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RESEARCH ARTICLE **Open Access**

Strains In Steel Reinforcement And CFRP Sheets In CFRP- Strengthened Reinforced Concrete Beams

Bayan Salim [1]*

[1] Civil Engineering Department, Tishk International University, Erbil, Iraq

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**Email address:*
bayan.salim@tiu.edu.iq
**Corresponding Author*

Abstract: Results of an experimental program, published by the author on reinforced concrete beams strengthened with Carbon Fiber Reinforced Polymer CFRP laminates, were analyzed in this work in terms of the strain development in tensile steel bars and CFRP laminates until extreme loading that causes failure. The outcome of this work may help in investigating the ductility of such beams. It may be concluded that although strengthening with CFRP enhances the carrying capacity of beams, they require special consideration for ductility.

Keywords: *CFRP Laminates; Strengthening of Beams; Strains*

1. Introduction

The use of externally bonded fiber-reinforced polymer (FRP) systems for strengthening concrete structures emerged as an alternative to traditional methods, such as steel plate bonding and steel or concrete column jacketing [ACI Committee 440.2R, 2008].

Fiber reinforced polymer (FRP) materials are characterized by their high ratio of (strength/weight), and corrosion resistance, in which corrosion is a risky issue with the steel plates strengthening option. It is also easy to apply. Easy to transport, and easy to install. However, it is of high cost, and risky to damages caused by fire and vandalism, or any other accidental damage. Protection to the strengthening sheets must be provided.

The addition of Carbon Fiber Reinforced Polymer (CFRP) composites, which is another form of tension reinforcement, affects the ductility of concrete beams strengthened with CFRP sheets, despite using tension reinforcing steel bars, which play a major role in determining the flexural ductility of reinforced concrete beams. Therefore, there is a need to investigate the effect of the CFRP laminates on the overall ductility of strengthened beams [Aboutaha et al. 2003], [Naaman, A. and Jeong, S., 1995], [Oudah, F. and El-Hacha, R., 2012]

External Fiber Reinforced Polymer (CFRP) composites of strengthened beam-column joints were studied by [Al Rouasan and Al Khawaldeh, 2021]. The work revealed that in almost all the specimens, the steel rebar strains in tension were well over the yielding strain threshold.

Taking the initial debonding as the ultimate limit state of CFRP-strengthened RC beams with debonding failure was studied by [Guibing Li et al, 2023], and then develops a new model for calculating CFRP strain and according to the theoretical analysis and test results of six CFRP-strengthened RC beams. They found that the values of CFRP strains at failure are well below ACI limits.

2. Research significance

This work aims to put more light on the behavior of CFRP-strengthened reinforced concrete beams by taking an in-depth look at the strains in steel bars and CFRP sheets up to failure. This would help in investigating the ductility of such beam.

3. Experimental Program

The experimental program [Al-Numan, Bayan S. and Ali, O. K., 2016] includes the preparations of fourteen beams of reinforced concrete having similar concrete strength of 45 MPa and similar workability level within 100 ± 10 mm slump. Twelve of these beams were strengthened with laminates of CFRP, and two of these beams were considered as control beams with no strengthening. All beams were tested under third point loading to failure. Details of beams are shown in Fig. (1). Learning the legend in Fig. (1), the tested strengthened beams are L1-10-75, L2-10-75, L1-12-75, L2-12-75, L1-16-75, L2-16-75, L1-10-60, L2-10-60, L1-12-60, L2-12-60, L1-16-60, and L2-16-60.

The first number (L1 or L2) is the number of CFRP layers, the second (10, 12 or 16) is the bar size in mm (2 tension steel bars), and the third (60 or 75) is the grade of tension steel bars in ksi.

The reinforced concrete beams span 2200 mm with a clear span of 2000 mm. The section dimensions are 100 mm width and 150 mm depth. Strengthening laminates of CFRP (applied as one, or two layers) were applied to the bottom face of the 12 strengthened beams only by one and two layers. The design of these beams follows the ACI code [ACI Committee 318, 2014] and ACI committee 440 report [ACI Committee 440, 2008].

The compressive strength of concrete was 45 MPa with a 100 mm slump in the fresh state. Carbon Fiber Reinforced Polymer (CFRP) used in this work is known as SikaWrap-230 C/45 sheets. The CFRP properties are tensile strength of 4300 MPa, modulus of elasticity of 230,000 MPa, and the elongation at break was 1.8%.

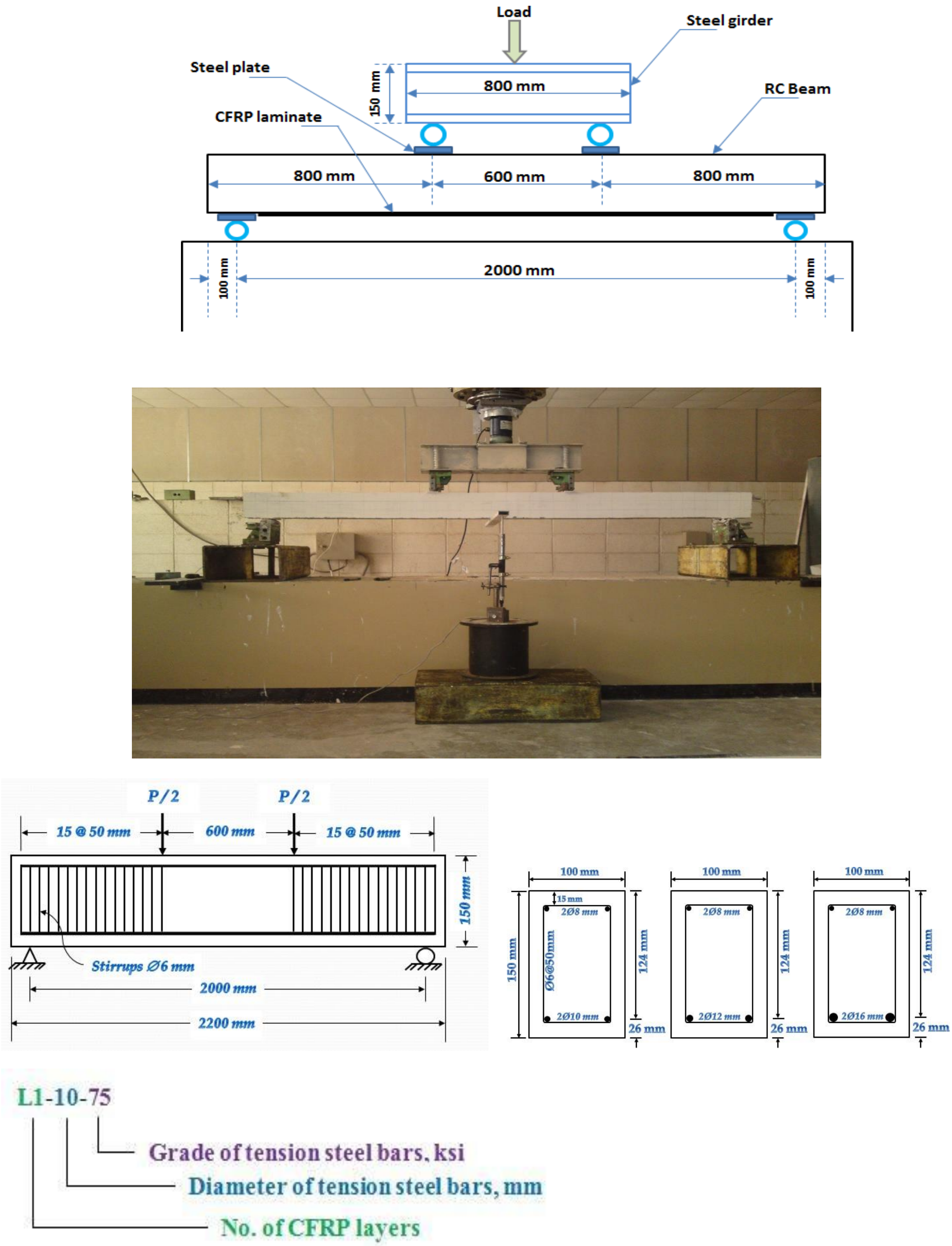

Figure 1: Details and test setup of beams [Al-Numan, Bayan S. and Ali, O. K., (2016)].

4. Results and Discussion

To read the strain in tensile steel bars and CFRP laminates, strain gages were placed on the tension steel bar and CFRP laminate at the mid span for all beam specimens. At the beginning of the test the strain increased at a constant rate and has a linear form, but after cracking an abrupt change in the strain was observed and strain increased at a higher rate.

4.1 Steel strains

Figs. (2) to (4) show the load-steel strain curves for beams with Grade 75-ksi (520 MPa) steel. Figs. (5) to (7) show the load-steel strain curves for beams with Grade 60-ksi (420 MPa) steel. Test results illustrate that the decrease of CFRP amount, yield strength of tensile steel reinforcement and reinforcement ratio resulted in higher steel strain values for the same load level. This is due to ductile behavior of the beams with low CFRP reinforcement ratio, low yield strength of steel bars, and low steel reinforcement ratio.

The strengthening layers of CFRP have a clear effect on steel bars strains. For control beam with 1.27% steel ratio and yield strength of 75-ksi, the strain is shown 0.0045 at load of 20 kN. At the same load, in CFRP beams, the steel strains reduced to 0.002 and 0.001 or less in one-layer and two-layer CFRP strengthened beams, respectively.

Maximum strains were approximately 0.008 or more for control beams, 0.007 for one-layer and 0.0065 or less for two-layer CFRP beams.

Strains were reduced as the steel ratio increased. At load of 20 kN, the steel (75-ksi) strain in one-layer strengthened beam was reduced from 0.002 to 0.0015 when steel ratio was increased from 1.27% to 3.24%. For the corresponding two-layer beams, strains were reduced from 0.002 to 0.0012.

Strains were reduced as the steel grade increased. At load of 20 kN, the steel (1.82% ratio) strain in two- layer strengthened beam was reduced from 0.002 to 0.001 when steel grade was increased from 60-ksi to 75-ksi.

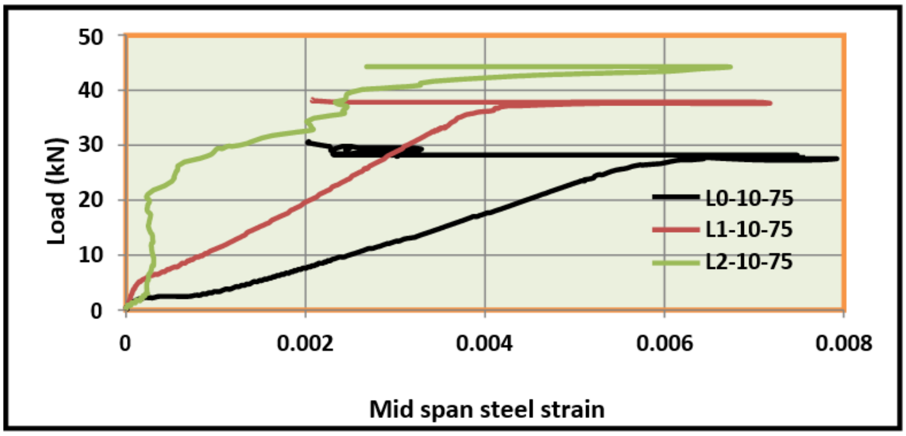

Figure 2: Effect of CFRP amount on the load steel strain relationship for 75-ksi steel grade beam with reinforcement ratio (0.0127)

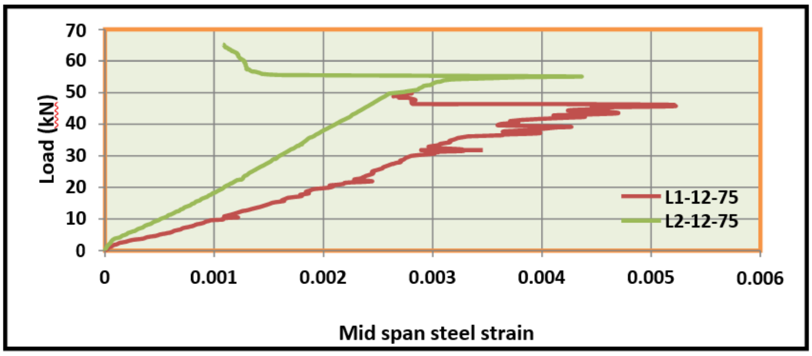

Figure 3: Effect of CFRP amount on the load steel strain relationship for 75-ksi steel grade beam with reinforcement ratio (0.0182)

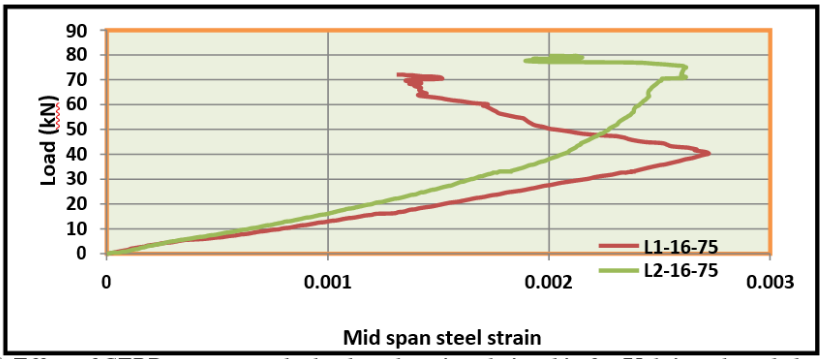

Figure 4: Effect of CFRP amount on the load steel strain relationship for 75-ksi steel grade beam with reinforcement ratio (0.0324)

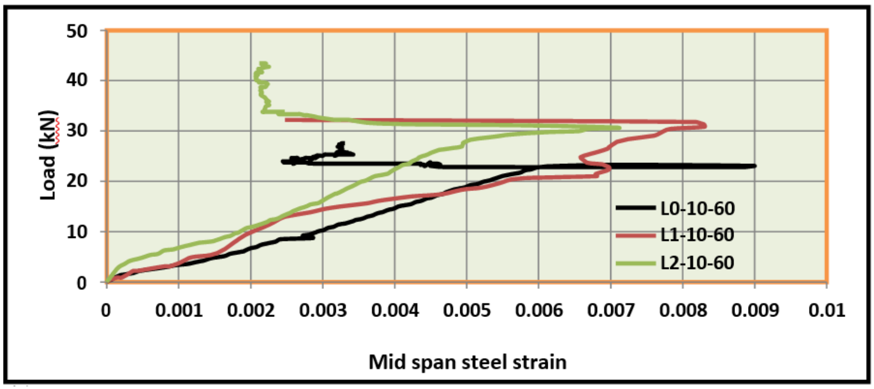

Figure 5: Effect of CFRP amount on the load steel strain relationship for 60-ksi steel grade beam with reinforcement ratio (0.0127)

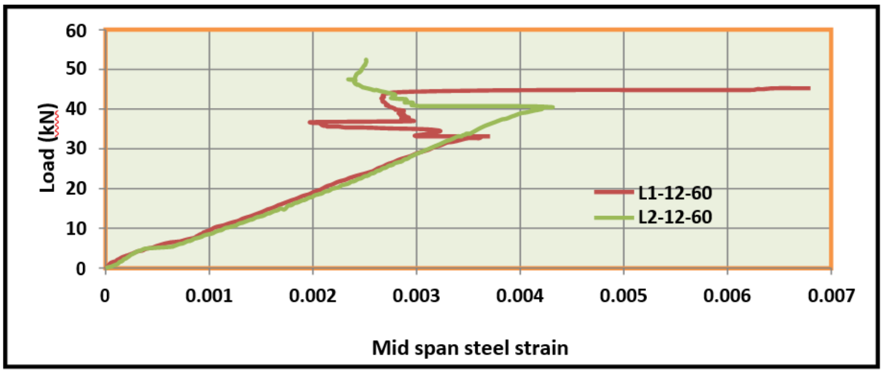

Figure 6: Effect of CFRP amount on the load steel strain relationship for 60-ksi steel grade beam with reinforcement ratio (0.0182)

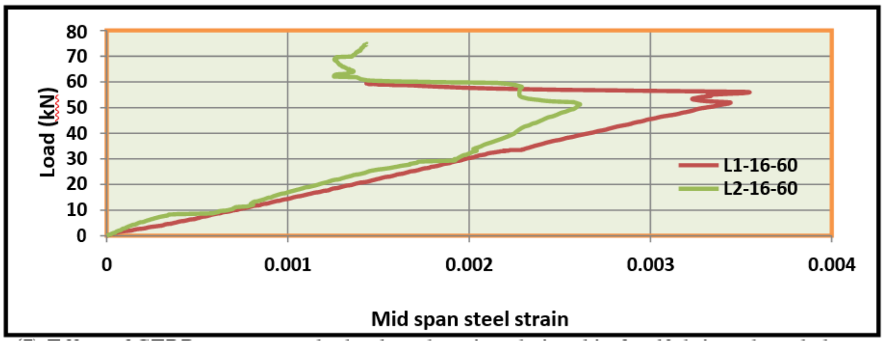

Figure 7: Effect of CFRP amount on the load steel strain relationship for 60-ksi steel grade beam with reinforcement ratio (0.0324)

In all specimens, steel strains at failure were well over the yield strain, except in the beam with 16 mm bar size of yield strength of 75 ksi (520 MPa) with reinforcement ratio (0.0324) (Fig. 4) where steel strains were approximately or little more than the yield strain. This finding is also confirmed in cases of strengthened beam-column joints with FRP [Al Rauashdeh and Al Khawaldeh, 2021]

4.2 CFRP strains

Figs. (8) to (10) show the load- CFRP strain curves for beams with Grade 75-ksi steel. Figs. (11) to (13) show the load- CFRP strain curves for beams with Grade 60-ksi steel. Test results illustrate that the decrease of CFRP amount, yield strength of tensile steel reinforcement, and reinforcement ratio resulted in higher CFRP strain values for the same load level. This is due to ductile behavior of the beams with low CFRP reinforcement ratio, low yield strength of steel bars, and low steel reinforcement ratio.

The increase of CFRP amount, yield strength of tensile steel reinforcement (fy) and steel reinforcement ratio (ρ) resulted in gradual reduction in steel and CFRP strains at the same load level. This reduction in the strain may be attributed to that the increase of CFRP amount, (fy) and (ρ) resulted in an increase of the neutral axis depth of the beam cross section, which in turn resulted in a substantial reduction in CFRP and steel strain at the same load level.

For CFRP strains, it is shown that there is a clear reduction in strains when two-layers are applied compared to one-layer of CFRPs especially at higher amounts of strains.

For beams with 1.82% steel ratio and yield strength of 60-ksi, the CFRP strains at load of 30 kN were 0.0065 and 0.005 or less for one-layer and two-layer CFRP beams, respectively. For corresponding beams with 75-ksi steel, the CFRP strains were 0.0034 and 0.0023, respectively.

Maximum CFRP strains were 0.0110 and 0.0092 in 1-layer and 2-layer strengthened beams.

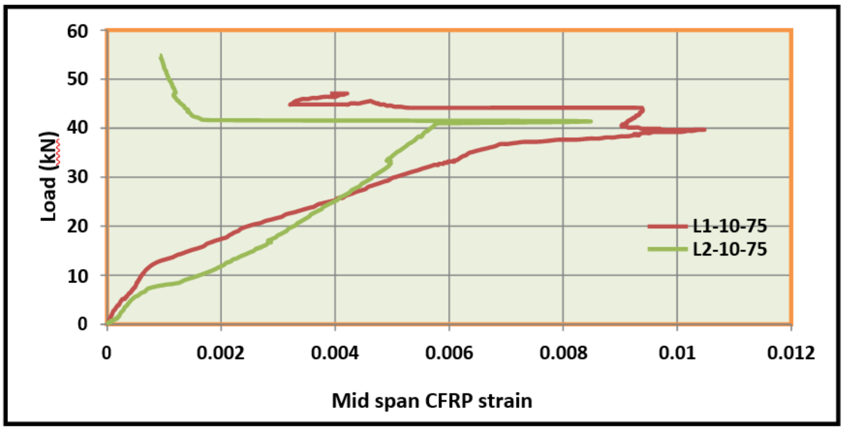

Figure 8: Effect of CFRP amount on the load CFRP strain relationship for 75-ksi steel grade beam with reinforcement ratio (0.0127)

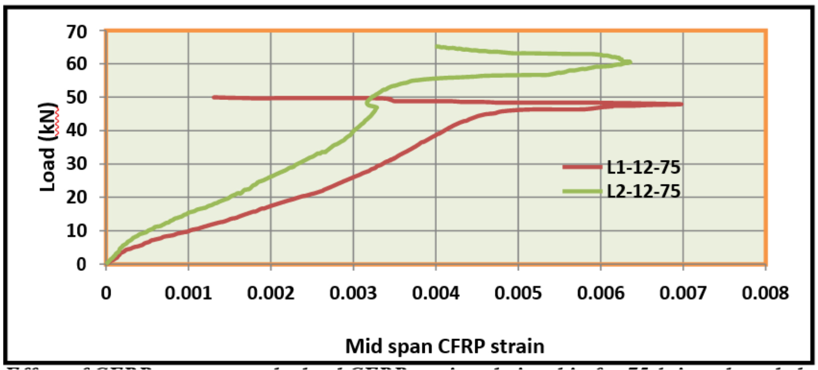

Figure 9: Effect of CFRP amount on the load CFRP strain relationship for 75-ksi steel grade beam with reinforcement ratio (0.0182)

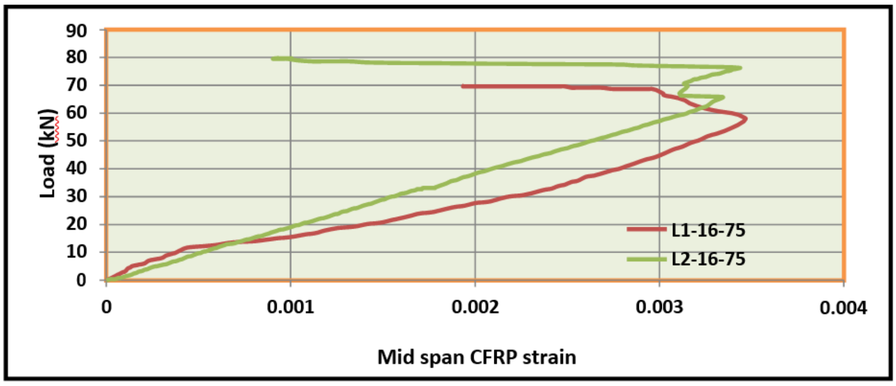

Figure 10: Effect of CFRP amount on the load CFRP strain relationship for 75-ksi steel grade beam with reinforcement ratio (0.0324)

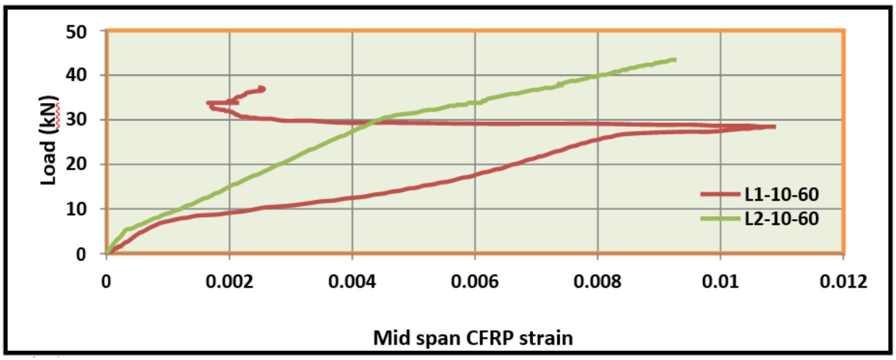

Figure 11: Effect of CFRP amount on the load CFRP strain relationship for 60-ksi steel grade beam with reinforcement ratio (0.0127)

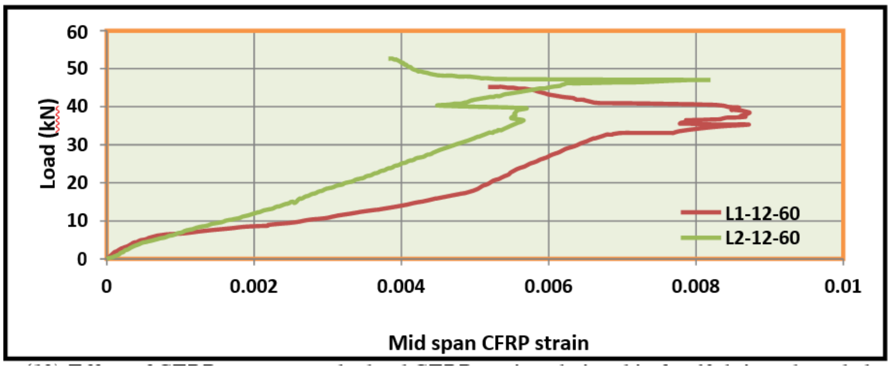

Figure 12: Effect of CFRP amount on the load CFRP strain relationship for 60-ksi steel grade beam with reinforcement ratio (0.0182)

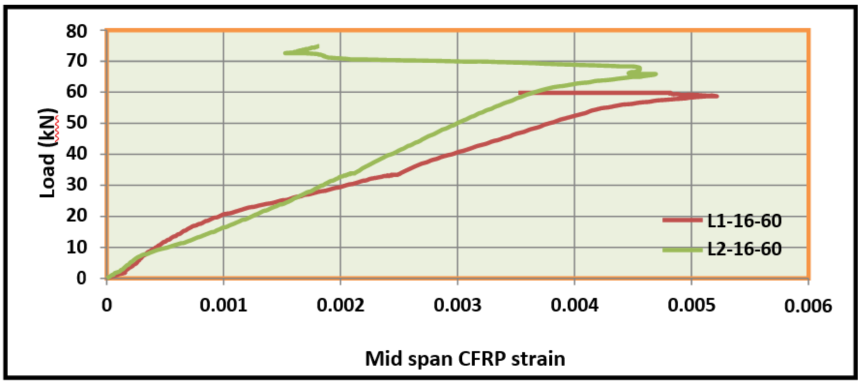

Figure 13: Effect of CFRP amount on the load CFRP strain relationship for 60-ksi steel grade beam with reinforcement ratio (0.0324)

Fig. 14 shows that, for a reinforcement ratio ρ = 1.27%, steel strains at failure are well over the yield strains (0.0021 and 0.0026 for steel yield strengths 60 and 75 ksi, respectively). It also shows the reduction of steel strains as CFRP layers are introduced and increased.

Fig. 15 shows for various reinforcement ratios (ρ), at steel yield strength of 60 ksi, the reduction of steel strains at failure as the number of CFRP layers is increased. It can be noticed that at ρ =3.24% the steel strains at failure dropped to approximately the yield value of steel strain. This may raise concerns of ductility behavior and the mode of failure.

Fig. 16 shows for 1-layer and 2-layer CFRP strengthening cases, the strains of CFRP at failure vs. various reinforcement ratios (ρ), at steel yield strength of 60 ksi. The reduction of CFRP strains at failure is obvious as the reinforcement ratios (ρ) are increased. It can be noticed that CFRP strains at failure are reduced when increasing the number of layers. However, the CFRP strain values are well above the limits 0.004 to 0.006 stated by (ACI 440.2R – 17), except at high values of steel reinforcement approaching ACI maximum ratio. Results of this work agree with [Guibing Li et al, 2023] findings.

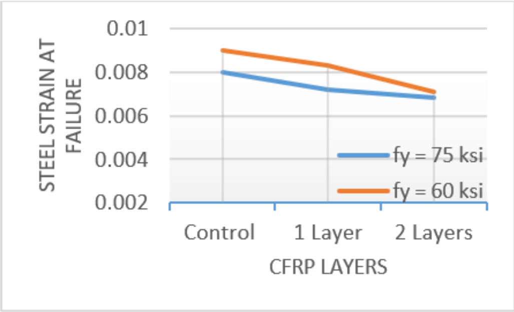

Figure 14: Steel strain vs. CFRP no. of layers

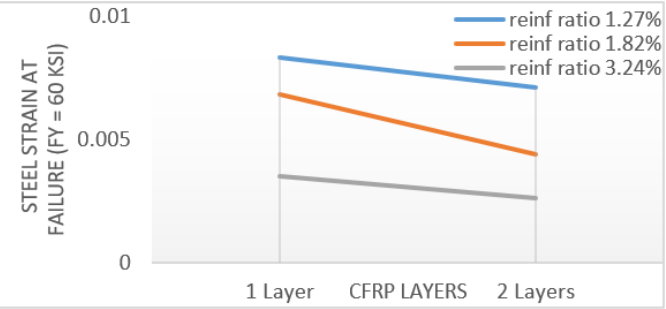

Figure 15: Steel strain vs. CFRP no. of layers for various ρ values

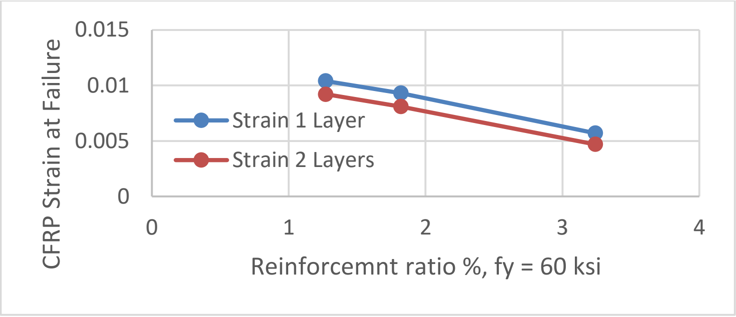

Figure 16: CFRP strain vs. reinforcement ratio

5. Conclusions

It may be concluded that although strengthening with CFRP enhances the carrying capacity of beams, they require special consideration for ductility. A substantial reduction in steel strains was recorded as the CFRP layers were introduced and increased in the number of layers. On the other hand, a substantial reduction in CFRP strains was recorded as the steel reinforcement ratio increased.

It is recommended to test beams at higher strain amounts using anchorages and/or wrapping to check enhancement of ductility of CFRP beams.

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