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Research paper

Analysis of reinforced concrete deep beam strengthened by CFRP strips using ANSYS program

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Abstract

This paper presents the results of finite element analysis of strengthened reinforced concrete deep beams using the software package ANSYS 12.
The work includes modeling seven reinforced concrete deep beams, same configuration have been considered with different strengthening schemes. In order to find out the best strengthening mechanisms, the main variables considered in this work include the effect of fiber orientation (90° or 45° CFRP strips with respect to beam longitudinal axis), the effect of using longitudinal CFRP strips with transverse CFRP strips (90° or 45° CFRP strips) and effect of anchoring the transverse CFRP strips (90° or 45° CFRP strips).
The analytical results were discussed based on shear resistance, mid span deflection. The results reveal that externally CFRP strips can significantly increase the ultimate shear resistance and increase the stiffness of the deep beams.

Keywords: *Deep Beam; Strengthened; Bolts; Reinforced Concrete; CFRP; ANSYS.*

1. Introduction

Deep beams are recognized by relatively small values of span-to-depth ratio. As per code provisions given by American Concrete Institute (ACI 318-11) [1], a beam shall be considered as deep beam when the ratio of effective span to overall depth ratio is less than 4.0 or regions with concentrated loads within twice the member depth from the face of the support.
Typical application of deep beams include tanks, transfer girders, pile caps, folded plates and foundation walls, often receiving many small loads in their own plane and transferring them to a small number of reaction points. Before cracking, elastic solutions of reinforced concrete deep beams provide a good description of the behavior, but after cracking, a major redistribution of stresses occurs and hence the beam capacity must be predicted by inelastic analysis [2].
Carbon fiber reinforced polymers (CFRP) are becoming widely used as an external reinforcement in upgrading and rehabilitation of reinforced concrete members such as beams and columns [3]. CFRP offers excellent properties such as corrosion resistance, light weight, possesses higher strength and stiffness compared to steel and ease of handling and application.
Many papers present the experimental behavior and strength of R. C. beams in shear strengthened with CFRP [4, 5, 6, and 7]. Belal [7] studies the influence of strengthening and repairing deep beam with CFRP, experimental results showed a significant improvement in the behavior and carrying capacity of R. C. deep beams.
A large number of software available in market incorporate finite element based analysis. In this paper, an attempt has been made using FEM based software (ANSYS version 12) [8] to illustrate the powerful analytical capabilities of finite element technique.

2. Research significant

This paper presents the results of an analytical model of reinforced concrete deep beams strengthened in shear with externally bonded CFRP strips using FEM analysis (software package ANSYS 12). Different configuration of strengthening mechanisms and effect of anchoring CFRP strips on both sides of the deep beams were used in this study.

3. Element types

The elements types shown in Table (1) were used to model the beams.
A Solid65 element was used to model the concrete [8]. This element has eight nodes with three degrees of freedom at each node translations in the nodal x, y, and z directions. The element is capable of plastic deformation, cracking in three orthogonal directions, and crushing. A schematic of the element was shown in Figure (1).

Table 1: Element Types

Element No.	Element type	Representation
1	SOLID65	Concrete
2	LINK8	Steel reinforcement (ϕ16 mm)
3	LINK8	Steel reinforcement (ϕ6 mm)
4	SHELL41	CFRP
5	SHELL41	Anchorage steel plates (thickness 2 mm)
6	LINK8	Connector bolts (ϕ8 mm)
7	SOLID45	Steel plate for supports and loading (thickness 6 mm)

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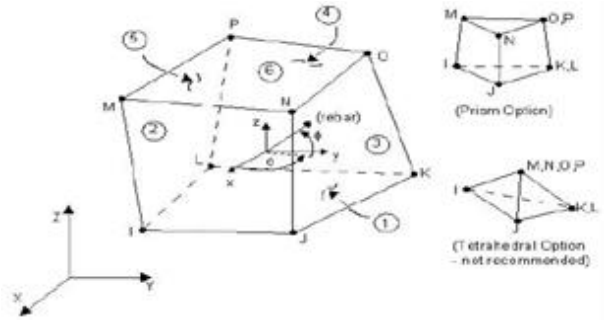


Fig. 1: SOLID65 Element [8].

A Link8 element was used to model steel reinforcement [8]. This element is a 3D spar element and it has two nodes with three degrees of freedom translations in the nodal x, y, and z directions. This element is capable of plastic deformation and element was shown in the Figure (2). This element was also used for conector bolts (Φ8 mm).

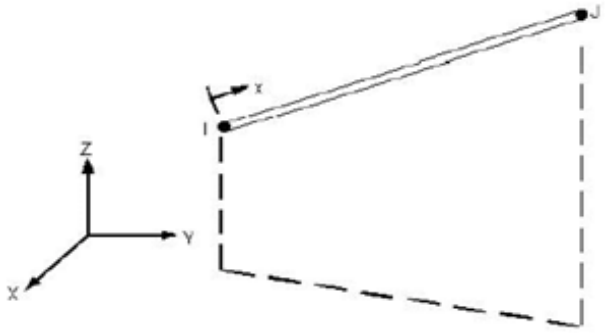


Fig. 2: LINK8 Element [8].

SHELL41 shown in Figure (3) is a 3-D element having membrane (in-plane) stiffness but no bending (out of plane) stiffness. It is intended for shell structures where bending of the elements is of secondary importance. The element has three degrees of freedom at each node: translations in the nodal x, y, and z directions.

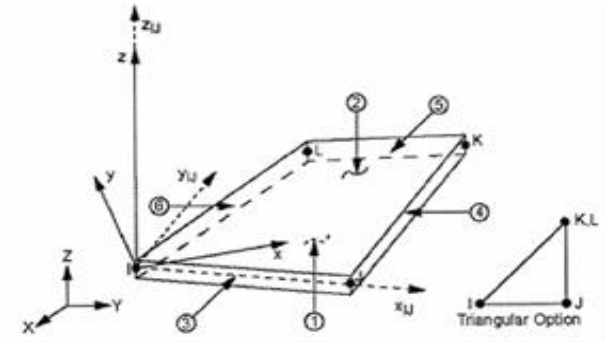


Fig. 3: SHELL41 Element [8].

The element has variable thickness, stress stiffening, and large deflection. This element was used to model CFRP strips and the anchoring steel plates.

Steel plates were added at support and point of loading locations in the finite element models (as in the actual beams) to provide a more even stress distribution over the support and point of loading areas. SOLID45 element was used for this purpose. This element is defined with eight nodes having three degrees of freedom at each node translations in x, y and z directions [8]. The geometry and node location for this element type are shown in Figure (4).

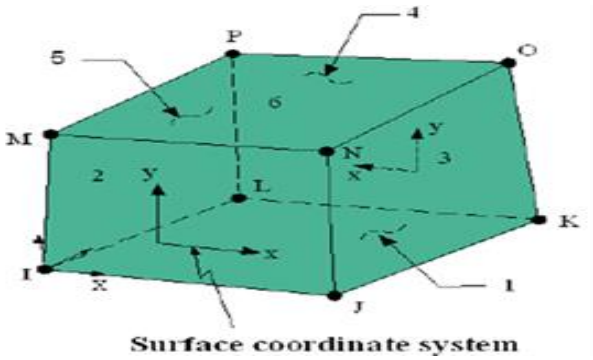


Fig. 4: SOLID45 Element [8].

The steel plates were assumed to be linear elastic materials, an elastic modulus equal to 200000 MPa and Poisson's ratio of 0.3 were used.

4. Real constant

Table 2: Shows the Real Constant for the Model Beams.

Real Constant set	Element type	Constant			
			Real Constant for Rebar 1	Real Constant for Rebar 2	Real Constant for Rebar 3
1	SOLID65	Material number	0	0	0
		Volume ratio	0	0	0
		Orientation angle	0	0	0
		.			
2	LINK8	Cross-sectional area (mm2)	201.14		
		Initial strain (mm/mm)	0		
		.			
3	LINK8	Cross-sectional area (mm^2)	28.29		
		Initial strain (mm/mm)	0		
		.			
4	SHELL41	Shell thickness at node I (mm)	0.13		
		Shell thickness at node J (mm)	0.13		
		Shell thickness at node K (mm)	0.13		
		Shell thickness at node L (mm)	0.13		
		Element x-axis rotation	0		
		Elastic foundation stiffness	0		
		Added mass/unit area	0		
		.			

5	SHELL41	Shell thickness at node I (mm) Shell thickness at node J (mm) Shell thickness at node K (mm) Shell thickness at node L (mm) Element x-axis rotation Elastic foundation stiffness Added mass/unit area	2 2 2 2 0 0 0
6	LINK8	Cross-sectional area (mm^2) Initial strain (mm/mm)	50.3 0
7	SOLID45	Hourglass stiffness factor	0

5. Material modeling

5.1. Concrete

The ANSYS program [8] adopted the uniaxial stress – strain relationship for concrete in compression. This relationship is described by multi – linear isotropic hardening curve shown in Figure (5), linear elastic up to 30 percent of the maximum compression strength ($f'c$).

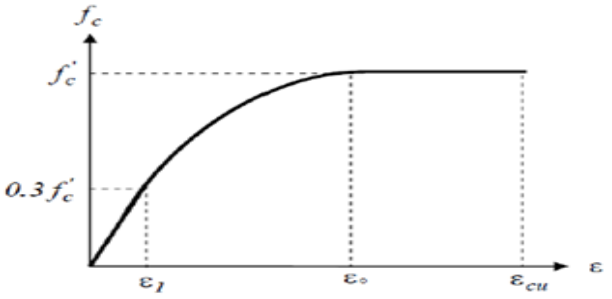


Fig. 5: Multi-Linear Compressive Uniaxial Stress-Strain Curve for Concrete [9].

The following equations adopted to describe the multi - linear properties of concrete [9]

$$f_c=\varepsilon E_c \text{ for } 0 \le \varepsilon \le \varepsilon_1 \quad (1)$$

$$f_c=(\varepsilon E_c)/(1+(\varepsilon/\varepsilon_0)^2) \text{ for } \varepsilon_1 \le \varepsilon \le \varepsilon_0 \quad (2)$$

$$f_c=f'c \text{ for } \varepsilon_0 \le \varepsilon \le \varepsilon_{cu} \quad (3)$$

$$\varepsilon_1=(0.3\,f'c)/E_c \quad (4)$$

$$\varepsilon_0=(2\,f'c)/E_c \quad (5)$$

Where:
ε_1 = strain corresponding to (0.3 $f'c$), ε_0 = strain at peck point, ε_{cu} = ultimate compressive strain.
Concrete non – linear material chosen here adopts the smeared pattern for cracking of concrete [10]. Other parameters of concrete are the shear transfer coefficients. These coefficients range from 0.0 to 1.0.The coefficient of 0.0 representing a smooth crack (complete loss of shear transfer), which specify the open crack and coefficient of 1.0 representing a rough crack (no loss of shear transfer), which specify the closed crack. The poisson ratio for concrete is usually taken as 0.2 [11]. The modulus of elasticity (E_c) and the modulus of rupture (f_r) for concrete are calculated by equations below according to the ACI 318-011 specification [1].

$$E_c=4700\sqrt{(f'c)} \quad (6)$$

$$f_r=0.62\sqrt{(f'c)} \quad (7)$$

Where:
E_c : Modulus of elasticity in N/mm^2.
$f'c$: Ultimate compression strength in N/mm^2.
f_r : Rupture modulus in N/mm^2.

5.2. Steel reinforcement

The stress – strain behavior of steel reinforced can be assumed to be identical in tension and in compression. Linear isotropic and bilinear kinematic hardening properties are required for steel. The bilinear hardening property requires the yield stress of steel and hardening modulus of steel. To obtain the hardening modulus of steel or after yielding, $E'_s=0.01\ E_s$. Figure (6) shows the stress – strain for reinforcement.

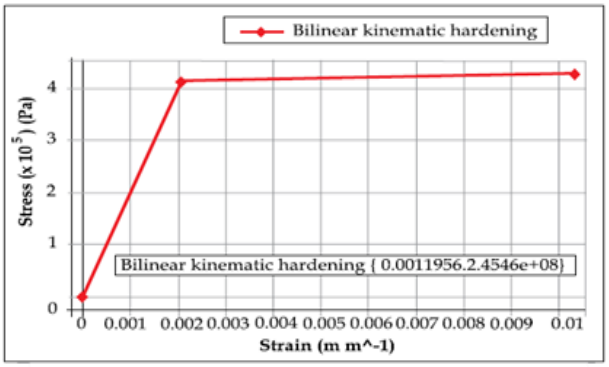


Fig. 6: Stress – Strain Curve for Steel Reinforcement [2].

5.3. CFRP laminates

FRP composites are material that consists of two constituents. One constituent is the reinforcement, which is embedded in the second's constituent, a continuous polymer called the matrix. The CFRP composite are orthotropic material. Hence their properties are not the same in all directions. A rupture point on the stress – strain relationship defines the maximum stress and strain of the FRP materials as shown in Figure (7) [12]. Table (3) shows all material properties of the model beams.

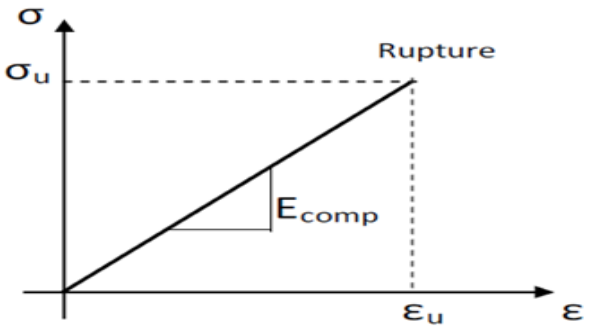


Fig. 7: Stress – Strain Curve for CFRP [12].

Table 3: Material Properties of the Model Beams

Material Model Number	1	Element Type	SOLID65
Material Properties:			
Linear Isotropic:			
EX	25743		
PRXY	0.2		
Multilinear Isotropic:			
	Strain		Stress
Point 1	0		0
Point 2	0.00035		9
Point 3	0.0007		16.5
Point 4	0.001		21.7
Point 5	0.00233		30
Point 6	0.003		30
Concrete:			
ShrCf-Op			0.2
ShrCf-CI			0.7
UnTensSt			3.4
UnCompSt			30
BiCompSt			0
HydroPrs			0
BiCompSt			0
UnTensSt			0
TenCrFac			0

Material Model Number	2	Element Type	LINK8
Material Properties:			
Linear Isotropic:			
EX	200000		
PRXY	0.3		
Bilinear Isotropic:			
Yield Stss		540	
Tang Mod		10	

Material Model Number	3	Element Type	LINK8
Material Properties:			
Linear Isotropic:			
EX	200000		
PRXY	0.3		
Bilinear Isotropic:			
Yield Stss		294	
Tang Mod		10	

Material Model Number	4	Element Type	SHELL41
Material Properties:			
Linear Isotropic:			
Ex	230000		
Ey	1		
Ez	1		
PRXY	0.3		
PRYZ	0		
PRXZ	0		
Gxy	1		
Gyz	1		
Gxz	1		

Material Model Number	6	Element Type	SHELL41
Material Properties:			
Linear Isotropic:			
EX	200000		
PRXY	0.3		

Material Model Number	7	Element Type	LINK8
Material Properties:			
Linear Isotropic:			
EX	200000		
PRXY	0.3		
Bilinear Isotropic:			
Yield Stss		623	
Tang Mod		10	

Material Model Number	8	Element Type	SOLID45
Material Properties:			
Linear Isotropic:			
EX	200000		
PRXY	0.3		

6. Model beams details and strengthening schemes

A total of seven reinforced concrete deep beams were modeled under two concentrated loads. Each beam was 800 mm long with an overall cross – section of 80 mm x 320 mm. The beams were simply supported on a span L of 660 mm giving an L/D ratio of 2, which is less than 4 as recommended by the provisions of the ACI code 318 – 11 [1] for deep beam requirements. All the deep beams designed to fail in shear and they had the same flexural and shear reinforcement (2 Φ16 mm flexural reinforcement and Φ6 mm at 100 mm c/c stirrups).

The details of the modeled beams are summarized in Table (4); beam (B1) included to provide a basis for comparison of the strength and behavior of the strengthening beams. The remaining deep beams strengthened by CFRP strips of 40 mm wide and spaced at 100 mm c/c with different configurations. Figure (8) shows the strengthening scheme of the modeled beams

Table 4: Summary of Model Beams Details

Beam No.	Details of Strengthening	Anchoring of CFRP
B1	Deep beam (control beam) without strengthening	---
B2	Deep beam strengthened with 90˚ CFRP strips	---
B3	Deep beam strengthened with 90˚ CFRP strips and longitudinal CFRP strips	----
B4	Deep beam strengthened with 45˚ CFRP strips	----
B5	Deep beam strengthened with 45˚ CFRP strips and longitudinal CFRP strips	---
B6	Deep beam strengthened with 90˚ CFRP strips and longitudinal CFRP strips	With anchoring 90˚ CFRP
B7	Deep beam strengthened with 45˚ CFRP strips and longitudinal CFRP strips	With anchoring 45˚ CFRP

7. Modeling and meshing

The beam was modeled as volume in order to obtain good results from the SOLID65 element, the use of a rectangular mesh was recommended [8].

No mesh of the reinforcement was needed because individual elements were created in the modeling through the nodes created by the mesh of the concrete volume. The meshing of steel reinforcement and CFRP of the beams were shown in Figure (9).

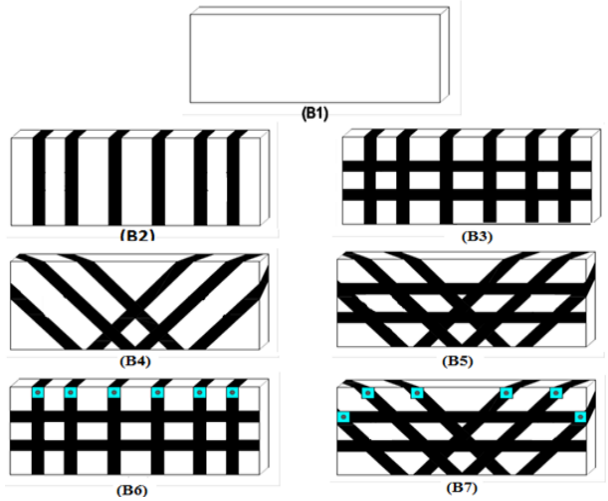


Fig. 8: Strengthening Schemes of the Model Beams.

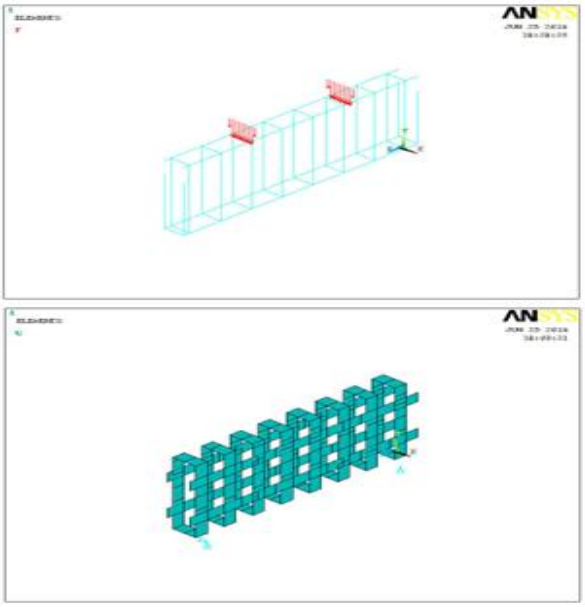


Fig. 9: Mesh of Steel Reinforcement and CFRP.

8. Boundary Conditions and Loads

The boundary conditions for the models created with 3D SOLID45 element representing the supporting plates are defined as follows: pin support: the nodes along the transverse line at the middle bottom of the supporting plate were locked against translation in vertical (y-direction), transverse (x-direction) and free in longitudinal (z-direction). Roller support; the nodes along the transverse line at the middle bottom of the supporting plate were locked against translation in only one vertical direction (y-direction). The loading profile is applied to the model. The loading plate serves as a medium that uniformly distributes the pressure on the loaded area. The model beam boundary conditions can be seen in Figure (10).

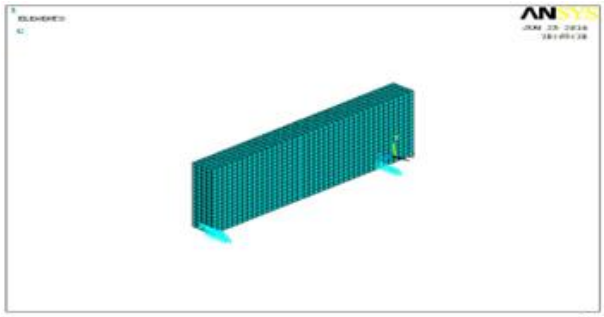


Fig. 10: Boundary Conditions of the Model Beams.

9. Result and discussions

9.1. Effect of fibre orientation (90° CFRP, 45° CFRP)

Table (5) shows that model beam B4, strengthened with 45º CFRP strips provided higher ultimate load as compared to model beam B2, strengthened with 90º CFRP strips, the increase was (18.4 %). This is due to the fact that the inclined web reinforcement in deep beam had effectively arrested the growth of diagonal cracks, so that the usual diagonal – cracking failure could not occur [13].
Figure (11) shows the load – deflection curves of beam B2 and beam B4. Deep beam B4 behaved in a stiff manner, although both beam B2 and beam B4 show a slightly higher stiffness in the post cracking stage of response as compared with the deep beam B1, without strengthening.
Model beam B3 was strengthened with longitudinal CFRP strips and with 90º CFRP strips. From Table (5), it can be seen that model beam B3 increase the ultimate load by (24.6 %), as compared with beam B2. Figure (12) shows the deflection curves of these two beams. Model beam B3 shows a higher stiffness in the post cracking stage of response as compared with model beam B2.

Table 5: Ultimate Load of the Model Deep Beams

Beam No.	Ultimate Load V_u (KN)	Mid – Span Deflection (mm)	Percentage Increase in Ultimate Load with Respect to B1
B1	149	2.1	---
B2	176.5	4.2	18.5
B3	220	4.6	47.7
B4	209	2.8	40.3
B5	291.5	5.1	95.6
B6	274	6.4	84.0
B7	321	4.8	115.4

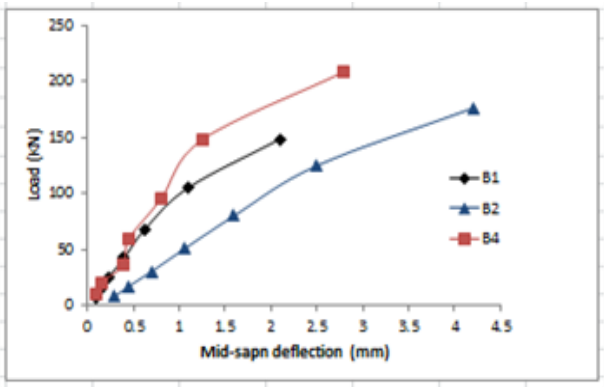


Fig. 11: Load – Deflection Curves: Effect of Fiber Orientation.

Model beam B5 was strengthened with longitudinal CFRP strips and with 45º CFRP strips. From Table (5), it can be seen that model beam B5 increase the ultimate load by (39.5 %), as compared with model beam B4. Figure (13) shows the deflection curves of these two beams. Beam B5 shows a higher stiffness in the post cracking stage of response as compared with beam B4.
Analytical results reveals that strengthening using CFRP strips arranged longitudinally and wrapped with transverse CFRP strips (90º strips or 45º strips) will enhance significantly the ultimate strength and post – cracking deflection.

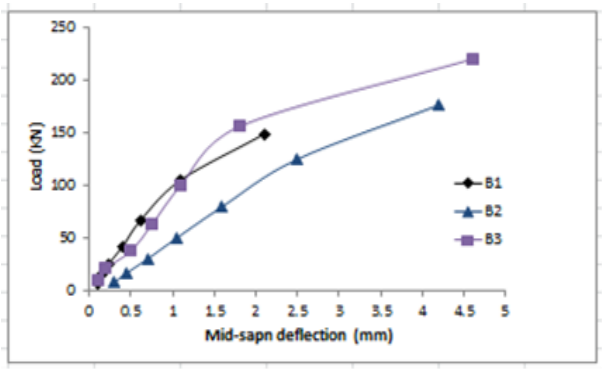


Fig. 12: Load-Deflection Curves: Effect of Strengthening in Both Longitudinal and Transverse Direction (90 CFRP).

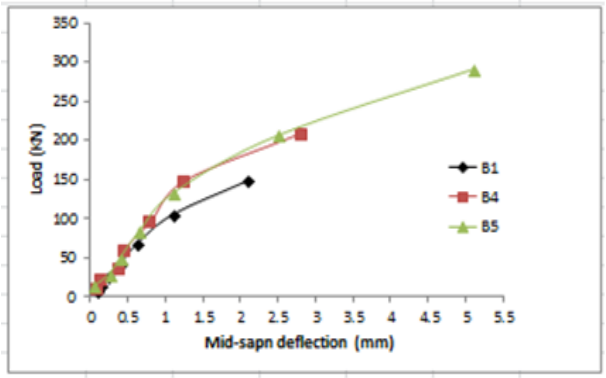
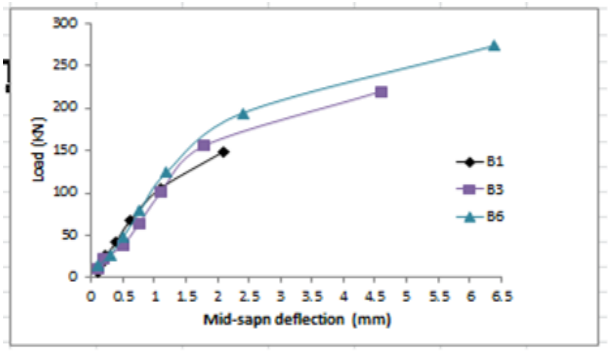


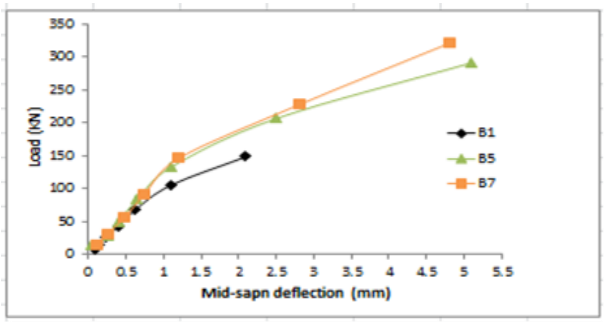
Fig. 13: Load – Deflection Curves: Effect of Strengthening in Both Longitudinal and Transverse (45 CFRP).

9.2. Effect of anchoring CFRP strips

Model beam B6 and model beam B7 were used to illustrate the effect of anchoring CFRP strips on the behavior of deep beams.
From Figure (14a) and Table (5), it can be seen by using anchors in beam B6, the CFRP contribution to the ultimate shear resistance of the beam was increased by (24.5 %) (beam B6 versus beam B3). But the increase was (10.1 %) (beam B7 versus beam B5, Figure (14b)).
Figure (14) shows that the presence of anchors increases the post – cracking deflection when compared to deep beam B3 and beam B5 without anchors.



(a) Load – Deflection Curves: Effect of Anchoring 90° CFRP Strips



(b) Load – Deflection Curves: Effect of Anchoring 45° CFRP Strips

Fig. 14: (A, B): Effect of Anchoring.

10. Conclusions and recommendation

Based on the numerical investigation reported herein on reinforced concrete deep beams strengthened with CFRP, the following conclusions can be drawn:

1) Reinforced concrete deep beams strengthened with 45º CFRP strips exhibited higher ultimate load as compared with 90º CFRP strips.
2) When combining CFRP strips in the longitudinal direction of the deep beam followed by 90º CFRP strips, the results showed that there was an additional increase in ultimate load by (24.6 %).
3) When combining CFRP strips in the longitudinal direction of the deep beam followed by 45º CFRP strips, the results showed that there was an additional increase in ultimate load by (39.5 %).
4) Strengthening scheme of 45º CFRP strips with additional longitudinal CFRP strips is more efficient in upgrading the shear resistance of deep beam than 90º CFRP strip with longitudinal CFRP strips.
5) The additional longitudinal CFRP strips with transverse CFRP strips (90º or 45º CFRP) will improve the post cracking stiffness of the deep beam.
6) The bolt anchors of transverse CFRP (90º or 45º CFRP) increased the composite contribution to the shear resistance of deep beam by an additional (24.5 %) for 90º CFRP scheme and (10.1 %) for 45º CFRP scheme.

Further numerical research is needed to study the effect of CFRP strengthening of deep beams with different web opening location and different (a/d) ratio.

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