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Nonlinear analysis of RC deep beams strengthened with NSM CFRP anchor bars

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ABSTRACT

Studies on the effect of using externally bonded fiber reinforced polymer (FRP) laminates and near surface mounted (NSM) FRP bars on the shear strengthening of reinforced concrete (RC) beams has been widely conducted by various researchers globally. However, an innovative technique using NSM CFRP as anchor bars on the shear strengthening of RC deep beams has never been conducted. Current experimental work on NSM anchor bars has shown good enhancement in the shear capacity for the RC deep beams. This paper presents results obtained from the analytical model of the RC deep beams shear strengthened by NSM CFRP Anchor bars. The study comprises of developing four analytical models using finite element method software ANSYS Version 14. Results of the analytical model and experimental findings were compared for validation. All deep beams were simply supported and subjected to four point bending test with shear span to depth ratio a_v/d of 0.864. CFRP NSM bars of 5 mm diameter with 450 mm length and spaced at 100 mm (for beams R1 and R2) and 150 mm (for beams R3 and R4) were anchors into their respective beams. Similar properties from the experimental work were adopted for the analytical model. Results from the analytical model such as crack pattern, failure mode and load displacement profile were observed to have good agreement with the experimental findings. Shear capacity shows proximity between the analytical model and experimental results observed at 15 % for beams R1 and R2, and 7 % for beams R3 and R4.

1. Introduction

A wide previous existing research on flexural and shear strengthening of reinforced concrete (RC) deep beams (Ehsan et al., 2011; Mofidi et al., 2013). All of those researchers focused on the experimental investigation of flexural and shear strengthening of RC beams by using fiber reinforced polymer composites (FRP) as externally bonded. Moreover, the FRP locations, amount of fiber and shear effect to depth ratio were also investigated (Barros et al., 2007; El-Ghandour, 2011; Godat et al., 2010; Rahimi and Hutchinson, 2001).

Rehabilitation and strengthening by using FRP as a NSM of members like beams and columns have become a good way to increase shear and flexural strength of existing composite members (Tavarez et al., 2003). Strengthening of composite members by externally bonded FRP laminates is very interested and accepted technique (Khalifa et al., 1998). Many studies on strengthening and repairing by using NSM technique showed that using of FRP laminates to the reinforced concrete members provide efficiency, reliability and cost-effectiveness in rehabilitation.

Further, many studies were conducted to predict the shear and bending load capacity of FRP that used to strengthen and repair RC beams (Rahimi and Hutchinson, 2001; Al-Zaid et al., 2012; Camata et al., 2007; Yang et al., 2003; Supaviriyakit et al., 2004; Rabinovich and Frostig, 2000). In addition, using FRP as a NSM for strengthening and rehabilitation were proved to be successful in enhancing the shear capacity of RC deep beams (Zhang et al., 2004; Islam et al., 2005; Maaddawy and Sherif, 2009).

In this research, total four Deep beams having same design are tested with two possible strengthening schemes as shown in Fig. 1 by Samad et al. (2017). The CFRP NSM anchoring bars are

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applied inside of the Deep beam to strengthen the beam for shear. Some of the parameters are presented and discussed in this paper such as ultimate load, CFRP contribution to shear, modes of failure and load-deflection profile of CFRP NSM bars. Finally, all the results are gotten from finite element analysis by using ANSYS software are compared with the experimental results carried out by Samad et al. (2017).

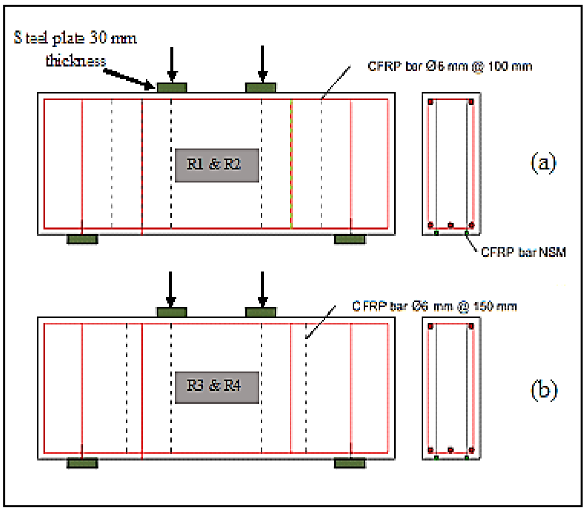

Fig. 1: (a) Beam specimens R1 and R2 with CFRP anchor bars at 100mm c/c (b) Beam specimens R3 and R4 with CFRP anchor bars at 150 mm c/c

2. Finite element modelling

In this research, a three-dimensional nonlinear Finite Element Analysis (FEA) was conducted by using ANSYS V14. The dimensions and properties of experimental work conducted by Samad et al. (2017) were used to analyze and validate the finite element analysis results.

2.1. Material properties

2.1.1. Concrete

Some of the requirements for concrete material as linear isotropic elasticity and multi-linear isotropic hardening properties are important to describe the concrete nonlinear behavior (Ibrahim and Mahmood, 2009). In this analytical study, the concrete is assumed as homogeneous and initially isotropic material. Fig. 2 shows the compressive stress-strain curve for concrete.

The compressive stress-strain curve was drawn depending on three equations. The first value of strain was calculated at the stress of 0.3 f´c from Eq. 1 for linear behaviour. For the plastic zone, the concrete behaviour is non-linear, and the stress was measured from Eq. 2, in which ε_0 is calculated from Eq. 4. Finally, the ultimate stress was measured at $f = f'c$ or at ε_0 from Eq. 3. Moreover, the concrete nonlinear properties can be shown in Table 1.

$$E_c = \frac{f}{\varepsilon} \tag{1}$$

$$f = \frac{E_c \varepsilon}{1+\left(\frac{\varepsilon}{\varepsilon_0}\right)^2} \tag{2}$$

$$f = f'c \tag{3}$$

$$\varepsilon_0 = \frac{2}{E} f'c \tag{4}$$

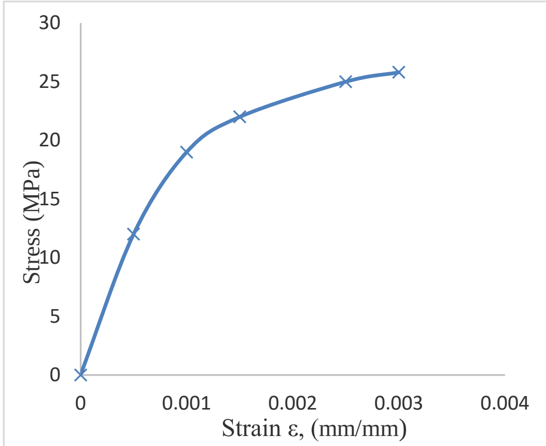

Fig. 2: Concrete stress-strain relationship curve

Table 1: Properties of concrete

Density	2400 kg/m3
Reference temperature	25^0C
Linear Isotropic	
Modulus of elasticity (Ec), MPa	23873
Poisson's ratio (μ)	0.15
Multi-linear Isotropic	
Strain	Stress (MPa)
0	0
0.0005	12
0.001	19
0.0015	22
0.0025	25
0.003	25.8

2.1.2. Steel reinforcement

The reinforcement has uniaxial stiffness only and is assumed to be smeared throughout the element. Directional orientation is accomplished through user-specified angles. The bilinear stress-strain curve is similar to that shown in Fig. 3. The properties of steel reinforcement can be shown in Table 2.

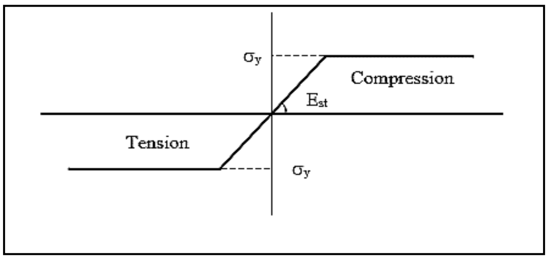

Fig. 3: Idealized bilinear stress-strain curve for steel

Table 2: Steel bars properties

Density	7850 kg/m3
Reference temperature	250c
Linear Isotropic	
Modulus of elasticity (ES), MPa	2×105
Poisson's ratio (μ)	0.15
Bilinear Kinematic Hardening	
Yield stress (fy), MPa	680
Tangent modulus (E's), MPa	2×103

2.1.3. CFRP bars

The FRP composites are used as a fully bonded bar with the concrete surface. Table 3 illustrates the properties of CFRP bars.

Table 3: CFRP bars properties

Density	1.4 gm/cm3
Poisson's ratio	0.164
Modulus of elasticity (GPa)	115
Tensile strength (MPa)	2300
Ultimate Strain (%)	0.02

2.2. Material modelling and meshing

Many element types that available in ANSYS software can be used for the composite member for finite element method.

SOLID 65 (3-D reinforced concrete solid) is a very important element model that is used to investigate concrete nonlinear behavior. Santhakumar et al. (2007) used SOLID 65 as concrete in their finite element analysis using ANSYS software (ANSYS User's Manual Revision 14.0). The geometry properties of SOLID65 can be illustrated in Fig. 4.

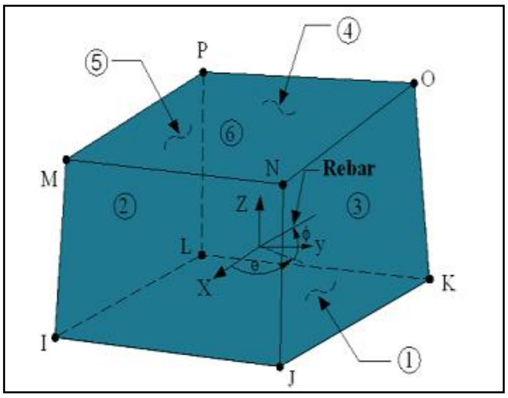

Fig. 4: Element (SOLID65) geometry

LINKE 180 element is a spar (or truss) element which may be used in a variety of engineering applications. This element can be used to model trusses, sagging cables, links, springs, etc. The 3-D spar element is a uniaxial tension-compression element with three degrees of freedom at each node: translations of the nodes in x, y, and z-directions. As in a pin-jointed structure, no bending of the element is considered. Plasticity, creep, swelling, stress stiffening, and large deflection capabilities are included. This element is used, in this study, to simulate the behavior of steel reinforcement and CFRP bars which works as main steel reinforcement. The geometry, node locations, and the coordinate system for this element (ANSYS User's Manual Revision 14.0) are shown in Fig. 5.

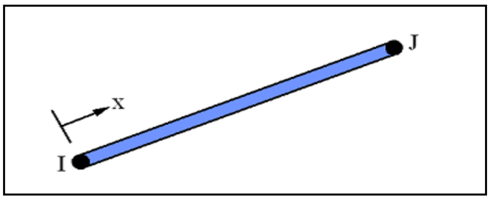

Fig. 5: Element (LINK8) geometry

From ANSYS software, the multi-physics state was used, and material properties are appointed to various parts of the deep beam. The steel reinforcement properties were confirmed from structural steel property, and the concrete beam was assigned concrete nonlinear property. The meshing of the finite element model is conducted as shown in Fig. 6. Two loading plates and two support plates are required to make for bending load according to the experimental model. The support and the plate at the load point are150 mm x 100 mm x 25 mm steel plate. Fig. 7 shows the meshing of CFRP anchoring bar, the steel plate of bending point and steel reinforcement. Table 4 shows the element type mesh attributes for the models were used in this paper.

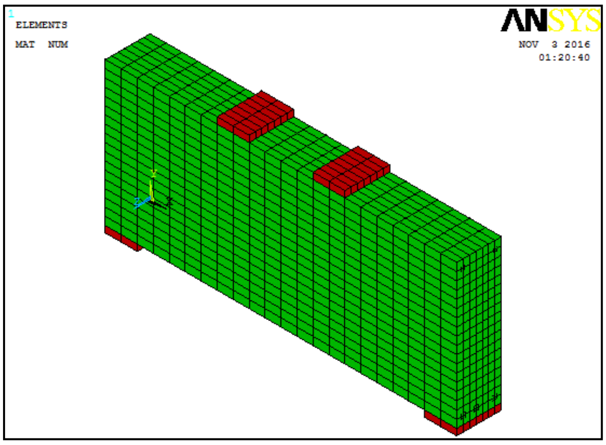

Fig. 6: Deep beam mashing

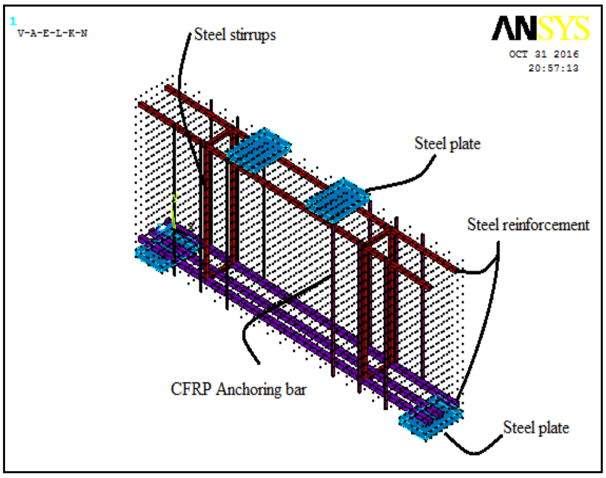

Fig. 7: CFRP bars, Steel plate and reinforcement meshing

Table 4: Mesh attributes for the models

Model Parts	Element Type	Material Number	Real Constant Set
Concrete Beam	SOLID65	1	1
Steel Ø16 mm Rebar	LINK180	2	2
Steel Ø12 mm Rebar	LINK180	2	3
CFRP Ø5 mm Rebar	LINK180	3	4
Steel Plate and support	SOLID185	4	N/A

3. Analysis results and discussion

3.1. Deformation diagrams

The deformation diagrams of analysed deep beams at failure load are shown in Fig. 8.

3.2. Crack pattern at failure load

Fig. 9 shows the crack pattern and mode of failure for analysed deep beams, the simulated model shows good agreement with experimental model in Fig. 10.

3.3. Failure load

Table 5 shows the comparison of shear capacity between finite element and experimental results. From this table, the finite element results show good agreement with the experimental results (Samad et al., 2017).

3.4. Shear- deflection profile

Fig. 11 shows the shear-deflection curve of analysed deep beams. This figure shows the shear-deflection profile from finite element analysis respect the experimental results (Samad et al., 2017).

4. Conclusion

A simulation study on the shear strengthening of RC deep beams with NSM CFRP anchor bars was conducted using finite element software ANSYS Version 14. Four (4) RC deep beams FE models were developed with similar test set-up and material properties from the experimental work. Results from the analytical model and experimental work were compared. The observation from the study can be concluded as follows:

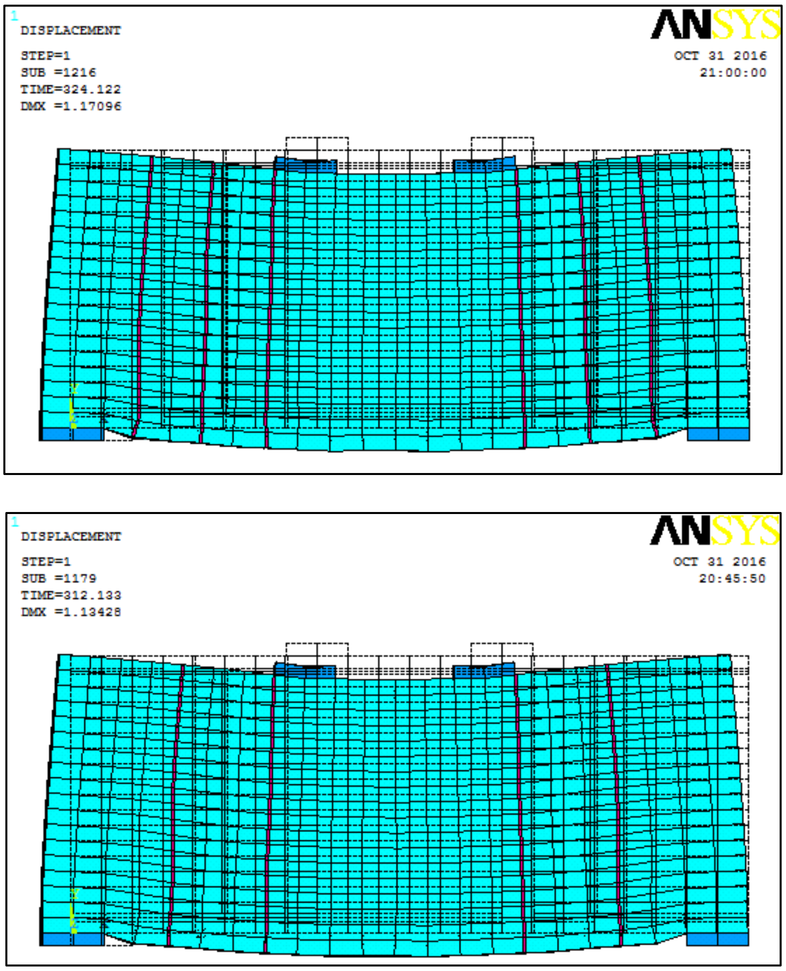

Fig. 8: Deep beams deformation

1. The CFRP NSM anchor bars technique shows its ability to enhance the shear capacity of RC deep beams.
2. Shear capacity from the analytical to experimental results shows close agreement. A small difference of 7 % to 15 % was observed.
3. The crack pattern and failure mode also shows good agreement but the load displacement profile from the analytical model shows a slightly stiffer behaviour than the experimental results.
4. All deep beams from the analytical model were observed to fail in shear compression similar to the findings from the experimental work.

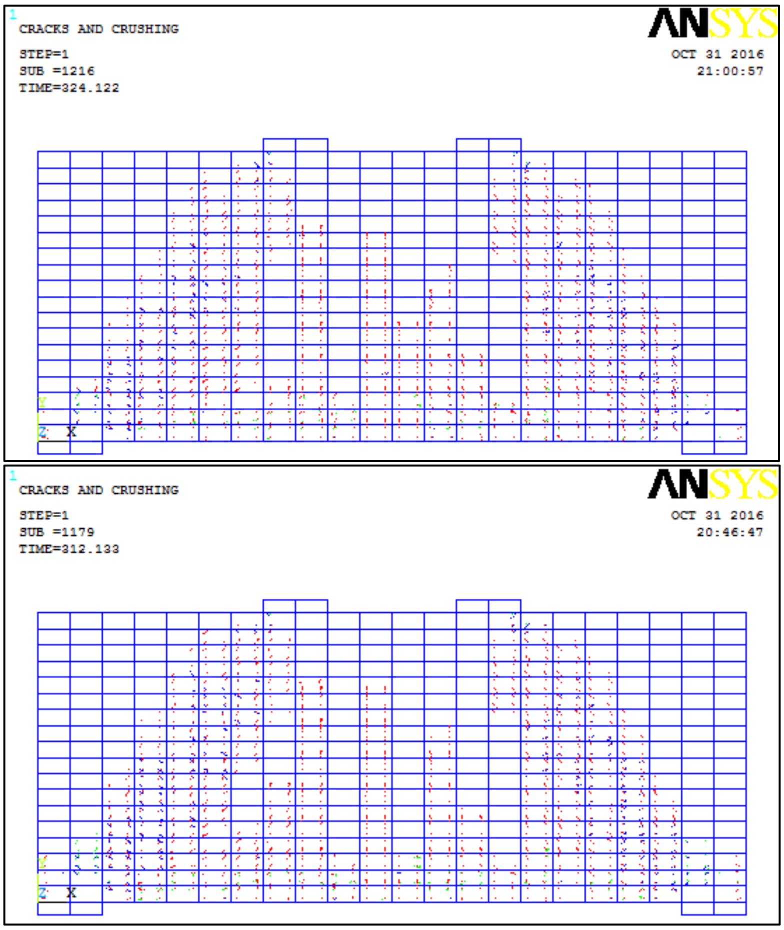

Fig. 9: Crack pattern mode of failure at failure load

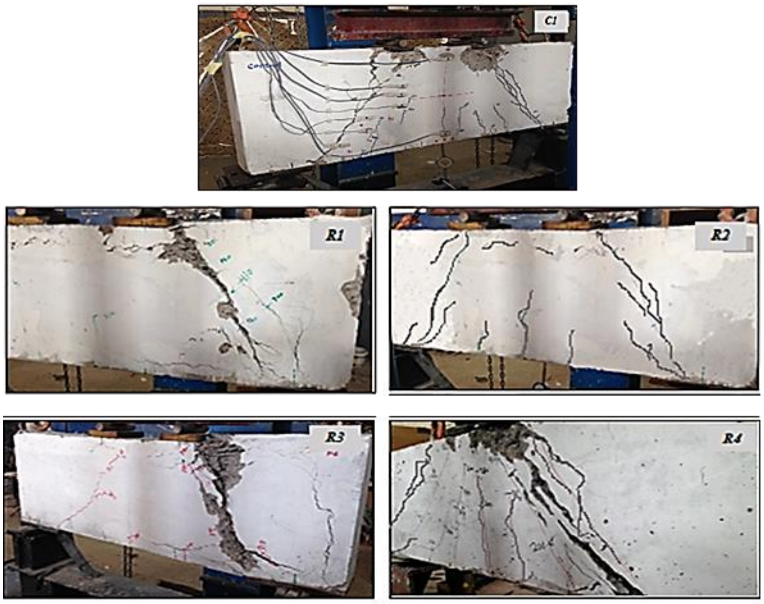

Fig. 10: Crack pattern mode of experimental work (Samad et al 2017)

Table 5: Shear capacity results

Specimens	Vu (Numerical) (kN)	Vu (Experim-ental) (kN)	Vu (Numerical)/Vu (Experimental)
R1(0/90-100)	370	320.5	1.154
R2(0/90-100)	370	318	1.163
R3(0/90-150)	328	307	1.068
R4(0/90-150)	328	299	1.096

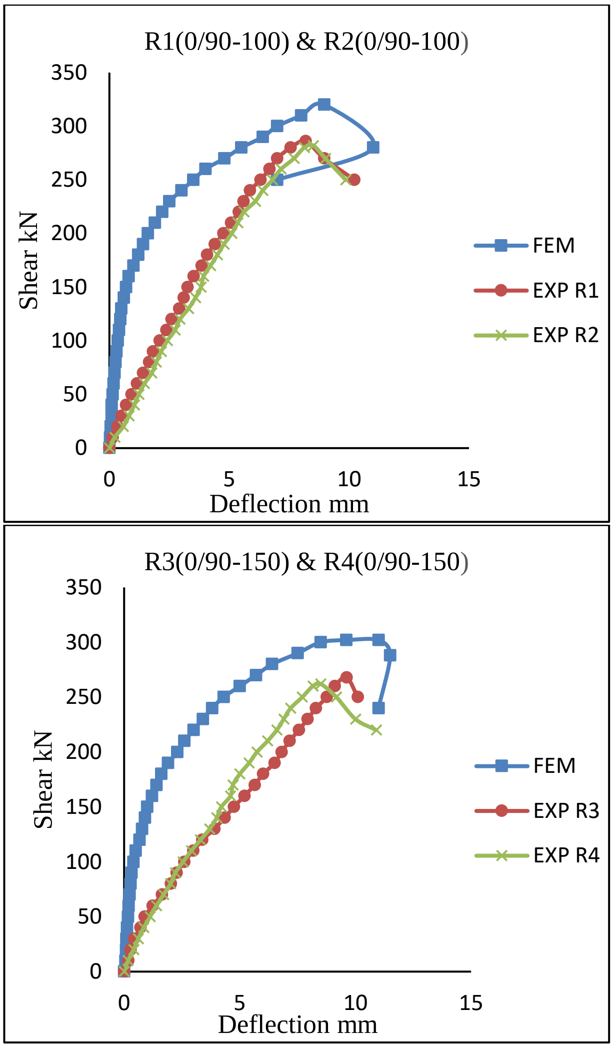

Fig. 11: Comparison of shear force – deflection profile between experimental and simulation of deep beams

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