Numerical study to investigate the behavior of reinforced concrete slabs with CFRP sheets

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ABSTRACT
The current study implements nonlinear finite-element analysis using ANSYS15 software for the preparation of models to investigate the behavior of reinforced concrete slabs strengthened with carbon fiber-reinforced polymer (CFRP) sheets. A comparison between the results of ANSYS, experimental works, and equations of Egyptian Standing Code (ESC) was made for strengthened slabs with different sheet areas. Also, comparisons were carried out between strengthened slabs with equivalent applied areas that differ in distributions. The effects of the change of main reinforcement, compressive strength of concrete, slab thickness, and sheet thickness on strengthened slab behavior were investigated. The results of ANSYS are in good agreement with equation of ESC. The strengthening of examined slabs with CFRP sheets improves the flexural strength capacity. The distribution of CFRP sheets enhances the performance of studied slabs. The increase in compressive strength of concrete, slab thickness, and sheet thickness leads to increase in failure load magnitude of strengthened slabs. The increase in the main reinforcement increases the failure load to a certain limit. For the studied slabs, reinforcement bigger than 12 mm in diameter leads to a reduction in failure load.

Introduction
Several structural elements such as slabs, beams, and columns require strengthening during their service life period. Many factors affect the requirement for strengthening of these elements including design or construction defects, increased load, change of structure operation, or new code requirements. Strengthening of reinforced concrete (RC) structure with fiber-reinforced polymer (FRP) sheets is one of the methods implemented to raise the load-carrying capacity. FRP has many advantages, which make it more attractive for the civil engineering industry. They are available in several forms such as laminates and sheets. Additionally, these materials have a high strength-to-weight ratio, corrosion resistance, fast processing time, and flexibility.

The use of FRP composite for strengthening RC element causes significant enhancements to durability, economics, and success. In general, the flexural strength capacity increase due to using FRP composite and the mode of failure remained flexural mode which is better than shear or compression failure. The influence of strengthening beams with FRP on strain, deflection, failure load and mode, ductility of beam, and flexural and shear strengthening were thoroughly studied (Al-Rousan, Issa, & Shabila, 2012; Barros, Dias, & Lima, 2007; Dias & Barros, 2012; Elgabbas, El-Ghandour, Abdelrahman, & El-Dieb, 2010; Grace, Sayed, Soliman, & Saleh, 1999; Michel, Ferriera, Agbossou, & Hamelina, 2009; Rosemol, Ashokkumar, & Ananya, 2015). Scott, Shenghua, Seo, & Rudolf (2011) studied the effectiveness of FRP anchors in increasing the strength and deflection of FRP flexurally strengthened RC slab (RCS). There was an increase in strength over the unanchored but strengthened control counterparts. Tamer & Khaled (2008) studied RCS strengthened with mechanically anchored un-bonded FRP system. They concluded that external bonding–FRP strengthening system without end anchorage increased the yield and the ultimate loads by about 38% and 46%, respectively, relative to those of the control.

Li, Guo, Liu, & Bungey (2006) studied strengthened beams with single and double layer at three lengths of carbon fiber-reinforced polymer (CFRP). The simulations and results of tests showed a good agreement and indicate that initial cracking loads of strengthened beams increase slightly, while stiffness and ductility increase more and the ultimate loads increase considerably. Hedong, Alvaro, & Vistasp (2005) studied experimentally and analytically the effect of material configuration on strengthening of concrete slabs by CFRP composites. They concluded that failure mechanisms were based on the form of strip. The pultruded strips showed a higher tendency for debonding, and the wet layup strips showed a combination of full-width fiber rupture and debonding. In this research work, the researchers (Sameha,
Eehab, Hamed, & Abdel Hamid, 2013) tested models for slabs reinforced with CFRP laminates and sheets. They concluded that the CFRP sheets showed a cost reduction of 70% with respect to laminates. Also, for most of the equivalent applied area, CFRP sheets have more significant influence on the behavior of the strengthened slabs than laminates. Many researchers implemented finite-element (FE) method to simulate the behavior and failure mechanisms of different strengthened elements with FRP (Hamdy, Ahmed, & Kareem, 2017; Khaled, El-sayed, & Mahmoud, 2019; Mariappan, Raghunath, & Sivaraja, 2016).

The objective of this study is to use ANSYS 15 model to investigate the behavior of RCS strengthened with CFRP sheets and compare the results with Egyptian Standing Code (ESC, 2005). In addition, this study shows the effect of width and distribution of CFRP on the flexural behavior of RCS. Also, the effect of changing in main reinforcement, compressive strength of concrete, slab thickness ($t_s$), and sheet thickness ($t_f$) has been studied.

**Finite-element analysis**

In the present study, ANSYS 15 (ANSYS Version Houston) FE program was utilized. The models of FE for RC structures have substantially been established on work discretization of a perpetual area into an arrangement of unattached sub-areas. These unattached sub-areas usually called elements appearing the steel reinforcement and the concrete. The approach of discrete elements is used to simulate the reinforcement. The drawback of using the discrete model is that the concrete mesh is restricted by the location of the reinforcement. Also, full bond is generally assumed between the reinforcement and the concrete. The reinforcement is modeled using beam elements connected to the concrete at certain shared mesh nodes (Figure 1). Furthermore, concrete exists in the same regions occupied by the reinforcement since the reinforcement is superimposed in the concrete mesh.

![Figure 1. Discrete model for reinforced concrete (ANSYS Version Houston [Computer software]).](image1)

### Table 1. Element types and description for working models (ANSYS Version Houston).

| Material type       | ANSYS element | Description                                                                 |
|---------------------|---------------|-----------------------------------------------------------------------------|
| Concrete            | SOLID65       | 3D 8-node solid elements with 3 degrees of freedom and has the ability to account for material nonlinearity. It is capable of cracking in three orthogonal directions, plastic deformation, crush, and creep. |
| Steel reinforcement | LINK180       | 3 degrees of freedom at each node.                                           |
| Steel supports      | SOLID185      | 8-node with 3 degrees of freedom at each node. It is capable of large strain capabilities, large deflection, plasticity, hyper-elasticity, stress stiffening, and creep. |
| CFRP                | SHELL41       | It has membrane (in-plane) stiffness with no bending (out-of-plane) stiffness and has 3 degrees of freedom at each node. |

**Elements discretization**

Table 1 illustrates the element types for working models (ANSYS Version Houston). SOLID65 is used to model the concrete (Hamdy et al., 2017). This element is capable of cracking in three orthogonal directions, plastic deformation, crush, and creep. Steel reinforcement was modeled by LINK180 element. SHELL41 element was used to model the CFRP composite. The steel plates of the supports and the CFRP sheets were modeled by SOLID185 element. SHELL41 element is shown in Figure 4 and was used to model the CFRP composite. It has membrane (in-plane) stiffness with no bending (out-of-plane) stiffness and has three degrees of freedom at each node.

**Material modeling**

**Concrete constitutive model**

SOLID65 element requires linear and multilinear isotropic material properties for modeling concrete. Figure 2 shows the typical uniaxial compressive stress–strain concrete curve (Kachlakev et al., 2001).

![Figure 2. Typical uniaxial compressive stress–strain concrete curve (Kachlakev et al., 2001).](image2)
shows a uniaxial concrete compressive stress–strain curve in the following equations (Kachlakev, Miller, & Yim, 2001; Raongjant & Jing, 2008; Wolanski, 2004):

\[ f = \frac{E_c x \varepsilon}{[1 + (\varepsilon/\varepsilon_o)^2]} \]  

(1)

\[ \varepsilon_o = \left(2f'_c/E_c\right) \]  

(2)

\[ E_c = f/\varepsilon \]  

(3)

where \( f \) = stress, \( \varepsilon \) = strain, \( \varepsilon_o \) = strain at \( f'_c \), and \( f_g'c \) = the ultimate compressive strength.

**Steel reinforcement**

The reinforcement element was assumed to be a bilinear isotropic elastic-perfectly plastic material and identical in tension and compression (Figure 3).

**FRP constitutive models**

The properties of FRP composite material are directional. It has three mutually orthogonal planes of material properties, (xy, xz, and yz planes) for the unidirectional lamina. The principal material coordinate axes were xyz. The x-direction is the fiber direction, and the y and z directions are perpendicular to the x-direction. The fiber direction may be considered as an isotropic material. The stress–strain relationships are roughly linear for FRP laminates up to failure (Figure 4).

**Boundary conditions and loads**

In this study, temperature change, shrinkage, and creep are not included. The Poisson’s ratio is assumed to be constant. Perfect bond between steel and concrete is assumed. Two supports of steel plates of dimensions of 1000 mm length, 100 mm width, and 25 mm thickness were situated under slabs to deny local cracking in concrete. In these models, the nodal displacement load is used to model the boundary condition by a zero assignment to restrained motions. The coupled Degrees of Freedom (DOFs) were created for all nodes of the mid area located at \( x = 750 \) mm to apply load at the center of the created coupled DOFs. The total load was divided into a series of load steps by ANSYS parametric design language. Newton–Raphson equilibrium iteration was implemented. All slabs were loaded until failure.

**Model cases**

The FE investigations used the RCS (one way) of dimensions 1500 mm length, 1000 mm width, and 80 mm thickness. All slabs were rectangular in cross-section and prismatic. The compressive strength of concrete is 30 N/mm². The slabs were reinforced with the minimum amount of mild steel 5Ø6 mm/m length in short direction and 7Ø6 mm/m in long direction. The line load would be applied on the slab at mid span. Figure 5 shows the reference slab without any strengthening and its FE model. Table 2 and Figure 6, respectively, show the details and description of the tested specimens strengthened with different sheet areas and distributions. Slabs S20 strengthened with sheet 20 cm width, S30 strengthened with sheets 30 cm width, S40 strengthened with sheet 40 cm width, and S60 strengthened with sheet 60 cm. Slab S30D

| Group | Specimen | Slab code | Resistance Area (cm²) | Length (cm) | Width (cm) | No. of strips |
|-------|----------|-----------|-----------------------|-------------|------------|---------------|
| 1     | Reference slab | RS | Reference Slab without Fiber | | | |
| 2     | Strengthen slabs with sheets | S20 | 3000 | 150 | 20 | 1 |
|       |         | S30 | 4500 | 150 | 30 | 1 |
|       |         | S40 | 6000 | 150 | 40 | 1 |
|       |         | S60 | 9000 | 150 | 60 | 1 |
|       |         | S20D | 3000 | 150 | 10 | 2 |
|       |         | S30D | 4500 | 150 | 10 | 3 |

Table 2. Description of tested slabs.
strengthened with sheet 30 cm width (three strips each one 10 cm) and S20D strengthened with sheet 20 cm width (two strips each one 10 cm). The characteristics of CFRP sheets were taken from the data sheets of manufacturing company product as well as the instructions of the installation process (Table 3). In this paper, the used numerical model was calibrated and verified with the results of the research (Sameha et al., 2013).

**Comparison between the results of ANSYS and experimental works**

For all specimens, the first crack was at mid span followed by other cracks produced and propagated also in the middle zone up to failure (Figure 7); Figure 7(a) shows increasing cracks for RS and Figure 7(b) shows increasing cracks for strengthened slabs in the middle zone up to failure. The strain in reinforcement is greater than the limited value of strain in Egyptian code; therefore, the mode of failure of all strengthened slabs with CFRP started by yielding of steel reinforcement pursued by partial rupture of CFRP sheets and lastly by crushing of concrete in compression zone. It can be specified as flexural failure. Table 4 shows the results of the ultimate load and maximum displacement of the reference slab and all strengthened slab specimens. The failure mode for all specimens was a flexural failure.

Figure 8 represents the failure load and the displacements, respectively, at mid span in the models after nonlinear FEM for RS and strengthened slab with sheet (S20). The results showed that the failure load in strengthened slab with sheet increased 72% with respect to the reference slab and also the displacement decreased by 12%. Three additional specimens are modeled using sheets, with different number of layers and different sheet shapes. Figure 9 shows the comparison between strengthened slabs with different sheet areas and distributions S20, S30, S40, and S60.

![Figure 5](image1.png)  
**Figure 5.** Details of 3D finite-element model and reinforced mesh of the reference slab (RS).

![Figure 6](image2.png)  
**Figure 6.** Steel bars and boundary conditions.

### Table 3. Properties of sheets Hex® –230 C (Sameha et al., 2013).

| Properties                        | Sheets Hex® –230 C |
|-----------------------------------|-------------------|
| Density (g/cm³)                   | 1.76              |
| Adhesive strength on concrete     | 4 MPa             |
| Tensile strength of fibers (nominal) | 4300 MPa        |
| Tensile E-modulus of fibers (nominal) | 234,000 MPa   |
| Strain at break of fibers         | 1.8%              |
| Fabric design thickness           | 0.13 mm           |
| Tensile force = area × strength   | 337,980 N         |

### Table 4. Maximum displacement and ultimate load obtained for all the specimens.

| Slab code | Failure load P_f (KN) | Max. displacement at mid span (mm) | %Increase in load-carrying capacity (P_f – P_fRS) / P_fRS | %Decrease in displacement (D_f – D_fRS) / D_fRS | Failure mode |
|-----------|-----------------------|-----------------------------------|----------------------------------------------------------|--------------------------------------------------|--------------|
| RS        | 23.83                 | 32.57                             | –                                                        | –                                                | Flexure      |
| S20       | 41.00                 | 28.675                            | 72.1                                                     | 12.0                                             | Flexure      |
| S30       | 44.00                 | 19.65                             | 84.6                                                     | 39.7                                             | Flexure      |
| S40       | 48.83                 | 22.38                             | 104.91                                                   | 31.3                                             | Flexure      |
| S60       | 55.26                 | 15.00                             | 131.9                                                    | 53.9                                             | Flexure      |
The results show that the highest failure load was observed in the strengthened slab S60. The highest displacement was observed in the strengthened slab S20. This means that the failure load increased and displacement decreased with the increase in the sheet area.

Figures 10 and 11 illustrate the comparison between strengthened slabs (S30 and S20) and the
same slabs with same area sheets but different distribution (S30D and S20D), respectively. 

**Table 5.** Failure load values obtained from numerical and experimental results.

| Slab code | Numerical model Failure load $P_f$ (KN) | Experimental work (Sameha et al., 2013) | % Error between numerical model and experimental work |
|-----------|-----------------------------------------|------------------------------------------|----------------------------------------------------|
| S20       | 41.00                                   | 43.00                                    | 4.65                                               |
| S30       | 44.00                                   | 43.64                                    | 0.83                                               |
| S40       | 48.83                                   | 47.77                                    | 2.23                                               |
| S60       | 55.26                                   | 55.60                                    | −0.62                                              |

**Table 6.** Failure load values obtained from numerical and FRP code.

| Slab code | Numerical model Failure load $P_f$ (KN) | FRP code (2005) | % Error between numerical model and FRP code |
|-----------|-----------------------------------------|-----------------|----------------------------------------------|
| S20       | 41.00                                   | 39.37           | 4.14                                         |
| S30       | 44.00                                   | 43.64           | 0.83                                         |
| S40       | 48.83                                   | 47.77           | 2.23                                         |
| S60       | 55.26                                   | 55.60           | −0.62                                        |

**Figure 8.** Load and displacement at mid span for RS and S20.

**Figure 9.** Load and displacement at mid span for strengthened slabs with sheets.

**Figure 10.** Comparison between S30 and S30D.

**Figure 11.** Comparison between S20 and S20D.
illustrates the comparison between crack pattern of strengthened slabs S30 and S30D. The results show that the distribution of CFRP sheets efficiently enhanced the performance of RCS. Increasing the number of CFRP strips with the same areas significantly increases the ultimate load.

**Table 7.** Failure load values for different steel diameters.

| Steel diameter (mm) | S20 | S30 | S40 | S60 |
|---------------------|-----|-----|-----|-----|
|                      | Pf  | Pf  | Pf  | Pf  |
|                      | In. | In. | In. | In. |
| 6                   | 39.37 | 43.64 | 47.77 | 55.60 |
| 8                   | 56.00 | 59.46 | 62.77 | 68.98 |
| 10                  | 70.46 | 72.87 | 75.14 | 79.26 |
| 12                  | 77.54 | 80.29 | 79.67 | 81.23 |
| 16                  | 43.03 | 40.91 | 38.64 | 33.70 |

**Table 8.** Failure load values for different concrete compressive strength.

| Compressive strength of concrete (N/mm²) | S20 | S30 | S40 | S60 |
|-----------------------------------------|-----|-----|-----|-----|
|                                        | Pf  | Pf  | Pf  | Pf  |
|                                        | In. | In. | In. | In. |
| 30                                      | 39.37 | 43.64 | 47.77 | 55.60 |
| 26                                      | 38.40 | 42.46 | 46.35 | 53.65 |
| 28                                      | 38.92 | 43.09 | 47.11 | 54.70 |
| 32                                      | 39.76 | 44.12 | 48.34 | 56.40 |
| 34                                      | 40.11 | 44.54 | 48.85 | 57.10 |

**Figure 12.** Comparison between S30 and S30D for crack pattern.

**Figure 13.** Load and displacement at mid span of S20 for different reinforcement.

**Figure 14.** Load and displacement at mid span of S30 for different reinforcement.
The study (Sameha et al., 2013) presented experimental results for 10 RCS externally reinforced with CFRP sheets and laminates. The mentioned study concluded that strengthening of RCS with CFRP improves the...
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exural strength capacity as well as the increase in the fl
exural strength and the reduction in the ductility increased with the increase in the area of CFRP sheets.

Table 5 illustrates a comparison between failure loads, values obtained from the FE model, and experimental work. The calibrated results showed the applicability of

Table 10. Failure load values for different sheet thickness.

| Sheet thickness, $t_f$ (mm) | Slab code | $P_f$ (KN) | Increase in $P_f$ (%) | $P_f$ (KN) | Increase in $P_f$ (%) | $P_f$ (KN) | Increase in $P_f$ (%) | $P_f$ (KN) | Increase in $P_f$ (%) |
|---------------------------|-----------|------------|-----------------------|------------|-----------------------|------------|-----------------------|------------|-----------------------|
| 0.131                     | S20       | 39.37      | –                     | 43.64      | –                     | 47.77      | –                     | 55.60      | –                     |
| 0.262                     | S30       | 56.00      | 4.38                  | 59.46      | 5.28                  | 62.77      | 6.11                  | 68.98      | 7.60                  |
| 0.393                     | S40       | 70.46      | 6.20                  | 72.87      | 7.77                  | 75.14      | 9.17                  | 79.26      | 11.56                 |
|                           | S50       |            |                       |            |                       |            |                       |            |                       |
|                           | S60       |            |                       |            |                       |            |                       |            |                       |
implementing numerical analysis to extend the parametric study beyond the limited number of specimens tested experimentally.

**Comparison between the results of ANSYS and the equations of ESC**

The FE results were compared to the results obtained from equations of ESC (2005). Table 6 illustrates a comparison between failure loads, values obtained from the FE model, and FRP code models. The results of the numerical and FRP code are in good agreement with a percentage of tolerance between +5% and −1%.

The obtained results showed that the FE model could be used to investigate the behavior of other combinations of slabs with the same assumptions.

**Investigation of the slab behavior based on different parameters**

The FE test program is extended further beyond the experimental cases to investigate the behavior of other strengthened slabs with the same dimensions and areas of CFRP sheets. Cases were considered by studying the effect of increasing the main reinforcement from 6 to 16 mm in diameter, changing of concrete...
compressive strength from 26 to 34 N/mm$^2$, changing of slab thickness from 80 to 120 mm, and using sheet thicknesses 0.131, 0.262, and 0.393 mm on strengthened slab behavior. Figures 13–17 show the effect of changing the reinforcement on strengthened slab behavior. Table 7 shows values of failure loads and increasing percentage of failure load capacity for different steel diameters. For all strengthened slabs, increasing the main reinforcement leads to an increase in the ultimate load. However, in the case of the reinforcement diameter is higher than 12 mm, a reduction in failure load occurs.

Figures 18–22 show the effect of changing compressive strength of concrete on strengthened slab behavior. Table 8 shows the failure load values and increasing percentage of failure load capacity for different compressive strength of concrete. Increasing compressive strength of concrete above 30 N/mm$^2$ leads to increase in the ultimate load for all strengthened slabs. Compressive strength of concrete over 30 N/mm$^2$ leads to increase in the ultimate load, while less than 30 N/mm$^2$ leads to decrease in the ultimate load for all strengthening slabs.

Figures 23–27 show the effect of changing of slab thickness ($t_s$) on strengthened slab behavior. Table 9 shows the failure load values and increasing percentage of failure load capacity for change in slab thickness. The increase of slab thickness leads to increase in the ultimate load for all strengthened slabs. Increasing strengthened slab thickness from 5 to 4 mm for slabs S20, S30, S40, and S60 leads to increase in failure load from 4% to 17%, 5% to 23%, 6% to 28%, and 8% to 35%, respectively.

Figure 28 shows the effect of changing of sheet thickness ($t_f$) on strengthened slab behavior. Table 10 shows the failure load values and increasing percentage of failure load capacity for change in slab thickness. The increase of sheet thickness to double and triple leads to significant increase of failure load.

Conclusions

1- Externally bonded CFRP sheets to the tension face are effective method in enhancing the ultimate carrying capacity of RCS.

2- The failure load of strengthened slabs with CFRP sheets increases with a percentage up to 132% more than un-strengthened slabs and the deflection decreases by a percentage up to 54%.

3- Yielding of steel reinforcement pursued by partial rupture of CFRP sheets and lastly by crushing of concrete in compression zone. It can be specified as flexural failure.

4- Increasing CFRP sheet area leads to increase of failure load and decrease of displacement at mid span.

5- Distributing CFRP sheets showed more efficiency with regard to enhancing performance of RCS. Flexural capacity was found to be slightly higher when the sheets were distributed equally along the slab width.

6- The results show that the results of the FE model and ESC are in good agreement.

7- Using reinforcement diameter higher than 12 mm leads to a reduction in failure load.

8- Compressive strength of concrete over 30 N/mm$^2$ leads to increase in the ultimate load, while less than
30 N/mm² leads to decrease in the ultimate load for all strengthening slabs.

9. Due to increase in both slab thickness and CFRP strip width, failure load increases.

10. The increase of sheet thickness to double and triple leads to significant increase of failure load.

**Disclosure statement**

No potential conflict of interest was reported by the author.

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