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Experimental investigation on the behavior of composite laminates bonded on masonry

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ABSTRACT: This paper investigates the bonding behavior of carbon- and glass-fiber reinforced polymers (FRP) glued on various kinds of masonry elements. Clay-bricks as well as some natural masonry elements (i.e., tuff or limestone) have been used for preparing a series of specimens for double shear pull-out tests. A preliminary experimental work has been carried out on some samples of the masonry blocks for identifying the basic features of their mechanical behavior. Then, twenty-four pull-out tests have been carried out. The discussion of the results of those tests focuses on the ultimate strength of the FRP-to-masonry joints. Finally, the experimental results will be utilized for assessing the theoretical formula for the ultimate strength of composite laminates glued on masonry provided by a recently issued Italian Code for Structural Strengthening. Since all the relevant mechanical properties of the masonry materials are available, a consistent relationship between such mechanical properties and the observed strength of the FRP laminates failing in delamination is finally proposed.

1 INTRODUCTION

Masonry structures are rather common even in seismic regions, like the countries in the Mediterranean basin and other regions which have been recently struck by significant earthquake. Hence, structural strengthening of their principal members is often necessary for enhancing their seismic resistance to meet the required safety standards. Shear strengthening of masonry wall is one of the most common interventions which can be carried out for improving the lateral strength of the structure in order to face the earthquake induced actions. The use of composite materials for this purpose is one of the possible solutions, characterized by the reduced increases in structural weights. Various composite materials are nowadays available for using in the civil field and, moreover, a large variety of masonry qualities, in terms of both materials and textures, can be found in existing structures. Consequently, general formulae to structural strengthening of masonry members are much less established than the corresponding ones completely accepted for concrete structures. In fact, few codes of standards devoted to structural strengthening of existing structures through composite materials address the topic of masonry structures. The recently issued Italian Code (CNR DT-200, 2004) actually does that. Although a large variety of masonry structures exist, only few experimental data are available and the calibration of the formulae adopted within that document would deserve further study. In particular, the present paper is devoted to the aspect of the adhesion of composite materials to masonry. Pull-out tests can be usually carried out to quantify the mechanical properties of the FRP-to-masonry interface. However, only few experimental tests are available and generally cover particular kinds of natural stones (Aiello & Sciolti, 2005) or the common clay bricks (Briccoli Bati et al., 2007). In the present paper, four kinds of masonry elements, either natural or artificial, will be considered; moreover, carbon fiber-reinforced polymers (CFRP), glass fiber-reinforced polymers (GFRP) and carbon fiber-reinforced cement matrix (CFRCM) will be considered. The experimental results in terms of maximum bond strength will be compared with the corresponding formula provided by the Italian Guideline, recently issued for covering the use of FRP material as external strengthening of both concrete and masonry members. Finally, an alternative proposal will be calibrated for evaluating the key mechanical parameter describing the behavior of the FRP-to-masonry interface.

2 MATERIALS

The results of preliminary tests carried out for quantifying those properties and describing the mechanical behaviour of the materials are briefly summarized in the present section.

2.1 Masonry

Four kinds of either masonry bricks or natural stones have been considered in the tests:
- dune limestone (commonly called *calcarenite* in the following);
- yellow-tuff stone masonry;
- clay brick masonry;
- limestone masonry.

Compression and bending tests have been carried out on samples of the above mentioned materials with the aim of identifying the key aspects of their mechanical behaviour. Table 1 and Table 2 summarize the main mechanical properties of the masonry samples. In particular, the compressive and the tensile strength, $f_{b,m}$ and $f_{bt,m}$, as well as the secant Young modulus $E_{b,m}$ and the ultimate strain $\varepsilon_{m,b}$ are reported therein. The coefficients of variation CoV of the first two properties are also reported in the mentioned tables.

Table 1. Mechanical properties of masonry samples: compression tests

Material	Number of tests	$f_{b,m}$ [MPa]	CoV	$E_{b,m}$ [MPa]	$\varepsilon_{m,b}$
Calcarenite	11	2.48	0.130	360.44	0.0060
Yellow Tuff	21	4.41	0.264	404.31	-
Clay bricks	8	25.51	0.084	322.65	0.0720
Limestone	37	70.04	0.135	489.72	0.0740

Table 2. Mechanical properties of masonry sample: results of bending tests in terms of tensile strength

Material	Number of tests	$f_{bt,m}$ [MPa]	CoV
Calcarenite	4	0.710	0.320
Yellow Tuff	5	0.614	0.160
Clay bricks	5	9.808	0.096
Limestone	3	11.380	0.195

2.2 Composite materials

The two types of fibre-reinforced polymer (FRP) materials utilized in the tests are listed in Table 3, along with their main mechanical properties. The adhesive MapeWrap 31 has been utilized for gluing fabrics on masonry; the relevant properties of the adhesive are omitted herein for the sake of brevity, but are available in the documentation of the product (Mapei, 2000).

Table 3. Properties of GFRP and CFRP composites

Fiber	Trademark	Equivalent thickness t_f [mm]	Young Modulus E_f [GPa]	Tensile strength f_{fu} [MPa]	Ultimate axial strain ε_{fu}
Glass (G)	MapeWrap G-UNI-AX	0.48	80.7	2560	3-4 %
Carbon (C)	MapeWrap C-UNI-AX	0.166	230	4830	2 %

3 PULL-OUT TESTS: DESCRIPTION AND RESULTS

Twenty-four specimens have been tested in pull-out for investigating the adhesion properties of composite materials glued on masonry blocks. Figure 1 reports three pictures taken for the three main kinds of bricks and stones whose adhesion properties are investigated in the present study.

a) brick masonry b) tuff masonry c) limestone masonry

Figure 1. Tested specimens

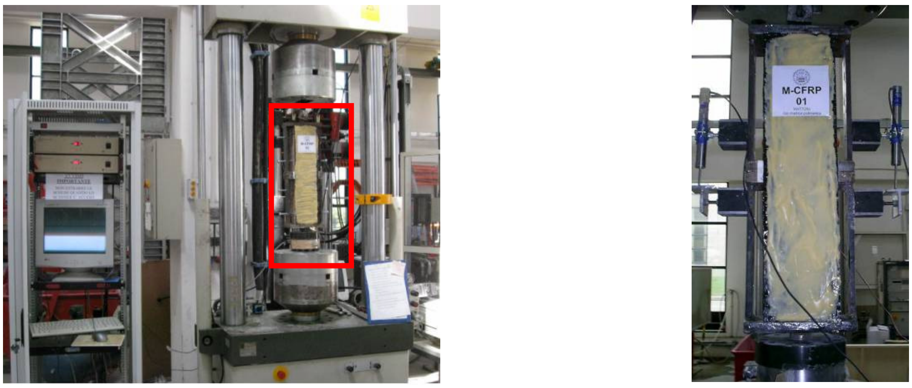


Figure 2. Layout of the pull-out tests

Double-lap pull-out tests have been carried out on specimens like those represented in Figure 2. The loading process has been applied in displacement control and the relative displacements between the two connected blocks has been monitored trough a series of LVDT sensors, along with the resulting load P which has been measured by a load cell (Figure 2).

Table 4 reports both the relevant typological and geometric data (i.e. the breath b_f and the bonded length L_f) of the tested specimens and the key results obtained by the pull-out shear tests. In particular, the values of the ratio between the ultimate load P_{max} and the strip width b_f have been reported for all the 24 specimens as a preliminary quantitative measure of the adhesion between the FRP strip and the masonry substrate.

Table 4. Experimental results of the pull-outs tests (* S=in the masonry, M=mixed)

#	Test	Masonry	Composite	b_f [mm]	L_f [mm]	$2P_{max}$ [kN]	Failure Mode [S/M*]	P_{max}/b_f [N/mm]
1	C-CFRP 01	Calcarenite (Type 2)	C	118	242	28.03	S	118.77
2	C-CFRP 02			119	241	27.58	S	115.88
3	C-CFRP 03			121	242	30.13	S	124.50
4	T-GFRP 01	Yellow Tuff (Type 2)	G	123	245	30.65	S	124.59
5	T-GFRP 02			120	243	25.80	S	107.50
6	T-GFRP 03			121	241	17.00	S	70.25
7	T-CFRP 01		C	119	244	37.48	S	157.48
8	T-CFRP 02			121	236	38.93	S	160.87
9	T-CFRP 03			120	241	30.25	S	126.04
10	B-CFRP 01	Clay Bricks (Type 2)	C	115	243	62.40	S	271.30
11	B-CFRP 02			116	246	64.48	S	277.93
12	B-CFRP 03			117	245	64.70	S	276.50
13	SB-GFRP 01		G	51	238	31.875	S	312.50
14	SB-GFRP 02			57	238	30.575	S	268.20
15	SB-GFRP 03			57	236	31.15	S	273.25
16	SB-CFRP 01		C	56	237	29.8	S	266.07
17	SB-CFRP 02			55	238	30.3	S	275.46
18	SB-CFRP 03			57	238	33.85	S	296.93
19	L-GFRP 01	Limestone	G	122	246	71.78	M	294.18
20	L-GFRP 02			123	243	68.15	M	277.03
21	L-GFRP 03			123	240	78.35	M	318.50
22	L-CFRP 01		C	120	239	-	-	-
23	L-CFRP 02			121	243	70.63	M	291.86
24	L-CFRP 03			123	240	85.55	M	347.76

Besides the clear quantitative results, Table 4 reports key qualitative information about the observed failure mode. In particular, two main failure modes have been observed:

- the so-called mode "S" is the expected failure mode due to loss of bonding or adhesion between the composite layer and the masonry substrate;
- a mixed failure mode involving both the composite-to-masonry interface and the masonry brick has been observed in some cases (letter "M" in Table 4).

4 ANALYSIS OF THE EXPERIMENTAL RESULTS

The experimental campaign reported in section three is the second stage of a wide programme of pull out tests carried out on FRP strips glued or cast on masonry blocks (Faella et al., 2008). Thus, all the available results are considered in this section with the aim of deriving a design-oriented formula for evaluating the bonding strength of composite strips glued on masonry.

4.1 Overview of the result obtained in a previous campaign

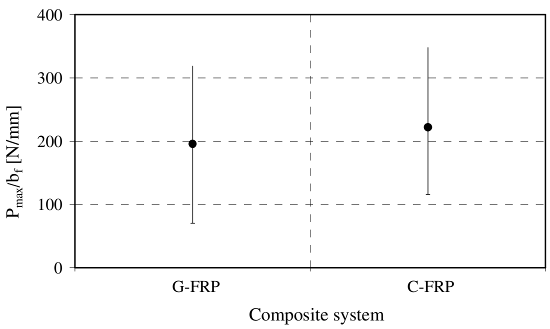
A similar experimental program has been implemented in a previous campaign. In particular, both epoxy- and cement-matrix composites have been consider, but only the former exhibit failure modes of interest for the present investigation (Faella et al., 2008). The following types of masonry have been considered therein for the specimens:

- calcarenite;
- yellow-tuff stone masonry;
- clay brick masonry.

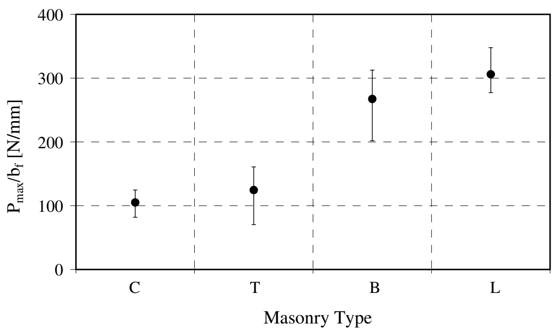
The natural stones considered in the two campaigns (namely, calcarenite and tuff stones) are characterized by slightly different values of the mechanical properties, as they have different origins. A complete overview of both the mechanical properties and the results of the tests can be found in (Faella et al., 2008) and are omitted herein for the sake of brevity.

4.2 Elaboration of the experimental results

A selection of relevant experimental results, taken by both the campaign reported in section 3 and the tests described in Faella et al. (2008), is considered herein for investigating the behaviour of FRP strips bonded to masonry and calibrating a design formula.
In particular, twenty-two out of the twenty-four tests reported in Table 4 are considered in this investigation. The result of test no.22, in which a sliding-shear failure throughout the masonry block has been observed, as well as that of test no.6 are not considered in the following analysis. Moreover, the relevant five experimental results reported in Faella et al. (2008) for epoxy-based specimens failing in debonding are also considered in the following.
Thus, a database collecting a total of twenty-seven experimental results of double-lap-pull-out tests carried out on specimens substantially made out of the materials described in section 2 is considered. Since only epoxy-based composite joints are considered herein, the present paper does not cover also the behaviour of cement-matrix composites cast of masonry (Faella et al, 2010). The mechanical properties of masonry considered in that database vary in a rather wide range, even spanning between almost two orders of magnitude, as reported in Table 1.
Figure 3 represents the values of the ultimate strength-per-unit-width P_{max}/b_f observed in the tests considered in the above mentioned database. In particular, it reports the average values of the parameter P/b_f determined on subsets considering the specimens made-out of the same type of either composite material or FRP strip. Figure 3a shows the average values determined for all the tests on specimens with G- and C-FRP strips. It points out that the average values of the ultimate strength P_{max}/b_f are almost the same for the two kinds of composite materials and in both cases they are affected by a huge scatter which is clearly related to the different behavior of the various masonry blocks. On the contrary, Figure 3b represents the average values determined for the four subsets of specimens characterized by the same masonry. It points out a significant variation of average values of P/b_f obtained for the various types of masonry. Moreover, the scatter around those average values are much smaller that in Figure 3a.



a) depending on the composite system;



b) depending on the type of masonry;

Figure 3. Maximum ultimate strength-per-unit-width observed in the pull-out tests.

On the one hand Figure 3 confirms under the quantitative standpoint the mechanically-based conjecture about the key role played by masonry on the adhesion of composites and, on the other one, points out the limited influence of the properties of composites. However, it is worth to precise that the latter cannot be taken as a general conclusion, as in the present campaign the two composite materials described in the subsection 2.2 are characterized by similar values of the specific axial stiffness $E_f t_f$ (see Table 3) which is the key parameter for evaluating the ultimate strength P_{max} of FRP strips glued on masonry. In particular, the following well-know relationship can be stated between them:

$$P_{\max} = b_f \sqrt{2 G_F E_f t_f} \ , \tag{1}$$

where G_F is the so-called specific fracture energy of the adhesive-to-masonry interface. The relationship in (1) can be applied to FRP strips whose bonded length is longer than the so-called “transfer length” (Täljsten, 1997). Since the specimens collected in the present database comply with this requirement, the experimental value $G_{F,i}^{exp}$ can be evaluated for the i-th specimen by simply inverting equation (1).

4.3 Assessment of the available formulations for fracture energy

The values of $G_{F,i}^{exp}$ can be firstly utilized in assessing the available theoretical formulations for evaluating specific fracture energy for FRP strips bonded on masonry blocks. In the authors' knowledge, no well-established formula is currently available for determining G_F looking after the huge variety of the mechanical properties of masonry. One of the most recent and general formulations has been proposed by the Italian Guidelines for Strengthening of concrete and masonry structures (CNR-DT 200, 2004). It defines the characteristic value G_{Fk} of fracture energy G_F (namely, the 5% percentile of its probability distribution) as follows:

$$G_{Fk} = c_1 \cdot \sqrt{f_{mk} \cdot f_{mtm}} \ , \tag{2}$$

in which the constant value c_1=0.015 is proposed for the every kind of masonry substrate whose influence is described through the compressive and tensile strength devoted by the symbols f_{mk} and f_{mtm}. They are considered as characteristic and median values, respectively.
Figure 4 compares the average experimental values of fracture energy obtained for the various masonry specimens with the corresponding theoretical predictions obtained through eq. (2). According to the suggestions of the mentioned Guidelines, the mechanical properties of masonry relevant for applying eq. (2) have been assumed equal to the corresponding ones determined on the masonry elements and reported in Table 1 and Table 2.

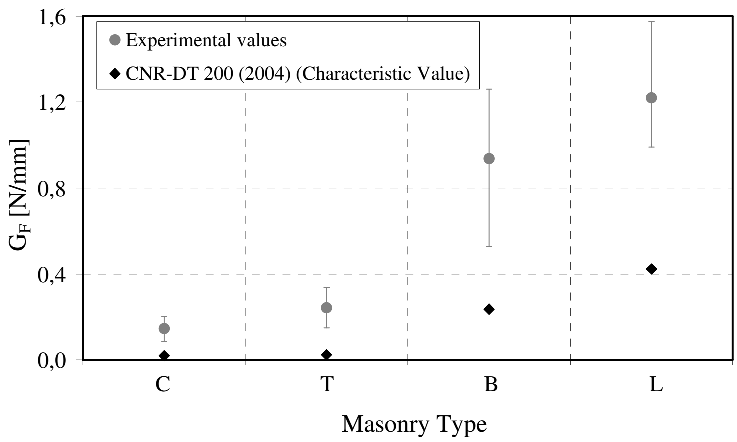


Figure 4. Experimental values and a possible theoretical prediction of fracture energy.

Although the relation in eq. (2) has been applied by considering the average values for both the compressive and the tensile strength of masonry, the theoretical prediction is significantly lower than the corresponding experimental results. As a matter of principle, since G_{Fk} is defined in (2) as a 5% percentile, this theoretical prediction should be lower than the average value observed in the tests, but the Figure 4 show that it is even much lower than the minimum values obtained for $G_{F,i}^{exp}$ in pull-out tests for every kind of masonry.

4.4 Calibration of a design-oriented formulation

An alternative formulation is proposed in this section for evaluating the fracture energy in FRP-to-masonry interfaces covering the wide range of mechanical properties of masonry reported in the database mentioned in subsection 4.2. Since the values of the tensile strength f_{mt} are not generally available in common applications and simplified correlations are generally accepted between the compressive strength f_m and f_{mt}, only the former one will be considered in the following study as a relevant parameter for masonry. In particular, the following relationship is considered between G_F and the compressive strength f_m:

$$G_F\left(f_m;a,b\right)=a\cdot\frac{f_m}{f_m+b}, \tag{3}$$

where the two constants a and b should be basically calibrated through the least-square procedure described by the following expression:

$$\left(\bar{a},\bar{b}\right)=\underset{(a,b)}{\operatorname{argmin}}\sum_{i=1}^{n_s}\left[G_{F,i}^{\ \exp}-G_F\left(f_{m,i};a,b\right)\right]^2. \tag{4}$$

Besides their numerical values, the two constants $\bar{a}$ and $\bar{b}$ have also a rather clear mechanical meaning. In particular, constant $\bar{a}$ can be regarded as a reference value for fracture energy and $\bar{b}$ is dimensionally a stress quantity. Considering all the results in Table 4 in the least-square procedure described by (4), the values $\bar{a}$=1.623 and $\bar{b}$=20.323 can be evaluated. Figure 5 shows the comparison between the values of G_F derived by the experimental observations and the curve described by eq. (4), with the optimal values of the constants a and b. It points out the significant enhancement of the analytical prediction, especially in the cases of low values of the compressive strength $f_{b,m}$ of masonry.

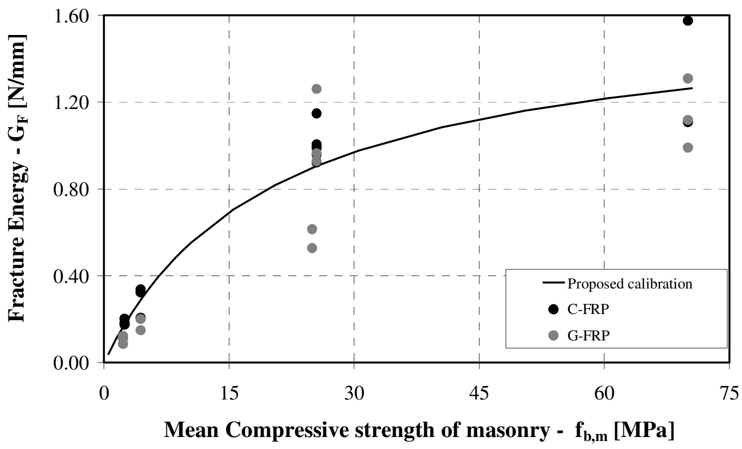


Figure 5. Fracture energy G_F vs. mean compressive strength of masonry: proposed rational relationship

Finally, a further information about the experimental data deals with the distribution of the experimental-to-theoretical ratio $\delta=G_F/G_F\left(f_m;\bar{a},\bar{b}\right)$. It can be reasonably approximated by a normal distribution with a median value close to the unity and a standard deviation 0.267. This information is needed for defining through well-established statistical procedures (EN 1990, 1990) the value of the safety factors to be considered in the framework of a design code.

5 CONCLUSIONS

The results of a wide experimental campaign carried out on specimens made out of four types of composite systems glued on several kinds of masonry supports have been reported. Those results have been collected in a reasonably wide experimental database along with other results of tests carried out previously by the authors on similar specimens. A total of 27 experimental tests have been utilized for calibrating a general design formula for predicting adhesion strength of composites on masonry, mainly depending on the key mechanical properties of the latter.
The following conclusions can be drawn out by analysing the experimental results:

– the value of fracture energy G_F is deeply influenced by the nature of masonry and composite;
– as expected, the strongest the masonry the greater the value of the specific fracture energy G_F of the interface;
– a less-than-linear relationship can be stated between the mean compressive strength of masonry $f_{b,m}$ and the inherent value of G_F.

Finally, it is worth noting that the proposed calibration for evaluating fracture energy G_F in composite-to-masonry interfaces ought to be intended as a preliminary proposal whose accuracy could be enhanced by considering a larger set of experimental results, possibly deriving from tests on specimens made out of a wider variety of both masonry and composite materials.

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