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Original Article

Confinement of Concrete Specimens Reinforced with Carbon Fiber Reinforced Polymers: Comparison Between Experimental Results and Numerical Modeling

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Abstract *- Following the industrial evolution experienced by the modern world, the abundance of CO_2 in the environment has directly induced the degradation of RC (reinforced concrete) structures due to the corrosion of the reinforcements; faced with these challenges, the confinement of RC structures with CFRP (Carbone Fiber Reinforced Polymers) becomes a minimalist solution with several advantages such as increasing resistance and ductility, as well as the ease of implementation on different types of geometry given the flexibility of CFRP and The lightness of this composite. This article will present a confrontation between the results of a test campaign carried out on cylindrical concrete specimens confined with several layer thicknesses of CFRP and then compare them with the results of numerical modeling carried out on finite element software. The numerical results obtained are close to those of the experimental ones, and the model can reproduce the ruptures and the various modes of damage observed. The models also gave a good prediction of the loading levels and the ultimate compressive strengths that caused the specimens to fail.*

Keywords *- CFRP, Confinement, Ductility, Failure, Reinforced concrete.*

1. Introduction

In order to overcome the problem of structural degradation, concrete structures may require reinforcement during their service life. In addition to the classic jacketing, reinforcement by external bonding, on the surface, of Fiber Reinforced Polymers (FRP) through resin hardening at ambient temperature is used for its efficiency and ease of implementation.

In recent years, the use of FRP composed of resin and reinforcements in the field of civil engineering has increased. Composite materials have great flexibility in adapting to the most complicated geometric shapes of the reinforced elements and for their lightness compared to steels, ease of transport and implementation on site, and their greater mechanical resistance than other reinforcements. These mechanical and physico-chemical advantages allow the use of composite materials as a promising method of reinforcement and rehabilitation of reinforced concrete structures [1,2,3,4,5,6]; the application of fabrics or strips [7,8,10,11,12,22] is an interesting alternative to conventional repair methods (Figure 1).

In order to evaluate the efficiency of this solution, a survey of compression tests was carried out on concrete specimens, which were reinforced with CFRP confinement. The program contains 12 cylinders subjected to a simple compression test:

- 3 unconfined concrete specimens
- 3 cylinders confined with a single layer,
- 3 cylinders with double layers and
- 3 cylinders with 3 layers

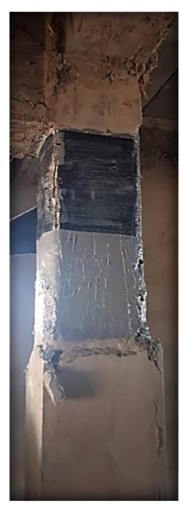

Fig. 1 Reinforcement of critical column areas with CFRP in a building under construction in Beni-Mellal, Morocco

Then numerical modeling will be made on a finite element software in order to:

- Evaluate these stresses and deformations in areas difficult to instrument and analyze.
- Study the contribution of the proposed repair techniques, namely: the use of composite materials such as CFRP.
- Compare and validate the results with those of the experimental results.

2. Experimental Study

This chapter deals with the experimental program that was carried out containing short cylindrical samples (slenderness λ=2) in concrete confined with a carbon fibre-reinforced polymer "CFRP".

The specimens were subjected to simple compression tests; this test determines the mechanical characteristics (compressive strength, modulus of elasticity E and the Poisson's ratio υ) and the behavior law of the concrete. The cylindrical specimens, with dimensions 160 mm in diameter and 320 mm in height, are tested according to the procedure defined in standard ASTM C39/C39M-03. The stressing must be carried out without shock and in a continuous manner at a speed of 12.063 KN/second.

2.1. Material Characteristics

2.1.1. Concrete

In this experimental program, the concrete used to manufacture the specimens studied was recovered from a concrete plant in a construction site in Rabat-Morocco. The concrete used is C30/37 concrete with a compressive strength after 28 days of hardening of 30 Mpa on a cylindrical specimen and 37 Mpa on a prismatic specimen.

2.1.2. CFRP

A carbon fiber fabric of the SikaWrap-230C type is used for the confinement of the specimens of the program of this study. It is a structural reinforcement fabric based on carbon fibers woven in a unidirectional way.

The SikaWrap-230C consists of 99% warp yarn and 1% weft yarn. The fabric is provided with special weft threads, giving good dimensional stability (Figure 2).

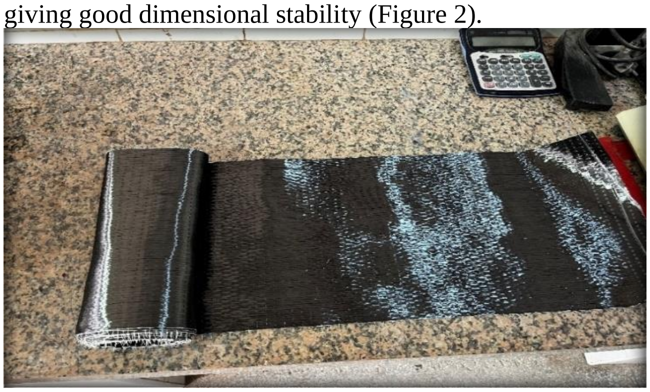

Fig. 2 CFRP Sikawrap 230C used in the experimental study

Table 1. Identification of specimens from the experimental program

Identification	Section (mm)	No. of layers «CFRP»	f'co (MPa)	Slenderness L/D
L0-E1	Ø160 x 320	0	30	2
L0-E2				
L0-E3				
L1-E1		1		
L1-E2				
L1-E3				
L2-E1		2		
L2-E2				
L2-E3				
L3-E1		3		
L3-E2				
L3-E3				

2.2. Test Program

In this experimental program, we adopted the following identification Lx-Ey for the 12 specimens tested, where x is the number of reinforcement layers of the specimen and y is the number of samples tested. The twelve specimens prepared will be identified according to the designation and identification displayed in Table 1.

All specimens have a circular section of 16 cm in diameter and 32 cm in height and a compressive strength without reinforcement with CFRP, estimated at 30 Mpa.

The Sikadur 330 resin is applied to the prepared support using a notched trowel to achieve a deposit of approximately 0.7 to 1.2 kg/m², depending on the roughness of the support. The "PRF" fabric is placed, in the desired direction, on the resin layer and then carefully embedded in it by smoothing it with an impregnation roller. The latter allows the resin to be distributed until a homogeneous structure is obtained. The smoothing is done in the direction of the fibres. For the application of new "PRF" plies, a new layer of resin is spread each time on the old pile at a rate of approximately 0.5 kg/m² (Figure 3). The previous coat must be applied within 60 minutes (at 20°C). If this is impossible, we must wait at least 12 hours before applying a new coat.

The strips of reinforcing fabric (carbon fibers) were measured and then cut using scissors. The length of the bands of a confinement fold corresponded to the perimeter (for one layer) or to n times the perimeter of the specimen considered (for n layers) and increased by a length to ensure an overlap of 1/4 of the perimeter [3] which allows the full strength of the fibers to be developed, without slippage or detachment of the composite layer, (Figure 4).

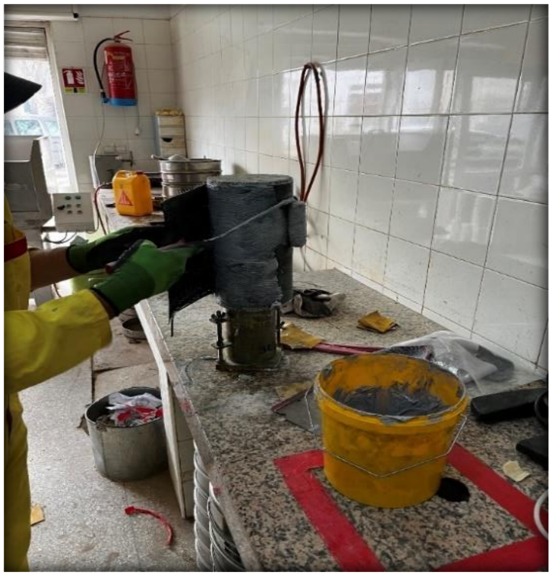

Fig. 3 Impregnation of the CFRP using the resin on the concrete support

Fig. 4 Overlap length for confined circular specimen with 1 "PRF" layer

Fig. 5 Failure mode of cylindrical specimens confined with CFRP

After applications of the CFRP on the specimens, and to allow the complete adhesion of the polymer with the concrete through the applied resin, we proceed to the storage of these specimens in a place at a constant average temperature of 22.8°C and humidity not exceeding 72% for a period of 10 days.

2.3. Failure Mode

The collapse of cylindrical specimens (Ø160x320 mm) reinforced with confinement in CFRP is generally marked by a sudden break, preceded by cracks in the composite, in a direction perpendicular to the carbon fibers, followed by a failure in the circumferential direction of the cylinder along bands of different widths (Figure 5).

This circumferential failure mode is probably due to the unidirectional nature of the carbon fabrics used. In the case of highly confined concrete cylinders (3 layers of CFRP), the failure of the composite envelope propagates over almost the entire height of the cylinder. On the other hand, in the case of weakly confined cylinders (1 CFRP layer), the casing breaks over a length of approximately 100 to 150 mm.

In all concrete cylinders confined with CFRP used in these tests, the rupture is generally localized in the central third of the specimen.

At the level of the overlapping zones or the interfaces, the composite fabric suffered neither breaking nor apparent slippage.

2.4. Analysis and Interpretation of Experimental Results

The twelve specimens, including the three control specimens L0E1, L0E2 and L0E3, were subjected to the crushing test, the maximum breaking load, and the maximum compressive strength for the three tests listed in Table 2.

Table 2. Compression test results

Specimen ID	Breaking load (KN)	Resistance (Mpa)	% Increased Resistance
L0E1	607,917	30,24	-
L0E2	583,40	29,02	-
L0E3	633,33	31,50	-
L1E1	900,78	44,80	48,10%
L1E2	927,44	46,13	52,49%
L1E3	961,11	47,80	58,02%
L2E1	1 398,13	69,54	129,87%
L2E2	1 188,37	59,10	95,39%
L2E3	1 207,28	60,05	98,50%
L3E1	1 527,14	75,95	151,08%
L3E2	1 674,47	83,28	175,31%
L3E3	1 528,27	76,01	151,27%

The experimental results are presented in Table 2, presenting for all the specimens tested, the maximum values obtained for the breaking loads, the compressive strengths, the gains in compressive strength of the cylinders confined with composite materials of the " PRFC" to the unconfined cylinders (witnesses: L0E1-L0E2-L0E3).

Table 2 shows the effect of increasing confinement stiffness on the behaviour of specimens subjected to the axial compression test; increasing confinement stiffness leads to an increase in compressive strength. The higher the number of layers of the CFRP reinforcements (and therefore the stiffness of the containment), the greater the compressive strength at break. This implies that the ultimate breaking load increases with the increase in the number of CFRP layers (increase in the thickness of the composite envelope).

On the three control specimens tested (L0E1-L0E2-L0E3), the average strength of the unconfined concrete f'_{co} (initial strength of the concrete before the external confinement by the CFRP composite) f'_{co} = 30 Mpa.

Based on this resistance, we have observed a very remarkable increase in the ultimate load and, consequently, in the compressive strengths of the specimens confined with CFRP composite materials. The external containment with CFRP composites has made it possible to considerably increase the ultimate load of the cylindrical concrete specimens subject to the tests.

C30/37 concrete cylinders confined with 1 CFRP layer gave compressive strength gains of 48.10%, 52.49%, and 58.02%, respectively, for L1E1, L1E2 and L1E3, an average increase of 52 .87% equivalent to single layer CFRP containment.

C30/37 concrete cylinders confined with 2 CFRP layers gave compressive strength gains of 129.87%, 95.39%, and 98.50%, respectively, for L2E1, L2E2 and L2E3, an average increase of 107.92% equivalent to two-layer CFRP containment.

C30/37 concrete cylinders confined with 3 CFRP layers gave compressive strength gains of 151.08%, 175.31%, and 151.27%, respectively, for L3E1, L3E2 and L3E3, an average increase of 159.22% equivalent to three-layer CFRP containment.

The average values of the compressive strength gains of all the specimens in the experimental program are expressed in Figure 6. The increase in strengths of the specimens confined in CFRP with single and two layers is considerable. However, for the specimens confined with 3 layers of CFRP, the strength gains were very significant, with a 159.22% increase.

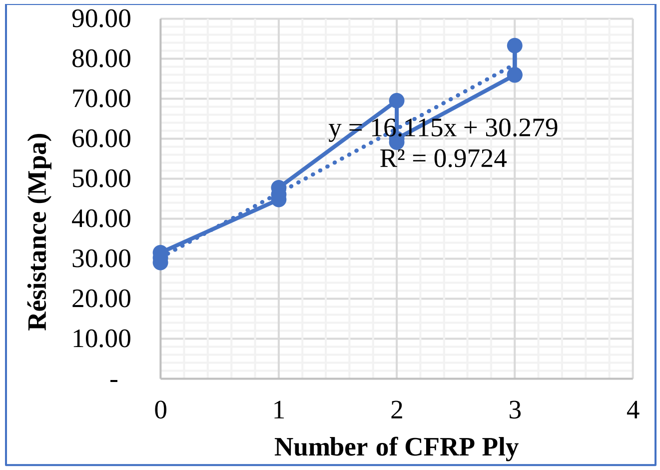

Fig. 6 Increase in Compressive Strength as a function of the number of CFRP reinforcing plies

The correlations obtained from Figure 5 show that the variation in the compressive strength of the confined concrete (f'_{cc}) as a function of the number of layers [n] of the CFRP composite corresponds to a linear function. However, for the variation of f'_{cc} according to the number of CFRP layers: the coefficient of variation $R^2 > 0.90$.

3. Numerical Modelling

The finite element calculation method is a method that makes it possible to transform a continuous problem into a discrete problem, the solution of which is approximated according to the data of the model.

This method provides a good approximation of the states of stress and strain inside the materials.

The finite element calculations were carried out using the most advanced techniques currently available.

3.1. Introduction of the Model and Mesh

We proceeded to the modelling of the compression test cylinder object and the reinforcement (CFRP) enveloping the specimen. The thickness of the reinforcement will be increased to assimilate the number of CFRP reinforcement layers.

An automatic rectangular mesh was adopted of size 20x20 mm². Therefore, a rectangular mesh was generated in the faces of the specimen. This correctly sets the width and length of the elements. The geometry and the overall mesh of the concrete volume are illustrated in Figure 7.

For more precision, we carried out a refinement of the mesh at the level of the CFRP reinforcement in order to be able to highlight the real behaviour of the composite object of study (Figure 8). Figure 8 illustrates the geometry and the rectangular mesh size of 10x10mm² adopted for the CFRP composite.

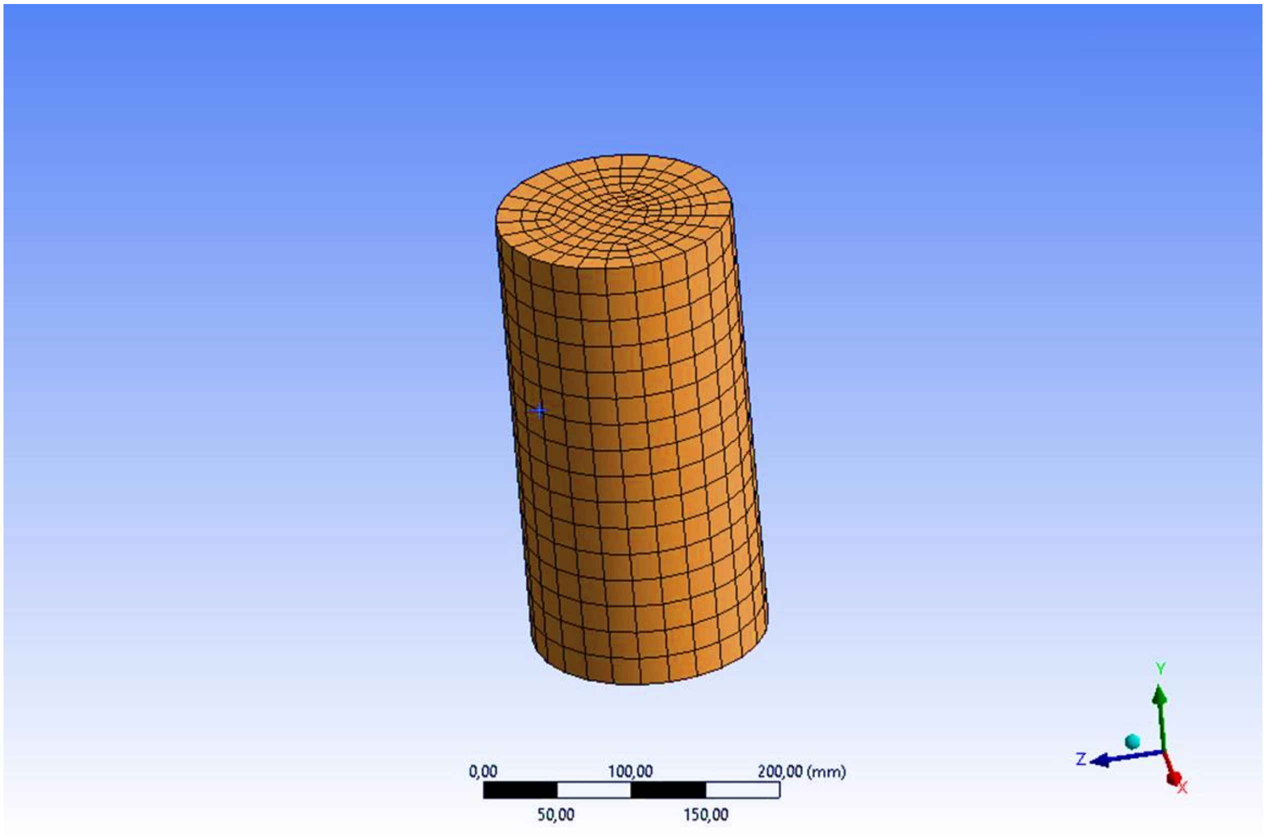

Fig. 7 Concrete cylinder 160x320 mesh

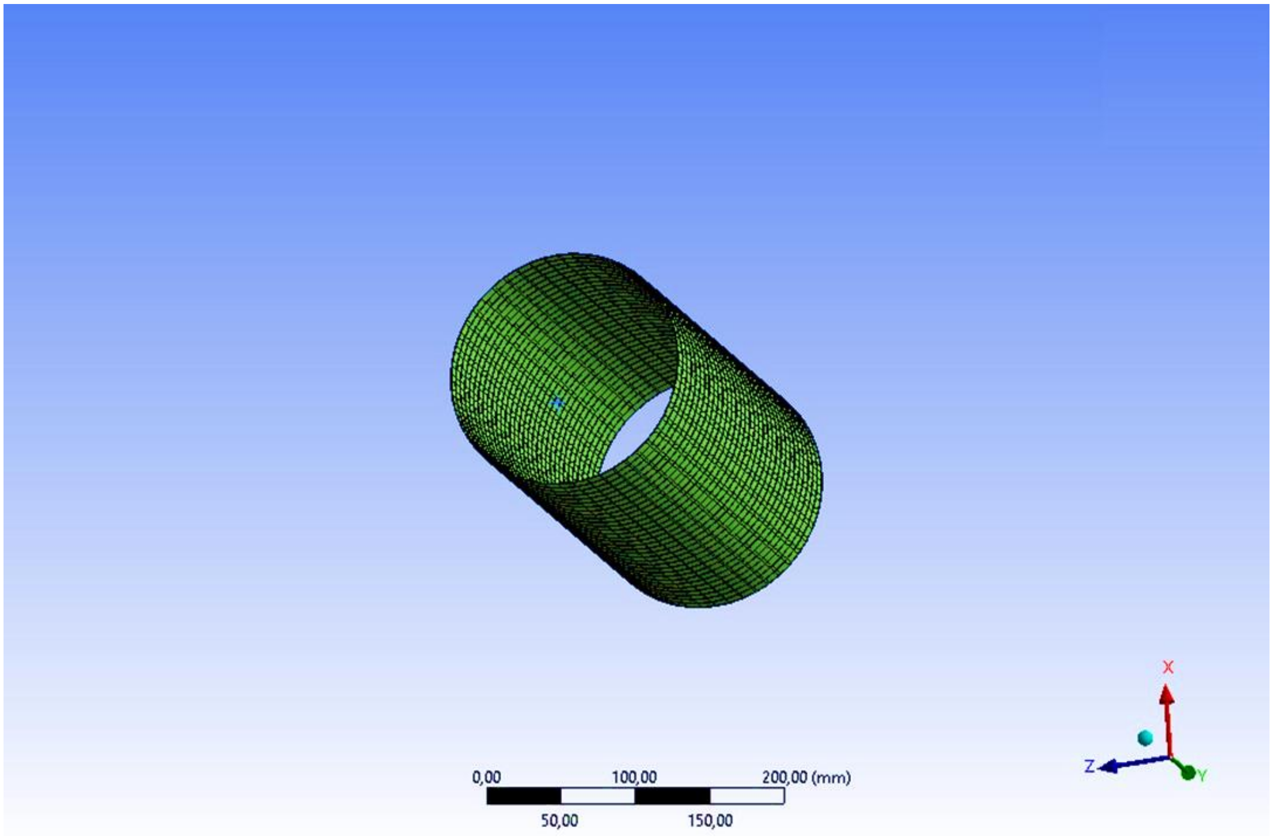

Fig. 8 CFRP composite mesh

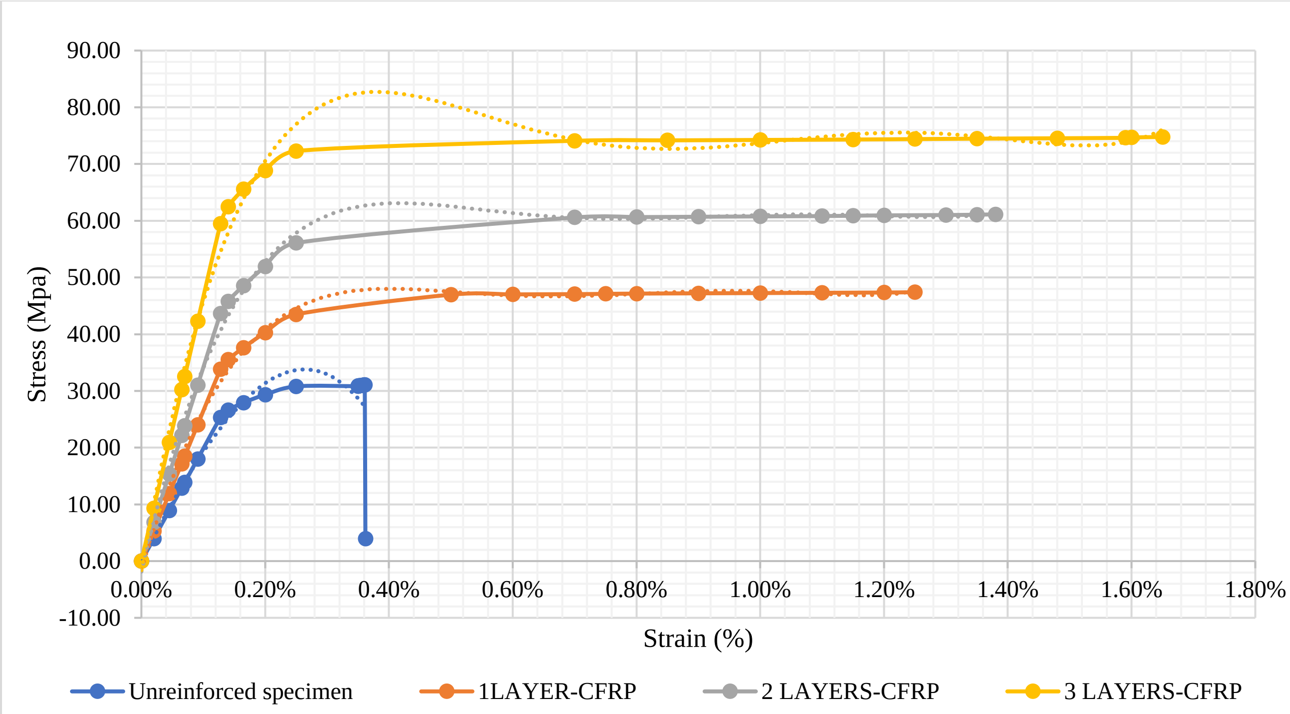

Fig. 9 Stress-Strain Curves

Table 3. Comparison of experimental and analytical results of compressive strength of CFRP reinforced specimens

Specimen Type	Experimental		Analytic	
	Rmoy (Mpa)	**% increase**	**Rmoy (Mpa)**	**% increase**
Unreinforced specimen	30,25	0%	30	0%
Reinforced specimen with a single layer of CFRP	46,24	52,86%	47,39	57,97%
Reinforced specimen with two layers of CFRP	62,9	107,93%	61,13	103,77%
Reinforced specimen with three layers of CFRP	78,42	159,24%	74,76	149,20%

3.2. Stress-Strain Curve

The numerical stress-strain curves for each configuration are compared (Figure 9). The comparison shows that the model can faithfully represent the mechanical response of the specimens under compressive loading along the longitudinal axis.

For the four models studied, it can be seen that the slope of the linear part of the stress-strain curve increases with the increase in the degree of reinforcement, hence an increase in Young's Modulus. The plastic zone becomes larger with the increase of the confinement in CFRP as well as the strain at break, which increases from 3.5‰ for an ordinary concrete of 30 Mpa to 12.5‰, 13.8‰ and 16.5‰ respectively, for a specimen reinforced with 1, 2 and 3 layers of CFRP.

On the other hand, we notice that the results of the numerical simulation and the experimental results are in fairly good agreement (Table 3).

4. Conclusion

The experimental work devoted to the study of the behaviour of concrete confined by CFRP composites is numerous [12,13,15,23]. The three-dimensional behaviour models proposed in the literature for confined concrete are often validated using this work carried out on small specimens [16,18,19,20,24]. However, the validation of the models on these tests is not sufficient to assess their ability to model the behaviour of concrete during complex loading paths that occur in the case of real reinforced concrete structures.

This article presented the results of the experimental study carried out on the 16/32 cylindrical specimens of a C30/37 concrete reinforced with CFRP fabrics, and this within the framework of an experimental investigation and also presented the finite element models developed to analyse the behaviour of specimens reinforced with CFRP confinement under uniaxial compressive loading.

The 3D finite element models have been implemented in the software using the dynamic structure solver. A series of simulations were performed to provide more detail on how the specimens are damaged and to simulate damage and failure in the specimens stressed in compression. The numerical results obtained are close to those of the experimental ones, and the model can reproduce the ruptures and the various modes of damage observed. The models also gave a good prediction of the loading levels and the ultimate compressive strengths that caused the specimens to fail, and the models also provided a better understanding of damage initiation and evolution than experimental tests.

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