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Repair and Strengthening of Damaged Reinforced Concrete Slabs With CFRP

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1 ABSTRACT

This paper is first devoted to the experimental analysis of the behaviour of RC slabs submitted to a complex loading. Eight RC slabs are submitted to a combined load corresponding to membrane and bending loads. The loading process is stopped just before the ruin, and then the structure is unloaded and repaired using CFRP layers. The loading process is repeated again until the collapse, which permits to gauge the effect of the reinforcement on the bearing capacity of the structure. The test results indicate that the application of the CFRP strips significantly increases the load bearing capacity, of about 50%, and improves the stiffness of the slab, of about 120%. Numerical simulations are also conducted with the finite element code Cast3M. A good agreement with the experimental results is obtained in the case of the RC slab, the simulation in the case of the repaired damaged slab by CFRP layer is still in progress. This study aims to valid the procedure of reinforcement of cooling towers shell structures.

2 INTRODUCTION

Experience has shown that reinforced concrete structures, exposed to severe environmental attacks such as alkali-silica reaction or corrosion of rebar, to cyclic load, or to accidental overloads inducing stresses greater than design stresses, are hence subjected to damage which generally corresponds to cracks appearance. The serious deterioration of materials, coupled to design errors or/and to accidental overload, or to differential settlement of supports, can lead to catastrophic failures; or at least, because of the propagation of the damage, to a diminution of the structure’s lifetime. It is now of a fairly common practice to repair concrete structures as it is a non-expensive and non-obstructive upgrading procedure. One of the common techniques for repairing and strengthening is to glue a CFRP layer onto the tension faces of the structures. Composite materials, thanks to their high strength, high stiffness, resistance to corrosion and low weight, can be of great interest in civil engineering structures. Their use is particularly attractive, especially in order to increase the structural performance, but also because of the ease to forming, the speed of installation, the optimisation possibility according to the direction’s reinforcement choice, and the multifunctionality (strength, anti-corrosion, tightness). In the past few years, several research programs were conducted to investigate the feasibility of using technologies of polymer composite for repair and retrofitting of structural elements Meier and all (1993 & 1997). While much research on RC structures reinforced by external bounded CFRP has been carried out in recent years, these studies mainly concern beams and columns Varastehpour & all (1996); only few researches have been done on reinforced concrete slabs Mosallam (2000), Khalid and all (2001), Ayman and all (2003), Rochdi and all (2006). In order to better understand the behaviour of the two-way RC slabs structures damaged cracked then repaired by FRP composite strips under various combinations of membrane and bending loads, an experimental program is conducted at INSA-Lyon, where eight large-sized RC slabs are subjected to this type of loads, or to cyclic loading. Here the results of one particular specimen are given and Finite Element simulations of this test are also conducted.

3 EXPERIMENTAL PROGRAM

3.1 Experimental device

The test setup used is shown in the figure 1a. In this experimental device, the test specimen is maintained in the vertical position and supported in the vertical symmetrical axis of the slab. It is a self-equilibrated system which principle's function is similar to that of the system of exterior pre-stressing. The test device has two main components: the test specimen or RC slab and the mechanic loading system corresponding to 12 hydraulic jacks, 6 in each direction (horizontal and vertical). The loading bars fixed on the two faces of the slab work only in tension and in compression with the help of pinned joints at the two extremities. The bending moments result from the difference between the forces in the loading bars and their eccentricity compared to the average plan of the specimen (Fig. 1b). This loading system allows various combinations of membrane and bending loads in one direction as well as in the orthogonal direction.

a) General view of the test setup *b) Mechanical loading system*

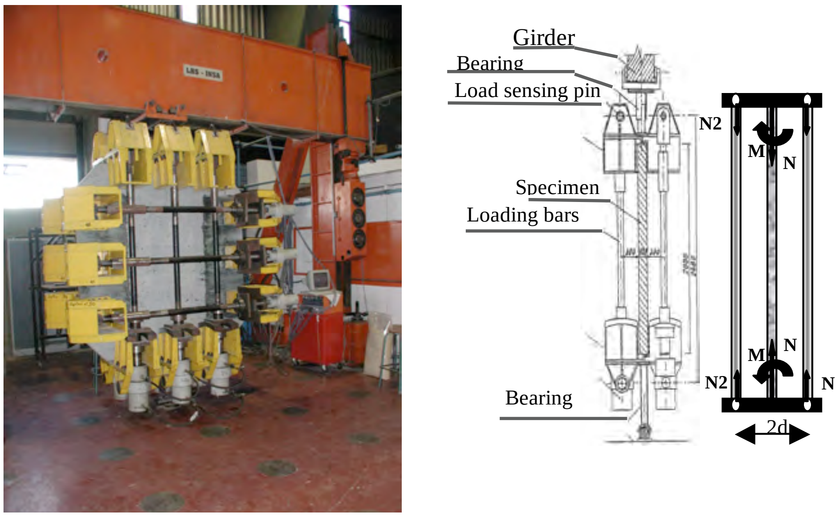
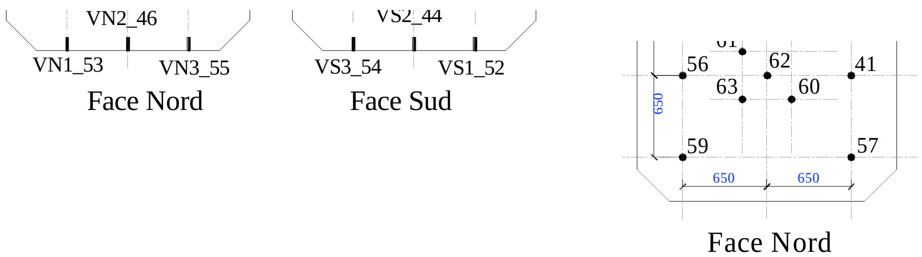


Figure 1. Test setup

Dynamometric axis strainsert SPA50, are used as load cell sensors for the vertical hydraulic jacks (150kN capacity), associated to vertical membrane load. SPA100 dynamometric axis strainserts are used for the horizontal jacks of 400KN generating the bending load. Both deflection and strains are measured according to a system of location lines defined over the slab surface. The deflections are measured with linear voltage displacement transducers (LVDTs), 10 points are considered including 6 points on the two vertical edges and 4 in the centre (Fig. 2(b)). The strains are measured with strain gauges of different sizes depending on the material, concrete, reinforcing steel or composite reinforcement.

(a) Load cells position (b) LVDT positions



North face South face North face

Figure 2. Load cells positions (44 to 55) and position of the LVDT transducers.

3.2 Specimen and material properties

Tests are carried out on 2x2 m^2 slabs, 0.1m thick (Fig. 3). Each slab represents an elementary facet of the shell of a cooling tower (one element associated to the meshing of the surface). According to the reinforcement of RC cooling towers, the slab has 2 reinforcing steel layers, on the two orthogonal directions, composed of steel rebar 10cm spaced. The minimum covering of steel rebar is 30mm and the bars diameter is 6mm. In the peripheral zone of the specimen, the reinforcing steel ratio is doubled, knowing that the excessive loads concentration can provoke the local premature failure of the slab near the load support transmission. Steel bars reinforcement details are given in figure 3, and their mechanical characteristics obtained from tensile tests are summarized in table 1.

Table 1. Characteristics of the steel bars reinforcement.

E (GPa)	fy (MPa)	y (10^{-3})	fu (MPa)	u (10^{-3})
218	506	2,51	621	60,95

The concrete was manufactured to class C40. Table 2 presents the ratio of components in the concrete mixture and the obtained mechanical characteristics. The compression tests were carried out on 11x22 test-samples in accordance with the NF P 18-406 standard, and the tensile strengths are obtained following the NF P 18-408 standard.

Table 2. C40 concrete formulation and characteristics.

Cement CPA 52,5 (kg/m^3)	Water (l/m^3)	Sand (kg/m^3)	Rock (kg/m^3)
320	190	765	1110
Characteristics	Values (MPa)		
Compression strength	45		
Tensile strength	4,8		

The composite reinforcement is made of TFC (carbon fibre tissue) a carbon sheet developed by the firm Freyssinet. Table 3 sums up the mechanical properties of the composite reinforcement.

Table 3 TFC mechanical properties (1 layer).

Tensile modulus E (GPa)	Tensile strength σ_L(MPa)	Thickness of the layer (mm)	Ultimate strain
105 000	1400	0,43	1,4%

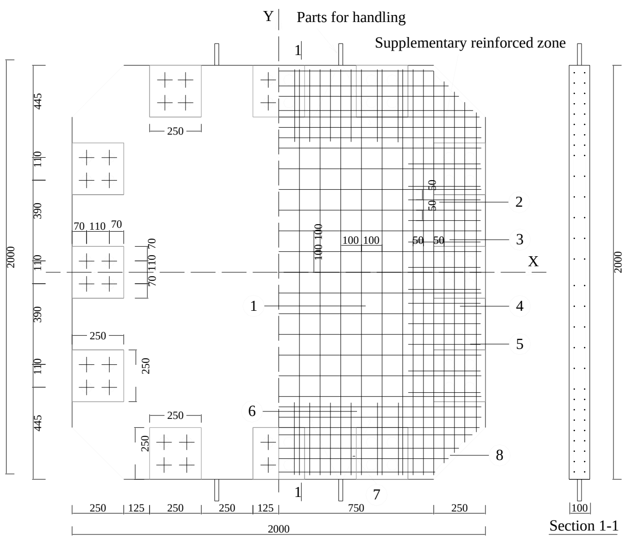


Figure 3. Geometric and reinforcement characteristics of the RC slab.

3.3 Test procedure

The RC slab is first axially loaded by a compression N1, corresponding to a vertical stress of 2,4MPa which is generally the stress induced by the self-weight of the cooling tower. This compression is kept constant while the horizontal bending moment is incremented until approaching the bearing capacity of the slab. The structure is then unloaded. The concrete to be strengthened with CFRP was sandblasted and cleaned properly with compressed air before bonding. The damaged slab is repaired with 2 CFRP composite strips, 300mm wide and 1400mm long for each one, glued onto the tension faces of the structure, in the central area (Fig. 5). A supplementary reinforcement is also considered on the two vertical edges of the slab to inhibit premature failure appearance near the zone of applied bending loads. Finally, the test of the repaired slab is conducted, with the same procedure as the initial test. The following graph presents the loading history.

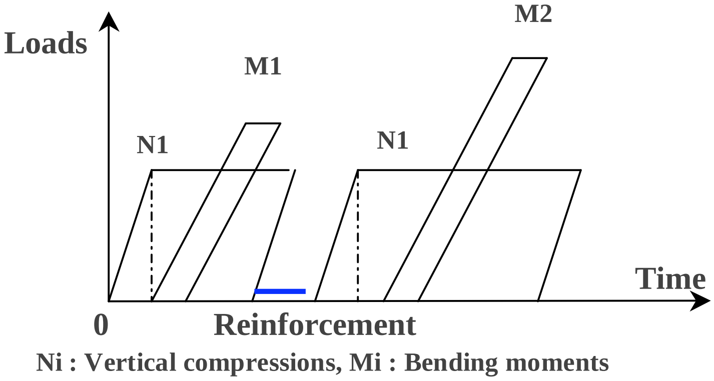


Figure 4. Graph of the loading history.

The reinforcement of the slab is presented in figure 5.

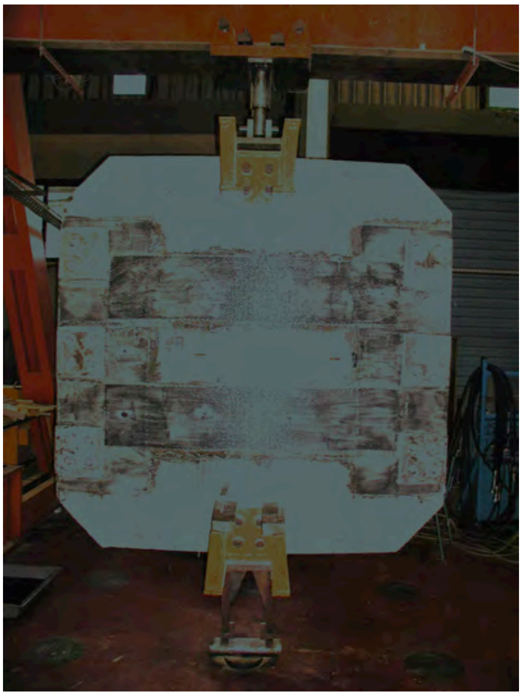


Figure 5. CFRP strips arrangement on the tensile face of the slab.

4 EXPERIMENTAL RESULTS

Vertical cracks are observed when the bending moment reaches the value of 4kNm/m, this value corresponds to a deflection of 1/1500 of the width of the slab. The cracks propagate and their number increases with the bending moment. These cracks are regularly 10cm spaced, which is the distance between the steel bars. The load is gradually enhanced until a moment of 20kNm/m which is approximately the bearing capacity of the slab. The load-deflection curve shows the initiation of the “yielding plateau” which generally annunciates the ultimate state or the ruin of the structure. The maximum horizontal deflection at the central part of the slab is about 28mm (Fig. 6). After the unloading, the structure is repaired with CFRP layers as described before and shown figure 6. After three days, for the polymerisation of the epoxy resin, the slab is loaded again following the same procedure as done initially. The maximum bearing capacity is of 30kNm/m corresponding to a gain of 50% compared to the unreinforced configuration.

The initial rigidity of both the RC and the repaired slab is the same. But when the bending load is higher than the threshold load associated to crack appearance, the CFRP layers inhibits crack opening and rebar deformation, plastic deformations are delayed. This conducts to an increase of the global bending rigidity of the repaired slab, up to 120% in comparison with the initial un-reinforced configuration. At the ultimate state, a brittle and sudden failure due to delamination of the CFRP sheet has been observed. The ruin of the slab is caused by the pulling out or debonding of the composite strips from the concrete cover of the slab on the edges of the local reinforcement (Fig. 7).

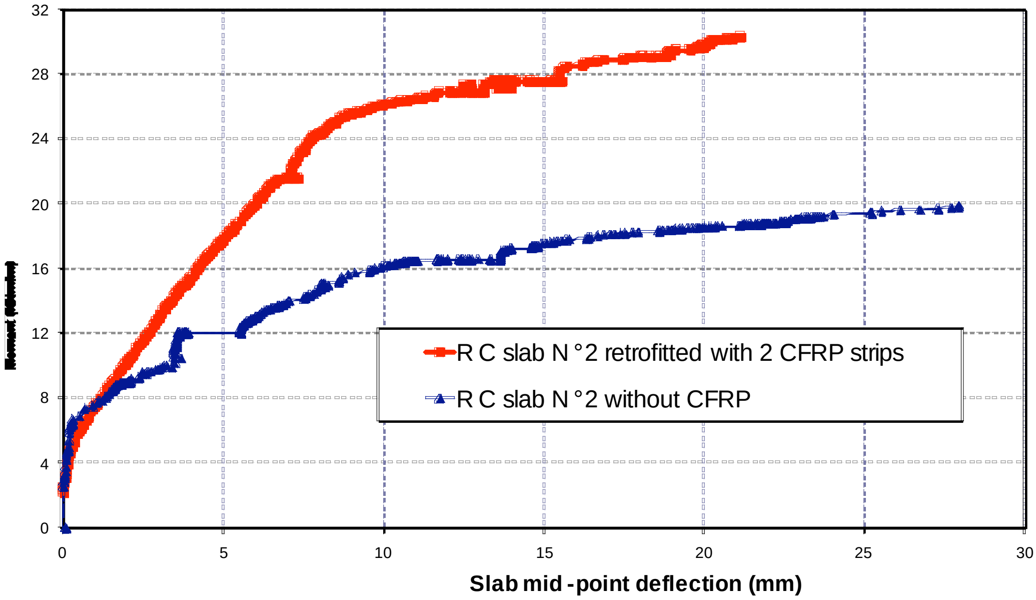


Figure 6. Comparison of the load-deflection curves for slab n°2 before and after reinforcement.

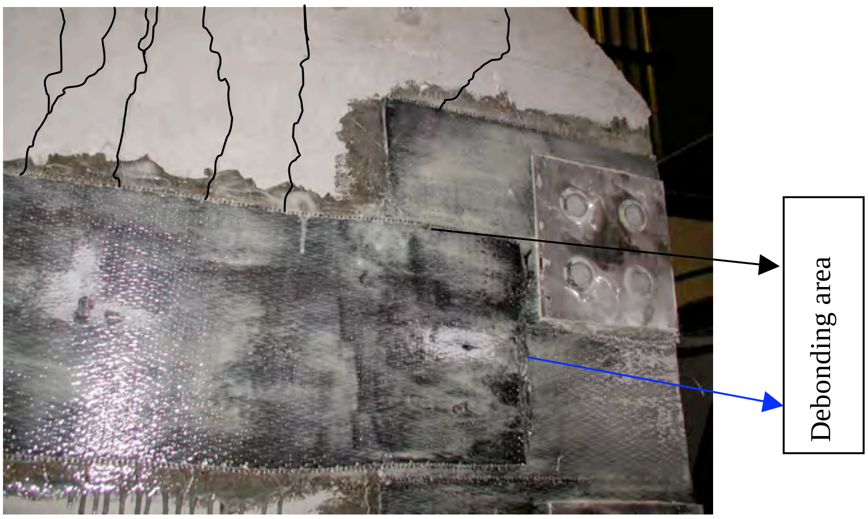


Figure 7. Crack pattern and failure mode corresponding to the debonding of the CFRP layer.

5 NUMERICAL SIMULATION

The numerical analyses have been performed using the general-purpose finite element program CAST3M developed at CEA-Saclay [Millard, 1993]. To predict the inelastic response with sufficient accuracy, a detailed model of the specimen has been created, taking into account the necessary geometric characteristics, construction details and boundary conditions. Due to the direction of the applied loading, in plane as well as out of plane, behaviour of the slab needed to be analysed. Therefore, a 3D thin shell representation was considered as sufficient to include the behaviour of interest. The finite element modelling of the structure resulted in the mesh shown in figure 8. Apparent symmetry in the model has been utilized resulting in a FE using only a quarter of the slab. Although the behaviour after the first crack appearance in the concrete dissolves this symmetry, it has been assumed that a quarter is adequate to gauge the response of the whole structure with sufficient accuracy. Layered thin shell discrete Kirchoff triangles (DKT) were used to model the slab response. Nine concrete layers of equal thickness were used to account for the flexural action. Discrete modelling was adopted to represent the horizontal and vertical reinforcement, through the use of truss-bar elements. Perfect bond was assumed to exist between concrete and reinforcement. Due to the specific supports and loading conditions of the concrete slab, the structure cannot be modelled by using simple prescribed boundary conditions. The supporting steel plates of the hydraulic jacks and the local reinforcements (steel plate and CFRP layers) located near the boundaries (Fig. 5) are then included in the model which leads to a better simulation of the loading process and load distribution (Fig. 8).The possibility of non-linear material behaviour was specified for all the elements, while the behaviour of the supporting steel plates of the hydraulic jacks was considered as elastic.

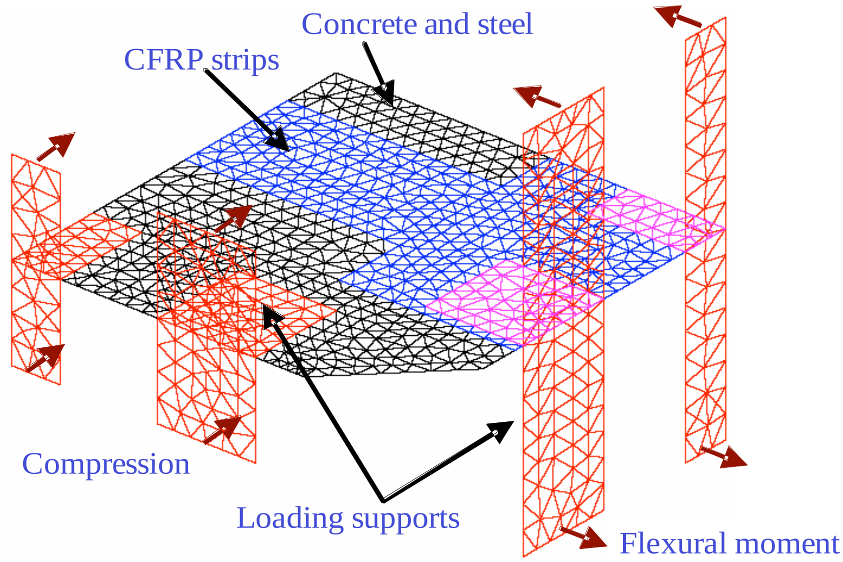


Figure 8. A quarter of the slab with rigid loading supports used to simulate bending loading.

In order to achieve a good compromise between simplicity and accuracy, a biaxial concrete model that provides acceptable representation of the inelastic behaviour of reinforced concrete was used. This model [Merabet & Reynouard, 1999], adopts the concept of a smeared crack approach with a possible double cracking only at 90°. It is based upon the plasticity theory for uncracked concrete with isotropic hardening and associated flow rule. Two distinct criteria describe the failure surface: Nadai in compression and bi-compression and Rankine in tension. Hardening is isotropic and an associated flow rule is used. When the ultimate surface is reached in tension, a crack is created perpendicular to the principal direction of maximum tensile stress, and its orientation is considered subsequently as fixed. Each direction is then processed independently by a cyclic uniaxial law, and the stress tensor in the local co-ordinate system defined by the direction of the cracks is completed by the shear stress, elastically calculated with a reduced shear modulus μG, (with $0 < \mu < 1$, and μ being a function of the crack opening strain) to account for the effect of interface shear transfer. The model has been described in detail and verified elsewhere [Ile & Reynouard 2000]. Its validity has been demonstrated by using it to predict the behaviour of beams, slabs and shear walls, with different span-to-height ratio under monotonic, cyclic and dynamic loading conditions for which experimental observation was available.

The constitutive model for steel is assumed to be ideal elasto-plastic.

Before applying the bending load, vertical loads, including the slab weight and axial load on the wall, were imposed to the model. A monotonic enhancement of the applied bending load was then considered, while maintaining the initial vertical load as constant. To solve the non-linear equilibrium equations, a modified Newton-Raphson iteration solution scheme was used.

The load-deflection curve associated to the numerical result gives a same initial global rigidity as the experimental one (Fig. 9). The main difference between the observed behaviour and the numerical analysis is found at the beginning of the non linear behaviour associated to crack initiation. The simulation provides a threshold value of 12kNm/m, corresponding to crack initiation; while the experiment gives a value of approximately 6kNm/m for the initiation and a smooth propagation of cracks is observed until the same value of 12kNm/m. This difference is believed to be a consequence of the boundary conditions and the model inability to represent the crack propagation in a proper way. The final load carrying capacity of 20kNm/m obtained numerically is in good agreement with the experimental result.

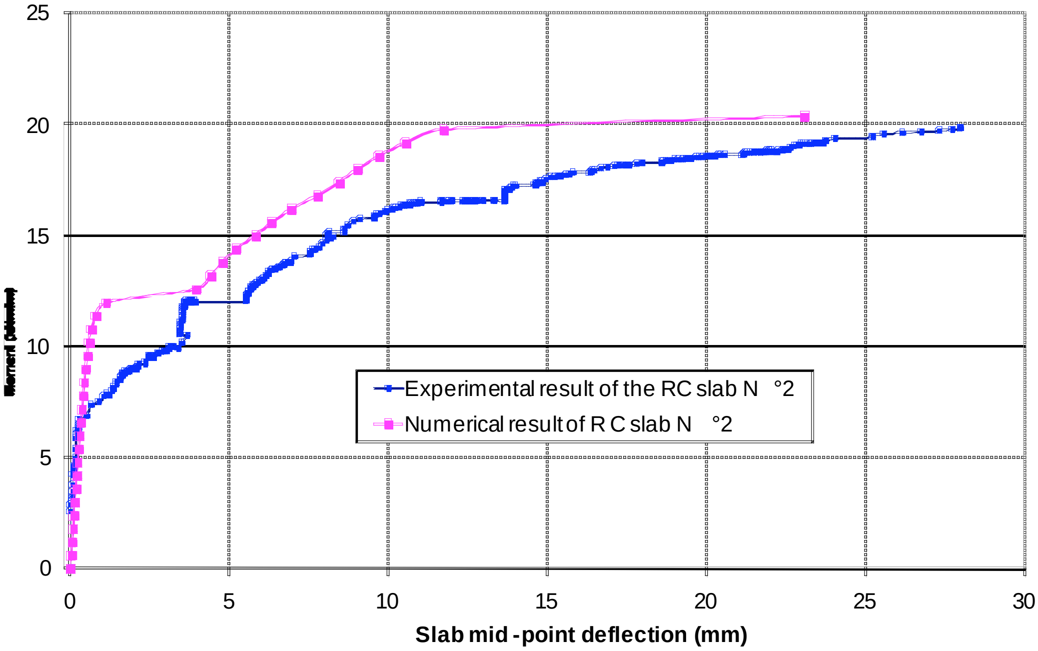


Figure 9. Comparison of the numerical and experimental results of the RC slab n°2.

Further researches are still in progress, where Finite Element analysis is used to simulate the behaviour in the case of damaged repaired concrete slab. In this case, a damage plasticity approach and a specific criterion to capture the bond failure have to be considered.

6 CONCLUSION

The work presented in this paper shows that CFRP sheets can be used to increase the original load- capacity of two way concrete slabs. The repaired slab with only 2 CFRP strips has an initial rigidity equivalent to that of the non damaged one. The reinforcement allows the enhancement of the bearing capacity; a gain of 50% is obtained. The composite layer allows limiting the excessive opening of the cracks during the loading process, and thus delays the plastic deformation of the reinforcing steel. During this phase, a gain of 120% is noted in terms of global rigidity compared to the un-reinforced slab. The numerical analysis conducted in the case of un-reinforced slab showed good agreement with experimental results.

Acknowledgements

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