

Analysis on the effective bond length of a basalt Textile Reinforced Mortar strengthening system submitted to single lap shear test; the contribution of Digital Image Correlation

Carmelo Caggegi¹, Denise Sciuto², Massimo Cuomo²

¹ *University Claude Bernard Lyon 1, Laboratory of Composite Materials for Construction (LMC2), Site Bohr, 82 Boulevard Niels Bohr, Campus de la DOUA, 69622 Villeurbanne Cedex, France, email: carmelo.caggegi@univ-lyon1.fr*

² *Department of Civil and Environmental Engineering, University of Catania, V.le A.Doria, 6, 95125 Catania, Italy, e-mails: denisesciuto@gmail.com, cuomo@dica.unict.it*

Abstract – The Textile Reinforced Mortar strengthening systems (TRM) seems to be one of the better solutions to reinforce the historical masonry structures. The study of the testing methods more appropriate to define the mechanical design parameters is actually of main interest for scientific community. The experimental research presented herein was carried out to define the effective bond length of a Basalt_TRM system applied to a homogeneous substrate. The use of the Digital Image Correlation (DIC) based on a cross correlation function has permitted to define the displacement and strain fields and to better describe the debonding phenomena recorded during the tests.

I. INTRODUCTION

The use of Textile Reinforced Mortar systems (TRM) in the strengthening of historical structures has become widespread in the last years. The TRM systems are constituted by a textile (frequently made by carbon, glass, basalt, PBO, Aramid) embedded in a mortar matrix [1]. The application of this kind of materials to the structural elements permits to strength the structure by means of minimal, reversible and compatible interventions.

The literature shows that the bond between the textile and the mortar matrix plays a central role in the efficiency of the reinforcement [1][2]. Several studies were been carried out to define the parameters and testing protocols useful to design the TRM strengthening systems [3][4][5]; specifically the Technical Committee RILEM TC 250 CSM proposed to characterize the reinforcements by using tensile tests and shear bond tests [6]. The tensile tests are carried out on TRM strips to identify the mechanical parameters related to the composite only (tensile stress and stiffness related to each

phase of the test). The shear tests concern the adherence between the composite and the substrate. In the case of TRM systems, an adhesive debonding inside the composite is frequently recorded between the textile and the matrix [1][5]. One of the parameters that mainly affects the efficiency of TRM systems is the bond length of the composite onto the substrate. An “effective” bond length exists (l_e); the latter corresponds to the longitudinal extent of the stress transfer zone. A bond length greater than l_e doesn’t implies an increment of ultimate load.

Since the debonding is recorded inside the TRM composite, “ l_e ” is strictly related to the mechanical properties of textile and matrix.

The experimental study presented herein has been carried out by means of Single-lap Shear Test (SST) to evaluate the effective bond length between a thixotropic mortar and a basalt textile by studying deeply the slippage phenomena by means of Digital Image Correlation (DIC) measurements. Five series of tests, each one characterized by a different bond length “ l ”, were been tested.

The digital image correlation is a non-destructive method of measurement based on the matching of different photos of the specimen taken during the tests. The DIC algorithm used in the experimental campaign is based on a cross correlation function that permits to define the displacement fields on all the analyzed surface [7][8].

II. EXPERIMENTAL PROGRAM

The experimental study was carried out by shear test on concrete substrate reinforced by Basalt_TRM. Eight series of specimen, each one characterized by a different bond length, were tested in the session. The boundary conditions of the so called “Near-End Supported Single

Shear Test" (NES-SST) have been reproduced to study the evolution of debonding (Fig.1). The experimental protocol proposed by RILEM committee TC 250 CSM was implemented in the experimental campaign. The dimensions of the concrete substrate prism are 320x250x120 mm³ (h x L x t). The thickness and the bond width of the TRM composite are respectively 10 and 90 mm. The bond length concerning each one of the series is reported in table 1. The TRM was carry out directly onto the surface to reinforce. Three longitudinal roving of basalt net are embedded in the matrix (Fig. 1). on the free extremity of the TRM, the roving come out from the mortar matrix to permit a better interpretation of the slipping phenomena (Fig. 2).

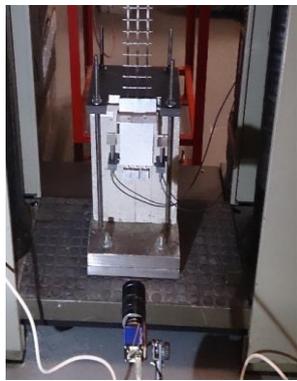


Fig.1 Single shear test and digital image camera.

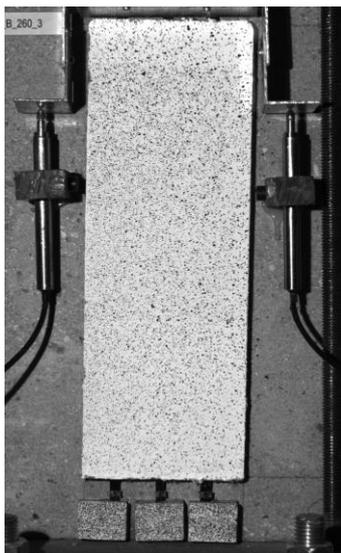


Fig.2 Detail of a TRM surface analysed by DIC (CS_B_260_3).

Table 1. Experimental series and bond length.

Series	l [mm]
CS_B_50	50
CS_B_75	75
CS_B_100	100
CS_B_125	125
CS_B_150	150
CS_B_200	200
CS_B_230	230
CS_B_260	260

A. Materials

The TRM was constituted by a basalt fiber balanced net with a special high temperature resistive coating for textile stability. The bidirectional roving are spaced 25 mm in each direction. The average cross section of each roving is 1.61 mm² [9]. In literature, the average tensile strength (f_{ft}) and the elastic modulus (E_{ft}) of the coated fiber are defined respectively as 1089 MPa and 56 GPa [9].

The mortar matrix was a single component, dry, thixotropic mortar with 1 mm aggregates and additives. The compressive and the flexural strength obtained by using the European standards EN 1015-11 were 20.6 and 5.5 MPa [9].

B. Testing setup

The tests were carried out in displacement control at a speed of 0.3 mm/min. An aluminum device bonded to the textile net close to the loaded end of the TRM permitted to measure the slip (s) applied to the specimen. This device is characterized by an "Ω" shape, and it is in contact to two LVDT transformers (Fig. 2).

The bi-dimensional displacements on the external surface of the TRM system were measured by Digital Image Correlation. The evaluation of displacements was made by matching the photos of the interested surface taken during the test. A treatment of the external surface of TRM was carried out before the test by making a stochastic speckle pattern of black points on a homegeneous layer of white paint (Fig. 2). The high contrast between the black points and the white background increase the quality of the correlation.

The photographs were obtained by using a Charge Couple Device (CCD) camera (1.9 MPixels).

C. Digital Image Correlation

The Digital Image Correlation was made by an algorithm based on a cross correlation function [7][8]. A

multi scale approach was used. In the correlation process, a Region Of Interest (ROI) is defined in the photo of reference; the ROI is subdivided in several square zones (Zone Of Interest – ZOI). The ZOIs are placed homogeneously onto the Region of Interest; the size of these subzones is related to the size of speckle. The DIC permits to define the displacement of each Zone Of Interest during the test. The value of displacement is the one that maximizes a cross correlation product between the reference signal $f(x,y)$ and the deformed signal $g(x,y)$.

In our study the ROI corresponds to the TRM external surface, the ZOIs had a size of 64×64 pixels, the distance “dx” between the ZOI’s centers was 32 pixels. The ratio R_z (mm/pixels) varies between 0,08 (series CS_B_75) and 0.19 (Series CS_B_260); the latter is related to the distance between the camera and the surface of interest.

III. RESULTS

The results are presented below in term of Force- Slip curves. Each curve of Figure 3 concerns a representative specimen belonging to each series. Figure 4 collects the failure modes defined by the TC RILEM 250 CSM [6].

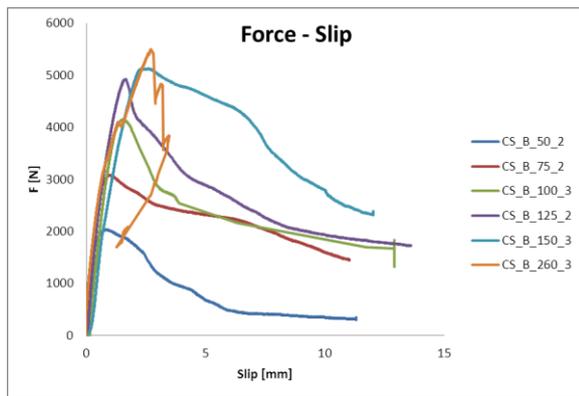


Fig.3 Force-slip relations concerning the representative specimens.

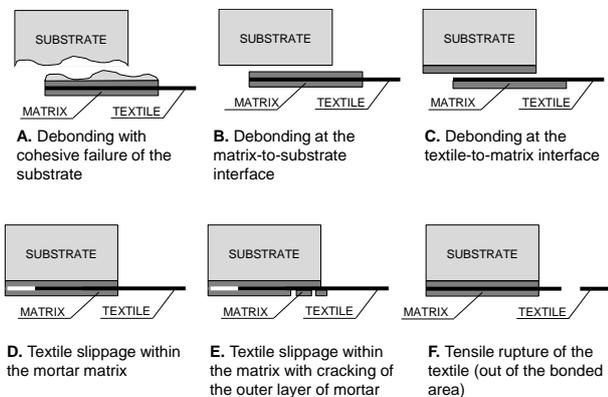


Fig.4 Failure modes defined by TC RILEM TC 250 CSM.

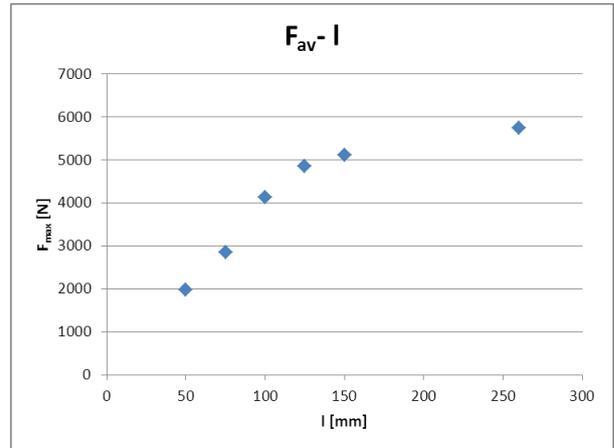


Fig.5 Graph relating average maximal force recorded in each series (F_{av}) and corresponding bond length (l).

The maximal force “ F_{max} ”, the corresponding slip “ s ”, the σ_{max} (equal to F_{max} divided by the cross section of the three roving), and the failure mode corresponding to each specimen are plotted in Table 2. Additionally, the latter collects the average value F_{av} corresponding to the average of F_{max} obtained in each series. The relation between average force F_{av} and the bond length l is presented in Figure 5.

The Digital Image Correlation was carried out on all the representative specimens of the experimental session. Figure 6 shows the ROI concerning an image of reference; the grid connecting all the ZOI center is plotted in red. The DIC analysis allows to obtain the displacement field $V(x,y)$ in the direction of loading (direction y), and the displacement field $U(x,y)$ in the perpendicular direction to y axis. The displacements have been obtained for each ZOI; they are considered applied to the center of each zone of interest. The differentiation of displacements V for a fixed x along the y axis has permitted to obtain the strain values ϵ_{yy} ; in a similar way, the differentiation of displacements U for a fixed y has permitted to calculate the strain ϵ_{xx} . Figure 7 defines ten steps of load related to the specimen CS_B_125_2; the strains ϵ_{xx} ($y=100$ mm) concerning these steps are plotted in Figure 8. The strain fields $\epsilon_{xx}(x,y)$ (Figure 9) and $\epsilon_{yy}(x,y)$ have been obtained for all the DIC steps. The DIC steps and the strain fields related to a specimen of series CS_B_260 are presented in Figures 10 and 11.

Table 2. Specimens, tensile stress in the rowing, failure modes and average maximal force.

Specimen	σ_{max} [Mpa]	Failure Mode	F_{av} [N]
CS_B_50_1	369,44	D	1984
CS_B_50_2	421,84	D	
CS_B_50_3	441,25	D	
CS_B_75_1	544,13	D	2848
CS_B_75_2	637,94	D	
CS_B_75_3	586,83	D	
CS_B_100_1 ^{*1}	-	-	4128
CS_B_100_2	850,80	D	
CS_B_100_3	858,57	D	
CS_B_125_1	1005,78	D	4853
CS_B_125_2	1019,02	D	
CS_B_125_3	989,26	D	
CS_B_150_1 ^{*1}	-	-	5105
CS_B_150_2	1052,02	D	
CS_B_150_3	1061,72	D	
CS_B_200_1 ^{*1}	-	-	
CS_B_200_2 ^{*1}	-	-	
CS_B_200_3	830,73	D	
CS_B_230_1 ^{*2}	-	-	
CS_B_230_2 ^{*2}	634,86	B	
CS_B_230_3	1331,15	D+F	
CS_B_260_1	1286,23	F	5746,35
CS_B_260_2	1275,88	F+D	
CS_B_260_3	1139,36	F	
CS_B_260_4	1203,42	F+E	
CS_B_260_5	1088,25	F	
CS_B_260_6	1145,19	F	

IV. DISCUSSION

The Force-slip curves show that the reinforced systems have the same stiffness during the first phase of the test (Fig. 3); a reduction of stiffness due to starting of damage is recorded close to the achievement of the peak load. The post peak branch is frequently characterized by a gradual decrease of load related to the slippage of the rowing inside the mortar matrix. The graph F_{av} -l shows that for the series characterized by a bond length longer than 125 mm a slow increment of F_{av} is recorded. Therefore, the effective bond length is almost equal to 125 mm; the difference between the maximal average load achieved in

series CS_B_125, CS_B_150 and CS_B_260 is related to the contribution of friction [5]. All the specimens with a bond length lower than 125 mm are characterized by a failure mode D (textile slippage inside the mortar matrix); in the series CS_B_260 all the specimens failed by a tensile fracture of the rowing.

Unfortunately, several specimens of series CS_B_200 and CS_B_230 was damaged during the curing process and their results haven't been inserted in the post-treatment analysis (table 2). The specimens noted (^{*1}) in table 2 had several roving pre-damaged before the tests. The specimen CS_B_230_2 (^{*2}) was characterized by a reinforced surface not pretreated before the TRM manufacturing.

A bond length longer than " l_c " permits to maximize the tensile stress acting in the rowing. The experimental analysis shows that the tensile failure of the fibers is promoted before the slippage of the longitudinal rowing.

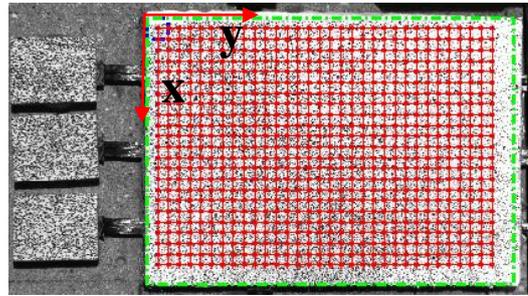


Fig. 6 Region Of Interest subdivided in ZOIs and reference axis.

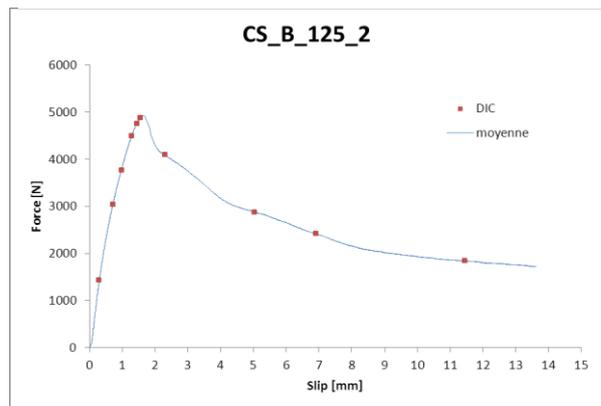


Fig. 7 Force-slip relation and DIC analysis steps (specimen CS_B_125_2).

The DIC has permitted to better describe the damaging process during the test. It is interesting to analyze the strain fields ϵ_{xx} of specimen CS_B_125_2; in the loading steps 5 (L=4753 N) and 6 (L=4881) a concentration of positive strain is recorded on the surface of the specimen close to the longitudinal rowing (Figg. 8, 9). In a first time only the loading end is interested; since the peak load is

achieved, the roving starts to slip and the positive strain interest all the surface of TRM from the loaded side to the unloaded side (Fig. 9, DIC steps L=4088, L=2878). The presence of positive strain is an indicator of the location of stress transfer zone (Fig. 12).

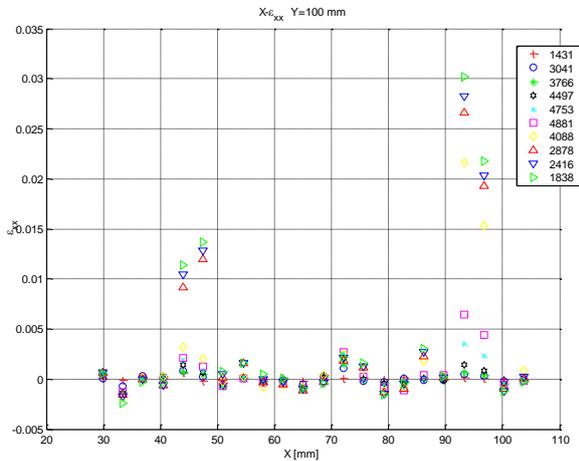


Fig.8 Strain ϵ_{xx} along the x , at $y=100$ mm, corresponding to the different DIC steps (specimen CS_B_125_2).

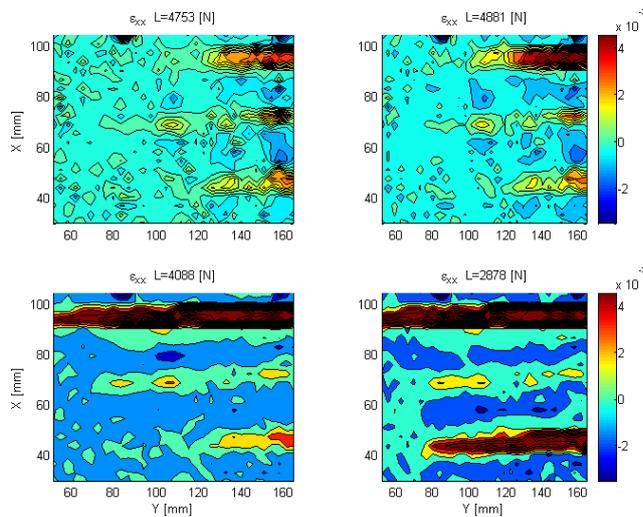


Fig.9 Strain fields $\epsilon_{xx}(x,y)$ related to DIC steps 5,6,7 and 8 (CS_B_125_2).

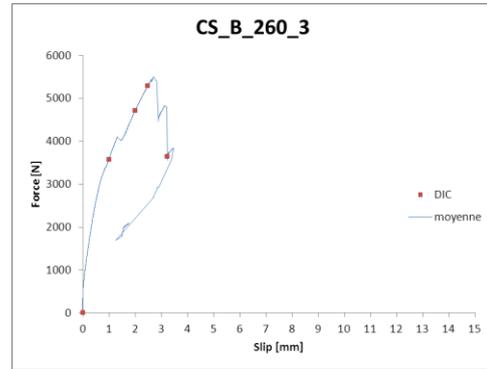


Fig.10 Force-slip relation and DIC analysis steps (specimen CS_B_260_3).

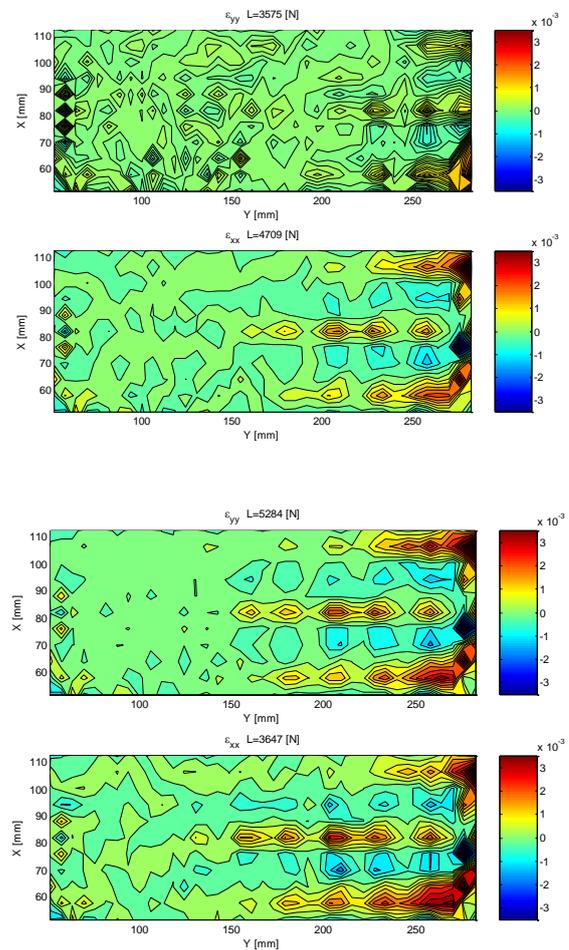


Fig.11 Strain fields $\epsilon_{xx}(x,y)$ related to DIC steps (CS_B_260_3).

The data obtained by DIC on specimens of series CS_B_260 shows that the stress transfer zone interests a zone close to the loaded end (Fig. 10, 11); the strain fields ε_{xx} concerning the DIC steps defined in Fig. 10 show that the zone affected by the positive strain does not exceed the extension of about 125 mm (before and after the achievement of peak load). The latter corresponds to the effective bond length obtained by the analysis of graph “average maximal force – bond length” (Fig. 5).

The experimental analysis shows that the longitudinal deformation of the roving during the test promotes a transversal strain ε_{yy} on the external surface of the mortar matrix (fig. 12).

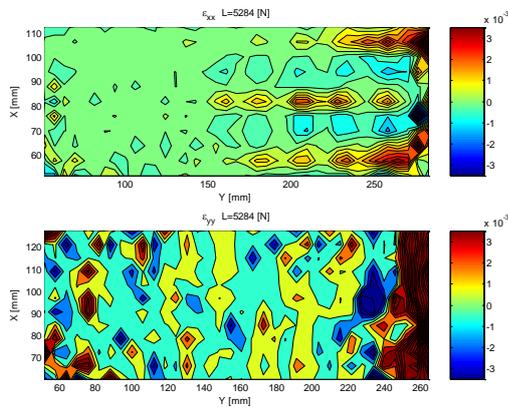


Fig.12 Strain fields $\varepsilon_{xx}(x,y)$ and $\varepsilon_{yy}(x,y)$ the loading step $L=5284$ (CS_B_260_3).

V. CONCLUSIONS

The experimental study has permitted to define the effective bond length l_e related to a Basalt_TRM strengthening system. This one is equal to about 125 mm. The use of Digital Image Correlation has permitted to describe deeply the evolution of damage and to have more information on the location of the stress transfer zone during the test. In this framework, the study of transversal strain fields ε_{yy} shows a deformation of the mortar matrix close to the roving before the achievement of the peak load.

The effective bond length has been obtained by analyzing the maximal force peaks achieved in eight series of specimens characterized by different bond length; the “ l_e ” obtained is almost equal to the maximal extension of the positive strain ε_{xx} recorded on the surface of specimens characterized by $l > l_e$. This preliminary study permits to suppose that the study by Digital Image

Correlation on only one series of specimen characterized by $l > l_e$ could permit to define the value of l_e . Several studies will be carried out in future on this subject.

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