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Experimental response of FRP reinforced members without transverse reinforcement: Failure modes and design issues

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FRP reinforcement is well known as a possible alternative to steel bars in order to improve durability of reinforced concrete members. However, the intrinsic brittleness of concrete and FRP materials may induce problems at the ultimate conditions due to premature failure modes; the performance under service loads is a critical issue as well. To investigate response of concrete members reinforced with longitudinal glass or carbon FRP bars without shear reinforcement, an experimental program has been developed. The sixteen specimens designed and cast within this project were characterized by different study variables concerning cross section geometry, concrete grade and type of reinforcement. The results of tests performed on FRP-reinforced specimens are presented in this paper. In particular, different failure modes due to flexure and shear have been observed; response under load levels simulating service conditions has been also examined. Results of FRP-reinforced specimens have been compared with those given by control specimens provided with conventional steel bars. Finally, analytical procedures to evaluate immediate deflections of FRP-reinforced members have been assessed.

1. Introduction

The use in the construction industry of composite materials made of continuous fibers embedded in an organic or inorganic matrix is strongly increasing since the last two decades. In the field of structure retrofitting, externally bonded fiber reinforced polymer (FRP) materials are widely used to increase the load carrying capacity and the ductility of existing reinforced concrete [1,2], masonry [3,4], and timber [5] structures. The use of unbonded FRP bars to increase the load carrying capacity of arches and vaults has been also proposed [6]. Recently, new composite materials made of continuous fibers embedded in cement based mortars (fiber reinforced cementitious mortars, FRCM) have been proposed [7,8] to overcome the typical shortcomings of FRP materials, essentially consisting in their moderate heat and fire resistance and lack of water permeability.

In the field of new concrete constructions the use of pultruded FRP bars in place of conventional steel bars in RC elements is a promising technology, especially for concrete structures subjected to aggressive environments or to electromagnetic fields [9–12]. For this reason, great attention from scientific and technical communities has been devoted to FRP materials as alternative materials for concrete reinforcement. Design guidelines have arisen from these studies in different countries [13–16].

Advantages of these materials are their good corrosion resistance, high tensile strength and low weight. Other typical characteristics of FRP materials are their relatively low modulus of elasticity, linear stress–strain relationship until failure and variable bond properties, depending on the type of FRP product and surface treatment [17]. The anisotropic behavior of FRP materials affects the shear strength, as well as the bond performance of reinforcement. Furthermore, the anisotropic behavior of FRP bars and the high value of transverse coefficient of thermal expansion with respect to concrete may produce splitting cracks and the concrete cover failure [18]. FRP bars are generally characterized by an elastic modulus lower and by a tensile strength higher than those of steel bars. As a results the serviceability limit states often govern the design and

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FRP reinforced concrete beams need to be over reinforced in order to fulfill the limitations of deflection and crack width [9,10,19,20]. For this reason many research efforts have been devoted to theoretical advances about specific models of composite structures [21–30] and to the developments of reliable analytical, numerical and design methods for the prevision of deflections and crack width [31–40]. Some of the proposed methods [36,37], involve the local bond slip relationship characterizing the FRP–concrete interface, which is a unique feature of each single FRP product. Other studies [32–35] are aimed to calibrate the coefficients of a simple equation for the prevision of the deflection in the frame of the Branson's method [41].

The bond to concrete shear stress transfer phenomenon is different in the cases of FRP and steel bars. This is due to the lower modulus of elasticity of the FRP bars, to the lower shear strength of the resin matrix with respect to steel and to the difference of coefficient of thermal expansion. Furthermore, the influence of transversal stresses and size of concrete cover is also different in the case of FRP and steel bars [42–44]. Many experimental studies have been conducted on this topic [45]; some of them were based on pull-out tests which seem to be unsuited to investigate bending behavior of concrete elements [46]. Other studies were performed to evaluate the correlation between concrete strength and bond characteristics [47]. Achillides and Pilakoutas [48] found that bond-to-concrete of FRP bars is not affected by concrete strength. Okelo and Yuan [49] studied the bond behavior of FRP reinforced elements considering concrete strengths ranging from 29 to 60 MPa. They found that bond performance improves as the concrete grade increases. Other studies stated that good bond is not always desirable in FRP bars since it can lead to local overstress with a possible premature failure of the member [50].

The absence of plastic deformations of FRP bars reveal incompatibility of FRP reinforcements with a ductile behavior as required, for instance, in case of primary members (beams and columns) of earthquake-resistant frame structures. For this reason, most applications using FRP reinforcing bars in many countries [12] have regarded structural members for which ductility is a minor concern, such as floor structures, concrete slabs, and concrete members supporting hollow-tile floors. Another advantageous application of FRP bars consists in their use in the construction of bridge decks [51]. In fact, in this case, deflections are limited by the static redundancy of the structure [37,52] and the characteristics of high resistance to corrosion of the FRP bars play a primary role. In addition, these structures are often without transverse reinforcement; so they are exposed to an early failure due to shear [53,54].

This paper presents the results of an experimental study on flexural response of concrete members without shear reinforcement and longitudinally reinforced with glass or carbon FRP bars (GFRP and CFRP, respectively). The experimental program involved the test of sixteen specimens, conceived according to three main variables: the cross section geometry, the compressive strength of concrete and the type of reinforcement. Response of FRP-reinforced specimens has been compared to that of control specimens reinforced with conventional steel bars. The experimental results were compared with the provisions of different guidelines on design and construction of concrete element reinforced with FRP bars in terms of shear strength, flexural strength and deflection under service loads.

2. Experimental study

2.1. Specimens characteristics and test setup

Sixteen reinforced concrete beams, divided into two series of eight specimens each, were cast and tested in flexure (Fig. 1). Specimens were 2800 mm long; the total length includes two parts of 400 mm beyond supports providing an additional bond length for the intrados reinforcing bars. The specimens of the first series (Fig. 1a) had a shallow rectangular cross section 200 mm × 100 mm (width × depth). These specimens represent a portion of a one way slab. The specimens of the second series (Fig. 1b) had a deep cross section 100 mm × 200 mm (width × depth). These specimens represent a member supporting a hollow-tile floor, typical of the Italian construction practice. The specimens were reinforced only in flexure with different types of bars. In particular, for each series, two beams were reinforced with GFRP bars, two beams with CFRP bars and four beams (control specimens) with conventional steel deformed bars. Some of the adopted arrangement of steel bars is unusual for the current construction practice. They have been adopted to reproduce geometrical and mechanical reinforcement ratios similar to those characterizing the FRP-reinforced beams, for comparison purposes. Mechanical properties of FRP and steel bars are summarized in Table 1. Fig. 2 shows the surface conditions of the adopted FRP bars.

Characteristics of the tested specimens are listed in Table 2, including the geometrical and mechanical ratios of reinforcements (ρ_r and ω_r, respectively). Different concrete grades have been used, depending on mechanical properties of reinforcements; cube compressive strengths R_c ranged from 39 to 80 N/mm^2. FRP reinforcements consisted of sand coated and helically wound GFRP bars (Fig. 2a) with the diameter $d_b = 13$ mm and externally treated CFRP bars (Fig. 2b) with the diameter $d_b = 9$ mm. Steel deformed bars having diameters of 8 mm and 14 mm were used to prepare control specimens.

Portland cement of different grades was employed to produce concrete used in this study. River sand of nominal size limited to 3 mm and crushed stone of nominal size limited to 10 mm were used as fine and coarse aggregates, respectively. The quantities of constituent materials required for one cubic meter of concrete were varied to obtain three different concrete grades: 39, 49 and 80 N/mm^2. A superplasticizer was used only for the concrete with the highest grade. The cubic compressive strength R_c defining each concrete grade was obtained by averaging results of compression tests of four cubes having side of 150 mm, cast at the same time of corresponding specimens.

The specimens were subjected to one-point transverse load monotonically applied until failure, over a clear span L of 2000 mm. Tests were performed by means of a reaction steel frame provided with a mechanical actuator to transmit the displacement-controlled transverse action. Instrumentation consisted of a load cell to measure the applied force and linear variable differential transformers (LVDTs) to gauge deflections.

2.2. Criteria for dimensioning FRP reinforcements

FRP reinforcements of specimens have been dimensioned in order to avoid both the rupture of bars and the bond failure; a failure mode governed by concrete crushing or a shear failure has been then assumed. The above assumption requires that the FRP reinforcement ratio $\rho_r = A_r/(bd)$ satisfies

$$\rho_r > \rho_{rb} \tag{1}$$

where ρ_{rb} is the balanced reinforcement ratio, given by the expression [13]

$$\rho_{rb} = \frac{A_{rb}}{bd} = 0.85\frac{f_c}{f_{ru}}\beta_1\frac{E_r\varepsilon_{cu}}{E_r\varepsilon_{cu} + f_{ru}} \tag{2}$$