Debonding process of masonry element strengthened with FRP

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Abstract

The influence of mortars joints in masonry substrate reinforced with FRP is investigated from the numerical point of view. The analysis has been conducted by means of a new interface model specifically developed to reproduce the debonding process occurring between an elastic thin body in adhesion with a cohesive support material. The model accounts for mode I and mode II of failure, considering the effect of the in-plane deformation of the interface, i.e. the possible elongation or confinement of the material constituting the interface. Numerical results are compared with experimental evidences showing good performances of the proposed model in investigating the transferring phenomena and in studying the influence of the presence of mortar joints in the masonry texture in the debonding process.

Keywords: masonry; FRP; mortar joints; debonding.

1. Introduction

A common practice to strengthen concrete or masonry structural elements consists in applying to them Fiber Reinforced Polymer (FRP) strips. Experiments have provided evidence that the most frequent failure mode for this arrangement is the debonding of the FRP from the substrate. This mechanism involves the presence of a crack which nucleates and propagates a few millimeters underneath the gluing surface inside the substrate, usually resulting as the weakest element in the reinforced system. Numerical and analytical investigations permitted to generalize the mechanical behavior by means of parametric relationships, allowing thus to define the resistance against debonding as a function of the main involved parameters.

Due to material similarity between concrete and masonry, such as low tensile strength and brittleness, the debonding mechanisms for retrofitted masonry have been shown to be analogous to those of retrofitted concrete members and the reinforcement is designed following common rules. A significant amount of recent literature (see [7], [3] for an almost complete list of references) is devoted to the investigation of debonding in concrete and masonry substrate but very limited attention has been paid to analyze the influence of mortar joint type in masonry [1], [6].

In the present work the effects of mortars joints in masonry substrate reinforced with FRP is investigated from the numerical point of view. The analysis will permit to determine the influence at the local interface level and the global

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response of the strengthened elements. For the interface an innovative damage model that considers an enhanced kinematics at the interface level. The original idea presented in [5] will be adopted and slightly modified. The model introduces an enhanced formulation for cohesive interface that keep into account the effect of in-plane deformations of the gluing surface, thus, permitting to keep into account at the interface level the effect of the substrate confinement. In the actual formulation, the kinematic at the interface level is differentiated by considering specific thickness for the interface and the process zone in order to correctly describe the global response and local failure mode.

2. Detachment model

When the glue is applied on the surface of the support material it is quite fluid, with low density and also reduced viscosity. The epoxidic resin penetrates the pores of the support body for a thin depth, creating a layer of cohesive material mechanically improved. The glue is characterized by good mechanical properties, so that the detachment of the FRP reinforcement for the cohesive support occurs in a thin layer below the improved layer of support. As a consequence, three layers can be schematically distinguished in modeling the interaction between the reinforcement and the support: glue layer made of epoxy resin, skin layer where the epoxidic resin penetrates inside the support and detachment layer.

In Fig. 1(a) the FRP reinforcement, the three layers above introduced and the cohesive support material are schematically illustrated. The first two layers can be modeled considering a linear elastic response, the third layer has to account for the nonlinear behavior as it is responsible for the failure of the system. As the layers are very thin, interface models can be adopted to reproduce the mechanical response of the interaction between the FRP and the cohesive support. As consequence, two interfaces are introduced to simulate the response of the structural system as illustrated in Fig. 1(b): the glue interface $I_g$ with linear elastic law, reproducing the response of the glue and skin layers, and the detachment interface $I_d$ with nonlinear law describing the detachment layer.

In Fig. 2, the scheme of the interface system is reported. Note that in the structural system three surfaces can be distinguished, denoted in the following as $S^-$, bottom surface of $I_d$, $\hat{S}$ top surface of $I_g$ and bottom surface of $I_g$, $S^+$ top surface of $I_g$. Limiting the analysis to two-dimensional structural problems, a local coordinate system is introduced, with $x_t$ and $x_n$ the tangential and normal axes to interfaces.

The displacement vectors of the points belonging to $S^-$, $\hat{S}$ and $S^+$ are denoted as $u^-$, $\hat{u}$ and $u^+$, respectively. The displacement jumps in the interfaces $I_g$, $I_d$ and in the whole interface $I$ are defined as:

$$s^g = u^+ - \hat{u} \quad s^d = \hat{u} - u^- \quad s = u^+ - u^-.$$  

2. Glue interface

Concerning the interface $I_g$, characterized by a physical thickness $t^g$, the kinematic enriched model proposed in [5] is considered; thus, the control displacement vector of the interfaces $I_g$ is introduced as:

$$e^g = \begin{bmatrix} u_{tg} & t^g & s^g_n & s^g_t \end{bmatrix}^T,$$  

Fig. 1. FRP reinforcement applied on the masonry support (a) and interaction scheme of the system (b).

Fig. 2. Scheme of the double interface system and reduction to a single interface.
and the stress state $\sigma = \left[ \sigma_t^g \ \sigma_n^g \ \tau_{tn}^g \right]^T$ is obtained as function of the control displacement vector $\mathbf{e}^g$ by the linear elastic relationship:

$$\sigma^g = K^g \mathbf{e}^g,$$

where $K_t^g$ and $K_n^g$ are the shear and normal stiffnesses of the interface and $C^g = E^g / t^g$ represents the longitudinal stiffness of the interface, with $E^g$ the homogenized Young’s modulus of the glue and skin layers and $t^g$ the physical thickness of $I_g$.

### 2.2. Detachment interface

The constitutive relationship of the detachment layer has to account for the nonlinear interface response. As discussed in [5], the debonding of the FRP from the support material is significantly influenced by the presence of the in-plane stress components. The presence of compressive in-plane normal stresses leads to a confinement effect, which can improve the behavior of the interface. On the contrary, tensile in-plane normal stresses induce a reduction of the interface strength. Then, it becomes important to consider in the failure mechanism, at the interface level, the presence of the in-plane strain and stress. The detachment layer control displacement is introduced as:

$$\mathbf{c}^d = \left[ u_t^d \ t_n^d \ s_t^d \right]^T,$$

where $t^d$ is the physical thickness of $I_d$, the stress state $\sigma^d = \left[ \sigma_t^d \ \sigma_n^d \ \tau_{tn}^d \right]^T$ in the interface $I_d$ is obtained as:

$$\sigma^d = (1 - D) K^d \mathbf{e}^d \quad \text{with} \quad K^d = \begin{bmatrix} C^d & 0 & 0 \\ 0 & K_t^d & 0 \\ 0 & 0 & K_n^d \end{bmatrix},$$

where $K_t^d$ and $K_n^d$ are the shear and normal stiffnesses of the interface and $C^d = E^d / t^d$ is the longitudinal stiffness of the interface, with $E^d$ the Young’s modulus of the support cohesive material. Equation (5) is written in the framework of the Damage Mechanics, as $D$ indicates the damage parameter affecting the constitutive equation.

The effective stress in the detachment layer $\sigma^e = \left[ \sigma_t^e \ \sigma_n^e \ \tau_{tn}^e \right]^T$ is obtained by the relationship:

$$\sigma^e = \frac{\sigma^d}{1 - D} = K^d \mathbf{e}^d,$$

where it is set:

$$\mathbf{J}^m = \frac{1}{3} \left[ \begin{array}{ccc} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{array} \right], \quad \mathbf{J}^d = \frac{1}{3} \left[ \begin{array}{ccc} 2 & -1 & 0 \\ -1 & 2 & 0 \\ 0 & 0 & 6 \end{array} \right].$$

The equivalent effective stress is introduced as:

$$\sigma_{eq} = \sigma^e + \alpha s_m,$$

where $\alpha$ is the material parameter ruling the influence of the hydrostatic pressure ($s_m$) on the failure. According to the Drucker–Prager criterion, failure occurs when it occurs:

$$f = \sigma_{eq} - \kappa = 0,$$
with \( k \) the limit threshold equivalent effective stress, which allows the starting of the damage evolution.

A damage evolution law, characterized by a linear softening branch in the stress-strain relation, is considered; the damage variable is given by the relationship:

\[
D = \max \left( 0, \min \left( 1, \hat{D} \right) \right) \quad \text{with} \quad \hat{D} \geq 0, \quad \text{with} \quad \hat{D} = \frac{k_u \left( k - \sigma_{\text{eq}} \right)}{\sigma_{\text{eq}} \left( k - k_u \right)},
\]

(11)
denoting by \( k_u \) the ultimate value of the equivalent effective stress \( \sigma_{\text{eq}} \) for which the stress vector is trivial, i.e. \( \sigma = 0 \).

### 2.3. Overall interface

The state of stress in the overall interface is governed by the stresses in the glue and detachment interfaces. In particular, the overall longitudinal stress components can be simply determined by averaging the stresses in the two interfaces as:

\[
\sigma_t = \frac{1}{t} \left( \sigma_t^g t^g + \sigma_t^d t_d \right),
\]

(12)
being \( t = t^g + t^d \) the total thickness of the interface.

Substituting the expressions derived from equations (3) and (5) for \( \sigma_t^g \) and \( \sigma_t^d \) into formula (12), it results:

\[
\sigma_t = \frac{1}{t} \left[ C_t^g e_{t,l} (t^g)^2 + (1 - D) C_t^d e_{t,l} (t^d)^2 \right],
\]

(13)
Taking into account the equilibrium equations \( \sigma_{t,l}^g + \tau_{nt,n}^g = 0 \), and \( \sigma_{t,l}^d + \tau_{nt,n}^d = 0 \) and assuming that the stresses \( \sigma_t^g \) and \( \sigma_t^d \) can vary very slowly along the direction \( x_t \), it results that \( \tau_{nt,n}^g = 0 \) and \( \tau_{nt,n}^d = 0 \), i.e. the shear stresses in \( I_g \) and \( I_d \) are considered constant along the interface thickness.

The equilibrium condition of the shear and normal stresses among the interfaces leads to the evaluation of the overall interface shear and normal stresses as:

\[
\sigma_n = \sigma_n^g = \sigma_n^d, \quad \tau_{nt} = \tau_{nt}^g = \tau_{nt}^d.
\]

(14)
Taking into account equations (1), (3) and (5), conditions (14) become:

\[
K_t^g (u_t^g - \hat{u}_t) = (1 - D) K_t^d (\hat{u}_t - u_t^g) \quad K_t^g (u_t^g + \hat{u}_t) = (1 - D) K_t^d (u_t^g - \hat{u}_t),
\]

(15)
that, solved with respect to \( \hat{u}_t \) and \( \hat{u}_n \), give:

\[
\hat{u}_t = \frac{1}{K_t^g + (1 - D) K_t^d} \left[ K_t^g u_t^g + (1 - D) K_t^d u_t^g \right] \quad \hat{u}_n = \frac{1}{K_t^g + (1 - D) K_t^d} \left[ K_t^g u_t^g + (1 - D) K_t^d u_t^g \right].
\]

(16)
As consequence, the displacement jump components in equations (1) take the form:

\[
s_t^g = \frac{(1 - D) K_t^d}{K_t^g + (1 - D) K_t^d} (u_t^g - u_t) \quad s_t^d = \frac{(1 - D) K_t^d}{K_t^g + (1 - D) K_t^d} (u_t^g - u_t)
\]

(17)
\[
s_t^g = \frac{K_t^g}{K_t^g + (1 - D) K_t^d} (u_t^g - u_t) \quad s_t^d = \frac{K_t^g}{K_t^g + (1 - D) K_t^d} (u_t^g - u_t)
\]

(18)
The shear normal stress in the overall interface can be deduced substituting formulas (17) into the constitutive laws (3), or substituting formulas (18) into the constitutive law (5), obtaining in any case:

\[
\tau_{nt} = \frac{(1 - D) K_t^g K_t^d}{K_t^g + (1 - D) K_t^d} s_t, \quad \sigma_n = \frac{(1 - D) K_t^g K_t^d}{K_t^g + (1 - D) K_t^d} s_n.
\]

(19)
Assuming, for simplicity, equal elastic properties for the glue and detachment interfaces, and collecting the overall constitutive equations (13) and (19), it is obtained:

\[
\sigma_t = E_t \frac{1}{t} \left[ e_{t,l} t^g + (1 - D) e_{t,l} t^d \right], \quad \sigma_n = E_n \frac{1 - D}{t^g + (1 - D) t^d} s_n, \quad \tau_{nt} = E_t \frac{1 - D}{t^g + (1 - D) t^d} s_t,
\]

(20)
In first of equations (20), the quantity \( \varepsilon \), can be evaluated at mid-plane of the glue interface \( I_g \).

To simplify the model, the first of equations (20) can be slightly modified with the aim to get zero longitudinal stiffness when the damage is complete; this effect can be obtained setting:

\[
\sigma = (1 - D) K(D) \mathbf{c}
\]

with 
\[
K(D) = \begin{bmatrix}
\frac{E_t}{t} & 0 & 0 \\
0 & \frac{E_n}{td + (1 - D) tg} & 0 \\
0 & 0 & \frac{E_t}{td + (1 - D) tg}
\end{bmatrix}, \quad \mathbf{c} = \begin{bmatrix} u_{t, t} \\ s_n \\ s_t \end{bmatrix}, \tag{21}
\]

where \( \mathbf{c} \) is the control displacement vector of the overall interface.

3. Numerical simulations

The investigation of the influence of mortar joints in the debonding process of masonry brick has been conducted by numerical test that reproduces the single lap shear experimental test presented in [2] on handmade 19-th century bricks reinforced by single layer CFRP. In the numerical examples a cartesian coordinate system has been introduced as illustrated in Fig. 3(a), so that the following stress components are considered \( \sigma^d = [\sigma_{11} \sigma_{22} \sigma_{12}]^T \), \( \sigma^d = [\sigma_{11} \sigma_{22} \sigma_{12}]^T \).

![Fig. 3. a) Geometry and b) structural scheme of the experimental test [10]; c) elastic domain \( \sigma_{11} - \sigma_{12} \) adopted for the masonry substrate.](image)

In [2] the masonry prisms were realized with four units connected by lime mortars. Joints thickness was about 10 mm and the reinforcement has been glued on the head of the bricks. A nominal length of the bonded zone \( l_b = 150 \) mm was chosen. The specimen geometry is illustrated in Fig. 3(a). The principal mechanical parameters of the glue declared by the producer are: Young’s modulus \( E_g = 3000 \) MPa and tensile strength \( f_{tg} = 70.0 \) MPa. The material parameters have been experimentally determined in [2] through specific experimental tests. The average Young’s modulus of the reinforcement measured during the tests and referred to the effective mean thickness \( t_{f, eff} = 1.4 \) mm is \( E_{f, eff} = 63500 \) MPa. The obtained mechanical properties (Young modulus \( E_m \), Poisson ratio \( v \), compressive and flexural tensile strengths \( f_{cm} \) and \( f_{m, f} \)) of materials that have been adopted for the interface parameters in the numerical simulations are reported in Table 1. The coefficients \( k \) and \( k_u \) have been obtained according to the CNR DT200 [4]: they represent the maximum shear values and the ultimate state in a pure shear test. The chosen value of the parameter \( \alpha \) for the brick and the mortar corresponds in both cases to an internal frictional angle of about 30°. Finally, the adopted values of the whole interface thickness \( t_e + t_d \) are mean values suggested in CNR DT200 [4] and has been assumed equal to 9 mm. The geometrical dimension of the specimen are reported in Table 2.

The problem was modeled in two dimension in plane stress condition. The setup of the test, details and boundary conditions are showed in Fig. 3(b). Right side, top and bottom portions of the specimen are constrained in order to have no displacements in the direction normal to the surface and free displacements tangent to it. The elastic domain
Table 1. Geometrical and mechanical properties of specimens considered in numerical simulations.

<table>
<thead>
<tr>
<th>Material</th>
<th>$E_p$ (MPa)</th>
<th>$\nu$</th>
<th>$f_{cm}$ (MPa)</th>
<th>$f_{cm,fj}$ (MPa)</th>
<th>$k$ (MPa)</th>
<th>$k_u$ (MPa)</th>
<th>$\alpha$</th>
<th>$t_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brick</td>
<td>8300</td>
<td>0.13</td>
<td>12.6</td>
<td>3.2</td>
<td>5</td>
<td>27.3</td>
<td>1.65</td>
<td>3</td>
</tr>
<tr>
<td>Mortar</td>
<td>7500</td>
<td>0.26</td>
<td>4.8</td>
<td>1.1</td>
<td>1.25</td>
<td>21.8</td>
<td>1.65</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 2. Dimensions of the masonry specimen.

<table>
<thead>
<tr>
<th>$b_m$ (mm)</th>
<th>$h_m$ (mm)</th>
<th>$l_m$ (mm)</th>
<th>$l_b$ (mm)</th>
<th>$b_f$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>138</td>
<td>88</td>
<td>258</td>
<td>150</td>
<td>38.5</td>
</tr>
</tbody>
</table>

Now, the local behavior at the interface level is investigated; in fact, the stress components $\sigma_{11}$, $\sigma_{22}$, $\sigma_{12}$ and $\sigma_{11}$ are plotted as a function of the slip $s_1$ in different points of the bricks in Figs. 6, 7 and in the two joints in Fig. 8.

Firstly, the constitutive relationship is reported in Fig. 6 at the brick level in undisturbed positions located at $x_1 = 140$ mm and $x_1 = 90$ mm. At these points, it is clearly evident the role played by the confinement stress component $\sigma_{11}$ in the failure mode. In both cases it moves from limited values in traction to significant values in compression in the softening branch.

The influence is much more evident if two points located at the border of a joint are investigated. In particular, points at $x_1 = 61$ mm and $x_1 = 49$ mm are located respectively before and after a joint. At $x_1 = 61$ mm, due to the limited resistance of the mortar joint the behavior of the brick presents a small decrement of the maximum transmissible stress values and a nearly linear softening branches. Differently, at $x_1 = 49$ mm the high values of compression confinement stress $\sigma_{11}$ lead to a noticeable increment of the shear stress peak together with a rather
brittle behavior at the beginning of the softening branch due to the reduction of the confinement effect. The influence of the confinement stress $\sigma_{11}$ is even much higher at the joint level reported in Fig. 8.

4. Conclusions

An innovative interface model, recently proposed in [5] and specifically modified in order to correctly reproduce the kinematic of debonding process mode, has been proposed to analyze the detachment mechanism of the FRP from a masonry support. In particular, the influence of the presence of mortar joints in the masonry texture is numerically investigated.
Load drops, commonly obtained in the experimental response and associated with the presence of mortar joints, are confirmed numerically. In fact, the analysis evidenced that the load drop is influenced by the mortar joint stiffness and strength. The load drop occurs when the mortar joint is involved in load transfer. As the load-carrying capacity of the mortar interface is lower than that of the brick a decrease in the overall load carrying capacity results from a longer portion of the transferring zone corresponding to the mortar joint. Finally, it can be underlined that averaging the force-displacement curve during the decohesion phase, a reduction of the overall resistance of the masonry (with mortar joints) with respect to the behavior obtained considering the solely brick is obtained. The decrease of the carried load is in accordance with the prescription of the CNR document CNR DT200 [4], which suggest a cutback of 15% of the debonding load in presence of mortar joints.

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References