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Reinforced concrete beams strengthened with SRP/SRG systems: Experimental investigation

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HIGHLIGHTS

- Results of bending tests on RC slabs strengthened with SRP/SRG systems are presented.
- Number of layers and steel tape density are the main study parameters.
- Slabs strengthened with SRG and SRP systems have shown comparable strength increases.
- Fracture and debonding of the SRP/SRG system were both experienced during tests.
- Analytical predictions of the ultimate bending moment are presented and discussed.

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ABSTRACT

Steel reinforced polymer (SRP) and steel reinforced grout (SRG) have emerged as promising and cost-effective technologies for the external strengthening of RC structures.

Although the first studies date back to 2004, so far the literature related to the flexural strengthening of RC slabs/beams with steel tapes is rather limited. As a result, the application of such materials on a real structural member may be discouraged and, conversely, the use of carbon/glass FRP alternative systems may be preferred.

The study presented in this paper contributes to filling this knowledge gap by presenting the results of 10 four-point bending tests performed on RC slabs strengthened with SRG/SRP systems. Test results have provided valuable information in terms of maximum forces, deformability and failure modes by varying number of layers and density of the steel tape. In particular, it has been shown that, disregarding the nature of the matrix (inorganic or polymeric), the presence of the external strengthening significantly increased the flexural strength of slabs, with percentage increases over the control (unstrengthened) member ranging from a minimum value of 27%, when using a single layer of low density tape, to a maximum of 106% in the case of SRP system with one layer of high density sheet.

Preliminary analytical studies were also performed in order to investigate the possibility of extending to the SRP/SRG systems the applicability of formulations currently reported in some national and international guidelines for the flexural strengthening of RC members with FRP sheets.

1. Introduction

Over the years, the use of Fiber Reinforced Polymer (FRP) materials for the strengthening of reinforced concrete (RC) structural members has met an increasingly widespread consensus at both the academic and industrial levels, representing today a competitive alternative to traditional techniques.

In the case of external strengthening, it is well known that behind the FRP terminology, systems employing carbon fibers are typically referred to, whereas fewer applications make use of glass or aramid fibers. The successful application of such composites in the civil engineering has also been recognized through the spread of specific guidelines around the world, such as the Italian Guidelines CNR-DT 200 R1 [1] and the American Guidelines ACI 440.2R [2].

However, the growing interest in the composites industry toward the development of innovative and low cost solutions has led to the introduction of new techniques for the structural reinforcement that make use of other fibers in lieu of the carbon or glass ones. Among the "new generation" materials, the class of composites made of steel fiber sheets has emerged as one of the

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most promising and cost-effective solutions for external strengthening of RC members.

The steel tape consists of high carbon steel cords made by twisting steel wires within a micro-fine brass or galvanized coating; it can be in situ applied via wet lay-up by using epoxy resin or inorganic matrix, thus obtaining strengthening systems known with the acronym of SRP (“*Steel Reinforced Polymer*”) and SRG (“*Steel Reinforced Grout*”), respectively. The tape can be required according to different densities (generally denoted as low, medium or high), depending on the number of wires distributed in the sheet width.

Although the first studies date back to 2004 [3,4], so far the scientific papers dealing with the use of steel fiber composites for the strengthening of RC structural members (due to bending, shear, or confinement deficiencies) are rather limited, as well as specific guidelines have not been published yet. As a result, the lack of an extensive knowledge on the applicability of these materials might guide the designer toward the choice of “proven” strengthening solutions or more marketed composite systems, i.e., those employing the above mentioned carbon or glass fibers.

By focusing on the flexural strengthening of RC beams/slabs with steel fiber materials, the bibliography reports the main papers by authors contributing to provide some information about the effectiveness of using SRP/SRG systems in the structural rehabilitation [3–15]. In particular, the experimental studies performed by Wobbe et al. [3], by Prota et al. [5], by Kim et al. [6] and Balsamo et al. [9], are pointed out.

Wobbe et al. [3] just performed a first experimental study devoted to prove the potential of the SRP/SRG technology in improving the performance of RC members.

In addition to highlight the influence of using different tape densities on the specimens’ response, Prota et al. also investigated the flexural behavior of beams strengthened with SRG sheets mechanically anchored to the concrete substrate by using nail anchors. It was shown that such nails do not improve the performance of the steel tape impregnated with cementitious grout, being the used tape of unidirectional type, as generally commercialized in the market; in fact, lacking a transverse link, the distribution of the local stress concentration at anchor location was not allowed; as a result, the subsequent bearing failure of nails was unable to improve the bond and delay the tape debonding [5].

Kim et al., instead, examined the efficiency of the SRP system by varying the width of the employed tape and the beneficial role played by the use of U-shape SRP wraps as end anchorages to prevent the peeling-off failure of the external reinforcement at the beam’s intrados [6]. It was again proven the positive contribution of the SRP reinforcement in increasing the flexural capacity of RC beams; also, it was shown that the U-wraps improve the flexural stiffness by controlling diagonal crack width and providing anchorages to the longitudinal SRP sheets, which reduces their slip.

Finally, a comparative analysis of different composite material systems (CFRP-SRP-SRG) for the flexural strengthening of prestressed RC beams was performed by Balsamo et al. [9]; in that work, the convenience into using steel fiber sheet with respect to the carbon ones was verified, since a lower amount of materials and, thus, minor costs allow for obtaining similar effectiveness to CFRP systems in terms of maximum loads.

A few papers also report preliminary considerations regarding the theoretical prediction of the bending moment of RC beams strengthened with SRP at ultimate and service loads [6,11]. Conversely, a more detailed study is highlighted on the numerical simulation of the load–displacement behavior of SRP/SRG strengthened beams [12], whereas the behavior under serviceability conditions of SRP/SRG strengthened RC beams tested by Prota et al. [5] was deepened by Ceroni and Pecce [13]. These authors evidenced: (a) the comparable behavior between SRP and CFRP strengthened RC members, when characterized by equivalent amount of external reinforcement, and (b) the more deformability exhibited by members strengthened with SRG sheets with respect to those upgraded with SRP.

Finally, some field applications have been also performed. In particular, an experimental study performed by Casadei et al. [14], explored the efficiency of the SRP systems in increasing the flexural strength of “double T” prestressed RC beams which were extracted from a decommissioned two-storey parking garage.

Lopez et al. [15], instead, proved that the application of the SRP strengthening to a concrete bridge structure has the potential to be a reliable and relatively easy-to-install technique; also they pointed out that the design procedure for SRP systems is comparable to that suggested by the Guide ACI 440 for FRP materials in force in 2007 [16]. In this regard, it can be reasonable to assume that the failure of an RC member strengthened with adhesively bonded steel fiber system, independently on the type of matrix (epoxy or cementitious), is attributable to concrete crushing (when the ultimate concrete compressive strain is reached) or to the failure of the composite system; the latter, in turn, can be due to the rupture of the fibers in tension or to the debonding mechanism which abruptly occurs with the detachment of more or less large concrete thickness. Therefore, the effectiveness of SRP/SRG systems in increasing the flexural response of RC members may significantly depend, from one side, on the bond behavior at the concrete/reinforcement interface (that is mostly related to the matrix type) and, from the other side, on the efficiency of the used matrix (mainly the inorganic one) to impregnate the steel fabric.

With the aim to better focus on these two key aspects, the experimental study presented in this paper contributes to increase the current knowledge on the flexural behavior of RC members strengthened with steel fiber sheets. In particular, the work deeply analyzes the results of 10 four-point bending tests performed on RC slabs strengthened with galvanized steel fiber tapes applied by using epoxy resin (SRP system) or thixotropic mortar (SRG system).

The main study parameters were: the number of layers (1 or 2); the different density of the steel tape (denoted as low, medium or high); the typology of reinforcement’s application (from the top, by turning upside the slabs, or from the bottom, by placing them on a scaffold).

Test results have provided valuable information in terms of maximum forces, specimens’ deformability, measured strains and curvatures which, coupled with the observed failure modes, are fundamental for a subsequent definition of an accurate design procedure for RC beams/slabs strengthened with SRP/SRG systems. To this purpose, it is highlighted that the bending tests presented herein are part of a wider experimental campaign also including several bond tests performed on SRG/SRP sheets adhesively connected to concrete blocks; such tests, whose results are under publication, will allow for a more specific evaluation of the concrete/SRG (or SRP) interface behavior, on which only few papers are actually available in literature [6,17,18].

The experimental evidence has also allowed for verifying the good performance of the SRG systems, whose effectiveness was not reduced by applying the strengthening system from the bottom, i.e., after having placed two slabs on a scaffold (at a height of about 1.80 m from the floor), in order to simulate the typical working operations found in the field.

Finally, preliminary analytical studies were performed to investigate the possibility of extending to the SRP/SRG systems the applicability of formulations devoted to the flexural strengthening of RC members with FRP sheets which are currently reported in both the Italian Guidelines CNR-DT200 R1 [1] and the American ones ACI 440.2R [2].