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A novel methodology for shear cohesive law identification of bonded reinforcements

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ABSTRACT

Repair of structural elements with bonded fiber reinforced polymers (FRPs) is widely used in many engineering applications. Within the strengthening of civil structures, failure usually occurs due to FRP debonding by in-plane shear mode fracture. In this work, mode II fracture behavior of concrete specimens, reinforced with pultruded FRP, was investigated by the authors. Shear tests were performed by using both conventional equipment and a non-contact optical technique, Digital Image Correlation (DIC). Starting from the experimental data, the evaluation of the J-integral and of specimens' fracture toughness was carried out. Subsequently, a cohesive law was associated to the J-integral and thus identified by comparison with experimental data, by means of the theoretical approach proposed by Rice. The proposed cohesive zone (CZ) model can be adopted in a Finite Element (FE) code for simulating the debonding failure in composite structures.

1. Introduction

In recent years, adhesive bonding as joining technique has become frequent for structural purposes in many engineering fields, also as a consequence of the increasing use of composite materials. In mechanical engineering applications, bonded composites are typically used for the realization of industrial, automotive, naval and aerospace high-tech structural elements [1,2]. Moreover, adhesive bonding is currently the most popular technique in repair and rehabilitation of existing civil structures (reinforced concrete and masonry structures), due to the development of innovative and cheaper FRP materials [3–6]. In particular, the use of FRPs provides the strengthening of structures subject to axial, bending, and shear loads [7–11] and guarantees the reversibility of the intervention. This is an attractive aspect with respect to conventional rehabilitation techniques, especially referring to historical buildings.

Although numerous are the advantages of strengthening by bonding composite plates and sheets, this method suffers from the uncertainty in estimating residual strength. No specific standards are required to be applied to the strengthening and construction of reinforced concrete and masonry civil structures until now, but some technical recommendations are provided in the American ACI 440.2R-17 [12], the European fib T.G. 9.3 [13] and the Italian CNR-DT 200 R1/2013 [14] guidelines. Within this context, some specific aspects of this technique have yet to be studied in deeper detail, like as the stress transfer mechanisms from composite to strengthened member. These mechanisms depend on the specific type of junction: adhesive interface [15], anchorage device [16]. With reference to the adhesive junctions, it is well-known that their mechanical behavior can be modeled via a cohesive law, that allows also the prediction of the mode II fracture mechanism experimentally observed in failure of strengthened systems [17,18].

The identification of cohesive law requires the evaluation of relative displacements between FRP and structural element and FRP strains along the loading direction. The former are conventionally measured by means of either linear variable displacement transducers (LVDTs) or laser meter devices installed on composite plate and located at the beginning of bonded area. Whilst, the latter are commonly acquired through strain gauges, positioned along longitudinal direction [19–21].

Some recent studies have proposed a non-contact optical technique, DIC, to obtain relative displacements on extended areas of tested specimen rather than only on the beginning of bonded area [22–30]. This promising method also allows for an estimation, with a good accuracy, of the strain field on FRP and external surfaces of concrete core.

Such measuring method is prone to some problems, like the needs of a large amount of computer resources for mapping the strain field by DIC or the wide scatter of data.

A new and innovative methodology for the identification of cohesive law at the adhesive interface of strengthened systems is presented and validated in this work. The proposed approach is based on the *J*-

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integral formulation and DIC outcomes, without requiring any strain gages and LVDTs/laser meter records.

Experimental debonding tests on concrete blocks externally reinforced with GFRP pultruded laminates have been conducted for validation purposes by the authors at the Structural Engineering Testing Hall of the University of Salerno. Within experimental investigation, DIC method is applied only to selected regions of interest (ROI). This drastically reduces the computational burden, pointing out experimental displacements in a more accurate way and overcoming the boundary effects of inhomogeneous zones.

A first validation of the proposed identification methodology has been performed by comparing the resulting predicted cohesive law with those obtained in a conventional way, i.e. starting from strain gauges records.

Further validation test has been done by comparing such a predictive cohesive law with that given by a direct identification scheme based on an accurate finite element model of the tested specimens (FEM virtual test).

2. Experimental activity

Experimental characterization of adhesive interface of concrete reinforced with GFRP composite laminates is presented thereinafter. In detail, six samples were tested under quasi-static boundary conditions, according to the CNR-DT 200 R1/2013 guidelines.

Experimental tests were performed at the Structural Engineering Test Hall of the University of Salerno, using a universal servo hydraulic machine Schenck Hydropuls S56 equipped with a strain gauge data acquisition system (System 5000 by Vishay) and with a vision system (5 MPx CMOS camera sensor by IDS) for non-contact displacement measurements (Fig. 1).

The specimens were constrained using a steel anchoring device mounted on the testing machine. The ends of the concrete block were clamped, whilst the composite laminate was gripped to the actuator for applying the loading condition, as suggested by the CNR-DT 200 R1/2013 guidelines.

Fig. 1. Testing layout.

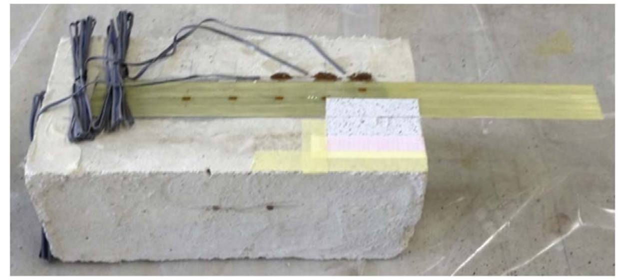

Fig. 2. Details of a tested specimen.

Concrete blocks were fabricated using low strength concrete to best simulate the interface behavior of strengthened existing structures. Composite reinforcement was made of a pultruded E glass/polyester fiber reinforced polymer (E-glass fiber volume fraction equal to 35%). A two component epoxy resin Sikadur 30 by Sika was used for bonding.

The investigated typical specimen is shown in Fig. 2.

The specimens were realized using a GFRP pultruded laminate, whose total bonded length is 300 mm starting 50 mm from the front side of concrete block. No specific surface treatment of concrete was adopted before bonding step. The specimens were cured at room temperature (21 °C) for 7 days. Concrete block and GFRP laminate dimensions are shown in Fig. 3.

First, six cubic samples of concrete (150 × 150 × 150 mm^3) were prepared and tested in order to evaluate the mean compressive strengths, respectively cubic R_{cm} and cylindrical f_{cm}. Second, tensile tests, according to ASTM D3039M standard, were performed to obtain the mean Young's modulus E_{GFRP} and ultimate tensile stress f_{GFRP} along fiber direction of the pultruded GFRP composite. The experimental mechanical properties of concrete and GFRP laminate, together with the nominal Young's modulus E_r and tensile strength f_r of resin Sikadur 30, as stated in the technical data sheet by manufacturer, are listed in Table 1.

Fig. 4 shows the strain gauges configuration applied to each specimen, whilst their location along the loading direction x is specified in Table 2. The origin of x axis corresponds to the top edge of the bonded area.

The strain-gages location was modified for the specimens # 2–6, accounting for the response of specimen #1 testing, thus reducing the distance between consecutive sensors and removing unneedful strain gauges (i.e. the strain gauges 3c and 5GFRP).

The tests were conducted under displacement control with a rate of 0.01 mm/s until the complete debonding occurred. The experimental data acquired during test execution are:

1) Digital video for image processing with DIC technique;
2) Relative displacement between specimen edges by the test machine

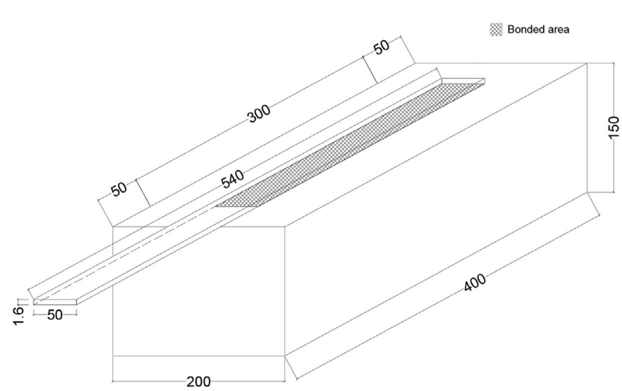

Fig. 3. Geometry of the concrete blocks and the composite laminates [dimensions in mm].