The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM)
ISSN: 2602-3199

The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM), 2022

Volume 21, Pages 288-294

IConTES 2022: International Conference on Technology, Engineering and Science

Modeling the Nonlinear Behavior of Predamaged Reinforced Concrete Beams Retrofitted with Bonded and Jacketed FRP Sheets

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Abstract: This paper consists on the numerical simulation based-finite element modeling carried out on reinforced concrete (RC) beams predamaged and strengthened with carbon fiber sheet (CFRP) and a fiberglass (GFRP) jacket under monotonic bending loads. The retrofitted RC beams were modeled using ABAQUS to estimate the effect of concrete and steel damage rate. After the experimental validation of the proposed model, four configurations of damage rate were considered according the initial compression resistance of undamaged concrete. Indeed, the geometrical model and the choice of the finite element models were generated in a full three-dimensional (3D) space. Moreover, the real behavior of each used material has been simulated using the experimental laws of each one, namely: concrete damaged plasticity, elastoplastic steel model with isotropic hardening and orthotropic elastic one for FRP composites. The discussion of the numerical outcomes in terms of bearing capacity curves and the tensile damages maps provides the full interest of the FRP repair technology on the overall and local flexural response of predamaged RC beams.

Keywords: Predamaged beams; Repair; CFRP sheets; GFRP Jacket; Nonlinear FE simulation.

Introduction

Materials and structures damage has been almost considered as unwanted behavior state, which may cause catastrophic consequences (Ali Ahmed el al., 2022). Although the causes of a mechanical failure can be analyzed, the prediction and prevention of failures remain difficult (Djenad et al., 2022a; 2022b). Accordingly, the macroscopic mechanical behavior was generally resulting from the average effects of the microstructure (Jirawattanasomkul et al., 2020). Moreover, damages result from the combination of loading peaks, localization effect and microstructure defects (Lee el al., 2012).

In this connection, the repair and rehabilitation of damaged structures are primordial to lifetime and service usage (Malek et al, 1998; Huang et al, 2018; Rashid et al, 2019). Certainly, the most mentioned approach for the retrofitting of exciting RC beams for recovery the bearing capacity degradation was the external bonding of FRP on the critical zones susceptible to collapse (Al-Sulaimani et al, 1994; Raouf et al., 2000; Hussain et al., 1995; Daouadji, 2013; Si Salem et al., 2020). Recently, the use of FRP fibers with high corrosion and strength characteristic was widely highlighted to improve the mechanical performances of damaged existing members (Raouf et al., 2000). Furthermore, FRPs oppose to the deformations on longitudinal and transverse direction caused by dead and dynamic loads, which improve the ultimate flexural stress of pre-damaged concrete (Ait Taleb et al., 2016). In addition, numerous studies have been conducted to study the behavior and the capacities of retrofitted RC beam fully or partially wrapped with FRP. One can cite, the works of (Huang et al., 2018) on

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- Selection and peer-review under responsibility of the Organizing Committee of the Conference

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the strengthening of RC beams with bonded GFRP and CFRP in the critical zone. The authors have shown the effectiveness of FRP to improve the flexural and the shear performances of RC beams.

Regarding the cited researches above, the present work consists to advocate a finite element base according to the initial pre-damage in the rehabilitation of the critical zones of RC beams under four-point bending. Indeed, the repair was smeared in flexion with externally bonded CFRP plates and in shear by applying and GFRP jacket. The structural analysis was established under (ABAQUS, 2014) to estimate the variation of concrete and steel damages. In this respect the bearing capacity curves are provided to assess the effective repair layout in function of bearing capacity ratio.

Finite Element Simulation Procedure

The key objective of the suggested FEM procedure is to highlight the consequence of concrete and steel damage on the characteristics which may increase the resistance ratio of pre-damaged RC beams. Accordingly, a simulated model which allows to estimate the resistance of pre-damaged and repaired RC beam submitted to monotonic loads was provided and valeted using experimental literature results.

Simulated Specimens

The real scale RC beams and FRP strengthened RC ones designed and tested by (Huang et al., 2018) were considered in the current research to validate the proposed modeling. The modeled beam's geometrical and reinforcement characteristics are illustrated in Figure 1 and Table 1. Indeed, bending/shear reinforcement was applied with CFRP sheet and GFRP Jacket respectively.

Table 1. Steel and FRP design reinforcement of simulated beams tested by (Huang et al., 2018)

Beam dimension (mm)	Steel reinforcement	FRP reinforcement
Span: 800	Repartition rebar: 2A8	Flexural: CFRP sheet
Width: 100	Flexural bars: 2C12	Shear: GFRP Jacket
Height: 160	Stirrups: 15Ø8	Combined: Carbon and glass fibers

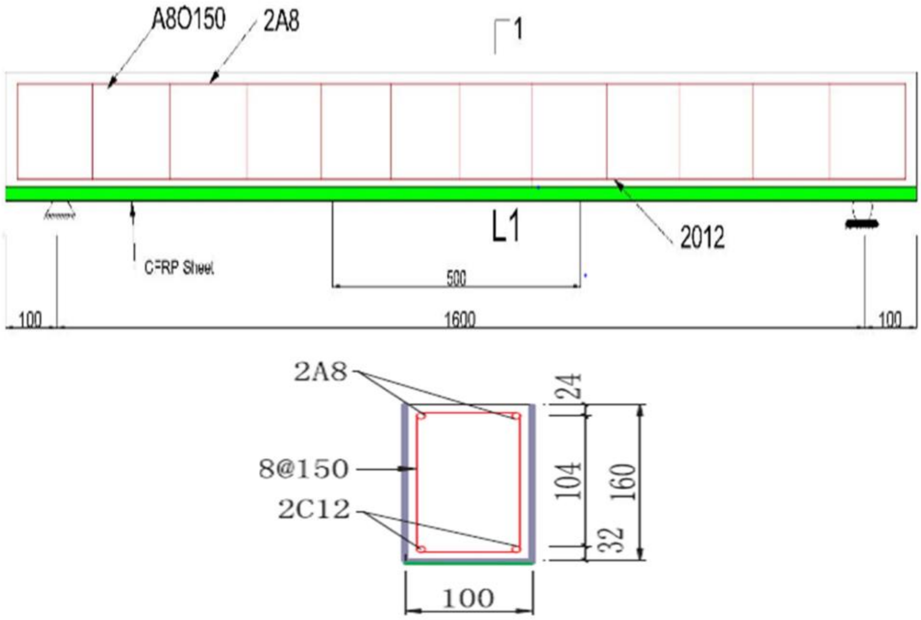

Figure 1. Longitudinal and traversal views of simulated beams tested by (Huang et al, 2018)

Used Materials Laws

All the mechanical characteristics of the materials which constitute the models, namely: concrete, steel and FRP were carefully and separately introduced for each element of our model, to take into a consideration the study's parameters and to validate the established finite element model. In this context, three materials models integrated in (ABAQUS, 2014) were used, namely: Concrete damaged plasticity (CDP); elastoplastic behavior with kinematic and isotropic strain hardening for steel and orthotropic elastic behavior for composites.

CFRP and GFRP were modelled by quadratic finite elements model (2D), with an eight nodes solid element, with 1 cm dimension in the mains directions. The quadratic finite elements models are coupled with the hexahedral linear finite element models of concrete ones with no additional slip conditions i.e. no friction between the various components of the flexural beam. However, elastic-plastic model with isotropic strain hardening assuming bilinear behavior was used for steel reinforcement. Indeed, Table 2, recapitulates the parameters of used FRP and steel.

Table 2. Used steel and FRP parameters.

Materials	Young Modulus (GPA)	Density (kg/m^3)	Poison's ration	Thickness (mm)
GFRP	79.7	2.3E-06	0.31	0.60
CFRP	221.7	2.8E-06	0.31	0.24
Steel bars	210	7.4E-06	0.30	8 - 12

The mechanical response of concrete under a uniaxial loading, and the changes of the variables of the damage according to the stiffness recovery respectively in compression and tension are presented in the numerical concrete model. Cracking is considered to be the significant aspect of the material response. The elastic-plastic damage model involves values for material failure ratios and for tension stiffening parameters. Table 3 and 4 summary the multiaxial loading parameters of the used concrete and damaged concrete models.

Pre-damaged Modelling

To estimate the parameters influencing the materials reinforcement of RC specimens, the variation of the rate of concrete damage is focused. Indeed, the characteristics governing the values of the variables of concrete damage are summarized on Table 4. Four configuration of damage rate were considered according the initial compression resistance of undamaged concrete, as used by (Si Salem et al., 2015; Ait Taleb et al., 2015; Si Salem et al., 2017). It is important to notice that this later was experimentally measured by (Huang et al., 2018). The compressive resistance of used concrete was 41.3 MPa.

Table 3. Parameters of Concretes models.

Proprieties	Values
Dilatation Angle (°)	32
Compressive stress (Mpa)	41.3
Yield stress on compression (Mpa)	12.39
Yield stress on tension (Mpa)	3.08
Poisson's ratio	0.2
Ratio of biaxial to uniaxial compressive strength	1.16
Parameter of the flow potential	0.1

Table 4. Concrete parameters according to damage rate.

Damage rate (%)	Dilatation angle (°)	Parameter controlling the cracking energy (b_f)	fc_{28} (MPa)
10	30	30	37.17
20	28	35	33.04
30	23	40	28.91
50	15	45	20.65

Numerical Outcomes and Analyzes

Orderly to confirm the consistency of the simulation procedure, a comparison of the outcomes found with those of the tests taken on the basis of the literature review already established by different authors. Figure 4 shows the evolution of applied load versus deflection curves of the various bending-loaded RC beam. The curves obtained below are extracted from some experimental research carried out by (Huang et al., 2018) on FRP strengthened RC beams, also the results of our proposed numerical model.

Validation of Proposed FEM

Since our advocated FEM and the experimental model issued on the basis of the literature review present the same geometry and materials with the same physical properties, a comparison study was performed numerical vs. test outcomes. To verify the efficacy of the modeling, qualitative and quantitative predictions on the response of the studied structures with the test observations of Liang Huang et al [5] were established. With regard to the quantitative feature of the confrontation, the variation of the parameters identified experimentally i.e. vertical displacement and bearing capacities was emphasized. Figure 2 and 3 show the applied load versus the imposed monotonic mid-span displacement for both RC and FRP strengthened beams.

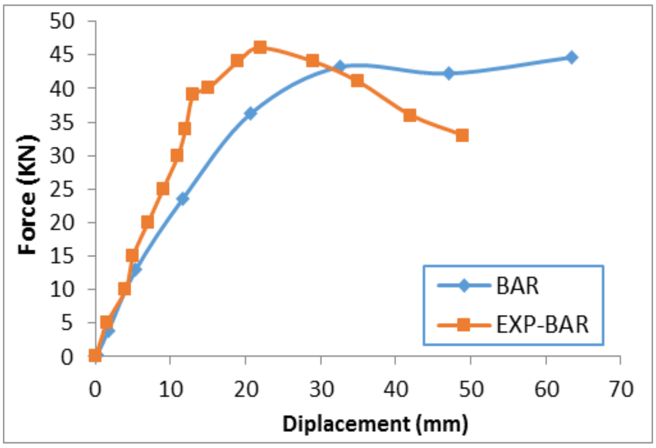

Figure 2. Confrontation of load capacity curves for RC beam: NLFEM vs. experiments

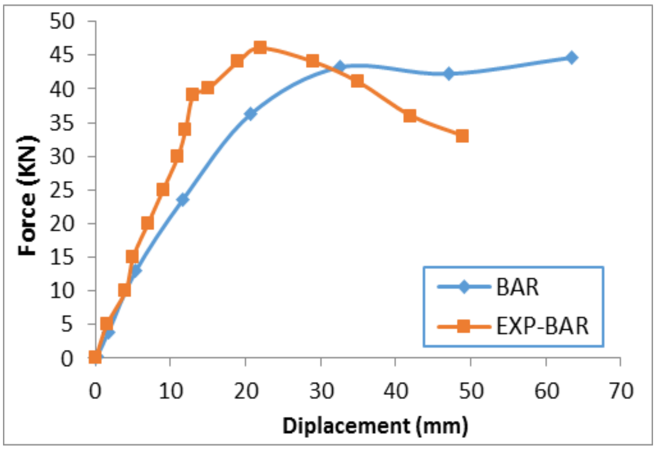

Figure 3. Confrontation of load capacity curves for FRP strengthened RC beam: NLFEM vs. experiments

The numerical outcomes present a good correspondence with experimental analysis ones of (Huang et al,2018). The values of the bearing capacity are significantly different. For the RC beam, the maximum load given by the simulation is 33.04 KN, however the average bearing capacity obtained by the tests was around of 33.81 KN. For the reinforced RC beam, the maximum load given by the simulation is 44.76 kN, however the average bearing capacity obtained by the tests is around of 47.09 KN. Indeed, a good correlation is observed, knowing that the difference between the FEM model and the experimental analysis is less than (<2.5%), which is much less than the normal experimental dispersion.

Pre-damaged Concrete Effect

Figure 4 shows the load bearing capacities of the various studied beams as function of concrete damage rate. The analysis of the outcomes, namely the of force-displacement curve clearly shows the improvement of the beam strength reinforced with FRP sheets in comparison to the reference RC beam, which represents a strength of 33.04 kN. The 10% pre-damaged reinforced beam has a maximum strength of 33.46 KN with a resistance increase of 53.14%. Also, the 20% of damage model reaches a resistance of 46.06 KN with a contribution of 48.19 %. The pre-damaged reinforced beam with 50% damage rate has a minimum resistance value to the variables of 10% and 20% respectively, which is 38.78 KN and a ratio of 69.75%.

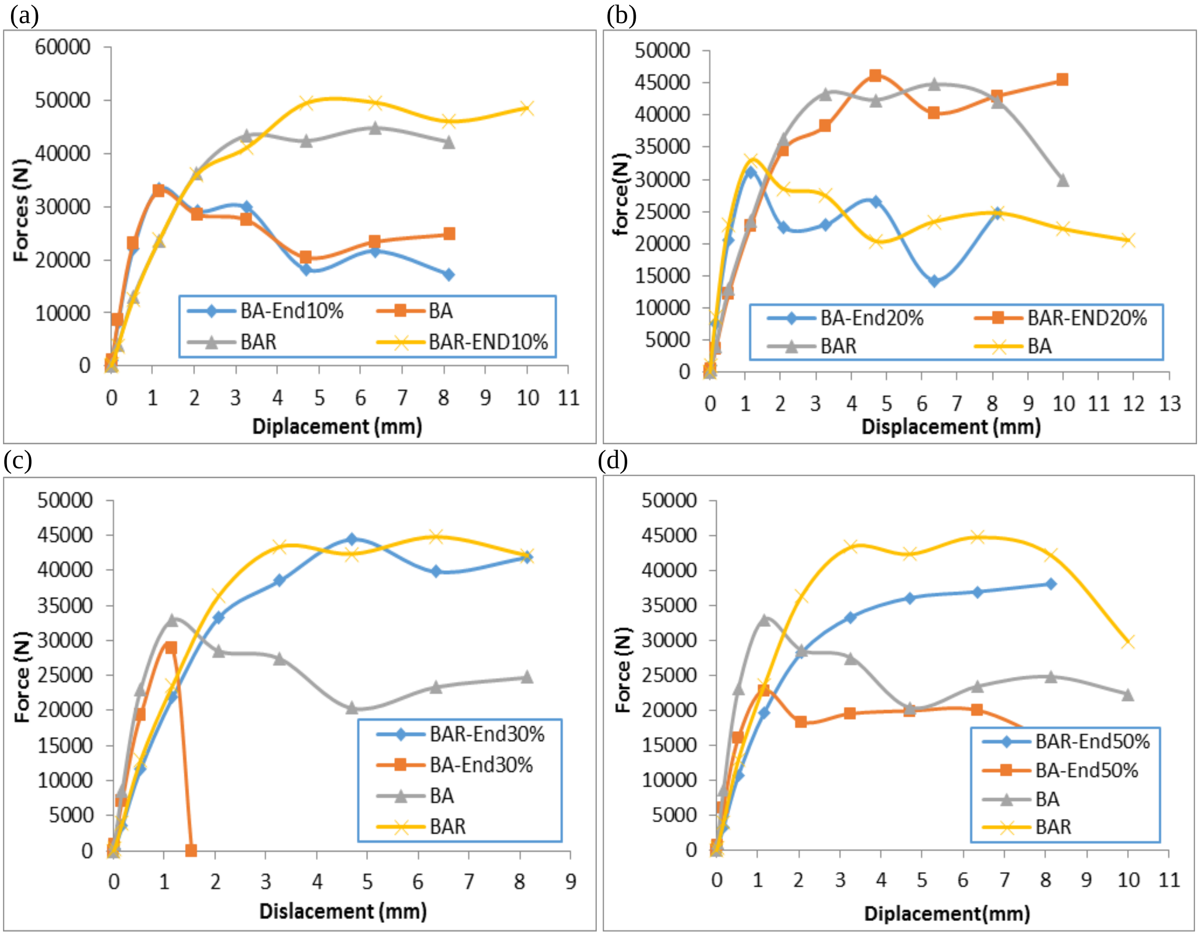

Figure 4. Load-displacement curves a) 10% damage rate; b) 20% damage rate; c) 30% damage rate; d) 50% damage rate.

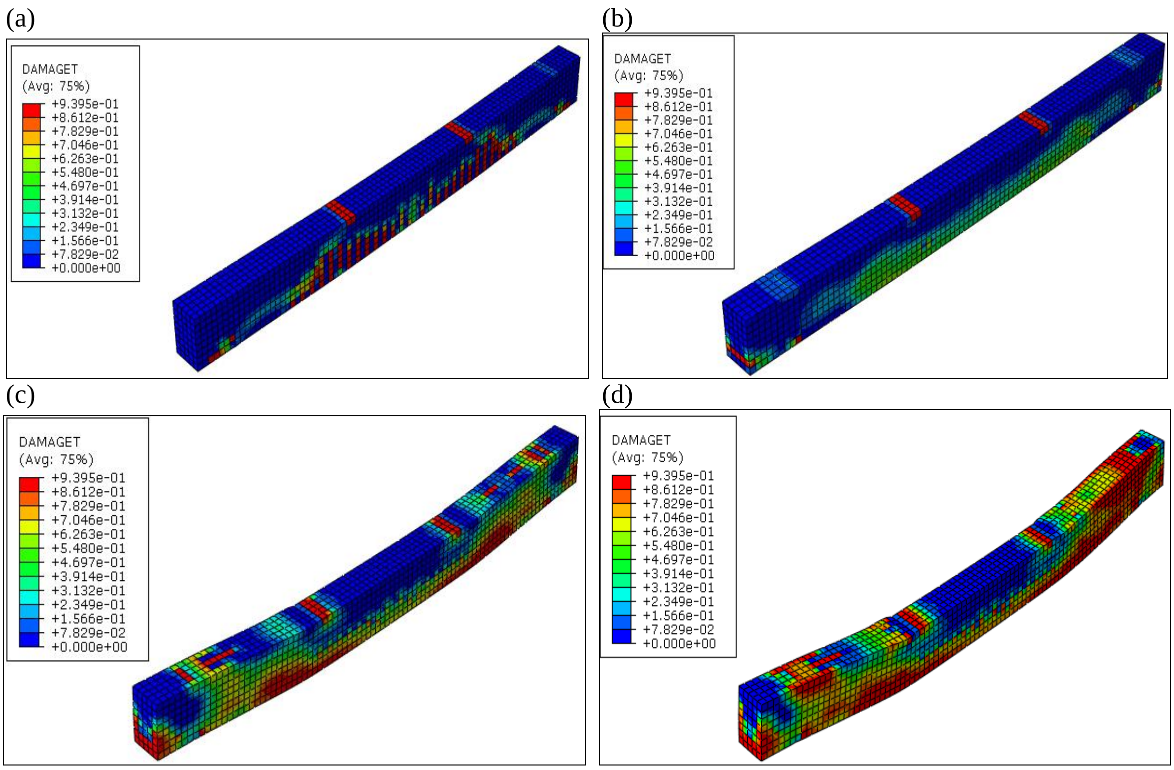

Figure 5. Tensile damages mapping a) RC beam; b) 10% damage rate; c) 30% damage rate; d) 50% damage rate.

Table 5 represents the bearing capacities of the pre-damaged beams. Indeed, the resistance contribution increases proportionally with the damage rate. Conferring to the comparison between the bearing capacity of the RC beam which is 33.04 kN and that of the FRP reinforced beam pre-damaged to 10% which is 50.30 kN one can confirm that contribution in terms resistance increases up to 52.70%. The 20% pre-damaged specimen represents a resistance of 46.10kN with a 50.70% gain; the 30% pre-damaged specimen with a strength of 28.52kN and a contribution of 22.68%. The minimum resistance is obtained on the specimen pre-damaged at 50% which is 36.72 kN. The confrontation of the outcomes of this series confirms that the damage rate has a considerable impact on the resistance of repaired RC beams.

Table 5: Numerical outcomes according to concrete damage rate

Concrete damage rate	Pre damaged RC beams strength (kN)	FRP repaired pre-damaged RC beams strength (kN)	Strength gain (%)
10%	33.46	51.24	53.14
20%	31.08	46.06	48.19
30%	28.95	44.44	53.5
50%	22.81	38.72	69.75

Conclusion

This research advocates a nonlinear models able to calculate the full bending response of repaired pre-damaged RC beams designed and already tested. Indeed, the analysis of obtained outcomes i.e. global response of the various reinforcement configurations considered, allows us to list the following conclusions:

• Reinforcement and repair using bonded FRP sheet and jacket considerably improves the bearing capacity of RC beams designed using undamaged or pre-damaged materials;

• The influence of the FRP strengthening on beam's resistance increases proportionally with the rate of damage. Indeed, damaged concrete allows the conjugation of the used composite materials characteristics;

• The growth in the damage of both concrete and steel leads to a significant reduction in the resistance gain. Indeed, steel yielding leads to brittle failure of damaged beams;

• RC beams retrofitted with GPRF and CPRF bands and pre-damaged are considered by a decrease in damage, this explains the increase in the resistance ratio of reinforced beams at a high level of damage.

Recommendations

Despite the satisfactory obtained results, which suggests the interest of the use of RFP composites to retrofit RC members, nevertheless it is necessary to supplement this study with other numerical analyses to take into account the FRP damage model as well as the interaction between all the beams components.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Acknowledgements

* This article was presented as an oral presentation at the International Conference on Technology, Engineering and Science (www.icontes.net) held in Antalya/Turkey on November 16-19, 2022.

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To cite this article:

Ait Taleb, S. Medjmadj, S & Si Salem, A. (2022). Modeling the nonlinear behavior of predamaged reinforced concrete beams retrofitted with bonded and jacketed FRP sheets. *The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM), 21*, 288-294.