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Experimental investigation on the debonding failure mode of basalt-based FRP sheets from concrete

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ABSTRACT

In this paper, the debonding failure mode of basalt-based FRP (BFRP) reinforcements from concrete supports is experimentally investigated. In detail, more than 40 push-pull double shear tests on BFRP-concrete specimens with different geometrical configurations were carried out. Results in terms of debonding load and strain patterns arising at the BFRP layer are presented and discussed, furnishing indications about the influence of: composite thickness, width ratio between the BFRP width and the concrete one, anchor length. On the basis of the proposed experienced evidence, the design indications provided by the Italian Technical Document CNR DT200/R1 and addressing the assessment of the debonding load have been critically analysed. Accordingly and as a further result, a novel effective calibration of the corresponding empirical correction parameter k_g (introduced to improve the previsional effectiveness of the fracture-mechanics-based theoretical estimate of the debonding force), has been provided. In detail, in order to ensure the best agreement between proposed experimental data and theoretical predictions associated to concrete elements externally strengthened by the *in-situ* application of BFRP sheets, the value k_g = 0.117 mm (5% fractiles 0.079) is specifically proposed, resulting very different from the indication by the Italian technical document (k_g = 0.077 mm, 5% fractiles 0.037 mm).

1. Introduction

In the last decades, fiber reinforced polymers (FRP), since their good mechanical and physico-chemical properties, have been successfully employed for strengthening and retrofitting of existing concrete structures, allowing for cost effective and minimally-invasive solutions.

In particular, FRP plates or sheets mainly based on carbon, glass and aramid fibers have been widely employed for improving flexural bearing capacity of beam-like concrete structural elements, inducing fully negligible alterations of weight loading [1]. In this case, FRP layers are usually applied at the tension beam side after a suitable support preparation, in order to guarantee an effective adhesion between composite layers and concrete substrate. As a matter of fact, one of the critical issues of this strengthening technique is represented by the FRP debonding that may occur in correspondence of the extremity ends of the reinforcement plates (namely, end-debonding) or in correspondence of the cracked zone of the beam (namely, intermediate-debonding). Such a failure mode, mainly due to the development of high shear stresses at the concrete-FRP interface, is essentially associated to a brittle mechanism, that may widely jeopardise the achievement of the ductility degree associated to the design concept of the reinforced structural element.

In order to understand and to properly describe onset and effects of debonding mechanisms, many experimental campaigns have been carried out [2–13] and several modelling strategies have been recently proposed [16–24], furnishing a number of effective design indications in terms of the debonding load as well as of the bond-slip relationship at the FRP-concrete interface. In particular, available studies have clearly highlighted that the debonding failure mode is highly affected by geometrical parameters of both FRP sheets (i.e., thickness and width) and beam [5,7,11,16], as well as by stiffness and strength features of the involved materials [22,43,44]. Nowadays, present design guidelines and technical standards (e.g., Refs. [43,44]) try to account for these coupled influences by means of semi-empirical formulations that allow for the estimate of the debonding load and of the minimum FRP anchor length which ensures the maximum loading transmission performance. Nevertheless, mechanical response of concrete beams strengthened via FRP systems, as well as the analysis of FRP-concrete debonding mechanisms, are usually investigated by restricting to the case of traditional carbon-based and glass-based FRP (referred to as CFRP and GFRP, respectively). Thereby, calibration of technical rules and design indications are generally referred to carbon, glass or aramid-

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based FRP.

In the last years, an increasing interest has been gained by a new class of FRP composites based on basalt fibers (BFRP) [38–40]. Basalt is a natural material derived from the solidified magma and, therefore, widely spread in volcanic areas. Through a process of basaltic rock melting and extrusion, basalt continuous fibers may be easily produced, allowing for the manufacturing of FRP composites also in the form of plates and sheets [25,29,30]. Fabrication process of basalt-based FRP is usually charaterized by good processability features and it is related to significant economic advantages related to basalt availability and to a production process that does not require special additives and procedures. As a result, basalt fibers are cheaper than carbon fibers and they have a production cost which is almost comparable with glass fibers [25,29]. From a mechanical point of view, basalt fibers exhibit good mechanical properties (in terms of strength and stiffness), resulting in BFRP composites with mechanical performance usually comparable or better than glass-based FRP [26,29]. Moreover, unlike other fiber types, basalt fibers practically exhibit almost constant mechanical properties in a wide range of temperature values (from about -250 °C up to $+650$ °C), they are more resistant to aggressive alkaline or acid environments, and represent an eco-compatible solution, since they do not entail recycling problems [27,28]. Thereby, the use of BFRP for perspective and advanced applications in many engineering fields, as well as for the reinforcement of existing masonry and concrete structures, can be surely considered as potentially effective and feasible [27,35].

As a matter of fact, recent experimental and analytical studies [31–38,40–42] have shown feasibility and effectiveness of BFRP-based reinforcement systems for concrete beams undergoing flexural loads. Nevertheless, as it has been previously stated, technical standards and design guide-lines are defined and calibrated on the basis of evidence mainly related to CFRP and GFRP. Thereby, since possible differences in stress transmission mechanisms, associated to different bonding features and stiffness distribution, the use *tout court* of available indications in the case of BFRP could be not effective. Aiming to contribute towards the filling of such a gap, and specifically referring to the debonding failure mechanisms, in this paper experimental results obtained from more than 40 debonding tests on BFRP-concrete specimens (characterized by different geometrical configurations) are proposed and discussed. In detail, results are presented in terms of debonding load and active transmission length, also focusing on the analysis of strain patterns and bond-slip relationships at the BFRP-concrete interface.

Moreover, proposed results are critically compared with the technical guidelines suggested within the Italian Technical Document CNR-DT 200/R1 by the National Research Council [43], allowing for the proposal of a novel and effective calibration of the corresponding design indications, with reference to the prediction of the debonding load and specifically addressing the use of BFRP for flexural strengthening.

2. Experimental campaign

Aiming to investigate about debonding failure mechanisms occurring in BFRP-concrete systems, an experimental campaign was conducted at the Laboratory of Structures and Materials of the University of Rome “Tor Vergata”. In particular, 43 debonding tests on BFRP-concrete specimens, obtained through the *in situ* application of BFRP sheets on prismatic concrete block by means of fresh epoxy resin, were performed (see Fig. 1).

As well-established and recent experimental evidence confirms [6,8], the debonding failure mode of FRP attached to concrete supports is strongly affected by the testing procedure. Although different test setups have been proposed in available experimental studies, the push-pull shear testing procedure (also denoted as near-end supported shear test) has been recognized to give reliable and almost reproducible results [6,22]. It consists in pushing the concrete block and pulling the attached FRP sheet via a force system comprising two opposite forces acting as parallel to the bonding interface. In order to eliminate loading eccentricity effects, possibly inducing non-shear mechanisms, the debonding tests presented in this study were performed by following a push-pull double shear approach [45–47], as schematically depicted in Fig. 2.

2.1. Specimen geometry and preparation

In agreement with the notation introduced in Fig. 1, the concrete blocks (dimensions $b \times h_c \times L_c$) were realized by referring to two different dimensional configurations: $200 \times 150 \times 400$ mm (in the following referred to as S20) and $300 \times 150 \times 600$ mm (referred to as S30).

BFRP sheets with different aspect ratios were employed for defining the BFRP-concrete test specimens. In detail, four different values of both anchor length L_f (specifically 200, 250, 300, 350 mm) and width b_f (50, 75, 100, 200 mm) were considered. Moreover, experiments were performed by referring to both single (corresponding to the BFRP thickness $t_f = 0.14$ mm) or double sheet ($t_f = 0.28$ mm) configurations. In order to avoid critical local failure in correspondence of the concrete corner [14], the composite sheets were applied to the concrete samples by leaving a not-attached zone $L_{na} = 50$ mm long. Furthermore, as shown in Fig. 1, an U-shaped configuration of the BFRP sheets was adopted outer to the concrete sample (characterized by a curvature radius equal to 75 mm in the curved region) for applying the pulling action via a steel cylinder.

Test samples and their geometrical properties are summarized in Table 1. As a notation rule, the nomenclature adopted in what follows for addressing BFRP-concrete samples is defined by $Sb\_b_f\_L_f\_n_f$, where Sb identifies the concrete sample type (S20 or S30) and n_f is the number of BFRP sheets.

Concrete samples were realized through the casting in wooden formworks purposefully built (see Fig. 2a). In order to allow a good adhesion of the BFRP reinforcement, the opposite faces of the concrete prisms characterized by dimensions $b \times L_c$ were properly leveled by removing the excess top mortar layer. Afterwards, they were cleaned via both a mechanical brushing and a compressed air jet, in order to eliminate dust and other particles. A layer of primer resin, provided by the BFRP manufacturer, was applied on the bonding surfaces (see Fig. 2b) and, after the curing time, the BFRP sheets were attached by following three phases:

- application of a layer of epoxy resin;
- implementation of basalt-based unidirectional FRP sheets, with fiber direction aligned along the loading direction (namely, along the concrete length L_c);
- application of a further layer of epoxy resin (see Fig. 2d).

In order to avoid any air bubble and to eliminate any resin surplus, BFRP sheets were manually impregnated with the resin by performing a brushing process. Moreover, for ensuring a dimensional accuracy for the BFRP-concrete bonding areas, active bonding regions were externally delimited by adopting an adhesive tape (for a fine delimitation) and a plastic transparent film. As a result, any possible resin occurrence outside of the active bonding areas did not induced any adhesion effect (see Fig. 2c).

2.2. Material characterization

The mechanical properties of the concrete were deduced through: 15 compression tests on $15 \times 15 \times 15$ cm cubic samples (see Fig. 3a), leading to a measure of the mean cubic compressive strength R_{cm}; 3 indirect tensile tests (Brazilian splitting tests) on cylindrical samples, 15 cm in diameter and 30 cm height (see Fig. 3b), furnishing a measure of the tensile strength f_{ctm}. All concrete samples were realized through concrete R40 and tested after 28 days from the casting.

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