Numerical Analysis of RC Beams Reinforced with CFRP Rods

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Abstract - Due to the superior characteristics of Carbon Fiber Reinforced Polymer (CFRP) especially corrosion resistance, CFRP rods became the suitable replacement of the conventional steel bars. Based on the rigid body spring method (RBSM) a non-linear numerical model was presented to simulate the flexural behavior of beams reinforced with CFRP rods. The presented model supports the nonlinear constitutive laws for the different materials and nonlinear bond stress-slip relationships for FRP rods-concrete and steel rods-concrete interfaces. The degradation of bond between the different reinforcing materials and concrete due to concrete cracking and loading, unloading and reloading cycles was considered in a simple ways. The presented model was validated by analyzing the previous experimental works to confirm the ability of the proposed model to simulate the experimental observations. An agreement with accepted accuracy between the numerical and the experimental observations were obtained in terms of ultimate carrying capacity, load-deflections behavior, and failure mode, showing the capabilities of the model to evaluate the efficiency of using CFRP rods as internal reinforcement comparing to the traditional steel reinforcement.

Key Words: Numerical Analysis, RC, Beams, CFRP, Rods, Bond Degradation

1. INTRODUCTION

Steel reinforced concrete (RC) structures are subjected to corrosion of the reinforcement. This corrosion induces tensile stresses within the concrete which often leads to degradation of the concrete. Corrosion also reduces the area of reinforcement available to provide strength, thus weakening the structure. Therefore, corrosion leads to deterioration that may progress to failure of the structure. Fiber reinforced polymer (FRP) reinforcing bars do not corrode electrochemically, making this technology an attractive solution for structures in corrosive environments. FRP reinforcing bars have become a preferred alternative to conventional steel reinforcement in new concrete structures due to the superior durability properties of FRP [1]. Recent advances in polymer technology have led to the development of the latest generation of FRP reinforcing-bars [1].

Over the last two decades, a number of studies have been carried out to investigate the flexural response of FRP-reinforced-concrete beams. Some research related to experimental studies of FRP bars in reinforced concrete (RC) structures can be found in [1-6]. A good review of the practical application of FRP rods can be found in [7]. Several Finite Element (FE) models have been developed to simulate the behavior of concrete beams reinforced with steel, carbon, aramid, glass bars [8-13].

2. ANALYTICAL APPROACH

A displacement-controlled nonlinear load-displacement analysis of beams reinforced with CFRP rods is carried out using the pre-developed two-dimensional (2D) rigid body spring method (RBSM) code that was developed by the third author [14-16]. The formulations for the concrete, steel, and CFRP rods of this software package are employed in our analysis. They are described in details in [14-16].

3. CONSTITUTIVE LAWS

3.1 Concrete

The concrete in compression shows the non-linear behavior up to the compressive strength and after the peak the softening branch exists until failure as shown in Fig -1. The hardening behavior up to the compressive strength is modeled as parabolic curve, while a linear softening branch is assumed after the peak-stress. The stress-strain relationships in compression are idealized as were mentioned in Farah and Sato 2011[14].

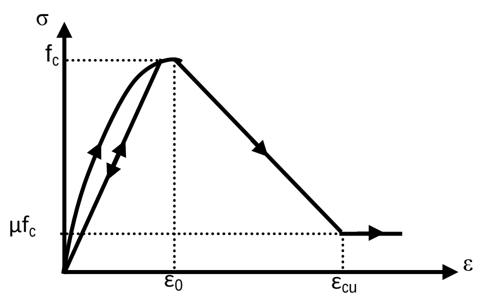

Fig -1: Compression model for concrete[14]

When the tensile stress equals the tensile strength, a transverse crack appears. A fictitious crack model is subsequently used to define the cohesive tensile stresses in concrete as a function of the fictitious crack opening [17]. In a displacement-controlled test, when a new transverse crack appears and grows, partial closure of previously formed cracks may occur. Therefore, both loading and unloading curves are defined, for concrete in tension, as shown in Fig -2.

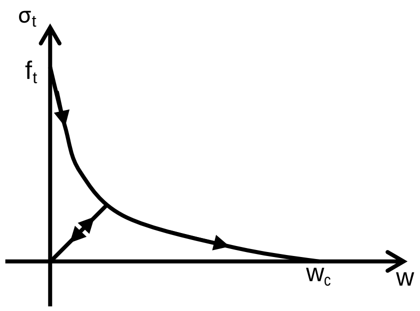

Fig -2: Uni-axial behavior of concrete in tension Reinforcement Material Models [14]

Tangential springs represent the shear transferring mechanism of concrete. The shear strength is assumed to follow the Mohr-Coulomb type criterion with the tension and compression caps [16].

3.2 Steel Bars

The material stress-strain relationship for reinforcement steel bars is modeled as a tri-linear curve, as was proposed in [14] While the FRP rod was modeled as linear relationship up to the FRP rupture.

3.3 Bond Stress-Slip Model for Steel Bar Reinforcement-Concrete Interface

The behavior of the bond between the steel bar and concrete is modeled by adapting the bond stress-strain-slip relationship proposed by Farah and Sato 2011[14] with loading, unloading and reloading paths. Also the bond deterioration of the steel-concrete bond due to cyclic loading was considered by reducing the bond strength as shown in Fig -3.

The effect of concrete cracking that causes bond deterioration takes place in steel bar-concrete zones. The bond deterioration mechanism is emphasized in several studies [14]. To consider this influence, the behavior of the bond between the steel bar and concrete is modeled by adapting the bond deterioration model proposed by Farah and Sato 2011[14] as shown in Fig -4.

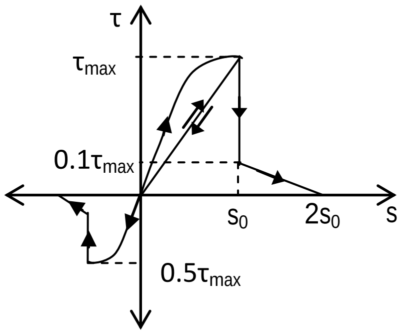

Fig -3: Bond stress-strain slip model for steel bar-concrete interface [14]

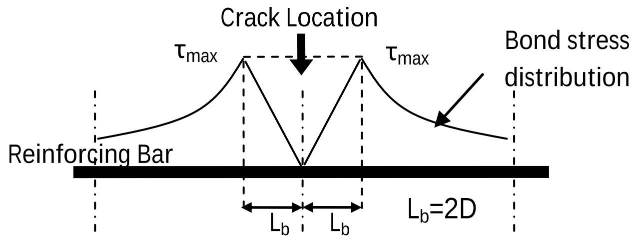

Fig -4: Bond deterioration model for steel-concrete interface close to cracks [14]

3.4 Bond Stress-Slip Model for FRP Rod Reinforcement-Concrete Interface.

In this study the modified BPE model was applied [18] to model the FRP rod-concrete interface. The effect of surface treatment on bond strength is considered in this model. As discussed in the case of a steel-concrete interface, cyclic laws for the CFRP Rods-concrete interface are required since. The simplified un-loading and re-loading paths were applied here. The reversed slip phenomenon is considered a factor in determining FRP Rods-concrete bond properties deterioration. This phenomenon is considered here.

4. EXPERIMENTAL EVIDENCE

The experiments reported by Rafi et al. 2007 [6] are used as experimental evidence to validate the proposed analysis method and models. The experimental program is described and discussed in detail by Rafi et al. 2007[6]. The details of the tested beams shown in Fig-5. Duplicate steel and CFRP reinforced beams were tested in bending. Each individual beam was 2000 mm long with a rectangular cross section of 120×200 mm. These were reinforced with two longitudinal bars on the tension face (CFRP bars for FRP reinforced beams (BRC) and steel bars for steel reinforced beams (BRS)) [6].

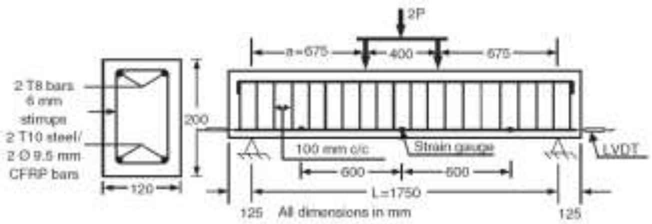

Fig -5: Details of the experimental evidence beams [6]

5. NUMERICAL MODEL

Fig -6 shows the numerical model of the analyzed beams. The concrete material is divided into a number of continuum elements with average size about 16.0 mm by applying random geometry by using a Voronoi diagram. The internal steel bars and CFRP rods reinforcement are divided into a number of beam elements with an average size of 12.0 mm. The boundary conditions of the test are shown in Fig -7. The loading is statically displacement controlled, and is applied as four points bending test.

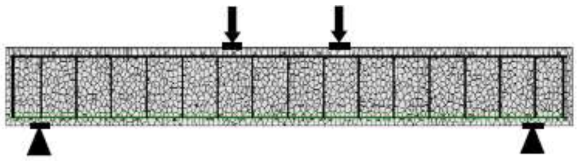

Fig -6: Numerical Model of The Tested Beams

6. NUMERICAL RESULTS AND DISCUSSION

6.1 Cracking Load and Ultimate Load Carrying Capacities.

The comparisons between the RBSM numerical predictions and the average experimental results for the duplicated specimens, in terms of the cracking load and the ultimate load carrying capacities are summarized in Table 1. The ratio of the numerical-to-experimental load capacity is given for each beam. As seen from Table1, there is an accepted agreement between the numerically predicted load capacities and the experimental results for all the test specimens. The average numerical-to experimental cracking load ratio is 103%. The average numerical-to experimental ultimate load ratio is 103%. Table 1 shows the average cracking loads of the beams reinforced with steel bars (BRS) plus beams reinforced with CFRP rods (BRC). It can be seen that the cracking loads for both types of beams are very close to each other, as can be expected where the cracking load depends mainly on the concrete tensile strength. The ultimate load carried for the beams is also shown in Table 1 where it can be noted that the BRC beams carried more than twice the load on the BRS beams. This was due to strength of CFRP rods, which was much higher than the yield strength of a steel bar.

6.2 Failure Modes.

The BRC beams were designed as over-reinforced using reinforcement ratio (0.0070) greater than the balanced reinforcement ratio (0.0032). The BRS beams were under-reinforced beams having reinforcement ratio (0.0077) less than the balanced reinforcement ratio (0.0277). A compression failure for the BRC beams those were reinforced with CFRP rods and a tension failure for the BRS beams reinforced with the traditional steel can be expected during their testing. The observed modes of failure of all beams are presented in Table 1. For all the test specimens, the RBSM analyses accurately predict the mode of failure observed in the experiments. The BRS beams failed by the crushing of concrete after the tension reinforcement yielded while the BRC beams failed in compression.

Table 1 Comparison between the numerical and experimental results

Beam	Cracking load (kN)		Num/Exp (%)	Failure load (kN)		Num/Exp (%)	Failure mode	
	Exp	Num		Exp	Num		Exp	Num
BRS	7.65	7.8	102	41.0	43	105	Steel yielding	Steel yielding
BRC	7.1	7.5	105	87.7	90	102	compression	compression

6.3 Deformational Characteristics

The results shown in Fig -7 refer to comparisons between the numerical RBSM results and experimental results for the tested beams. The comparisons are made in terms of load– deflection relationships for both the CFRP-reinforced (BRC) and the steel reinforced control specimens (BRS). The recorded deflection behavior of the beams is traced in Fig. -7. The initial linear part of the curves has a very steep slope, which corresponds to the un-cracked condition of these beams. In this region the deflection is proportional to the applied load and the entire concrete section is considered effective in resisting the loads. As can be seen from Fig -7, the behavior of both types of beams is similar before cracking when beams are stiff. The end point of this linear part is an indication of the initiation of cracking in the beam.

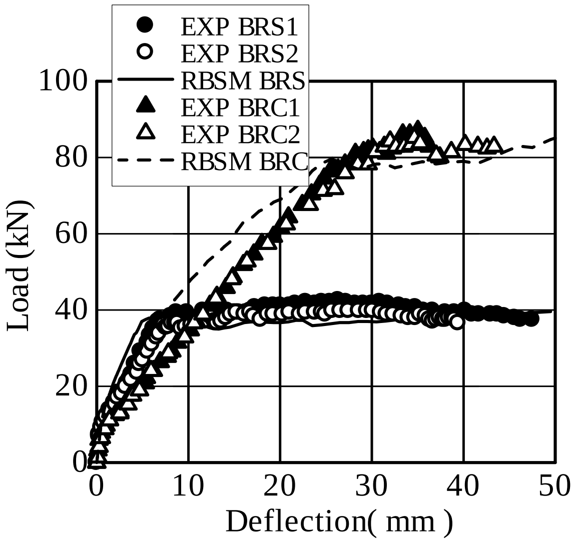

Fig -7. Load – Deflection Relationships

The results shown in Fig -7 refer to comparisons between the numerical RBSM results and experimental results for the tested beams. The comparisons are made in terms of load– deflection relationships for both the CFRP-reinforced (BRC) and the steel reinforced control specimens (BRS). The recorded deflection behavior of the beams is traced in Fig. -7. The initial linear part of the curves has a very steep slope, which corresponds to the un-cracked condition of these beams. In this region the deflection is proportional to the applied load and the entire concrete section is considered effective in resisting the loads. As can be seen from Fig -7, the behavior of both types of beams is similar before cracking when beams are stiff. The end point of this linear part is an indication of the initiation of cracking in the beam.

The next segment that immediately follows this linear part provides information about the bond quality and tension stiffening effects due to crack spacing. The slope of this part is smaller than the slope of the initial linear segment. This shows that the rate of deflection per unit load is higher after the beam has cracked, which is an indication of the reduction in the stiffness of the cracked beam. Stiffness here is defined as load per unit deflection. However it can be seen from the widening of the gap between the BRS and BRC curves in Fig -7 that the rate of reduction in the stiffness of BRC beams became higher with the increase in the applied load. The last part of the curve is an indication of possible failure mechanism of the structure. As shown in Fig -7, both BRS beams showed a very ductile behavior and both beams failed at nearly the same load after undergoing considerable deformation with very small increase in the load once steel yielded. The ultimate load of the BRS beams was around 53% lower than the BRC beams.

7. CONCLUSION

In this paper, numerical results from displacement-controlled RBSM analyses have been presented and compared to experimental data beams reinforced with CFRP rods in addition to beams reinforced with the traditional steel reinforcement. In the analyses, suitable different materials constitutive laws were applied plus suitable interface elements to utilized the CFRP and steel reinforcement / concrete interfacial behaviors. The RBSM models predicted the cracking load and the ultimate load carrying capacities with an average numerical-to-experimental ratio, 103%. The proposed model could simulate the different failure modes ranging from the conventional failure modes such as concrete crushing after steel yielding and compression failure mode.

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