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Efficiency of different techniques in flexural strengthening of RC beams under monotonic and fatigue loading

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ABSTRACT

In the context of flexural strengthening of concrete structures, fibre reinforced polymers (FRPs) have been used mostly by two main techniques: *Externally Bonded Reinforcement* (EBR) and *Near-Surface Mounted* (NSM). Both strengthening techniques are applied on the cover concrete, which is normally the weakest region of the element to be strengthened. Consequently, the most common problem is the premature failure of the strengthening system that occurs more frequently in the EBR one. In an attempt of overcoming this weakness, another technique has been proposed, called MF-EBR – *Mechanically Fastened and Externally Bonded Reinforcement*, which uses multi-directional carbon fibre laminates, simultaneously glued and anchored to concrete. To compare the efficiency of NSM, EBR and MF-EBR techniques, four-point bending tests with RC beams were carried out under monotonic and cyclic loading. In this work the tests are described in detail and the obtained results are discussed. Additionally, to assess the performance of a FEM-based computer program for the prediction of the behaviour of RC beams strengthening according to these techniques, the beams submitted to monotonic loading were numerically simulated.

1. Introduction

Over the last two decades, extensive research has been developed on the strengthening of reinforced concrete (RC) structures with fibre reinforced polymer (FRP) materials. High stiffness and tensile strength, low weight, easy installation procedures, high durability (no corrosion), electromagnetic permeability and practically unlimited availability in terms of geometry and size are the main advantages of these composites [1,2].

The most common techniques for applying FRP's are, in general, based on the use of unidirectional FRP's through the: (i) application of fabrics (in situ cured systems) or laminates (pre-cured systems) glued externally on the surface of the element to strengthen (EBR – Externally Bonded Reinforcement); (ii) insertion of laminates (or rods) into grooves opened on the concrete cover (NSM – Near-Surface Mounted) [2,3]. Epoxy adhesives are the most used to fix the FRP to concrete. The strengthening performance of these techniques depends significantly on the resistance of the concrete cover, which is normally the most degraded concrete region in the structure due to its greater exposure to environment conditions. As a result, premature failure of FRP reinforcement can occur and, generally, the full mechanical capacity of the FRP's is not mobilized, mainly when adopting the EBR technique. To avoid this premature failure complements have been applied to the aforementioned strengthening techniques, such as the application of anchor systems composed of steel plates bolted in the ends of the FRP, the use of strapping with FRP fabric or the use of FRP anchor spikes. In addition to the stress concentration that these localized interventions introduce in the elements to strengthen, they require differentiated and time consuming tasks that can compromise the competitiveness of these techniques.

More recently, some FRP-based alternatives for structural strengthening have been proposed [4]. The mechanically fastened fibre reinforced polymer (MF-FRP) technique has been introduced to strengthen concrete structures, and is mainly characterized by the use of hybrid (carbon and glass) FRP strips that are mechanically fixed to concrete using closely spaced fastening pins and, if necessary, anchors at the ends of the strip are applied to prevent debonding. According to the search performed the MF-FRP concept was initially explored at the University of Wisconsin under supervision of Lawrence Bank in 1998 [4]. This technique has already been used in some applications, e.g. reinforced concrete, wood and masonry structures, and several benefits have been pointed out, namely, quick installation with relatively simple hand tools, no need for special labour skills, no surface preparation required, and the strengthened structure can be immediately used after the installation of the FRP. From these tests an increase of up to 50% of the carrying capacity was observed in some cases, when compared with the reference structure. Additionally, the occurrence of a more ductile failure mode for the FRP system is referred [5–12]. Nevertheless, some notable disadvantages of this technique have been reported,

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including greater initial cracking induced by the impact of fasteners in high-strength concrete, and less-effective stress transfer between the FRP and concrete due to the discrete attachment points [13].

Based on the MF-FRP technique, the mechanically fastened and externally bonded reinforcement technique (MF-EBR) has been proposed [14,15]. The MF-EBR combines the fasteners from the MF-FRP technique and the externally glued properties from the EBR. In addition, all the anchors are pre-stressed. When this strategy is applied high levels of efficacy can be observed.

To assess the efficiency of EBR, NSM and MF-EBR techniques, four-point bending tests with RC beams were carried out under monotonic and fatigue loading. The tests are described and the results are presented and discussed in detail. To appraise the capabilities of a computer program for the prediction of the behaviour of RC beams strengthening according to these techniques, a code package based on the finite element method (FEM) which includes several constitutive models for the material nonlinear analysis of RC structures was applied on the simulation of the beams submitted to monotonic loading.

2. Experimental program

To appraise the effectiveness of the EBR, MF-EBR and NSM techniques, an experimental program composed of two series of four beams each was carried out. The difference between the series is restricted to the loading configuration: one series was subjected to monotonic loading, while the other to fatigue loading. Each series is composed of a reference beam (REF) and a beam for each investigated strengthening technique.

2.1. Specimens and test configuration

The RC beams have a cross section of 200 mm wide and 300 mm height, and 2000 mm of support distance. All the beams have three longitudinal steel bars of 10 mm diameter (3Ø10) at the bottom, and 2Ø10 at the top (see Fig. 1). The transverse reinforcement is composed of steel stirrups of 6 mm diameter (Ø6) with a constant spacing of 100 mm in order to avoid shear failure. Fig. 2 includes the cross section of the strengthened beams.

Table 1 presents the main properties of the beams. In this table t_f, L_f and w_f are the thickness, the length and the width of the laminates, respectively, and $\rho_{s,eq}$ is the equivalent longitudinal steel reinforcement ratio defined by Eq. (1), where b is the width of the beam; A_s and A_f are the cross sectional area of the tensile longitudinal steel bars and FRP systems, respectively; E_s and E_f are the modulus of elasticity of steel and FRP, respectively; and, d_s and d_f are the distance from the top concrete compression fibre to the centroid of the steel bars and FRP systems, respectively. For all the strengthened beams an almost similar $\rho_{s,eq}$ was applied

$$\rho_{s,eq} = \frac{A_s}{bd_s} + \frac{E_f}{E_s} \cdot \frac{A_f}{bd_f} \qquad (1)$$

In this experimental study, a four-point bending test configuration was adopted for the monotonic and fatigue tests (see Fig. 3a). A servo-controlled hydraulic system was used to perform the monotonic tests under displacement control, with a deflection rate of 20 μm/s, using the linear variable differential transducer (LVDT) located at the mid-span of the beam (LVDT3 in Fig. 3).

The fatigue tests were performed between a minimum fatigue level of S_{min} = 25% and maximum fatigue level of S_{max} = 55%, where the S is the ratio between the applied load and the load carrying capacity, F_m, of the corresponding monotonic beam. According to [2] at 1 million cycles, the fatigue strength of the CFRP material is generally between 60% and 70% of the initial static ultimate strength and is relatively unaffected by the moisture and temperature exposures of concrete structures unless the resin or fibre/resin interface is substantially degraded by the environment. In addition, for the present specimens the yielding

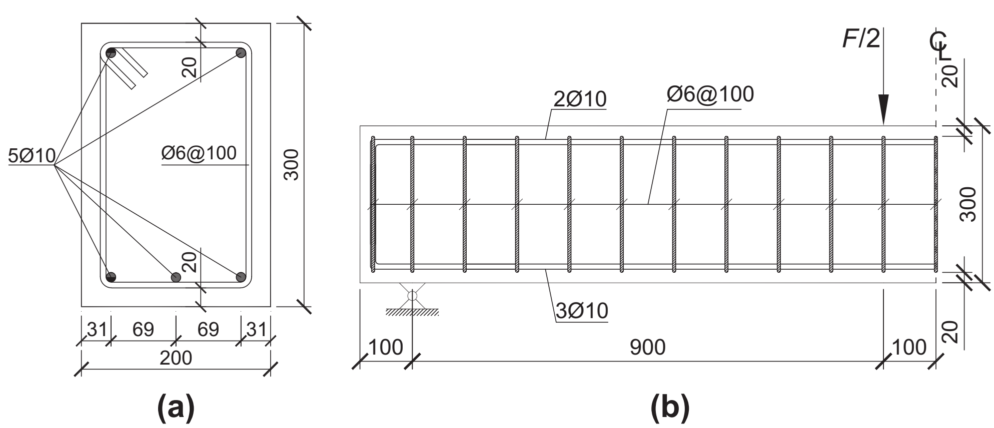

Fig. 1. RC beam: (a) cross section; (b) longitudinal view. Note: all dimensions are in millimetres.

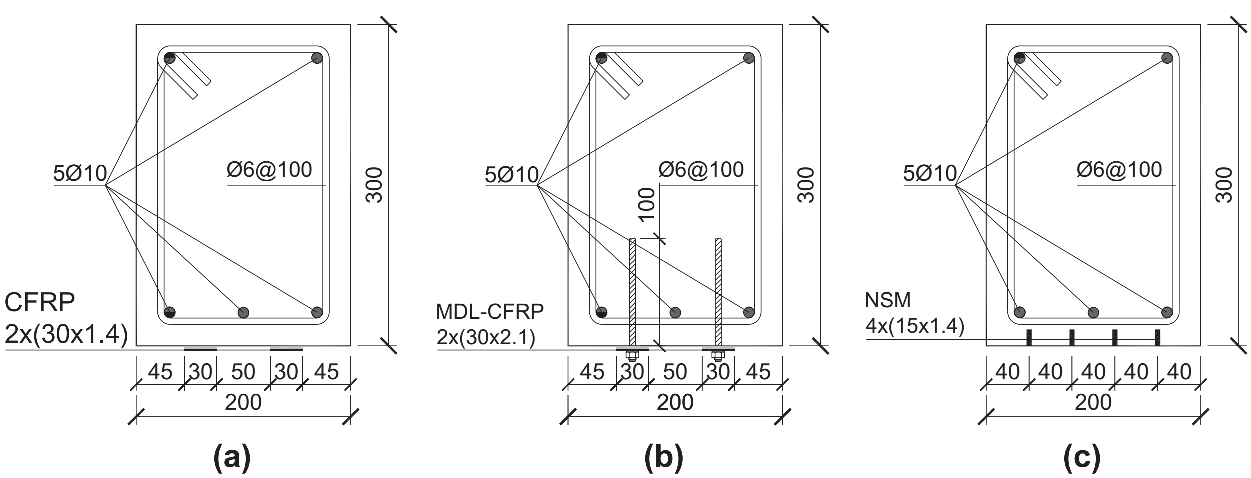

Fig. 2. Cross section of the strengthened beams: (a) EBR; (b) MF-EBR; (c) NSM. Note: all dimensions are in millimetres.