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EXPERIMENTAL AND NUMERICAL INVESTIGATION ON THE PERFORMANCE OF SHEAR DEFICIENT RC BEAMS STRENGTHENED WITH NSM GFRP REINFORCEMENT UNDER CYCLIC LOADING

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Abstract. *This paper presents experimental and nonlinear Finite Element (FE) simulation of shear deficient reinforced concrete (RC) cantilever beams strengthened with Near Surface Mounted (NSM) Glass Fiber Reinforced polymer (GFRP) rods and subjected to cyclic loading. Two RC beam specimens were casted; the first beam is used to serve as a control specimen while the second was strengthened with GFRP NSM bars reinforcement. The two beams were tested under cyclic loading up to failure of the specimens. Then, a 3D Finite Element (FE) model that integrate different nonlinear constitutive material modeling laws and techniques such as concrete cracking, steel yielding, and imperfect bonding was developed using the finite element code ANSYS. The imperfect bonding captures the bond slip behavior between the NSM reinforcement and concrete surfaces. In addition, the developed FE models were validated against the experimental tests via a comparison of the load-deflection response envelopes and hysteresis loops. A Good matching between the experimental results and FE simulation were observed. Further experimental testing and numerical validation will be carried out in a future extensive research study to further investigate the performance of such systems when subjected to cyclic loading as in a seismic event.*

1 INTRODUCTION

In the last decade, strengthening reinforced concrete (RC) structures using externally bonded fiber reinforced polymer (FRP) materials have become a preferred technique to engineers and designers. Extensive research has been carried out to evaluate the contribution of FRP to different structural elements i.e. columns, beams, slabs etc. [1-3]. Although theoretically it is possible to achieve full capacity of strengthened elements, performed tests showed that achieving full capacity of FRP is unattainable due to debonding of the FRP sheets from the concrete surfaces [3-5]. A new strengthening technique known as near surface mounted (NSM) system seemed to be more efficient than the conventional externally bonded system. The NSM practice uses embedded FRP bars or strips into predefined groves cuts in the concrete cover, thus achieving better bonding and protection from environmental exposures.

Extensive research has been performed on the performance of RC beams strengthened with carbon fiber reinforced polymer (CFRP) bars or strips [6-8]. Limited studies have been conducted on the use of glass fiber reinforced polymers (GFRP) bars as possible strengthening materials in shear. The aim of this study is to investigate experimentally and numerically the performance of RC beams strengthened in shear with NSM GFRP rods when subjected to cyclic loading. Two RC beams were casted and tested under cyclic loading up to failure of the specimens. In addition, a finite element (FE) model is developed to capture the response and behavior of such strengthening system. The developed model was validated by comparing the load-deflection response envelopes and load-displacement hysteresis loops with that of the obtained experimental data.

2 EXPERIMENTAL PROGRAM

Two RC cantilever beams deficient in shear are casted. The first beam "SPEC-1" was kept unstrengthened to serve as a control specimen. The detailing of the control beam is shown in Figure 1. The beams were 200mm wide, 350mm high and 1700mm long as shown in Figs. 1 and 2. Four 20mm diameter bars in the compression zone and four 20mm diameter bars in the tension zone are used as longitudinal reinforcements. A concrete clear cover of 30mm was used to avoid any embedding problems.

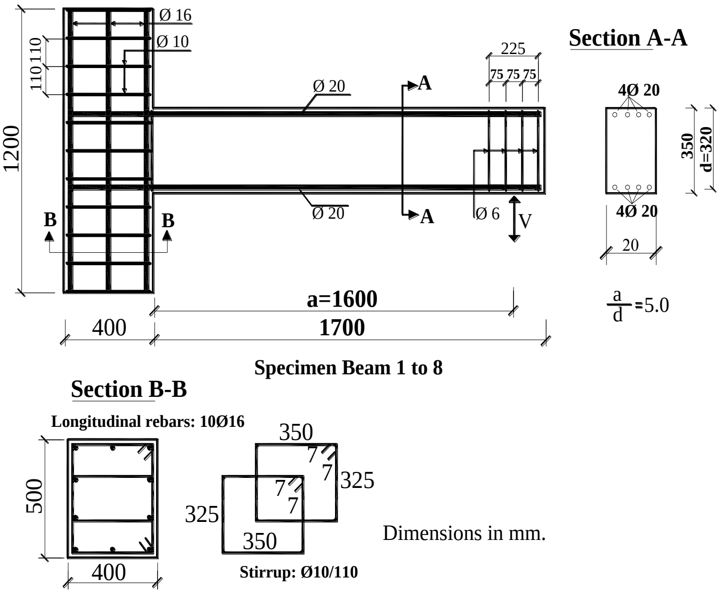

Figure 1: Reinforcement Details of Specimen Beams

The second RC beam specimen "SPEC-2" is strengthened in shear with GFRP NSM bars as shown in Fig. 2. The center-to-center spacing between the NSM GFRP bars was 160 mm.

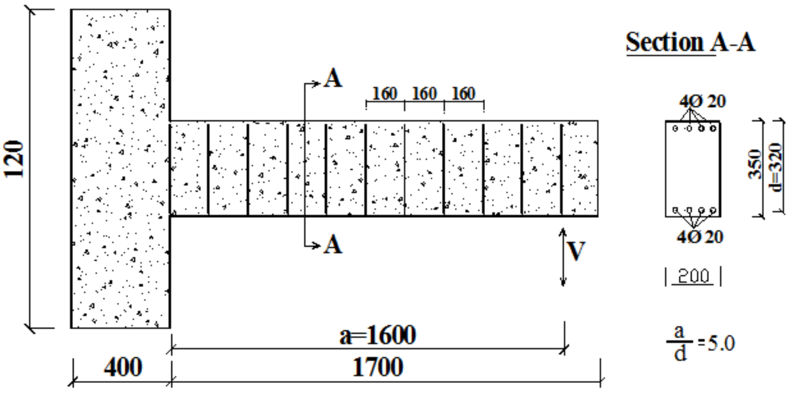

Figure 2: Strengthening scheme used for SPEC-2

3 MATERIALS

The maximum aggregate size in the concrete mix used was 20mm. Four concrete cylinders were casted and tested after 28 days to determine their compressive strengths The average compressive strengths of concrete was 25MPa. Deformed mild steel reinforcement is used and tested in tension to obtain their mechanical properties. The measured elastic modulus and yield strength was 205 GPa and 414 MPa for the longitudinal steel bars and 192 GPa and 275 MPa for the steel shear reinforcement (stirrups), respectively. In addition, coupon tensile tests for the GFRP bars reinforcements were carried out in a serco-controlled test machine. The stress-strain relationships obtained was linear up to failure. The tensile strength and elastic modulus of the GFRP bars were 550MPa and 40.8GPa, respectively. The adhesive (Sikadur®-330) used to bond the GFRP bars was composed of two parts, base and hardener. The direct tensile strength and secant elastic modulus of the epoxy Sikadur®-330 was 30MPa and 3.8GPa, respectively.

4 BONDING PROCEDURE

The sizes of the groove cuts were equal to $1.5d_f$ where d_f is the diameter of the FRP bar. The height of each groove was equal to the height of the beam’s cross section. The strengthening procedure starts by filling half the grooves were with epoxy resin. Then, the GFRP bar was subsequently inserted and gently pressed to ensure that the epoxy flowed around the bar and fill any pores between the rod and sides of the groove. Finally, the beam was left to cure at room temperature for a period of two weeks prior to testing.

5 EXPRIMENTAL SETUP

A loading column was designed as shown in Figs. 1 and 2 to connect to the beam’s free end in order to perform cyclic loading. The loading column contained two hinges, a load cell and a hydraulic jack. The capacities of the hydraulic jack and the load cell were 500 kN and 400kN, respectively. The two specimens were tested under increasingly cyclic loading up to failure. The loads were applied in cycles of loading and unloading and the applied loading history is shown in Fig. 3.

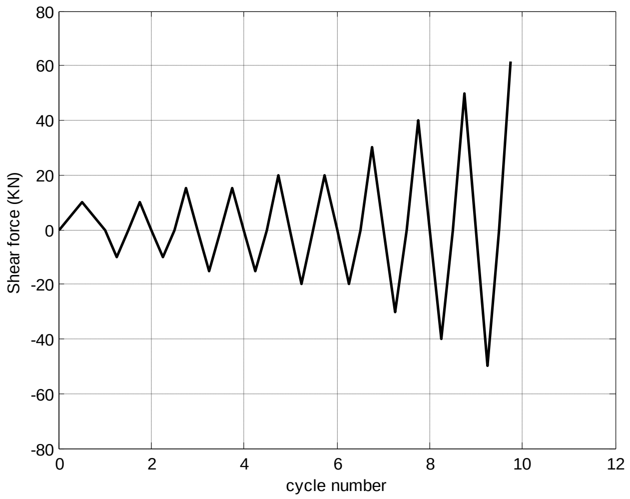

Figure 3: Applied cyclic loading history

6 FINITE ELEMENT MODEL

The developed Finite Element (FE) model has the same geometry, dimensions, material properties, and boundary conditions of the tested beams. The FE model was developed and simulated using the commercial finite element software, ANSYS [9]. Only one half of the tested beam was modeled, due to the symmetry in the transverse direction. Such decision would reduce the overall computational time while maintain the same accuracy. The developed finite element model is shown in Fig. 4.

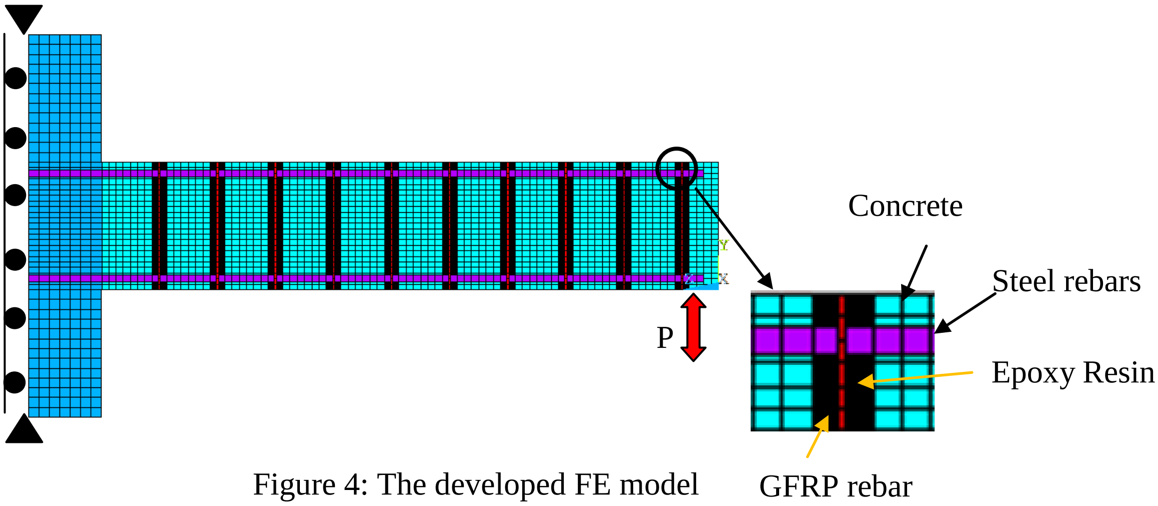

Figure 4: The developed FE model

Both the concrete and epoxy materials were simulated using ANSYS SOLID65 [9] elements. SOLID65 is defined by 8-nodes, each node of has three translational degrees of freedom in the x, y, and z directions and the element is capable of modeling the nonlinear behavior of materials and cracking in tension. The steel and GFRP bars were modeled using LINK8 [9] element. LINK8 is defined by two nodes with three translational degrees of freedom at each node. The element is capable of elastic-plastic deformation, stress stiffening, and large deflection. The rigid concrete column support used in the experimental program didn't observe any cracking during testing and thus was modeled as an elastic material using

SOLID45 [9] elements. Perfect bond assumption is used herein between the longitudinal steel bars and concrete, GFRP bars and epoxy, and epoxy and concrete surfaces.

Table 1 lists the mechanical material properties used in the FE simulation. The nonlinear plastic behavior of concrete in compression is defined using the Hognestad (parabola) model [10]. The William and Warnke [11] model implemented in the concrete constitutive material model in ANSYS [9] is used. The model requires values for the open and closed shear coefficients which typically ranges from 0.0 and 1.0. In this study a value of 0.2 is used for both coefficients. In addition, the constitutive material model for concrete in tension assumes a linear elastic behavior up to the tensile strength of concrete listed in Table 1. The nonlinear response of the steel reinforcement bars is assumed to be linear elastic-perfectly plastic. The Von-Misses failure criterion is used to define yielding of the steel reinforcement. The GFRP reinforcement was modeled as a linear elastic material up to failure. Failure in the FE simulation is defined once divergence in the solution occurs.

Table 1 Material Properties used in the FE simulation

	Compressive strength (MPa)	Yield strength (MPa)	Tensile strength (MPa)	Elastic Modulus (GPa)	Poisson ratio
Concrete	25	-	3.1*	24**	0.20
Steel	-	414	-	200	0.30
GFRP***	-	-	550	40.8	0.28
Epoxy	-	-	30	3.8	0.29

*$f_t = 0.62\sqrt{f_c'}$ in MPa

**$E_x = 4800\sqrt{f_c'}$ in MPa

7 RESULTS AND DISCUSSIONS

The Control specimen "SPEC-1" failed in shear due to a critical shear crack that was developed at a load level of 61.90kN that corresponds to a maximum deflection of 11.69mm. The first crack appeared as a flexural crack for both specimens. The developed flexure cracks propagated through the sides of the beam specimens and caused shear crack propagations. In addition, shear cracks were developed at the unstrengthened part of the strengthened specimen "SPEC-2" between the GFRP bars. As the applied load increased, the shear cracks were propagated until reaching the edges of adjacent epoxy-filled grooves on both sides of the crack. Additional loads caused the development of a major crack that resulted in failure of the specimens. The strengthened specimen failed at a load 92.68kN with a maximum deflection of 22.68mm. Thus, the use of NSM GFRP bars as strengthening materials in shear increased the load carrying capacity of the RC beam by 94% over the control beam.

The measured and predicted load-deflection response envelopes of SPEC-1 and SPEC-2 are shown in Fig. 5. In addition, Fig. 6 shows a comparsion between the predicted and measured load-deflection hysteresis loops. Table 2 draws a comparison between the tested and simulated specimens according to their ultimate load and maximum deflection. It is clear from Figs. 5 and 6 and Table 2 that there is a good agreement between the tested and simulated FE numerical results with a maximum deviation less than 5%.

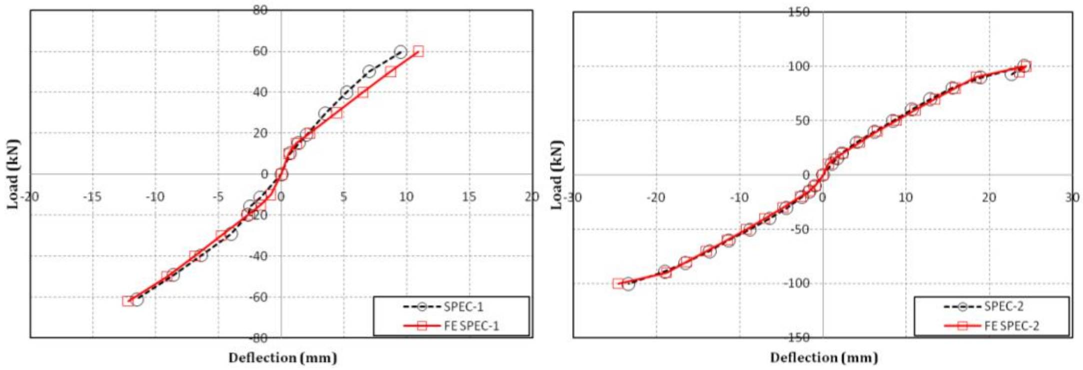

Figure 5: Comparison of the response hysteresis

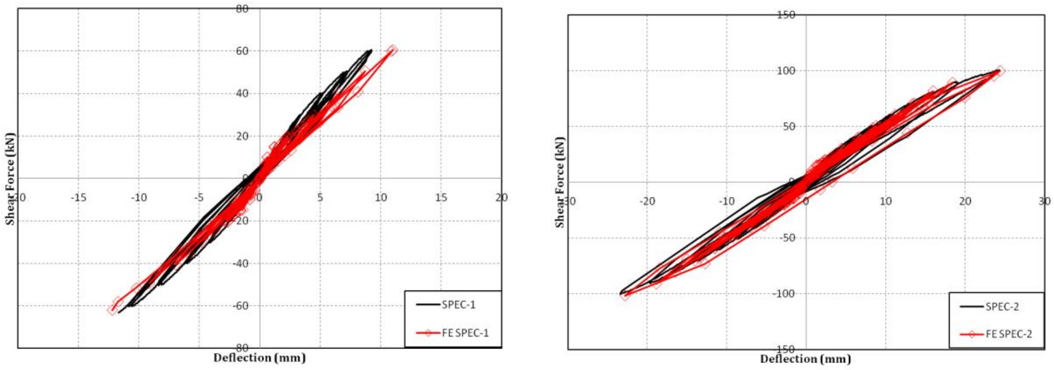

Figure 6: Comparison of the load-deflection envelopes

Table 2 Comparison between the FE predicted and experimental results

Specimen	**FE Model**	**Failure Load (KN)**		**Percentage Difference**	**Maximum Deflection (mm)**		**Percentage Difference**
		Exp.	FE	1-(Exp./FE)	Exp.	FE	1-(Exp./FE)
SPEC-1	FE SPEC-1	-61.90	-62.1	0.3%	-11.69	-12.2	4.2%
SPEC-2	FE SPEC-2	92.68	95.05	2.5%	22.68	23.6	3.9%

7. Summary and Conclusions

This paper presented an experimental and numerical simulation of two shear deficient rectangular RC beams subjected to cyclic loading. The first beam was unstrenghtened to serve as a control specimen, while the second beam was strengthened by means of NSM GFRP bars. The following conclusions can be drawn from the results of this study:

- The use of NSM GFRP bars can enhance the load-carrying capacity of shear deficient RC beams.
- The ultimate obtained load for the strengthened beam was greater than that of the unstrengthened specimen by 94%.

- The developed FE models are in close agreement with the measured experimental data at all stages of loading up to failure.
- The developed and verified finite element model in this study could be used as a valid tool for further investigation of NSM GFRP strengthened RC beams under cyclic loading and as a supplement or alternative to expensive and time consuming experimental testing.

The authors will conduct further experimental testing and numerical validation a future extensive research study to further investigate the performance of such shear deficient RC beams strengthened with NSM reinforcement and subjected to cyclic loading.

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