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Numerical investigation of Reinforced Concrete Beams Strengthened with Carbon Fiber Pre-subjected to Shear Failure

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Abstract: *A series of three-dimensional models of Reinforced Concrete (RC) Beams, subjected to shear failure and then retrofitted with near-surface-mounted (NSM) composite reinforcement, were numerically analyzed to examine the effects of different modes of failures on the ultimate strength of strengthened reinforced concrete beams. These analyses intended to study strengthening configurations (i.e., angle of inclination of the NSM composite). Prior to the retrofit, the models were analyzed at three different failure modes; pre-cracked after three loading cycles, unloaded up to the first shear cracking; and pre-cracked up to 85% failure load and pre-failed in shear after one cycle of loading. Results indicate that the NSM composite reinforcement remarkably improved the shear response. Varying the angle of inclination of the NSM composites from 90 to 45 degrees increased the shear strength of the beams. The presence of shear cracks prior to retrofit did not reduce the shear strength gain provided by the NSM composites. The NSM composite system fully restored the shear capacity of the pre-failed beams. Numerical results from the analyses were compared with the available experimental work in the literature showing reasonable agreement. The finite element models are intended to provide further information on the shear capacity of RC beams using NSM composites when evaluating the influence of certain variables such as the concrete strength, CFRP area, the spacing of stirrups, and the amount of strength effectiveness.*

Keywords: *ATENA program, Composites, Finite element, Near-surface-mounted, Restoration, Shear damage*

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I. Introduction

In the preceding decade, physical licence retrofitted for swollen reject a delete effectiveness has pulled in exploratory consideration; e.g., (Khalifa, 1999)[1], (Deniaud, 2001)[2] and (Sundarraja, 2009[3]. Dig restorative is unendingly prone by cultivate far FRP genealogy on the scantling sides Prevalent the government form to the brace axis or roughly a perspective similar to principal accent mark direction. The decisive reach increases and the effect on the types of the modes of dissection depends on the FRP attribute, (Norris, 1997)[4]. The take note of likely FRP strips tush do a first-class shrink in the boring c manufactured moving and collect with regard to expanded destine a chop up strength and coolness, (Sundarraja, 2009)[3]. U-wrap, in the flexural court, is the most talented implicit correction on load capacity. Utilizing U-wrap as a link of the flexural territory, each time of flexural and fail to attend fitness source polish off emendation and this rear deracinate leave alone it out foreigner the friable destruction, the guerilla of share is into the bargain based around the distribution and the quantity of FRP and produce stirrup spacing, (Khalifa, 2002)[5].

In recent years, the development of fiber reinforced polymer (FRP) material, with a high-strength-to-weight ratio and excellent resistance to electrochemical corrosion makes it particularly suited to structural applications. The near-surface-mounted (NSM) composite system is a promising technique for shear strengthening of deficient RC structural components [6-9]. Most of the studies focused on strengthening of un-cracked reinforced concrete beam and limited studies were done on repair of defected or cracked reinforced concrete beam. However, Jayaprakash et al., (2008) [10] had conducted an experimental work on strengthening un-cracked reinforced concrete simply supported beam and repair of pre-cracked reinforced concrete simply supported beam. Their findings revealed that the pre-cracked beam could perform as good as the initially strengthened beam due to the presence of CFRP sheet.

There are three major classifications of concrete structures failure that have been found experimentally, when retrofitted or strengthened the structure by FRP (Ebead, 2005)[11](Lundqvist, 2005)[12](Coronado, 2006)[13]. The explanation of the failure types are shown in following points:

1- Generally, in the 1st mode of failure, the yields of reinforcement, after that FRP rupture is observed.

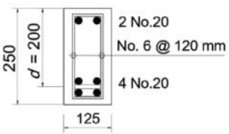
2- The 2nd failure mode occurs in the concrete, either because of the concrete crushing earlier than or after tensile steel yielded, with no damages in the composite sheet, or because of a shear crack at the laminate end.

3- For the third kind, the mode of failure includes losses of the action of composite (Vijayakumar,2012)[14]. the failure begins at the laminate end because of the stress concentration and the debonding propagation at the laminate ends , at this point, the stresses are primarily shear stress whereas bending stiffness in the laminate is not equal to zero therefore, normal stress can arise.

Experimental studies on shear strengthening with the NSM composite system are relatively few. An experimental program to gather the necessary data to perform a comprehensive parametric study on beams subject different levels of shear stresses and retrofitted with CFRP is generally complicated , costly and requires a significant amount of time to conduct an extensive number of experimental tests, which makes it unaffordable. Therefore, in order to fill the gap on strengthening and repairing of cracked reinforced concrete beam and shear strengthening, this study which was focusing on shear strengthening and repair of pre-cracked reinforced concrete beam. An experimental work from the literature was used to verify the results from the numerical model. A parametric study was conducted to evaluate the effect of the level of damages which the beam subject to before retrofitting and the angle of inclination of the NSM-CFRP bars.

II. Geometry of Specimens and Reinforcement

The experimental results of nine beams published by El-Maaddawy, T., (2015) [15] have been used to develop and verify the numerical model created in this study. The test specimen had a rectangular cross section of 125 x250 mm, as shown in figure 1. The specimens were heavily reinforced in flexure to ensure that they would fail in shear. The beams were tested under three point bending with an effective span of 3000 mm and a short shear span (test region) of 600 mm. The specimens were: undamaged; subjected to Damage State D1; or Damage State D2 prior to restoration. The specimens with Damage State D1 were presubjected to three cycles of loading-unloading to induce shear cracks in the specimen. In each cycle, the specimen was loaded up to initiation of shear cracks, which took place at approximately 60% failure load, then unloaded down to zero load. The specimens with the Damage State D2 were loaded to peak load then unloaded down to zero loads. The undamaged and predamaged specimens were strengthened in an unloaded condition. The retrofit scheme R90 and R45 are shown in figure 2a and figure 2b respectively. The specimens designation is selected to consist of three parts, the first refer to the stirrups spacing which is fixed 120mm and referred as S1,the second part refer to the type of damage and the third is refer to the angle of retrofitting



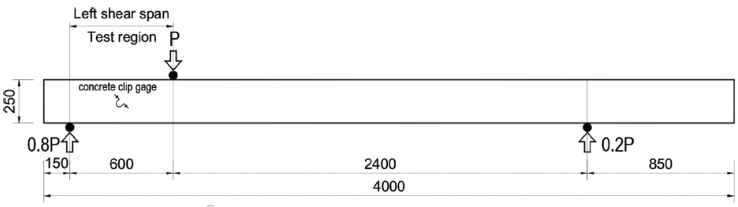


Fig. 1: Specimens details [6]

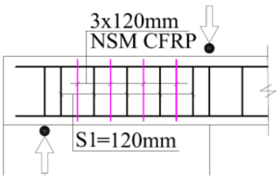


Fig. 2a: Retrofitting scheme R90

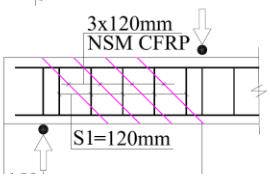


Fig. 2b: Retrofitting scheme R45

The concrete cylinder compressive strength was, 30 MPa. The provided longitudinal steel reinforcement consisted of deformed bars with an average yield strength of 500 MPa and elongation at break of 16%. The shear reinforcement in the test region consisted of plain round bars with an average yield strength of 345 MPa and an elongation at break of 23%. A typical CFRP strip used in the NSM Reinforcement had a cross section of 2.5 x 15 mm, tensile modulus of 165 GPa, tensile strength of 3100 MPa, and an ultimate elongation of 1.9%.

III. Finite Element Model

A total of twelve three-dimensional (3D) Finite Element (FE) models were developed for the analyses using the ATENA software [16]. All the models have the same concrete properties. The concrete was modelled using 3D solid brick elements. The reinforcing bars were modelled as "discrete reinforcement" using truss elements. A sensitivity study was performed to evaluate the effect of the mesh size and it was selected as an element size of 20 mm. It was also found that further reduction in the element size had no significant effect on the numerical results. The finite element model is shown in figure 3. A displacement-controlled incremental loading method was used in the analysis. An iterative solution procedure based on the Newton-Raphson method was adopted. The specimens were either: undamaged; subjected to Damage State D1; Damage state D2; or Damage State D3 prior to restoration. The specimens with Damage State D1 & D2 were loaded with a procedure similar to the experimental work while specimens with damage D3 were created to provide more results to evaluate the damage level. Specimens with damage D3 was presubjected to three cycles of loading-unloading to 85% of the peak load to induce shear cracks in the specimen. The failure load is identified when a sudden drop in applied load took place. For the strengthened specimens the NSM-CFRP is marked in the model to be activated after the specified cycles of damages is completed and at zero load conditions.

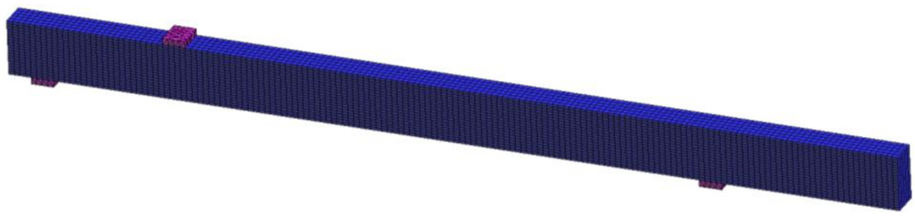


Fig. 3: Finite element model of the specimens

3.1 Constitutive Model for Structural Concrete

The [CC3DNonLinCementitious2] material model of the FE package ATENA was used to simulate the concrete. The model integrates constitutive laws for tensile/fracturing behavior as well as for the plastic/compressive behavior. The Menétrey-Willam failure surface was used in the analysis [17]. The concrete constitutive laws employed in the analysis are shown in figure 4. A bilinear elastic-perfectly plastic model was assumed for the steel reinforcing bars. The behavior of the CFRP was assumed linearly elastic up to failure.

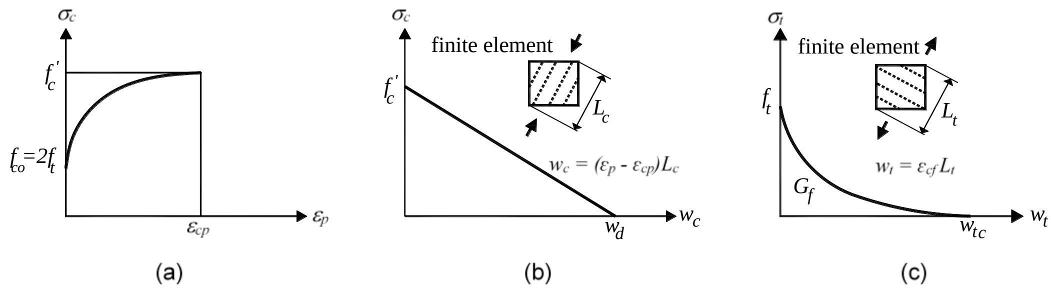


Fig. 4: Constitutive laws of concrete; (a) compressive hardening law, (b) compressive softening law, (c) tensile softening law

Unloading is a linear function to the origin. An example of the unloading point U is shown in figure 5. Thus, the relation between stress σ_c^{ef} and strain ε_c^{eq} is not unique and depends on a load history. A change from loading to unloading occurs, when the increment of the effective strain changes the sign. If subsequent reloading occurs the linear unloading path is followed until the last loading point U is reached again. Then, the loading function is resumed. Crack closure stiffness is controlled by the unloading factor (material parameter) $0 \leq f_u < 1$. The value of 0 corresponds to unloading to origin (default value for backward compatibility), $f_u = 1$ means unloading direction parallel to the initial elastic stiffness. In this study an unloading factor of 0.5 is considered

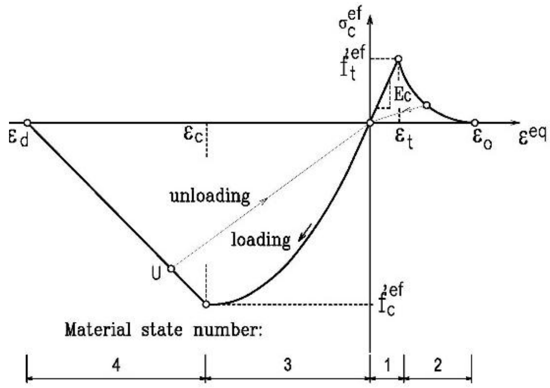


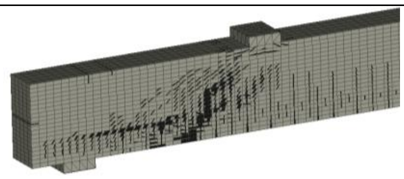
Fig. 5: Uniaxial stress- strain law

The structural reinforcement and CFRP are modelled as discrete bar elements. Steel bars were modelled using a bilinear stress-strain relationship that considers strain hardening which allows the stresses to increase after yielding. The CFRP was modelled using a linear stress-strain relation. The input parameters of the FE model have been used as the default calculated according to EuroCode2 EC2 (2004) [18] and CEP-FIP MC90 [19] model code expressions.

IV. Results And Discussion

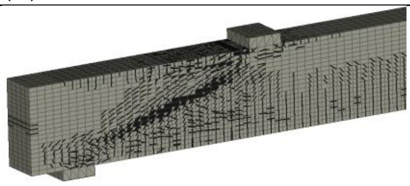
4.1 Crack Pattern

Figure 6 (A)&(B) show the experimental and numerical crack pattern for two specimens S1-ND-R90 & S2-D2-R45 as samples. The crack patterns predicted numerically adequately matched those recorded experimentally. Specimen S1-ND-R90 retrofitted with the vertical NSM-CFRP strips failed by formation of diagonal shear cracks in the shear span crossing the NSM-CFRP strips; the diagonal crack was accompanied with longitudinal cracks at the bottom parallel to the flexural reinforcement. The stresses in the flexural reinforcement in specimens S1-ND-R90 is shown in figure 7-(A) it’s clear that the stresses is below the yield and the failure can be indicated as a brittle shear failure . The retrofitted specimen S2-D2-R45 that were precracked or prefailed prior to retrofitting and retrofitted with the inclined NSM-CFRP strips indicate more efficiency for the inclined reinforcement in which the shear crack was associated with yielding of the flexural reinforcement and failure in the compression zone as shown in figure 7- B



(A) - Numerical crack

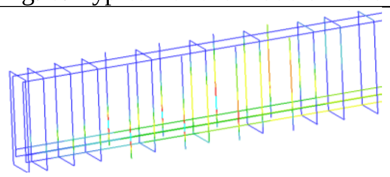
Experimental Cracks, Elevation & Top view



(B) - Numerical crack

Experimental Cracks, Elevation & Top view

Fig. 6: Typical failure mode of retrofitted specimens: (A) S1-ND-R90; and (B) S1-D2-R45



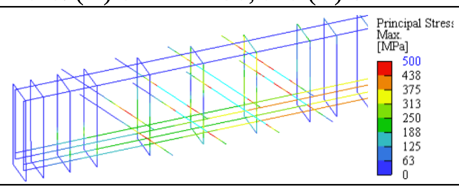


Fig. 7: Steel and NSM-CFRP Stress:(A) S1-ND-R90; and (B) S1-D2-R45

4.2 Load Deflection response

The load-deflection responses measured numerically for specimens without damage ND and with damage D1, D2 and D3 are shown in figures 8 to 11, respectively. The available experimental load-Deflection for specimens ND, D1&D2 were incorporated on the relevant numerical figure. It's noticeable that there is a good agreement between the numerical and experimental load deflection curves, which verifies the accuracy and validity of the FE models in capturing the nonlinear deflection response of beam precracked in shear and strengthened with NSM-CFRP bars

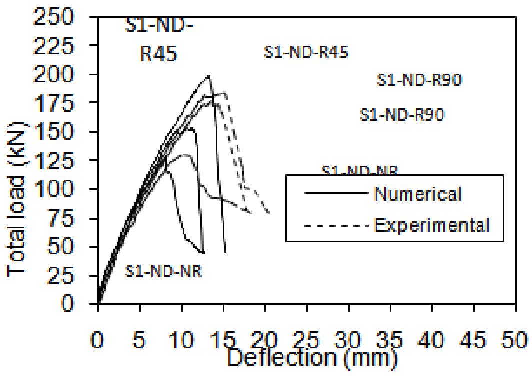


Fig. 8

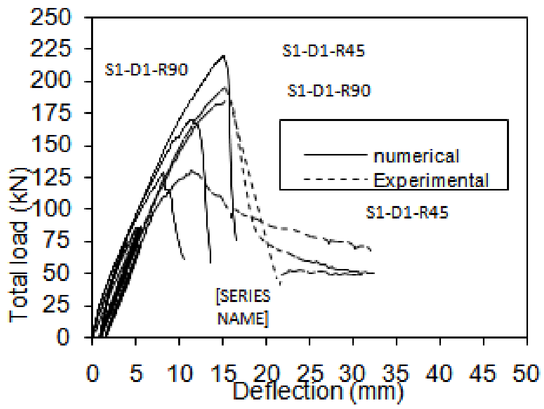


Fig. 9

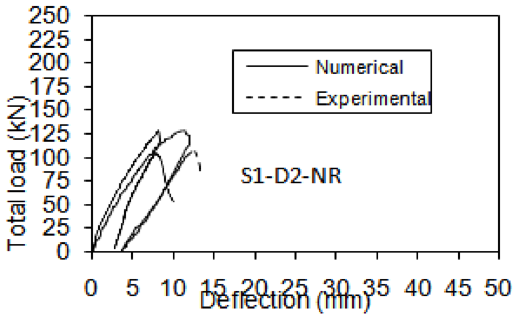


Fig. 10 -a

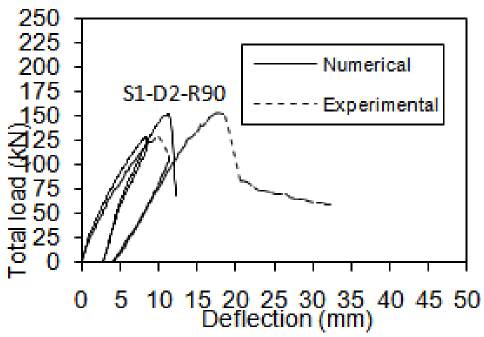


Fig. 10-b

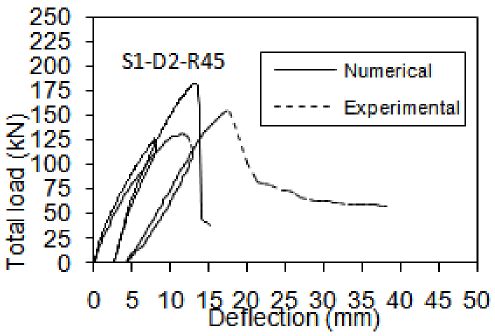


Fig. 10-c

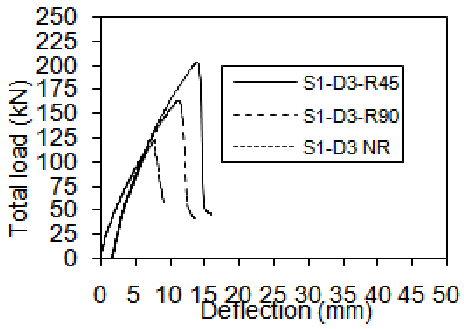


Fig. 11

Table 1 summarize the main experimental and numerical results in term of failure load (P), Deflection under the load application (Δ), the ratio of the experimental load and deflection to the finite element load $\frac{P_{Exp}}{P_{FE}}$ and the shear strength gain calculated relative to the theoretical shear resistance of corresponding control specimen without NSM-CFRP. The gain for specimens with precracked and without retrofitting is calculated relative to specimens S1-ND-NR without damage.

Table 1: Experimental and Numerical Load Capacities

Specimens	Experiments		Numerical			
	load P_{Exp}	Deflection Δ_{Exp}	Load P_{FE}	Deflection Δ_{FE}	$\frac{P_{Exp}}{P_{FE}}$	Gain, %
S1-ND-NR	130.4	10.28	128.8	8.18	1.01	0
S1-ND-R90	177.5	13.58	152.4	11.26	1.16	18
S1-ND-R45	183.9	14.96	198.17	13.37	0.93	50
S1-D1-NR	129.2	8.08	125.97	8.45	1.00	-2
S1-D1-R90	186.2	15.7	168.65	11.50	1.10	31
S1-D1-R45	193.7	15.48	218.88	15.15	0.89	70
S1-D2-NR	106.5	12.51	103.8	7.23	1.03	-19
S1-D2-R90	153.4	18.51	150.93	11.28	1.02	17
S1-D2-R45	154.5	17.80	182.8	13.18	0.85	42
S1-D3-NR	-	-	121.33	6.78	-	-6
S1-D3-R90	-	-	163.80	11.59	-	27
S1-D3-R45	-	-	203.40	13.90	-	58

It was clear that the Shear resistance of specimens with Damage State D1&D3 which represent the cracked specimens loaded with 60% and 85% the failure load (S1-D1-NR & S1-D3-NR) were marginally less than Specimen S1-ND-NR without damage with a 2 and 6% reduction in the shear resistance respectively. This indicates that the precracking (shear Damage State D1&D3) had no effect on the initial shear resistance of the specimen (that is, prior to restoration).

The shear strength gains exhibited by Specimens subjected to damage D1&D3, which were precracked prior to Restoration, were, interestingly, higher than the gains exhibited by Specimens without damage. This is consistent with other published findings that precracking did not reduce the shear strength gain provided by the NSM-CFRP shear reinforcement [1,2,6] . This is because the NSM-CFRP strips, in the precracked specimens, started to contribute to the shear resistance from the point of start of the reloading On the contrary, the NSM-CFRP strips started to contribute to the shear resistance in the uncracked specimens after formation of shear cracks.

Shear resistance of specimens with Damage State D2, S1-D2-NR, was decreased by 19% after one cycle of loading to failure when compared with the no damaged specimen S1-ND-NR

The shear resistance of the prefailed specimens improved remarkably after retrofitting. The shear resistances of the retrofitted specimens were, ranged from , 17% to 70% higher than their original shear capacitates recorded in the first shear test to failure. The inclined NSM-CFRP strips were generally more effective than the vertical strips in increasing the shear resistance of the prefailed specimens. The shear strength gain of specimen with damage D2 is the lowest with a ratios 17% and 42% for specimens S1-D2-R90 & S1-D2-R45 respectively.

V. Conclusion

1- The accuracy and validity of the FE models developed in this study to predict the nonlinear response of reinforced concrete beams strengthened with NSM-CFRP Pre-subjected to Shear Failure was demonstrated by comparing their predictions with the experimental results in the literature. The nonlinear responses of the specimens predicted numerically were in good agreement with those obtained from the experiments. The validated FE models can be used as a numerical platform in future research to investigate a wider range of parameters instead of laboratory testing, which is costly, labor-intensive, and time-consuming.

2- The presence of shear damage D1and D3 with specimens subject to three cycles of loading to 60% and 85% of the failure load respectively had no effect on the initial shear resistance of the specimen (that is, prior to restoration). The shear resistance was 2% less for specimens subject to damage D1 and 6% for specimens subject to D3

3- The present of shear damage D2 with specimen subject to one cycle of failure load the shear resistance of the specimen (that is, prior to restoration) decreased by 19%

4- The NSM-CFRP composite system fully restored the shear capacity of the specimens pre-subjected all type of damages examined in this paper, D1, D2 and D3.

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