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On the Retrofitting of Full Scale Pre-Damaged RC Columns Using Externally Bonded Carbon Sheets: NLFEM Local Approach

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Abstract:

Repair and rehabilitation of reinforced concrete (RC) structures by external bonding of composite materials have shown significant and promising advantages to restore the mechanical performances. Indeed, recent researches focused on the behavior of RC columns under static and dynamic monotonic loading have provided that the most damaged and collapsed zones were the top and the footing of the columns. In this regards, the aim of the present contribution is to propose a nonlinear finite element model (NLFEM) to predict the response of pre-damaged columns rehabilitated by external and partial bonding of carbon fibers reinforced polymer (CFRP) sheets under lateral loads. The reinforcement is carried out according to the failure rods in order to optimize the initial damage rate and the CFRP reinforcement. The main obtained results show that total confinement can restore the load-bearing capacity of a damaged column with 30%, while partial confinement can restore the load-bearing capacity of a 15% damaged columns.

Keywords — **Pre-damaged RC columns, CFRP retrofitting, NLFEM, Stiffness recovery.**

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I. INTRODUCTION

Recent researches on the behavior of reinforced concrete columns under static, monotonic and dynamic loading have shown that the most stressed, and even damaged zones are the columns tops and bases footing [1-3]. In this connection, repair and rehabilitation of RC structures by external bonding and integration of composites has shown promising issues to restore mechanical performance [4-10].

Therefore, Xie et al [5] discussed the assessment of the seismic behavior of reinforced concrete structures and the benefits of local strengthening with FRP. The authors have developed a model to describe the nonlinear behavior of RC columns under horizontal loading. Wang et al [11] proposed a technique for near-surface reinforcement using aluminium alloy bars and carbon-fiber reinforced polymer (CFRP) to improve the seismic behavior of reinforced concrete columns. In addition, Huang et al [12] studied the effect of axial compression ratio, torsion-flexion ratio and eccentricity on the mechanical performance of FRP strengthened RC columns under combined loads, the authors proposed a new design of reinforcement. In the same context, Djenad et al [13] introduced a new honeycomb fiberglass stirrups as internal reinforcement technique based on the incorporation of hexagonal honeycomb-shaped fiberglass inside the RC columns.

However, the scientific literature offers few contributions about the initially damaged RC members. Ali Ahmed et al [14] experimentally investigated the behavior and accuracy of pre-damaged concrete columns externally repaired with composite spiral under centred compression. Also, Ait Taleb et al [15, 16] proposed a modelling approach to assess the rupture response of pre-damaged reinforced concrete members retrofitted with bonded and wrapped FRP sheets.

Accordingly, the present work consists in proposing a numerical model to predict the response of pre-damaged and rehabilitated columns with externally bonded carbon fiber strips (CFRP) under lateral loads. The FRP reinforcement is carried out according to the failure rods, with and initial damage rate and reinforcement design. Numerical simulations are established under ABAQUS [17] for full-scale RC columns under lateral monotonic loading. The post-elastic behavior of all used materials is modelled using plasticity coupled with damage theory. The main obtained results emphasized in terms of capacity curves and damages maps show that CFRP confinement can restore the load-bearing capacity of a damaged column with around of 30% of the undamaged RC columns without reinforcement.

II. FINITE ELEMENT SIMULATION

The present numerical work involves assessing the performance and studying the behavior of RC columns under horizontal loading. The main objective is to optimize the characteristics of the FRP strips, which improve the column's strength the successive appearance of cracks at critical sections.

The various steps of the modelling in accordance with recent published works of [18-22] are detailed in the sections below. The geometric model and the selection of finite element models for the mesh are generated in three-dimensional (3D) space taking into account the experimental behavior of the component materials. The interaction of separated elements, as well as the assembly and loading steps are also presented.

A. *Geometrical model generation*

A full scale RC column designed and experimented by Xie et al [5], subjected to horizontal loading was simulated. The modelled column illustrated in Fig. 1, present the following characteristics: Total column height 2548 *mm*; footing length 2100 *mm*, cross-section 500*500 mm^2 and footing cross-section 700*900 mm^2.

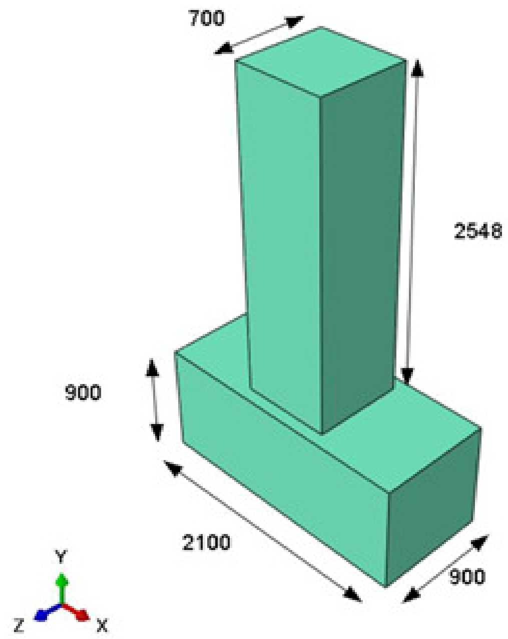

Fig. 1 Generated geometric model for the simulation of the RC column tested by Xie et al [5].

The steel reinforcement of the columns was ensured with 12T28 mm longitudinal bars and 3 stirrups T14 mm. The footing is reinforced with 10T28 mm longitudinal bars and 4 stirrups T14 mm. Fig. 2 depicts the steel reinforcement detail of the columns and the loading setup and application of boundary conditions procedure.

a) b)

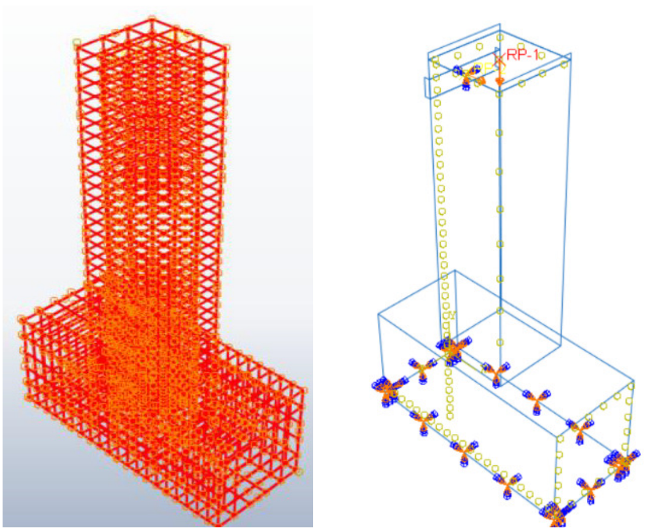

Fig. 2 Generated geometric model for the simulation of the RC column: a) Steel reinforcement details, b) Loading and BC application.

B. Materials models implementation

Concrete Damaged Plasticity numerical model is used in the simulation to moded concrete response. It is a coupled model with plasticity and damage including irreversible deformations, mainly intended for a general analysis capability of concrete structures under cyclic and/or dynamic loading. Plasticity theory is used to describe the irreversible nature of deformations ε_{pl}. The partition of total deformation ε is made into an elastic and a plastic part. Elastic ε_{el} deformations involve so-called reversible elastic energy, which is therefore restored during any discharge, while plastic εpl deformations lead to the dissipation of irreversible energy.

TABLE I
CONCRETE MODEL PARAMETERS

Parameter	Dilatation angle (°)	Crack energy ratio	Compressive strength (MPa)	Young Modulus (MPa)
Undamaged concrete	30	25	29.5	36000
Damaged concrete	20	30	22.5	22400

The main parameters to be carefully defined are: the stress-strain law to calculate strain-hardening values, which corresponds to the experimental model of Xiu et al [5]. The parameters of the numerical concrete model are shown in Table I.

Steel is described by an elasto-plastic behavior with identical compression and tensile strain-hardening. The parameters of the numerical model of the used steel are Young's modulus E_s= 203000 MPa, Poison's ratio of 0.3 and 7.2e-06 Kg/m^3 density.

Composite materials have a particular behavior, which is essentially due to two factors: the first one results from their anisotropic behavior in the elementary layers, and the second derives from layering, which consists in the stacking of several layers. The parameters of the numerical CFRP strip model used in this study are shown in Table II.

TABLE II
CFRP MODEL PARAMETER

Elasticity modulus Mpa)	**E1**	**E2**	**Nu12**	**G12**	**G13**
	130000	15000	0.25	7700	7700
Fail stress (MPa)	**X1**	**X2**	**Y1**	**Y2**	**S**
	3500	1600	2500	670	235

C. FEM and calulation procedure

The use of coarse meshes may reduce the accuracy of the simulation. In particular, numerical modeling overestimate the axial strength of the columns. Acordingly, the results of the performed convergence study suggest that an appropriate mesh with the size of 30 *mm* for concrete column. GFRP and stell reinforcement were meshed uniformly, with an approximate size of 20 mm and 50 *mm* respectively. The meshing of the CFRP reinforcement strips is provided in Fig. 3.

Three spcimens are simulated namely: reinforced concrete RC colomns with CFRP stregheing, patialy CFRP strenghetehend RC columns (PCRC) and totally confned RC columns (TCRC). It is to notice that for each spicimen group, damaged and non damaged conrete is considered. Dynamic explicit calculation step was used for more acuracy and reduced calcul-time with a period of 1 s, determined by verifying the energy criterion for the static load

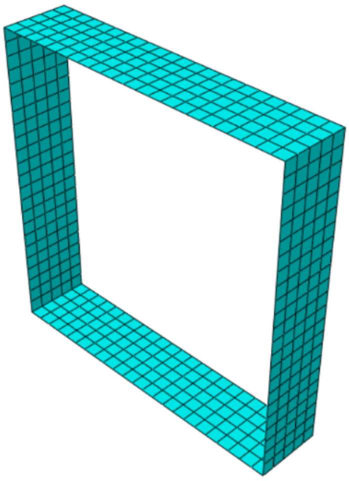

Fig. 3 Meshing of the CFRP reinforcement strips.

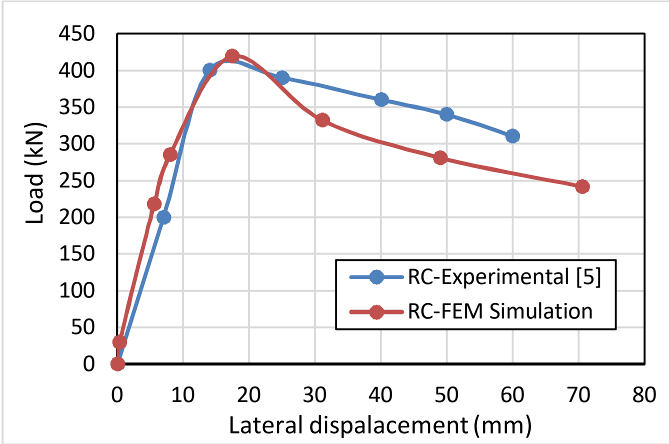

Fig. 4 Proposed FEM capacity curve comparison with RC column tested by Xie et al [5].

In addition, contact definition was intodduced between each part and introduces the first assumptions concerning contacts, stresses and possible connections. Perfect contact between steel and concrete, defined as “Embedded region”, which means including the reinforcement in the concrete block and having an almost homogeneous material. Surface contact between concrete and GFRP strips with TIE option is used, which considers a near-perfect bond between the two selected surfaces.

However, a momotonic horizontal load is applied at the collum top and the fotting is fully encastred (Fig. 2a).

III. RESULTS ANS COMMENTS

Simulation results emphasized for both global and local behavior are presented and discussed using the capacity curves and the damages maps and evolution. The gain in terms of lateral currying capacity was quantified to highlight stiffness losses and CFRP contributions.

A. Model validation and calibration

In order to check the reliability of the numerical procedure, the simulation predictions of the behavior of the studied structures are quantitatively compared with the experimental observations of Xie et al [5]. Fig. 4 shows the evolution of applied external loading as a function of horizontal displacement up to failure for RC specimens.

Numerical simulation FEM curve shows a good correspondence with the experimental one of Xie et al [5]. The load-bearing capacity values are significantly correlated for the reinforced concrete column, the simulation gives a maximum load of 418.92 kN, while the test gives an average load-bearing capacity of around 400 kN. For the displacement, the simulation gives a maximum value of 70.57 mm, while the measured one is 60.24 mm. Indeed, a satisfactory agreement is observed in terms of load and displacement.

B. Currying capacity curves

Fig. 5 and 6 show the load-bearing capacities of the different studied variants in the form of a lateral force vs. displacement graph both undamaged and damaged concrete respectively. The parameters controlling the values of the concrete damage variables are summarized in Table II.

Analysis of the results clearly shows the improvement in strength of the RC columns strengthened with CFPR-strip compared to RC ones, which represents a force of 509.76 kN and a maximum displacement of 85.84 mm. The pre-damaged RC column achieves a maximum force of 371.93 kN and a maximum displacement of 48.95mm, with a force contribution force contribution of 7.85% and displacement of 44.26 %.

As resistance decreases consistently, the correlation of strength decreasing is strongly related to the percentage of damage as shown in Fig. 7.

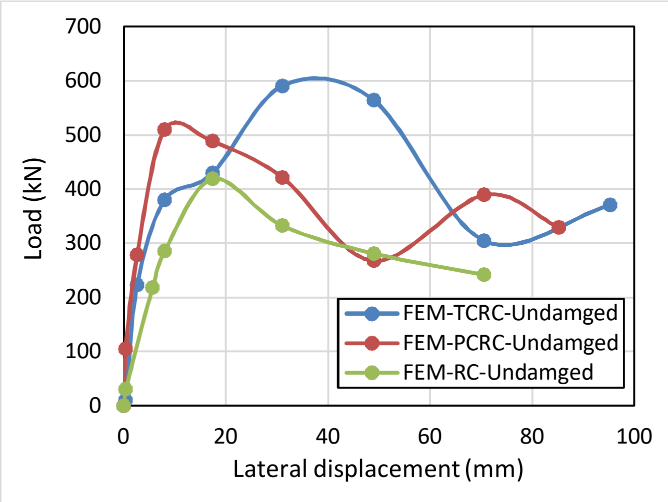

Fig. 5 Proposed FEM capacity curves for undamaged concrete specimens

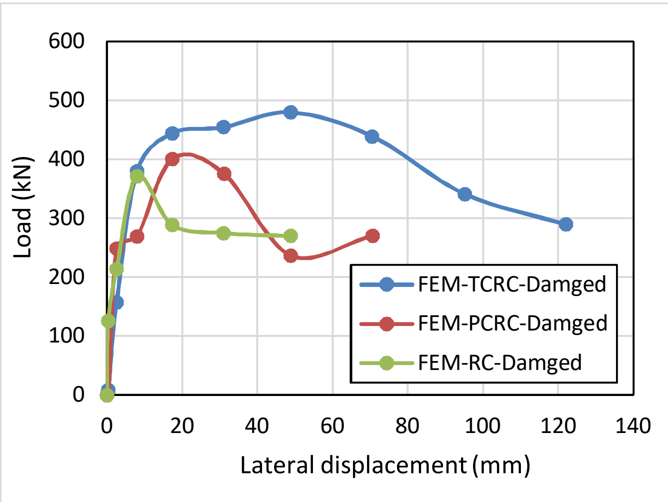

Fig. 6 Proposed FEM capacity curves for pre-damaged concrete specimens

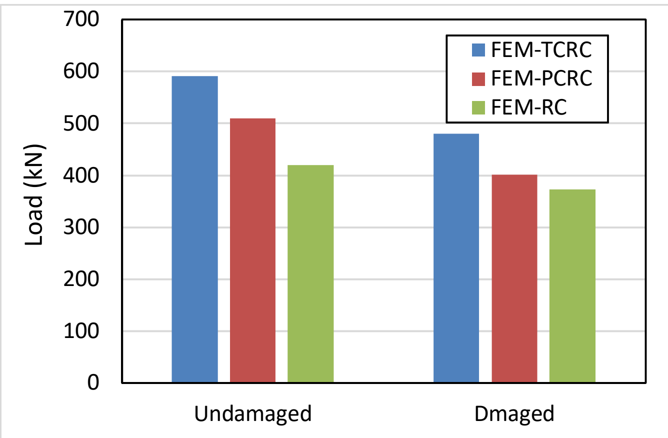

Fig. 7 Ultimate loads comparison of all simulated specimens

In other words, as damage ratios increase, a proportional decrease in resistance is observed, which translates into a significant increase in the percentage of damage. This observation underlines the crucial importance of damages in understanding the damage effect on the response of the columns.

C. Damages evaluation

Fig. 8 and 9 show the damages concentration and localization for RC and PCRC specimens respectively. The pre-damage in concrete leads to a decrease in strength for each type of specimen.

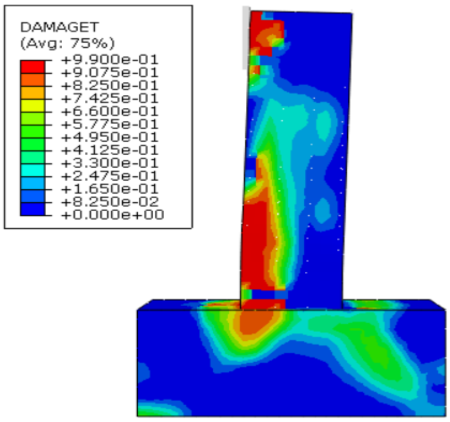

Fig. 8 Damages localisation for the simulated RC columns.

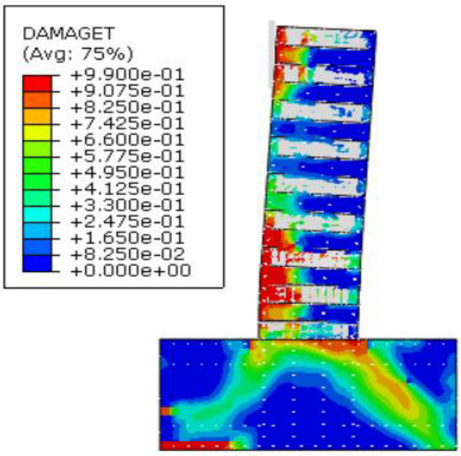

Fig. 9 Damages localisation for the simulated PCRC columns.

However, TCRC pre-damaged columns present highest strength among the different samples. This result suggests that, despite the increase in damage percentage, the specific concrete formulation used in the case of BTC maintains a higher strength than the other samples. This may be attributed to specific characteristics of this formulation, such as improved bonding properties of the components or a more homogeneous distribution of constituent materials.

IV. CONCLUSIONS

This paper is a part of the contribution of composite materials in the reinforcement of RC columns under horizontal loads. The objectives of this study is to improve the mechanical behavior of a pre-damaged reinforced concrete column by bonding of carbon fiber composite strips. Analysis of the various results obtained in terms of capacity curves and visualization of damages allows to achieve the following conclusions:

- The strength is increased of around of 45% and 25% for undamaged RC columns reinforced with total and partial bonding of CFRP.
- The displacement corresponding to the final collapse is increased by around of 95% for partially reinforced concrete-based RC columns and 150 % for totally confined ones.
- The gain of reinforcement in terms of load-bearing capacity and ductility increases proportionally with the rate of damage.
- Total confinement can restore the load-bearing capacity of a column damaged up to 30%, whereas partial confinement can restore the load capacity of a 15% damaged columns.

As potential future researches, the authors suggest to conduct a sensitivity analysis to determine the impact of various parameters such as bond strength, thickness of carbon sheets and damage levels on the effectiveness of retrofitting. In addition, explore the behavior of retrofitted columns under extreme loading conditions and seismic events.

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