STATIC AND DYNAMIC BEHAVIOR OF CONCRETE STRUCTURES REINFORCED WITH NANOTUBES MODIFIED COMPOSITES

OUADAH NOUREDDINE[1] , ABDESSEMED MOULOUD[2*] , KECHOUANE FOUAD[1]
[1] Laboratory of Geo-Materials and Civil Engineering, Department of Civil Engineering, University of Blida1, Soumaa Road – P.O.Box 270, 250320 - Blida, Algeria
[2] Laboratory of Geo-Materials and Civil Engineering (LGMCE), Department of Civil Engineering, University of Blida1, Soumaa Road – P.O.Box 270, 25032 - Blida, Algeria.

The use of composites for the reinforcement of concrete structures, sometimes poses the problem of the detachment of the composite plates/fibers from the surface of the concrete support, especially in arid or dry climates. This phenomenon of disbonding, due to the poor performance of the matrix (adhesive glue), affects nearly 8% of the structures reinforced with FRP in Algeria and negatively influences the durability and bearing capacity of the reinforced structure over time. This article presents the results of a study on reinforced concrete structures. It concerns the insertion of carbon nanotubes (CNT) in epoxy resin, used as an adhesive for CFRP composites. The objective is to evaluate the improvement of the mechanical performances of the resin used and to contribute to reduce the phenomenon of disbonding. An experimental work carried out on a set of reinforced concrete beams, strengthened by CFRP plates, with the insertion of carbon nanotube powders (CNT) in the resin used, with percentages varying from 0 to 2%, has been performed. To validate the results obtained, a numerical work based on the finite element method was developed taking the case of a concrete bridge requiring repairs. The results showed that the nano-composites (CNTs) improve the mechanical performance of the epoxy resin and bring an appreciable gain of the order of 50 to 170% to the constraints. Moreover, this technique of moderation of composites by adding nanotubes (CNTs), gives an appreciable gain at vibration frequencies. This was confirmed by the results of the modal analysis of the bridge structure repaired with 2% addition of CNTs.

Keywords:*Concrete, reinforcement, composite, adhesive, nanotube, disbonding, frequency, analysis, structure*

1. Introduction

Over the last decades, the use of fiber reinforced polymers (FRPs) in civil engineering applications has become very remarkable. Especially considering that many civil engineering structures (buildings, bridges, other structures) are old and represent an important heritage requiring repair and/or reinforcement [1]. External bonding of fiber-reinforced polymer (FRP) sheets with epoxy resin is an effective technique for strengthening and repairing reinforced concrete beams, slabs and bearings (RCB) under static, dynamic or moving loads. However, this resin, due to its limited mechanical performance, compared to polymer fibers, represents the weak point and causes tearing and debonding of the composites from their support. It is becoming increasingly necessary to find remedies to eliminate the phenomenon of composite tearing, knowing that in more than 300 bridges, this phenomenon is apparent, especially in areas of dry and hot climates. Several researchers have tried to find remedies to these anomalies and propose effective and reliable solutions, which do not influence the environmental conditions. Among these solutions are the "nano-composites", which designate a new class of compound materials, whose dimensions are nanometrics. These are achieved by dispersing in general, small amounts of nano-reinforcement inside a polymer matrix to ensure a much larger exchange surface and a better distribution of stresses inside the nano-composite. The nano-renfort (carbon nanotube) located at the heart of a polymer matrix could be imagined as a group of cylindrical coaxials packed together, with uniform thickness interval [2]. The main causes that prompted researchers to think about the use of nanotubes in the matrix (resin) is the improvement of the mechanical performance of the matrix [3, 4], as they can be adapted to present excellent properties for potential application in the engineering of flexible pavements in civil engineering [5] or to prevent composite fibers (reinforcement) from detaching from the concrete support for the elements of repaired structures. Generally, the problems survived in this case of composite detachment figures, are observed in cases exposed to thermal gradients, excessive temperatures or tough environmental conditions. Experimental studies have been conducted to observe the influence of temperature on an epoxy resin matrix [6,7], especially when it is known that structures, such as bridges that are located in hot climates are always exposed to this problem.The phenomenon of debonding has been widely studied in recent years [8]. Indeed, specifically for reinforced concrete beams strengthened with steel plates [9, 10] or with plastic reinforcements (FRP) [11, 12] and this, in the

*Autor corespondent/*Correspondingauthor*,
E-mail:abdesmoul@yahoo.fr

tensile parts of the flexural beam. These studies have shown that the modulus of elasticity and the amount of applied reinforcement excessively influence the stiffness of the FRP composite. Also, these studies have shown that the use of thin plates favors this debonding failure.

The reading of the literature shows that few (perhaps rarely) works have been carried out in cases of real scale structures, with application of FRP composites (inserted by carbon nano-tubes in their reinforcements) [13]. Indeed, the literature, has shown that, although a number of researchers have studied the use of nano-particles from a materials point of view [14], only a limited amount of research has been carried out to use nanotube matrices for civil structures [15 - 17]. For this reason, through this study, we will attempt to contribute to the generalization of the increase in mechanical performance of composite reinforcements by CNTs and ensure the durability and survival of structures repaired by composites. Studies of RC beam reinforcement, by composites with the addition of carbon nanotubes (CNTs), over the last 10 years, have shown the potential improvement in properties and performance of fiber-reinforced polymer matrix materials in which nano and micro scale particles have been incorporated. From the existing literature, considerable efforts have been made to synthesize and process these unique polymers, but relatively little work has been done on fiber-reinforced epoxy composites to improve its overall stiffness. Irshidat and al. [18] investigated the influence of using carbon nanotubes (CNTs) on the flexible strength recovery of heat-damaged RC beams repaired with carbon fiber reinforced polymer composites (CFRPs). It has also been shown that the use of CFRPs modified with carbon nanotubes to strengthen RC beams [19] and columns [20] improves the load carrying capacity of the confined columns and the flexural strength of the retrofitted beams.

The effect of multi-murated carbon nanotubes (MWCNTs) on the behavior of RC beams under monotonic loading has been studied by Qissab and al. [21]. The application of innovative constituents and materials that can significantly affect the mechanical behavior of concrete structures has been developed by M. Bacclocchi [22]. It concerns the modeling and numerical study of the viscoelastic behavior of laminated concrete beams reinforced with CFRP strips and carbon nanotubes. Rousakis and al. [23] showed that concrete columns confined with glass fibers embedded in CNTs-modified epoxy have a higher load capacity than columns confined with glass fibers embedded in pure epoxy. Irshidat and al. showed that the pull-out bond strength between fiber reinforced polymer (FRP) rebar and concrete with carbon nanotubes (CNTs) is significantly improved as a function of the content of CNTs nanotubes [24]. In this paper, we present two parts: An experimental analysis in the laboratory, with the preparation of twelve reinforced concrete beams (RC), of dimensions (1700-180-160) mm. whose configuration is as follows. Two control beams without reinforcement, two beams reinforced externally by laminated plates CFRP in traction with an equivalent epoxy glue. The other beams are reinforced by the same type of laminated plates CFRP in traction with epoxy glue, but with insertion of carbon powder nanotubes in percentage: 0.5% (for the first two beams), 1.0% (for two other beams) and 1.5% (for two identical beams) and 2.0% for the last two beams. The objective is to see the influence of the percentage of carbon nanotubes (CNTs) powders on the behavior of these beams tested in 4-point bending and thus see their effect on the stiffness of the reinforcement performed. In order to validate the results found experimentally, the second part consists in a numerical analysis by applying of the finite element method (FE). The application is taken for a case study in situ for an old bridge, whose beams are reinforced by composite materials, with insertion of carbon nanotubes, with the optimal percentage determined during the experimental results. A modal analysis, with a dynamic behavior, has been performed in order to determine the modes and the frequencies of vibration of the tested structure.

2. Experimental program

2.1 Tests to the laboratory

The tests discussed in this paper were carried out on simply supported RC beams reinforced in bending with laminate plates CFRP glued to the outside. The beams were tested in a four-point loading condition. The Sika-carbodur laminate plates are positioned at the lower fiber of the beam (Fig.1) and the measurement of stresses and deformations will be done using the P3500- Model SB10 portable extensor bridge (Fig.2). All beams were reinforced longitudinally (horizontally) with two steel bars of nominal diameter of 10mm (on top) and three steel bars 12mm (at the bottom) and with crossbars (stirrups) of nominal diameter of 6 mm spaced to 120 mm. The test program and details of the specimen are summarized in Table1, where (NC) refers to normal concrete, (RPC) refers to reference concrete, numbers 10, 12 refer to the longitudinal diameter of steel bar. The incorporation of carbon-nanotubes into epoxy, with the aim of improving the mechanical properties of epoxy, was made [25]. Low nanoparticles concentrations (CNTs) of 0.5%, 1%, 1.5% and 2%, were added with adequate mixture to have homogeneity in the epoxy resin used (Fig.3). The detail of the tested beams is illustrated in the Table1.

The adhesive glue is the Sikadur30, epoxy commercially available in Algeria incorporated multi-wall nano carbon tube (MWCNT), was used (Fig.3) [26]. The carbon nanotubes (CNTs) were


Fig.1 - Laminated plate located in the beam.


Fig.2 - Extensive bridge for deformation.


Fig.3 - The adhesive glue used.

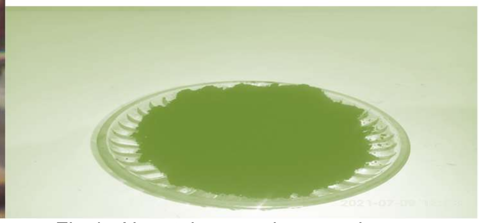


Fig.4 - Nanatubes used as powders

Table 1

Details of the Tested Beams

Beam notation	Dimension (mm)	Flexural Reinforcement [(a)]	Composite	Ratio CNTs/resin
BC	(160×180×1700)	3D12	Laminate CFRP	-
BL	(160×180×1700)	3D12	Laminate CFRP	0%
BR1	(160×180×1700)	3D12	Laminate CFRP	0.5%
BR2	(160×180×1700)	3D12	Laminate CFRP	1%
BR3	(160×180×1700)	3D12	Laminate CFRP	1.5%
BR4	(160×180×1700)	3D12	Laminate CFRP	2%

Note: BC= Beam control, BL= Plain reinforcing by laminated plate CFRP.
BR1= Insertion 0.5% CNTs, BR2= Insertion 1.0% CNTs, BR3= Insertion 1.50% CNTs, BR4= Insertion 2.0% CNTs
[(a)]Three bars: 12-mm diameter is indicated by 3D12 (intense face).

used as a powder (Fig.4) form with an external diameter (20-30 nm). Surface treatment of MWCNT was done using a mixture of nitric and sulfuric acids to develop hydroxyl or carboxyl end groups on the outer surface of nanotubes [27]. The used CFRP laminate has a modulus of elasticity of 165 GPa and an ultimate tensile strength of 2800 MPa, while the used epoxy has a tensile strength and a modulus of elasticity of 30 MPa and 12.8 GPa, respectively, as reported by the manufacturer. The steel bars used have an ultimate resistance of 980 MPa. The CFRP laminated plates are of 80 × 1500 × 1.2 mm dimensions were used at the bottom of the beam [28, 29].

2.2. Measures and instrumentation

All the test beams were tested as part of a four-point loading system. The length and range of each beam was 1.70m and 1.50m and the distance between the loads was 0.6m. The loads acting on the tested beams were measured by a 600 kN load cell where, in several stages, each beam was loaded up to failure. A voltage gauge with a gauge length of 10 mm was mounted on the central pull bar in the bending span. Deformation gauges were also mounted on the lower part of the beam in its middle. The reading of the gauges was made by the use of the extended bridge which can withstand ten exits. These gauges used have the following characteristics: Concrete gauge: R:120/0.3%, (Ohm), gauge factor: K: 2.07. Steel gauge: R:120/ 0.2% (Ohm), gauge factor: K:2.1.

2.3. Test Results

Looking at the evolution of the load with the rapture mode, we observed that for the control beam (BC), the first minimal flexural cracks were produced in the loading zone where the maximum bending moment is located. But suddenly, the shear cracks appeared, of which the major crack, appeared on the left side at a load of about 46.5 kN. The crack extended from the loading point to the support and, as the load progressed, a second inclined crack appeared on the right side with the presence of other minor vertical and ascending cracks. The beam ruptured at a load of about 84 kN. The main crack is inclined and the failure was fragile, it was less aggressive than in the case of all the other reinforced beams. For other reinforced beams. The same phenomenon is repeated, however with a slower time and the deviations of the values of the first cracking and failure loads are illustrated. All beams are classified as short beams due to the a/h value [30] (Fig.5). The major fracture crack was reported to be oblique in shape (45%) in each case. Table 2 gives all the values found for the different test beams.

Fig.5 - Major crack in the test beam BC

Table 2

Results values after the test.

Beam	Load/first crack (kN)	Major crack	Load/Rupture (kN)	Max/deformation µm	Ratio crack/rupture
BC	46.5	Tilted/45%	84.3	987.6	55.16
BL	73.4	Tilted/45%	90.0	1167.3	81.56
BR1	81.2	Tilted/45%	134.8	1186.7	60.02
BR2	87.4	Tilted/45%	157.6	1242.1	55.42
BR3	93.8	Tilted/45%	169.5	1342.5	55.34
BR4	100.23	Tilted/45%	184.7	1395.6	54.27

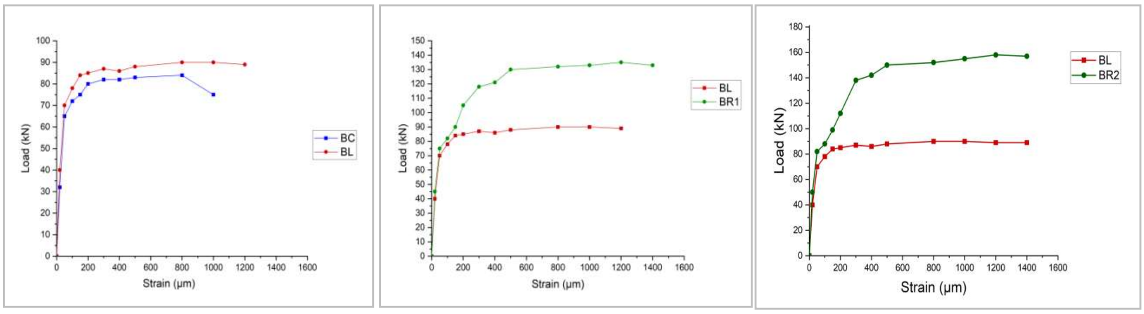


Fig. 6a - Load- strain curves BC-BL. Fig.6b - Load- strain curves BL-BR1. Fig.6c.- Load- strain curves BC-BR2.

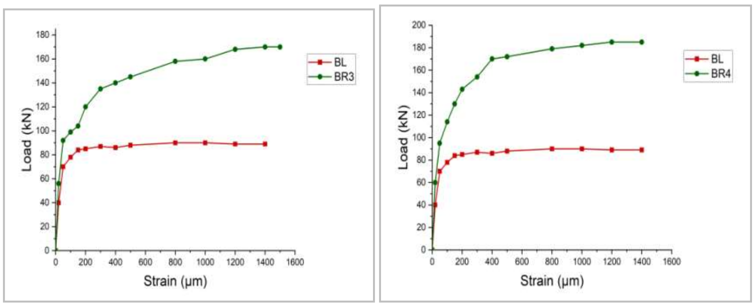


Fig.6d - Load- strain curves BL-BR3.Fig.6e - Load- strain curves BL-BR4.

CNTs are known for their high mechanical properties [31]. They have shown great potential in the reinforcement of carbon fiber composite materials (CFRP). This was confirmed by the results found in our study. Indeed, Figures: 6a, 6b, 6c, 6d and 6e, show that the reinforcement by composites influence the behavior of the beams and this influence is more precise depending on the participation rate of CNT nanotubes in the epoxy resin. As the rate increases, the load (stress) increases and the crack/break rate is reduced.Comparing the different types of reinforcement, with the percentage of inserted nanotubes (CNTs), we can see that the BR4 beam (2% CNTs) has more promising results with an increase in breaking load reaching the value of 184.5 kN, which represents a gain of 105% (Fig.6e), compared to 169.5 kN for the BR3 beam (1.5% CNTs), representing a gain of 88.34%, or 157.6 kN (BR2 beam-Fig. 6d) and 134.8 kN, representing gains of 75.11% and 49.78% (Figs.6c and 6b), respectively. These results confirm the interest of the insertion of nanotubes in the resin/matrix of the applied composite on the behavior of the beams and consequently on the stiffness of the reinforcement [25]. Regarding the ratio of the first cracks appearance force/breakage force, it shows that the percentage varies between 54% and 81%, with an appreciable reduction for the case of reinforcement of the composite modified by the addition of nanotubes (CNTs)/percentage of 2%. The value of 54.27%, gives an idea on the dissipated energy that is significantly reduced.

2.4 Numerical Simulation

Three-dimensional finite element (FE) models were generated using appropriate commercial

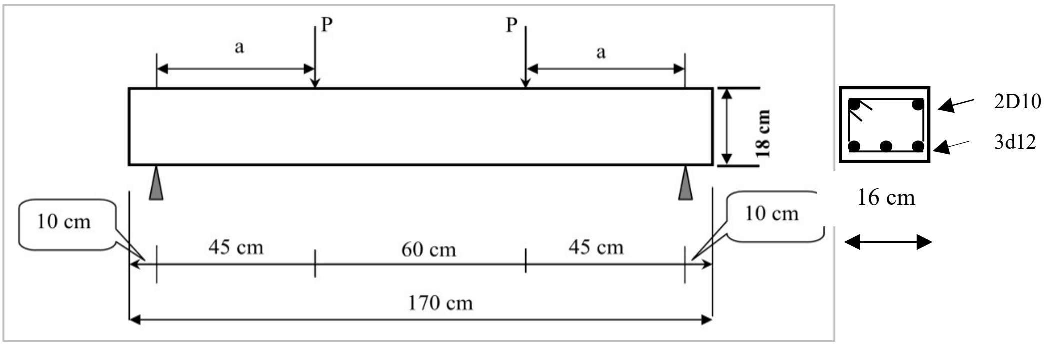


Fig. 7 - RC beam dimensions and reinforcements and loading configuration.

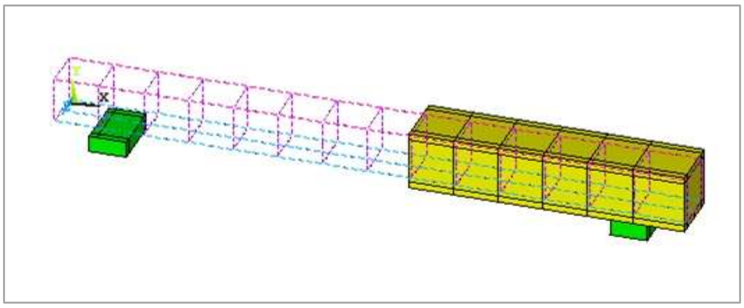


Fig.8 - Finite element model of the beam with steels bars.

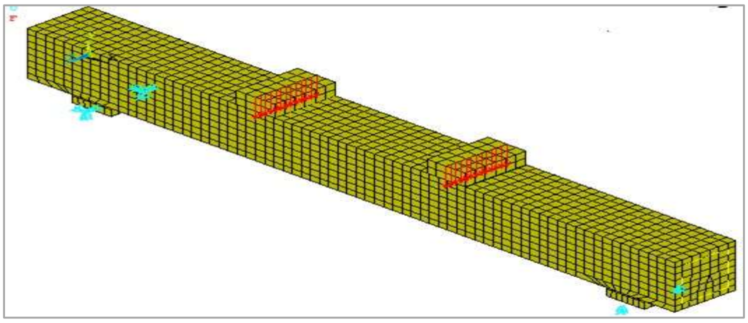


Fig.9 - Discretization and meshing of the test beam by FE

software. The geometry, support conditions and loads of geometry, support conditions and loads are similar to those of the developed experimental work (Fig.7). The FE model of the beam is shown in Figures 8 and 9. Due to symmetry and for saving computational time, a quarter model of the tested beams was modeled and simulated [32]. Meshing and convergence analyses were performed by testing the different models. Table 3 shows all the mechanical characteristics of the laminated plates (CFRP) as well as the adhesive epoxy sikahard (reinforced with CNTs). For the other materials, the same characteristics were taken as those taken in the experimental part (Table 3).

In order to (To) simulate the behavior of the reinforced beams, the concrete geometry (Solid65 3D) is constructed by a volume element (block), which is defined using eight nodes located on its edges. The steel bars were modeled using (Link 180), which is a three-dimensional spar element with uni-axial tension and compression properties. Link180 was defined using two nodes located on its edges and CFRP composites modified with CNTs, were modeled using the element (Shell 181). The nodes of the CFRP layer element (shell 181) and the discretized pieces of the steel element (link 180) are connected to the nodes of the adjacent concrete elements (solid 65) to provide the perfect bond (glue) between the two materials. For the single-bearing plates of the beam, the element chosen is Solid 185. These elements are connected with the concrete node by node [33] In order to establish the proper load distribution, and to ensure the best connectivity between the different discretized elements.

The discretization by finite elements gave a significant number of elements for the six tested beams. The Table4 below, gives us a summary of the overall number of model elements used. A total number of 2980 elements for the control beam (BC) and an identical number of 3076 for all other beams reinforced with CFRP/CNTs. The finite element modeling yielded significant values of bearing capacity, and concrete-deformation of each tested

Table 3

Mechanical characteristics of composites modified by CNTs

Beam notation (Ratio CNTs)	Modulus E LaminateSika (GPa)	Modulus E Epoxy Sikahard (GPa)	Poisson Ratio
BC	165	-	-
BL (0%)	165	12.5	0.25
BR1 (0.5%)	165	20	0.25
BR2 (1%)	165	25.5	0.25
BR3 (1.5%)	165	30	0.25
BR4 (2%)	165	38.5	0.25

Table 4

Summary of the elements of the FE model mesh

Model beam	Number of elements				
	Solid 65	Link 180	Shell 181	Solid 15	Total
BC	2448	404	/	128	2980
BL (0%)	2448	404	96	128	3076
BR1 (0.5%)	2448	404	96	128	3076
BR2 (1%)	2448	404	96	128	3076
BR3 (1.5%)	2448	404	96	128	3076
BR4 (2%)	2448	404	96	128	3076

Table 5

Comparison between numerical and experimental model values

Beam notation (Ratio CNTs)	Ultimate load (kN) Exp.	Ultimate load (kN) FE	Variation (%)	Strain (μm/m) Exp.	Strain (μm/m) FE	Variation (%)
BC	84	87.5	3.50	987.6	993.5	5.97
BL (0%)	90	95.3	5.90	1167.3	1175.2	6.78
BR1 (0.5%)	134.8	141.2	4.75	1186.7	1251.7	5.48
BR2 (1%)	157.6	165.3	4.90	1242.1	1314.2	5.77
BR3 (1.5%)	169.5	178.2	5.13	1342.5	1407.4	4.83
BR4 (2%)	184.5	192.1	4.12	1395.6	1451.8	4.03

beam. Table 5 presents a comparison of numerical and experimental values of the bearing capacity, deflection and concrete deformation of the different beams tested. These values show a good correlation between the finite element analysis and the experimental results, with a stiffness finding in favor of the finite element model. Several factors may be responsible for this high stiffness in the finite element models, among others, the connection between the concrete and the steel reinforcement, on the one hand, and the connection between the concrete and the composite (CFRP-matrix), on the other hand, are assumed to be perfect (no slip) in the finite element models.

To validate the finite element model, a comparative study with the published experimental results was carried out. The verification of the FE results goes through a gradual path by comparing the FE result and the experimental results through the values found for the load-deflection, as shown in Table 5. For the analysis of the ultimate load result (bearing capacity) which is, for the control beam BC, 84 kN compared to 87.5kN in favor of the FE model, i.e. a difference of 3.5%. Similarly, for beams strengthened with CFRP (modified with CNTs), the FE model gives a slight difference between 4.12% and 5.90%, which is acceptable [34]. For the deformations, the maximum value appears for the beam rigidly reinforced with 2% CNTs (both experimentally and by the FE model). The difference between the two approaches varies between 4.03% and 6.78%. based on several recent investigations [35-36], the established model, with the non-significant deviations, remains acceptable.

Numerical FE analysis with adapted software records a crack pattern at each stage of the applied loading. Figures 10(a), 10(b) and 10(c), show the evolution of the cracks developing for each beam tested, up to the last loading stage [34]. It can be seen that circles appear at the cracking locations or crushing in the concrete elements. Cracking is represented by the outline of a circle in the plane of the crack. The first crack at an integration point is represented by a red circle, the second crack by a green circle and the third crack by a blue circle.

3. Diagnostic and Numerical analysis

3.1. Study object

In order to monitor the behavior of a reinforced concrete beam bridge, located in a seismic region in Algeria, which requires repairs of some of its load-bearing elements, the carbon fiber composite material plating technique was applied.

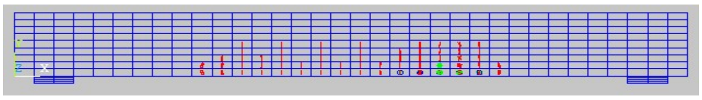


Fig. 10a. Cracks initiation for control beam by FE

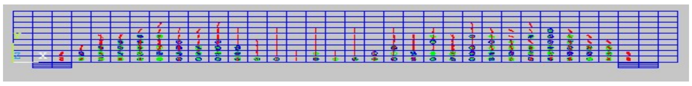


Fig. 10b. Crack propagation for tested beam by FE

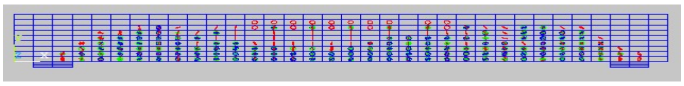


Fig. 10c. Cracking before beam failure

Fig.11 - View of the hyperstatic bridge on Oued Hachem.

Fig.12 - View from inside the degraded beams and support.

A preliminary modeling work using the finite element method (FEM), with appropriate software, was undertaken.

The aim of this study is to see the influence of nanotubes (CNTs) inserted in the epoxy resin of the composite materials, with the worst - case percentage of 2% (results of the experimental study). After a diagnosis was made, determining the causes of degradation, a modal analysis study of the structure in question was made for three cases: modeling of the unreinforced bridge in its actual state, modeling of the composite reinforced bridge (without nanotubes) and modeling of the composite reinforced bridge with the insertion of the resin/matrix of nanotubes (CNTs) at 2%.

3.2. Case study

It is a viaduct over the Oued elHachem located in the commune of Cherchell in the city of Tipaza, 80 km west of Algiers, located in zone III characterized by high seismic activity [37]. The structure was built in 1978, is a hyper-static bridge with three spans, the deck consists of four reinforced concrete master beams, with variable inertia, connected by spacers and concrete beams topped by a reinforced concrete slab, while the substructure is composed of two intermediate piers and a central pier and two wind chests in the form of simple reinforced concrete supports (Fig.11). The geometrical characteristics of the bridge are:

- Total apron length: 69m;
- Number of beams: 4 beams spaced 1.8m;
- Thickness of the slab on beams: 25cm;
- Total width of the bridge: 10.40m with two sidewalks of 1.7m each;
- Infrastructures: Sail stacks - 2 sums;
- Hyperstatic bridge at 2 spans (24m) and twoconsoles (10.5m);
- Foundations: surface type;
- Bedrock: 9m×1m×4m;
- Support height: 4.5m.

3.3. Dignostic of degradations

Degradations are visible on the structural elements of the bridge (beams, supports and sails), with cracking in the concrete cover and corrosion of the reinforcement in the beams and supports. The corrosion of the piles affected the concrete lid with minimal loss of steel and concrete section probably due to the aggressive marine environment (Fig. 12). The diagnosis also reveals concrete bursts at the levels of some main elements indicating an increase in bending stresses mainly due to the increase in road traffic. This damage was probably exacerbated by the earthquake that struck the region in 1989 at a magnitude of 6.1 on the Richter scale. The analysis of the degradation and their causes enabled the proposition of rehabilitation and strengthening solution of the deteriorated elements to restore their initial load capacity and gives to the structure its initial performance [1]. The procedure used to strengthen the bridge elements was as follows:

- Repair of all degraded parts with appropriate mortars;

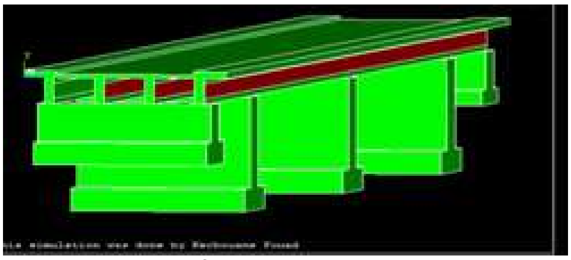


Fig.13 - Application of sikawrap sheet

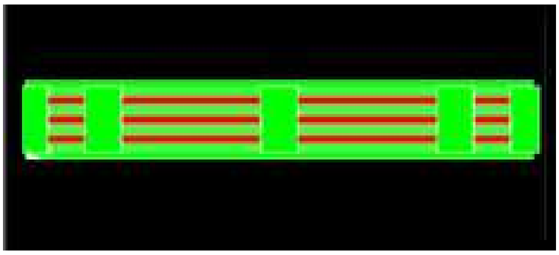


Fig. 14 - The laminate plates on the bottom side beam

Table 6

Mechanical characteristics of the materials used

Used materials	Modulus E (MPa)	Density	Tensile strength (MPa)	Compressive (MPa)	Extension at failure (%)	Thickness (mm)
Concrete	35	2.5	3.0	33.5	-	-
High strength steel	210	7.8	550	550	-	12
Mild steel	210	7.8	400	400	-	6
Epoxy sikahard 30	12.8	1.8	30	55	-	-
Sika wrap sheet	230 000	-	3500	-	1.5	0.13
Laminate sika	165 000	-	2800	-	1.7	1.2

Table 7

Values of the concrete for classic technical of repair

Values of the materials	Elasticity Modulus (MPa)	Poisson coefficient	Tichness (mm)
Before reinforcement	23 000	0.2	varied
After reinforcement	35 000	0.2	added of 10cm

- Injection of cracks by epoxy resin improved by nanotubes (2%);
- Reinforcement of the beams by application of laminated plates (CFRP);
- Application, by confinement, of vertical facings (beams and supports).

In order to restore the initial rigidity of the deteriorated elements and strengthen them in order to be able to withstand new road traffic overloads and extreme weather conditions, the choice of appropriate repair materials is important. Repair techniques are: flexural and shear reinforcement by carbon fiber composite materials for beams and supports. Unidirectional Sika wrap sheets (80 mm in width and 0.13 mm in thickness) were applied to the side faces of the main beams to increase their shear resistance while the carbon fiber laminate Sika carbohard (80 mm in width and 1.2 mm in thickness) were applied to the lower faces of these same beams to increase their flexural strength (Figs 13 and 14). To see the influence of carbon nanotubes (CNTs), inserted in each epoxy resin, used (for the unidirectional Sika wrap or sika Carbodur), on the dynamic behavior of the structure, we took, for the modeling, the most critical results found in the experimental part, namely without reinforcement (0% of CNTs) and 2% of nanotubes (CNTs) insertion in the epoxy. For this, the modeling will focus on three cases:

- Modeling of the bridge in the real state (unreinforced);
- Modeling of the bridge with reinforcement by CFRP without nanotubes (CNTs);
- Modeling of the bridge with CFRP reinforcement, with 2% nanotubes (CNTs).

The characteristics of the repair and strengthening materials used are summarized in Table 6. The repair and strengthening of the bridge structure took 8 months. Data for the testing and modeling was collected on-site from the provincial public works department and other experts or stakeholders.

In the case of the repair by application of the concrete shell, for the other elements of the bridge (supports such as piers and abutments), the added thicknesses gave a slight change and the Young's modulus (E), which will be increased from 15% to 25% [38], compared to the Young's modulus of the existing concrete, due to the improved composition of the added material (concrete). This is a 400Kg/m^3 concrete, composed of washed sand and corrective sand, as well as 3/8 and 8/15 gravel, added with drinking water. This concrete was sprayed on the degraded areas after the preparation of the supports. Table 7 below illustrates the values introduced in the modeling of the selected case study.

3.4. Numerical modeling by finite elements

3.4.1. Analysis data

The application of the finite elements method through with appropriate software allowed the data to be introduced to calculate the mass and cross-sectional rigidity, before and after the repair and reinforcement of the structure of this bridge. If the global mass is not influenced by the insertion of composites (given their lightness), the transverse rigidity (K) on the other hand increases considerably by the increase in the value of the Young module (E).

3.4.2. Numerical analysis

The three-dimensional modeling was carried out by finite elements (EF) and with the software chosen for this purpose. The ground-to-structure interaction has been neglected. The non-linear behavior of concrete and steel, as well as those of applied composites and resins, was taken into account. The finite elements types used in the modeling of the reinforced concrete elements (beams and slabs) with steel fibers are listed in Table 7 [39].

Composite materials were introduced in the calculation of Young's modulus and transverse stiffness of the structure. Concrete reinforced with carbon fiber sheets is considered to retain its actual nonlinear behavior. The deterioration is taken into account, in the finite element modeling, by the choice of the value of the longitudinal elasticity modulus (Young's modulus) E. The E-value of the damaged concrete (before the bridge repair) is significantly lower than that of the concrete after its repair. The beams are simply supported and the supports are anchored in the foundations (Fig.15).

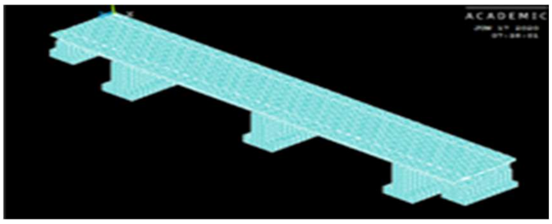


Fig.15. - Modeling of the bridge structure

The modeling was performed by modal analysis of the structure, where the objective is to determine the frequencies and fundamental modes, before and after the reinforcement of the structure to see the influence of the composites and the effect of nanotubes (CNTs) inserted in the resin. The number of modes taken into account is six (6), so that the whole selected modal masses represents the total mass of the structure (about 90%) in our case.

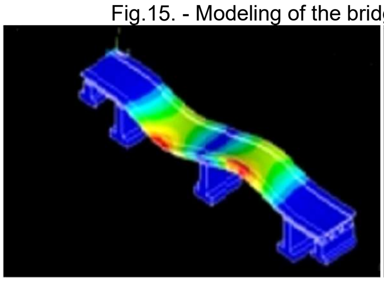
4. Results and discussion

4.1. Numerical modeling

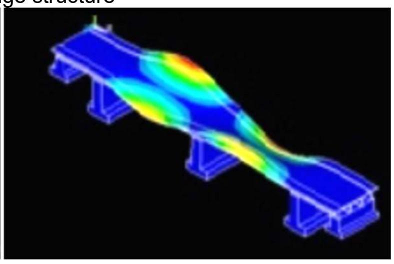
The three-dimensional finite element model that was chosen for the determination of the fundamental frequencies and modes of vibration was able to provide insight into the influence of bonded composites on the overall behavior of the bridge structure. This was not easy, since in order to develop this complex finite element model, several approximations were adopted, taking into account the material properties, the stiffness of the bridge load-bearing elements, the influence of the composite materials, as well as the insertion of nanotubes CNTs in the resin of these materials, adding the bonding mode on the girders and the model of the bridge supports. The finite element model chosen allowed the adjustment of the selected parameters until reasonable values were obtained for the natural frequencies and modal shapes [40].

4.2 Numerical results of the selected model

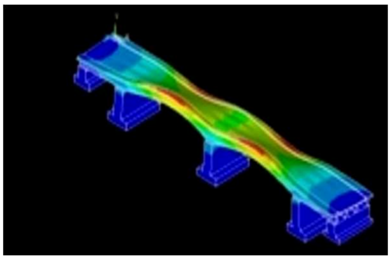
The modal analysis of the structure taken as a case study led to its modal parameters [41]. The modal frequencies obtained by FEM analysis are given in Table 8, with the corresponding modes illustrated in Figure 16.



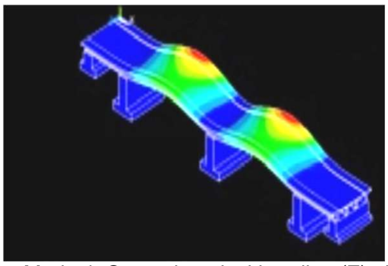
Mode1. Longitudinal Translation (N)



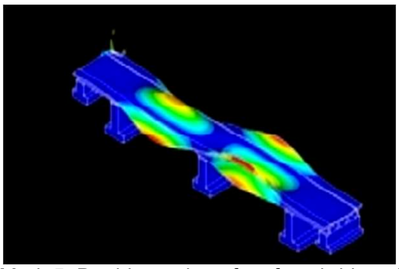
Mode2. First vertical bending (Z)



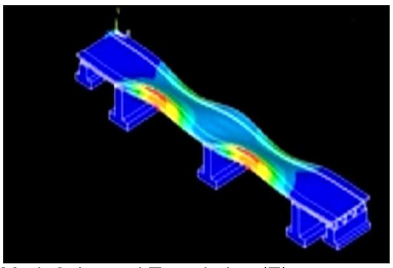
Mode3. Simple torsion



Mode 4. Second vertical bending (Z)



Mode5. Double torsion of surface bridge



Mode6. Lateral Translation (E)

Fig.16 - The different modes obtained for modal analysis testing bridge.

Table 8

Finite elements types

Composing element	Number of nodes
Concrete	8-node brick
Steel	2-node discrete
Composite	8-node brick

Table 9

Frequency values obtained by MEF analysis

N°	Frequency before repair/ CFRP (Hz)	Frequency after repair/ CFRP (Hz)	Frequency after repair with CFRP/CNTs (Hz)	Mode of excitation
1	3.02	3.82	4.93	Horizontal (N)
2	3.28	4.27	6.51	Vertical (Z)
3	4.09	5.08	7.11	Torsion
4	6.53	7.42	9.07	Vertical (Z)
5	8.82	10.12	12.13	Double Torsion
6	12.34	14.07	16.22	Horizontal (E)

The first six dominant modes were distinguished for the three comparisons (before application of reinforcement and after reinforcement by CFRP composites (with and without application of CNTs nanotubes). The dominant mode is the longitudinal translation mode (N) with clear increases (from 3.02 to 3.82 Hz) and (from 3.02 to 5.02 Hz), respectively for the reinforcement with only CFRP composites and for the reinforcement with improved bonding resin performance (Table 9). These are 26.5% and 63.25% gains. It was found that the insertion of nanotubes increased the frequency by almost 34%, with only 2% of use of CNTs by weight. For the other modes, the CFRP composite was found to improve the frequency by about 31% at most, compared to almost 98.5% for the CFRP with resin mixed with CNTs. The improvement in the quality and performance of the adhesive of the composite is very beneficial for the repair of concrete structures due to the appreciable increase in transverse stiffness Ky. For the shapes of the vibration modes, the same observation (type of mode) is generalized and this is understandable given the transverse stiffness Ky much higher than the longitudinal stiffness Kx of the tested structure [42].

4.3 Comparaison and comments

By correlating the experimental results obtained from the laboratory bending test (on a reduced scale) on beams reinforced by insertion of na-notubes (CNTs) and the numerical model of the reinforced structure (full scale), we clearly see the gain brought by the increase in the performance of the resin glue (adhesive). In fact, the parameters that influence the static behavior of the beams (breaking force) or the dynamic behavior of the bridge (natural frequencies of vibration), are the Young's modulus of the composite element (concrete - CFRP) and the more adequate adhesion in the interface (glue - fibers).

5. Conclusions

The present paper studied the behavior of reinforced concrete structural elements strengthened by the application of composite materials with CNTs nanotubes insertion. The work consisted, on the one hand, of an experimental investigation where twelve reinforced concrete beams were fabricated, strengthened by CFRPs (without or with CNTs nanotubes), and then tested under four-point bending loads. In the second part, a modal analysis using the finite element method was undertaken on an old concrete bridge structure, whose load-bearing elements were reinforced with CFRP composites reinforced with 2% CNTs nanotubes. The following conclusions can be drawn:

- The incorporation of nanotubes (CNTs) in the adhesive of the composite increased the strength of the tested beams, with dosages varying from 0.05% to 2% of these nanotubes. The latter gave gains ranging from 68% to 116% (BR1, BR2, BR3 and BR4 beams), against 57% without CNTs (BL beam), an average increase of 40%.
- The finite element model chosen to calibrate the experimental results of the reinforced beams, gave values very close to the experimental reality, with values ranging from 3.5% to 7% (for failure load or deformation), which suggests that the model was adequate. The numerical modeling by application of the Finite Element Method (FEM), widely used universally, allowed us to choose a numerical model close to reality and allowing a thorough reading of the results.
- It is possible to apply the technique of bonded composite reinforcement, improved by the insertion of nano-composite powders CNTs (at the level of the resin) on the support of a concrete beam deck, to avoid the delamination (debonding) of the composite, especially in aggressive climates.
- The value of the modulus of elasticity E indicates the actual condition of the material and possible damage to the deck. The transverse stiffness Ky, before and after strengthening, reflects the changes in the structure.
- The predominant mode of the bridge is vertical bending, in the horizontal direction, with a frequency of 3.02 Hz before the CRFP reinforcement and 3.82 Hz and 4.93 Hz respectively after (without and with CNT).

- The obtained results, both experimental and numerical, allow recommending an adequate choice of the repair and/or strengthening technique for all old or deteriorated structures of the existing reinforced concrete heritage.

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