EXPERIMENTAL INVESTIGATION ON DELAMINATION PHENOMENA BETWEEN FIBER REINFORCED PLASTIC (FRP) AND MASONRY

L. La Mendola[1], G. Campione[1], C. Mascari[2], G. Zingone[1]

ABSTRACT

In the present investigation the bond phenomena between fiber reinforced plastic (FRP), glued with epoxy resin, and calcarenite stone blocks were analyzed. The knowledge of the interfacial behavior between structural members and reinforcing materials is required to estimate the effectiveness of reinforcing techniques, which today are very often utilized. The choice of calcarenite stone is related to the fact that this kind of stone is currently utilized for the construction of masonry structures of historical and monumental interest constituting the monumental heritage. The experimental investigation was planned to study the delamination phenomena of unidirectional FRP materials from masonry structures made of calcarenite ashlars and it aimed in the first phase of the research to obtain the full load-slippage curves and to observe the mode of failure at the interface. Preliminarily, compressive and indirect tensile tests on specimens taken out of the calcarenite ashlars were carried out. Bonding tests were also carried out using an open-loop displacement control testing machine and recording the complete load-slippage curves up to failure. Finally, the maximum load was evaluated analytically and it was correlated to the tensile strength of the calcarenite stone and the main parameters governing the behavior at the interface were identified.

Key words: experimental investigation, calcarenite ashlar, fiber reinforced plastic, delamination, interfacial phenomenon, retrofitting

[1] Dipartimento di Ingegneria Strutturale e Geotecnica, Università di Palermo, Viale delle Scienze, I90128 Palermo (Italy); email: campione@stru.diseg.unipa.it
[2] Via Inveges 23, Palermo (Italy); email:claudiomascari@inwind.it

INTRODUCTION

Reinforcing techniques for strengthening or retrofitting of structures, using steel plate or fiber reinforcing plastic (FPR) glued to structural members, are the object of several studies presented in the literature. Some of these researches aim to study the delamination (or peeling) phenomena affecting reinforced concrete beams strengthened with steel plate or FRP materials with the objective of increasing the flexural bearing capacity and modifying the mode of failure from brittle to ductile (Oehlers and Moran 1990, Biraba et al. 1994, Zhang et al. 1995).

Recently, the attention in research has prevalently been on the use of FRP plates for reinforcing beams in shear and in flexure (Arduini et al. 1997, Leung et al. 2000). This technique is not invasive because the reinforcing element is removable, and moreover it allows one to avoid the disadvantages involved in using steel plate related to the high dead-load, to the difficulty in placing in cast and to the poor durability connected especially to the corrosion of steel.

One of the most important aspects to take into account in utilizing steel plate or composite materials for strengthening of structural members is the above mentioned delamination problem. It consists, if it occurs, in a brittle failure at the interface between structural members and strengthening materials, affecting the fiber, the adhesive layer and a very thin layer of reinforced material.

These phenomena, and more in general the problems related to the reinforcing techniques, have been widely discussed in the last decades, but only in the last few years has the attention been addressed to on the use of these materials in masonry structures, often representing a monumental and historical heritage to preserve (Antinucci 2000, Cosenza et al. 2000).
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In this context the present investigation refers to the study of the detachment phenomenon between carbon fiber reinforced plastic (CFRP) and calcarenite ashlars, calcarenite being the most common stone utilized for the construction of masonry structures in the Mediterranean area.

The study was carried out through an experimental investigation on stone specimens reinforced with CFRP wraps, glued on the surface of the stone previously treated with the support material necessary to regularize the surface. Tensile tests were carried out, changing the anchorage length of the CFRP wraps, and for each load step the corresponding displacement was recorded in order to obtain the entire load-deformation curves up to the complete detachment of FRP due to delamination failure. Finally, through simple equilibrium considerations, and assuming a known stress distribution at the interface (Oehlers and Moran 1990), the maximum load corresponding to the delamination failure was determined.

REVIEW OF TESTS AVAILABLE IN LITERATURE

Experimental investigations aiming at the mechanical characterization of the local bond relationship (load-slippage curves) between reinforcing materials (steel plate or FRP composites) and reinforced materials (cementitious materials, stone, steel, etc.) can be grouped into two categories: - direct bonding tests; - indirect bonding tests using flexure tests on beams. In both cases for each load step (or for each displacement step, if the test is carried out in displacement control mode) the slippage of reinforcing material from the support (concrete, stone, etc.) is recorded by means of displacement transducers. Also, if a high speed electronic data acquisition system is available and strain gauges are placed on the composite material, it is possible to record deformation on the strengthening materials, giving useful information on the interfacial phenomena.

Figure 1 shows the scheme recently utilized by Leung et al. (2000) in an indirect flexure test on reinforced concrete beams strengthened with steel plate.

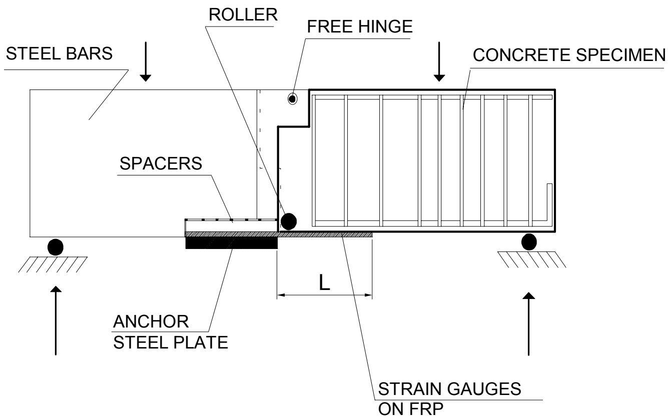

Figure 1. Bonding test by means of flexure on R.C. beams reinforced with steel plate

In this test, steel plate was fixed on one side of the beam with steel devices and glued on the other side to the bottom of the beams. The beams were loaded in flexure and the load-slippage curves of FRP plates with the variation in anchorage length L were recorded. In the meantime, for each load step, local deformations were recorded through strain gauges glued on the steel plate.

Also of particular interest, in the field of strengthening of reinforced concrete members with FRP wraps, are direct tensile tests. An example of this kind of test is that carried out by Pecce et al. (2000), the test set-up of which is shown in Fig. 2.

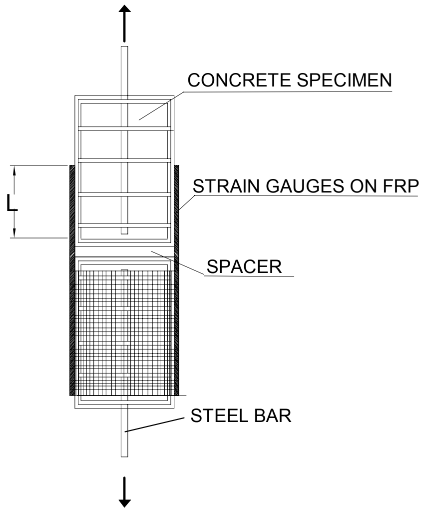

Figure 2. Direct bonding tests

In both the above mentioned tests it was observed that delamination effects often govern the entire bonding behavior at the interface and in particular that: - the mode of failure is characterized by detaching of a thin layer of concrete connected to the fiber at the interface; - cracking of concrete determines a nonlinear behavior at the interface characterized by a loss of stiffness with increases in the external load; - bonding and detaching phenomena depend on the mechanical characteristics of the glue and the reinforcing material and on the tensile strength of the concrete. A further consideration regards the possibility of defining a transfer length of stresses beyond which the ultimate load is constant and any further bonding length is ineffective.

Recent studies have shown that bonding tests currently utilized in the case of strengthened reinforced concrete structures can also be extended to the case of masonry. For instance, in Fig. 3 the test set-up recently arranged by Antinucci (2000) is shown. It allows one to study bonding on brick masonry strengthened with FRP composites by using flexure tests in the presence of axial forces.

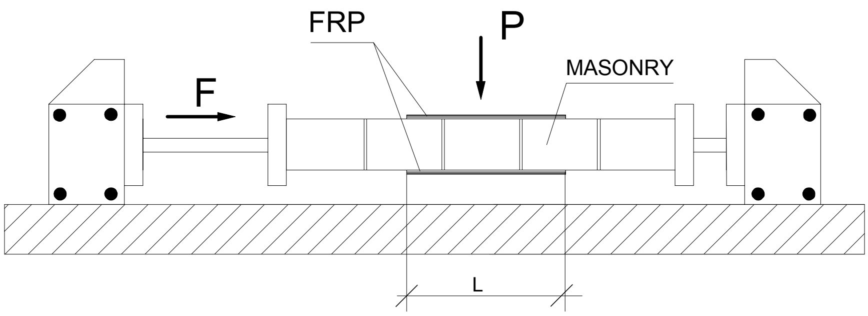

Figure 3. Bonding tests on masonry elements

In the case of masonry structures reinforced with FRP materials, experimental results confirm that failure at interface between FRP and masonry is often governed by delamination of the composite at the interface due to the poor tensile strength of the masonry. From these studies it also emerges that by using an adequate retrofitting technique it is possible to avoid delamination failure, making it possible to exploit the full tensile strength of FRP. However, although all available FRP materials have considerably better mechanical properties with respect to those of stone materials, since the interface behavior is strongly affected by the weakest component, that is the stone, it is probably not advantages to utilize FRP materials with high properties (high strength, high initial modulus of elasticity) in masonry structures if adequate bonding techniques are not adopted.

EXPERIMENTAL INVESTIGATION

In the present section we report on the experimental investigation carried out to characterize material behavior, particularly referring to compressive and indirect tensile tests on masonry and to bonding tests on FRP glued to calcarenite ashlars.

Mechanical properties of constituent materials

To characterize the compressive behavior of calacarenite stone, compressive tests were carried out on cylindrical specimens having diameter 100 mm and length 100 mm and on cubic specimens with a side of 150 mm. All specimens were extracted from blocks of the same material measuring 210 x 160 x 360 mm and coming form local sources in the Mediteranean area.

To perform compressive tests and to record the complete load-deformation curves an open-loop displacement control testing machine was utilized. A load cell of 60 t bearing capacity was utilized to record loads. A slow rate of displacements (0.2 mm / min) was utilized to ensure a quasi-static test.

To record deformations three LVDT's, with a gauge length equal to the entire length of the specimens and placed at an angle of 120° to one another in plan, were utilized. A spherical joint at the head-cross of the testing machine allows one to adjust the end portions of the specimens during the test. All tests were carried out in the presence of shear friction between the specimens and the steel plates of the testing machine.

Fig. 4 shows the stress-strain curves of cylindrical specimens tested in compression.

From the shapes of the curves it emerges that there is a scattering of data both in terms of maximum strength and of initial tangent modulus of elasticity.

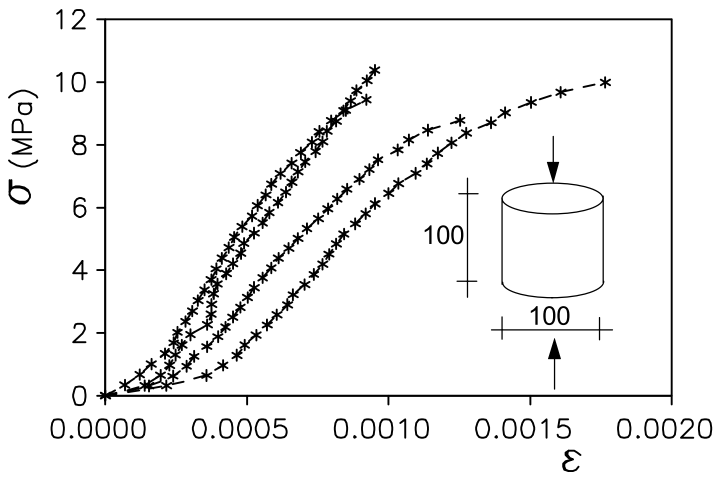

Figure 4. Results of compressive tests on cylindrical specimens

With reference to the compressive tests on cube specimens the results are given in Table 1. For the indirect tensile tests (split tension and flexural tests) load-displacement control tests were also performed utilizing the same testing machine as for compressive tests. A slow rate of displacement (0.2 mm / min) was adopted.

To ensure that splitting tests were carried out correctly, that is applying the load reducing the loaded area to a diametrical plane, a small steel bar measuring 10 x 10 x 200 mm was interposed between testing machine and specimens.

Flexure tests were carried out on prismatic specimens measuring 100 x 100 x 350 mm and adopting a three-point bending test.

Table 1 gives the most significant results of the compressive and indirect tensile tests. R_c is the compressive strength measured on cubes and ε_0 the corresponding strain, E_t is the initial tangent modulus, f_t' the splitting tensile strength and MOR is the modulus of rupture obtained by means of flexure tests.

Table 1. Strength and strain values of tests on calcarenite stone

Specimens	Compression on cube with 150 mm side			Indirect tension	
N°	R_c (MPa)	ε_0	E_t (MPa)	f_t' (MPa)	MOR (MPa)
1	6.97	0.0010267	12868	1.344	3.67
2	6.58	0.0009689	6276	0.977	3.48
3	3.41	0.0014144	3448	/	/
4	4.56	0.0013438	4576	0.660	2.75
5	3.55	0.0011170	3828	/	/
6	4.14	0.0013265	4144	/	/

The experimental results of the tension tests are scattered around average values, as observed in the compressive tests, and for this reason it is very difficult to establish a correlation between compressive and tensile strength values, as instead it is generally possible to do for concrete.

Figure 5 shows the failure mode of specimens in split tension tests, pointing out the very brittle nature of the materials tested, characterized by a clear failure plane across the loaded diametrical plane.

Figure 5. Cylindrical specimens after split tension failure

To characterize the behavior of the mortar utilized to assemble the calcarenite stone in masonry, compressive tests were performed on cubes having 100 mm side and flexure tests on 40 x 40 x 160 mm beams. The mortar was constituted by the following components: one part by volume of normal strength Portland cement Type 325, one part by volume of hydratic lime and five parts by volume of limestone sand. The compressive tests gave average values in strength of 3.41 MPa, and modulus of elasticity 950 MPa; instead, the flexure tests gave a maximum average modulus of rupture of 3.43 MPa.

Extra-small masonry wall specimens measuring 750 x 215 x 900 mm and constituted by subassemblages of two rows of calcarenite stone put together with mortar were tested in compression and they gave strength values between those of the constituent materials.

The geometrical and mechanical characteristics of the reinforcing fibers constituted by carbon unidirectional one-layer wrap were: weight density 1820 kg/m^3, width 500 mm, equivalent thickness 0.165 mm, modulus of elasticity in tension 230000 MPa, tensile strength 3430 MPa and ultimate strain 1.5%. Tests carried out on the carbon fiber wrap by the manufacturer has shown an elastic-brittle behavior until the maximum strain in tension was reached.

Bonding tests

Bonding tests were carried out by submitting to direct tension the above mentioned fiber wrap glued to calcarenite blocks measuring 320 x 160 x 100 mm. Each specimen was inserted in a stiff steel box fixed to the bottom of the testing machine that was the same as for the previous tests. The free end portion of the fiber, glued on one side of the calcarenite block, was fixed on the other side in a special grip of the testing machine and was submitted to tensile forces. Tensile stresses in the glued portion of fibers were induced by the reciprocal action between the calcarenite elements and the top part of the steel box as shown in Fig. 6.

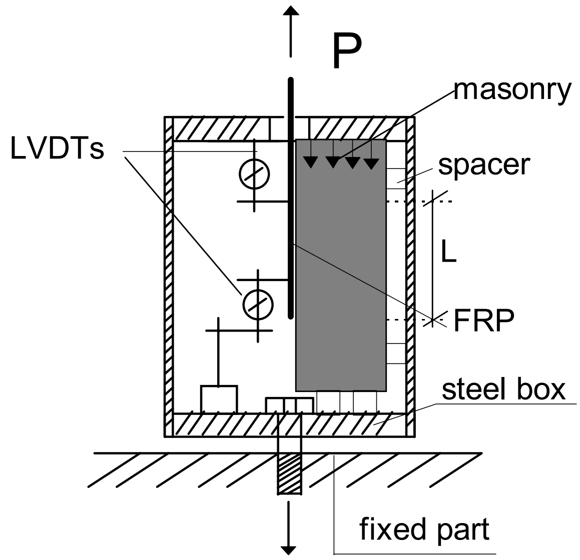

Figure 6. Scheme of test set-up for direct bonding test

Fibers were glued to calcarenite blocks on one side of the specimens with different anchorage lengths, 100, 150 and 250 mm, and ensuring that the end portion of the fiber was not in contact with the calcarenire stone. This was done to make sure that local compressive forces arising between calcarenite specimens and steel box could not produce confining pressures, introducing erroneous results in bonding tests. During the tests the calcarenite specimens were well fixed to the steel boxes, also avoiding rotations of specimens during the tests, which can cause disalignment of the external load with respect to the fiber axis. The test set-up utilized allows one to record continuously the external load P applied to the fiber wrap by using a load cell and also to record the slippage s of fibers by using two digital displacement transducers placed as shown in Figs. 6 and 7. This instrumentation allows one to measure slippage of fibers purged of elastic deformation effects.

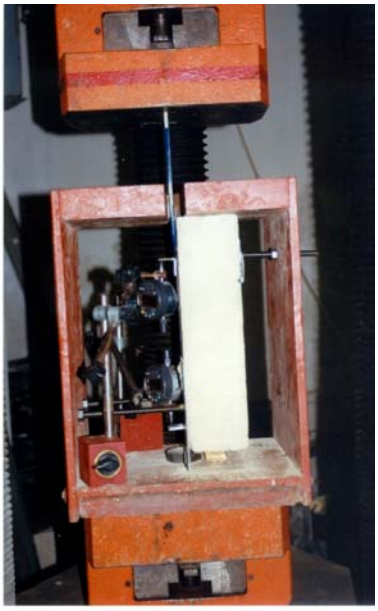

Figure 7. Test set-up for direct bonding test

Figure 8 gives the load-slippage curves for the cases examined. The results show that the behavior at the interface is characterized by the following steps: elastic behavior in which a perfect bond exhists between fibers and calcarenite; nonlinear behavior in which a progressive rupture at the interface occurs with loss of stiffness and increase in load and corresponding slippage; failure condition correspsonding to the maximum load (lower than the maximum tensile strength of the fiber) in which a sudden loss of bearing cacacity and a complete detachment of fibers together with a thin layer of calcarenite stone occurs.

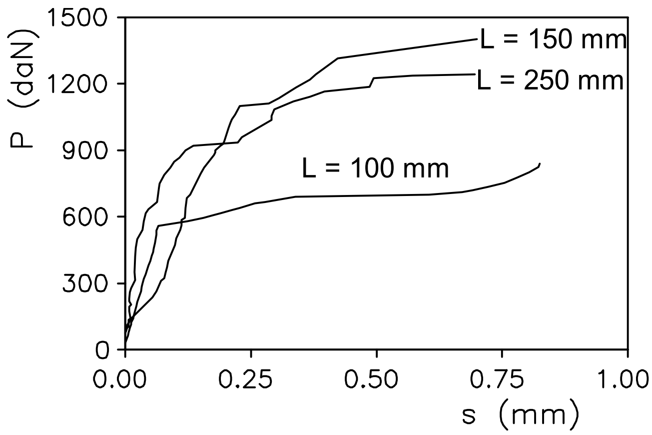

Figure 8. Results of bonding tests

Table 2 gives the maximum load values P_d and displacements s_d corresponding to the delamination phase. In the same table the average shear stresses τ_m measured with reference to the assumed anchorage length L are also given.

Table 2. Strength and deformation values of bonding tests

Specimens n°	L (mm)	P_d (daN)	s_d (mm)	τ_m (MPa)
1	100	840	0.825	1.40
2	150	1314	0.695	0.62
3	250	1245	0.423	1.46

Figures 9 and 10 shown the failure mode of the specimens tested consisting, as already mentioned, in detachments of the reinforcing layer from the calcarentite stone. A comparison of results related to different anchorage lengths shows that the maximum load P_d does not increase with an increase in L. It is reasonable to believe that there exists a critical length beyond which the corresponding load remains constant, and a further anchorage length will be ineffective.

Figure 9. Failure mode

ANALYTICAL EVALUATION OF DELAMINATION LOAD

The axial force applied to the FRP wrap is transmitted to the adhesive layer and to the support layer of the masonry (applied on the masonry to regularize it before attaching FRP) with shear and perpendicular stress distributions, the latter normal to the fiber axis. If the principal stresses locally exceed the tensile strength of the reinforced material (which is generally the weakest component) brittle and sudden failure occurs at the interface, as shown in Fig. 10, because the very brittle nature of masonry materials with unstable propagation of fracture and delamination of FRP with a thin layer of calcarenite stone renders reinforcement ineffective.

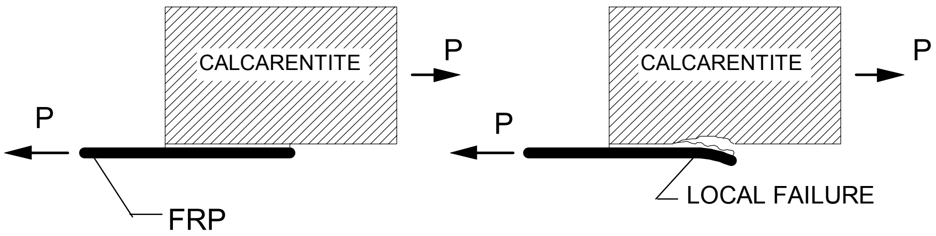

Figure 10. Detachment phenomena at the interface

The above mentioned delamination phenomenon is extremely dangerous because, if it occurs, it is independent of the anchorage length of FRP and it is characterized by a very brittle mode of failure. It is interesting to observe that the delamination phenomenon is triggered by the stresses perpendicular to the fiber having the distribution shown in Fig. 11 with a reduced extinction zone with respect to the entire anchorage length. According to Oehlers and Moran (1990) this length can be assumed ≈ 2÷4 times the thickness of the reinforcing element.

The previous considerations highlight the importance of accurately evaluating the interface stress distribution and particularly ensuring that the maximum stress value does not exceed the tensile strength of the calcarenite stone.

The analytical approach to the delamination problem can be based on a continuum model as already observed in a previous investigation (Taljsten 1997).

If only the ultimate transfer load is to be calculated, the simple model shown in Fig. 11 can be utilized. This model is derived from that proposed by Oehlers and Moran (1990) in the case of R.C. members reinforced with steel plates, when only the axial load is considered.

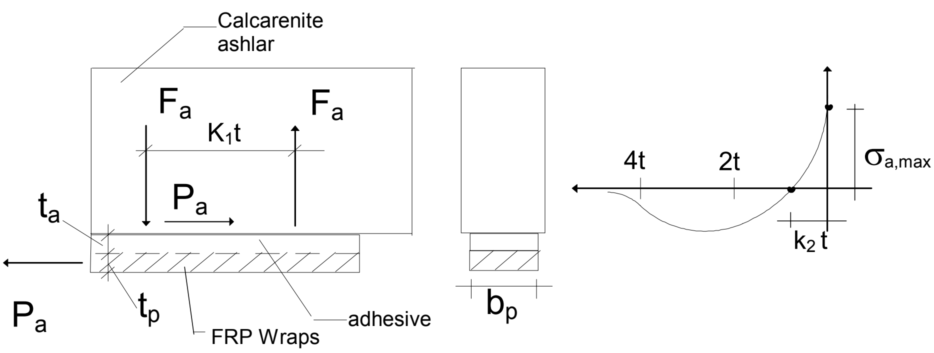

Figure 11. Physical model to evaluate delamination load

Axial force P_a applied to FRP wraps with thickness t_p, is transfered through the adhesive layer having thickness t_a to the masonry producing a shear stress distribution at the interface τ having resultant P_a and axial stress distribution σ_a, having as the resultant a moment due to the F_a force, acting on a very small area and in equilibrium with the moment induced by P_a for the arm $t = t_a+t_p/2$.

The delamination force P_a, induced by axial deformation of the fiber, can be evaluated from the equilibrium by using the following expression:

$$P_a \times t = F_a \times k_1 \times t \qquad (1)$$

k_1 being a coefficient depending on the distribution of the stresses σ_a and on the extension of the effective loaded area. This coefficient can be evaluated through a finite element analysis supported by experimental validation.
The F_a force can be evaluated as the resultant of the tensile stress acting for an extension of $k_2 \times t$:

$$F_a = s_a \times \sigma_{a,max} \times k_2 \times t \times b_p \qquad (2)$$

in which s_a is the ratio between the mean value of perpendicular stress σ_a and the maximum value $\sigma_{a,max}$ and k_2 is a coefficient depending on the distribution of the stress σ_a.
By substituting the expression (2) in eq. (1), the axial load becomes:

$$P_a= (s_a \times k_1 \times k_2) \times t \times b_p \times \sigma_{a,max} \qquad (3)$$

Assuming that the ultimate condition is reached when the axial stress $\sigma_{a,max}$ is equal to the tensile strength of the calcarenite stone f_t', the maximum load can be obtained as:

$$P_d = (2 \times k_a)^{-1} \times t \times b_p \times f_t' \qquad (4)$$

in which $k_a= (2\, k_1 \times k_2 \times s_a)^{-1}$
The k_a coefficient can be calibrated on the best fitting prediction of the experimental results. It is interesting to observe that by using eq. (3) the delamination force proves to be proportional to the tensile strength of the calcarenite stone and to the geometrical characteristics of the fibers, while the anchorage length and the mechanical properties of the fibers do not appear. In Table 3, for all cases examined, experimental and theoretical values are given, the latter obtained by using in eq. (3) $k_a = 0.0083$, which is the same value as that obtained in the experimental tests carried out by Oehlers and Moran (1990).

Table 3. Comparison between analytical and experimental results

Specimens n°	L_c (mm)	P_d experimental (daN)	P_d analytical (daN)
1	10	840	1479
2	15	1314	1479
3	25	1245	1479

CONCLUSION

It is interesting to observe that when FRP materials are utilized in strengthening masonry structures, very often delamination failure governs the strength problem and determines a strength lower than the effective bearing capacity of the fibers in tension. To reduce this negative effect it could be suitable to increase the width b_p of the fiber or to fix the fiber mechanically in the end portion, but further investigations are needed to draw more general conclusions.

REFERENCES

Antinucci, G., (2000). Il rinforzo di strutture in muratura con materiali compositi fibrosi (FRP). L'industria dei Laterizi, # 65, pp 331-342.

Arduini, M., Di Tommaso, A., Nanni, A., (1997). Brittle failure of FRP plate and sheet bonded beams. ACI Structural Journal, vol 9, # 4, pp 363-370.

Biraba, Y. N., Baluch, M. N., Basunbul, I. A., Sharif, A. M., Azad, A. K., Al-Sulaimani, G. I., (1994). Guidlines toward the design of reinforced concrete beams with external plates. ACI Structural Journal, vol 91, # 6, pp 639-646.

Cosenza, E., Manfredi, G., Occhiuzzi, A., Pecce, M.R., (2000). Toward the investigation of the interface behaviour between tuff masonry and FRP fabrics. Proc. of Mechanics of Masonry Structures Strengthened with FRP Materials: Modelling, Testing, Design, Control. Venezia, Italy, pp 91-108.

Leung, C. K. Y., Klenke, M., Tung, W. K., Luk, H. C. Y., (2000). Investigation of nonlinear interfacial behaviour for concrete beams retrofitted with composite plate. Proc. Int. Symp. "Brittle Matrix Composites 6" A. M. Brandt, V. C. Li, I. H. Marshall eds. Warsaw, October 9-11, 2000, Zturek and Woodherd Publ., Warsaw 2000, pp 286-295.

Oehlers, D. J., Moran, J. P., (1990). Premature failure of externally plated reinforced concrete beams. ASCE Journal of Structural Engineering, vol 116, # 4, pp 978-995.

Oehlers, D. J., (1992). Reinfroced concrete beams with plates glued to their soffits. ASCE Journal of Structural Engineering, vol 118, # 8, pp 2023-2038.

Pecce, M., Ceroni, F., Prota, A., Cosenza E., (2000). Alcune osservazioni sulla valutazione delle tensioni di interfaccia del rinfrozo esterno con FRP. Atti del 13 Congresso C.T.E 9-11 novembre Pisa, Italy , pp 413-422.

Taljsten, B., (1997). Strengthening of beams by plate bonding. ASCE Journal of Materials in Civil Engineering, vol 9, # 4, pp 206-212.

Zhang, S., Raoof, M., Wood, L. A., (1995) Prediction of peeling failure of reinforced concrete beams with externally bonded steel plates. Proc. Instn. Civ.Engrs. Struct of Bldgs, vol 110, pp 257-268.