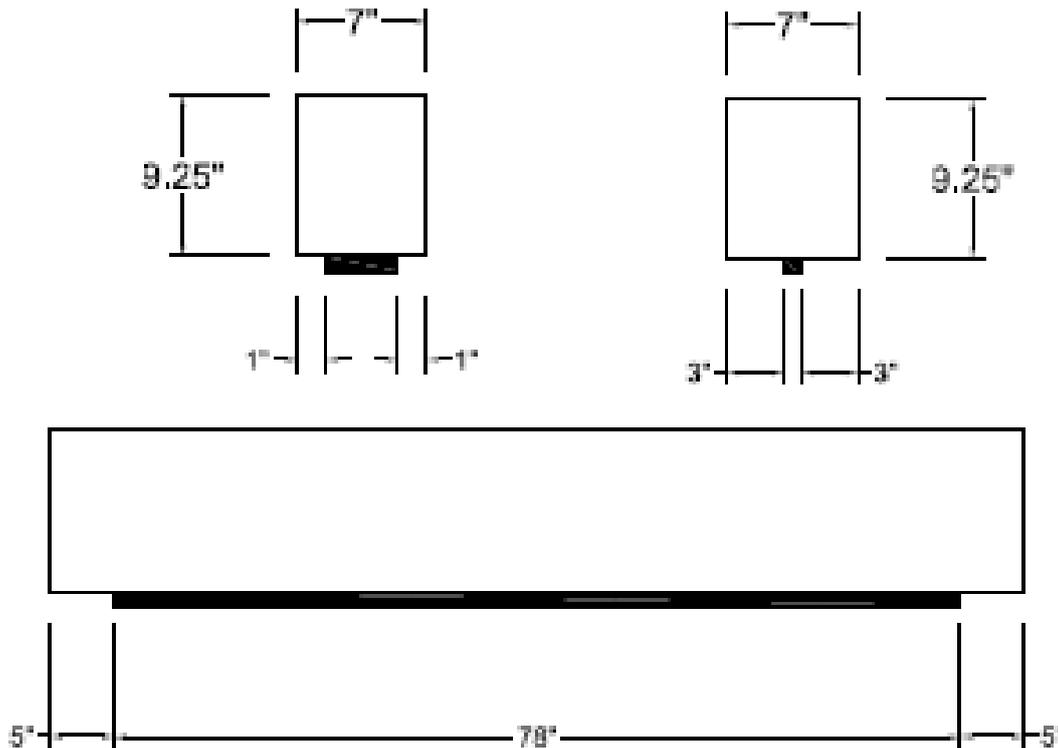

Figure (2): FRP Position with Respect to Beam Dimensions

EXPERIMENTAL SETUP

Instrumentation
Strain Measurement

In order to determine the bending stresses carried by each of the three materials, three uniaxial electronic strain gauges were installed on each of the three materials at mid span on each of the eleven reinforced concrete beams.

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.
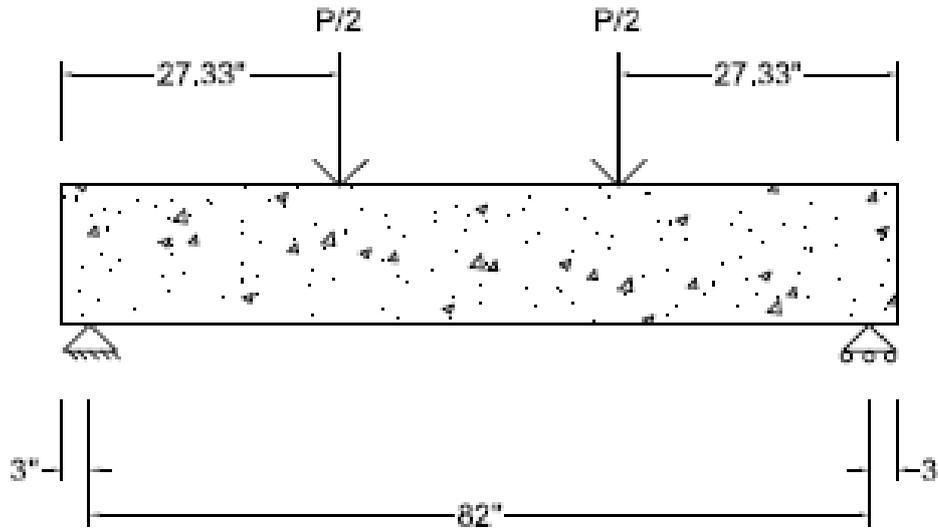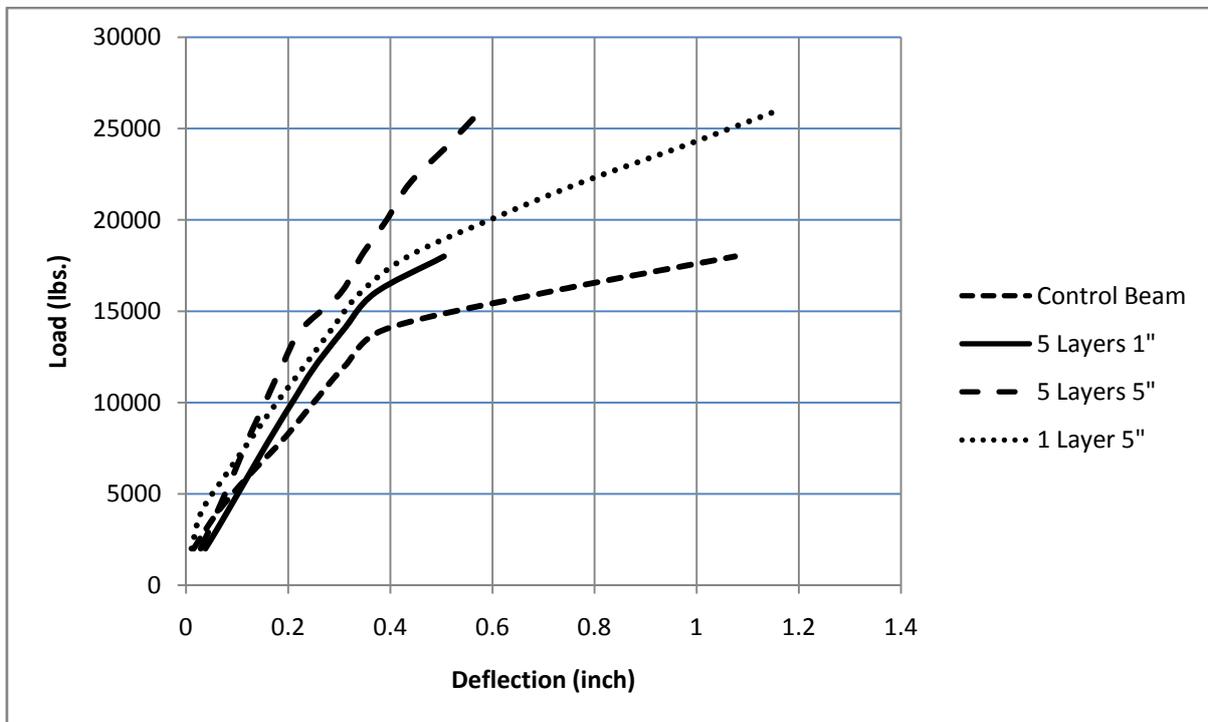
Figure (3): Experimental Setup

Figure (4): The Deflection at Mid-span for Typical Beams

Each of the ten beams retrofitted with FRP was preloaded with a 10,000 lbs load. Beams had a nominal design load of 12,820 lbs; therefore these beams were preloaded to a point prior to yielding of steel reinforcement.

Some of the beams were tested with one layer and five layers of material. Those beams were first retrofitted with one layer of FRP and tested. Once the

one layer test was completed, the beams were again removed from the load frame. Four additional layers of FRP were added for a total of five layers. The beams were then placed back in the load frame and taken to failure. The ultimate load was recorded as well as the observed failure mode.

DISCUSSION OF RESULTS

Load Carrying Capacity

Beam 1, the control beam, failed, as expected from an under-reinforced beam, by yielding of the reinforcing steel.

The load carrying capacity of reinforced beams strengthened with 5 inch FRP, whether a single layer or five layers, showed an increase in strength ranging

from 23.6% to 64%. However, the ultimate load carrying capacity of beams strengthened with five layers of one inch strips was not enhanced. The ultimate load carrying capacity of each beam and the failure modes are summarized in Table 1.

The single layer 5" wide strips contributed to the extra load of the beams strengthened, failure mode was FRP rupture or shear failure at FRP end. Beams strengthened with a single layer of FRP had an additional strength ranging from 23.6% to 47.2% with an average of 35%.

Beams strengthened with 5 layers of 5" FRP showed that the FRP contributed to an added strength ranging from 54% to 66% with an average of 60%, and the failure mode of these beams was shear failure at FRP end.

Table 1. The Failure Modes and Ultimate Load of Tested Beams

Beam	FRP Type	FRP Width	No. of Layers	Failure Mode	Ultimate Load (lbs.)	Load Increase
1	Non	N.A.	N.A.	Yielding of steel reinforcing bars	19300	N.A.
2	FRP-1	5"	5	Shear failure at FRP end	32050	66%
3	FRP-1	1"	5	FRP debonding	18986	-1.6%
4	FRP-2	1"	5	FRP debonding	19394	0.5%
5	FRP-2	5"	5	Shear failure at FRP end	29869	54%
6	FRP-1	1"	5	FRP debonding	19937	3.3%
7	FRP-1	5"	5	Shear failure at FRP end	31779	64%
8	FRP-1	5"	1	FRP rupture	26290	36.2%
9	FRP-1	5"	1	FRP rupture	23862	23.6%
10	FCV	5"	1	Shear failure at FRP end	28413	47.2%
11	FRP-2	5"	5	Shear failure at FRP end	29960	55.2%

A pattern is obvious in the observed failure mode of strengthened beams. Beams strengthened with 5 layers

of 1" FRP strips always failed by debonding of FRP. Therefore, it is clear that although there is added

strength in terms of FRP area (5 layers of 1" strips), there is not enough bonding between the first 1" narrow strip and the reinforced concrete beam to transfer the extra load to the beam. Thus, the load carrying capacity remained the same as that of the un-strengthened beam, and unless the purpose of retrofitting is to reduce deflection of the beam, strengthening with multiple layers of 1" strips will be redundant. Fig. 4 shows the typical deflection at mid-span for typical beams of each strengthening procedure.

Ductility

Table 2 shows the strain values of strengthened beams at yield and at failure and the ductility value as the ratio of the strain in steel reinforcement at failure to that at first yield. It is evident from this table that beams strengthened with a single 5" layer of FRP sheets gained extra strength without jeopardizing the ductility of the member, while beams strengthened with five layers of 5" FRP sheets showed an average of

59% loss of ductility.

The strain values of beams strengthened with 5 layers of 1" narrow strips can be explained by the fact that debonding of the FRP material occurred before the beam reached its ultimate load carrying capacity because of small bonding area available, although the FRP area is the same as for the 5" wide sheets and thus behaved as the control beam 1.

FRP Strength

The first two FRP materials used had slightly different strength and modulus of elasticity, but the third material had nearly half the ultimate yield strength and modulus of elasticity. We noticed that this had little or no effect on the final strength of the strengthened beams, since the failure modes are predominantly debonding of the FRP sheets or shear failure at the end of the FRP sheet (Table 1), but we noticed an improvement on the ductility of these beams (Table 2).

Table 2. Strain Values of Strengthened Beams, and Ductility

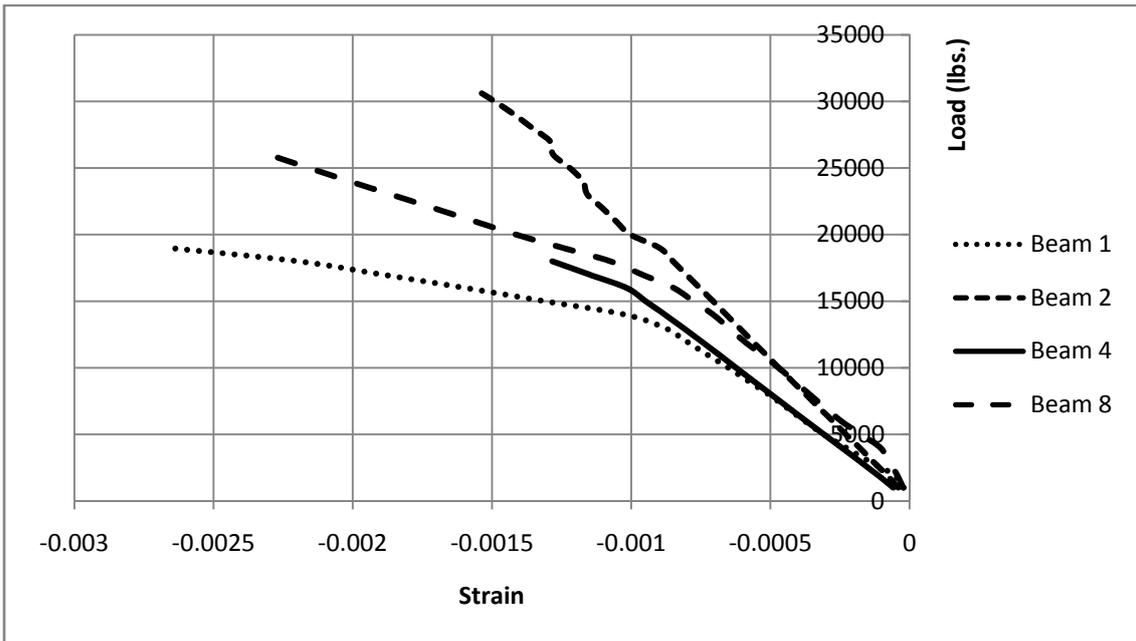| Beam	FRP Type	FRP Width	No. of Layers	Strain at Yield ε_y	Strain at Failure ε_u	Ductility $\dfrac{\varepsilon_u}{\varepsilon_y}$
1	Non	N.A.	N.A.	0.002	0.008	4
2	FRP-1	5"	5	0.002	0.0026	1.3
3	FRP-1	1"	5	0.002	0.010	5
4	FRP-2	1"	5	0.002	0.0034	1.7
5	FRP-2	5"	5	0.002	0.0024	1.2
6	FRP-1	1"	5	0.002	0.0094	4.7
7	FRP-1	5"	5	0.002	0.0052	2.6
8	FRP-1	5"	1	0.002	0.0073	3.65
9	FRP-1	5"	1	0.002	0.0064	3.2
10	FCV	5"	1	0.002	0.010	5
11	FRP-2	5"	5	0.002	0.0027	1.35

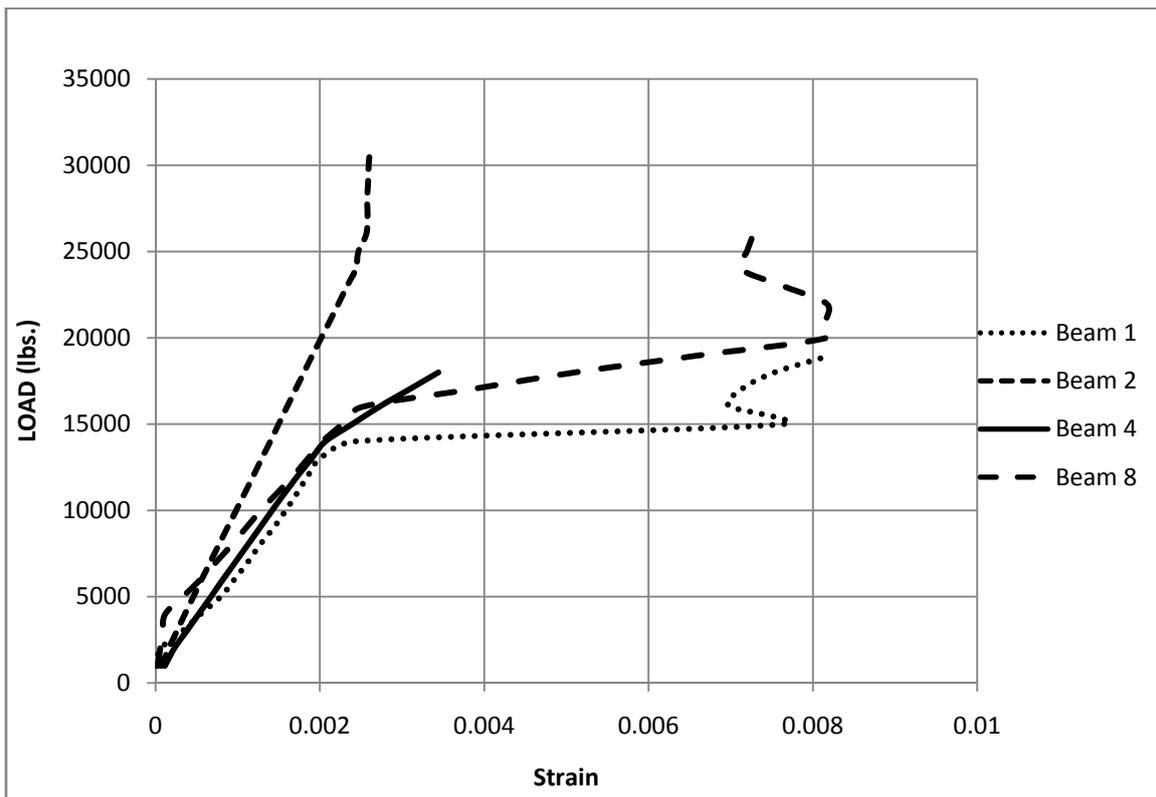**Figure (5):The Strain in Concrete at Mid-span for Typical Beams**

Figure (6):The Strain in Steel Bars at Mid-span for Typical Beams

CONCLUSIONS

- Using a single layer of FRP wide sheets for strengthening reinforced beams in flexure is an effective method to gain extra strength; while the ductility of the beam is not affected.
- Multiple layers of FRP wide sheets can contribute to additional strength of the beam, but will reduce the ductility of beams.
- Using multiple layers of FRP narrow strips does not add to the strength of the beam, but has an adverse effect on ductility.
- The strength of the FRP material has little significance for the strength or the strengthened beams, but the lower modulus of elasticity contributed to an enhanced ductility; therefore, it is recommended to use FRP with low modulus of elasticity to improve ductility.
- Enough care should be taken regarding the bonding between the beam and the FRP material by introducing a clause for the bonding surface area between the concrete and FRP.

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