3-D numerical modeling of single-lap direct shear tests of FRCM-concrete joints using a cohesive contact damage approach

Christian Carloni[a,*1], Tommaso D'Antino[b], Lesley H. Sneed[c], Carlo Pellegrino[d]

[a]Associate Professor, University of Bologna, Viale Risorgimento 2, 40136 Bologna, Italy

[b]Assistant Professor, Politecnico di Milano, Piazza Leonardo da Vinci, 20133 Milan, Italy

[c]Associate Professor, Missouri University of Science and Technology, 1401 North Pine Street, Rolla, MO, 65409, USA

[d]Full Professor, University of Padova, via Marzolo 9, 35131 Padova, Italy

Abstract

The bond behavior of fiber reinforced cementitious matrix (FRCM) composites applied as externally bonded reinforcement is the most critical concern in this type of application. FRCM-concrete joints are generally reported to fail due to debonding (slippage) of the fibers from the embedding matrix. However, depending on the characteristics of the composite and substrate employed, failure may also occur due to detachment of the composite strip at the FRCM-support interface, interlaminar failure (delamination) of the matrix, or tensile failure of the fibers. In this paper, a three-dimensional (3-D) numerical model is developed to reproduce the behavior of polyparaphenylene benzo-bisoxazole (PBO) FRCM-concrete joints. The numerical model accounts for the fracture mechanics mixed Mode-I and Mode-II loading condition observed in single-lap direct shear tests by means of non-linear cohesive contact damage laws associated with different interfaces considered in the analysis. The numerical results obtained are compared with those obtained by experimental tests of PBO FRCM-concrete joints. The model is capable of predicting the different failure modes, and it correctly

[1] *corresponding author: christian.carloni@unibo.it*

reproduces the experimental load responses including the contribution of friction to the applied stress.

Keywords: FRCM; Fabrics/textiles; Fiber/matrix bond; Finite Element Analysis (FEA)

Introduction

Fiber reinforced cementitious matrix (FRCM) composites represent a newly-developed alternative to fiber reinforced polymer (FRP) composites for strengthening existing reinforced concrete (RC) and masonry elements (Triantafillou and Papanicolaou 2006; D'Ambrisi and Focacci 2011; Ombres 2012; Pellegrino and D'Antino 2013; Loreto et al. 2013). FRCM composites are comprised of layers of fiber nets embedded within inorganic matrix layers that are responsible for the stress transfer between fibers and matrix and between the composite and the support. Compared with FRP composites, FRCM composites exhibit a higher resistance to high temperatures and do not suffer of UV degradation. Furthermore, inorganic matrices have unvarying workability time and can be applied to wet surfaces, whereas FRP composites cannot. FRCM composites can be applied on both concrete and masonry substrates and appear particularly promising for strengthening interventions on heritage buildings due to their reversibility and vapor permeability (de Felice et al. 2012).

Different authors employed single- and double-lap direct shear tests to study the bond behavior of FRCM composites observing that failure generally occurs due to debonding (slippage) of the fibers from the embedding matrix (D'Ambrisi et al. 2012; D'Ambrisi et al. 2013; Sneed et al. 2014; Sneed et al. 2015; de Felice et al. 2014). However, depending on the characteristics of composite, substrate, and experimental set-up adopted, detachment of the composite strip at the FRCM-substrate interface (D'Antino et al. 2015), interlaminar failure (delamination) of the matrix with detachment of the matrix layer that covers the fibers (de Felice et al. 2014; D'Antino et al. 2015), and tensile failure of the fibers inside and outside the bonded length (Carozzi and Poggi 2015) have been observed.

In direct shear tests, and particularly single-lap shear tests, the eccentricity between the applied load and the restraint entails for the presence of a fracture mechanics Mode-I and Mode-II loading condition on the composite strip. Several researchers (e.g. De Lorenzis and Zavarise 2008; Carrara and Ferretti 2013) studied the debonding phenomenon in FRP-concrete joints, which typically occurs within the concrete substrate (Carrara and Ferretti 2013), by taking into account the presence of Mode-I and Mode-II loading conditions (Carrara and Ferretti 2013; Rabinovitch 2008; Mazzucco et al. 2012; Neto et al. 2016). If a macro-scale approach is used, the Mode-I loading condition is described by the relationship between the normal stress σ_{zz} (axes are defined in Figure 1) at the interface and crack opening w (lifting of the composite). The Mode-II loading condition is described by the relationship between the interfacial shear stress τ_{zy} and slip s (De Lorenzis and Zavarise 2008). The area under the σ_{zz}-w and τ_{zy}-s curves is the Mode-I and Mode-II critical energy release rate (fracture energy), respectively.

The bond behavior of FRCM-concrete joints has been studied employing numerical approaches that assumed a pure Mode-II loading condition at the matrix-fiber interface (Carloni et al. 2015a). However, the presence of a Mode-I loading condition, which was reported to be dominant for FRCM-concrete joints with short bonded lengths (Sneed et al. 2014), and the occurrence of different failure modes should be taken into account to fully describe the debonding process.

In this study, a three-dimensional (3-D) numerical model is used to describe the bond behavior of FRCM-concrete joints comprised of one layer of polyparaphenylene benzo-bisoxazole (PBO) fiber net embedded within two layers of a polymer-modified cement-based mortar. The numerical model developed accounts for the possibility of interlaminar failure of the matrix, debonding at the matrix-fiber interface, and detachment of the composite strip at the FRCM-support interface. The results obtained by numerical analyses are compared with those obtained by experimental tests of PBO FRCM-concrete joints.

Experimental set-up and materials

In this study, the results of single-lap direct shear tests on FRCM-concrete joints previously published (D'Antino et al. 2014) are compared with the results obtained by a 3-D non-linear numerical model. Sixty-seven of the 82 specimens reported in (D'Antino et al. 2014) were considered reliable according to a criterion proposed by the authors (Carloni et al. 2015b) and were employed for the comparison, while the remaining 15 were excluded. The FRCM composite was comprised of one layer of a PBO bidirectional unbalanced fiber net embedded within two 4 mm thick cementitious matrix layers. The composite strip was applied to one face of a concrete block with length L=375 mm (batch A) or L=510 mm (batch B) (Table 1). The fibers were bare outside the bonded area with a length l=270 mm. Transversal fiber bundles, which were all on one side of the longitudinal fiber bundles in the fiber net, were placed against the external matrix layer for some specimens and against the internal matrix layer for some others. Details of the test set-up adopted are reported in Figure 1.

Concrete blocks with L=375 mm (batch A) were used for specimens with bonded length ℓ =100 mm, 150 mm, 200 mm, 250 mm, and 330 mm, whereas concrete blocks with L=510 mm (batch B) were used for specimens with ℓ=450 mm. Experimental tests were conducted to obtain mean values of the compressive strength f_c and tensile strength f_t of the concrete and matrix (Carloni et al. 2015b) and elastic modulus E and tensile strength f_t of the PBO fibers (D'Antino et al. 2013) (Table 1).

Each fiber bundle was assumed to have a rectangular cross-section of width b^*=5 mm and thickness t^*=0.092 mm. Poisson ratios ν, which were not measured experimentally and are needed to completely define a material mechanical behavior, were assumed equal to 0.2 for the concrete and matrix (fib 2001) and to 0.3 for the PBO fibers (Carloni et al. 2015a).

The direct shear tests were carried out by increasing the loaded end slip, named global slip g, at a constant rate of 0.00084 mm/s. Additional information on the testing procedure is provided in (Sneed et al. 2014; Carloni et al. 2015b).

The peak stress σ^* is used in this paper to compare experimental and numerical results. Values of σ^* are obtained with Eq. (1) when the applied load P is equal to the peak load P^*:

$$\sigma = \frac{P}{nb^*t^*} \tag{1}$$

where n is the number of longitudinal fiber bundles within the composite bonded width.

Assuming a Mode-II fracture condition, a fracture mechanics approach was used to obtain matrix-fiber interface τ_{zy}-s relationships. Only one cohesive law was determined assuming that the same behavior occurs at the internal and external matrix layer-fiber interfaces (Carloni et al. 2015b). This approach allowed to determine the value of the effective bond length l_{eff}, defined as the minimum length needed to develop the load-carrying capacity of the interface (D'Antino et al. 2014), whose average value was found to be $\bar{l}_{eff}$ =260 mm. The value of $\bar{l}_{eff}$ was confirmed by comparing the trend of the peak stress-vs-bonded length curve, which included results of the same composite obtained by other authors with both single- and double-lap shear test set-ups (Sneed et al. 2015; D'Antino et al. 2014).

Numerical formulation

Debonding of FRCM composites applied to a concrete support was studied with a numerical model developed using the commercial software Abaqus (Simulia 2016). All materials were treated as homogeneous isotropic linear elastic materials and were connected through zero-thickness interfaces. The assumption of material linear elasticity adopted was confirmed by the strain observed in the numerical models, which was always lower than the elastic limit strain of each material. Four different interfaces were considered in the FRCM-concrete joint: i) FRCM-concrete, ii) internal matrix layer-fibers, iii) external matrix layer-fibers, and iv) internal-external matrix layer (Figure 2). Although failure at the internal-external matrix layer interface was never observed by the authors for PBO FRCM-concrete joints, such failure was observed for other FRCM composites (D'Antino et al. 2015). The interfaces between the matrix and the side faces of the fiber bundles, each having an area equal to 0.092 mm^2 per unit length, were neglected.

Each interface considered was modeled by means of a specific master-slave cohesive damage contact interaction. The interfacial response is initially linear and, when a damage criterion is met, it degrades according to a specific damage evolution law. The contact interaction linear ascending branch was defined by a traction-separation model defined by the elastic constitutive matrix $\mathbf{K}$ (Simulia 2016):

$$\mathbf{t} = \begin{Bmatrix} t_n \\ t_s \\ t_t \end{Bmatrix} = \begin{bmatrix} K_{nn} & K_{ns} & K_{nt} \\ K_{sn} & K_{ss} & K_{st} \\ K_{tn} & K_{ts} & K_{tt} \end{bmatrix} \begin{Bmatrix} \delta_n \\ \delta_s \\ \delta_t \end{Bmatrix} = \mathbf{K}\boldsymbol{\delta} \tag{2}$$

where $\mathbf{t}$ is the traction vector of normal component t_n and shear components t_s and t_t, and δ_n, δ_s, and δ_t are the corresponding components of the separation vector $\boldsymbol{\delta}$. When a specific damage criterion is satisfied, damage occurs and the damage variable D controls the traction vector $\mathbf{t}$:

$$\bar{t}_n = \begin{cases} (1-D)\cdot t_n & \text{if } t_n > t_n^0 \\ t_n & \text{otherwise} \end{cases} \tag{3a}$$

$$\bar{t}_i = \begin{cases} (1-D)\cdot t_i & \text{if } |t_i| > t_i^0 \\ t_i & \text{otherwise} \end{cases} \qquad i=s,t \tag{3b}$$

where superscript 0 indicates the elastic limit values, $\bar{t}_n$ is the traction vector damaged normal component, and $\bar{t}_s$ and $\bar{t}_t$ are the traction vector damaged shear components. According to Eq. (3a) compressive stress does not cause damage.

Different damage evolution laws were associated to each interface. In the case of the FRCM-concrete and internal-external matrix layer interfaces, damage was defined through the exponential damage evolution law:

$$D = \int_{\bar{\delta}_0}^{\bar{\delta}_f} \frac{\bar{T} \cdot d\delta}{G_C - G_0} \tag{4}$$

where $\bar{\delta}_0$ and $\bar{\delta}_f$ correspond to the effective separation $\bar{\delta}$ at the onset of damage and at complete failure, respectively, $\bar{T}$ is the *effective* traction (Simulia 2016; Mei et al. 2010), G_0 is the energy release rate at damage initiation, and G_C is the critical energy release rate (Camanho and Davila 2002):

$$\bar{\delta} = \sqrt{\langle \delta_n \rangle^2 + \delta_s^2 + \delta_t^2} \tag{5}$$

$$\bar{T} = \sqrt{\langle \bar{t}_n \rangle^2 + \bar{t}_s^2 + \bar{t}_t^2} \tag{6}$$

$$G_0 = \int_0^{\bar{\delta}_0} \bar{T} d\delta \tag{7}$$

$$G_C = \int_0^{\bar{\delta}_f} \bar{T} d\delta \tag{8}$$

where $\langle \cdot \rangle$ denotes the Heaviside function. The damage evolution law associated with the matrix layer-fiber interfaces was defined by specifying directly the damage variable D with respect to the non-dimensional i-th component of the displacement $\bar{\delta}_p$:

$$\bar{\delta}_p = \bar{\delta} - \bar{\delta}_0 \tag{9}$$

Mode-I and Mode-II, which are described by the σ_{zz}-w and τ_{zy}-s relationships, respectively, were coupled at the FRCM-concrete and internal-external matrix interfaces adopting the expression of the coupled critical energy release rate G_F proposed by Benzeggagh and Kenane (1996) (B-K). If a Mode-III loading condition is present, the B-K critical energy release rate G_F is (Camanho and Davila 2002):

$$G_F = G_{IF} + \left(G_{IIF} - G_{IF}\right)\left(\frac{G_{shear}}{G_T}\right)^{\eta}, \text{ with } G_T = G_I + G_{shear} \tag{10}$$

where G_{IF} and G_{IIF} are the critical energy release rates for pure Mode-I and Mode-II loading conditions, respectively, G_I, G_{II} and G_{III} are the Mode-I, Mode-II, and Mode-III energy release rates, respectively, $G_{shear}= G_{II} + G_{III}$, and η is a parameter that should be calibrated using mixed mode bending (MMB) tests at different mode ratios (Camanho and Davila 2002). According to the B-K criterion, debonding occurs when the total energy release rate G_T is equal to or greater than the critical energy release rate G_F (Krueger 2008). Equation (10) was employed without distinguishing between sliding (Mode-II) and tearing (Mode-III) modes of fracture and simply assuming G_{III} as the energy release rate associated with the Mode-II loading condition in direction *x*.

Mode-I and Mode-II loading conditions were considered uncoupled for the matrix-fiber interfaces. This assumption is justified in the case of FRCM-concrete joints where the external matrix layer contrasts the out-of-plane displacement of the fibers and consequently limits the Mode-I loading condition (D'Antino et al. 2016). A different numerical approach able to describe the coupling of Mode-I and Mode-II at the matrix-fiber interfaces is currently under development by the authors and will be used to reproduce the behavior of FRCM composites without the external matrix layer.

In all the contact laws adopted, damage initiates when the quadratic stress criterion expressed by Eq. (11) is satisfied:

$$\left(\frac{\langle \bar{t}_n \rangle}{t_n^0}\right)^2 + \left(\frac{\bar{t}_s}{t_s^0}\right)^2 + \left(\frac{\bar{t}_t}{t_t^0}\right)^2 = 1 \qquad (11)$$

Numerical model

The numerical approach proposed in this paper can be employed to study the bond behavior of different FRCM composites applied to various substrates. The numerical model parameters calibrated in this study are valid only for the particular FRCM composite and concrete substrate studied. Since the behavior of FRCM composites depends on different factors, such as the matrix, fiber, and substrate characteristics and their bond behavior, the parameters of the numerical approach proposed will be different depending on the specific FRCM and substrate considered.

Characteristics and Geometry

Twelve different numerical models, summarized in Table 2, were used to study the bond behavior of PBO FRCM-concrete joints. Models were named following the notation NDS_X_Y_(C or G or H), where NDS indicates the numerical model of a direct shear specimen, X=bonded length ℓ in mm, Y=bonded width b_1 in mm, C (if present) indicates that the concrete block was not modeled, G (if present) indicates that the Mode-I and/or Mode-II fracture energy of the FRCM-concrete interface or the matrix-fiber interfaces was increased with respect to calibrated values, and H (if present) indicates that the thickness *h* (Figure 1) of the concrete block was reduced.

For six models, indicated as "Condition E" in Table 2, the concrete block and FRCM composite were modeled with the geometry and constrains according to the experimental test set-up employed by the authors (D'Antino et al. 2016). For these models, the parameters needed to define the behavior of a specific contact interface (see section *Numerical formulation*) were calibrated according to the experimental results or assumed based on the literature (section *Loading condition and parameters employed*). For five models, indicated as "Condition 1, 2, 3, 4, or 5" in Table 2, the parameters needed to define the behavior of a specific contact interface and/or the specimen geometry were varied to investigate the effect of the load eccentricity and of the different interfaces, as described in the next sections. The effect of a high FRCM-concrete bond capacity was investigated for all bonded lengths ℓ considered by assuming that the Mode-I and Mode-II fracture energies of the FRCM-concrete interface were equal to those corresponding to debonding in a thin layer of concrete. Since the results obtained were not affected by this assumption except for ℓ=100 mm, only model NDS_100_60_G (Condition 1) is reported in this paper. For model NDS_330_60_H (Condition 2) the thickness *h* of the concrete block was reduced to 1 mm, and it was fully constrained at the face opposite to the face where the FRCM composite was applied. For models NDS_330_60_C_1 (Condition 3) and NDS_330_60_C_2 (Condition 4), the concrete block was omitted, and the composite strip was fully constrained at the internal matrix layer bottom face. For model NDS_330_60_G (Condition 5), the Mode-II fracture energy of the internal matrix layer- and external-matrix layer fiber interfaces was increased relative to those of the other numerical models to investigate the effect of a high matrix-fiber bond capacity (Table 2).

The FRCM-concrete joints tested experimentally were modeled considering FRCM composite strips with bonded widths b_1=60 mm and different bonded lengths ℓ (see Table 2). In addition to numerical models that reproduce the actual geometry of the specimens tested, an FRCM-concrete joint comprised of a concrete block with L=1000 mm and an FRCM strip with b_1 = 60 mm and ℓ = 955 mm, which was not tested experimentally, was also modeled to investigate the behavior of an FRCM-concrete joint with a long bonded length (model NDS_955_60, Condition 6, Table 2). The geometry, constraints modeled, and properties of the contact interfaces of model NDS_955_60 were consistent with those of the experimental test set-up.

The length of the bare longitudinal PBO fiber bundles beyond the composite loaded end was kept equal to 270 mm in each model. Further details on the specimen geometry are reported in Figure 3.

The concrete blocks were constrained by a hinge along the x-direction at the bottom edge, back face of the blocks (Figure 3). The concrete top face was constrained by a series of springs acting in the y- and z-directions located along the top face's axis of symmetry parallel to x (Figure 3). Since the geometric and mechanical properties of the experimental set-ups employed were known, the stiffness of each spring was computed by assuming rigid rotation of the concrete block, which is equivalent to assuming that the concrete block deformation is negligible (Carloni et al. 2015b), and imposing the equilibrium condition to the system (D'Antino et al. 2016). For the case of the concrete block with

L=1000 mm (model NDS_955_60), which was not tested experimentally, values of the spring stiffness were obtained assuming the same cross-sectional dimensions as the frames used for concrete blocks with *L*=375 mm and *L*=510 mm (D'Antino et al. 2016).

The FRCM composite was bonded to the concrete block through the FRCM bonded area, whereas the individual matrix layers, whose thickness was 4 mm, were connected to each other through the openings between the bundles of the fiber net. Transversal fiber bundles were assumed to be placed against the external matrix layer according to the majority of experimental tests (D'Antino et al. 2014; Carloni et al. 2015b). The contact areas of the different interfaces considered are shown in Figure 2, whereas the interfaces (i, ii, iii, iv) considered for each model are indicated in Table 2.

Each component of the models (concrete block, matrix layers, fiber bundles) was implemented using 8-node brick elements. The mesh sensitivity of the model was investigated by varying the mesh size and comparing the solutions obtained. Except for models NDS_100_60 and NDS_100_60_G, for which the mesh size of concrete block elements in proximity to the FRCM strip was reduced to accurately describe the FRCM-concrete interaction (Figure 3), square concrete block elements with approximate edge dimensions equal to 17 mm (Table 3) were adopted. For model NDS_330_60_H, three mesh elements were present in the thickness (*z*-direction) of the 1 mm concrete block. The mesh size adopted, reported in Table 3 together with the resulting number of elements per direction, allowed for reducing the computational time without affecting the accuracy of the results.

Loading condition and parameters employed

The numerical analyses were carried out in displacement control, adopting the large deformation formulation, by enforcing displacements *v* (Figure 3) in *y*-direction using the arc-length method with automatic determination of the step amplitude.

The mechanical properties of concrete, mortar matrix, and PBO fibers reported in Table 1 were used to define the parameters needed by the numerical models. In model NDS_330_60_H, the elastic modulus of the 1 mm thick concrete block was set equal to 10^6 MPa to simulate a rigid support. For model NDS_955_60, which was not tested experimentally, the mechanical characteristics of concrete blocks with length L=375 mm (i.e. batch A) were assumed.

Since the fracture properties of the FRCM-concrete interface could not be investigated experimentally, analytical models available in the literature were used to obtain reference values of the Mode-I and Mode-II fracture energies. For the concrete employed in this study, the analytical models proposed by fib Bulletin 70 (2013) provided a value of the Mode-I fracture energy between G_{Ic}=0.070 N/mm and G_{Ic}=0.147 N/mm. Karihaloo et al. (1994) reported, as a reference value, a concrete fracture energy of G_{Ic}=0.05 N/mm, whereas Hoover and Bazant (2013), who investigated the size effect on the fracture properties of notched concrete beams, reported a value of the concrete Mode-I fracture energy of approximately G_{Ic}=0.1 N/mm. The characteristics of the concrete mixture used to cast the concrete blocks with L=375 mm employed in this study are comparable with those of Hoover and Bazant (2013), who employed a concrete mixture with a compressive strength of 46.53 MPa (at 31 days) and maximum aggregate diameter of 10 mm.

The analytical models proposed in the literature provide values of the Mode-I fracture energy needed to open a unit crack in a thin layer of concrete. For the FRCM-concrete joints considered, when failure occurred at the FRCM-concrete interface it was observed to be characterized by detachment of the composite strip without damage of the substrate (Sneed et al. 2014; D'Antino et al. 2015b). Therefore, the Mode-I fracture energy associated to the FRCM-concrete interface should be lower than corresponding Mode-I fracture energy of concrete reported in the literature. Starting from G_{Ic}=0.07 N/mm, which is the average of values reported in the literature (fib 2013; Karihaloo et al. 1994; Hoover and Bazant 2013), and assuming a ratio between Mode-II and Mode-I fracture energies equal to 4 (De Lorenzis and Zavarise 2008) and a stress normal to the crack surface equal to zero for a crack opening of approximately 0.1 mm (Karihaloo et al. 1993), the Mode-I fracture energy of the FRCM-concrete interface, G_{Id}, was calibrated to reach failure by detachment of the composite strip for the numerical model with bonded length ℓ =100 mm, as observed experimentally. The components of the elastic stiffness matrix **K,** assumed equal for the Mode-I and Mode-II loading conditions, were calibrated to obtain, using the exponential damage evolution law (see section *Numerical formulation*), a shape of the σ_{zz}-w and τ_{zy}-s relationships similar to those obtained experimentally for the Mode-II loading condition of the matrix-fiber interface and were found equal to 16 N/mm^3 (Figure 4). The fracture energies G_{Id}=0.013 N/mm and G_{IId}=0.052 N/mm were obtained. As a first attempt the B-K exponent η was assumed equal to 2 as found for woven composites comprised of brittle resin (Benzeggagh and Kenane 1996). It should be noted that the fracture energy value found is valid only for the specific matrix and concrete support employed.

The effect of a high FRCM-concrete bond capacity was investigated in model NDS_100_60_G by assuming that the Mode-I and Mode-II fracture energies of the FRCM-concrete interface were equal to those corresponding to debonding in a thin layer of concrete, as in the case of FRP-concrete joints. In order to evaluate the FRCM-concrete interface Mode-II fracture energy the analytical model proposed in CNR-DT 200 R1/2013 (CNR 2013) was adopted:

$$G_{IIc} = \frac{k_b \cdot k_G}{FC}\sqrt{f_{ctm} \cdot f_{cm}} \tag{12}$$

$$k_b = \sqrt{\frac{2 - b_f / b}{1 + b_f / b}} \geq 1 \tag{13}$$

where b_f and b are the width of the composite strip and concrete cross-section, respectively, k_G is a corrective factor that depends on the type of composite used (pre- or in-situ-impregnated), FC is a factor depending on the level of knowledge of the strengthened element, and f_{ctm} and f_{cm} are the mean concrete tensile and compressive strength, respectively. It should be noted that Eq. (12) does not correctly take into account the effect of the width ratio b_f/b, expressed by k_b. If applied to the Mode-II fracture energy equation, k_b should be raised to the power of 2, so that it would have the correct magnitude when the fracture energy [Eq. (12)] is used to compute the load-carrying capacity (for reference see (fib 2001; Chen and Teng 2001). Furthermore, coefficient k_b should not be employed in calculating G_{IIc} that, since it is a fracture parameter, should not depend on geometrical characteristics. For the FRCM-concrete joints studied in this paper, assuming b_f=b_1 and k_G=0.07, which is the average value of k_G for pre- and in-situ-impregnated FRP composites, Eq. (12) provided G_{IIc}=0.85 N/mm. The coupled Mode-I fracture energy of the FRCM-concrete interface was set equal to $G_{Ic}= G_{IIc}/4$, as assumed for FRP-concrete joints (De Lorenzis and Zavarise 2008).

The fracture properties of the matrix employed, which were not investigated experimentally, could not be directly validated by the load responses available, as in the case of FRCM-concrete interface properties. Considering that the mean compressive and tensile strengths of the mortar employed in this study were relatively high (Table 1), a Mode-I fracture energy of G_{Im}=0.05 N/mm was assumed for the internal-external matrix layer interface (fib 2013; Karihaloo et al. 1994). Applying the same ratio G_{IIm}/G_{Im}=4 assumed in the case of the FRCM-concrete interface, the matrix Mode-II fracture energy was assumed equal to G_{IIm}=0.20 N/mm. As in the case of the FRCM-concrete interface, the components of the elastic stiffness matrix **K** were assumed equal for the Mode-I and Mode-II loading conditions and, considering a stress normal to the crack surface equal to zero for a crack opening of approximately 0.1 mm (Karihaloo et al. 1993), were found equal to 50 N/mm^3 (Figure 4). The coupling of Mode-I and Mode-II loading conditions was obtained by assuming the B-K criterion with the exponent η=2.

A parametric study was conducted to investigate the validity of the ratio G_{Ic}/G_{IIc}=4 and G_{IIm}/G_{Im}=4 made for the FRCM-concrete and internal-external matrix layer interfaces, respectively. The results suggest that varying this ratio has a limited influence on the behavior of the specific composite and substrate considered. This can be attributed to the limited effect of the Mode-I condition on the behavior of FRCM-concrete joints with the external layer of matrix (D'Antino et al. 2016).

For the internal matrix layer- and external matrix layer-fiber interfaces, the damage variable was specified for discrete values of the displacement $\bar{\delta}_p$ to reproduce the τ_{zy}-s relationships obtained experimentally (Carloni et al. 2015b). The area under the τ_{zy}-s curve between s=0 and $s=\bar{s}_f$=1.57 mm, where $s=\bar{s}_f$ is the slip corresponding to complete matrix-fiber debonding measured experimentally (Carloni et al. 2015b), is G_{IIf}=0.481 N/mm. As a first attempt, the τ_{zy}-s curves associated with the internal matrix layer- and external matrix layer-fiber interfaces were assumed equal (Carloni et al. 2015b). The σ_{zz}-w relationship, which was not measured experimentally, was obtained by assuming the same shape of the τ_{zy}-s relationships and a Mode-I fracture energy of G_{If}=0.04 N/mm (Figure 4). This assumption is justified by the limited effect of the Mode-I condition, which did not affect significantly the behavior of the matrix-fiber interface. The elastic stiffness obtained experimentally for the Mode-II loading condition, equal to 9.85 N/mm^3, was assumed also for the Mode-I loading condition.

For model NDS_330_60_G the value of G_{IIf} was increased to a value at which model NDS_330_60_G failed due to detachment of the composite strip instead of debonding at the matrix-fiber interface. The increased value of G_{IIf}=0.843 N/mm was obtained by increasing the shear stress corresponding to the onset of damage τ^0_{zy}=0.3 MPa to τ^0_{zy}=1.5 MPa. Values of stresses σ^0_{zz} and τ^0_{zy} corresponding to the onset of damage are reported in Figure 4 for each interface considered.

Results and discussion

Models with bonded length ℓ=330 mm and bonded width b_1=60 mm

The numerical applied stress σ -global slip g curves of specimens with bonded length **ℓ**=330 mm and bonded width b_1=60 mm were compared with corresponding envelopes of the experimental curves obtained from specimens with the same bonded dimensions (Figure 5). The envelopes in Figure 5a were obtained considering specimens with $\boldsymbol{\ell}$=330 mm and b_1=60 mm. Some specimens, indicated in Figure 5a with dashed lines, reported a load response different from those of other specimens with the same characteristics and were not considered in the envelopes. Specimens that were considered in the envelopes are shown in Figure 5a with light grey lines.

The scatter observed between the experimental curves depicted in Figure 5a is due to the quasi-brittle nature of the matrix-fiber interface and can be observed for different FRCM composites (Carozzi and Poggi 2015; D'Ambrisi et al. 2012; de Felice et al. 2012). However, the accuracy of numerical models that employ a contact damage interface to reproduce the behavior of FRCM-concrete joints was studied in Carloni et al. (2015a), where a pure Mode-II loading condition at the matrix-fiber interface was assumed and a good agreement between experimental and numerical results was observed.

The load response obtained by model NDS_330_60 resembles the idealized load response put forward by the authors (D'Antino et al. 2014). The numerical σ-g curve shows an initial linear behavior, which corresponds to the linear elastic region of the τ_{zy}-s and σ_{zz}-w relationships of the different interfaces. As the global slip increases, the normal stress σ_{zz} associated with all interfaces considered remains lower than the corresponding elastic limit, whereas the shear stress at the matrix-fiber interfaces attains the elastic limit, which triggers the onset of damage at the matrix-fiber interface causing the load response to become non-linear. When the energy release rate associated with the matrix-fiber interfaces is equal to the corresponding Mode-II fracture energy, the stress transfer zone (STZ) (D'Antino et al. 2015) is fully developed, and debonding at the matrix-fiber interface occurs. For bonded lengths $\boldsymbol{\ell} > l_{eff}$, as in the case of model NDS_330_60, the applied stress further increases after the onset of debonding due to the contribution of friction (interlocking) along the debonded matrix-fiber interface as the STZ translates toward the free end. In the experimental response, after reaching the peak stress σ^*, the applied stress decreases with increasing global slip until the fibers are completely debonded from the matrix and a constant stress σ_f due to friction is present. The post-peak softening curve, which was experimentally obtained by increasing the global slip at a constant rate (section *Experimental set-up and materials*), could not be observed in the numerical analyses that were carried out by controlling the displacement at the bare fiber end. It should be noted that the softening branch of the applied load curve does not play a key role in the behavior of FRCM strengthened elements, for example beams, which do not show a softening behavior (D'Ambrisi and Focacci 2011). In order to verify if the interface shear stress-slip relationship can successfully capture the experimental response, it is important that the numerical applied load curve of direct-shear tests reproduce the experimental response only up to the peak load, i.e. without considering the softening branch. In fact, the interface shear stress-slip relationship is fully exploited when the peak load is reached. The numerical approach adopted was effective in reproducing the overall theoretical behavior of FRCM-concrete joints, i.e. including the snap-back. The snap-back phenomenon observed in the numerical models, which could be obtained by employing the arc-length method, was observed in experimental tests of FRP-concrete joints carried out by controlling the slip between fibers and concrete at the loaded and free ends (Carrara et al. 2011).

The numerical load responses show that damage affects only the Mode-II matrix-fiber contact interactions, whereas the numerical shear stress at the FRCM-concrete and internal-external matrix interfaces and peeling stress at all interfaces considered were lower that the corresponding elastic limit during the entire analysis.

The load response obtained by model NDS_330_60_H, where the concrete block thickness was equal to 1 mm, resembles the load response obtained by model NDS_330_60. This confirms that the effect of the eccentricity between the load and constraints of single-lap direct shear tests is not significant for FRCM-concrete joints with a (relatively) long bonded length and where the external layer of matrix contrasts the occurrence of out-of-plane displacement of the fibers (D'Antino et al. 2016). Models NDS_330_60_C_1 and 2, in which the concrete block was omitted, also show a load response very similar to the load response of model NDS_330_60. Model NDS_330_60 provided a peak stress σ^*=2002 MPa, whereas models NDS_330_60_H, NDS_330_60_C_1, and NDS_330_60_C_2 provided values of σ^* equal to 2005 MPa, 2009 MPa, and 2012 MPa, respectively. The slight differences between peak stress values can be explained by the different loading conditions and different contact interfaces of the models. The eccentricity between the point where displacement *v* is enforced and the concrete block constraints of model NDS_330_60 entails for a higher Mode-I loading condition with respect to models where the concrete block was either omitted or its thickness was reduced to 1 mm, which entails for a reduced eccentricity.

As discussed in section *Loading condition and parameters employed*, for model NDS_330_60_G the Mode-II fracture energy at the internal matrix layer- and external matrix layer-fiber interfaces was increased with respect to that obtained experimentally to simulate the effect of a higher matrix-fiber bond capacity. Model NDS_330_60_G failed due to detachment of the composite strip at the FRCM-concrete interface at a peak load 18% lower than the peak load obtained by model NDS_330_60, where debonding occurred at the matrix-fiber interface (Figure 5a). It should be noted that failure occurs at a specific interface depending not only on the corresponding fracture energy value but also on the value corresponding to the onset of damage. Assuming the matrix-fiber Mode-I and Mode-II fracture energies employed for model NDS_330_60_G, if the Mode-I and Mode-II fracture energies associated with the FRCM-concrete interface would be calibrated such that failure would occur within the concrete substrate, and not by detachment as observed in model NDS_330_60_G, the corresponding peak stress would be higher than that obtained for model NDS_330_60_G. The results obtained show that the matrix bond properties with both the fibers and the substrate should be considered, and that improving the matrix characteristics may not lead to a better overall bond performance of the joint.

Effect of bonded length ℓ

The numerical approach adopted allowed for studying the effect of different bonded lengths on the load response of PBO FRCM-concrete joints. Results of numerical models with the same bonded width b_1=60 mm and seven different bonded lengths ℓ (Table 2) were analyzed. Figure 6a shows the numerical σ-*g* curves obtained for numerical models with different bonded lengths ℓ. FRCM-concrete joint models with the bonded length equal to or longer than 150 mm failed due to debonding of the fibers from the embedding matrix, which is consistent with the experimental results. In addition, model NDS_100_60_G (Condition 1) presented in section *Loading condition and parameters employed*, which failed due to debonding at the matrix-fiber interfaces, was included in Figure 6a for comparison with model NDS_100_60. According to the fracture mechanics approach proposed by the authors, the debonding stress σ_{deb} of the FRCM-concrete joint is (Carloni et al. 2015b):

$$\sigma_{deb} = \frac{P_{deb}}{nb^* t^*} = \sqrt{\frac{4EG_{IIf}}{t^*}} \tag{14}$$

where E is the fiber elastic modulus. The numerical debonding stress σ_{deb}, which is attained when the matrix-fiber slip at the loaded end is equal to 1.57 mm for models with bonded length ℓ greater than 250 mm (Figure 6a), is approximately equal to the theoretical value obtained by Eq. (14), although it increases slightly with increasing bonded length (see models NDS_450_60 and NDS_955_60 in Table 2). The authors postulate that the variation of σ_{deb} with ℓ is due to the energy contributions associated with the FRCM-concrete and internal-external matrix interfaces, which increase with increasing bonded length.

The variation of the peak stress σ^* with the bonded length ℓ is shown in Figure 6b. Figure 6b also reports the average peak stress obtained by averaging σ^* of the experimental tests with the same bonded length and width considered. The numerical peak stress values are in good agreement with corresponding experimental tests for each bonded length adopted except for joints with ℓ=150 mm, where the numerical models overestimated the experimental average peak stress by approximately 20%. This discrepancy may be due to limits of the numerical approach adopted in describing the matrix-fiber stress-transfer mechanism for short bonded lengths and to the limited number of experimental tests carried out with ℓ=150 mm. The scatter between the experimental results obtained affects the comparison with corresponding numerical results shown in Figure 6b. However, the good agreement observed, particularly for specimens with bonded length equal to 200 mm and 250 mm (for which experimental results were not used to calibrate the numerical models), confirms the effectiveness of the numerical approach proposed in studying FRCM composites.

When $\ell > l_{eff}$, the peak stress σ^* increases with increasing bonded length due to the contribution of friction. The contribution of friction to the applied stress is clearly recognizable from the linear increasing branch after the debonding stress is attained (Figure 6a and b) and from the constant applied stress, at the end of the analyses (Figure 6a).

Conclusions

Three-dimensional non-linear numerical models were used in this paper to study the behavior of PBO FRCM-concrete joints. The numerical approach assumed linear constitutive laws for the materials and non-linear cohesive contact damage laws for the different interfaces considered. Results obtained by the numerical models are in good agreement with corresponding experimental results. Based on the findings of this paper the following conclusions can be drawn:

- The numerical model developed in this study is capable of reproducing different failure modes observed in direct shear tests of FRCM concrete joints, namely debonding of the fibers from the embedding matrix, interlaminar failure within the matrix, or detachment of the composite strip.

The model can potentially be used to investigate the influence of different parameters and reproduce the load response of different FRCM systems.

- The numerical load response correctly reproduces the idealized load response put forward by the authors. When $\ell > l_{eff}$, the contribution of friction to the applied stress is clearly recognizable from the linear increasing branch after the debonding stress is attained and from the constant applied stress at the end of the analyses. The softening observed in the post peak descending branch in the experimental tests is not observed in the numerical load response.
- Varying the properties of the matrix does not necessarily improve the FRCM-concrete joint response. Increasing the Mode-II fracture energy of the matrix-fiber interfaces with respect to that obtained experimentally caused premature detachment of the FRCM composite at a load lower than the peak load obtained for the same FRCM-concrete joint with the matrix-fiber Mode-II fracture energy obtained experimentally.

References

Benzeggagh, M.L., and Kenane, M. (1996) “Measurement of mixed-mode delamination fracture toughness of unidirectional glass/epoxy composites with mixed-mode bending apparatus.” *Compos. Sci. and Tech.*, 56, 439-449.

Camanho, P.P., and Davila, C.G. (2002) “Mixed-mode decohesion finite elements for the simulation of delamination in composite materials.” NASA/TM-2002-211737 2002, 1-37.

Carloni, C., D’Antino, T., Sneed, L.H., and Pellegrino, C. (2015a) “An Investigation of PBO FRCM-Concrete joint behavior using a three-dimensional numerical approach.” *Proc., 15th Int. Conf. Civil, Struct. and Env. Eng. (CC 2015),* J. Kruis, Y. Tsompanakis and B.H.V. Topping, ed., Civil-Comp Press, Stirlingshire, Scotland, Paper 113.

Carloni, C., D’Antino, T., Sneed, L.H., and Pellegrino, C. (2015b) “Role of the matrix layers in the stress-transfer mechanism of FRCM composites bonded to a concrete substrate." *J. of Eng. Mech.*, 141(6), 1-10.

Carozzi, F.G., and Poggi, C. (2015) "Mechanical properties and debonding strength of fabric reinforced cementitious matrix (FRCM) systems for masonry strengthening." *Compos. - Part B: Eng.*, 70, 215-230.

Carrara, P., and Ferretti, D. (2013) "A finite-difference model with mixed interface laws for shear tests of FRP plates bonded to concrete." *Compos - Part B: Eng.*, 54, 329-342.

Carrara, P., Ferretti, D., Freddi, F., and Rosati, G. (2011) "Shear tests of carbon fiber plates bonded to concrete with control of snap-back." *Eng. Frac. Mech.*, 79, 2663-2678.

CEN (European Committee for Standardization). (2004). "Design of concrete structures-part 1-1: general rules and rules for buildings." *Eurocode 2*, Brussels, Belgium.

Chen, J.F., and Teng, J.G. (2001) "Anchorage strength models for FRP and steel plates bonded to concrete". *J. Struct. Eng.*, 127(7), 784-791.

CNR (National Research Council). (2013). "Advisory Committee on Technical Recommendations for Construction, Guide for the design and construction of externally bonded FRP systems for strengthening existing structures." *CNR-DT 200/R1/2013*, Rome.

D'Ambrisi, A., and Focacci, F. (2011) "Flexural Strengthening of RC Beams with Cement-Based Composites." *J. Comp. Constr.*, 15(5), 707-720.

D'Ambrisi, A., Feo, L., and Focacci, F. (2012) "Bond-slip relations for PBO-FRCM materials externally bonded to concrete." *Compos. – Part B: Eng.*, 43(8), 2938–49.

D'Ambrisi, A., Feo, L., and Focacci, F. (2013) "Experimental analysis on bond between PBO-FRCM strengthening materials and concrete." *Compos. – Part B: Eng.*, 44(1), 524–32.

D'Antino, T., Carloni, C., Sneed, L.H., and Pellegrino, C. (2014) "Matrix-fiber bond behavior in PBO FRCM composites: a fracture mechanics approach." *Eng. Frac. Mech.*, 117, 94-111.

D’Antino, T., Pellegrino, C., Carloni, C., Sneed, L.H., and Giacomin, G. (2015a) “Experimental analysis of the bond behavior of glass, carbon, and steel FRCM composites.” *Key Eng. Mat.*, 624, 371-378.

D’Antino, T., Sneed, L.H., Carloni, C., and Pellegrino, C. (2013) “Bond behavior of the FRCM-concrete interface.” *Proc., 11th Int. Symp. Fiber Reinf. Polymer Reinf. Concr. Struct. (FRPRCS-11)*, J. Barros and J. Sena-Cruz, ed., UM, Guimaraes, Portugal.

D’Antino, T., Sneed, L.H., Carloni, C., and Pellegrino, C. (2015b) “Influence of the Substrate Characteristics on the Bond Behaviour of FRCM-Concrete Joints.” *Constr. Build. Mat.*, 101(1), 838-850.

D’Antino, T., Sneed, L.H., Carloni, C., and Pellegrino, C. (2016) “Effect of the inherent eccentricity in single-lap direct-shear tests of PBO FRCM-concrete joints.” *Comp. Struct*, 142, 117-129.

De Felice, G., De Santis, S., Garmendia, L., Ghiassi, B., Larrinaga, P., Lourenco, P.B., Oliveira, D.V., Paolacci, F., and Papanicolaou, C.G. (2014) “Mortar-based systems for externally bonded strengthening of masonry.” *Mater. and Struct.*, 47, 2021-2037.

De Lorenzis, L., and Zavarise, G. (2008) “Modeling of Mixed-Mode Debonding in the Peel Test Applied to Superficial Reinforcements.” *Intl. J. of Solids and Struc.*, 45(20), 5419-5436.

fib (Fédération Internationale du Béton). (2001). “Externally bonded FRP reinforcement for RC structures.” *Bulletin 14*, Lausanne.

fib (Fédération Internationale du Béton). (2013). “Code-type models for structural behavior of concrete – Background of MC2010.” *Bulletin 70*, Lausanne.

Hoover, C.G., and Bazant, Z.P. (2013) “Comprehensive concrete fracture tests: size effect of Type 1 & 2, crack length effect and postpeak.” *Eng. Fract. Mech.*, 110, 281-289.

Karihaloo, B.L., Carpinteri, A., and Elices, M. (1993) “Fracture mechanics of cement mortar and plain concrete.” *Adv. Cem. Based Mater.*, 1, 92-105.

Krueger, R. (2008) “An approach to assess delamination propagation simulation capabilities in commercial finite element codes.” NASA TM/2008-215123.

Loreto, G., Leardini, L., Arboleda, D., and Nanni, A. (2013) “Performance of RC slab-type elements strengthened with fabric reinforced cementitious matrix composites.”, *J. Compos. Constr.*,18(3), 1–9.

Mazzucco, G., Salomoni, V.A., and Majorana, C.E. (2012) “Three-dimensional contact-damage coupled modeling of FRP reinforcements - simulation of the delamination and long term process.” *Comp. Struct.*, 110-111, 15-31.

Mei, H., Gowrishankar, S., Liechti, K.M., and Huang, R. (2010) “Initiation and propagation of interfacial delamination in integrated thin-film structures.” *Proc., 12th Intersociety Conf. Therm Thermomech. Phen. Elect. Syst. (ITherm 2010)*, Institute of Electrical and Electronics Engineers (IEEE), ed., 993-1000.

Neto, P., Alfaiate, J., Dias-da-Costa, D., and Vinagre, J. (2016) “Mixed-mode fracture and load misalignment on the assessment of FRP-concrete bond connections.” *Compos. Struct.*, 135, 49-60.

Ombres, L. (2012) “Debonding analysis of reinforced concrete beams strengthened with fiber reinforced cementitious mortar.” *Eng. Fract. Mech.*, 81, 94-109.

Pellegrino, C., and D’Antino, T. (2013) “Experimental behavior of existing precast prestressed reinforced concrete elements strengthened with cementitious composites” *Compos. - Part B: Eng.*, 55, 31-40.

Rabinovitch, O. (2008) “Debonding analysis of fiber-reinforced-polymer strengthened beams: cohesive zone modeling versus a linear elastic fracture mechanics approach.” *Eng. Fract. Mech.*, 75, 2842-2859.

Ruredil (2009). *X Mesh Gold Data Sheet*, Ruredil S.p.A, Milan.

Simulia (2016). *Abaqus 6.13 Extended Functionality Online Documentation* (generated Jan 15, 2016).

Sneed, L.H., D'Antino T., and Carloni, C. (2014) "Investigation of Bond Behavior of PBO Fiber-Reinforced Cementitious Matrix Composite-Concrete Interface." *ACI Mater. J.*, 111(5), 569-580.

Sneed, L.H., D'Antino T., Carloni, C., and Pellegrino, C. (2015) "A comparison of the bond behavior of PBO-FRCM composites determined by single-lap and double-lap shear tests." *Cem. Concr. Compos.*, 64, 37–48.

Triantafillou, T.C., and Papanicolaou, C.G. (2006). "Shear strengthening of reinforced concrete members with textile reinforced mortar (TRM) jackets." *Mater. Struct*, 39, 93-103.

<u>Figure Captions</u>

Fig. 1. a) Photo of specimen DS_450_60_S_1 (Carloni et al. 2015b; D’Antino et al. 2014). b) Front and c) side view of the experimental set-up illustrating the equivalent constraints assumed.

Fig. 2. Contact areas the different interfaces considered. a) Front view and b) back view.

Fig. 3. Geometry (in mm) of numerical model NDS_100_60.

Fig. 4. Internal-external matrix layer, FRCM-concrete, and matrix-fiber interface: a) σ_{zz}-w and b) τ_{zy}-s relationships adopted

Fig. 5. a) Comparison between applied load-global slip curves of numerical models and experimental curves envelope of specimens with bonded length and width $\boldsymbol{\ell}$=330 mm and b_1=60 mm, respectively. b) Enlarged detail of peak stress of curves reported in Figure 4a.

Fig. 6. a) Applied stress σ-global slip g curves of numerical models with different bonded length. b) Applied peak stress σ^* versus bonded length $\boldsymbol{\ell}$.

Table 1. Mechanical properties of the materials.

Material	f_c [MPa]	f_t [MPa]	E [GPa]	ν [−]	Material	f_c [MPa]	f_t [MPa]	E [GPa]	ν [−]
Concrete batch A	42.5	3.4[*]	34.0[**]	0.2	Concrete batch B	33.5	3.0[*]	31.6[**]	0.2
Matrix	28.4	3.5[*]	7.0[+]	0.2	PBO fibers	-	3014	206.0	0.3

[*]Splitting tensile strength; [**]Obtained from the mean compressive strength according to (CEN 2004); [+]Reported by the manufacturer (Ruredil 2009).

Table 2. Characteristics of the numerical models.

Name	Cnd[+]	Interface				σ_{deb}	σ^*	Name	Cnd[+]	Interface				σ_{deb}	σ^*
		i	ii	iii	iv	[MPa]	[MPa]			i	ii	iii	iv	[MPa]	[MPa]
NDS_100_60	E	✓	✓	✓	✓	1053	1053	NDS_330_60_H[2]	2	✓	✓	✓	✓	1934	2005
NDS_100_60_G	1	✓[1]	✓	✓	✓	1330	1330	NDS_330_60_C_1	3	-	✓	✓	✓	1935	2009
NDS_150_60	E	✓	✓	✓	✓	1666	1666	NDS_330_60_C_2	4	-	✓	✓	-	1935	2012
NDS_200_60	E	✓	✓	✓	✓	1815	1815	NDS_330_60_G	5	✓	✓[1]	✓[1]	✓	1645	1645
NDS_250_60	E	✓	✓	✓	✓	1901	1901	NDS_450_60	E	✓	✓	✓	✓	1935	2139
NDS_330_60	E	✓	✓	✓	✓	1933	2002	NDS_955_60	6	✓	✓	✓	✓	2073	2793

[+]Condition. [1]The Mode-I and/or Mode-II fracture energies were increased relative to those of the other numerical models. [2]Thickness *h* of the concrete block was 1 mm. i) FRCM-concrete. ii) internal matrix layer-fiber. iii) external matrix layer-fiber. iv) internal-external matrix layer.

Table 3. Approximate size of mesh element adopted and resulting number of elements.

Component	Size (number) *x*-direction [mm]	Size (number) *y*-direction [mm]	Size (number) *z*-direction [mm]
Concrete block interface	1.90 (31)	2.50 (40)	1.00 (3)
Concrete block	17.00 (7)	17.00 (8)	17.00 (22[1], 29[2])
Internal matrix layer	1.00 (46)	3.00 (32[3])	1.00 (4)
External matrix layer	1.00 (40)	5.00 (55[3])	1.00 (4)
Bonded fiber bundles	1.00 (5)	2.50 (6[3])	0.03 (3)
Bare fiber bundles	1.00 (5)	6.00 (2.5[3])	0.03 (3)

[1]Concrete block with length 375 mm. [2]Concrete block with length 510 mm. [3]Total number of elements (within the fiber bundle cross-section) per mm in *y*-direction.