Composites Part B 90 (2016) 14–29

Contents lists available at ScienceDirect

Composites Part B

journal homepage: www.elsevier.com/locate/compositesb

Flexural strengthening of reinforced low strength concrete slabs using prestressed NSM CFRP laminates

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ARTICLE INFO

Article history:
Received 4 August 2015
Received in revised form
12 October 2015
Accepted 12 November 2015
Available online 30 November 2015

Keywords:
A. Carbon fibre
B. Strength
C. Numerical analysis
D. Mechanical testing
Prestressed NSM CFRP laminates

ABSTRACT

The effectiveness of the Near Surface Mounted (NSM) technique with prestressed CFRP (carbon fiber reinforced polymer) laminates for the flexural strengthening of reinforced concrete (RC) slabs of low strength concrete was assessed. Four RC slabs were tested, a reference slab (without CFRP), and three slabs flexurally strengthened using NSM CFRP laminates with different prestress level of the ultimate tensile strength of the CFRP: 0%, 20% and 40%. The experimental program is described and the main results are presented and analyzed in terms of the structural behavior of the RC slabs, failure modes and performance of the NSM technique with prestressed CFRP laminates. The results show that prestressing CFRP laminates with NSM technique is an effective technology to increase cracking, service, yielding and maximum loads of RC slabs made by low strength concrete. By applying NSM CFRP laminates prestressed at 20%, the cracking, service and maximum loads have increased, respectively, 258%, 123% and 125%, when the corresponding values of the reference slab are taken for comparison purposes, while 400%, 190% and 134% were the increase when applying laminates prestressed at 40%. Using available experimental results obtained with the same test setup, but using RC slabs of higher strength concrete, it can be concluded that as minimum is the concrete strength as more effective is the NSM technique with prestressed CFRP laminates in terms of serviceability limit states. A numerical strategy was used to evaluate the load-deflection of the tested RC slabs and to highlight the influence of the percentage of CFRP, the percentage of tensile longitudinal bars and the elasticity modulus of the CFRP on the effectiveness of the NSM technique with prestressed CFRP laminates for the flexural strengthening of RC slabs, by performing a parametric study.

1. Introduction

Using carbon fiber reinforced polymers (CFRP), competitive structural strengthening solutions can be developed due to the high strength-to-weight and stiffness-to-weight ratios, high durability (non corrodible), electromagnetic neutrality, ease of handling, rapid execution with low labor, and practically unlimited availability in size, geometry and dimension of these advanced materials [1–3].

For flexurally strengthening of reinforced concrete (RC) structural elements, CFRP materials can be applied according to the followings two main techniques: bonding wet lay-up sheets or laminates to the external tension faces of the elements to be strengthened (Externally Bonded Reinforcement – EBR – technique) [4–6]; installing CFRP bars (circular, square or rectangular cross section) into pre-cut slits opened on the concrete cover of the elements to strengthen (Near Surface Mounted – NSM – technique) [6–10]. Due to the largest bond area and higher confinement provided by the surrounding concrete, narrow strips of CFRP laminates of rectangular cross section, installed into thin slits and bonded to concrete by an epoxy adhesive, are the most effective CFRP strengthening elements for the NSM technique [8].

The efficacy of the NSM strengthening technique with passive CFRP laminates to increase the flexural resistance of RC beams [6–10] and slabs [11,12] was already well assessed. In fact, NSM CFRP laminates without any prestress level can increase significantly the ultimate load carrying capacity of RC structural elements, and high mobilization of the tensile properties of the CFRP can be assured. However, for deflection levels corresponding to the serviceability limit states the benefits of the CFRP are, in general, of small relevance. By prestressing the CFRP, its high tensile capacity

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http://dx.doi.org/10.1016/j.compositesb.2015.11.028
1359-8368/

is more effectively used, contributing to increase significantly the load carrying capacity of the strengthened elements under both service and ultimate conditions. The prestress can also contribute to close eventual existing cracks, to decrease the tensile stress installed in the existing flexural reinforcement, and to increase the shear capacity of these elements. Thus, prestressing the CFRP seems to be a cost-effective solution to increase both the structural performance and the durability of the strengthened RC structure.

Recent experimental research has demonstrated that applying NSM CFRP laminates with a certain prestress level for the flexural strengthening of RC beams [13–16] and slabs [17] can mobilize better the potentialities of these high tensile strength materials, with an appreciable increase of the load carrying capacity at serviceability and ultimate limit states.

There are several reasons that justify the relevance of a study on the use of the NSM technique with prestressed CFRP laminates for the flexural strengthening of RC slabs of low strength concrete: old RC structures were built with low strength concrete; decrease of concrete strength due to several time dependent phenomena and environmental conditions; evaluate the role of the concrete in the effectiveness of this highly effective technique.

To appraise the potentialities of applying NSM prestressed CFRP laminates for the flexural strengthening of low strength concrete slabs, an experimental program was carried out. The average value of the concrete compressive strength at the age of the slabs tests was 15.0 MPa. The experimental program is outlined and the specimens, materials and test setup are described. The results of the tests are presented and discussed and a number of conclusions are drawn. Taking the results obtained in a previous experimental program [17], characterized by the same test setup, but using RC slabs of higher concrete strength (46.7 MPa instead of 15.0 MPa), the influence of the concrete mechanical properties in the performance of the NSM technique with prestressed CFRP laminates for the flexural strengthening of RC slabs was assessed.

A numerical strategy was used to evaluate the load-deflection of the tested RC slabs, and a comparison between experimental and numerical results was done. This numerical strategy was adopted to execute a parametric study in order to evaluate the influence of the percentage of CFRP, the percentage of tensile longitudinal bars and the elasticity modulus of the CFRP on the effectiveness of the NSM technique with prestressed CFRP laminates for the flexural strengthening of RC slabs.

2. Experimental program

2.1. Test series

The experimental program is composed of four RC slabs with a rectangular cross section of 120 × 600 mm^2, a total length of 2600 mm and a span length of 2400 mm. The longitudinal steel reinforcement consisted of 3 bars of 6 mm diameter (3ϕ6) in the compression zone and 4 bars of 8 mm diameter (4ϕ8) in the tension zone. Steel stirrups of 6 mm diameter spaced at 300 mm (ϕ6@300 mm) are adopted as transversal reinforcement, and have the main purpose of maintaining the longitudinal reinforcement in the aimed position. The adopted reinforcement systems were designed to assure flexural failure mode for all the tested slabs. Fig. 1 represents the cross section geometry and the reinforcement arrangement for each slab, as well as the longitudinal geometry, loading configuration and support conditions. The concrete clear cover of the longitudinal tensile bars was 31 mm.

The general information of the four tested RC slabs is represented in Table 1. The SREF is the reference slab without CFRP, and the S2L-0, S2L-20 and S2L-40 slabs are those flexurally strengthened using two NSM CFRP laminates (Fig. 2) with different prestress level: 0% (S2L-0), 20% (S2L-20) and 40% (S2L-40) of the ultimate tensile strength of the CFRP laminates. The CFRP laminates used in the present experimental program have a cross section of 1.4 (thickness) × 20 (depth) mm^2. Table 1 shows that the tested slabs have a percentage of longitudinal tensile steel bars (ρ_{sl}) of about 0.39%, while the CFRP strengthening percentage (ρ_f) is approximately 0.08%.

The four point slab bending tests (Fig. 3) were executed under displacement control at a deflection rate of 0.02 mm/s. All slabs were instrumented to measure the applied load, deflections and strains in the CFRP laminates and longitudinal tensile steel reinforcement. Positions of the LVDTs (linear variable displacement transducers) and strain gauges (SG) in the monitored longitudinal tensile bars and in the NSM CFRP laminates are indicated in Fig. 4. The deflection of the slabs was measured by five displacement transducers (LVDT 1 to LVDT 5) according to the arrangement indicated in Fig. 4a. To evaluate the strains on the steel bars, two strain gauges were installed (Fig. 4b) on the two bottom longitudinal steel bars (SG-S1 and SG-S2). In the non-prestressed slab (S2L-0), three strain gauges were installed on the two CFRP laminates (SG-L1 to SG-L3) according to the scheme represented in Fig. 4c, while in the prestressed slabs (S2L-20 and S2L-40) the disposition of the six strain gauges (SG-L1 to SG-L6) applied on the

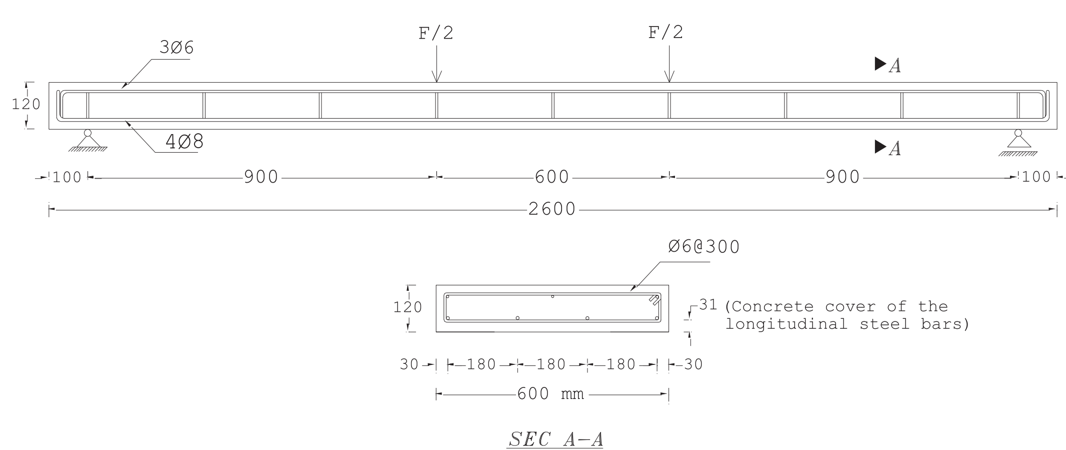

Fig. 1. General information about the tested RC slabs (dimensions in mm).