

# CFRP sheets bonded to natural stone: interfacial phenomena

M. Accardi<sup>1</sup>, L. La Mendola<sup>1</sup> & G. Zingone<sup>2</sup>

<sup>1</sup>*Dipartimento di Ingegneria Strutturale e Geotecnica, Università di Palermo, Italy*

<sup>2</sup>*CE.P.I.S. – Centro di Prevenzione e Istruzione Sismica, Dipartimento di Ingegneria Strutturale e Geotecnica, Università di Palermo, Italy*

## Abstract

The effectiveness of the reinforcing technique consisting of fiber reinforced polymer sheets bonded to the structural elements depends on a good connection at the joint. This has to be able to ensure the transfer length of the shear stress in order to avoid a premature failure due to debonding. In this paper, the bond phenomenon at the interface is examined with reference to the calcarenite stone and carbon fiber reinforced polymer (CFRP) sheets in order to evaluate the possibility of utilizing this technique on masonry structural members, consisting of calcarenite ashlar and mortar. An experimental investigation is carried out on nine specimens obtained by applying unidirectional CFRP sheets to calcarenite squared-stone by using epoxy resin layers. All specimens were submitted to tensile force until the failure of the bond joint took place. Results allow us to deduce the local bond stress versus slip relationship, which is an important step toward understanding bond behavior at the joint interface.

*Keywords: calcarenite stone, composite laminate, bond length, interfacial phenomenon, load transfer.*

## 1 Introduction

Many masonry buildings constituting artistic and architectural heritage often need retrofit or strengthening interventions, and the use of the technique of FRP laminates glued with epoxy resin appears adequate because of the lightness, the easiness of the application, and the possibility of removal. This reinforcing technique has been a topic of studies over the past ten years but the papers



present in the literature refer above all to reinforced concrete structural members [1-6].

The effectiveness of this technique depends on the anchorage between concrete and FRP laminate and for this reason theoretical and experimental researches have been undertaken recently to understand the bond behaviour of the joint and several mechanisms of bond failure in structural members with external FRP reinforcement, as debonding, delamination and peeling have been identified. The problem is analysed by Wu, Yuan and Niu [7] who, with reference to different kinds of adhesive joints and by assuming two different simplified models for the local bond stress-slip, derive analytically the expressions for the maximum transferable load, interfacial shear stress distribution and initiation and propagation of the interfacial cracks.

The purpose of this study is to investigate a similar application of the external composite reinforcement to the masonry structural members. Only a small number of contributions present in the literature consider this possibility [8, 9]. The masonry type considered in this study, also the object of experimental tests carried out by the authors in a previous paper [9], is composed of calcarenite ashlar and mortar, commonly used in the Mediterranean area.

This paper contains preliminary experimental investigations on the joint connection between calcarenite stone and CFRP. In particular, tensile tests have been performed and a data acquisition system has been utilized at each load step to record the slip at the section on which the load is applied and the strain distributions along the bonded length from which it has been possible to deduce the local bond stress-slip curve.

## 2 Experimental programme

In order to carry out double-lap shear tests, nine specimens were prepared. CFRP sheets impregnated with epoxy resin were bonded to the calcarenite surface for a bond length sufficient to understand the phenomenon of the stress transfer.

### 2.1 Specimens

The specimens realizing pull-pull double-lap joints were composed of calcarenite ashlar on which CFRP sheets were bonded in accordance with the scheme shown in fig. 1.

Specimens were obtained by two prisms of calcarenite connected only through the FRP laminate; CFRP sheets, of 50 mm width, were glued on two opposite sides and wrapped in one of the two prisms of the specimen; the bond length was 150 mm. At the ends of the specimen two steel plates with welded steel rods were glued in order to allow the gearing of the specimen.

Figure 2 shows a photo of the specimens and the details of bonded side.



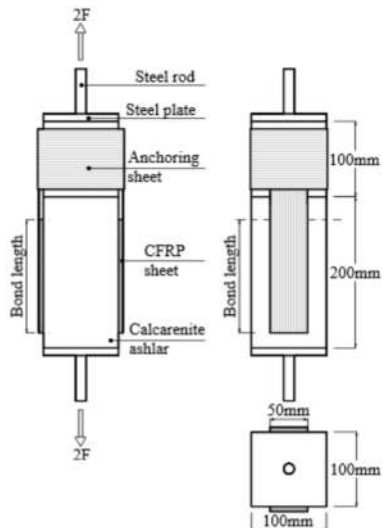


Figure 1: Sketch of the specimen.

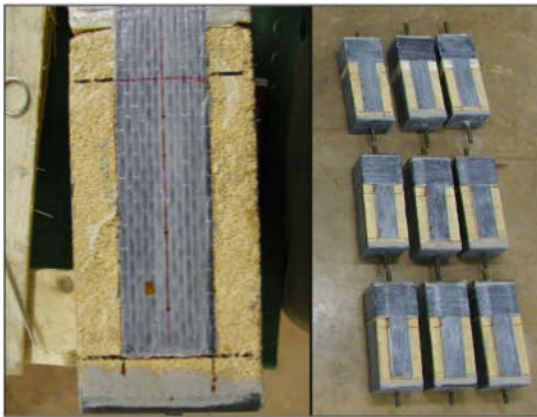


Figure 2: Bond test specimens.

The FRP system used in this research consists of two epoxy resin layers and a unidirectional carbon fiber sheet interlayer. The carbon fiber has a thickness of 0.13 mm, a modulus of elasticity of 230 GPa, and an ultimate tensile strength of 3500 MPa; the epoxy resin was Sikadur 330 and the thickness realized was 0.8 mm. The prisms of calcarenite stone utilized were extracted by ashlar from local quarries in the Mediterranean area and also utilized in previous research carried out by the authors [9]. Before the gluing, the calcarenite surface was cleaned by air blasting and then all loose particles were removed using a vacuum cleaner.



Preliminarily, in order to know the mechanical properties of the calcarenite stone, compressive tests on cubical specimens of 90 mm size and three point bending tests on beams with cross-section  $70 \times 90 \text{ mm}^2$  and length 360 mm were carried out. The size of the specimens was chosen in relation to the dimensions of the ashlar. The results obtained as the mean values of three tests are  $f_c = 3.17 \text{ MPa}$  and  $f_t = 0.15 \text{ MPa}$  respectively.

## 2.2 Test set-up

Testing was performed by using an electromechanical universal testing machine with maximum capacity equal to 600 kN. The test apparatus with the specimen is shown in fig. 3. Tests were carried out employing a displacement rate of 0.5 mm/min.



Figure 3: Test set-up.

Total slip between calcarenite and CFRP was measured using linear variable displacement transducers (LVDTs) placed in the sections in which the load  $F$  was applied. Ten strain-gauges placed on the laminate, five on each side in the bond length, allowed us to obtain the strain distributions. In the first specimen the strain-gauges were placed as shown in fig. 4; because of the difficulty connected to placement in the initial section both the LVDT and the strain-gauge, the latter was applied 20 mm before (see results presented in the next section).



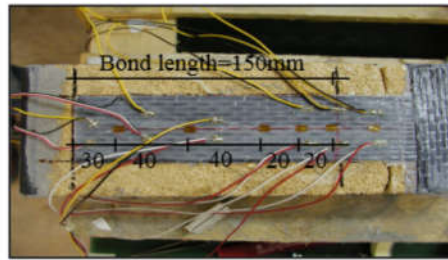


Figure 4: Strain-gauges position on laminate in specimen 1.

All specimens were submitted to tensile force until total failure of bond system took place.

### 3 Results

In Table 1, maximum loads at failure obtained in the tensile tests are shown together with the compressive strength and indirect tensile strength obtained in tests on specimens extracted from the relative ashlar.

Table 1: Test results.

Specimen	Ultimate tensile load $2F_{\max}$ (kN)	Calcarenite compressive strength $f_c$ (MPa)	Calcarenite indirect tensile strength $f_t$ (MPa)
1	10.08	3.73	0.16
2	7.84	2.33	0.11
3	9.32	2.17	0.14
4	8.55	2.87	0.13
5	9.46	4.13	0.20
6	9.66	4.37	0.22
7	7.78	3.50	0.15
8	8.01	3.53	0.16
9	8.40	2.92	0.15

In the following, for the sake of brevity, details of the experimental results are presented only for tests 1, 2 and 3. In fig. 5, load-slip curves are shown: the  $F$  load is half the load transmitted by the machine and the slip  $\delta$  is measured by the



LVDT at the initial section on the side in which the failure occurs. The curves show an initial linear branch followed by a nonlinear branch up to failure. The failure occurs in a progressive way because the effective bond length (region in which the loading transfer occurs) shifts until complete debonding takes place. In fig. 6, a specimen after the failure is shown: it can be observed that the debonding process involves a thin layer of calcarenite stone.

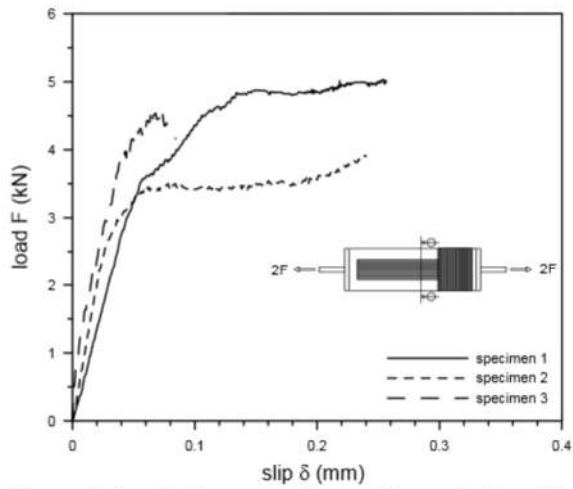


Figure 5: Load-slip curves for specimens 1, 2 and 3.

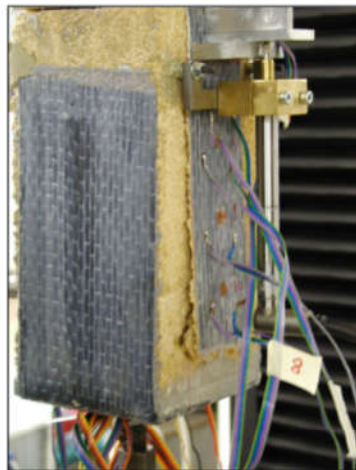


Figure 6: Typical failure mode.



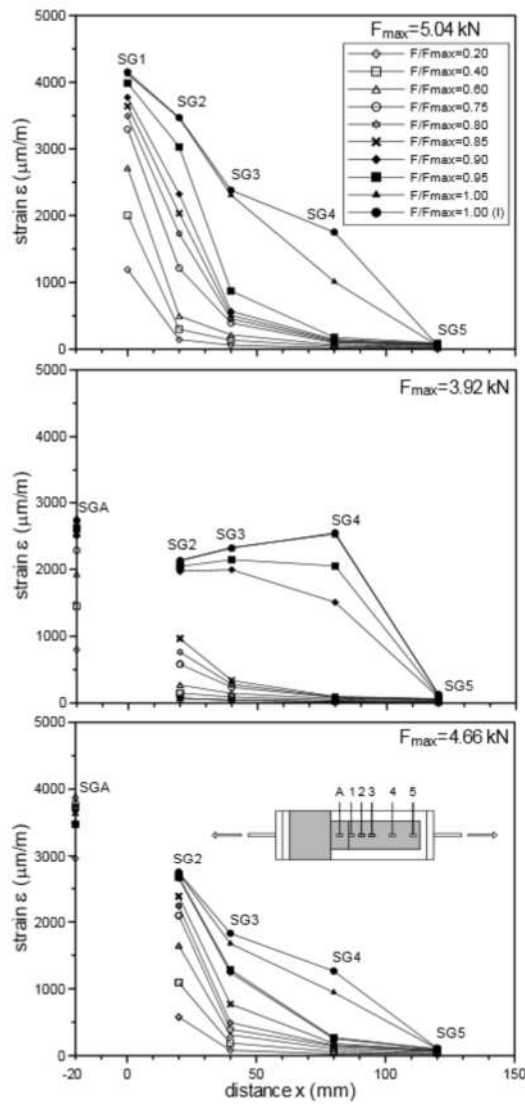


Figure 7: Strain distributions along the joint.

### 3.1 Strain distributions

In fig. 7, only some strain-gauge readings for tests 1, 2 and 3 are shown. Each curve is plotted for a given load level. The strain-gauges labelled SG1, SG2, SG3, SG4 and SG5 are located as shown in fig. 4, and the strain values shown in the graphs are relative to the side on which the debonding occurs. SGA is located 20 mm before the initial section of the bonded length. The trend of the strain

distribution is analogous to that recorded by similar experimental tests carried out on concrete [3, 5]. At early load levels the strain distributions decrease exponentially and the readings of the SG4 are not significant.

The strain distribution profiles allow us to observe that the initial transfer length, defined as the distance from the loaded end of the joint to the point where the exponential strain-profiles reach zero strain, is between 40 and 80 mm. For higher load levels the trend changes because the crack starts and the transfer region extends to strain-gauge SG5; in the curves  $F-\delta$  shown in fig. 5 this stage corresponds to the start of the nonlinear branch.

### 3.2 Local bond stress-slip curve

The local bond stress-slip curves relative to the mean points between two strain-gauges are obtained from the experimental data on the basis of the following assumptions: the package CFRP-epoxy resin is linear elastic; the calcarenite strain is negligible if compared to that of CFRP. For a fixed load-level a point of the curve is obtained. The slip in the abscissa is calculated as the area subtended by the strain profile between the section with zero strain and the section in which  $\tau$ -s curve is deduced. The average bond stress is calculated by dividing the difference of tensile force between two consecutive strain-gauges by the surface area of laminate. In order to obtain the tensile force in the section in which a strain-gauge is placed, the modulus of elasticity is calculated by applying the rule of mixture [10].

In fig. 8, the curves obtained from the strain measured in specimen 1 are shown; these refer to the points located at distances of  $x=10, 30, 60, 100$  mm respectively from the section in which the load is applied.

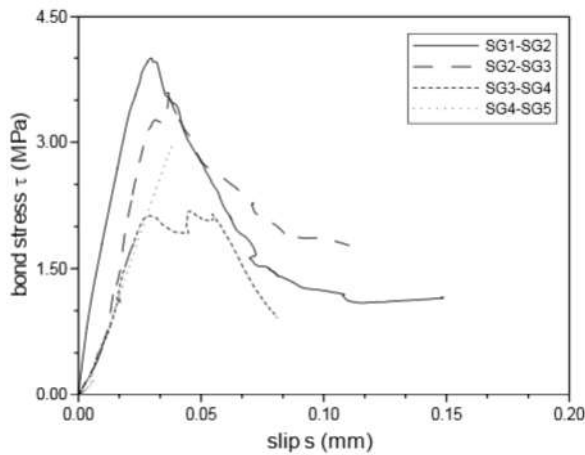


Figure 8: Local bond stress-slip curves in specimen 1.

It can be observed that the complete curve, relative at the point in which higher slip values are involved, presents the following characteristics: an





ascending branch that is linear as long as the bond resistance is created by adhesion; further loading mobilises the mechanical interlocking between the irregular particles of calcarenite and a nonlinear trend is observed up the maximum bond stress value; a descending branch appears when the cracking process in the calcarenite stone starts. The four curves have the same trend, even if the curve corresponding to the mean point between SG3 and SG4 ( $x=100$  mm) deviates from this trend before reaching the maximum value; this circumstance is due to the presence in this section of significant irregularities in the calcarenite stone consisting of fossil shells.

In fig. 9 the curves obtained at  $x=30$  mm (between SG2 and SG3) for the three tests are presented. The comparison highlights the same trend, but a different maximum value of bond stress; the latter, correlated with the calcarenite strength, is the main parameter that governs the debonding process.

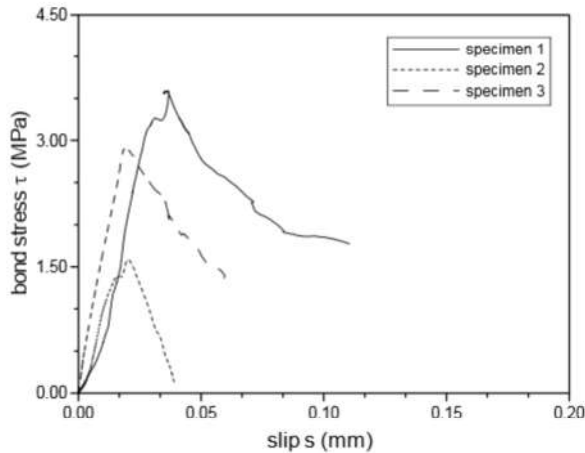


Figure 9: Comparison between the local bond stress-slip curves.

#### 4 Conclusions

The experimental study presented here allows us to express the following considerations relative to the interface behavior:

- the strain distributions recorded at each load step allow us to identify the threshold beyond which the cracking process starts;
- the bond stress-slip curves that have been deduced by the strain-gauge readings at each load step, have the same slope in the ascending branch, and the same slope in the descending branch, with maximum bond stress value correlated with the calcarenite strength.



## Acknowledgement

The authors are grateful to GEOPROGETTI Laboratory (Agrigento, Italy) for performing experimental tests.

## References

- [1] Täljsten, B., Strengthening of concrete prisms using the plate-bombing technique. *Int. Journal of Fracture*, **82**, pp. 253-266, 1996.
- [2] Täljsten, B., Defining anchor lengths of steel and CFRP plates bonded to concrete. *Int. Journal Adhesion and Adhesives*, **17(4)**, pp. 319-327, 1997.
- [3] Bizindavyi, L. & Neale, K.W., Transfer lengths and bond strengths for composites bonded to concrete. *Journal of Composites for Construction*, **3(4)**, pp. 153-160, 1999.
- [4] Tripi, J.M., Bakis C.E., Boothby, T.E. & Nanni, A., Deformation in concrete with external CFRP sheet reinforcement. *Journal of Composites for Construction*, **4(2)**, pp. 85-94, 2000.
- [5] De Lorenzis, L., Miller, B. & Nanni, A., Bond of fiber-reinforced polymer laminates to concrete. *ACI Materials Journal*, **98(3)**, pp. 256-264, 2001.
- [6] Nakaba, K., Kanakubo, T., Furuta T. & Yoshizawa, H., Bond behavior between fiber-reinforced polymer laminates and concrete. *ACI Structural Journal*, **98(3)**, pp. 359-367, 2001.
- [7] Wu, Z., Yuan H. & Niu, H., Stress transfer and fracture propagation in different kinds of adhesive joints. *Journal of Engineering Mechanics*, **128(5)**, pp. 562-573, 2002.
- [8] Kurtis, K.E. & Dharan, C.K.H., Composite fibers for external reinforcement of natural stone. *Journal of Composites for Construction*, **1(3)**, pp. 116-119, 1997.
- [9] Campione, G., Cucchiara, C., La Mendola, L. & Zingone, G., Interfacial phenomena in masonry members reinforced with FRP, *Proc. of the 12<sup>th</sup> European Conf. On Earthquake Engineering*, Barbican Centre, London, UK, Elsevier, paper reference 609, 2002.
- [10] FIB, CEB-FIP. Externally bonded FRP reinforcement for RC structures. *Technical report on the Design and use of externally bonded fibre reinforced polymer reinforcement (FRP EBR) for reinforced concrete structures*, Task Group 9.3 FRP, bollettin 14, July 2001.

