Composites Part B 110 (2017) 62–71

Contents lists available at ScienceDirect

Composites Part B

journal homepage: www.elsevier.com/locate/compositesb

Single-lap shear bond tests on Steel Reinforced Geopolymeric Matrix-concrete joints

Francesco Bencardino [a], Antonio Condello [a, *], Ashraf F. Ashour [b]

[a] Department of Civil Engineering, University of Calabria, Via P. Bucci, Cubo 39B, Rende 87036, Italy
[b] School of Engineering, University of Bradford, Richmond Road, Bradford BD7 1DP, United Kingdom

ARTICLE INFO

Article history:
Received 13 July 2016
Received in revised form
10 October 2016
Accepted 5 November 2016
Available online 8 November 2016

Keywords:
Fabrics/textiles
Debonding
Fibre/matrix bond
Analytical modelling

ABSTRACT

Nowadays Fiber Reinforced Polymers (FRPs) represent a well-established technique for rehabilitation of Reinforced Concrete (RC) and masonry structures. However, the severe degradation of mechanical properties of FRP under high temperature and fire as well as poor sustainability represents major weak points of organic-based systems. The use of eco-friendly inorganic geopolymeric matrices, alternative to the polymeric resins, would be highly desirable to overcome these issues. The present work aims to investigate the bond characteristic of a novel Steel Reinforced Geopolymeric Matrix (SRGM) strengthening system externally bonded to a concrete substrate having low mechanical properties. SRGM composite material consists of stainless steel cords embedded into a fireproof geopolymeric matrix. Single-lap shear tests by varying the bonded length were carried out. The main failure mode observed of SRGM-concrete joints was debonding at the fiber-matrix interface. Test results also suggest the effective bond length. On the basis of the experimental results, a cohesive bond-slip law was proposed.

1. Introduction

Fiber Reinforced Polymers (FRPs) materials are the most common type of composite systems used for structural strengthening and rehabilitation applications of Reinforced Concrete (RC) structures. FRPs are comprised of continuous fibers (usually carbon, glass, or aramid) and an organic resin, typically epoxy, as a matrix. The researchers [1–3] and civil engineers [4,5] are well-acquainted with the use of FRP composites Externally Bonded (EB) to RC members, and are eager to explore innovative materials that could lead to more sustainable alternatives to traditional composites without compromising the advantages of such retrofitting systems. Promising newly developed types of matrices, that are potentially represent a more sustainable, and durable alternative than epoxy, are the so-called inorganic matrix [6–9]. They can be used both with traditional [6] or innovative reinforcing strips/sheets [10–12]. Among these, novel steel strengthening strips, made of stainless or Ultra High Tensile Strength Steel (UHTSS) cords [13,14], poliparafenilenbenzobisoxazolo [15,16] and basalt fabrics [17] are now available in the construction industry. Different inorganic-based strengthening systems for RC structures were proposed, for example Textile Reinforced Concrete (TRC) [18,19], Textile Reinforced Mortar (TRM) [20], Fiber Reinforced Cementitious Matrix (FRCM) [11,21], Fiber Reinforced Grout (FRG) [22–24]. Some studies highlighted both the effectiveness of inorganic based composite materials as EB strengthening system and the different bond behavior and load transfer mechanisms compared to FRP system [16,25–27]. As regards to FRCM systems, friction between fiber filaments and between fibers and matrix was observed after the debonding process initiates [28,29]. Furthermore, a specific qualification method was proposed by Ascione et al. [30].

Within the broad category of inorganic matrices, geopolymers have raised some interest in recent years [31]. They are inorganic aluminosilicates produced by alkali activation solutions and source materials. Thus, geopolymers are manufactured using activated industrial waste materials such as fly ash in the presence of sodium hydroxide and sodium silicate solutions. The geopolymeric 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, no emission of toxic gases under intense fire, excellent durability even in strong aggressive conditions (coastal areas, deicing salts, acid rain) and high resistance against sulfates [8,9,24,32]. A further advantage of the geopolymeric matrices compared to epoxy adhesives is related

---

* Corresponding author.
E-mail address: antonio.condello@unical.it (A. Condello).

http://dx.doi.org/10.1016/j.compositesb.2016.11.005
1359-8368/

to their inorganic silico-aluminate nature, which makes these materials similar and alternative to cementitious materials, due to high mechanical properties and environmental advantages. In fact, the cement industry contributes around 6% of all CO_2 that is responsible for about 65% of global warming emissions [32], causing significant environmental issues. As a result, it is necessary to find new inorganic materials alternative to cementitious mortars which are environmentally stressful. To this end, geopolymers are a breakthrough development providing an essential alternative to cementitious materials, using novel environmentally friendly materials.

The use of geopolymer concrete in new RC members [33,34] and geopolymeric matrices in the repair and strengthening of existing structures [24,32] has been already investigated. With reference to the rehabilitation, two main applications were addressed: the use of geopolymeric mortars as repairing layer [32] or as binding agent to insure the adhesion between the external reinforcing sheets/strips/laminates and concrete substrate [24,32]. When the geopolymeric matrix is used to embedded steel strips, the strengthening composite system is labeled as Steel Reinforced Geopolymeric Matrix (SRGM) [35,36]. The studies available in literature show that geopolymer-based systems can be successfully used in strengthening applications of RC members [7,9,24,35,36], although their behavior is different from FRP composites due to differences in the debonding failure mechanism. Debonding failures are critical in strengthening applications because they can be brittles, and can control the overall performance of the system by triggering global member failure. With FRP composites, it is well-known that debonding typically occurs at the adhesive-concrete interface and usually involves a thin layer of the concrete substrate. Research available on debonding of steel reinforcing strips embedded into inorganic matrices is very limited. In general, the debonding was observed at matrix-steel cords interface [9,24,35,36]. Consequently, the substrate, on which the composite is applied, could not play a key role in the design of the strengthening system. A complete understanding of the mechanism of interfacial load transfer of SRGM system bonded to concrete substrate is critical to design and has not yet been analyzed.

This paper presents the results of an experimental investigation aimed to study the interfacial behavior and stress-transfer mechanism of the SRGM composite EB to a concrete substrate. To this end, single-lap shear bond tests were carried out. In order to simulate substrates of existing old RC structures, the specimens were cast with low concrete strength. This research is needed for the development and/or validation of analytical models to calculate the effective bond length, which can be used to evaluate the load carrying capacity of the interface.

2. Experimental program

The experimental campaign was carried out at the “Laboratory of Materials and Structural testing” of the University of Calabria (Italy). It is a part of a wider in-progress experimental program aimed at investigating the bond behavior of SRGM-concrete joints as well as the structural performance of full scale RC beams strengthened with this innovative system [35,36]. In this paper, the results of twelve single-lap shear tests, with variable bonded lengths, are presented and analyzed. Detailed information about the geometry and mechanical properties of the test specimens, the strengthening system and the test set-up are given in the following sections.

2.1. Geometric and mechanical properties

The single-lap shear test specimens comprised of the composite SRGM system bonded to a concrete prism as shown in Fig. 1. The concrete prisms were 150 mm wide × 200 mm deep × 600 mm long. The composite SRGM system was bonded to a 150 mm × 600 mm concrete face. The specimens were labeled with the bonded length (l_b) followed by “S” (if present), which indicates that the specimen was equipped with strain gages.

The concrete compressive cylinder strength (f_{cm}) was evaluated by testing six cylindrical samples (150 mm × 300 mm) at 28 days and the average value was 16.8 MPa. Splitting tensile tests were also carried out at 28 days on six cylindrical samples (150 mm × 300 mm) and the average tensile strength (f_{ctm}) was 1.7 MPa.

2.2. SRGM strengthening system

The SRGM composite material consists of a stainless steel strip (Fig. 2(a)) embedded in an inorganic fireproof matrix (Fig. 2(b)). The properties of the steel strip provided by the manufacturer and/or trading company [37] are given in Table 1. It is a unidirectional reinforcing fabric made of stainless cords, particularly resistant to corrosion, suitable for interventions on substrates subject to rising damp and/or exposure to aggressive environments. The base material used for the manufacturing of steel fabrics is the same as the one used for tires. Therefore, a design process of the steel fabrics using the disposed worn tires will be environmentally friendly as well as the manufacturing process of geopolymeric matrices [38]. The properties of the matrix are given in the technical data sheet [39] and are summarized in Table 2. It is a polymers-based inorganic mineral with the addition of synthetic fibers, ready to use with the addition of 1 L of water per 5 kg (Fig. 2(b)), and suitable for structural repairs of deteriorated cover concrete being able to be applied with thicknesses between 2 and 40 mm.

The main advantages of the polymer-based inorganic matrix are: high mechanical strength for both short and long curing, strong adhesion to concrete substrate, high resistance against sulfates, excellent durability even in sever aggressive conditions (coastal areas, deicing salts, acid rain), excellent resistance to corrosion and high value of transition temperature (about 800 °C).

The use of geopolymeric matrices in external strengthening applications is not yet widely known and used in practical applications, as it could potentially be, due to some critical issues that characterize these applications. Manufacturing of geopolymers represents the main issue [6]. So far, good mechanical and physical properties of geopolymeric composites were obtained by controlling the curing conditions at high temperature and pressure. The present work investigates the SRGM-concrete interface behavior on specimens cured at room temperature and atmospheric pressure.

2.3. Surface preparation and bond procedure

Before bonding of the external SRGM reinforcing system, faces of concrete blocks were carefully cleaned in order to remove dust, loose particles, oil stains, and other parts that could affect bonding. Subsequently, the concrete surface was subjected to moist sandblasting and hydraulic scouring. The matrix was only applied to the bonded area of the embedded fibers and to bond the composite to the concrete substrate. The matrix was applied from the edge of the external longitudinal cords on one side of the strip to the edge of external longitudinal cords on the other side of the strip. A 3–4 mm layer of matrix (internal layer) was applied using molds to control the composite width and thickness (Fig. 3(a)). A single layer of steel strip was applied onto the matrix, and the cords were pressed onto the matrix to assure proper impregnation (Fig. 3(b)). A second 3–4 mm external layer of matrix was applied over the steel strip (Fig. 3(c)). The bonded width was constant for all specimens ($b_f = 50$ mm), whereas the bonded length (l_b) of the composite was