

Mechanical behaviour of a new composite beam: Nonlinear Modeling analysis

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ABSTRACT — This work presents the numerical results of the mechanical behavior of a new concrete-composite beam under bending loads. The proposed design consists to integrate a tubular polymer member in the flexural tensile zone, wrapped by a GFRP composite Jacket, which mobilizes a lateral confinement pressure. An analytical modeling based on classical beams theory is carried out in order to assess the strains field and the stresses propagation of the cross-section using the non linear laws behaviour of all constitutive materials. In order to allow for a better understanding of analytical observations, a finite element model was performed to determine the flexural capacity and the failure modes. The effectiveness of the new concrete-composite beam design is highlighted by the comparison of obtained results to conventional reinforced concrete ones, in terms of strength and ductility.

Keywords: Concrete-composite, Design, Analytical modeling, Stiffness, Analysis.

I. Introduction

Composite materials have found their new applications in the rehabilitation and strengthening of reinforced concrete structure. Compared to the traditional ones, composites have a high strength and stiffness to weight ratio, attractive corrosion resistance and ease of handling and application [1]. The effectiveness in mechanical performances of concrete structures confined and strengthened with the composite materials was experimentally demonstrated by several authors [2-4]. One of the most used strengthening methods is the bonding of externally composite plates. The tests elaborated by Mufti et al [5] on simply supported beams reinforced with FRP plates, under four point flexural load showed that the reinforced beam recorded an increase in strength and a reduction in ductility compared to reference one. However, in the literature, one can found a many works and studies of the

bonding interface due to the stresses concentration [6-8]. These studies have confirmed that the mechanism of failure and the flexural capacity of reinforced beams with flexural plates depend mainly on the mechanical properties of the concrete/FRP debonding interface. This paper presents a new design technique of concrete composite beams. Beam element which has reduced own-weight and high mechanical performances is developed. This new design developed by Ait tahar K & co [9] consists to integrate a triangular polymer tube member in the flexural tensile zone of the concrete beam, wrapped by a GFRP composite Jacket. The E-Glass Fiber fabric is extended along the height of the cross section of the beam and disposed perpendicularly to the neutral axis of the section in order to improve its flexural stiffness, and to oppose to the development of lateral deformations. The mobilization of the lateral confinement pressure, due to the difference in stiffness between the compatible materials namely: concrete and GFRP composite fabric allows reducing the cracks initiation and the cracks propagation in the considered flexural beam.

A non linear finite element analysis is carried out on concrete-composite beams,

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simply supported under four-point flexural loading until failure. The modeling of the specimens is conducted in a full three dimensional space (3D); to determine the failure modes and the corresponding flexural capacity. The concrete material is modeled according to the Concrete Damaged Plasticity model. The numerical concrete model take account the asymmetry of the concrete behavior in compression and in tension, and a coupling with the damage evolution to represent the cracks initiation and the cracks propagation. While an elastic orthotropic model is used for the composite fabric materials with the Hill-Tsai failure criterion in the case of an anisotropic material. The numerical modeling results in terms of stress, strain and stiffness degradation are presented and discussed. To highlight the contribution of the new design proposed compared to equivalent structure ones, with reinforced concrete. The confrontation of the curves: load-mid span deflection and the different failure mechanisms are also presented. The numerical and theoretical studies represent a promising revelation and indicate that the adopted confinement system produces a noticeable increment in strength and ductility.

II. Beam system design

The analysis of the global behavior of concrete beams under bending loading showed that the tensile zones carry no contribution in terms of mechanical strength and ductility. In this connection, our proposal technique consists to embed a triangular polymer member reinforced with a GFRP composite fabric in the tension zone. In order to maintain an acceptable flexural stiffness, and also to ensure the continuity between the compressive and the tensile concrete zones and to reduce the structure mass ratio

The new mechanical system developed is shown in Figure 1. The geometrical characteristics, as well as the loading system setup and the boundary condition are illustrated in Fig 1a. The dimensions of the beam are 1100 x 160 x 80 mm; the length of the triangular polymer member is 40 mm. The distance between two successive warps and wefts of the composite fabric Jacket is 15mm.

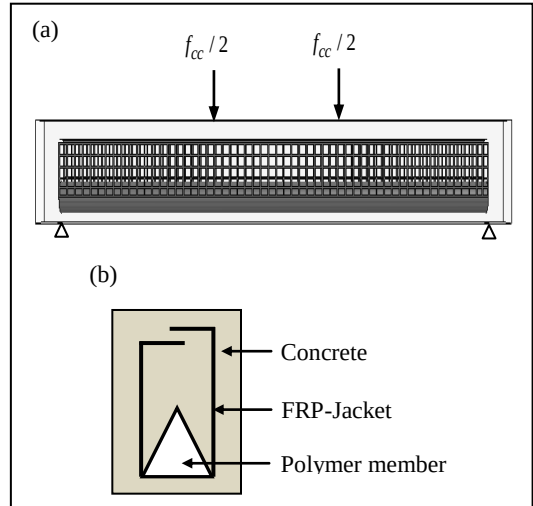


Fig. 1 Longitudinal and transversal view of the developed composite beam

III. Analysis of a new beam

Analytical modeling is a means of evaluating the response of the new concrete-composite beam, with a cross section (S), and an average line (γ) under bending test. The displacement and the strain fields are assessed on the basis on the theory of Navier-Bernoulli. The theoretical modeling is conducted according two approaches; firstly, to evaluate finely the deformation and the stress fields, using the laws of behavior of the materials in order to take account of their nonlinearity. The second one is a global approach, based on classical beam theory, allowing to evaluate the overall displacement and the stress fields.

III.1. Cross section equilibrium

Let us consider the concrete-composite cross section located at mid-span of the beam, in equilibrium under increasing bending moment as shown in figure 2. The failure is achieved when the flexural strength is reached due to yielding of the polymer member, followed by the rupture of the composite Jacket. The lateral confinement pressure acted in the post-cracking state of the section, and it is assumed to follow a rectangular stresses distribution.

The total deformation fields components in the (x) direction can then be derived easily to the displacement field obtain, it is assumed by the equation (1).

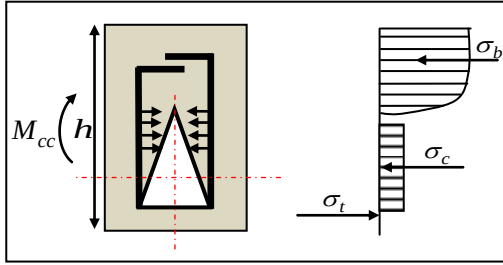


Fig. 2. Stress distribution of the section.

$$\varepsilon = \varepsilon(z) = \varepsilon_G + \phi \cdot z \quad (1)$$

Where ε_G denote the components of displacement of a point on the plane $z = 0$; ϕ is the rotation angles of the transverse normal about the (z) axis. The internal resisting efforts are given by the equation (2).

$$M = \int_s \sigma(z) \cdot z \cdot ds, \quad N = \int_s \sigma(z) \cdot ds \quad (2)$$

The constitutive equations can be deduced by the proper integration. These relations of the beam can be expressed using the generalized Hook's law is given by the relationship (3).

$$\begin{Bmatrix} N \\ M \end{Bmatrix} = \begin{bmatrix} \bar{A} & \bar{B} \\ \bar{B} & \bar{C} \end{bmatrix} \begin{Bmatrix} \varepsilon_G \\ \phi \end{Bmatrix} \quad (3)$$

The coefficients $\bar{A}$ and $\bar{C}$ are the well known bending rigidities and $\bar{B}$ is the extensional coupling and bending rigidity. Whereas it is easy to assess the internal efforts accruing to a given deformation, however, the reverse, which consist to deduce the deformations from the internal efforts requires more complicated numerical operations. The effort increment of the corresponding deformations is assessed by a successive substitution using the Newton-Raphson method. A theoretical model was performed and validated to predict the experimental behavior of a concrete-composite cross section under increasing flexural load.

IV. Numerical Simulation

Numerical simulations with parametric finite element models are powerful and robust tools for comprehensive investigations of flexural capacities and failure mechanisms of a new

concrete composite beam. An elasto-plastic damage model is used to describe the nonlinear material properties of concrete. This model bases on the classical continuum damage theory. An elastic orthotropic model is used for the modeling behavior of the composite fabric.

IV.1. Finite element model

The beams are thinly meshed, in the zones subjected to the failure, with tetrahedral finite element (3D), with four nodes and 12 degrees of freedom. The concrete beam is meshed with a size of 2 cm in three directions. The composite fabric is meshed by quadratic finite elements (2D) with four nodes 8 degrees of freedom, with a dimension of one centimeter (1cm) in both directions, which ensures a very refined mesh.

IV.2. Modeling materials

The concrete is modeled according to the "concrete damaged plasticity" model [10] existing in the computer software ABAQUS [11], which allows coupling between plasticity (irreversible deformation representation) and damages (cracks representation), and takes into account to the asymmetry of the behavior of the concrete in compression and in tension. In the numerical concrete model, cracking is considered to be the most important aspect of the material response. The elasto-plastic damage model requires values for material failure ratios and for a tension stiffening parameter. Table (1) shows the mechanical parameters of the used concrete model. In the software, the stress-strain curves for used concrete are input point by point, according to experimental data. However, the materials are assumed to be homogeneous and isotropic.

Table 1 Concrete numerical model parameters

Proprieties	Values
f_c Compressive stress (Mpa)	25
f_{ce} Yield stress on compression (Mpa)	7.5
f_t Yield stress on tension (Mpa)	2.1
E_c Young Modulus (Mpa)	32165
ν Poisson's ratio	0.2
ϕ Angle of dilatation	32
a_f Ratio of biaxial to uniaxial strength	1.16
a_e Parameter of the flow potential	0.1

The E-glass composite fabric is manufactured with the unidirectional filaments, crossover at 90°; it has three orthogonal planes of symmetrical pairs, and is modeled as an orthotropic elastic material. The elastic behavior of the composite fabric (GFRP) in the hypothesis of orthotropic plane stress is described by introducing of stiffness constants.

The elastic behaviors of the fabric composite (The failure stresses of the composite fabric measured by tensile, compressive, and shear test system) are given in Table (2). They were modeled using the Hill - Tsai failure criterion in the case of an anisotropic material.

Table 2 Elastic orthotropic model parameters.

Proprieties	Values
E_1 Longitudinal modulus (Mpa)	72000
E_2 Transversal modulus (Mpa)	13600
G_{12} Shear modulus (Mpa)	4700
ν_{12} Longitudinal poison's ration	0.31
ν_{13} Transversal poison's ration	0.33

V. Results and Confrontation

The numerical results based on the finite element modeling in terms of stresses progress, strains progress and the stiffness degradation as function of the exterior loading applied relatively to the two specimens considered in this study namely: the concrete composite beam developed (C-C-B) and the reinforced concrete with traditional design (R-C-B) reference beam.

The contribution of the new mechanical system proposed in terms of flexural capacity and ductility behavior due to the mobilization of the lateral confinement pressure compared to

the reference beam is quantified through the confrontation of the curves (load-mid span deflection). The finite element model proposed for the mechanical behavior modeling of the

V.1. Overall behavior

Performance and flexural behavior at ultimate limit state was experimentally studied by means of four-point bending test on two specimen series. A set of six concrete-composite beams (C-C-B), and a set of the reference beams made respectively, with reinforced concrete beams (R-C-B) with two steel reinforcement bars.

The summary of test results such as the details of average crack initiation load, ultimate load, mid-span deflection at crack initiation, ultimate load and the failure mechanisms for each test series obtained from six identical specimens are given in Table (3). This average test results confirm the effectiveness of the new design technique in terms of positive contribution in strength (flexural capacity) and ductility (Ultimate deflection), and in terms of own weight reduction compared to conventional reinforced concrete beams.

The evolution of the external applied loading, as a function of the mid-span of the beam loaded in four-point bending until failure is shown in Figure (3). The confrontation of the load-mid span deflection curves shows the positive contribution in terms of flexural capacity of the order of 60% compared to the reference beam. The composite beam has a load capacity of 19.18 KN and a corresponding mid-span deflection of 4.62 mm. The reference beam specimen has a less significant flexural capacity of the order of 12.21 KN and a corresponding mid-span deflection of 2.61 mm.

Table 3 Results comparison between numerical modeling and theoretical analysis

Beam reference	Initial crack load (kN)	Initial crack deflection (mm)	Ultimate load (KN)	Ultimate deflection (mm)	Ultimate to crack load ratio
C-C-B: NLFEA	13.43	1.73	19.18	6.53	1.42
C-C-B: Theory	12.83	1.94	21.33	5.83	1.66
R-C-B	8.91	0.51	12.21	2.61	1.37

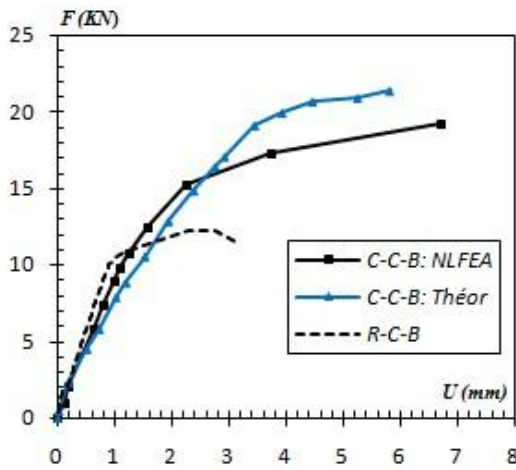


Fig. 3 Load-mid span deflection curves.

The load-mid span deflection curves analysis shows that the mechanical behavior of the new concrete composite beam developed is non linear. These curves can be decomposed into three phases: The first phase corresponds to low strains, the mid span deflection increases linearly with the external applied load; the beam element is in an un-cracked state, this behavior phase is common with that of the reference beam; The second phase corresponds to the cracks initiation and the cracks propagation. The control specimen Cracks spread are very fast, according inclined rods in the concrete matrix. The combination of the mechanical performances of the composite Jacket allows increasing the ultimate load corresponding to the cracks initiation and decrease the crack propagation rate in the flexural beam element through the mobilization of the lateral confinement pressure.

The last phase corresponds in the plasticization of the concrete matrix and the reinforcing bars for the control specimen. The cracks concentration in the compression zone of the new concrete composite beam developed is observed.

V.2. Moment-curvature curves

The locally deformation field evolution according to the external load applied of the concrete-composite cross section, are collected on the curves (moment-curvature) given by Figure (4).

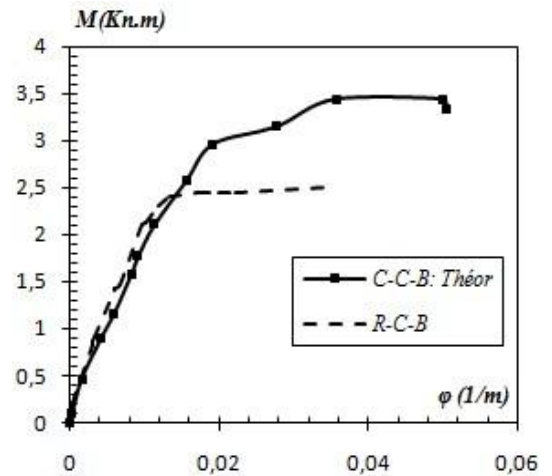


Fig. 4 Moment-curvature curves.

The evolution of the external load applied causes a significant evolution of the stresses field in the two specimens considered. Stresses field appears first in the flexural tensile zones in the both specimens, and then it propagates with a very high speed according inclined rods in the reference beam (R-C-B) up to flexural failure. Contrary to the concrete composite beam, which presents an acceptable level of strength and flexural stiffness under loading, the stresses field is concentrated at the compression zone, and it propagates with reduce stress field concentration.

The shear stresses progress due to the radial deformation of the triangular polymer member, in the developed specimen is prevented, through the mobilization of the lateral confinement pressure due to the difference in flexural stiffness between the two compatible materials namely: concrete and composite fabric. The mechanical performances of the GFRP fabric Jacket provides to the beam an acceptable strength level.

V.3. Failure patterns

The failure mechanisms of the different specimens obtained by the non linear finite element analysis are illustrated in Figure (5). The reference beam with reinforced concrete materials is achieved after the plasticization of the tensile reinforcement, with a bending failure mode. This failure mechanism occurs more

brutally than the failure mechanism of the new concrete composite beam developed.

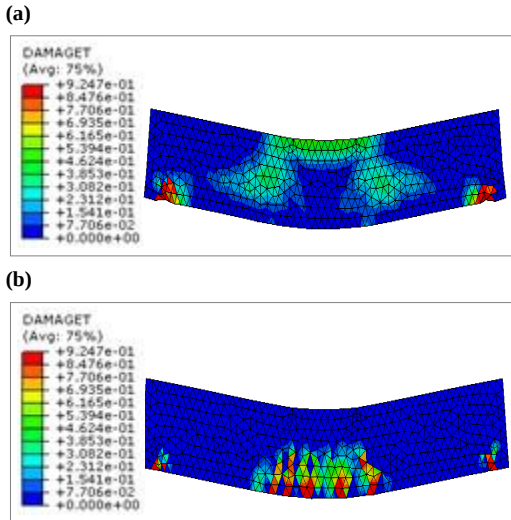


Fig. 5 Failure Modes: (a) Developed composite specimen (b) Reference beam.

The flexural cracks propagation in the new specimen developed shown in Figure (5.a) is prevented by the combination of the mechanical performances of the composite fabric GFRP Jacket, which allows in one hand to reduce the crack initiation and to ensure a relatively ductile behavior, which has an acceptable level of flexural strength and ductility compared the control beam shown in Figure (5.b).

VI. Conclusion

The main objective of this investigation is to study the non linear behavior of new concrete composite beams in order to reduce the structure weight and to improve the mechanical performance. The new design technique proposed consists in incorporating in the tensile flexural zone, a triangular polymer tube, wrapped by GFRP jacket to improve its flexural stiffness. The finite element analysis results show the effectiveness of this new design technique in terms of positive contribution in strength and ductility, and in terms of the weight reducing compared to conventional reinforced concrete beams.

The new design system proposed allows to reduce 20% of the structure weight and to increase the strength and the flexural capacity in order of 60%. The conjugation of mechanical performances of the GRFP composite fabric jacket and the mobilization of the lateral confinement pressure allow demining the flexural crack initiation and the crack propagation. Results analysis suggests the interest of the use of composite materials to improve mechanical performances, including flexural capacity and ductility under flexural loading.

More experiments and numerical analyses are necessary to draw complete conclusions about the interest of the proposed technology.

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