A Finite Element Model to Study the Behaviour of Corroded Reinforced Concrete Beams Repaired with Near Surface Mounted technique

B. Almassri, F. Almahmoud, R. Francois

Abstract— Near surface mounted reinforcement (NSM) technique is one of the promising techniques used nowadays to strengthen reinforced concrete (RC) structures. In the NSM technique, the Carbon Fibre Reinforced Polymer (CFRP) rods are placed inside pre-cut grooves and are bonded to the concrete with epoxy adhesive. This paper studies the non-classical mode of failure “the separation of concrete cover” according to experimental and numerical FE modelling results. Experimental results and numerical modelling results of a 3D finite element (FE) model using the commercial software Abaqus and 2D FE model FEMIX were obtained on two beams, one corroded (25 years of corrosion procedure) and one control (A1CL3-R and A1T-R) were each repaired in bending using NSM CFRP rod and were then tested up to failure. The results showed that the NSM technique increased the overall capacity of control and corroded beams despite a non-classical mode of failure with separation of the concrete cover occurring in the corroded beam due to damage induced by corrosion. Another FE model used external steel stirrups around the repaired corroded beam A1CL3-R which failed with the separation of concrete cover, this model showed a change in the mode of failure form a non-classical mode of failure by the separation of concrete cover to the same mode of failure of the repaired control beam by the crushing of compressed concrete.

Keywords— corrosion, repair, RC beams, NSM rods, failure mode, FEM, FEMIX, ABAQUS

1. Introduction

Corrosion of reinforcing steel is still a very important area of study for reinforced concrete structures as the cost induced by repairs to corroded RC structures world-wide exceeds millions of dollars each year (1). Much research has been conducted to assess the damage to corroded RC structures. (2–4) presented such damage, starting from the reduction of cross sectional area of the steel and reduction of its ductility and ending with cracking and bonding problems in the RC elements, which lead to the early failure of structures.

The near surface mounted reinforcement (NSM) technique is one of the most promising techniques used nowadays for strengthening deteriorated structures. In the NSM technique, the Carbon Fibre Reinforced Polymer (CFRP) rods are placed inside pre-cut grooves and are bonded to the concrete with epoxy adhesive. (5–8) have shown that the NSM strengthened members can be expected to be much more ductile than externally-bonded-laminate (EBR) strengthened members and fail at much higher strain levels. De Lorenzis and Teng (9) showed also some of the advantages of the NSM technique over the EBR strengthening technique, Bilotta et al. (10) showed that the tensile strength of FRP material used in the NSM technique was well exploited and debonding was delayed compared to the EBR technique.

Kreit et al. (11) and Al-Mahmoud et al. (12) showed that the use of NSM reinforcement could significantly increase the flexural performance of the RC beams, and Almassri et al. (13) showed that the NSM technique also restored sufficient ductility despite the ductility loss of steel bars induced by corrosion. Hawileh (14), presented an FE model that predicted the ultimate capacity of RC beams. It showed that the diameter of the FRP reinforcement rod had an important effect on the stiffness and the ultimate capacity of the RC beams strengthened with NSM.

The computer code FEMIX has been used by several researchers to simulate RC beams strengthened with NSM strips. Sena Cruz et al. (15) showed that the epoxy adhesive had a negligible effect on the global behaviour and the crack pattern and load-deflection curves obtained numerically in this study matched the experimental results.

The present paper studies the performance of two RC beams: one corroded and one control (non-corroded) repaired in bending with the NSM CFRP rod technique. All beams were tested statically in three-point loading up to failure. The failure modes, and the ultimate and the yield moment capacities for all beams were studied. An FE model for all RC beams was created using the computer code FEMIX, and the moment-deflection curves and the modes of failure were compared to the experimental results. A non-classical mode of failure was found both experimentally and in the FE model and it was investigated using another FE model which used external steel stirrups which changed the mode of failure to a classical one by the crushing of the compressed concrete.

2. Experimental programme and materials properties

2.1 Experimental model

An experimental programme was started at LMDC (Laboratory of Materials and Durability of Constructions) in 1984 with the aim of understanding the effects of steel corrosion on the structural behaviour of RC elements. Many experimental studies have been conducted on those beams to evaluate the development of corrosion cracking, to measure chloride content.

The two beams studied in this paper were of the same type (the same size and shape of reinforcement but different values of service loading). One corroded beam (A1CL3-R) and one

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control beam (A1T-R) were both repaired with one 6-mm-diameter CFRP rod and tested in bending by (13). The layout of the reinforcement is shown in Figure 1.

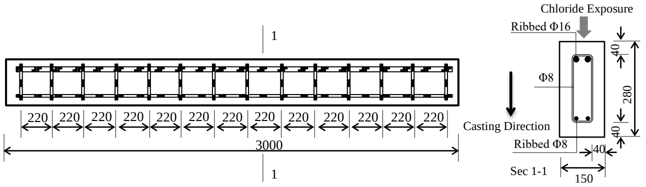


Figure 1 Reinforcement layout of type A beams. Dimensions are in mm

2.2 Concrete, CFRP, Epoxy and Steel bars properties

Table 1 shows the results of the core tests for the two beams studied in this paper,

Table 1 Mechanical characteristics of the concrete at 27 years (average values of 3 tests)

Mechanical characteristics	A1CL3-R	A1T-R
Compression strength (MPa)	62.2	58.9
Tensile strength (MPa)	6.85	6
Elastic modulus (MPa)	34 000	30 000

Table 2 shows the average values of steel bar properties and Table 3 and 4 show the properties of CFRP rods and epoxy adhesive respectively.

Table 2 Average values of steel bar properties

Specimen Type	Young's modulus (GPa)	Yield Strength (MPa)	Ultimate Strength (MPa)
Corroded specimen	200	550	604
Non-corroded specimen	200	550	645

Table 3 CFRP rod characteristics.

Type of test	Ultimate strength (MPa)	Modulus of Elasticity (MPa)
Manufacturer's test	2300	150000
Laboratory test	1875	145900

Table 4 Filling material properties

Material	Compressive Strength (MPa)	Tensile Strength (MPa)	Elastic Modulus (MPa)
Epoxy	83	29.5	4900

Figure 2 shows the experimental tensile stress-strain curves for corroded steel bars, non-corroded steel bars and CFRP rods.

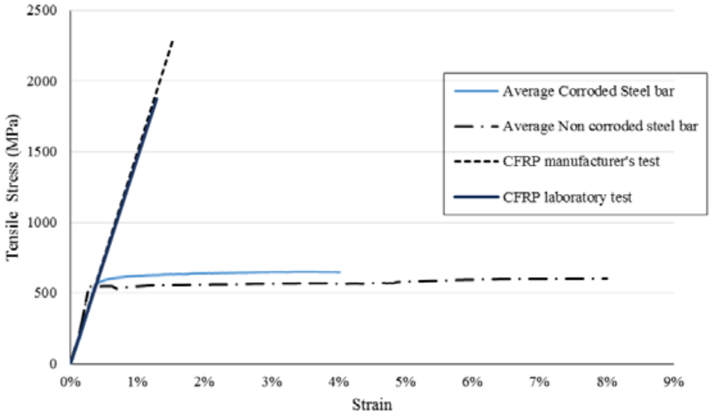
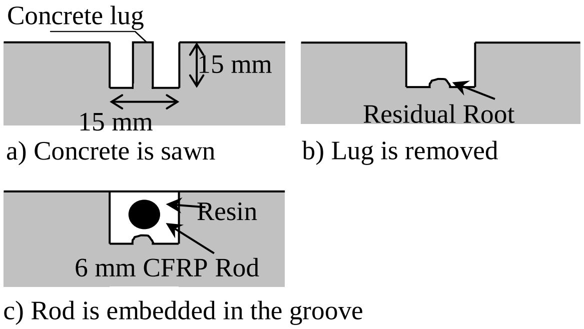


Figure 2 Tensile stress-strain curves for steel and CFRP rods (Corroded and control steel bar curves are average results of 2 tested specimens in each case)

2.3 NSM Technique

The NSM CFRP rod was installed in the corroded beam A1CL3-R and in the control beam A1T-R by making two cuts in the concrete cover in the longitudinal direction at the tension side. A special concrete saw with a diamond blade was used. The groove was 15 mm deep (only 20 mm of concrete cover for beams) and 15 mm wide (around 2.5 times the rod diameter)



a) Concrete is sawn
b) Lug is removed
c) Rod is embedded in the groove

Figure 3 Installation of CFRP rod in concrete surface

The two beams were tested 1 week after the installation of the CFRP rod in order to ensure the maximum degree of adhesion between the concrete surface and the epoxy resin material. Figure 4 shows the concrete surfaces of the RC beams after the installation the CFRP rods.

a. A1T Control Beam b. A1CL3 Corroded Beam

Figure 4 Concrete surfaces after installation of the CFRP rod.

3. Experimental results

The two repaired beams A1CL3-R and A1T-R were tested with 3-point loading up to failure. Figure 5 shows the bending moment versus the deflection for the two beams.

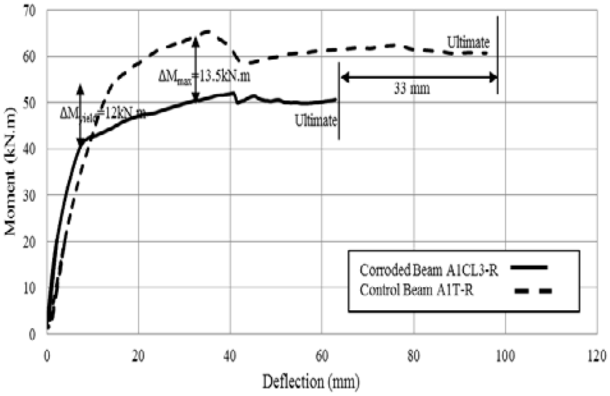


Figure 5 Moment-deflection curves for beams A1CL3-R and A1T-R tested experimentally

4. FE numerical model

FEMIX 4.0 is a computer code that has the ability to analyse structures by using the Finite Element Method (FEM). FEMIX code is integrated with GiD interface software which provides pre- and post-processing for numerical simulations analysis. FEMIX is based on the displacement method; it has a large number of types of finite elements inside, such as 3D frames and trusses, plane stress elements, flat or curved elements for shells, and 3D solid elements. Linear elements may have two or three nodes while plane stress elements may have 4, 8 or 9 nodes and 8 or 20 hexahedral nodes. Embedded line elements can be included in the analysis with the availability of static or dynamic tests using both linear and non-linear material configurations. Advanced numerical techniques are available, such as the Newton-Raphson method combined with arc-length techniques and path dependent or independent algorithms. Table 5 shows the concrete properties used in the FE numerical model.

Table 5 concrete properties used in FEMIX simulation analysis

Poisson's ratio	$v_c = 0.20$
Initial Young's modulus	$E_c = 30\,000$ N/mm^2
Compressive strength	$f_c = 60$ N/mm^2
Tri-linear tensile-softening diagram	$f_{ct} = 4.5$ N/mm^2 , $G_f' = 0.09$ N/mm $\xi_1 = 0.005$, $\alpha_1 = 0.5$, $\xi_2 = 0.3$, $\alpha_2 = 0.2$
Parameter defining the mode I fracture energy available to the new crack	$P_2 = 1$
Threshold angle	$\alpha_{th} = 30^o$

4.4 Modelling of RC beams

The objective of this part is to create a reliable numerical model that can simulate and predict the global behaviour of five RC beams and analyse the NSM strengthening effect in bending. To simulate the concrete in the beams, 8-node plane stress elements with 3×3 Gauss-Legendre integration were used. The steel bars and stirrup reinforcements, and the CFRP rods, were simulated using 3-node quadratic embedded cable elements with two Gauss-Legendre integration points. For this point, the steel bars and stirrups, as well as the CFRP rods, were assumed to be fully bonded with the concrete. Figures 6 shows the geometry, elements mesh, loading and support configuration.

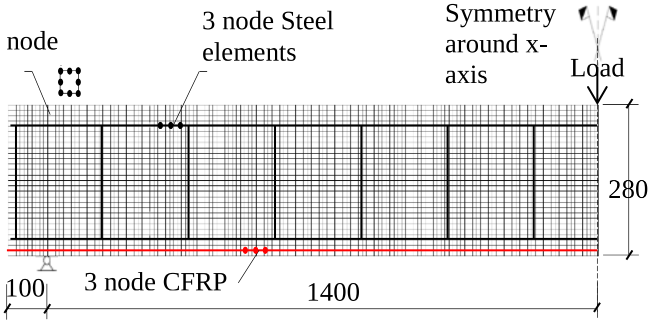
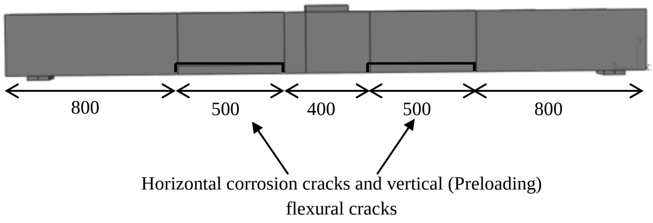


Figure 6 Geometry in (mm), mesh, loading and support conditions for non-strengthened beams with NSM CFRP

4.1 FE numerical model results

In order to simulate the corrosion interface between steel bars and concrete, the crack tool was used to simulate the corrosion the corroded repaired RC beam A1CL3-R as shown in the following figure.



Horizontal corrosion cracks and vertical (Preloading) flexural cracks

Figure 7 A1CL3-R corrosion cracks

The stress strain curves between experimental and FE numerical model were potted together and the model showed a satisfactory results.

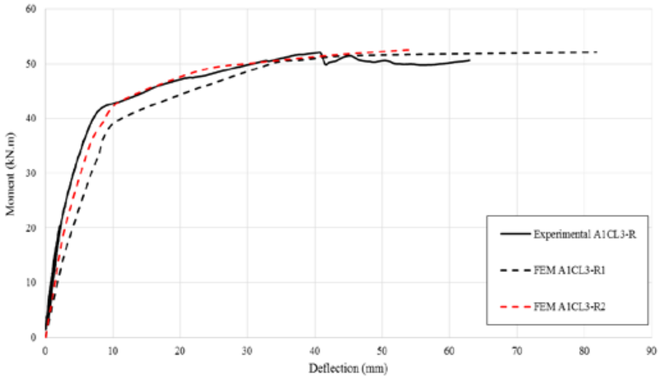


Figure 8 Stress- Strain curves A1CL3-R

Two different FE models were implemented using the computer code in order to simulate the A1CL3-R beam before and after using the external steel stirrups, in figure 8, the A1CL3-R1 (red line) shows the deflection curve before using the stirrups which showed more compatibility with the experimental one than the A1CL3-R2 without using the steel stirrups, moreover the failure modes were changed from the separation of concrete cover to the crushing of the compressed concrete as shown in the following section.

5. Failure modes

Figure 9 shows both experimental and FE results of the failure mode of RC beam before using the steel stirrup which happened due to the separation of concrete cover

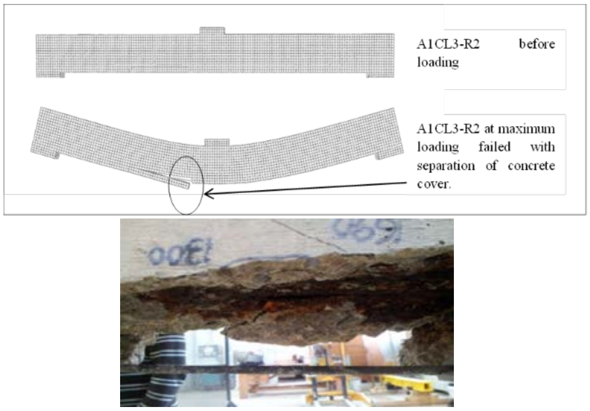
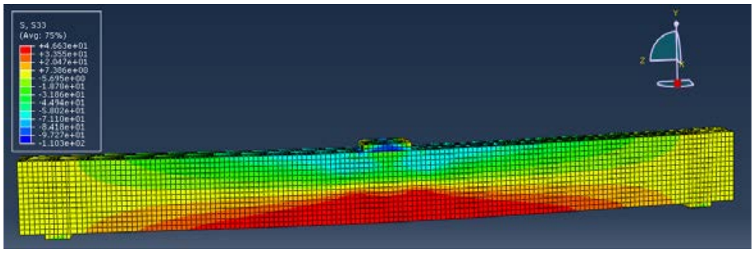


Figure 9 Failure modes of A1CL3-R

Figure 10 shows FE results of the failure mode of RC beam after using the steel stirrup which happened due to the crushing of the compressed concrete.



6. Conclusions

According to the findings of this paper, the following points can be concluded:

1. The damage induced by corrosion modifies the flexural response of repaired corroded beam and lead to a new non-conventional failure mode by separation of concrete cover in the plane defined by corrosion cracks.
2. NSM technique used to repaired corroded RC elements allow to restore a significant ductility by avoiding premature failure of tensile bars at pit location, nevertheless, the presence of cracks induced by corrosion coincident to the tensile reinforcement induced a new premature failure mode.
3. Using External steel stirrups along with the NSM as a repair technique for the corroded RC beams using the CFRP rods can change the mode of failure modes of these beams.

Acknowledgements

The authors wish to acknowledge the support provided by Professor Joaquim Barros and his structural composites group in the civil engineering department of the University of Minho, Guimaraes, Portugal.

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