Composite Structures 111 (2014) 249–258

Contents lists available at ScienceDirect

Composite Structures

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

Effectiveness of prestressed NSM CFRP laminates for the flexural strengthening of RC slabs

M.R. Mostakhdemin Hosseini *, S.J.E. Dias, J.A.O. Barros

ISISE, Dep. of Civil Eng., Univ. of Minho, Azurém, 4810-058 Guimarães, Portugal

ARTICLE INFO

Article history:
Available online 24 December 2013

Keywords:
CFRP laminates
NSM technique
Flexural strengthening
RC slabs
Experimental results
Numerical simulation

ABSTRACT

An experimental program was carried out to investigate the effect of the prestressed Near Surface Mounted (NSM) Carbon Fiber Reinforced Polymer (CFRP) laminates on the behavior of reinforced concrete (RC) slabs. 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 solution to increase cracking, service, yielding and maximum loads of RC slabs failing in bending. By applying 20% of prestressed NSM CFRP laminates, the service and ultimate loads have increased, respectively, 55% and 136%, when the corresponding values of the reference slab are taken for comparison purposes, while 119% and 152% were the increase when applying 40% of prestressed laminates. A numerical strategy was used to evaluate the load–deflection of the tested RC slabs, and a good agreement between experimental and numerical results was obtained.

1. Introduction

Carbon fiber reinforced polymer (CFRP) materials have high potential for an effective strengthening of reinforced concrete (RC) structural elements, since they are lightweight, have high durability (non-corrodible), exhibit high tensile strength and their availability are practically unlimited in size, geometry and dimensions [1–3]. The possibility of making relative fast interventions without interfering with the normal functionality of the RC structures and minor level of interference that this technique introduces in terms of architectural and esthetic point-of-views are important advantages of the CFRP-based strengthening solutions.

Existing studies confirm that among the flexural strengthening techniques of RC elements with passive CFRP materials, Near Surface Mounted (NSM), based on the installation of narrow strips of CFRP laminates, of rectangular cross section, into thin slits open on the concrete cover of the RC elements, is the most effective one [4–6]. The CFRP laminates are bonded to concrete by an epoxy adhesive.

The efficacy of the NSM strengthening technique with passive CFRP laminates to increase the flexural resistance of RC beams [4–9] and slabs [10] 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 is, in general, of small relevance. By prestressing the CFRP, its high tensile capacity 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 [11–14] has demonstrated that applying NSM CFRP laminates with a certain prestress level for the flexural strengthening of RC beams 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.

In this study, the effectiveness of the NSM technique with prestressed CFRP laminates for the flexural strengthening of RC slabs is assessed. Four RC slabs were executed with the purpose of evaluating the influence of the prestressed level in the behavior of this kind of structures in terms of serviceability and ultimate limit states. A detailed description of the carried out experimental

* Corresponding author.
E-mail addresses: hoseini_engineer@yahoo.com (M.R. Mostakhdemin Hosseini), sdias@civil.uminho.pt (S.J.E. Dias), barros@civil.uminho.pt (J.A.O. Barros).

0263-8223/$ - see front matter
http://dx.doi.org/10.1016/j.compstruct.2013.12.018

program is provided, and the obtained results are presented and analyzed. To simulate the response of the tested RC slabs in terms of force versus deflection, a numerical strategy based on a cross section layer model and matrix stiffness method was used. The numerical strategy is described and its predictive performance is assessed in this work.

2. Experimental program

2.1. Test series

The experimental program is composed of four RC slabs with a rectangular cross section of $120 \times 600\,mm^2$, a total length of 2600 mm and a span length of 2400 mm. The longitudinal steel reinforcement is consisted of 3 bars of 6 mm diameter (3∅6) in the compression zone and 4 bars of 8 mm diameter (4∅8) in the tension surface. Steel stirrups of 6 mm diameter spaced at 300 mm (∅6@300 mm) are adopted for transversal steel reinforcement, and have the main purpose of maintaining the longitudinal reinforcement in the aimed position. The adopted reinforcement systems were designed to assure flexurally failure mode for all the tested slabs (reinforcement yielding). Fig. 1 represents the cross section geometry and 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 20 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 0.35%, 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, three strain gauges were installed (Fig. 4b) on the two bottom longitudinal steel bars (SG-S1 to SG-S3). In the non-prestressed slab 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 the disposition of the five strain gauges (SG-L1 to SG-L5) applied on two CFRP laminates is indicated in Fig. 4d (the SG-L4 and SG-L5 strain gauges were installed near the end of one CFRP laminate to determine prestress losses).

According to Fig. 4c, the length of the laminates in S2L-0 slab was 2300 mm. For the RC slabs flexurally strengthened with prestressed laminates the slits were executed along the total length of the slab, but in the extremities of the laminates were not bonded to the concrete in a length of 150 mm, in order to provide the same bond length adopted in the S2L-0 slab.

2.2. Materials

The compressive strength [15] and the elasticity modulus [16] of the concrete were evaluated at the age of the slab tests (294 days), carrying out direct compression tests with cylinders of 150 mm diameter and 300 mm height. The values of the main tensile properties of the high bond steel bars (6 and 8 mm diameter) used in the tested slabs were obtained from uniaxial tensile tests performed according to the recommendations of EN 10002 [17]. The tensile properties of the CFK 150/2000 S&P laminates were characterized by uniaxial tensile tests carried out according to ISO 527-5 [18]. Table 2 includes the average values obtained from these experimental programs.

S&P Resin 220 epoxy adhesive was used to bond the CFRP laminates to the concrete substrate. The instantaneous and long term tensile behavior of this adhesive was investigated by Costa and Barros [19]. At 3 days, at which the elasticity modulus ($E_{0.5\sim2.5‰}$) has attained a stabilized value, the tensile strength and the $E_{0.5\sim2.5‰}$, determined according to the ISO 527-2 recommendations [20], was about 20 MPa and 7 GPa, respectively.

2.3. Application of the NSM CFRP laminates

To apply the passive CFRP laminates using NSM technique, the following procedures were executed: (1) using a diamond cutter, slits of about 5 mm width and 25 mm depth were opened on the concrete cover of the tension face according to the pre-defined arrangement for the laminates; (2) the slits were cleaned by

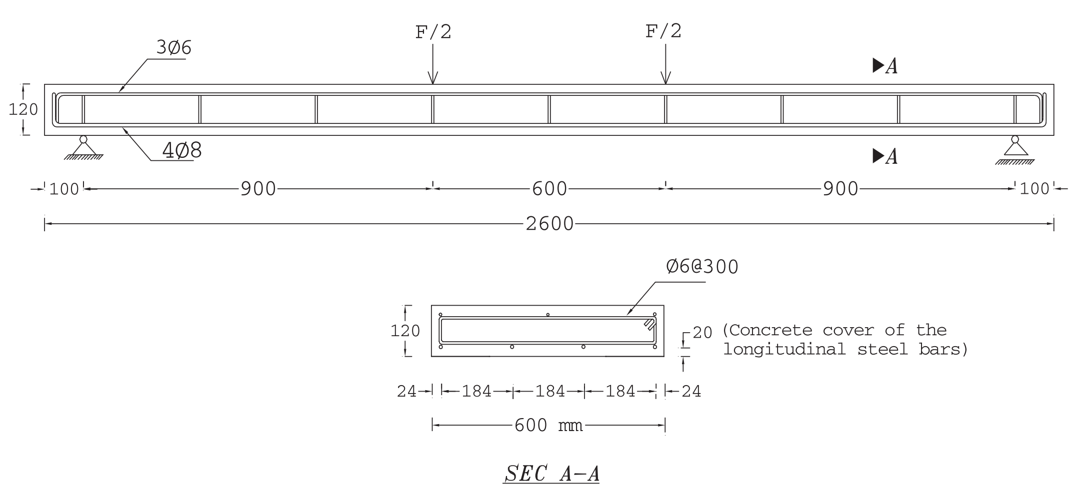

Fig. 1. General information about the tested RC slabs (dimensions in mm).