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An interphase model for the analysis of the masonry-FRP bond

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ABSTRACT

The present paper deals with the problem of the detachment of fiber reinforced polymer (FRP) from a masonry support. In particular, a new interphase model simulating the mechanical bond between masonry and FRP is proposed. It is obtained as a system of two interfaces: one reproduces the response of the glue and of the skin-deep layer and it is characterized by a linear elastic behavior whereas the second describes the nonlinear response of the detachment layer. The effect of the possible confinement due to the stress components acting in the plane of the detachment layer is also considered. Two numerical applications are reported. The first illustrates a comparison between the experimental laboratory tests and numerical simulations, showing the good performances of the proposed model. The second application is specifically devoted to the investigation of the effects of the presence of mortar joints in the detachment mechanism.

1. Introduction

The use of structural reinforcements characterized by high mechanical properties applied on elements made of cohesive, i.e. quasi-brittle, materials such as concrete or masonry promoted the development of new researches on the bond problem. In fact, the effectiveness of these types of reinforcement is mostly related to the performances of adhesion. As matter of fact, the bond is responsible for the stress transfer from the reinforcement to the cohesive support element; when the adhesion is no more ensured, the effectiveness of the reinforcement vanishes. Several type of structural reinforcement systems are nowadays available for the civil engineering applications [19]; in particular, different types of mineral fibers, e.g carbon, glass, basalt, steel, or natural fibers, e.g. flax, hemp, jute, coir are actually available on the market. Moreover, several kinds of organic and inorganic adhesives are used to bond the fibers to the structural element. Of course, the adhesive plays a fundamental role in the detachment failure mechanism; its mechanical properties and its density and viscosity at the time of application are very important for the overall response of the reinforced structural system and for the failure mechanisms.

Fiber reinforced polymers (FRP), e.g. carbon (or even, glass) fibers with epoxy resin, are one of the most used reinforcement system for concrete and masonry elements [6]. It results very effective and easy to install in many applications. On the other hand, its failure due to debonding is greatly feared as the detachment mechanism is very sudden and brittle.

Several experimental tests have been performed to investigate on the effectiveness of the bond between the cohesive support and the FRP reinforcement. Initially, laboratory tests have mainly been performed on concrete structural elements [12]; in the last decade, many tests on FRP reinforced masonry elements and structures have been executed. In particular, laboratory tests investigated the bond response of FRP applied on a single clay brick [10,26,27,37] and block [15], on an assemblage of bricks [9,18,32] and on structural elements [5,25,29,33].

Analytical and numerical models for the evaluation of the masonry-FRP bond response have been proposed in literature. They are mostly based on the use of the interface concept, within cohesive damage laws. Cohesive interface model assumes the relative displacement resulting between the two surfaces defining the interface as kinematic parameters governing their overall nonlinear behavior. The differences among the available proposed models are mainly in the definition of the damage law of the interface and in considering a linear or nonlinear behavior of the cohesive support [3,14,31,35]. Design formulas for evaluating the detachment force of a FRP applied on a masonry surface have also been proposed [13,15,28]. Models able to couple the interface damage with the damage occurring in the cohesive support material have been developed initially for concrete-FRP [4,17,34] and, then, for masonry-FRP [30,36]. Moreover, the effect of mortar joints has been investigated in [7,9,20,32].

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A new interface modeling approach has been proposed in [21], based on a kinematic enriched model for cohesive interface; in fact, the kinematics is defined by the relative displacement occurring between the two surfaces of the interface and, even, by the strain arising in the plane of the interface. In such a way, a damage model which accounts also for possible confinement of the interface layer is proposed. The model has been implemented in a finite element code remarking the significant role that the confinement can play in the detachment mechanism.

In the present paper, a further enhancement of the model presented in [21] is proposed and preliminary results have been illustrated in [22,23]. In fact, the masonry-FRP bond is modeled as an interphase which regarded as a system of two interfaces: the first interface reproduces the glue response and it is assumed to be characterized by a linear elastic constitutive law; the second interface layer emulates the specific response of the layer where the detachment process occurs and it is modeled considering a cohesive damage law which accounts for the confinement effect. In particular, a Drucker–Prager failure criterion is adopted for the nonlinear response of the detachment interface. Then, the overall behavior of the interphase system is deduced by a homogenization process accounting for the response of the two interfaces. The proposed model is implemented in a finite element code able to solve the nonlinear evolution problem by a predictor–corrector algorithm implemented in the backward Euler time-step procedure.

Numerical applications are carried out from one hand to assess the effectiveness of the proposed model and the developed numerical procedure, from the other hand to investigate on the role played by the confinement effect in the bond response. In particular, a numerical study on the detachment problem of FRP from masonry elements is performed, determining the influence of the presence of the mortar joints between clay bricks on the decohesion process. In order to verify the ability of the developed model to reproduce the detachment phenomenon, comparison between numerical and experimental results are reported.

It could be remarked that the problem of the detachment of the FRP from a masonry element should be investigated in a three-dimensional framework. In fact, no negligible normal and shear stresses arise along the FRP width direction that could play a role in the bond response. Simpler two-dimensional analyses based on plane stress or plane strain allow to describe the main phenomena of the debonding, even if both they are not able to capture the effect of the presence of transversal stresses. In order to manage a simpler model, the FRP masonry bond investigation has been performed under the assumption of 2D plane stress state. The classical Voigt notation is adopted, so that strain and stress are represented as 3×1 vectors and fourth order tensors as 3×3 matrices.

The paper is organized as follows: Section 2 deals with the description of the masonry-FRP bond model, introducing the kinematics of the interphase, the stress state in the adhesive and in the detachment layers and deriving the overall interphase response; in Section 3 the numerical simulations are reported illustrating the comparison with experimental evidences. Finally, in Section 4 concluding remarks are given.

2. Masonry-FRP bond model

The adhesive bond between the masonry support and the FRP reinforcement is rather peculiar, as it presents a significant heterogeneous nature at microscopic level. The FRP is applied on the masonry surface by means of fluid epoxy resin; because of its fluidity, the resin is able to penetrate into the shallow pores of the masonry support. When the FRP is cured, the adhesive epoxy resin becomes stiff and strong thus improving the mechanical properties of the skin-deep thin layer of the masonry. As consequence, the failure of the reinforcement system occurs, as well known, below this skin layer inside the masonry material. Thus, according to the above description, the masonry-FRP adhesive bond can be considered as composed by three different layers:

- The adhesive layer made of epoxy resin.
- The skin-deep layer, composed by the masonry material and the cured epoxy resin penetrated inside the masonry shallow pores.
- The detachment layer, which is the thin masonry layer located directly below the skin layer.

The FRP reinforcement, the three different layers previously detailed and the substrate material are schematically illustrated in Fig. 1(a).

As the failure occurs into the detachment layer, it can be assumed that this layer is completely responsible for the nonlinear response of the bond system, while the adhesive and the skin layer present a linear elastic behavior. As consequence, the adhesive and the skin layer can be modeled by a linear elastic interface and the detachment layer should take into account for the possible detachment. This implies that the adhesion system can be modeled as two interfaces in series: one characterized by linear elastic behavior, modeling the response of the adhesive and skin layers, and one by a damage law, representing the detachment layer. The scheme of two interfaces in series, denoted in the following as interphase, is illustrated in Fig. 1(b), where $\mathcal{I}_g$ models the adhesive and skin layer, while $\mathcal{I}_d$ models the detachment layer. The thickness of the interfaces $\mathcal{I}_g$ and $\mathcal{I}_d$ are denoted in the following as t_g and t_d, respectively. The total thickness of the interphase $\mathcal{I}$ is t; the ratios $\rho_g = t_g/t$ and $\rho_d = t_d/t$ are also introduced, such that $\rho_g + \rho_d = 1$.

In the structural system three surfaces can be distinguished, denoted in the following as:

- S^-, bottom surface of $\mathcal{I}_d$.
- $\widehat{S}$ top surface of $\mathcal{I}_d$ and bottom surface of $\mathcal{I}_g$.
- S^+ top surface of $\mathcal{I}_g$.

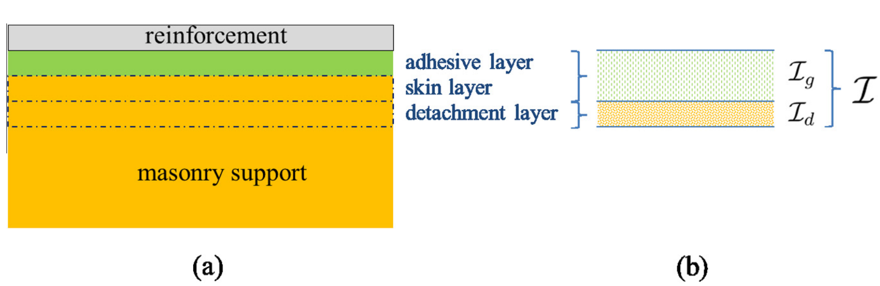

Fig. 1. FRP reinforcement applied on the masonry support: (a) heterogeneous nature of the adhesive bond and (b) modeling scheme of the system.