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BOND BETWEEN MASONRY AND CFRP SHEETS IN PRESENCE OF CURVATURE

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ABSTRACT: Repair and strengthening of masonry and reinforced concrete structures is becoming a very important topic in the field of the Civil Engineering. At this aim, the use of Fibre Reinforced Plastic (FRP) for repair and/or retrofitting of concrete and masonry structures is becoming a successful and increasingly utilised technique. The success of retrofitting techniques depends on more extent on the bond performance between the FRP reinforcement and the substrate. In particular, when curved concrete members are strengthened with FRP sheets, a combination of shear and normal stresses is transferred at the interface, causing, in many cases, a premature failure. In the present paper the influence of curvature of FRP-strengthened masonry elements is investigated, both in terms of bond-slip laws and failure mechanisms. In detail, an experimental investigation, aimed to analyse the bond between FRP sheets and curved masonry elements, is reported. At this aim a bending test has been performed on curved masonry elements reinforced with CFS (Carbon Fiber Sheet). In particular the state of stress and strain at the interface is analyzed varying the curvature of the elements and the width of the bonded sheets. Finally a theoretical analysis is performed in order to interpret the obtained results.

1. INTRODUCTION

As the behaviour of masonry is considered no tension resistant, in old masonry buildings curved geometrical shapes were used for some structural elements, such as arches, vaults and similar. In fact curved shape can transfer loads through a simply compression state of structural elements. Nevertheless, nowadays the need of repair and strengthening of old masonry structures is becoming a more and more felt and discussed issue, and the use of FRP (Fiber Reinforced Polymers) for such purposes seems to be a very promising technique. The effectiveness of the repair and strengthening technique is strictly depending on the bond between the reinforcing materials and the substrate, as structural elements may undergo a premature collapse because of the failure at the reinforcement substrate interface.

Several experimental and theoretical research works are available in the literature on bond between concrete elements and externally bonded FRP laminates ([1], [2]); in the last years some studies have been also focused on the interface analysis between FRP and masonry ([3], [4], [5], [9], [10], [11]), which evidenced the occurrence of a premature failure, due to the debonding of sheets from the masonry. Nevertheless, few researches have been addressed to the analysis of FRP-strengthened curved masonry members. Because of the presence of the curvature, in fact, the state of stress at the interface is characterized by a combination of shear and radial normal stresses that can cause a premature collapse. According to theoretical analysis the radial normal stresses arising from curvature are expressible as follows:

$$\sigma_r = \frac{\sigma_l}{R} \cdot t_r \qquad (1)$$

where σ_r= radial normal stress at the interface; σ_l= normal longitudinal stress in the FRP sheet; R= local curvature radius; t_r= reinforcement thickness. The issue of premature failure due to additional stresses arisen from curvature has recently been investigated by Aiello et al. ([6], [7], [8], [12]) on concrete substrate. In the present paper the issue is investigated with reference to masonry substrate strengthened with CFRP sheets, varying curvature, CFRP stiffness and sheet width.

2. EXPERIMENTAL INVESTIGATION

2.1 Materials

The bond behaviour between curved masonry elements and CFRP sheets was investigated through flexural tests performed on natural stone members reinforced at the intrados by an unidirectional CFRP sheet. The kind of material used for masonry members was a typical stone widespread in the Salentine peninsula, the so called "*Leccese Stone*", having a compressive strength *of 24 MPa* and a tensile strength of *5.5 MPa*. The elastic moduli of the CFRP sheets, applied by manual lay-up, were *234 GPa* for the High Strength Carbon, *390 GPa* for the High Modulus Carbon, as provided by the supplier (MAC-Degussa).

2.2 Tested Specimens and test set-up

The experimental investigation was performed on fifteen specimens with different radius of curvature, *R*. For the specimens with *R = 100 cm*, the width of the CFRP sheet and the modulus of the carbon fibres were also varied. In Figure 1 a picture of a specimen under testing and the corresponding four points load scheme are shown. A series of strain gages were glued on the CFRP sheets to monitor the strain distribution along the laminate as shown in Figure 2-a.

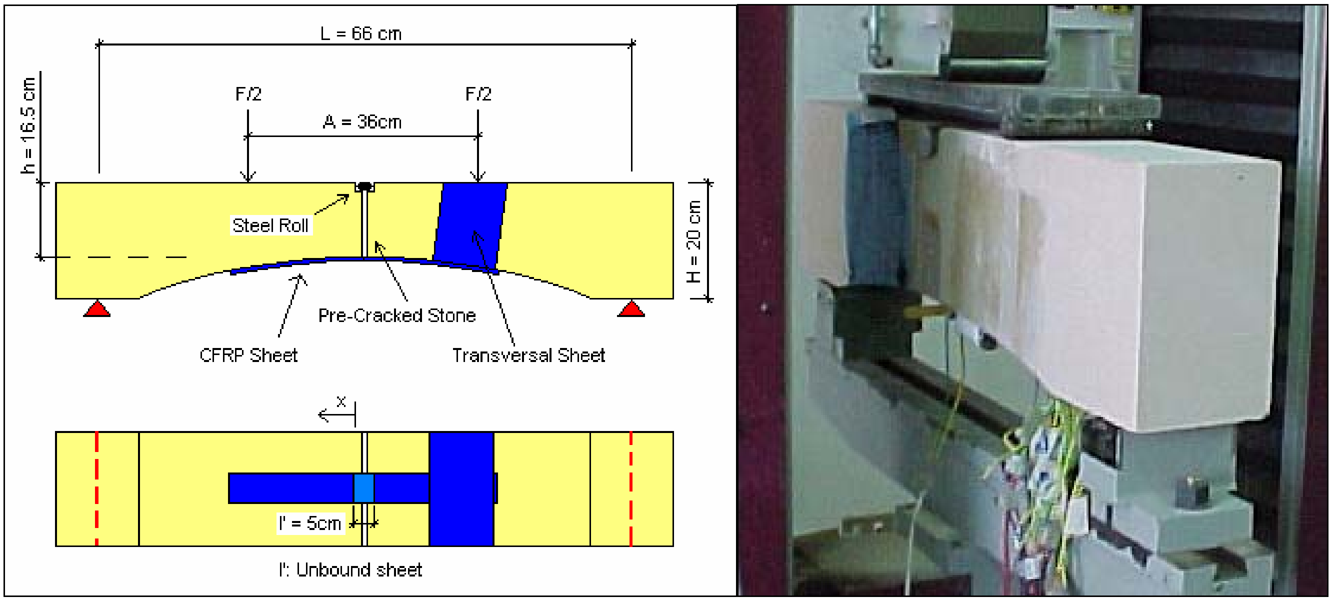

Figure 1 – Tested specimens: a) scheme of loading conditions, b) specimen under test

The specimens, subjected to a four points load, were pre-cracked in the midspan section, in order to clearly define the tensile force applied at the CFRP sheet. Moreover, in order to guarantee a uniform distribution of stresses at the tested zone of the laminate, a 5 cm wide unbound zone was left at the middle of the beam. The bonded length was in all cases, $l = 150mm$. Finally, in order to assure that the failure takes place in the instrumented region, an additional transverse CFRP sheet was applied, as shown in Figure 2-b.

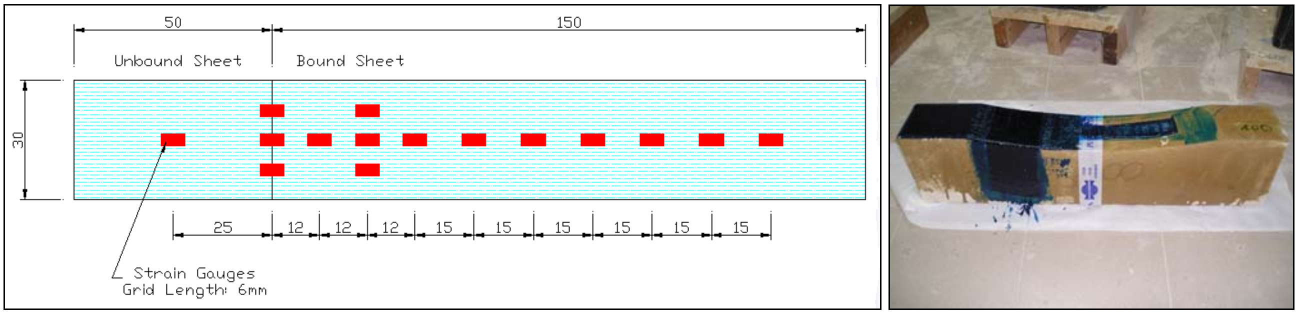

Figure 2 – a) Exact position of strain gauges, b) Specimen set up for test

3. TEST RESULTS AND DISCUSSION

In all the performed tests failure took place as debonding failure of the CFRP sheet. In Table 1, it is reported the value of the ultimate load, i.e. the value of the tensile force in the FRP corresponding to the bond failure (T_u). It was computed as reported in equation (2), being h is the distance between the centres of compression and tensile stresses and F_u the ultimate value of load F (Figure 1).

Table 1 – Tested Specimens

Specimens	R (Radius) [mm]	Carbon Type	Sheet Width - B [mm]	Element dimensions [mmxmmxmm]	Ultimate Load CFRP Sheet (T_u) [kN]	Collapse Mechanism (*)
000CHS_B3_A1	∞	CHS	30	120x200x800	4.20	mod. 3
000CHS_B3_A2	∞	CHS	30	120x200x800	7.12	mod. 2
150CHS_B3_A1	1500	CHS	30	120x200x800	4.46	mod. 1
150CHS_B3_A2	1500	CHS	30	120x200x800	4.19	***
100CHS_B3_A1	1000	CHS	30	120x200x800	5.66	***
100CHS_B3_A2	1000	CHS	30	120x200x800	4.36	mod. 3
100CHS_B3_A3	1000	CHS	30	120x200x800	3.14	***
75CHS_B3_A1	750	CHS	30	120x200x800	3.81	mod. 1
75CHS_B3_A2	750	CHS	30	120x200x800	4.24	mod. 1
100CHM_B3_A1	1000	CHM	30	120x200x800	5.72	***
100CHM_B3_A2	1000	CHM	30	120x200x800	4.13	***
100CHS_B10_A1	1000	CHS	100	120x200x800	11.52	mod. 1
100CHS_B10_A2	1000	CHS	100	120x200x800	12.65	mod. 2
100CHS_B10_A3	1000	CHS	100	120x200x800	11.95	mod. 2
100CHS_B5_B1	1000	CHS	50	200x330x1200	6.99	mod. 2

(*) mod. 1: FRP debonding with detachment of a very thin layer of stone; mod. 2: FRP debonding with partial detachment of a layer of limestone near the unloaded end of the sheet; mod. 3: debonding between the carbon sheet and the masonry element without any detachment of stone.

It can be observed that the *mod.3* type of failure, without any detachment of stone, involves a lower ultimate load; that phenomenon is probably correlated to a not excellent bond between FRP and masonry element.

$$T_u = \frac{(L-A)}{4 \cdot h} \cdot F_u \tag{2}$$

The T_u values are reported (Figure 3) as a function of the curvature and of the sheet width. It can be observed that the ultimate load, T_u is lightly descending increasing the curvature while it increases with the reinforcement width.

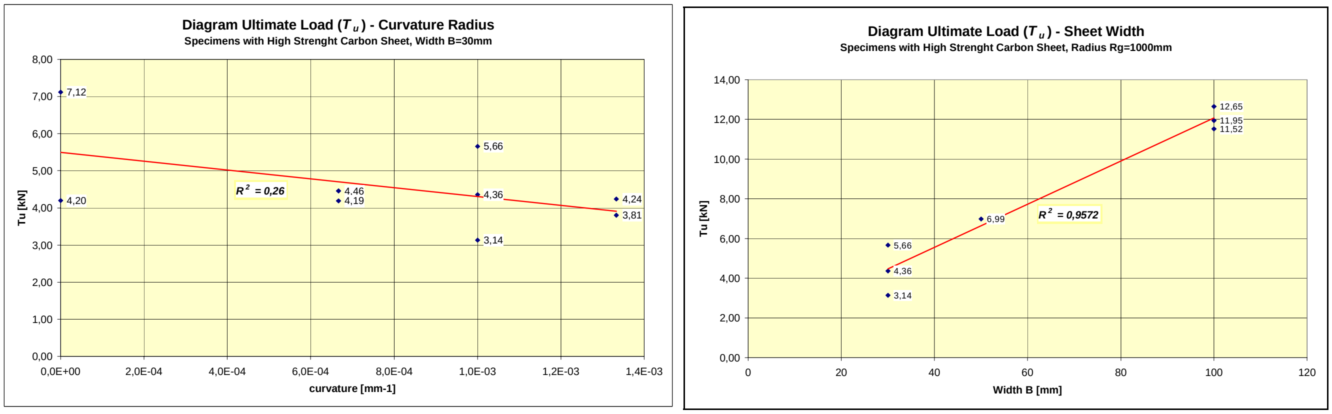

Figure 3 – Ultimate Load (T_u) function of Curvature Radius on the left (a), of Sheet Width on the right (b)

3.1 Strain and Shear Stresses Distribution

Two examples of the measured strain along the reinforcement are reported in Figure 4, evidencing an exponential trend, moving from the loaded end, almost up to the bond failure. The uniformity of the strain distribution in the transverse direction was also checked by strain gauges glued at different positions on the width of the sheet.

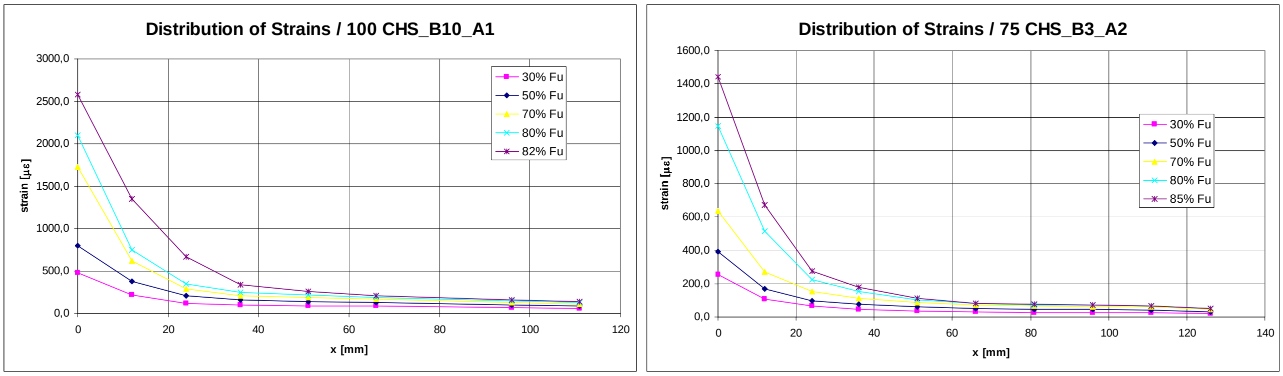

Figure 4 – Distribution of Shear Stresses in some tested specimens

The bond shear stress distribution, $\tau(x)$, along the reinforcement was computed by the equilibrium condition of the sheet; knowing t_r = sheet thickness (0.165 mm), E_r = elastic modulus of FRP, ε_i = strain value at position x_i:

$$\tau\left(\frac{x_{i+1}+x_i}{2}\right) = t_r \cdot E_r \cdot \frac{\varepsilon_i - \varepsilon_{i+1}}{x_{i+1}-x_i} \tag{3}$$

In Figure 5, the shear stress distribution patterns computed from the strain data reported in Figure 4 are shown. A decreasing exponential path is observable as well. In the tested specimens it was observed that above a certain load level, both the strain and the stress distributions become unstable and hardly explainable, probably due to the incoming local debonding.

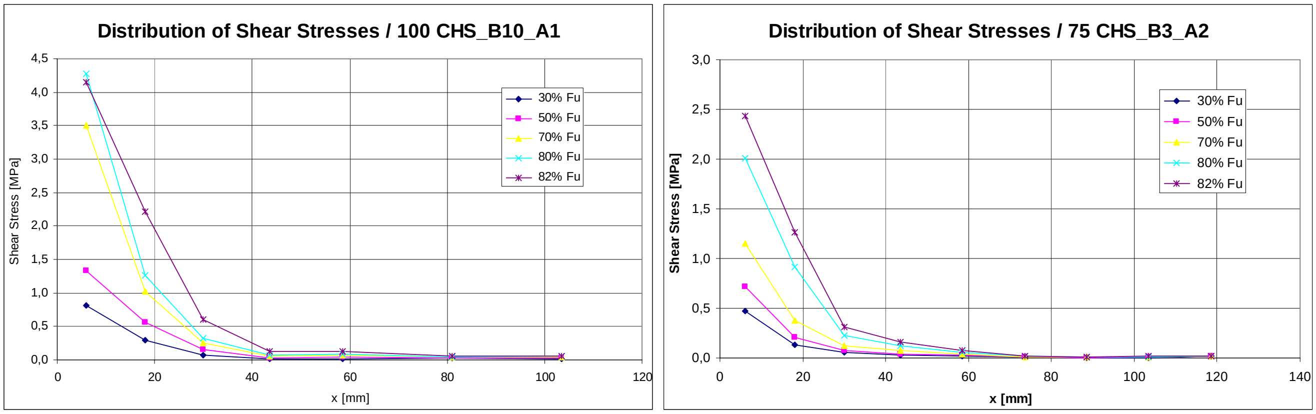

Figure 5 – Distribution of Shear Stresses in some tested specimens

The value of the ultimate tensile force (said *T'*) beyond which the strains or shear stresses distributions suddenly becomes highly irregular is also worth to be evaluated. In Figure 6 a diagram showing the ratio T' / T_u, as a function of the curvature is reported, from which it can be hypothesized that the increase of curvature causes an increasingly less ductile failure.

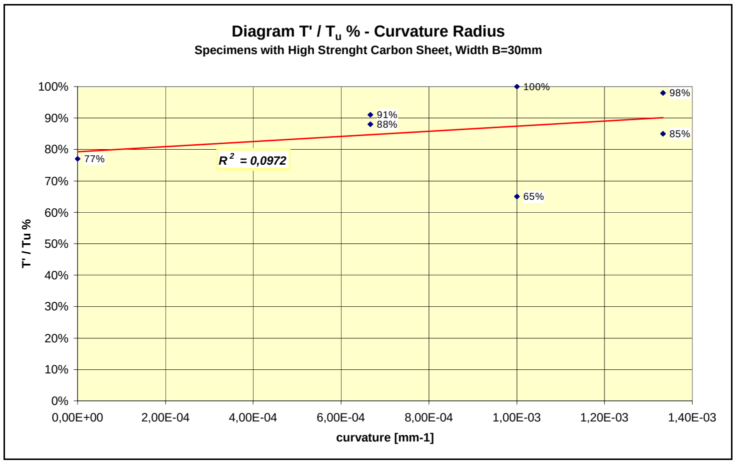

Figure 6 – Diagram T_{max} / T_u as a function of Curvature Radius

3.2 Shear Stress – slip diagrams

Shear stresses vs. slip diagrams were obtained on the basis of the recorded results. The slip was obtained by numerically integrating the strains along the carbon sheet, as reported in (4), neglecting the slip at the unloaded end of the sheet and the stone deformations.

$$s = \sum_i \varepsilon_{li} \cdot \Delta x_i \qquad (4)$$

In Figure 7 a typical shear stress vs. slip diagram is presented.

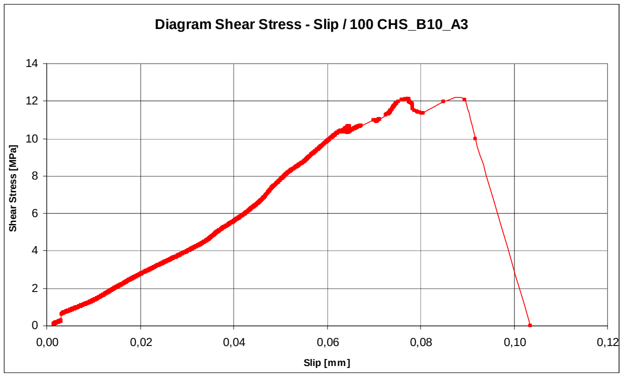

Figure 7 – Diagram Shear Stress vs Slip

Shear stress – slip diagrams were used to measure the G_a / t_a ratio (corresponding to the initial slope of the diagram), being G_a the shear elastic modulus of the adhesive placed between the CFRP sheet and the substrate and t_a its thickness. This ratio, having a mean measured value of *133.3 MPa/mm*, was the only parameter required for the following theoretical analysis of the shear stress distribution, being not necessary, in this analysis, to separately determine the values of G_a, t_a.

3.3 Theoretical analysis of shear stresses distribution

Making the hypothesis of linear elastic behaviour of materials and negligible flexural stiffness of FRP sheets, a theoretical analysis can be performed by imposing the translational equilibrium of the sheet and the compatibility condition between sheet, adhesive and stone. The resulting equation is presented in (5), while in (6) the solution in terms of shear stress distribution is reported (*l: sheet length*, *B: sheet width*, *(EA)$_r$: axial sheet stiffness*):

$$\frac{d^2\tau}{dx^2}+\lambda^2\tau=0 \quad \text{where} \quad \lambda^2=\frac{G_a}{t_a}\cdot\frac{B}{(EA)_r} \tag{5}$$

$$\tau(x)=\lambda\cdot l\cdot\tau_m\cdot e^{-\lambda\cdot x} \quad \text{where} \quad \tau_m=\frac{T}{B\cdot l} \tag{6}$$

In Figure 8 some diagrams showing the good agreement between the experimental and the theoretical formulations are presented.

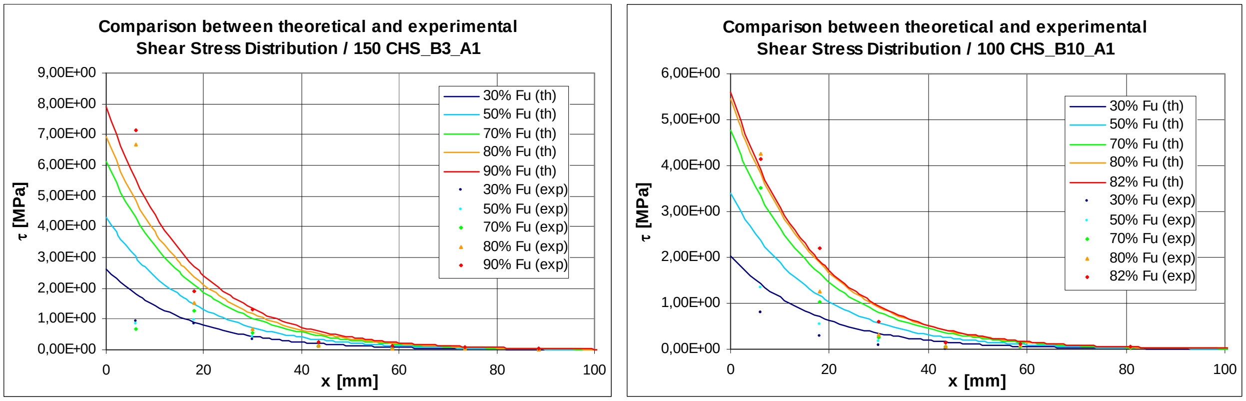

Figure 8 – Comparison between experimental and theoretical distribution of shear stresses

Such agreement suggested to use the theoretical expression to evaluate the maximum shear stress τ_{max} corresponding to the tensile force *T'*, that can be considered as the shear stress at incoming debonding. The obtained τ_{max} is reported in Figure 9 as a function of both curvature and sheet width. In Figure 9-a the influence of curvature in reducing the maximum shear stress bearable by the interface is fairly well identifiable, while in Figure 9-b a slight reduction with the sheet width is visible.

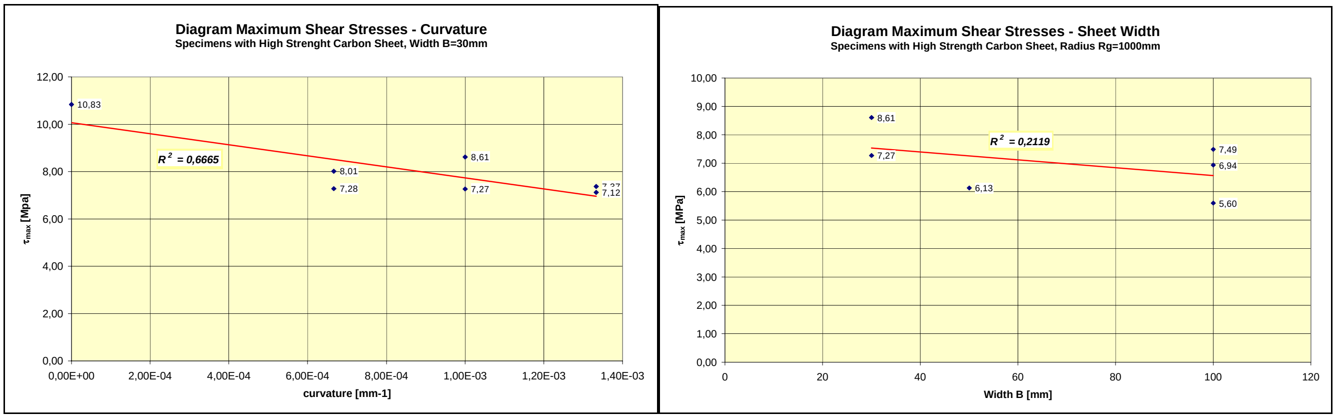

Figure 9 – Maximum Shear Stresses, function of radius on the left (a), of sheet width on the right (b)

Finally, the maximum radial normal stress σ_{rmax} corresponding to the maximum tensile force *T'*, was evaluated according to (1), occurring in the same section of the sheet where τ_{max} is present (x=0). A σ_{rmax} vs. τ_{max} experimental interaction diagram was then built, as reported in Figure 10, in which the influence of the normal stresses in reducing the interface shear resistance is clearly visible.

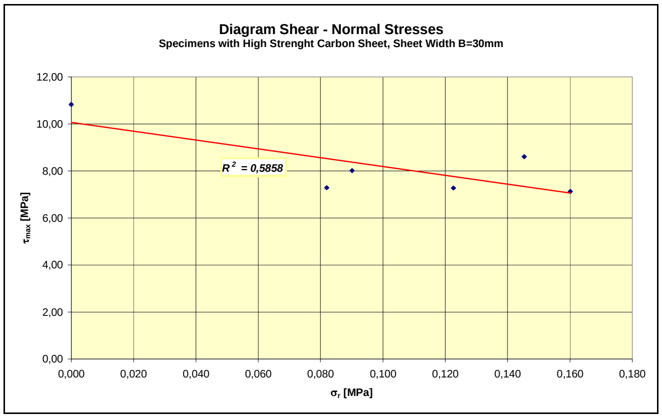

Figure 10 – Maximum Shear – Normal Stresses

4. CONLUSIONS

In the present an experimental and theoretical analysis devoted to the analysis of bond performance between FRP reinforcement and masonry substrate is reported. The main parameters considered were the curvature value, the reinforcement width and stiffness. On the basis of obtained results some consideration can be made as reported in the following:

- Increasing the curvature value the ultimate load decreases, as well as the maximum bond stress, i.e. the bond stress value at incoming debonding. In addition, the presence of curvature seems to be influential also on the type of failure; in particular, a more fragile failure was observed when the radial stresses increases as consequence of a curvature increase.

- The width of the reinforcement also influences the ultimate load value attained, however further analyses are required in order to investigate the influence of that parameter on maximum bond stress value.
- The theoretical analysis performed appears effective to predict the interface behaviour at the first stage, up to the debonding start.
- A wide experimental investigation is suggested in order to define a strength criteria for curved structural elements, taking into account local bond performance, that could be useful from a design point of view.

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