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Eco-friendly external strengthening system for existing reinforced concrete beams

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The paper presents an experimental and analytical study carried out on a set of Reinforced Concrete (RC) beams strengthened with a new eco-friendly composite material (Steel Reinforced Geopolymeric Matrix, SRGM) by using traditional Externally Bonded (EB) and innovative Inhibiting-Repairing-Strengthening (IRS) techniques. The proposed IRS solution is addressed to RC members with deteriorated cover concrete and/or corroded bars. It consists in the installation of a stainless steel fabric in the cover concrete, restoring this latter with an inorganic fireproof geopolymeric matrix which also acts as a corrosion inhibitor. The IRS solution reduces the time and then the costs of intervention with an environmentally friendly technology. It can be an effective alternative to EB technique.

In order to simulate existing RC structures, two groups of large-scale RC beams were casted with low concrete strength and corroded smooth round/ribbed bars. Four RC beams were strengthened with IRS-SRGM/EB-SRGM systems and monotonically tested under four-point bending. Test results showed that the IRS-SRGM system provided greater load carrying capacity and ductility than the EB-SRGM system.

Finally, a theoretical prediction of the tested beams, by means of a fracture mechanics based model, was carried out. The analytical/experimental comparisons are satisfactory.

1. Introduction

The most of the existing Reinforced Concrete (RC) structures and infrastructures have deteriorated cover concrete and/or corroded internal steel bars. Traditionally, these RC members have been repaired with steel plates. However, steel plates are prone to corrosion, and special equipments are needed to install these heavy plates. In recent years, Fiber Reinforced Polymer (FRP) materials in the form of fabrics, strips and laminates, have been widely used for retrofitting corroded and/or damaged RC members [1–3]. According to the current guidelines [4,5], the following independent operations are requested: removal of the deteriorated concrete, application of a corrosion inhibitor on internal reinforcing bars, repairing/restoring of the cover concrete and then installation of the strengthening layer with Externally Bonded (EB) technique. These operations, due to the used materials, have impacts on the environment.

The retrofit technology based on using FRP materials externally bonded on concrete substrate attracted the attentions of numerous Researchers [6–9], because it offers numerous benefits, such as corrosion-free, excellent weight to strength ratio, good fatigue resistance and flexibility to conform to any shape. Despite their high performance, FRP system have several drawbacks: high cost, low fire resistance, poor environmental sustainability and low compatibility with traditional building materials.

To overcome these shortcomings, a new class of composite materials, based on inorganic cementitious matrices, was developed. Different cement based strengthening systems for RC structures were proposed: Textile Reinforced Concrete (TRC) [10,11], Textile Reinforced Mortar (TRM) [12,13], Fiber Reinforced Cementitious Matrix (FRCM) [14,15], Fiber Reinforced Grout (FRG) [16–20]. The structural behavior of RC members strengthened with EB-TRC [10,11], EB-TRM [12,13], EB-FRCM [14,15,21,22] and EB-FRG systems [16–20,23,24], was investigated by some Researchers. Some studies highlighted both the effectiveness of cement based composite materials as EB strengthening system [25,26] and the different load transfer mechanisms compared to FRP system [27]. As a result, Ascione et al. [28] proposed a specific qualification method for cement based strengthening systems.

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The development of sustainable building materials with reduced environmental footprint for repairing and retrofitting of existing structures is attracting increased interest in the civil engineering field worldwide. Recently, new eco-friendly geopolymeric matrices have been introduced in the construction market [18–20,28,29]. Geopolymers represent a new class of high performance materials that can be synthesized by mixing reactive aluminosilicate materials, such as metakaolin, industrial or natural waste products [30].

These inorganic matrices have significant advantages compared to the traditional epoxy resin used for FRP system, such as: excellent resistance to corrosion, high value of transition temperature (about 800 °C), no emission of toxic gases under intense fire, excellent durability even in strongly aggressive conditions (coastal areas, deicing salts, acid rain), high resistance against sulfates [28–30]. A further advantage of the geopolymeric matrices compared to epoxy adhesives is related to their inorganic silicoaluminate nature, which makes these materials similar and alternative to cementitious materials, due to high mechanical properties and environmental advantages. In fact, geopolymers generates 80% less carbon dioxide and the global warming potential is 70% lower than Ordinary Portland Cement (OPC) [29]. Furthermore, future increase cost of OPC due to European Emissions Trading Scheme, that will put a price on carbon dioxide emissions generated during clinker production, will increase the economic and environmental advantage of the geopolymer based materials. The idea of using this type of matrix for structural applications has been already investigated [18–20,29]. Two main applications were addressed, the use of geopolymeric mortars as repairing layer or as binding agent to insure the adhesion between the FRP sheets/strips/laminates and the concrete substrate.

In the present work, a new potential structural application of geopolymers was experimentally evaluated. Specifically, the geopolymeric matrix was used, at the same time, as corrosion inhibitor, repairing/restoring layer and binding agent to embedded a stainless steel strengthening fabric in the cover concrete. The proposed solution, alternative to EB technique, was conceived for upgrading of RC structures with deteriorated cover concrete and/or corroded bars. It includes three operations in one, Inhibiting-Repairing-Strengthening (IRS), and consists in the installation of a new eco-friendly composite material (Steel Reinforced Geopolymeric Matrix, SRGM), made of a unidirectional steel fabric embedded in an geopolymeric fireproof matrix, during the repairing/restoring of the cover concrete (IRS-SRGM system).

Although the operative, economic and environmental benefits are relevant, it is necessary to assess the structural effectiveness of the IRS solution, comparing it with traditional EB technique. To this purpose, an experimental investigation was carried out on two groups (A and B) of three large-scale RC beams strengthened with EB-SRGM and IRS-SRGM systems. To simulate existing RC members built in the past, the beams were cast using low concrete strength and corroded smooth round/ribbed steel bars. It should be noted that the using corroded bar does not represent the actual service condition of RC structures. In fact, to simulate the damage induced by steel corrosion in RC structures, steel bars should be oxidized and corroded after concrete hardening. Nevertheless, the present study has been focused on the structural performance of the IRS technique, comparing it with that provided by traditional EB technique. A theoretical analysis, through a fracture mechanics based approach proposed for the FRP system [31], was also performed. The experimental results highlighted the good structural performance of the new IRS technique. Experimental and analytical comparisons showed the reliability and adaptability of the fracture based model to predict the behavior of the tested beams.

2. Experimental investigation

The experimental campaign was carried out at “Laboratory of Materials and Structural testing” of the University of Calabria (Italy). This is a first part of a wide experimental program, actually in progress, aimed to investigate the structural performance of the IRS-SRGM system, varying the geometrical dimensions of the RC beams, the steel reinforcement ratio and the type of the internal steel (smooth round or ribbed bars). The variable parameters were defined so as to assess a potential scale effect on the flexural behavior of the strengthened RC beams. In this study, potential scale effect on the increment of load carrying capacity was assessed by comparing test results of both groups (A and B). Specifically, if the ultimate load increment of the strengthened RC beams compared to the corresponding control RC beams is the same for both groups, no scale effect is detected. Consequently, the geometrical dimensions of the RC beams does not affect the performance of EB-SRGM and IRS-SRGM systems.

2.1. Geometrical and mechanical properties

The experimental program consists of two groups of specimens (A and B). Each group includes three RC beams: one beam strengthened with IRS-SRGM system (A-IRS, B-IRS), one beam externally strengthened with EB-SRGM system (A-EB, B-EB) and another unstrengthened control beam (A-CB, B-CB).

Geometrical parameters and strengthening configurations of the tested beams are shown in Fig. 1(a)-(c) and the values are given in Table 1. For each group it summarizes: length (L), width (b), and height (h) of the beams; shear or bending span (a); length to height ratio (L/h); shear or bending span to depth ratio (a/d), area of the tension (A_s) and compression (A'_s) longitudinal steel reinforcements; reinforcement ratio of A_s over the cross sectional area (ρ_s). It should be noted that the geometrical parameters b, L/h, a/d, ρ_s are equal for both groups. Also the width of the strengthening system (b_f) was defined by keeping constant the strengthening ratio (ρ_f) of reinforcing area (A_f) over the cross sectional area. As a result, the beams were strengthened with a single ply of steel fabric and b_f was equal to 100 mm and 150 mm for the beams of the groups A and B, respectively ($\rho_f = 0.06\%$). This geometrical configuration of the beams allows evaluate, comparing the test results of both groups, a possible scale effect as well as the structural performance of the traditional (EB) and proposed (IRS) techniques.

The mechanical properties of the concrete and internal steel reinforcement were experimentally evaluated. Specifically, the average concrete compressive (f_{cm}) and tensile (slip test, f_{ctm}) strengths, at 28 days, on twelve (six for each test) cylindrical samples (150 mm × 300 mm) were 16.8 MPa and 1.7 MPa, respectively. The average yielding strengths (f_{ym}) of the internal steel bars, on three samples for each diameter, were 543.8 MPa, 367.1 MPa and 492.0 MPa for the 8 mm, 12 mm (smooth round bars) and 16 mm diameters, respectively.

2.2. SRGM strengthening system

The composite material consists of a new stainless steel fabric/strip embedded in an inorganic geopolymeric fireproof matrix. It was applied on RC beams with traditional (EB) or innovative (IRS) technique.

The properties of the steel strip and geopolymeric matrix provided by the manufacturer and/or trading company [32,33] are given in Tables 2 and 3, respectively. The steel strip is an unidirectional reinforcing fabric made of stainless Ultra High Tensile Strength Steel (UHTSS) cords, particularly resistant to corrosion, suitable for interventions on substrates subject to rising damp and/