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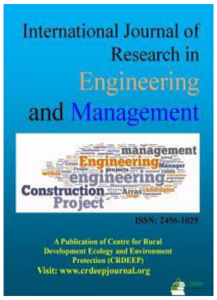

Full Length Research Paper

# Investigating of Composite T-Beams Strengthened with CFRP Plates Using Finite Element Modeling

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## ABSTRACT

*Generally, the research about the strengthening of steel–concrete composite structures is relatively few. One main reason is that the experimental investigation of such structures is very costly, regardless its difficulties. On the other hand, Finite Element (FE) modeling was proved as an accurate alternative of the experimental work for many structural systems. This paper examined the validity and the accuracy of FE modeling of Steel-RC composite T-beams strengthened using Carbon Fiber Reinforced Polymers (CFRP) plates, attached to tension zones, using the FE Package ANSYS. Then after, it investigated the strengthening / repairing of such beams. Parameters that assumed to affect the behavior of the strengthened beams were examined. These parameters were length, thickness, and number of layers of CFRP strengthening laminates. It was found that CFRP laminates are very effective in strengthening composite T-section beams regarding both flexural capacity and ductility. Definitions for the optimum values of CFRP-laminate length, thickness and number of layers were determined. In addition, the thickness of the reinforced concrete (RC) slab of the strengthened beams was examined. Increasing the thickness of the RC slab in the presence of the CFRP strengthening increases both the capacity and ductility of the T-section composite beams till a corresponding optimum value, after which ductility begins to decrease. As a conclusion, it was found that increasing the length of CFRP laminates is more effective, in strengthening composite steel-RC T-beams, than other parameters.*

## Introduction

Steel-RC composite beams are main parts of the steel road bridges, which used widely all over the world. These composite beams may be repaired or strengthened, due to steel corrosion or increasing of the bridge capacity, due to traffic increasing. **(**Ragab et al., 2007) reviewed the analytical and experimental studies, projects and field applications of using non-prestressed and prestressed FRP techniques in structures strengthening. Large-scale steel-concrete composite beams, typical of bridge structures, were examined by (Schnerch and Rizkalla, 2008) to consider the effect of CFRP modulus, prestressing of the CFRP strips and splicing finite lengths of CFRP strips. All of the techniques examined were effective in utilizing the full capacity of the CFRP material, and increasing the elastic stiffness (10-34%) and ultimate strength (up to 46%) of the beams.(Salama and Abd-El-Meguid, 2010) provided design guidelines for composite steel concrete bridge when using CFRP. (Sharif et al., 2016) used CFRP, at the top of the concrete slab at the negative moment region of continuous composite girders, to maintain the composite action. On the other hand, (El-Zohairy et al., 2017) recommended that the composite action between the steel beam and concrete slab has not to be less than 80% to achieve the optimum performance of CFRP strengthening. (Karam et al., 2017) investigated the flexural performance of pre-damaged steel-concrete composite beams repaired using CFRP laminates. The CFRP repair schemes were capable of restoring between 81 and 100% of the original load capacity of the damaged beams. (Abdel-Fattah, 2020) used ANSYS to study the strengthening of steel-RC composite beams using CFRP laminates. (Liu et al., 2022) showed that adding CFRP sheets on the top of the concrete slab, of a continuous composite concrete-steel beam, at hogging-moment region has a great effect on the structural performance of the examined beams.

## Verification of Finite Element Modeling

### *Experimental specimens and FE modeling*

Two simply supported beams strengthened in the tension zone using CFRP plates, of previous experimental work, will be used to verify the ANSYS modeling technique used in this research. The first is a steel CFRP-strengthened I-beam called (S405) from the work of (Deng and Lee, 2007) with the dimensions shown in Fig. 1. It was loaded in its mid-span at four points until failure. Elastic moduli are 205 and 212 GPa, for steel and CFRP, respectively. CFRP plate is bonded to steel through an epoxy resin of tensile strength, elastic modulus and shear modulus of 29.7 MPa, 8 GPa, and 2.6 GPa, respectively.

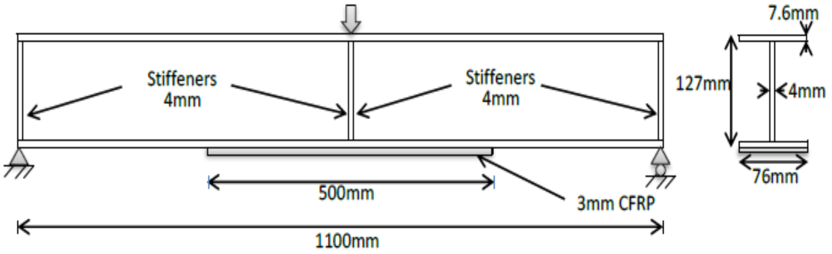

**Fig. 1** Details of steel I-beam strengthened using CFRP plate [Deng and Lee (2007)]

The second one is a composite steel-RC T-beam strengthened using CFRP plate from the work of (Schnerch et al., 2005) called HM-7.6-AB with the dimensions shown in Fig. 2. Steel beam's average yield strength is 373 MPa. Shear studs are 76 mm in length, 19 mm in diameter and spaced at 152 mm along the compression flange's length. Average concrete strength is 40.5 MPa. Longitudinal and transverse reinforcement bars are of diameter 12.7 mm and average yield strength of 449.5 MPa. Transverse reinforcement is spaced at 152 mm. The beam was loaded in four-point bending under displacement control to its ultimate strength, with loads applied symmetrically about the center of the span, as shown in Fig. 3.

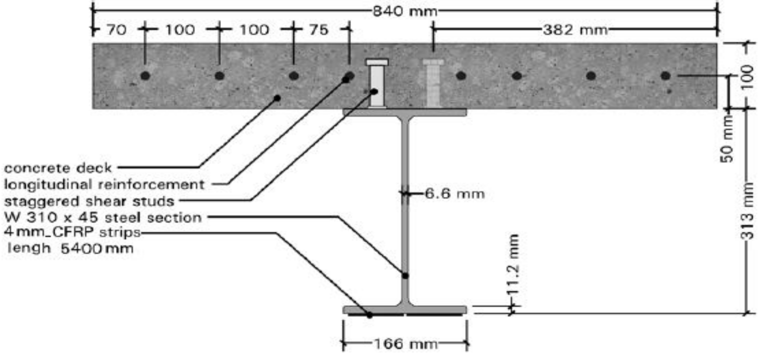

**Fig. 2** Cross-section dimensions of the tested composite beam

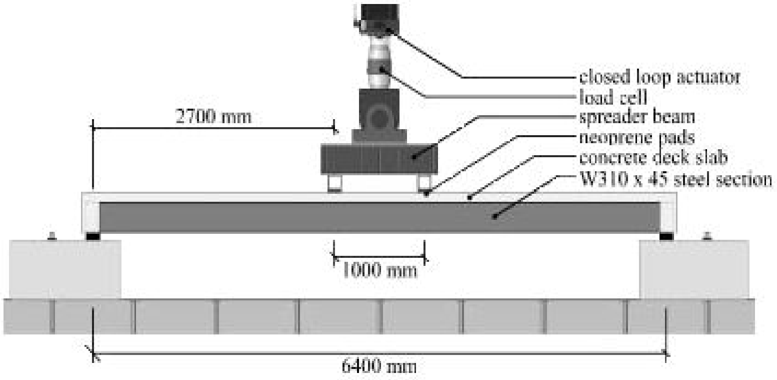

**Fig. 3** Loading configuration

The two experiments were modeled using ANSYS in the same procedure done by (Mohie Eldin et al., 2017).

## Results

Fig. 4 and Table 1 show the relations between applied load and mid-span deflection, experimentally and theoretically, for the steel I-Beam strengthened with CFRP plate, while Fig. 5 and Table 2 show the same relations for the steel-RC composite T-beam.Both experimental and theoretical (FE) results are in a very good agreement, which allows using ANSYS as a powerful tool for modeling of steel-RC composite T-beams strengthened by CFRP laminates.

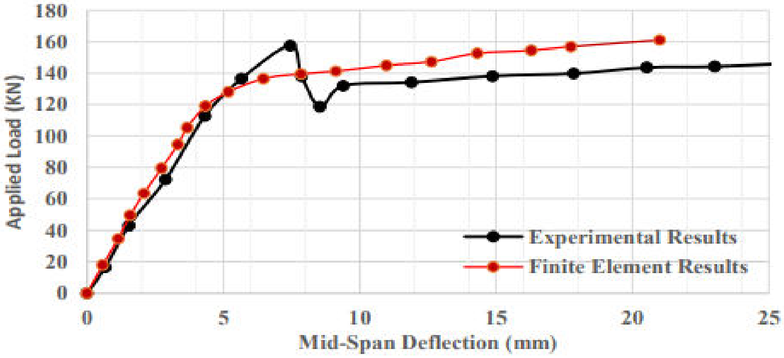

**Fig. 4** Load-deflection curve for strengthened steel I-beam (S405)

**Table 1** Results of beam (S405)

| Maximum Loading (KN) | | | Maximum Deflection (mm) | | |
|---|---|---|---|---|---|
| FE | Exp. | % | FE | Exp. | % |
| 161 | 157.5 | 102.2 | 21 | 25.90 | 81.1 |

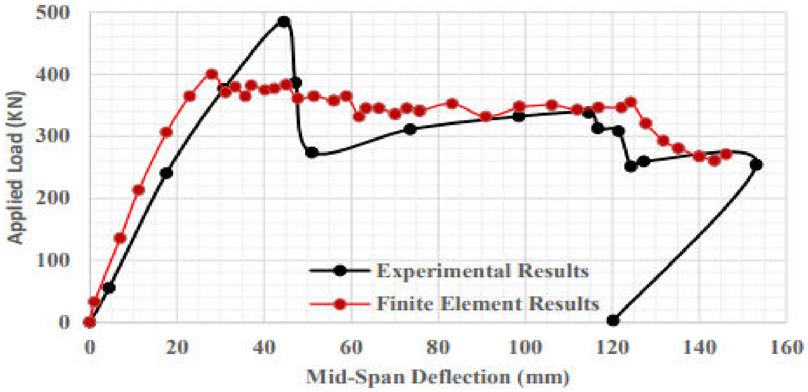

**Fig. 5** Load-deflection curve for steel-RC composite T-beam (HM-7.6-AB)

**Table 2** Results of beam (HM-7.6-AB)

| Maximum Loading (KN) | | | Maximum Deflection (mm) | | |
|---|---|---|---|---|---|
| FE | Exp. | % | FE | Exp. | % |
| 491 | 400 | 122.7 | 146.1 | 153 | 95.4 |

## Parametric study

### *Dimensions and data of modeled beams*

A parametric study of 15 FE beams, named CB0 to CB14, was made to investigate the effect of the dimensions of both CFRP laminate and RC slab upon the behavior of strengthened composite T-beams. Theses beams have the same cross section, material and loading configuration as shown in Figs. 2-3 for beam HM-7.6-AB of (Schnerch et al., 2005). CB0 is the control, or unstrengthened, beam. Results of CB0 show that its ultimate load ($P_0$) is 352.2994 KN with corresponding mid-span deflection ($\Delta_0$) of 26.503 mm.

The studied parameters are length ($L_{CFRP}$), thickness ($t_{CFRP}$) and number of layers ($N_{CFRP}$) of the CFRP laminate, and the thickness of the RC slab ($t_{RC}$). Standard dimensions are $L_{CFRP}$ = 5400 mm, $t_{CFRP}$ = 4 mm, $N_{CFRP}$ = 1, $t_{RC}$ = 100 mm and the width of CFRP laminate is 166 mm; beam CB1. Beams CB2 – CB4 have CFRP lengths of 2700, 2100 and 900 mm, respectively. Beams CB5 – CB6 have CFRP thicknesses of 1 and 3 mm, respectively. Beams CB7 – CB9 have 2, 3 and 4 layers of CFRP laminates, respectively. Beams CB10 - CB14 have RC slab thicknesses of 80, 120, 140, 160 and 180 mm, respectively. All the following results will be in KN and mm.

*Effect of CFRP lengths*

Fig. 6 and Table 3 show the results of beams CB1 to CB4, according to the change of CFRP-laminates lengths, relative to the results of the control beam CB0.

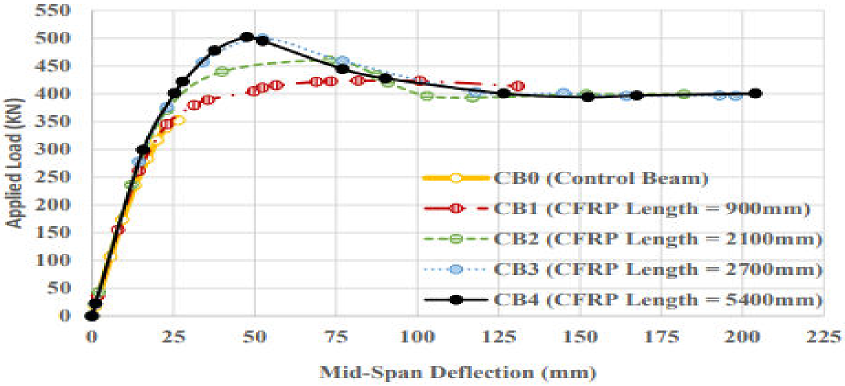

**Fig. 6** Load-deflection curves for different lengths of CFRP laminate

**Table 3** Effect of changing length of CFRP laminates

| Beam | $L_{CFRP}$/ $L_{Span}$ % | Ultimate Load $P_u$ (kN) | $P_u$ / $P_0$ | $\Delta_u$ (Deflection at $P_u$) (mm) | $\Delta_u$ /$\Delta_0$ | Maximum Deflection $\Delta_{max}$ (mm) |
|---|---|---|---|---|---|---|
| CB0 | 00.00 | 352.2994 | 1 | 26.503 | 1 | 26.503 |
| CB1 | 14.06 | 423.489 | 1.202071 | 81.852 | 3.088405 | 131 |
| CB2 | 32.81 | 459.5582 | 1.304453 | 72.9129 | 2.751119 | 182 |
| CB3 | 42.19 | 499.2381 | 1.417085 | 52.4424 | 1.978734 | 198 |
| CB4 | 84.38 | 502.4151 | 1.426102 | 47.5821 | 1.795348 | 204 |

Figs. 7 – 9 show the effect of changing CFRP length upon the ultimate load, its corresponding deflection and the maximum deflection, respectively, of the strengthened composite beams.

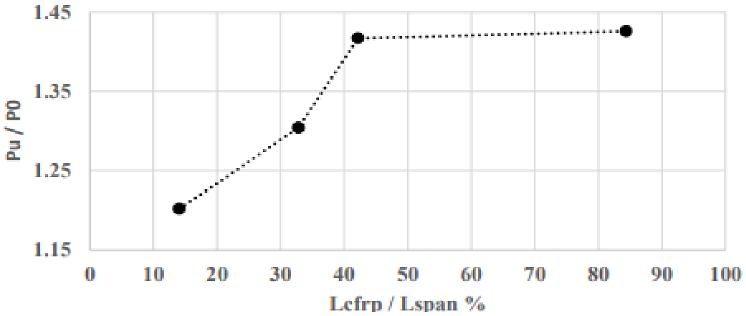

**Fig.** 7 Effect of CFRP-laminate length upon the ultimate load of strengthened beams

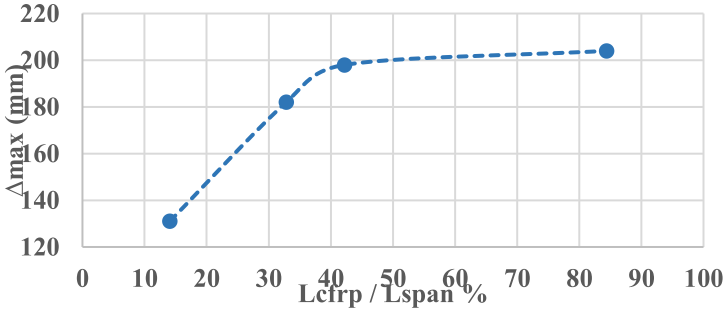

**Fig. 8** Effect of CFRP-laminate length upon the maximum deflection

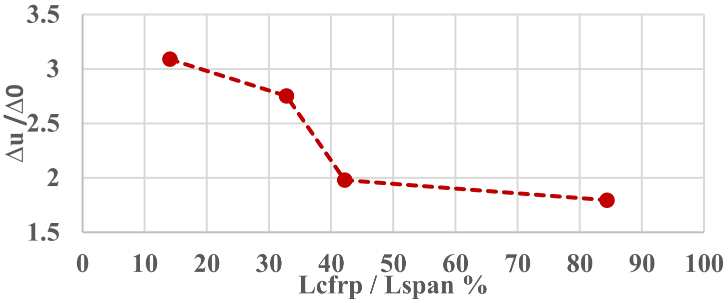

**Fig. 9** Effect of CFRP-laminate length upon the deflection at ultimate load

For design purposes, the softening part of the load-deflection curve will be neglected and the ductility is defined as the ratio between the deflection at the ultimate load and that corresponding to the yield or the end of the elastic stage of behavior. According to the results:

- Strengthening using CFRP laminates increases the capacity (flexural strength) and the maximum deflection of the strengthened composite T-beams, comparing with the unstrengthened ones. However, stiffness is not affected.
- CFRP strengthening, whatever its length, affect the behavior of the strengthened beams, only, in the plastic (post yield) stage; after first crack of RC slab.
- According to Figs. 6 and 9, increasing the length of CFRP laminate increases the capacity and decreases the ductility of the strengthened beams.
- According to Figs. 7 and 8, there is an optimum length for CFRP strengthening, e.g. about 42% for the studied case, after which both maximum load (capacity) and maximum deflection of the strengthened beams will not be, concretely, affected.
- In addition, it was found that increasing the CFRP length increases the stresses in the lower steel bars, which means much utilizing of lower reinforcement.

**Effect of CFRP thickness**

Table 4 and Fig. 10 show the results of beams CB1, CB5 and CB6, according to the change of CFRP-laminate thickness, relative to the results of the control beam CB0.

**Table 4** Effect of changing thickness of CFRP laminates

| **Beam** | **$t_{CFRP}$ (mm)** | **Ultimate Load $P_u$ (kN)** | **$P_u$ / $P_0$** | **$\Delta_u$ (Deflection at $P_u$) (mm)** | **$\Delta_u$ /$\Delta_0$** |
|---|---|---|---|---|---|
| CB5 | 1 | 517.507 | 1.468941 | 84.4172 | 3.185194 |
| CB6 | 3 | 540.8039 | 1.535069 | 65.8456 | 2.484458 |
| CB1 | 4 | 541.8682 | 1.53809 | 61.7707 | 2.330706 |

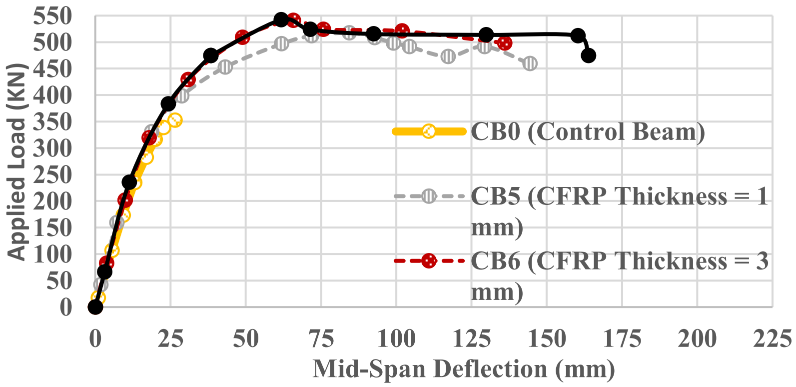

**Fig. 10** Load-deflection curves for different thicknesses of CFRP-laminates

Figs. 11 and 12 show the effect of changing CFRP thickness upon the ultimate load and its corresponding deflection, respectively, of the strengthened composite beams.

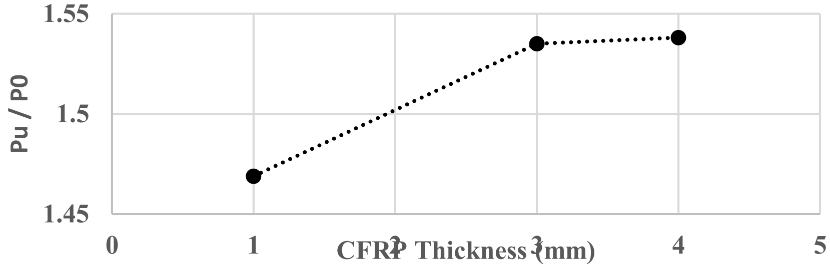

**Fig. 11** Effect of CFRP-laminate thickness upon the ultimate load of strengthened beams

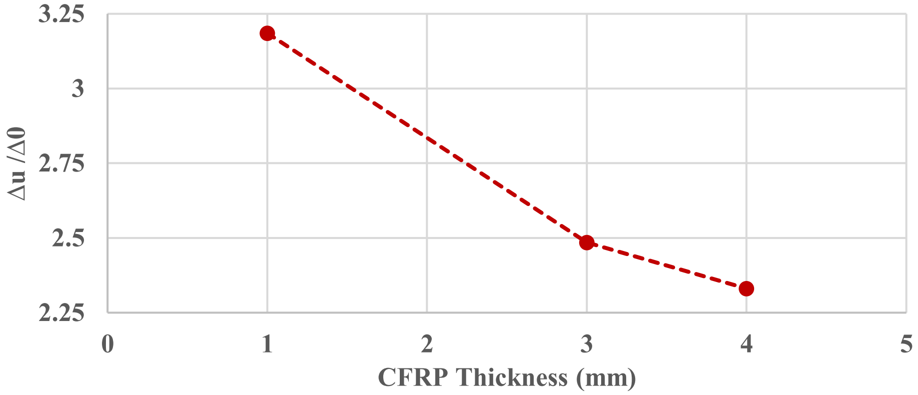

**Fig. 12** Effect of CFRP-laminate thickness upon the deflection at ultimate load

According to the results:

- Increasing the thickness of CFRP laminate increases the capacity and decreases the ductility of the strengthened beams. However, the rate of either increasing the capacity or decreasing the ductility decreases with increasing the CFRP-thickness. This means that there is an optimum CFRP-thickness, after which the effect of increasing the thickness is negligible. However, changing length of CFRP laminate is more effective than changing its thickness.
- Increasing CFRP thickness increases the stresses in the steel reinforcement, especially, at the ends of the CFRP laminate away from the position of the maximum positive moment.
- Effect of thickness change, according to stresses change in CFRP laminates, appears at the laminate's mid-length within about 25% of the laminate total length.
- Only small thicknesses of CFRP laminates give a transition length of zero-stresses, and make the behavior of CFRP laminates smoother without shocks.

Therefore, small thickness with enough length of CFRP laminates is the effective choice for utilizing the material of CFRP laminates.

### Effect of number of CFRP layers

Fig. 13 and Table 5 show the results of beams CB1 and CB7 to CB9, according to the change of number of CFRP layers.

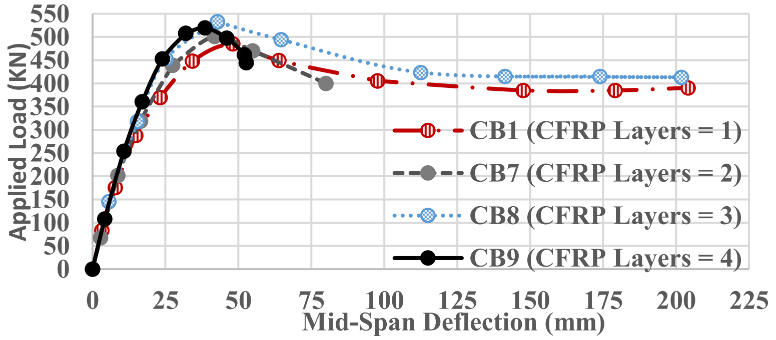

**Fig. 13** Load-deflection curves for different layers of CFRP-laminates

**Table 5** Effect of changing number of CFRP layers

| Beam | $N_{CFRP}$ | Ultimate Load $P_u$ (kN) | $P_u$ / $P_0$ | $\Delta_u$ (Deflection at $P_u$) (mm) | $\Delta_u$ /$\Delta_0$ |
|---|---|---|---|---|---|
| CB1 | 1 | 502.4151 | 1.426102 | 47.5821 | 1.795348 |
| CB7 | 2 | 515.6518 | 1.463675 | 42.8042 | 1.61507 |
| CB8 | 3 | 540.2745 | 1.533566 | 42.9088 | 1.619017 |
| CB9 | 4 | 530.8353 | 1.506773 | 37.6783 | 1.421662 |

Figs. 14 and 15 show the effect of the number of CFRP layers upon the ultimate load and its corresponding deflection, respectively, of the strengthened composite beams.

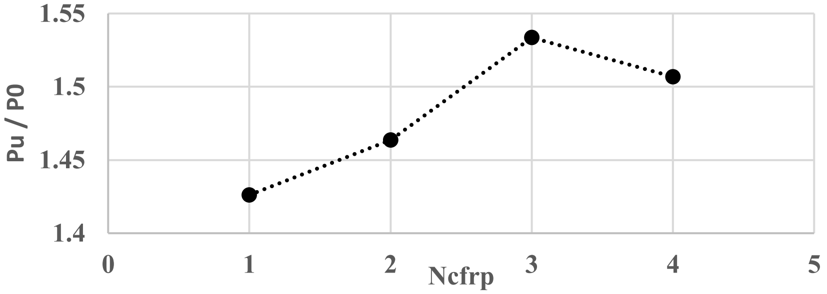

**Fig. 14** Effect of CFRP-layers-number upon the ultimate load of strengthened beams

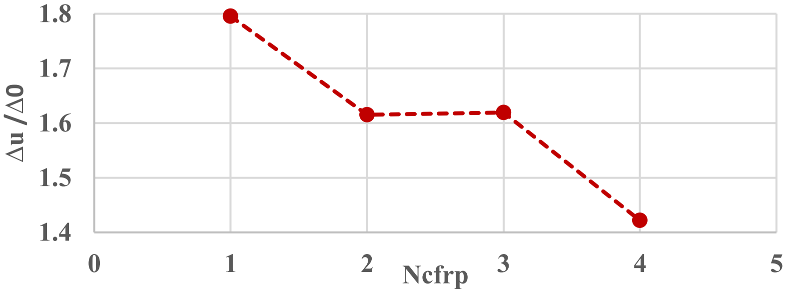

**Fig. 15** Effect of CFRP-layers-number upon the deflection at ultimate load

According to the results:

- Increasing the number of CFRP layers increases the capacity of the strengthened beams until the optimum number of CFRP layers ($N_{Opt}$). After that, i.e. $N_{CFRP} > N_{Opt}$, capacity will decrease with increasing the number of CFRP layers.
- Increasing the number of CFRP layers decreases the ductility. However, at $N_{CFRP} = N_{Opt}$, there is a very slight increasing in ductility comparing with the previous result. After that, ductility decreases again with increasing of NCFRP.
- Stresses in CFRP laminates increase with decreasing of number of layers.
- Whatever the number of layers, it was found that CFRP-strengthening increases the stresses in the reinforcement, which means more utilizing of steel.
- Increasing the number of CFRP layers decreases the length of reinforcement that has zero or compression stresses/strains.
- Increasing the number of CFRP layers decreases the steel's strain near the position of maximum positive moment and increases it in the remaining length of the reinforcement.

**Effect of thickness of RC slab**

Fig. 16 and Table 6 show the results of beams CB1 and CB10 to CB14, according to the change of RC-slab thickness, while $\delta_P = (P_n - P_{n-1}) / P_{n-1}$ and $\delta_\Delta = (\Delta_n - \Delta_{n-1}) / \Delta_{n-1}$.

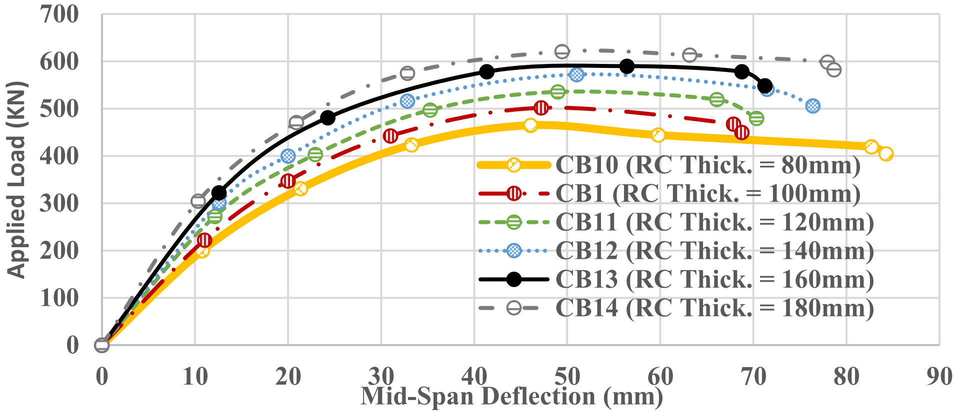

**Fig. 16** Load-deflection curves for different thicknesses of RC slab

**Table 6** Effect of changing RC-slab thickness

| Beam | $t_{RC}$ (mm) | Ultimate Load $P_u$ (kN) | $P_u / P_0$ | $\Delta_u$ (mm) (Deflection at $P_u$) | $\Delta_u / \Delta_0$ | $\delta_P$ % | $\delta_\Delta$% |
|---|---|---|---|---|---|---|---|
| CB10 | 80 | 464.0949 | 1.317331 | 47.6212 | 1.796823 | ---- | --- |
| CB1 | 100 | 499.7963 | 1.418669 | 48.8306 | 1.842456 | 7.69269 | 2.53963 |
| CB11 | 120 | 533.2725 | 1.513691 | 52.5145 | 1.981455 | 6.69797 | 7.54424 |
| CB12 | 140 | 570.6961 | 1.619918 | 53.6733 | 2.025178 | 7.01772 | 2.20663 |
| CB13 | 160 | 589.5066 | 1.673311 | 52.5224 | 1.981753 | 3.29606 | 2.14427 |
| CB14 | 180 | 618.2622 | 1.754934 | 52.3809 | 1.976414 | 4.87791 | 0.26941 |

Figs. 17 and 18 show the effect of the RC-slab thickness upon the ultimate load and its corresponding deflection, respectively, of the strengthened composite beams.

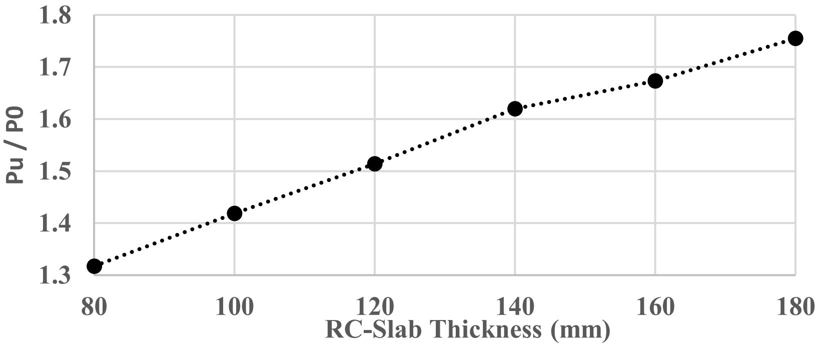

**Fig. 17** Effect of RC-slab thickness upon the ultimate load of strengthened beams

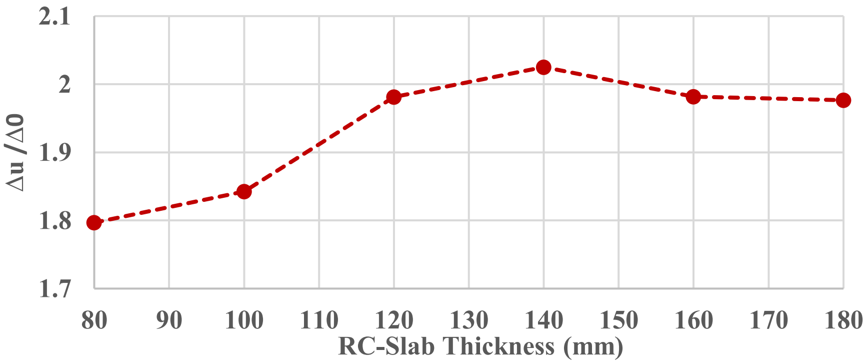

**Fig. 18** Effect of RC-slab thickness upon the deflection at ultimate load

According to the results:

- Increasing the thickness of RC slab increases the capacity of the strengthened beams.
- Increasing the thickness of RC slab until a certain value, i.e. $t_{RC}$ = 140 mm, increases the ductility of the strengthened beams. However, after this value, ductility decreases slightly.
- If optimum RC thickness ($t_{RC\text{-}Opt}$) is defined as the thickness after which $\delta p\%$ is minimum and $\delta_{\Delta}\%$ is negative, then $t_{RC\text{-}Opt}$ = 140mm.

## Conclusions

This paper examines the effect of using Carbon Fiber Reinforced Polymers (CFRP) plates, attached to tension zones, in strengthening or repairing of Steel-RC composite T-beams. According to the obtained results:

- CFRP laminates are very effective in strengthening of T-section composite beams regarding both capacity and ductility.
- Optimum length or thickness of CFRP strengthening is the dimension after which the effect of its increasing is negligible.
- After the optimum number of CFRP layers, capacity will decrease with increasing the number of CFRP layers.
- The length of the laminate is more effective than its thickness or number of layers. As a result, small thickness with enough length of CFRP laminate is the effective choice for utilizing the material of CFRP laminates.
- Using of CFRP changed the effect of increasing the thickness of the reinforced concrete slab from non-ductile to ductile.

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