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Bond response of NSM CFRP strips in concrete under sustained loading and different temperature and humidity conditions

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ABSTRACT

Near Surface Mounted (NSM) reinforcement has been increasingly recognized as an efficient technique for strengthening Reinforced Concrete (RC) structures using Fiber Reinforced Polymer (FRP) reinforcement. Although a number of studies have investigated the short-term bond behavior between NSM FRP and concrete, little work has been done on its long-term behavior under sustained loading. This paper aims to experimentally investigate the bond response of NSM Carbon FRP (CFRP) strips in concrete under sustained loading and different temperature and humidity conditions. Thirty-three single shear pull-out specimens were subjected to monotonic and sustained loading. The long-term pull-out specimens were subjected to different environmental regimes including four combinations of temperature, humidity and sustained loading. For each environmental combination, three bonded lengths were tested and two levels of sustained loading were applied. Specimens were kept loaded and conditioned in a climatic chamber for 1000 h, while the slip evolution with time was monitored throughout the testing period. Results revealed that the changes in the parameters being studied did have a relevant effect on the bond response.

1. Introduction

Fiber Reinforced Polymers (FRP) are being used extensively all over the world, either for reinforcing new concrete structures or for the rehabilitation and strengthening of existing ones [1–5]. Near Surface Mounted (NSM) reinforcement is one of the most efficient and promising methodologies used for strengthening concrete structures with FRP materials [6–10]. NSM methodology is being used in several applications such as enhancing the flexural and shear capacities of Reinforced Concrete (RC) members and repairing damaged/deteriorated RC elements. The wide interest in using NSM is attributed to number of advantages it may provide over applying FRPs when using the well-known Externally Bonded (EB) methodology: better anchorage capacity, does not require any surface preparation work except for grooving, better resistance against peeling-off, and better protection against fire and vandalism [11–14].

To ensure the efficiency of the NSM FRP strengthening system, an adequate bond between the FRP reinforcement and the concrete is required. A proper bond ensures the composite action between both materials (FRP and concrete), allowing the transfer of shear stresses between them during the loading process. Moreover, the bond has a major influence on both the load carrying capacity and the failure mode of the strengthened member [15–17]. In recent decades, several studies have investigated the short-term bond behavior between NSM FRP and concrete and the possible influence the main parameters related to that behavior have [18–30].

Materials involved in the NSM strengthening system (concrete, FRP and adhesive) are susceptible to experiencing time-dependent effects under sustained loading due to their nature, being epoxy adhesives the most sensitive components [31–34]. In addition to sustained loading, environmental conditions such as temperature and humidity may have dramatic effects on the mechanical behavior of epoxy adhesives [35,36], which, in turn can be reflected in the overall behavior of the NSM system.

Previous studies concerning both EB and NSM strengthening systems [37–39] demonstrated that the temperature being applied significantly influences short-term bond performance, in terms of bond stress, slip, stiffness and debonding failure of the adhesive joint.

In contrast to the wealth of literature available on short-term bond behavior, very little is available concerning the long-term bond performance of NSM FRP in concrete when subjected to different environmental regimes with the presence of sustained loading. Borchert

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and Zilch [40] performed an experimental study of the long-term performance of NSM FRP reinforcement adhesively bonded to concrete when subjected to temperature and different levels of prestressing. The results showed that the exposure to higher temperatures resulted in a significant increase in slip values with time. In addition, the performance of the NSM FRP system was significantly influenced by the characteristics of the epoxy resin used.

The time-dependent performance of RC beams strengthened with NSM CFRP strips was experimentally studied by Derias et al. [41]. Combined with the presence of sustained loading, some beams were exposed to a high temperature, while control beams were left at room temperature conditions. Observed failure modes included the rupture of the CFRP reinforcement, for the control beams, and debonding at the concrete-epoxy interface, due to its deterioration, for the beams exposed to the extreme environmental conditions.

Silva et al. [42] experimentally studied the durability of RC elements strengthened with NSM CFRP strips. Beam pull-out and slab specimens were subjected to sustained loading, some were at room temperature, while others were exposed to different environmental conditions. The conditions included wet/dry cycles and immersion in water with different chloride contents. The results showed that the effect of creep was found to be practically negligible in the case of the beam pull-out specimens; however, a noticeable creep effect was observed in the case of the slab specimens.

On the other hand, several studies concerning the time-dependent behavior of FRP plates/sheets externally bonded to concrete blocks were performed using different test setups and various study parameters such as bonded length, sustained load level, temperature, epoxy thickness and epoxy curing time before loading. For the concrete-FRP interface, it was found that the applied sustained loading level and adhesive curing time can be the major parameters that influence time-dependent behavior [43]. Moreover, due to creep deformation, shear stress redistribution was observed along the bonded length [44]. Results from the study performed by Dash et al. [45] showed that with the presence of sustained loading, larger creep displacements were observed in the specimens exposed to elevated temperatures or immersed in water than those exposed to high humidity. In the study carried out by Wu and Diab [46], the creep of the adhesive and the interfacial stiffness of the adhesive layer showed a significant effect on the effective bonded length. The increase in the effective bonded length, after 2000 h of loading, was 70% when the prestressing level equal to 25% of the failure load was applied.

The analysis of the existing literature shows that bonding between NSM FRP and concrete is a fundamental property that has received considerable critical attention for short-term conditions, but that far too little attention has been paid to the time-dependent performance of RC members strengthened with NSM FRP under environmental conditions and sustained loading, thus resulting in a general lack of research into this topic. This paper attempts to experimentally examine the significance different parameters have on the long-term bond behavior of NSM CFRP strips in concrete. The parameters studied include bonded length, sustained loading level and exposure to different temperature and humidity conditions.

2. Experimental program

2.1. Material characteristics

Ready-mixed concrete with a 28-day average compressive strength equal to 32 MPa (CoV 1.5%) was used. The tensile strength was 3 MPa (CoV 1.6%) and the modulus of elasticity was 31 GPa (CoV 2%). The concrete was characterized by testing standard concrete cylinders 150 mm in diameter and 300 mm high in accordance with UNE 12390-3 [47]. The concrete specimens were strengthened with CFRP strips 1.4 mm thick and 10 mm wide, supplied by S&P Clever Reinforcement Ibérica, Lda. The properties of the CFRP strips (obtained from standard

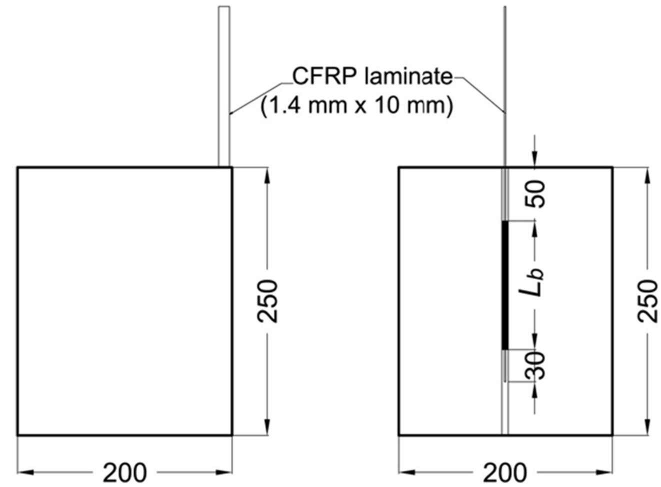

Fig. 1. Test specimen configuration (units in mm).

testes carried out according to the ISO 527-5 standards [48]) showed a tensile strength of 2400 MPa (CoV 3.8%) and a modulus of elasticity equal to 160 GPa (CoV 2%). The CFRP strips were installed into the grooves using a two-component epoxy resin marketed under the commercial name of S&P220. Standard tests were performed (after 10 days of curing at 20 °C and 55% RH) in accordance with ISO 527-2 [49] to determine the adhesive's properties. The tensile strength and the modulus of elasticity of the adhesive were found to be 20 MPa (CoV 2.3%) and 6600 MPa (CoV 2.5%), respectively.

2.2. Test specimens

Thirty-three concrete specimens were tested in this experimental program. The specimens were concrete blocks with cross sectional dimensions equal to 200 mm × 200 mm and 250 mm high, as shown in Fig. 1. After casting and curing the concrete blocks, 5 mm wide grooves 15 mm in depth were cut using a cutting saw and then cleaned out with compressed air. The epoxy paste was prepared by mixing the two components of the epoxy in a proportion of 4:1 by weight a homogenous paste without any streaks formed. Grooves were then filled with the epoxy paste, a strip was installed in the groove and then additional resin was added before leveling the resin in the groove to the concrete surface. Finally, specimens were left for 10 days so the resin could cure before testing. The curing conditions were 20 °C of temperature and a 55% relative humidity.

2.3. Test setup and variables

Nine specimens were tested under a direct pull-out shear test (Fig. 2)) to obtain their load capacity. Three different bonded lengths (L_b) equal to 60, 90 and 120 mm were used, thus three specimens were obtained for each bonded length. The bonded lengths were selected to introduce bonded lengths shorter than, equal to and longer than the expected effective length, which according to previous experimental programs [50] is within the range of 80 mm to 90 mm, and with FRP rupture being the failure mode to be observed. Both loaded-end and free-end slips were measured during the test. Two LVDTs were attached to the upper and bottom parts of the concrete specimen, in contact with two small plates fixed to the laminate. Tests were performed using a servo-hydraulic testing machine with a displacement control rate of 0.2 mm/min.

For the long-term pull-out test, twenty-four specimens were tested under sustained loading conditions. The long-term pull-out specimens were tested via loading frames designed for sustained loading (see Fig. 3) and based on gravity loading using a lever arm which provided a magnification factor of 8.3. Small concrete blocks were used to apply

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