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Static and dynamic behavior of composite concrete-based beams with embedded Polymer/FRP components

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Abstract

Recently, the seismic reassessment led to justify the behavior of concrete structures and to dispose members able to dissipate energy through a ductile behavior. In this respect, the present work aims to propose a new concrete-composite beam design, which allows the resumption of the shearing action under static and dynamic loads. The proposed design consists to incorporate in the tensile zone of the beam a rectangular polymer member wrapped by FRP, in order to prevent lateral deformation and to significantly enhance bending and shear strengths. A detailed experimental program is carried out on simply supported composite beams under typical four-point bending loads. Experiments are completed by nonlinear finite element modeling based on a local approach to simulate the real behavior of such elements and to allow a better understanding of experimental observations. The average test and numerical results in terms of overall and observed response are emphasized and discussed. In addition, the influence of the shear strength generated by static and dynamic loads as well as the adequate parameters improving the flexural capacity and ductility are assessed to highlight the mechanical performances of the new beam compared to classical RC beams.

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Keywords: Concrete; Composites; Shear behavior; Dynamic loads; FE Modeling.

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1. Introduction

The repair technologies of concrete members knew important progresses in past three decades, and several approaches for confined and strengthened concrete members by composites have been developed. In this respect, application of fiber reinforced polymer (FRP) materials for strengthening and confining concrete and RC structures has increased significantly as an alternative to substitute the steel plates [1]. Lightweight FRP sheets with high strength, stiffness and durability have become very attractive for rehabilitation and new design projects. The

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enhancement in terms of mechanical performances of strengthened and confined structures with FRP composites was experimentally, numerically and theoretically approved by several researches [2-4]. However, the earlier studies of the behavior of RC members strengthened with externally bonded FRP reinforcement have showed that the shear cracks propagation may result premature failure due the debonding of the external reinforcement, while the flexural capacity was increased compared to the reference one without reinforcement, and in some cases the deformation of a member becomes critical [5].

The new seismic recommendations led to dispose of structural elements able to dissipate energy, in particular through a ductile behavior, since it results in lower levels of stresses to be considered in the revaluation of safety margins. In this purpose, the mechanical behavior of civil structures under seismic loading is conditioned by their wind bracing members, both in terms of their dynamic characteristics and the materials resilience [6]. Despite of the adequate compressive strength of concrete, sudden failure mechanism takes place under cyclic dynamic loading. In addition to the need to improve the bearing capacity, this failure mechanism underlines the necessity to avoid brittle failures for evident reasons of saving human lives [7]. However, in order to provide high mechanical effectiveness of concrete-composite based beams, the new technique proposed in this work consists in incorporating a rectangular polymer member wrapped by FRP fabric within the concrete members. In this first stage of research, the present study is focused on preliminary investigation of structural behavior when the composite beams are subjected to static and cyclic flexural load. The effectiveness of this methodology has been experimentally evaluated on the basis of obtained test results.

In the second stage of this contribution, nonlinear finite element analyses (NLFEA) are carried out to allow a better understanding of experimental observations. The numerical modeling allows us to take into a consideration the nonlinear behavior of concrete under static and dynamic loading, through a cyclic elastic-plastic damage model, whereas an elastic orthotropic model with the Hill-Tsai failure criterion was used to describe the experimental behavior of used FRP reinforcement. The average test and numerical results in terms of flexural and shear capacity, deformability, flexural stiffness and damages evolution versus loads and times compared to conventional RC beams are emphasized and discussed. This enables us to assess the contribution of the composite jacket in terms of overall and observed behavior and to draw complete conclusions about the interest of the proposed concrete-based beams with embedded Polymer/FRP components.

2. Backgrounds and scopes

Concrete is high in compressive strength and low in tensile strength with brittle characteristics. In addition, the mainly researches carried out on RC beams under dynamic loading have showed that the concrete tensile zones are mechanically ineffective; they have no contribution in terms of shear strength and energy dissipation [8]. In this respect, the proposed design aims to partially substitute the tensile concrete by embedded polymer member, reinforced and confined with continuous GFRP Jacket, which allows reducing the structure weigh ratio.

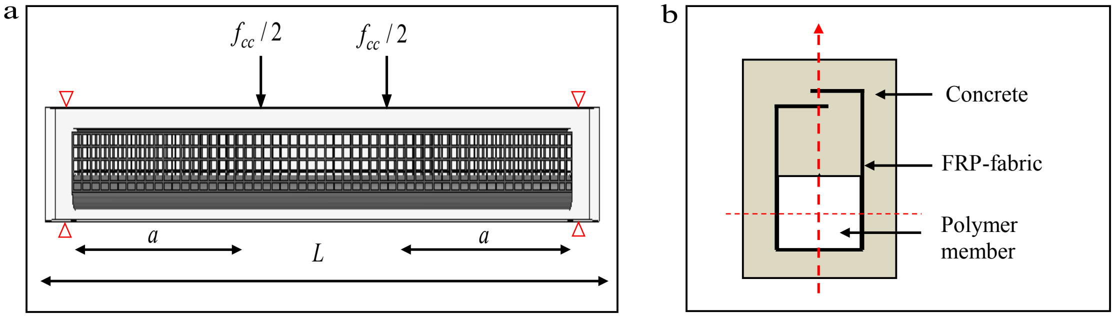

Fig. 1. (a) Proposed concrete-based beams with Polymer/FRP components; (b) Transversal view of the beam.

Figure 1 depicts the characteristics of the developed system, as well as the loading and boundaries condition. In order to prevent lateral deformations of the polymer member, the composite fabric was extended along the beam thickness; and disposed perpendicularly to the neutral axis of the cross section as shown in Fig. 1(b). The combination of the mechanical properties of all these materials namely: concrete, polymer and FRP allows making the beam most efficient under static and cyclic loading. The use of the GFRP fabric is generalized by the facilities of fibers mesh, the high mechanical properties and the reasonable cost and weight. The dimensions of the beam are 1100 *x* 160 *x* 80 *mm* and the overall length of the polymer member is 40 mm.

3. Experiments

The experimental program consists of testing rectangular beams according to classical experiment models used in the studies of members component under bending loads. Such procedure was conducted on two main phases. In the first one, characterization tests were carried out to assess the laws behavior of all used materials, namely: Concrete, FRP and Polymer member. In the second step, composite concrete-based beams referred to as (NEW-CCB) were cast and tested under static loading. Control specimens made with plain reinforced concrete RC with conventional design, referred to as (REF-RCB) with two longitudinal deformed steel bars were also casted to be used for comparison purposes. All casted beams were experimentally tested until failure using a universal test machine, that allow to observe the failure mode of the new beam and to measure the differences in strengths, and to assess the effect of the embedded polymer tube wrapped by the GFRP-Jacket compared to conventional steel stirrups.

3.1. Materials Characterization

Portland cement, gravel with a maximum coarse aggregate diameter of 20 mm, natural sand, water, and superplasticizers were used to manufacture the concrete batches. Table 1 summaries the mix proportion of concrete defined for this experimental protocol. In fact, concrete mixtures are prepared in a 300 kg capacity tilting drum mixer for about one minute mix followed by a slump test. The average 28-day compressive strength of used concrete was determined using six identical standard cylinders; it was found to be around of 26 MPa.

Table 1.Mix design of used concrete

Component	Portland cement	Fine aggregate	Coarse aggregate	Mixing Water *(l)*	Super-plasticizers *(l)*	Slump test (c*m*)
Amount (*kg/m*^{3})	350	825	1025	198	5	7

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The total thickness of the E-GFRP fabric is 1 mm, and the distance between two successive warps and wefts is 15 mm. The yield strength and the Young's modulus of elasticity provided by the manufacturer are respectively 1 400 MPa and 72 GPa. Moreover, the experimental behavior and a summary of used polymer member properties are given in Table 2. It is clearly seen that the observed deformations and the overall behavior of the member are in agreement with the mechanical properties of the used composites.

Table 2. Proprieties of used rectangular polymer member

Density (*g/cm*^{3})	Weight (*g/ml*)	Elasticity Modulus (*GPa*)	Failure strain (*%*)	Failure stress (*MPa*)
1.26	90	2,14 – 4,14	11,8 – 80	40,7 – 65,1

3.2. Beams fabrication and instrumentation

All the composite based beams were casted, compacted using a vibrating, finished, demolded, and then cured for 28 days in a standard curing room with 100% relative humidity until their testing in flexion. Before casting the reinforcement steel bars of the (REF-RCB) are introduced in the mould, and the polymer tube wrapped by GFRP is integrated in the mould for the (NEW-CCB), as shown in Figure 2.

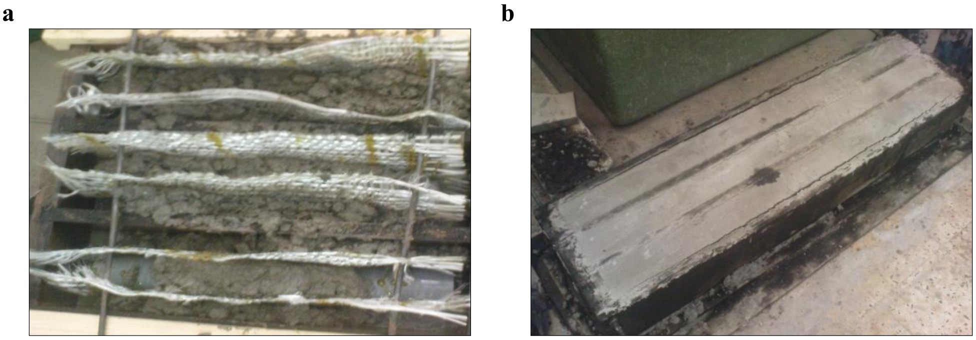

Fig. 2. (a) Composite based beams during casting; (b) Composite concrete-based beams after casting.

After 28 days, all the beams were subjected to bending loads using a universal ELE IBERTEST machine of 200 kN capacity, equipped with a digital software. The effective span of the beams was 1000 mm and the distance between the loads was 200 mm. The simply supported beams were loaded at the rate of 1 kN/min, which is kept constant during the test procedure. During loading, developments of cracks were observed at every 5 kN. The load at the formation of the first crack was also observed and recorded. Tests were terminated after the beam had attained the ultimate failure by any of the failure mode.

4. Simulated Models

Experiments were completed by nonlinear finite element analyses (NLFEA) in order to allow a better understanding of the behavior of the new beam. The numerical modeling was carried out on composite beams, under imposed cyclic and monotonic loads until failure with a step increment of 0.45 kN. Such analysis which is conducted with a full 3D nonlinear finite element analysis of the experimental setup, allows to estimate the full flexural and shear response and to determine the beams failure modes. The geometrical models established as shown in Figure 3 are identical to those of the tested specimens, as described in the above sections.

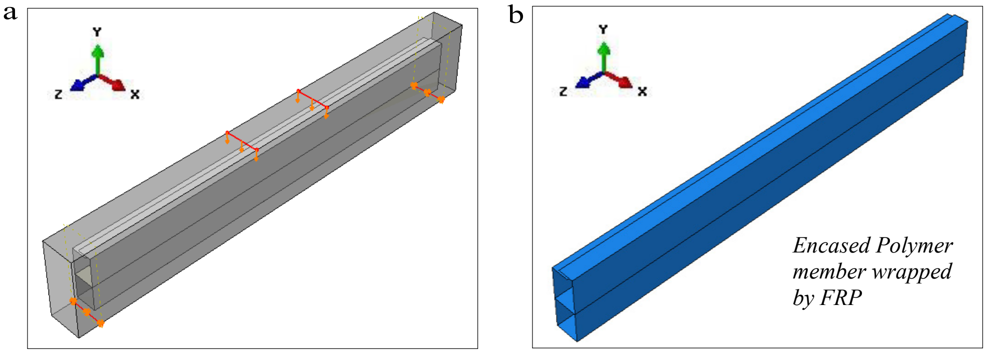

Fig. 3. (a) Geometrical model for simulated concrete based-beam; (b) Simulated Polymer member wrapped by FRP.

Using the dimensions of actual tested beams, a mesh sensitivity study was first performed. Finally, the beams are meshed thinly in the susceptible zones to failure, with hexahedral solid finite element model, with Lagrangian formulation and four nodes with 12 degrees of freedom. The solid elements have a dimension of approximately 2 cm in all three directions. However, the polymer member and the FRP jacket were modeled by quadratic finite elements models (2D), with eight nodes solid of 1 cm dimension in both space directions. The quadratic FE models are coupled with the hexahedral ones with the embedded elements function, available in the used Software.

4.1. Law materials

Concrete behavior modeling is much more complicated than that of FRP materials due to different response in compression and tension and non-linear stress-strain laws with hardening and softening branches. Failure criteria are also much more subtle than those of FRP and its numerical implementation is rather cumbersome. In our study, the Concrete Damaged Plasticity model bases on the classical continuum damage theory was used to describe the experimental behavior of used concrete. Such numerical model developed by Lubliner et al [9] provides a general capability for the analysis of concrete structures under static, dynamic, cyclic and monotonic loading [10]. The inelastic stress-strain relations in compression divided into two behavior phases are given by Equations (1, 2). In the software, the stress–strain values for used concrete are input point by point, according to experimental data. In addition, the concrete model requires values for material strength and failure, tension stiffening ratios and for a damage parameters (See detailed explanations of the model basic equations and parameters in Refs [11, 12]).

$$\sigma_{c(2)} = \frac{E_c \dfrac{\varepsilon_c}{f_c} - (\varepsilon_c / \varepsilon_{c1})^2}{1 + (E_c \dfrac{\varepsilon_{c1}}{f_c} - 2)\dfrac{\varepsilon_c}{\varepsilon_{c1}}} f_c \tag{1}$$

$$\sigma_{c(3)} = \left(\frac{2 + \gamma_c f_c \varepsilon_{c1}}{2 f_c} - \gamma_c \varepsilon_c + \frac{\gamma_c \varepsilon_c^2}{2 \varepsilon_{c1}} \right)^{-1} \tag{2}$$

The constitutive behavior of FRP was modeled according to an elastic-orthotropic model, with the Hill-Tsai failure criterion. Assuming plane stresses, the ultimate tensile strength and strain of FRP and adhesive were introduced in the software model to predict the behavior of used composites. The FRP behavior was essentially linearly elastic up to the tensile strength limit. Once the tensile strength has been reached, it is assumed to suddenly fail in a perfectly brittle mode. However, the FRP/concrete interface was modeled according to a bond-slip model.

4.2. Cyclic loading procedure

Figure 4 depicts the imposed cyclic displacement with 10 considered monotonous cycles applied to the load-time function for both studied beams. The periodic amplitude, the angular frequency (ϖ), the amplitude and initial stiffness parameters defining the loading function versus time are carefully introduced in the Software model.

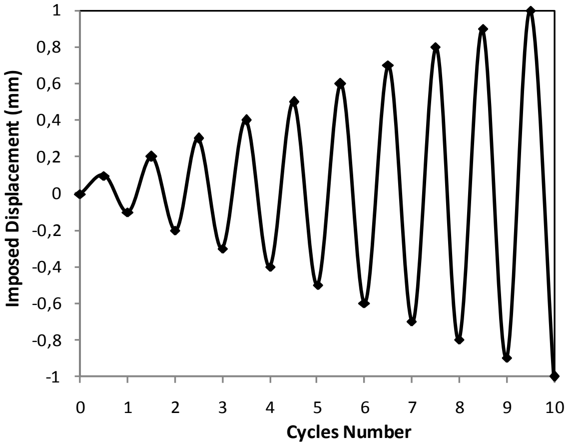

Fig. 4. Imposed cyclic monotonous displacement for the load function.

5. Results comparison

Static and cyclic flexural response at ultimate limit state was experimentally and numerically studied by means of four-point bending test. The finite element models used in this study is capable of predicting the experimental behavior of the specimens when these are subjected to loads. In this connection, the overall and the observed behavior of all tested and simulated beams are confronted, analyzed and discussed through the comparison of load-deflection curves and the depiction of failure patterns and damages evolution of each simulated beam specimens; that allows us to observe the failure mechanism of the new based beam and to measure the differences in strengths.

5.1. Static response

In order to highlight the effectiveness of the concrete based-beam technology and to validate the nonlinear finite element models, a comparative study was performed. Table 3 summarizes the average test results obtained from six identical specimens and the nonlinear finite element analysis (FEA) in terms of flexural load capacity, and mid-span deflection. In addition, Figure 5 shows the comparison morphology in terms of overall static behavior between studied specimens.

Table 3. Average test and simulation results comparison

Tested Specimens	Initial crack load *(kN)*		Initial crack deflection *(mm)*		Ultimate load *(kN)*		Ultimate load deflection *(mm)*	
	Test	*FEM*	*Test*	*FEA*	*Test*	*FEA*	*Test*	*FEA*
REF-RCB	6.32	8.13	0.97	1.11	12.94	13.71	6.58	5.43
NEW-CCB	15.88	13.56	1.93	1.59	22.18	20.71	7.43	8.65

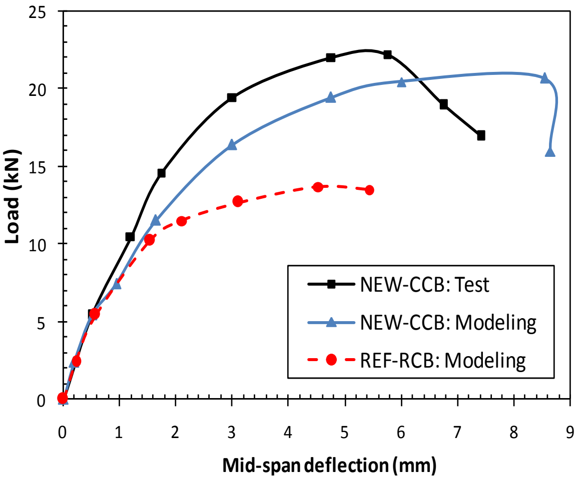

Fig. 5. Average test and simulation load-mid span deflection curves confrontation.

The experimental and numerical peak load compared at different sequences obtained from load–mid span curves shows a satisfactory agreement in terms of overall trend. In fact, the average ultimate load of the (NEW-CCB) given by experiment was 22.18 kN with a corresponding deflection of 7.43 mm, whereas simulation comes around of 20.71 kN with a deflection of 8.65 mm. Test and simulation results show clearly the enhancement in terms of bearing capacity and deformability of the composite concrete-based beams compared to the reference ones. In addition, results show that the average ultimate strength of the CCB was increased by an average of 60 %, while the ductility improvement was around of 20 %. Such confrontation allows us to assess the contribution of the Polymer/FRP components to reduce the cracks initiation and to oppose to the shear deformations.

In conclusion, the experimental results correlated well with the values predicted using the finite element modeling, and represent a promising revelation regarding the effectiveness of this design technology in terms of mechanical performances compared to conventional reinforced concrete beams. However, the peak load in numerical results was slightly different with than of experimental ones; this is due to initial defects in the beams, which cannot be calculated in finite element model. For more clarity, Figures 6 and 7 show respectively the changes and the cartography of the tensile and compressive damages versus the applied loading.

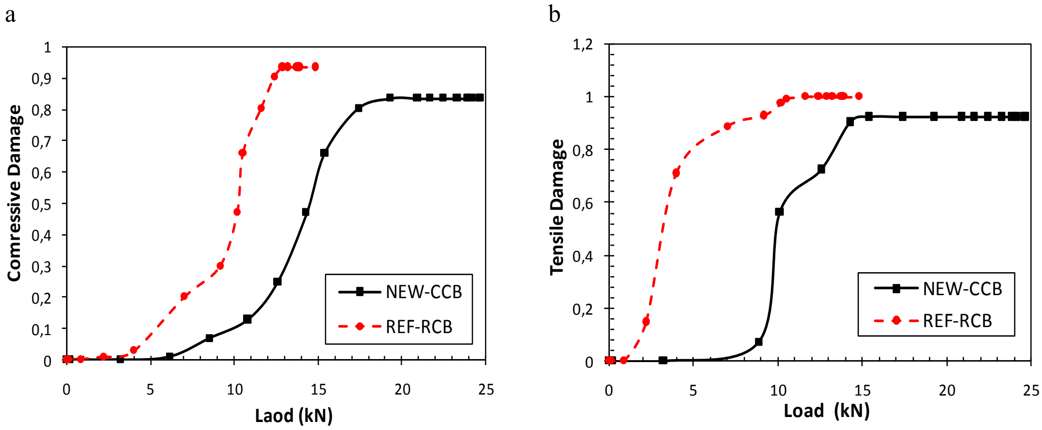

Fig. 6. (a) Compressive damages versus loads comparison; (b) Tensile damages versus loads comparison.

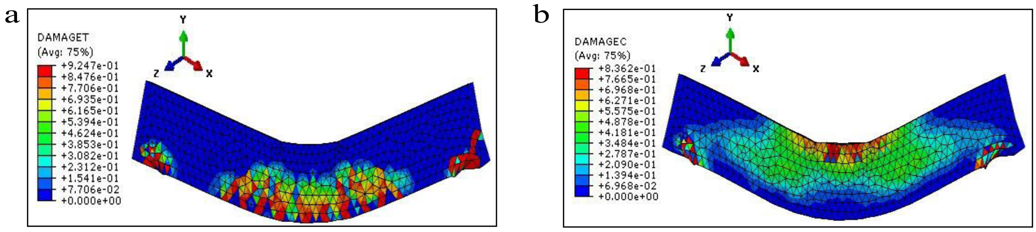

Fig. 7. (a) Tensile damages cartography at failure; (b) Compressive damages cartography at failure.

The compressive and tensile damages variables take values from zero, in which the beams are in a state of non-cracked state to the final failure of the beams. The first flexural crack appearance of the reference RC beam (REF-RCB) corresponds to an external load of 8.13 kN, while the latter appears for a load of 13.56 kN for the (NEW-CCB). The critical compressive damage value is reached for a load of 9.31 kN for the reference beam, however, for the composite based beam is reached for a load of 13.73 kN. The tensile cracks propagation was reduced by an average of 45%, whereas the compressive cracks one was reduced by around of 20 % compared to the RC beam.

5.2. Dynamic global response

Regarding the quantitative aspect of the dynamic global response comparison, the evolution of the bearing capacity and the shear damages generated under cyclic load versus time for both studied specimens respectively shown in Figure 8(a) and 8(b) is considered in the first stage of this study. The simulation results comparison as well as the final discussion illustrates the aforementioned advantages of the new beam under cyclic loads.

The ultimate bearing capacity of the new beam generated with an imposed cyclic displacement was around of 5 kN, corresponding to a 0.8 s time period. The curves comparison shows that the positive contribution in terms of cyclic load capacity is around of 30% compared to the RC beam.

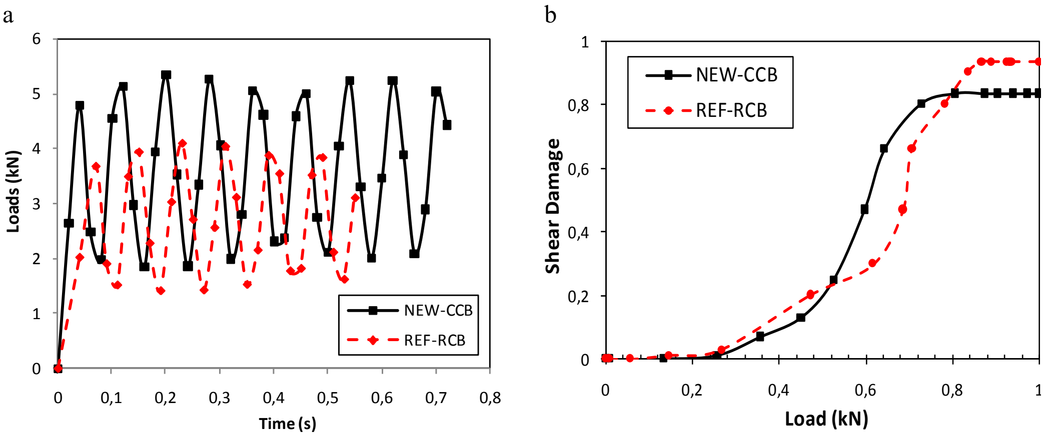

Fig. 8. (a) Cyclic loads versus time comparison; (b) Shear damages versus cyclic loads comparison.

In other hand, the appearance of the first shear crack of the RC beam corresponds to an external load of 1.34 kN, while this latter appears for a cyclic load of 3.64 kN for the new one. In fact, the shear cracks propagation rate was reduced by around of 23%. In addition, the shear stresses propagation due to the deformation of the polymer member is prevented, by the mobilization of the lateral pressure due to the difference in flexural stiffness between the two compatible materials namely: concrete and composites. Hence, the conjugation of the performances of the GFRP Jacket provides to the beam an acceptable strength level.

6. Conclusions

This investigation aims to study the non linear static and dynamic behavior of new composite concrete-based beams with embedded Polymer/FRP components designed to reduce the structure weight and to improve the mechanical performances under flexural loading. Test and numerical modeling results comparison shows a good correlation, and they agree on the contribution of the FRP Jacket to decrease the flexural and the shear cracks initiation and the cracks propagation. This study showed that with moderate own weight and reasonable coast, the average strength of the developed beam are improved by 60 % and 32 % respectively under static and dynamic loading. Finally, results analysis suggests the interest of composites usage to enhance the flexural capacity, ductility and to reduce the cracks propagation rare under static and dynamic loads. However, for future works it is necessary to complete the study by more dynamic and static experiments.

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