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DEBONDING PROBLEMS IN REINFORCING MASONRY WITH FRP PLATES

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INTRODUCTION

- The use of Fiber Reinforced Polymer matrix composites (FRPs: Fiber Reinforced Polymers) for structural rehabilitation has gradually increased over the past two decades.

- The applications have been principally used to strengthen reinforced concrete structures, with an extensive scientific and technical literature having been published as well as specific guidelines for the designing of interventions, their execution and their monitoring drawn up.

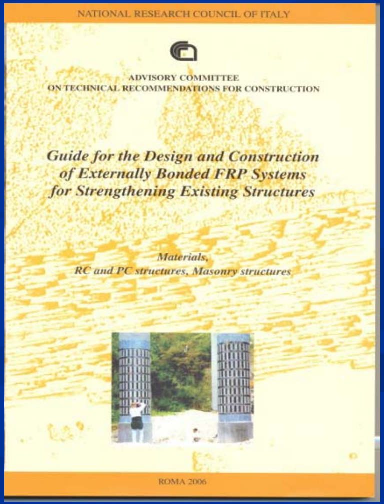
It is therefore worth mentioning both the Japanese (JSCE – 1997) and American (ACI440 - 2000, 2008) guidelines as well as, in Europe, the guidelines issued by the CEB-FIB (2001). They were complemented in 2004 by the guidelines issued by the Italian CNR (CNR-DT 200/2004), which have the specific characteristic of dealing with both applications of reinforced concrete structures as well as applications to masonry structures. The latter are particularly significant in number and importance in countries such as Italy, which is full of buildings dating back to several centuries, many of which have a historic and monumental significance.

INTRODUCTION

- There are many reasons that have promoted the use of FRPs in structural retrofitting: light-weight, high strength/weight and stiffness/weight ratio, corrosion resistance, ease of application and good reversibility of the process. In particular, the last characteristic makes FRPs competitive in applications on structures of historical and artistic importance.

This has created a particular interest in the subject within the Italian scientific community, as highlighted by the considerable amount of literature produced as well as the numerous projects dedicated to it.

- There are essentially two main aims of a FRP structural strengthening intervention: to transfer to the composite reinforcement the tensile stresses that can not be sustained by the materials which constitutes the strengthened element (concrete or masonry); to increase the load bearing capacity of a column subject to normal stress compression by confining it with FRPs.



INTRODUCTION

- In the first case, the interventions are known as active or “by adherence”, while in the second, the interventions are passive.

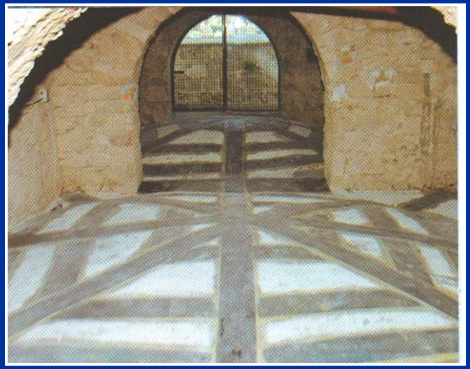
In active interventions, the tensile stress is transferred to the FRP through the interface that is made by bonding it to the support material. The success of the intervention is therefore conditioned by the resistance of the interface. An eventual debonding of the FRP strengthening renders the intervention ineffective, with the traction stresses being transferred onto the element, therefore causing the failure of the structure. This mechanism can originate both at the ends of the FRP strengthening as well as close to a structural crack in the strengthened element. In the first case, this is known as ***end debonding***, while in the second, ***intermediate debonding***. In fact, in both cases, the FRP/support interface is subject to high shear stresses that may cause failure at the cut off section as well as close to the crack. This type of mechanism is fragile and in the spirit of “hierarchies of resistance” should be carefully prevented.

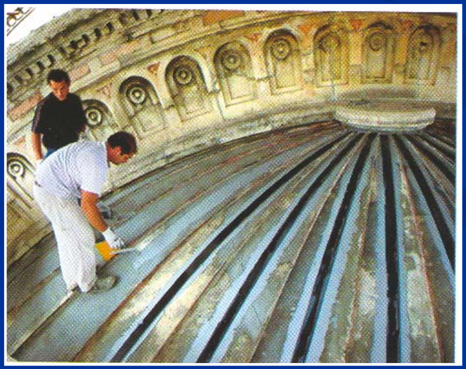
INTRODUCTION

- The study of the strength of a FRP reinforcement in relation to the debonding phenomenon is therefore of paramount and preliminary importance.

Particular attention has been given to this aspect by the entire international scientific community with both theoretical and experimental studies being carried out.

- The aim of this paper is to present the results of a detailed study carried out in Italy as part of the **RELUIS research project, funded by the Italian Department of Civil Protection in the period 2005-2008**. The results were largely used to draw up an updated edition of the guidelines CNR-DT 200/2004, almost five years after they were first produced by a study group of which **this speaker has been and still is the general coordinator**. The Chairman of the Advisory Committee on Technical Recommandations for Constructions of CNR is **Prof. Franco Maceri**.





A MECHANICAL MODEL

- The debonding phenomena of FRP strengthenings can be studied by analyzing the results of **bond tests**, which can be interpreted through appropriate mechanical models.

- A typical bond test is schematised in Figure 1 and designed to measure the ultimate value of the force transferred to the FRP system prior to debonding. This test can specifically analyse the phenomenon of the end debonding, with the information obtained also helping to interpret the phenomenon of intermediate debonding.

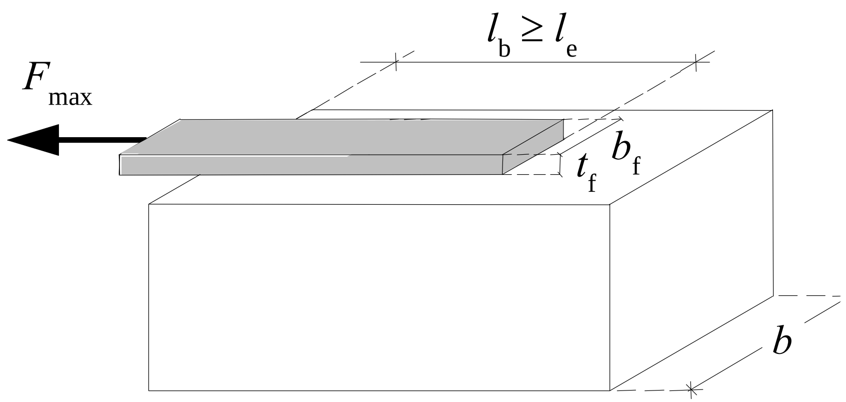


Figure 1 - Bond Test.

A MECHANICAL MODEL

- The ultimate value depends on, equal to all the other conditions, the length, l_b, of the bonded area. It increases with the increase of l_b and reaches a maximum for a definite length, l_e: further extension of the bonded area will not increase the force transmitted.

- The length l_e is defined as the optimal bonded length and therefore corresponds to the minimum length of the FRP anchoring area that ensures the transmission of the maximum bond load.

The most appropriate theoretical approach to analyse the problem presented is that of nonlinear fracture mechanics, introducing an interface constitutive law of a cohesive type between FRP strengthening and support.

- More specifically, it is sufficient to limit it to mode II fracture so that the interface law between strengthening and support (concrete or masonry) can be represented with sufficient accuracy for technical reasons as a relationship between the shear stress, τ_b, and the corresponding slip, s .

A MECHANICAL MODEL

- The interface relationship is typically non linear with a softening branch and can be approximated by a bilinear law (Fig. 2) as proposed by Neubauer and Rostasy in their 1997 study.

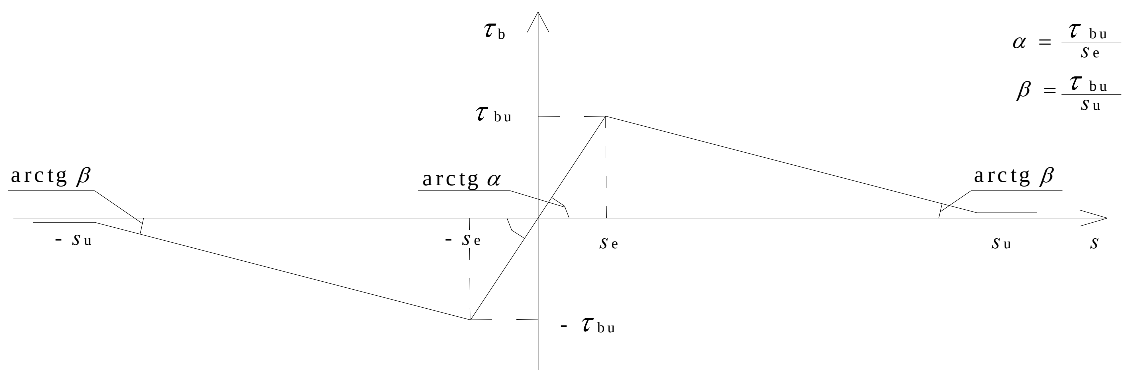


Fig. 2 – Bilinear bond-slip law.

A MECHANICAL MODEL

- The amount of slip s_e at the limit of the linear elastic branch of the diagram is usually negligible compared to s_u ($s_e \approx 0.1\ s_u$). **This allows the aforementioned linear elastic branch to be neglected, especially in the light of studying the Ultimate Limit State behavior** . The **linear elastic branches cannot be neglected in analyzing the Service Limit States**.

- The bond-slip law is therefore only reduced in the linear softening branch (Fig. 3).

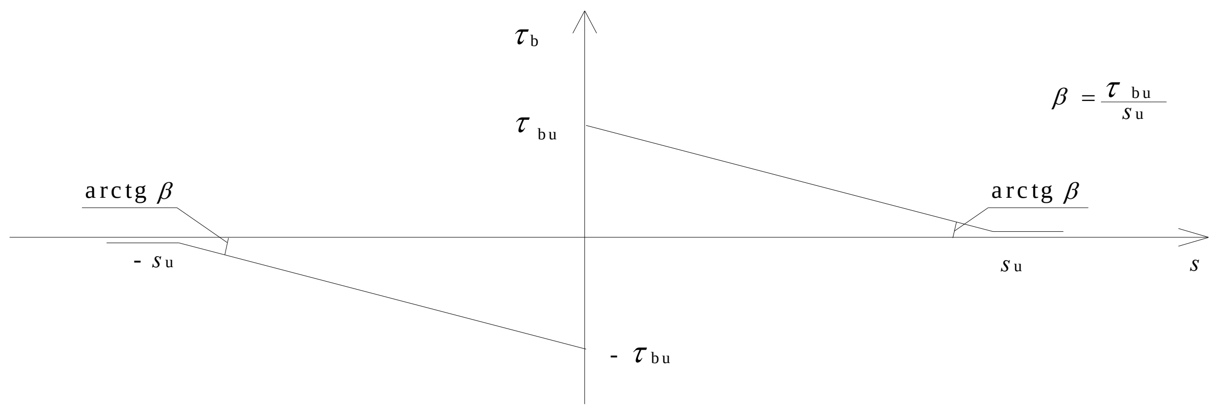


Fig. 3 – Rigid-softening bond-slip law.

A MECHANICAL MODEL

- Analytically, the rigid-softening relationship can be formulated as follows:

$$\tau_b = \frac{|\tau_{bu}|}{|s_u|}(s_u - s), \quad \forall\, s \in [-s_u, +s_u] \tag{1a}$$

$$\tau_b = 0, \quad \forall\, s \in \,]-\infty, -s_u[\, \cup \,]s_u, +\infty[\tag{1b}$$

- The areas subtended by the diagrams of Figure 2 and Figure 3 represent the fracture energy, Γ_f. It is evident that these energies are equal for both models, equal in τ_{bu} and s_u:

$$\Gamma_f = \frac{1}{2}\tau_{bu} s_u. \tag{2}$$

A MECHANICAL MODEL

- The assumption of a bond-slip law type $\tau_b = \tau_b(s)$ allows to schematize the problem illustrated in Figure 1, as the equilibrium problem of a linear elastic beam (made of FRP), which is constrained axially on a continuous set of independent springs, which are modeled under the law of Figure 3 (support), with the beam being subject to a traction force *F*. The structural scheme of the beam is shown in Figure 4. **The model is simple and suitable for technical purposes**.

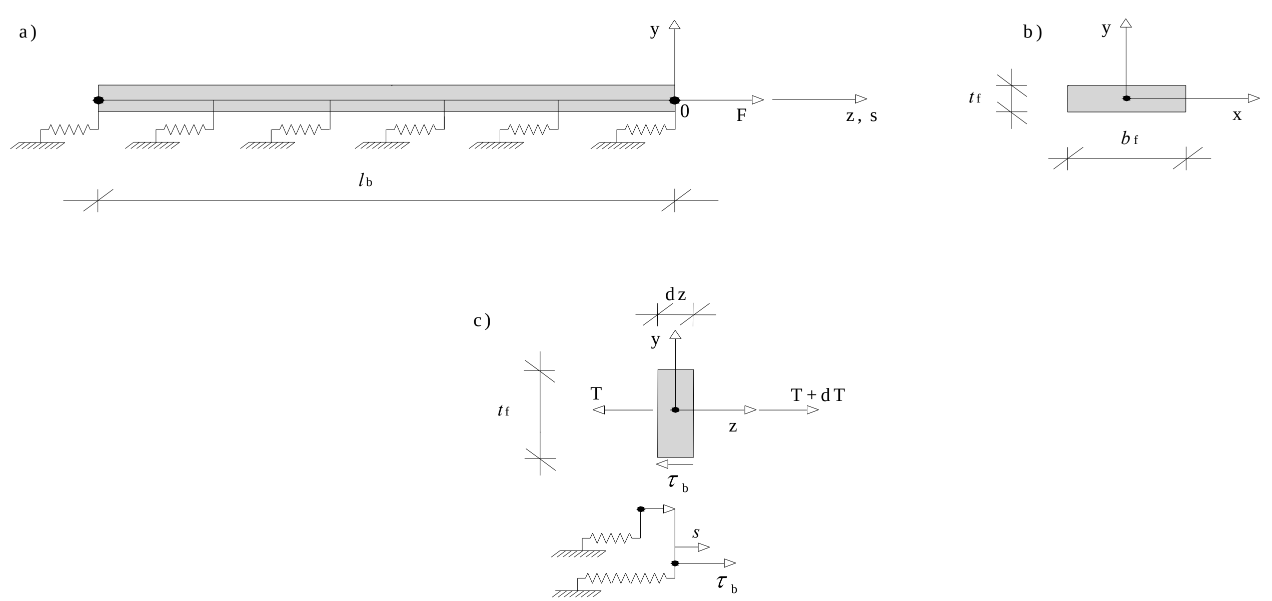


Fig. 4 – Structural layout (a); cross section of FRP strengthening (b): infinitesimal element of strengthening.

A MECHANICAL MODEL

- The equilibrium problem in Figure 4 is clearly non linear and has not necessarily a solution for an arbitrary value of the force F applied to the beam.

- Assuming that such a solution exists, the local equilibrium equation to the translation in the direction z of the FRP lamina is:

$$\frac{dT}{dz} - b_f \tau_b = 0, \tag{3a}$$

or

$$\frac{dT}{dz} + \beta \, b_f \left(s - s_u\right) = 0. \tag{3b}$$

- On the other hand, the axial force T is related to the linear expansion coefficient $\varepsilon = ds/dz$ through the relation:

$$T = E_f A_f \frac{ds}{dz}, \tag{4}$$

where A_f is the area of cross section of the FRP strengthening ($A_f = b_f \, t_f$) and E_f is the elasticity modulus of the FRP along the z axis.

A MECHANICAL MODEL

- Substituting (4) into (3b) through easy steps, the differential equation can be obtained:

$$\frac{d^2}{dz^2}\left(s\text{-}s_{\mathrm{u}}\right)+\omega^2\left(s\text{-}s_{\mathrm{u}}\right)=0, \tag{5}$$

where the quantity ω, which has the dimensions of the inverse of a length, is defined by the relation:

$$\omega^2=\frac{\beta\, b_{\mathrm{f}}}{E_{\mathrm{f}}\, A_{\mathrm{f}}}. \tag{6}$$

- The general integral of (5) takes the form:

$$s\text{-}s_{\mathrm{u}}=C_1 \, cos\, \omega\, z + C_2 \sin\omega\, z, \tag{7}$$

C_1 and C_2 being two integration constants by having to determine by means of the static boundary conditions imposed to the beam.

A MECHANICAL MODEL

They require:

$$E_f A_f \left.\frac{ds}{dz}\right|_{z=0} = F, \qquad (8a)$$

$$E_f A_f \left.\frac{ds}{dz}\right|_{z=-l_b} = 0. \qquad (8b)$$

Ultimately, it is:

$$s = s_u - \frac{F}{E_f A_f \omega} \cdot \frac{\cos\left[\omega\left(l_b + z\right)\right]}{\sin\omega\, l_b}. \qquad (9)$$

- The relation (9) suggests that to ensure that along the beam there is $s \leq s_u$, the following condition should be verified:

$$\omega\, l_b \leq \frac{\pi}{2}. \qquad (10)$$

A MECHANICAL MODEL

- The quantity:

$$l_e = \frac{\sqrt{2}}{4}\pi\, s_u \sqrt{\frac{E_f t_f}{\tau_f}} \tag{11}$$

is called ***optimal bond length***.

- The bonding stresses increase starting from the loaded end of the FRP strengthening. In particular, if $l_b = l_e$, it is:

$$\tau_b(-l_e) = \beta\left(s_u - s(-l_b)\right) = \beta \frac{F}{E_f A_f \omega}. \tag{12a}$$

- Instead, if $l_b < l_e$, it is:

$$\tau_b(-l_b) = \beta\left(s_u - s(-l_b)\right) = \beta \frac{F}{E_f A_f \omega} \cdot \frac{1}{\sin \omega l_b}. \tag{12b}$$

A MECHANICAL MODEL

- Since the maximum value of the tensile force, F_{max}, that can be applied to the FRP strengthening is one for which $\tau_b(-l_b) = \tau_{bu}$, it is also:

-for $l_b = l_e$

$$F_{max} = \frac{E_f A_f \omega}{\beta} \cdot \tau_{bu}, \quad (13a)$$

rewritable as

$$F_{max} = b_f \sqrt{2 E_f t_f \Gamma_f}; \quad (13b)$$

- for $l_b < l_e$:

$$F_{max} = \frac{E_f A_f \omega}{\beta} \cdot \tau_{bu} \sin \omega l_b. \quad (13c)$$

- Since $\sin \omega l_b \le 1$, the existence of an optimal bond length is confirmed by the model considered, with the meaning being attributed to that definition. It is possible to prove by using the well known Griffith criterion that the relation (13b) is independent on the particular shape of the cohesive law adopted and represents the maximum bond load that the FRP lamina is able to transmit to a rigid support. Consequently, relation (13b) can be utilized for the experimental evaluation of Γ_f starting from the measured values of F_{max}.

THE ITALIAN CNR GUIDELINES

- The guidelines issued by the Italian CNR suppose that the fracture energy Γ_f is an explicit function of τ_{bu} assumed to be equal to the support strength in a pure shear test.

- By adopting for the support the well known **Mohr-Coulomb criterion** (Figure 5), it is easy to verify that such limit stress can be expressed in terms of tensile strength, f_{ct}, and compression, f_c, of the support:

$$\tau_{bu} = \frac{f_c \cdot f_{ct}}{f_c + f_{ct}}. \tag{14}$$

- Consequently, the guidelines assume the following expression of the fracture energy:

$$\Gamma_{Fd} = \frac{k_b \cdot k_G}{FC} \cdot \frac{f_c \cdot f_{ct}}{f_c + f_{ct}}, \tag{15}$$

where the non dimensional geometric coefficient k_b allows to take into account the relationship between the transversal dimension of the FRP strengthening, b_f, and the support, b_c:

$$k_b = \sqrt{\frac{2 - b_f / b_c}{1 + b_f / b_c}} \geq 1; \tag{16}$$

and the factor k_G, whose dimension is a length, has to be determined on an experimental basis. FC is a useful safety factor.

THE ITALIAN CNR GUIDELINES

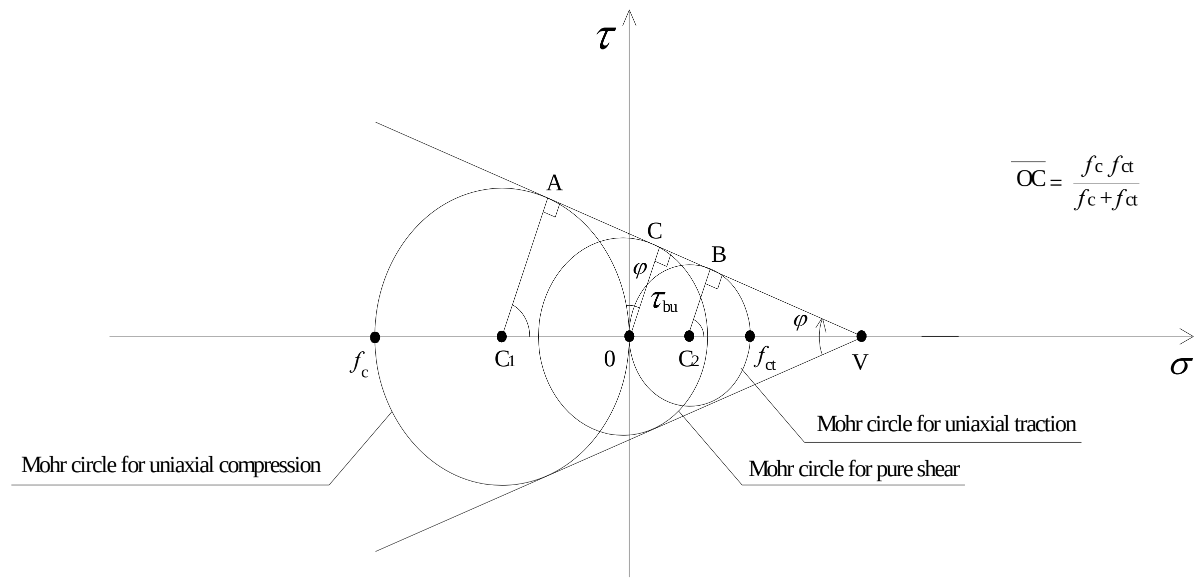


Fig. 5 – Mohr-Coulomb criterion.

- As part of the RELUIS research project, extensive experimental research was carried out that has allowed the coefficient k_G introduced above to be calibrated both for concrete and masonry support.

- In particular, for the concrete support 216 tests for fabrics and 68 tests for pultruted laminae were processed . For masonry support 50 tests were processed in all.

THE ITALIAN CNR GUIDELINES

- Consequently, the Document gives the following design and verification formulas:

$$f_{\mathrm{ffd}} = \frac{1}{\gamma_{\mathrm{f,d}}} \cdot \sqrt{\frac{2 \cdot E_{\mathrm{f}} \cdot \Gamma_{\mathrm{Fd}}}{t_{\mathrm{f}}}}, \tag{17}$$

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$$f_{\mathrm{ffd,2}} = \frac{1}{\gamma_{\mathrm{f,d}}} \cdot \sqrt{\frac{E_{\mathrm{f}}}{t_{\mathrm{f}}} \cdot \frac{2 \cdot k_{\mathrm{b}} \cdot k_{\mathrm{G,2}}}{FC} \cdot \frac{f_{\mathrm{c}} \cdot f_{\mathrm{ct}}}{f_{\mathrm{c}} + f_{\mathrm{ct}}}}, \tag{18}$$

where:

- f_{ffd} is the design maximum stress in the FRP under conditions of incipient **end debonding** from the support;
- $f_{\mathrm{ffd,2}}$ is the design maximum stress in the FRP under conditions of incipient **intermediate debonding** from the support;
- $\gamma_{\mathrm{f,d}}$ is a safety factor.

THE ITALIAN CNR GUIDELINES

$$l_{\mathrm{ed}} = s_{\mathrm{u}} \sqrt{\frac{\pi^2 \cdot E_{\mathrm{f}} \cdot t_{\mathrm{f}}}{8 \cdot \Gamma_{\mathrm{Fd}}}}, \qquad (19)$$

where:

- s_u is the ultimate slip, whose value, based on extensive experiments available in current literature, is to be assumed as follows:
  - for concrete supports **s_u = 0.2 mm**,
  - for masonry supports **s_u = 0.15 mm**.

THE ITALIAN CNR GUIDELINES

- On the basis of (15), the values of k_G and $k_{G,2}$ were obtained through a multivariate analysis.

- concrete support:

$$\begin{cases} k_G = 0.087 \text{ mm} & \text{(for pultruded laminas)} \\ k_G = 0.137 \text{ mm} & \text{(for wet lay-up materials);} \\ k_{G,2} = 0.31 \text{ mm} & \text{(for all materials)} \end{cases}$$

- masonry support: the evaluation of k_G and $k_{G,2}$ is in progress (for natural stone and for artificial clay).