A simplified model to estimate the contribution of EB-FRP to the shear strength of masonry panels

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Evaluation of the shear resistance of FRP reinforced masonry

EB FRP = **E**xternally **B**onded **F**ibre-**R**einforced **P**olymers

The application of EB FRP can be an effective way to improve the shear strength of unreinforced masonry (URM).

Evaluating the resistance improvement due to the FRP presence, however, is problematic (*also in the case of concrete beams there are still several open issues!*).

Available models commonly adopt strut-and-tie schemes to render the behaviour of a strengthened panel, derived, for example, from steel reinforced masonry design (…*and therefore from the reinforced concrete theory…*).

The efficacy of these approaches, however, relies on the deep knowledge of the bond behaviour of FRP applied to masonry substrates, which is presently far to be reached (*absence of standard tests, role of mortar joints, fracture energy calibrations, mode III behaviour…*).

Therefore,

the use of effectiveness curves may be an alternative way to fracture mechanics of FRP-to-masonry bond behaviour, and could lead to simplified estimations of the FRP contribution to masonry shear strength.

Shear strength of FRP-reinforced masonry panels

Nine experimental activities, focused on the shear strengthening of masonry panels by means of EB FRP, have been collected from literature (overall 76 specimens).

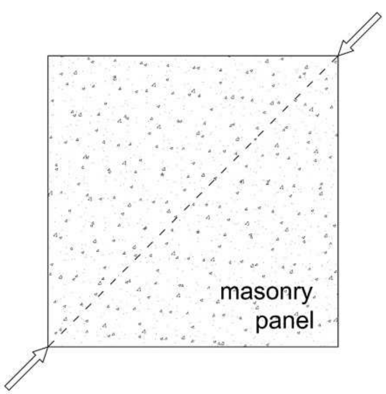
Main aspects of the data collection:

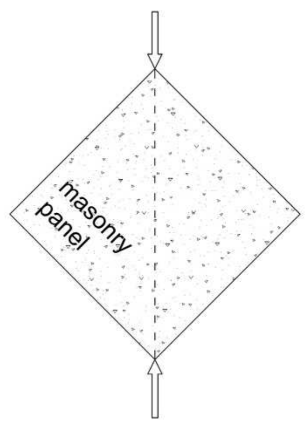
- ❑ diagonal compression test adopted as reference test (easier to perform, common until recent years,…);
- ❑ single-leaf masonry panels;
- ❑ different setups;
- ❑ various reinforcement configurations (net, diagonal,…)

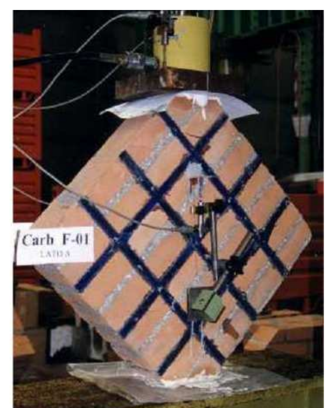

Salmaso 2000


Grando 2003


Morbin 2004





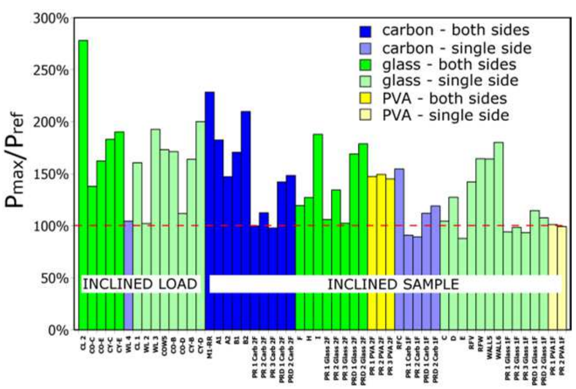


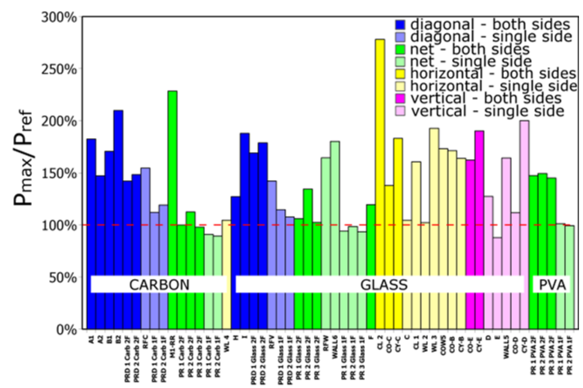
Data analysis

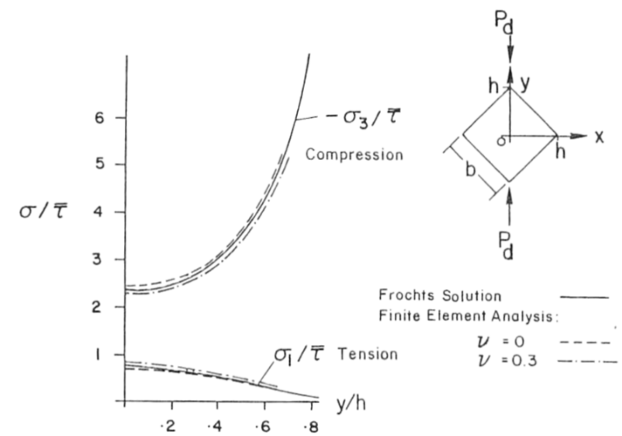
Assumptions:

- most part of principal tensile stresses, normal to the loaded plane, is assumed as distributed along the 80% of the loaded diagonal (according to Frocht, Yokel and Fattal…), which is between the corners where load P is applied;
- the strength increment ΔP, deduced by comparing results of unreinforced reference panels (P_{ref}) and strengthened ones (P_{max}), is essentially due to the applied FRP reinforcement;

$$\Delta P = P_{\max} - P_{ref}$$ strength increment imputed to FRP







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Data analysis

Subsequent steps:

- the overall increment in terms of tensile stresses is then integrated (obtaining the tensile force ΔP_t acting normally to the compressed diagonal) and supposed to be discretized in correspondence of FRP positions, consistently with reinforcement pattern and area;
- the calculated tensile force acting on each FRP strip (at failure) is compared to the tensile strength; their ratio is defined "effectiveness coefficient" k_v.

$$\Delta P_t = 0.391 \Delta P = 0.391 \left(P_{\max} - P_{ref} \right)$$

$$\Delta P_t = \sum_1^{n_f} T_{fi,eff} \qquad\qquad k_v = \frac{T_{f,eff}}{T_{f,\max}} = \frac{\varepsilon_{eff} E_f A_{fw}}{\varepsilon_{fu} E_f A_{fw}} = \frac{\varepsilon_{eff}}{\varepsilon_{fu}}$$

Other assumptions:

- strips without a sufficient anchorage length are considered as not working (therefore excluded from the count of n_f, that is the number of FRP strips);
- the tensile stress of each strips is considered uniform across the width.

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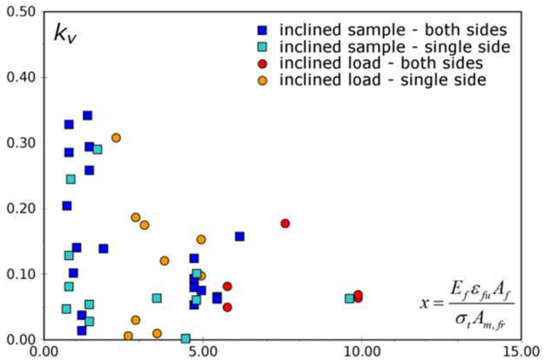
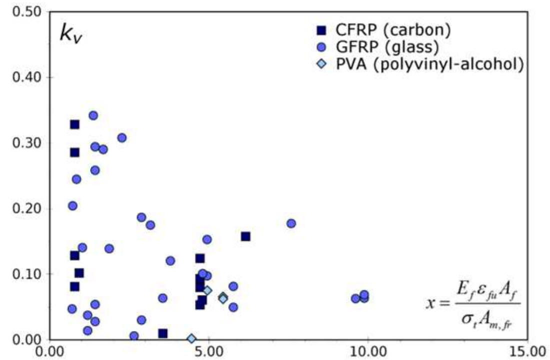
Effectiveness curves

The effectiveness coefficients k_v have been tabulated and plotted against a normalized abscissa x, which compares the maximum FRP tensile force to a nominal tensile force of masonry.



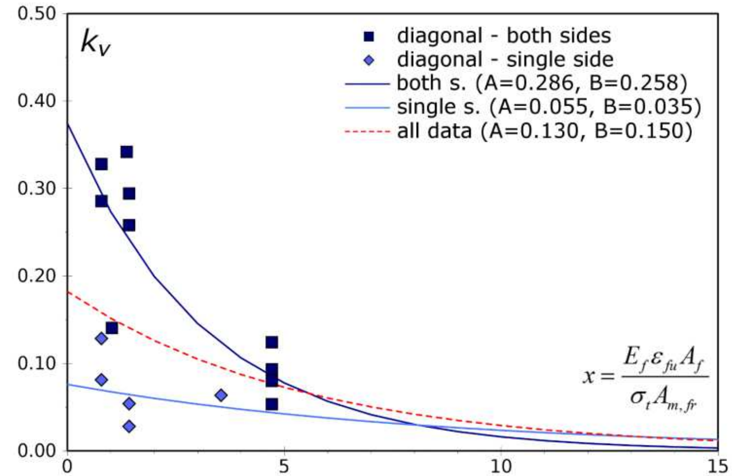


$$x = \frac{E_f \varepsilon_{fu} A_f}{\sigma_t A_{m,fr}}$$

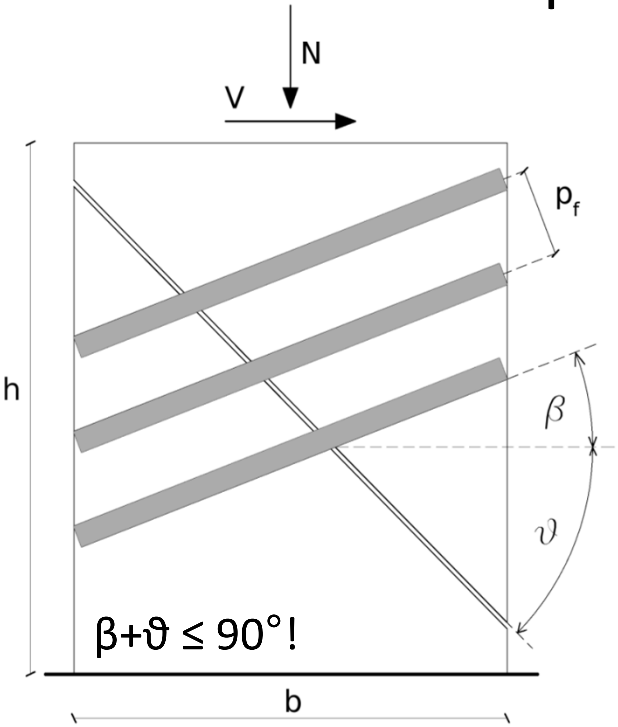
Based on the available data, k_v has been expressed as a function of the normalized abscissa x.

A and B are empirical regression coefficients.

$$k_v = Ae^{-Bx} = Ae^{-B\frac{E_f \varepsilon_{fu} A_f}{\sigma_t A_{m,fr}}}$$



Simplified (and provisional) model



Starting points:

- According to CNR DT-200 and ACI 440.7R, the FRP contribution to shear strength ($V_{Rd,f}$) can be considered as additional to the unreinforced masonry resistance ($V_{Rd,m}$)
- UR masonry shear resistance, according to the Italian Building Code (existing masonry structures), can be evaluated using a Turnšek-Čačovič based formula

$$V_{Rd} = V_{Rd,m} + V_{Rd,f}$$

$$V_{Rd,m} = bt \frac{f_{td}}{c} \sqrt{1 + \frac{\sigma_0}{f_{td}}}$$

h = height of the panel
b = width of the panel
t = thickness of the panel

f_{td} = masonry tensile strength (due to diagonal cracking)
σ_0 = nominal vertical stress (N/b·t)
c = corrective factor; $1 \leq c = h/b \leq 1.5$

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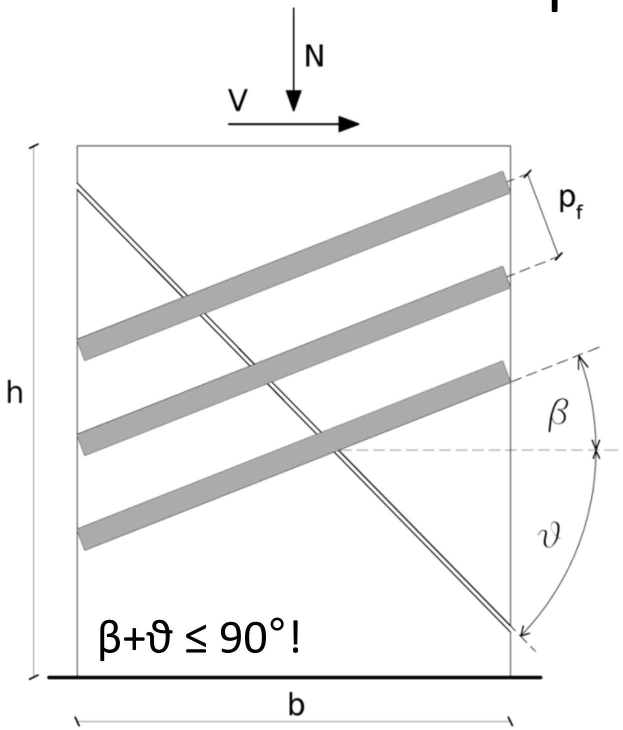


Basic ideas:

1. FRP strips cannot reach their tensile strength, since debonding is likely to occur before;
2. relative displacements between the edges of a shear crack are approximately horizontal, so horizontal strips should be more effective.

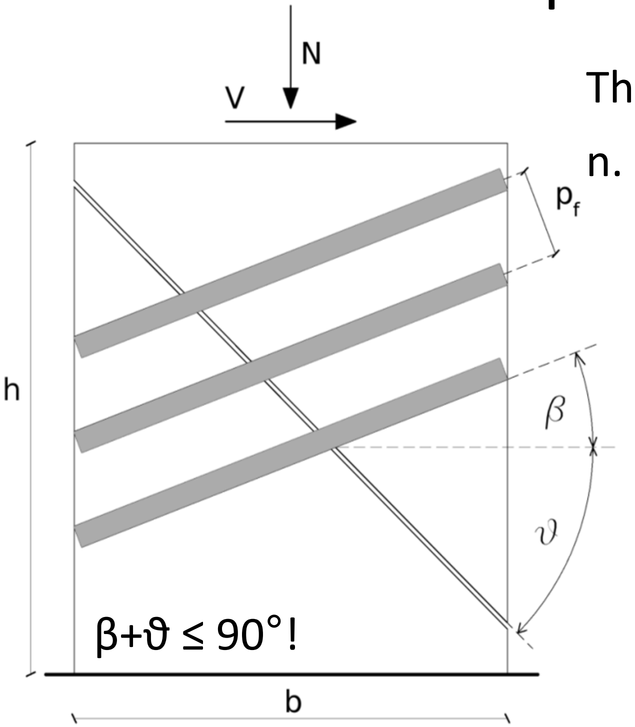
Therefore:

1. the FRP tensile strength is reduced by the *effectiveness coefficient* $k_v \leq 1$, empirically calibrated;
2. The maximum force of inclined strips (β > 0°) is reduced.

Maximum force for each strip: $$V_f = \underset{(1)}{k_v} A_{fw} \varepsilon_{fd} E_f \underset{(2)}{\cos(\beta)}$$

A_{fw} = single strip area (commonly equivalent thickness x width, $t_f b_f$)
ε_{fd} = design max strain for the FRP
E_f = FRP elastic modulus

Simplified (and provisional) model



The overall contribution of the FRP reinforcement is given by:

n. of strips crossed by the crack (n_f) **x** single strip contribution (V_f)

$$n_f = \mathrm{int}\left(\frac{l_{m,fr}}{p_f}\sin(\theta+\beta)\right)$$ ← n. of strips crossed by the crack

$$l_{m,fr} = \begin{cases} b/\cos\theta & \text{if } \theta \leq \arctan(h/b) \\ h/\sin\theta & \text{if } \theta > \arctan(h/b) \end{cases}$$ ← crack length

$$A_f = n_f A_{fw}$$ ← overall area of the FRP along the crack

Design FRP contribution to the shear strength →

$$V_{Rd,f} = \frac{1}{\gamma_{Rd}} k_v A_f \eta_a \frac{\varepsilon_{fk}}{\gamma_f} E_f \cos(\beta)$$

($\eta_a \frac{\varepsilon_{fk}}{\gamma_f} = \varepsilon_{fd}$)

$$\bar{x} = \frac{\eta_a(\varepsilon_{fk}/\gamma_f)E_f A_f}{f_{mtm} A_{m,fr}}$$

$$k_v = 0.286\, e^{-0.258\bar{x}}$$

$$\theta = 45°$$

...provisional suggestions

p_f = centre-to-centre spacing of FRP strips
ε_{fk} = characteristic max. strain for the FRP
η_a = conversion factor (environmental effects)
γ_{Rd} = partial factor for the shear model
γ_f = partial factor for the FRP

Conclusions

- this work focused on the collection from literature of diagonal compression tests on single-leaf masonry panels;
- the aim was providing a methodology to obtain a simplified formulation of the shear strength improvement given by EB-FRP reinforcements applied on existing masonry substrates, which show a large variability in terms of resisting elements, texture and structure;
- the empirical formulation is intended to consider the influence of numerous types of external FRP reinforcement that differ in morphology (unidirectional/bidirectional textiles, laminates, etc.) and constitutive materials (high strength/high modulus carbon, aramid, glass, basalt, etc.);
- effectiveness curves are aimed at taking into account debonding phenomenon into the computation of the FRP design strain. The use of effectiveness curves might be an alternative way to fracture mechanics of FRP-to-masonry bond behaviour, which is still far from being exhaustively investigated in the case of masonry;
- the next step, to become of practical use, should be the definition of a larger data-set to provide more reliable curves for the evaluation of effective factor k_v.

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THANK YOU

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