

Effect of Fiber Orientation on Shear Behavior of RC Beams Externally Strengthened with CFRP

Mohamed H. Arafa*, Mamoun A. Alqedra, Mohammed Hammad

Department of Civil Engineering, The Islamic University of Gaza, Gaza, Palestine

Abstract Strengthening of reinforced concrete beams with carbon fiber reinforced polymer (CFRP) is one of the recent applied strengthening techniques. It offers an attractive solution to enhance shear and flexural capacities of reinforced concrete (RC) beams. Behavior in shear and flexure of reinforced concrete beams externally strengthened with CFRP is highly influenced by the way in which these composites are bonded to the beam. In this paper reinforced concrete (RC) beams strengthened with CFRP was modelled using a nonlinear finite element (FE) model to study the influence of the orientation layer of CFRP on the overall response of strengthened RC beams in shear. This is carried out to achieve the optimum utilization of such strengthening technique in terms of load bearing capacity and possible deflection values. A nonlinear finite element software ANSYS was utilized in this study. The analysis of the results indicated that the overall behavior of the FE models have a good agreement with corresponding previous experimental results. Further, the parametric study proved that shear strengthening of RC beams with vertical CFRP fabric is more efficient than strengthening with CFRP fabric inclined at an angle of 45° . Furthermore, strengthening the reinforced concrete beams with one layer of U-wrap CFRP fabric inclined at an angle of 45° with an additional horizontal layer of CFRP fabric on both sides of the web is more efficient than strengthening with one layer of U-wrap vertical CFRP fabric with an additional horizontal layer of CFRP fabric on both sides of the web.

Keywords Carbon fiber, Strengthening, Reinforced concrete, Finite element, Modelling

1. Introduction

The use of fiber reinforced polymer (FRP) as a strengthening material is one of the applied strengthening techniques of reinforced concrete beams. This results from a number of advantages, such as excellent strength to self-weight ratio, high tensile strength, large fatigue resistance capacity, and high durability, [1] and [2]. Reinforced concrete (RC) beams strengthened with carbon and glass fiber-reinforced polymer (CFRP and GFRP) composites introduces a promising solution to improve shear and flexural capacities and ductility, as well as altering the mode of rupture, [3-6].

Obtaining the behavior of FRP strengthening reinforced concrete structures has become a very significant research field. Experimental wise, several studies were carried out to investigate the behavior of strengthened beams and the influence of various parameters, [7-11]. Despite the fact that performing laboratory experiments are extremely useful in

obtaining the composite behavior of FRP and reinforced concrete, developing validated and verified numerical models would assist establishing a good understanding of the behavior at lower costs in terms of time and money, [12-15].

In this research, non-linear finite element analysis models using ANSYS [16] software for strengthening reinforced concrete beams with carbon fiber reinforced polymers (CFRP) is presented. Moreover the validated and verified finite element model was applied to study the influence of CFRP layer inclination on the overall response of strengthened RC beams in shear.

2. FE Modelling of Strengthening of RC Beams with CFRP

The experimental investigation of [17] was applied to verify the developed FE model for strengthening RC beams in shear with CFRP using ANSYS software.

The control beam is a simply supported RC beam with a total length of 2130 mm, and a clear span of 1830 mm. The beam has a rectangular cross section with 230 mm width and 280 mm height, and a concrete cover of 25 mm was assumed. The beam was subjected to a concentrated static load at the middle of the beam. Tension reinforcement of the beam is $2\phi 25$ mm. Compression reinforcement of the beam is $2\phi 10$

* Corresponding author:

marafa@iugaza.edu.ps (Mohamed H. Arafa)

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mm. And shear reinforcement of the beam is 10 mm diameter stirrups spaced at 300 mm, as shown in Figure (1).

The control beam was externally strengthened by bonding a single U-wrap layer of CFRP fabric with 0.18mm thickness inclined at an angle of 90° to the longitudinal axis of the beam, as shown in Figure (2).

In the present study, the following are the assumptions made for FE model of RC beam to provide reasonably good simulations for the complex behavior:

1. Concrete and steel are modeled as isotropic and homogeneous materials.
2. Poisson's ratio is considered constant throughout the loading history.
3. Steel is considered an elastic-perfectly plastic material and identical in tension and compression.
4. Bond between concrete and steel reinforcement is assumed perfect.
5. Bond between concrete and CFRP fabric is simulated as perfect. The perfect bond assumption doesn't cause a significant error in the predicted load-deflection response, [18].
6. The CFRP composites is simulated as an especially orthotropic-transversely isotropic material. This means that the material properties of the fibers in the two perpendicular directions are identical.
7. The CFRP fabric is modelled to carry stress along its axis only.
8. Time-dependent nonlinearities such as creep, shrinkage, and temperature change are not included in this study.

2.1. Element Types

Several elements have been applied to simulate the behavior of CFRP-strengthened reinforced concrete beam. These elements are widely used in ANSYS and recommended by previous researchers, [1, 8, 9, 12, 14, 19-21].

For reinforced concrete, an eight-node solid element, Solid 65, was considered to simulate the concrete. The solid 65 element has eight nodes with three degrees of freedom at each node: translations in the nodal local x, y, and z directions. The element is capable of carrying plastic deformation, cracking in three orthogonal directions, and crushing.

Link 180 element was utilized to model steel reinforcement. The element is a uniaxial tension-compression element with three degrees of freedom at each node: translations in the nodal x, y, and z directions. Plasticity, creep, rotation, large deflection, and large strain capabilities are included.

Homogeneous structural solid with simplified enhanced strain formulation Solid 185 is used to model loading and supporting steel plates. This element is also defined by eight nodes having three degrees of freedom at each node. The element is capable of plasticity, hyper elasticity, stress stiffening, creep, large deflection, and large strain capabilities.

Shell 181 element is also applied to model Carbon Fiber Reinforced Polymer (CFRP). It is a four-node element with six degrees of freedom at each node.

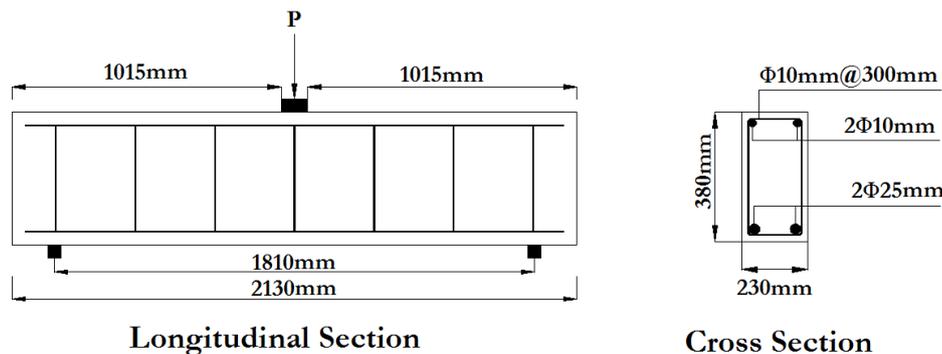


Figure (1). Shear Control Beam Model, [17]

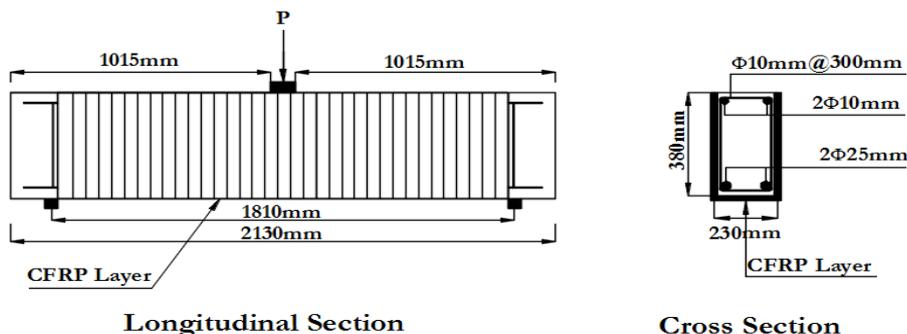


Figure (2). Shear Strengthened Beam Model, [17]

2.2. Materials Models

Hognestad model [22], has been used to simulate the stress-strain behavior of concrete. This model is also adopted in the work of [23] and [7]. In this research, the tri-axial behavior of concrete is modelled according to the constitutive model of [24].

To ensure the full connectivity between concrete and steel reinforcement nodes, discrete steel model was used. An elastic-plastic constitutive relationship with strain hardening is assumed for reinforcing steel. This model generally yields acceptable results for the response prediction of RC members, [14, 25, 26].

CFRP composites is modeled using the orthotropic linear elastic model, [2] and [27]. The properties of the CFRP composites were considered the same in any direction perpendicular to the fibers. This means that the properties in the y direction were similar to that in the z direction. The Maximum strain failure criterion and maximum stress failure criterion were used, based on the longitudinal tensile strength and maximum strain of CFRP fabrics.

2.3. Beam Geometry and Meshing

The advantage of the symmetry of the beams allows modelling a half of full beam size. This resulted in significantly reducing the computational time and computer disk space requirements.

Since half of the beam is to be modeled, the beam model is 1065 mm long, with a cross-section of 230 mm × 380 mm. The CFRP fabric layer bonded to the beam soffit and sides as U-wrap was modeled as three areas. The advantage of symmetry allows simulating half of loading plate and one support plate. The steel loading and supporting plates are 30 mm x 50 mm x 230.

To obtain good results from the Solid 65 element, a rectangular mesh is recommended by [28] and [3]. Therefore, the mesh is set up such that square or rectangular elements are to be created. Steel loading and supporting plates were meshed as solid elements in such a way that its nodes were oriented with adjacent concrete solid elements.

As mentioned earlier, perfect bond between materials was assumed. The modelling of perfect bond was done by linking the nodes of the steel reinforcement element with those of the adjacent concrete solid element. Sharing the same nodes ensures that both materials creates such perfect bond between them, [28] and [3]. Figure (3) illustrates the reinforcement configuration modeled in ANSYS for beam model.

CFRP composites were simulated as shell elements. These shell elements were oriented in such a way that its nodes establish the perfect bond assumption with the adjacent concrete solid elements. Figure (4) shows the overall meshing of all model components: concrete beam, steel loading and supporting plates, steel reinforcement, and CFRP layer for beam model.

For validation and verification purposes, it is required to develop a strengthened reinforced concrete beam computer

model which has the same dimensions, materials, properties and boundary conditions similar to that of the experimental beam. Therefore, boundary conditions is to be applied at points of symmetry, and where the supports and loadings exist, [28]. As half of the entire beam was to be simulated, the model being used are symmetric about one plane. Nodes defining a vertical plane through the beam mid-section represents a plane of symmetry, as shown in Figure (5). This plane of symmetry is represented by constraining the nodes on this plane in the perpendicular direction. Further, the support was modeled as a roller; so the beam is allowed to rotate as shown in Figure 6.

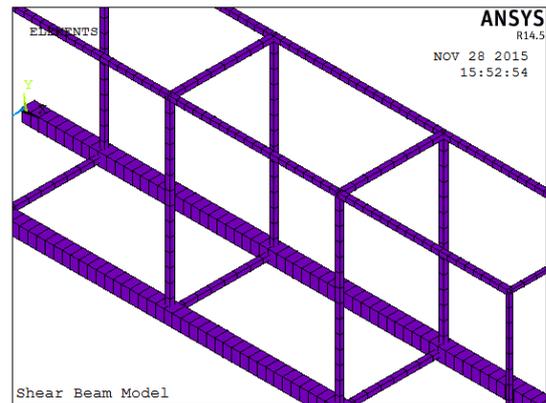


Figure (3). Reinforcement Configuration

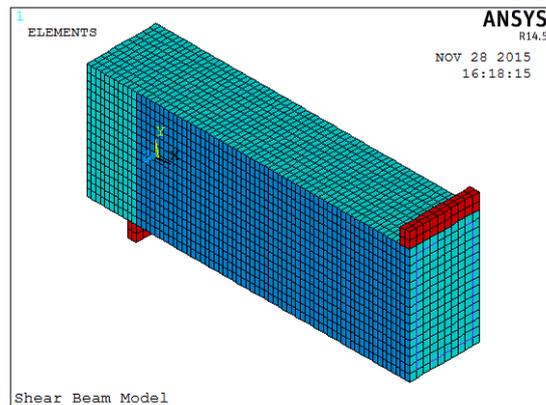


Figure (4). Overall Meshing of the Model

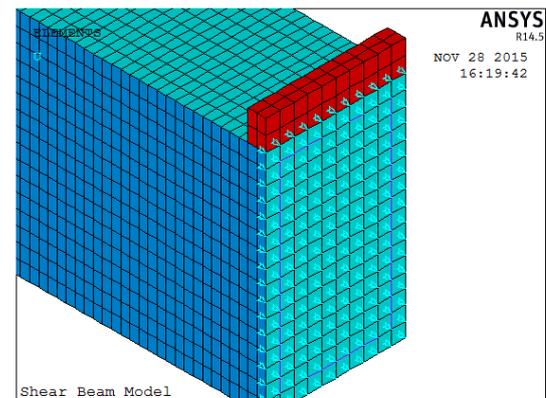


Figure (5). Plane of Symmetry

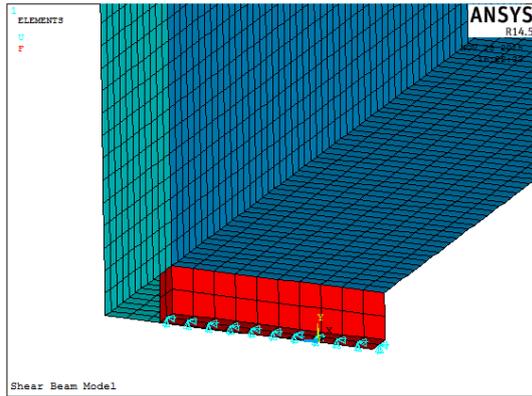


Figure (6). Beam Support Plate

2.4. Finite Element Model Verification

The load-deflection curve obtained from the finite element analysis agrees well with that of the experimental results for the same strengthened beam, as indicated in Figure (7). In the linear range, the finite element analysis indicated that load-deflection behavior is stiffer than that of the experimental results. The first cracking load of the finite element analysis is 50 kN. Beyond that, the finite element model indicated stiffer values than that of the experimental beam. The bottom steel reinforcement of the finite element beam model yields at 350 kN. The ultimate load of 410 kN from the finite element beam model is lower than the average ultimate load of 421 kN obtained from the experimental beam; this indicates a difference of 2.6%. The load-deflection behavior obtained from the finite element models for control and strengthened beams is shown in Figure (8).

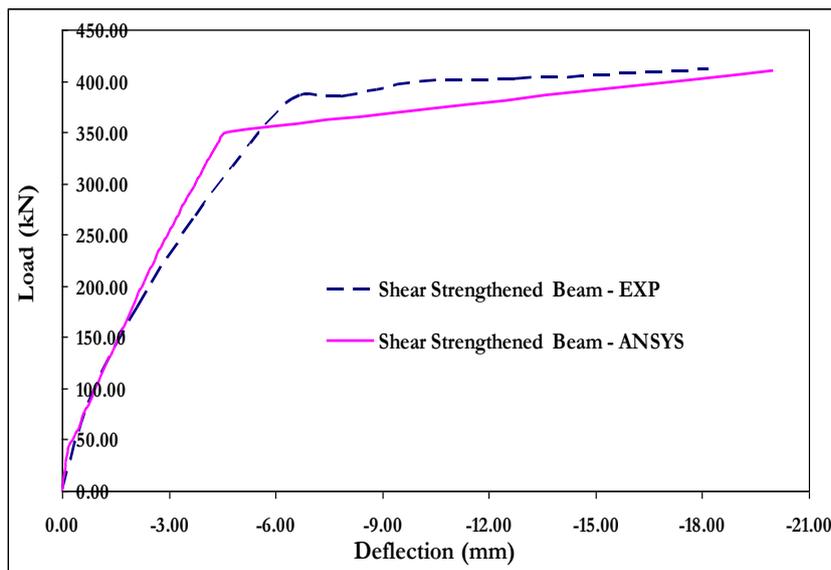


Figure (7). Load deflection curves of experimental and FE model of strengthened beam

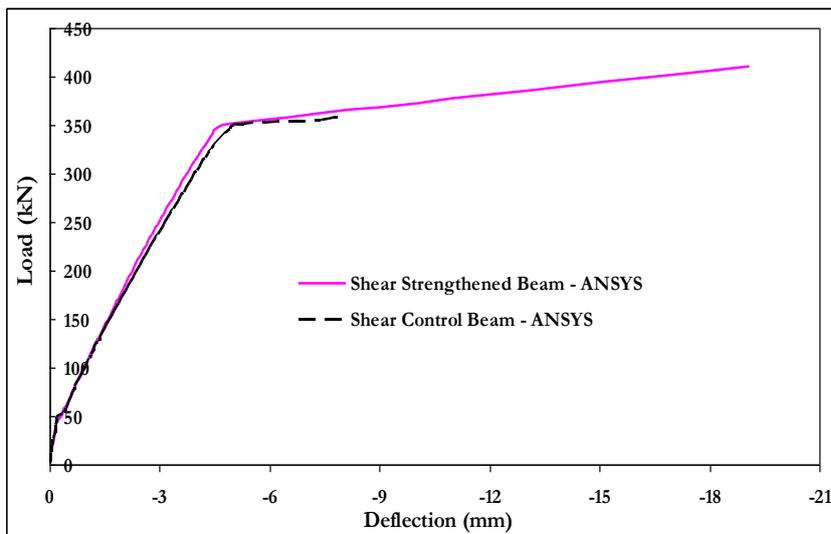


Figure (8). Load deflection curves of FE Model for control and strengthened beam

The finite element model showed that the load at the first crack of the control beam occurs at 50 kN. The bottom steel reinforcement of the finite element model beam yields at 346.5 kN. The ultimate failure load of the finite element model beam occurs at 359.6 kN. This is lower than the ultimate load of the experimental beam (397 kN) by 9.4%.

The crack patterns obtained by of the finite element model beam at the last converged load step indicated a very good agreement with that of the experimental beam, as shown in Figure (9). The experimental control beam failed in shear, in which diagonal tensile cracks propagate from the loading area toward the support. The cracks occur excessively in the high shear stress region.

As reported in the experimental investigation, [17], shear strengthened beam was failed in a shear-compression failure mode. Rupture and delamination of CFRP fabric was noticed at the final stages. The crack pattern computed by the finite element analysis at the last converged load step agrees very well with that of the experimental beam, as shown in Figure (10). The finite element (FE) model showed a maximum mid span deflection of 19.3mm, while mid span deflection of the experimental beam was 18.25 (i.e. 5% difference).

Figure (11) shows the tensile stress results of CFRP fabric obtained from the FE analysis of the strengthened beam at failure. The maximum tensile stress obtained from the model is 1993.3 N/mm^2 , which is lower than the ultimate tensile strength of CFRP fabric which equals to 2722.2 N/mm^2 .

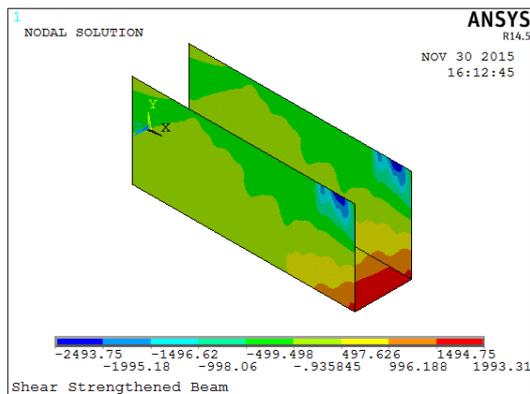
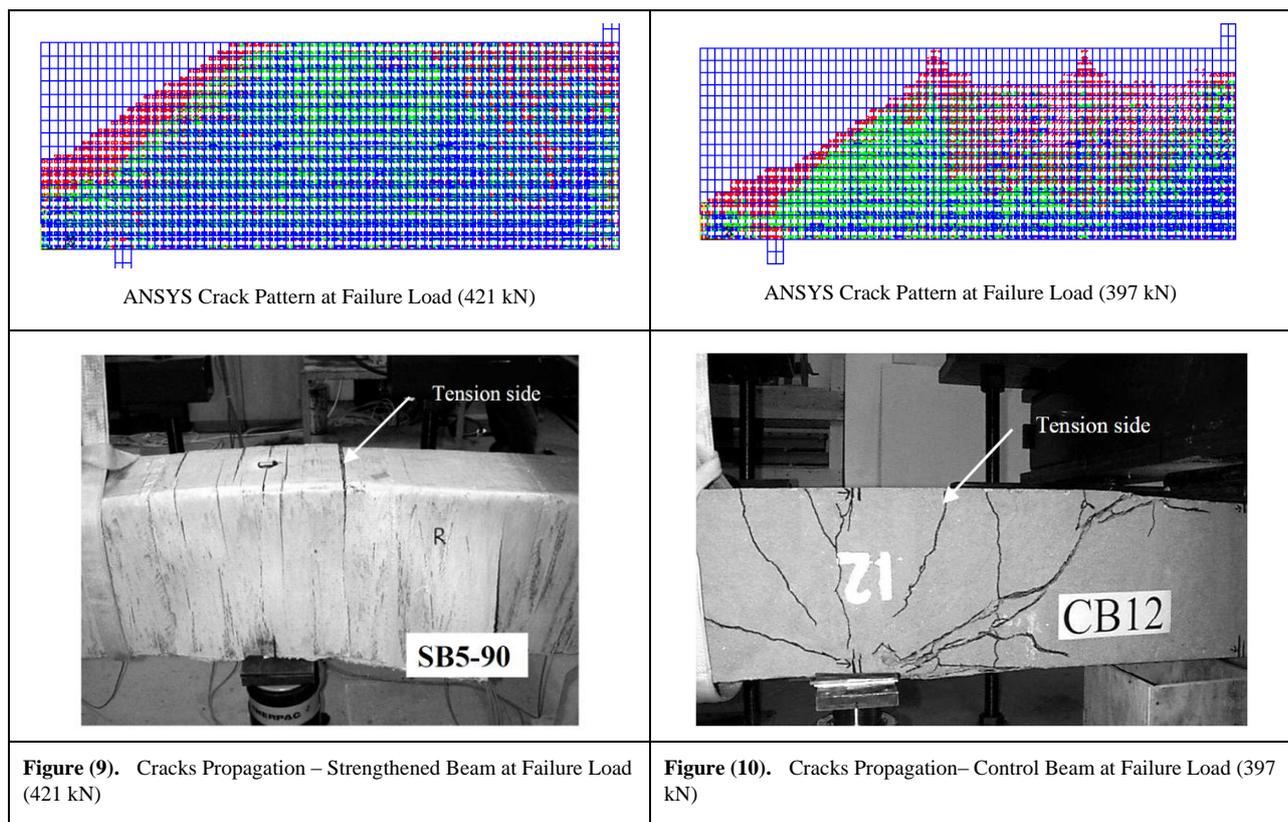


Figure (11). Stress of CFRP Fabric at Failure –Strengthened Beam

3. Effect of CFRP Orientation on the Shear Strength

To evaluate the effect of CFRP orientation with the longitudinal axis of the beam on the shear strength of the beam, four strengthening configurations were tested using the verified FE beam model:

- 1- Configuration A: one layer of vertical U-wrap CFRP, Figure (12).
- 2- Configuration B: one layer of vertical U-wrap CFRP and an additional horizontal layer of CFRP fabric on both sides of the web, Figure (13).

3- Configuration C: one layer of U-wrap CFRP fabric, inclined at an angle of 45° to the longitudinal axis of the beam, Figure (14).

4- Configuration D: one layer of U-wrap CFRP fabric inclined at an angle of 45° and an additional horizontal layer of CFRP fabric on both sides of the web, Figure (15).

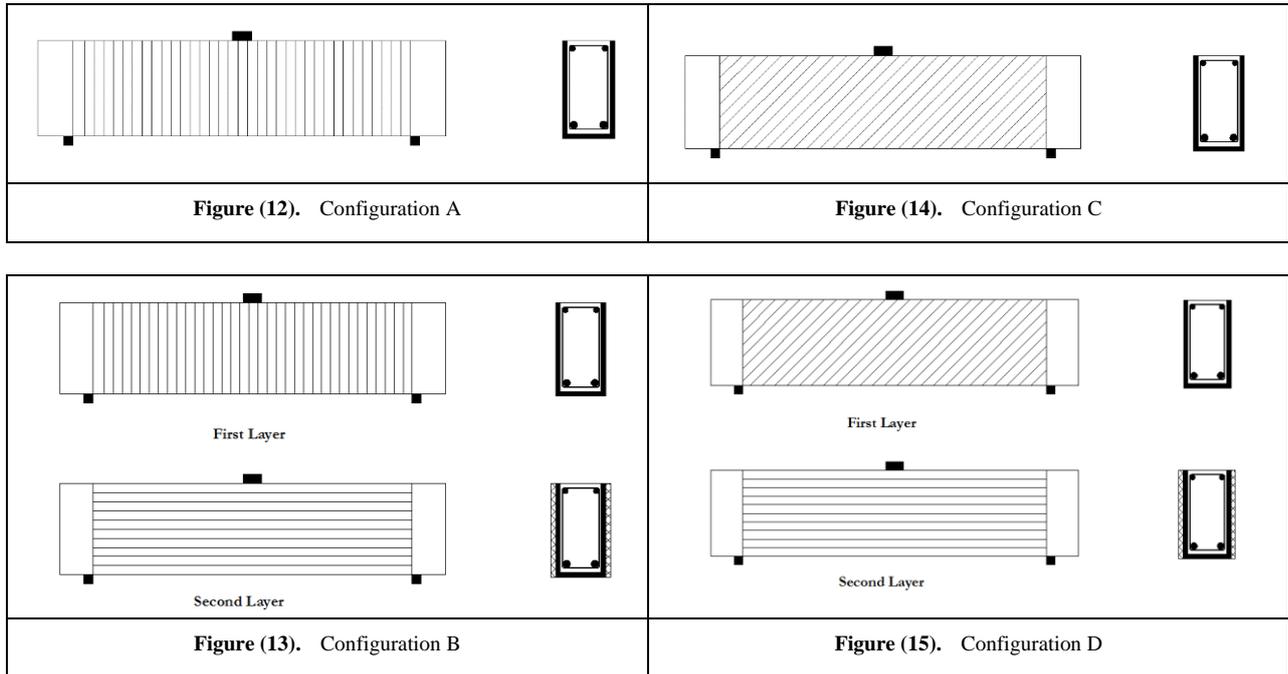


Figure (16) presents a comparison for load-deflection curves as resulted from the FE beam model for the four strengthening configurations. Table (1) includes the ultimate load and mid-span deflection for each strengthening configuration, as computed from the FE analysis.

It is noticed that strengthening the control FE beam model with one vertical U-wrap CFRP layer (configuration A) increases the beam ultimate load by 14% and increases the mid-span deflection at failure by 138.3%. Further, strengthening the control beam with one U-wrap CFRP layer inclined at an angle of 45° with the beam axis (Configuration C) increases the beam ultimate load by 11.5% and increases the mid-span deflection at failure by 38.3%. This results agrees well with the experimental works of [29] and [30]. This finding indicates that the beam with vertical U-wrap CFRP layer (Configuration A) is more ductile than beam with 45° U-wrap CFRP layer (Configuration C), and gives sufficient warning before failure, and that the beam has a higher load capacity with this configuration. Therefore, shear strengthening of RC beams with one vertical layer of CFRP is more efficient than strengthening with one layer of CFRP inclined at an angle of 45°.

In addition to that, strengthening the control beam with one vertical layer of U-wrap CFRP fabric and an additional horizontal layer of CFRP fabric on both sides (Configuration B) increases the beam ultimate load by 25.5% and increases the beam mid-span deflection by 65.4%. Strengthening the control beam with one layer of U-wrap CFRP fabric inclined at an angle of 45° with an additional horizontal layer of

CFRP fabric on both sides (Configuration D) increases the beam ultimate load by 46.3% and increases the beam mid-span deflection by 34.6%. In terms of load capacity, this proves that strengthening the control beam with one layer of U-wrap CFRP fabric inclined at an angle of 45° with an additional horizontal layer of CFRP fabric on both sides of the web (Configuration D) is more efficient than strengthening with one vertical layer of U-wrap CFRP with an additional horizontal layer of CFRP fabric on both sides of the web (Configuration B).

In general, the results of FE analysis are in good agreement with the experimental works conducted by other researchers such as [29-32].

Table (1). Effect of CFRP Inclination – Comparison of FE Analysis Results

Beam	Failure Load (kN)	Increased Strength (%)	Mid-Span Deflection at Failure (mm)	Increased Deflection at Failure (%)
Control Beam	359.7	-	8.1	-
Configuration A	410	14	19.3	138.3
Configuration B	401.2	11.5	11.2	38.3
Configuration C	455	25.5	13.4	65.4
Configuration D	526.3	46.3	10.9	34.6

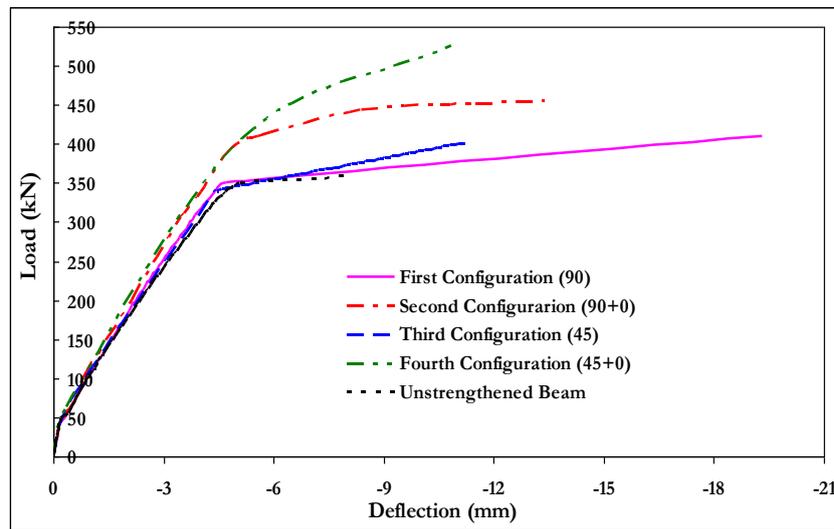


Figure (16). Effect of CFRP Inclination – Load Deflection Curves

4. Conclusions

The important conclusions drawn from the study are listed below:

1. Finite element model was successfully verified as compared with previously experimental test results. Therefore, ANSYS can be confidently used in analysis of RC beams externally strengthened with Carbon Fiber Reinforced Polymers (CFRP) fabrics.
2. The overall behavior of the finite element models represented by the load-deflection curves at mid-span shows acceptable agreement with the experimental data obtained from full-scale beam tests. However, the finite element models show slightly differed stiffness values as compared with the experimental data. The effects of bond slip between the concrete and steel reinforcing and micro-cracks occurring in the actual beams were excluded in the finite element models, contributing to the difference in stiffness of the finite element models.
3. Strengthening the RC beam by bonding a single vertical layer of U-wrap CFRP fabric, increases the shear strength of the beam by 14%, and increases the mid-span deflection at failure by 138%.
4. Strengthening the RC beam by bonding a single layer of U-wrap CFRP fabric, inclined at an angle of 45° to the longitudinal axis of the beam increases the shear strength of the beam by 11.5%, and increases the mid-span deflection at failure by 38%.
5. Shear strengthening of RC beams with one vertical layer of CFRP fabric is more efficient than strengthening with one layer of CFRP fabric inclined at an angle of 45° .
6. Strengthening of RC beams with one vertical layer of U-wrap CFRP fabric with an additional horizontal

layer of CFRP fabric on both sides of the web increases the shear strength of the beam by 25.5% and increases the beam mid-span deflection by 65%.

7. Strengthening of RC beams with one layer of U-wrap CFRP fabric inclined at an angle of 45° with an additional horizontal layer of CFRP fabric on both sides of the web increases the shear strength of the beam by 46.3% and increases the beam mid-span deflection by 34.6%.
8. Strengthening of RC beams with one layer of U-wrap CFRP fabric inclined at an angle of 45° with an additional horizontal layer of CFRP fabric on both sides of the web is more efficient than strengthening with one vertical layer of U-wrap CFRP fabric with an additional horizontal layer of CFRP fabric on both sides of the web.

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