Detachment analysis of dehumidified repair mortars applied to historical masonry walls

DETACHMENT ANALYSIS OF DEHUMIDIFIED REPAIR MORTARS APPLIED TO HISTORICAL MASONRY WALLS

Pietro Bocca[1], Silvio Valente[2], Alessandro Grazzini[3*], Andrea Alberto[4]

Department of Structural, Building and Geotechnical Engineering (DISEG) – Politecnico di Torino

Corso Duca degli Abruzzi 24, 10129, Turin, Italy

(1) Professor of Structural Mechanics, Ph: +39 011 0904843, email: pietro.bocca@polito.it

(2) Professor of Structural Mechanics, Ph: +39 011 0904853, email: silvio.valente@polito.it

(3) * corresponding author, Ph.D. Post-Doctoral Research, Ph: +39 011 0904918; fax: +39 011 0904899, email: alessandro.grazzini@polito.it

(4) Ph.D., Ph: +39 011 0904895, email: andrea.alberto@polito.it

ABSTRACT

An innovative laboratory procedure for the pre-qualification of repair mortars is described. The tested mortars are suitable for use with new dehumidified plasters applied to historical masonry walls. Long-term plaster detachment frequently occurs because of the mechanical incompatibility of mortar. The procedure consists of the application of static loads to mixed stone block-mortar specimens with particular characteristics, in terms of geometry and adhesion at the interface. A numerical simulation based on the cohesive crack model was used to follow the experimental data, in order to describe the evolutionary phenomenon of detachment as a function of a small number of parameters. The methodology is currently being used at Sacro Monte di Varallo Special Natural Reserve (UNESCO heritage site) in Piedmont (Italy).

Keywords: Durability, Historical masonry structures, Dehumidified mortar, Long-term plaster detachment, Cohesive crack model.

INTRODUCTION

Masonry walls of historical buildings are often subject to rising damp effects due to capillary action or rain infiltration, whose cyclic action in the time produces decay and detachment of historical plasters (Fassina et al., 2002; Collepardi, 1990). The restoration market offers a great number of dehumidified repair mortars to use as new transpiring plasters. Nevertheless their mechanical and thermo-hygrometric characteristics have not been compared carefully with those of historical masonry supports, often producing the failure of the restoration work. Long-term plaster detachment frequently occurs as a consequence of the non compatible mechanical characteristics of mortar. Preventing this phenomenon is the main way of increasing the durability of repair work. The use of similar materials to historical ones in terms of mechanical, chemical and thermo-hygrometric performances is preferable (Grazzini, 2006; Bocca & Grazzini, 2012).

The goal of this experimental and numerical analysis, developed at the Non Destructive Testing Laboratory of the Politecnico di Torino, was to focus attention on the preliminary pre-qualification of repair materials before their use, in order to avoid most of the mechanical or physical incompatibility, and at the same time to guarantee the maximum durability of the restoration work (Bocca & Grazzini, 2013).

The methodology is currently being used at Sacro Monte di Varallo Special Natural Reserve (UNESCO heritage site) in Piedmont (Italy). Situated at the top of the hill above the town of Varallo in Piedmont (Italy), the Sacro Monte is an artistic-religious complex consisting of 45 chapels, which contain frescoes and sculptures that tell the story of Christ's life (Figure 1). The aim of this particular architectural site was to reproduce the holy sites in Palestine where Christ had spent his early life. Constructed between the 15th and 18th centuries by the most important artists in Piedmont and Lombardy of that period, the Sacro Monte is also a wonderful example of park gardens. The chapels were constructed very simply, sometimes making use of natural materials, stone or brick walls, with wooden roofs and stone surfaces. Frescoes are located on internal and external plastered walls.

Figure 1. Transfiguration Chapel at Sacro Monte di Varallo

Because of the rising capillary damp, the freeze-thaw cycles and the abundant rain and snow precipitations that characterize this mountain area, the historical plaster of the chapels has been subjected to progressive material decay over the long term (Figures 2-3).

Figure 2. Detachment of historical exterior plasters at Transfiguration Chapel because of the rising damp effects due to capillary action or rain infiltration

Figure 3. Detachment of historical plasters because of the rising damp effects due to capillary action at Sacro Monte di Varallo

Since 2010, a research group at the Politecnico di Torino, composed of engineers, architects, physicists and chemists, has worked together on the RE-FRESCOS project, and has studied the decay of this plaster in different scientific ways, through sophisticated non destructive in situ and laboratory tests. The aim of the research was to offer appropriate technical solutions to stop this decay and to restore the masonry surfaces using compatible and durable materials and techniques in order to save the frescoes in the chapels (Binda et al., 1998).

A part of this project, the research group of the Laboratory of non Destructive Testing Materials at the Politecnico di Torino has carried out particular fatigue tests on ad hoc mixed stone block-mortar specimens in order to evaluate the mechanical adhesion of the new repair mortars to the masonry supports. Unfortunately, some recent restoration work on decayed plasters have already shown their poor durability because of the incompatibility of the employed repair mortars, which are not suitable for the thermal or mechanics stresses encountered at the site. This incompatibility has led to early detachment and decay of these new repair plasters.

This experimental research has focused one’s attention on the detachment of historical plasters without frescoes, for which the Government Department responsible for the historical building can authorize their substitution with similar lime mortar dehumidified plaster. A lot of historical chapels of the Sacro Monte di Varallo had the exterior walls plastered without frescoes that showed various phases of decay and large detachment areas due to damp effects. In these cases any consolidations and reattachment grouts can~~’t~~ restore and strength the original plaster.

On the contrary the restoration of the frescoes located on the plasters can occur only by means of specific consolidation grouts made by inorganic materials (Tulliani et al., 2011).

The experimental results have been compared with a numerical analysis through the cohesive crack model in order to study the evolutionary phenomenon of plaster detachment. The parameters used in the numerical simulation of experimental tests are able to characterize the mechanical behaviour of the interface. It is therefore possible to predict detachment in problems with different boundary conditions.

The experimental and numerical results described about the static tests represent the first step of this experimental study which is currently in progress. The next steps will concern the same type of mixed specimens subjected to cyclic tests.

MATERIALS AND EXPERIMENTAL SETUP

Four assembled specimens have been tested in compressive static load. This composite specimens were prepared by joining a stone block (similar to that of the Sacro Monte masonry) to symmetrical layers of repair mortar on the two shorter vertical sides of the stone block. It was obtained from cut stone placed in designed steel mould and joined to 40 mm thick layer of strengthening mortar cast onto it (Figure 4). This particular typology of assembled specimen has been tested already in precedents experimental researches to appraise the mechanical compatibility between strengthening mortars and historical masonry (Grazzini, 2006). The ad hoc geometry of this stone block-mortar specimens was able to test the adherence between the repair mortar and the masonry structures. The stone surfaces in contact with the mortar were treated by a specific pneumatic drill in order to improve the adherence (Figure 5).

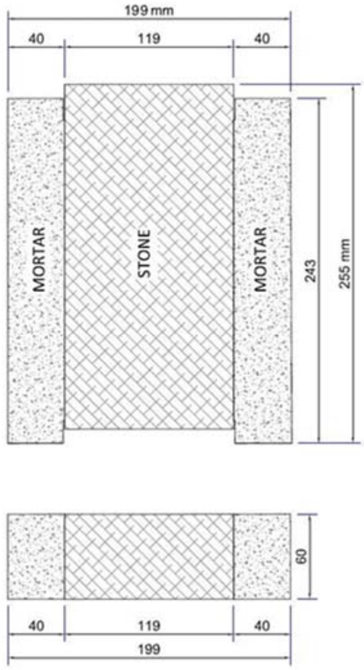

Figure 4. Geometry of composite specimen stone-repair mortar

Figure 5. Adherence surface of stone treated by pneumatic drill

The pre-blended mortar, chosen from among the main ones on the market, is the transpirant base made from natural hydraulic lime and Natural-Pozzolan, which is suitable for the restoration of historical masonry damaged by rising capillary damp and sulphate salts. Young's modulus of this repair mortar, evaluated according to UNI6556, was 4380 MPa. The compressive strength, evaluated according to UNI6556, was 33,8 MPa. The above mentioned values were evaluated 28 days after the casting. The repair mortar used was selected from a specific experimental research among four similar repair products tested and chosen for his best structural compatibility (Bocca & Grazzini, 2012).

The dehumidifying mortar layers were not applied in complete adherence with the stone block support; on the contrary they were applied in symmetrical and regular discontinuity at the bottom and the top of the specimen (Figure 4). These discontinuities behave like notches that are able to trigger multiple crack propagation, in order to simulate the adherence capacity of each repair mortar applied to a specific masonry wall as dehumidified plaster.

The assembled pieces were instrumented with two symmetrical couples of inductive displacement transducers shown in Figure 6. One transducer (SP0) per side was arranged horizontally in the lower part of the specimen and connected between the two opposite mortar layers, in order to measure the displacements due to bulging. The other transducers (SP2), one per side, were placed vertically on the stone block.

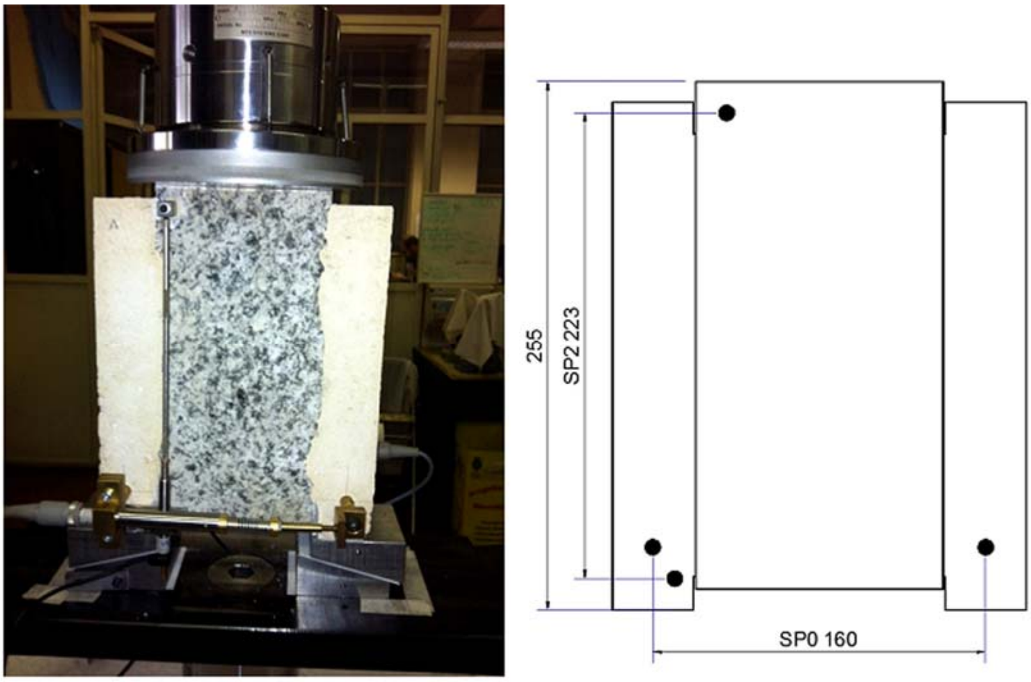

Figure 6. Composite specimen stone-repair mortar and transducer positions

The static compressive tests were performed with the aid of a 250 kN servo controlled machine, (model 810 MTS). Monotonous compression tests were carried out by controlling the horizontal opening (SPO transducers) with a speed opening at 0,0001 mm /s. The specimens were subjected to static tests after 28 days of maturation. The lower mortars layer support was made up of a double system of steel wedges (Figure 7), coupled with Teflon having thickness equal to 1 mm in order to reduce the friction related to the horizontal expansion of the plaster.

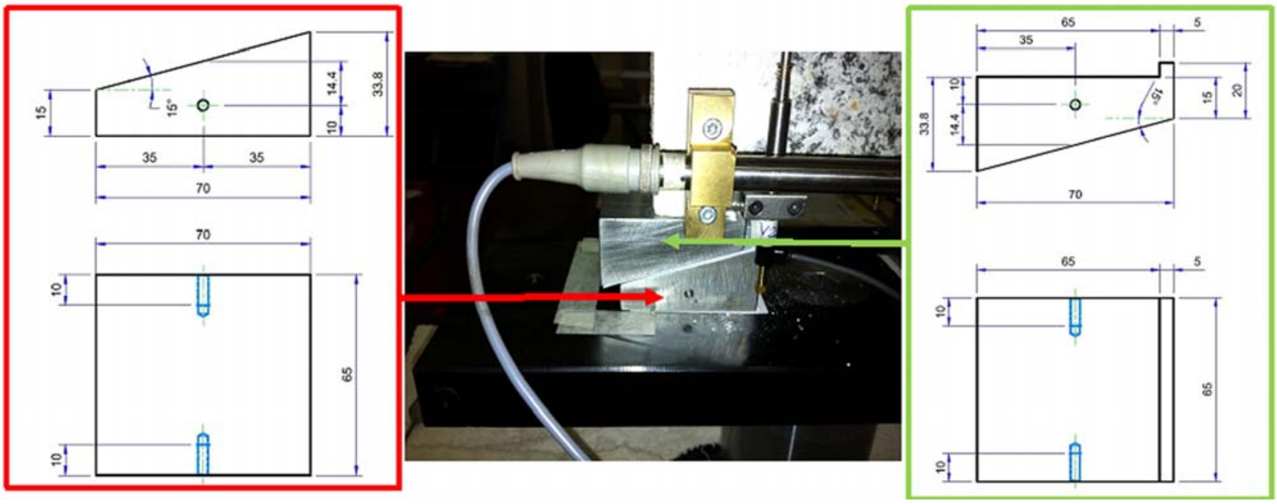

Figure 7. Geometry of the wedges

The assembled specimens were labeled with “SM” (Stone block-Mortar), followed by a number indicating the order.

EXPERIMENTAL RESULTS

The results of compressive static tests are showed in Table 1 and in Figure 8. The assembled specimens stone-mortar show four stress singularity points: two notch tips at the specimen top, and two at the specimen bottom (Figure 4). This points are the weakest planes involved in the singular stress fields. Because of the wedges, the cracks that start from the bottom of the specimen show a greater velocity than the cracks that start from the top of the specimen.

Specimen	Max load (N)	Max horizontal displacement (mm)
SM 01	2530	0,6077
SM 02	1910	1,3218
SM 03	2100	0,7695
SM 04	1970	0,3629

Table 1. Experimental results of static tests

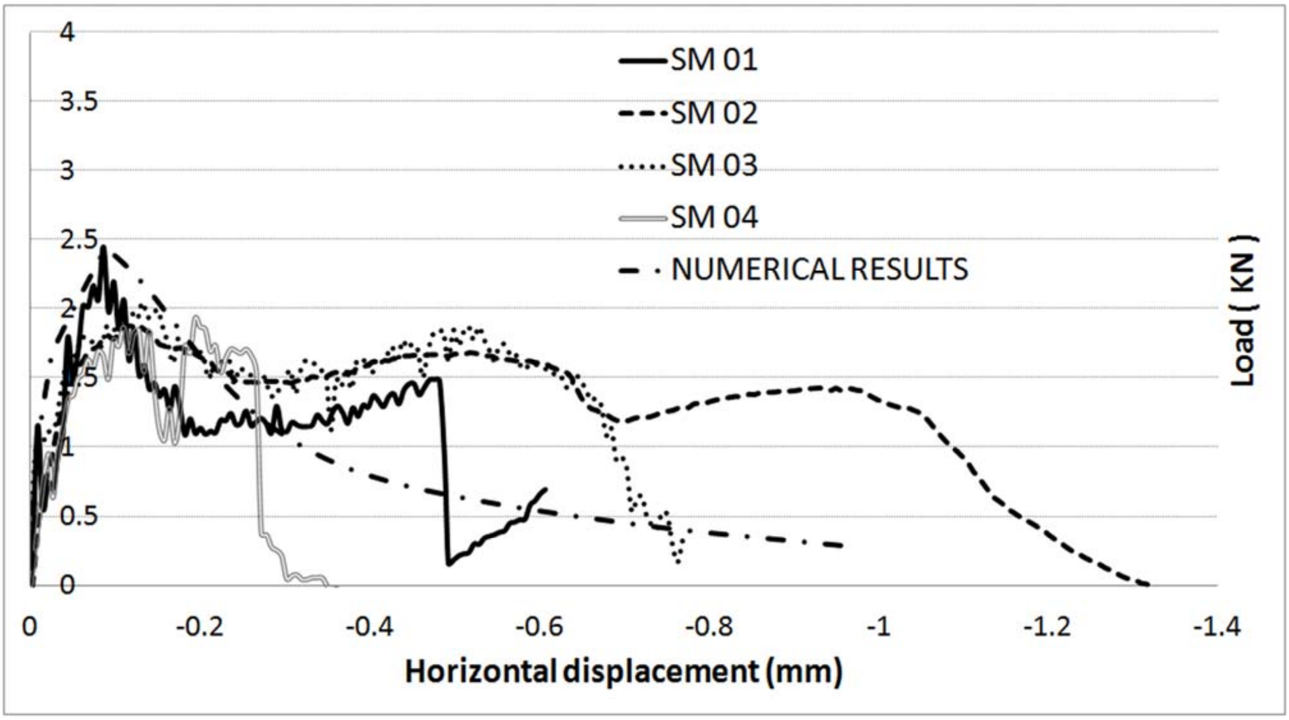

Figure 8. Load-horizontal displacement curves of static tests

To exception of SM 04, the other assembled specimens have shown a ductile behaviour keeping a residual load and displacement after the peak load. The ductile behaviour is a fundamental requirement for a durable service life of repair plasters subjected to fatigue loads as thermo-hygrometric cycles stress or rising damp effects. The specific geometry of the assembled specimens allows to test the adherence between the dehumidified repair plaster and the masonry structures, in order to pre-qualify the durability of the repair product. The notch tips put to the test the adherence of the repair plaster applied to the stone support simulating the fatigue loads that can compromise the restoration work. The teflon sheet, inserted at the contact surface between the upper and lower wedge, was able to reduce the friction and to stabilize the load curves.

This static compressive tests represent a rather fast laboratory procedure useful for the analysis of the detachment of the dehumidified repair plasters applied to the historical masonry of the Sacro Monte di Varallo. The next step of this experimental research, at the moment in progress, is to carry out the cyclic compressive tests in order to simulate the fatigue stress between the masonry stone and the repair mortar.

The pre-qualification procedure of repair materials is a basic preliminary step for a better restoration project. The complex problems of the decay materials in the historical buildings, often caused by different factors, need an increasing experimental time for carry out the pre-qualification tests and in situ monitoring tests with the purpose to better define the decay causes and the choice of the most suitable and durable repair product. Although the detachment problem is caused by damp and thermo-hygrometric phenomena, nevertheless this experimental methodology, even if not performed under the same hygrometric conditions, was useful to test and predict the durability of the dehumidified mortar. Infact, in consideration of the previous experimental results from a range of chosen deumidified mortars (Grazzini, 2006), also the detachment test in static load have given the realistic and reliable comparative predictions about the durability of some repair plasters applied to a specific historical masonry. The stress produced during static tests at the interface between the two materials were similar to hygrometric stress produced during damp effect on time. Therefore the compatibility of the dehumidified mortar were tested.

Although further freezing-thawing cyclic tests surely would be more precise to analyse the durability of the repair plaster subjected to damp, nevertheless their execution would require a lot of time, often not available for the quick choices performed in planning phase. Infact the purpose of this experimental procedure was to give to the restoration planners a brief experimental methodology that was able to simulate the same stress produced at interface between historical masonry and repair mortars during damp effects.

NUMERICAL SIMULATION THROUGH THE COHESIVE CRACK MODEL

The most realistic method used today for the numerical simulation of mortar and stone block fracture is the cohesive crack model, also known as Barenblatt – Dugdale - Hillerborg model for quasi-brittle materials; in the present work the crack initiation criterion is assumed as:

$$\left(\frac{\sigma_0}{f_t}\right)^2 + \left(\frac{\tau_0}{f_s}\right)^2 = 1 \tag{1}$$

where σ_0 and τ_0 are stresses evaluated along the directions normal and tangential to the interface and f_t and f_s are the related strength. The point where equation (1) is satisfied is called *fictitious crack tip*.

According to this method the cohesive stresses acting on the non-linear fracture process zone (shortened FPZ) are decreasing functions of the effective value of the displacement discontinuity (Cervenka et al.,1998; Barpi & Valente, 2002, 2004, 2005, 2008, 2010). In the present work it was assumed:

$$w_{eff} = \sqrt{\left(\frac{w_n}{w_{nc}}\right)^2 + \left(\frac{w_t}{w_{tc}}\right)^2} \tag{2}$$

where w_n is the mutual displacement component normal to the interface and w_t the tangential one. w_{nc} e w_{tc} are the related critical values.

If $w_{eff} > 1$ no stress transfer occurs and the crack is therefore stress free, otherwise, the stresses are decreasing functions of w_{eff} that follow a pre-defined softening law; in the present work the above mentioned law is assumed as follows (Cornelissen et al.,1986):

$$\frac{\sigma}{\sigma_0} = \frac{\tau}{\tau_0} = \left[1 - \frac{1 - \exp\left(-\alpha \cdot w_{eff}\right)}{1 - \exp\left(-\alpha\right)}\right] \tag{3}$$

Where it is assumed $\alpha = 5$. The point where is $w_{eff} = 1$ is called real crack tip. The behaviour of the material outside the FPZ is linear elastic.

In a symmetric model, it is well known (Barpi & Valente,1998; Alberto et al., 2011; Bocca et al., 2011) that the fracture process starts symmetrically, but loses this property before the peak load is reached. In order to prevent numerical difficulties related to loss of symmetry, a small scatter in strength was assumed, as shown in Table 2.

	f_t N/mm^2	1. f_s N/mm^2	2. w_{nc} mm	3. w_{tc} mm
right side	0,2097	0,3159	0,5	0,5
left side	0,2178	0,3249	0,5	0,5

Table 2. Interface parameters.

Therefore the collapse is determined by a detachment process occurring on the right (weaker) side.

The material properties shown in Tables 2 and 3 where calibrated on the experimental results by using the Principle of similitude. In particular, if both elastic modula and strength values are multiplied by the same factor f_1, when all other dimensionless ratio involved in the problem are kept constant, a solution with the same displacement and strain field is expected. Therefore the stress field and the load are multiplied by the above mentioned factor f_1.

Similarly, if both values of critical displacements w_{nc} and w_{tc} are multiplied by a factor f_2 and both elastic modula are divided by the same factor f_2, when all other dimensionless ratio involved in the problem are kept constant, a solution with the same stress field and reactions is expected.

Therefore the strain and displacement fields are multiplied by the above mentioned factor f_2.

In this way it was possible to reduce the number of numerical processes necessary to calibrate the material properties on the experimental results.

	Young's module N/mm^2	Poisson ratio -
Mortar	3942	0,15
Stone	21600	0,20

Table 3. Elastic properties.

The numerical processes were executed through the ABAQUS code (Dassault System Simulia, 2010) by applying a pre-defined downward velocity to the upper face of the stone block. The deformed finite element mesh is shown in Figure 9.

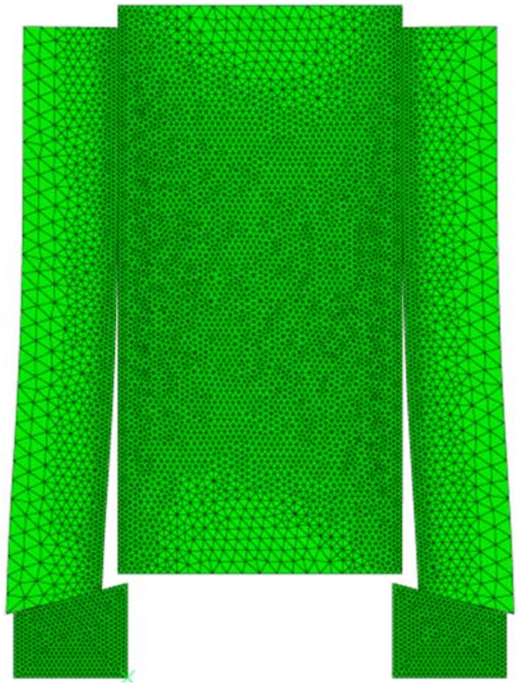

Figure 9. Finite element mesh at the maximum load. Displacements are enlarged 100 times.

DISCUSSION ON EXPERIMENTAL AND NUMERICAL RESULTS

A preliminary elastic analysis shows four points of stress singularities: two notch tips on the specimen top, and two on the specimen bottom (Figure 8). From these points, four cohesive cracks start to propagate along the bi-material interfaces, which are the weakest planes involved into the singular stress fields.

Because of the wedges (Figure 8), the cracks starting from the specimen bottom show a growing velocity larger than the cracks starting from the specimen top. Therefore the second couple of cracks plays the role of main cracks. The surface treatment increases the values of w_{nc} and w_{tc} in comparison to the case of the interface between the same type of mortar and brick (Bocca et al., 2011).

Figure 7 shows that the teflon sheet, inserted at the contact surface between upper and lower wedge, is able to reduce the friction and therefore it reduces the load values too. In the numerical simulation the friction is disregarded.

As far as the horizontal displacement is smaller than 0.2 mm, Figure 10 shows a good agreement between numerical and experimental results.

For larger values of the horizontal displacement, Figure 8 shows a large scatter in the experimental results; this scatter can't be simulated numerically through a fixed set of material properties (deterministic model).

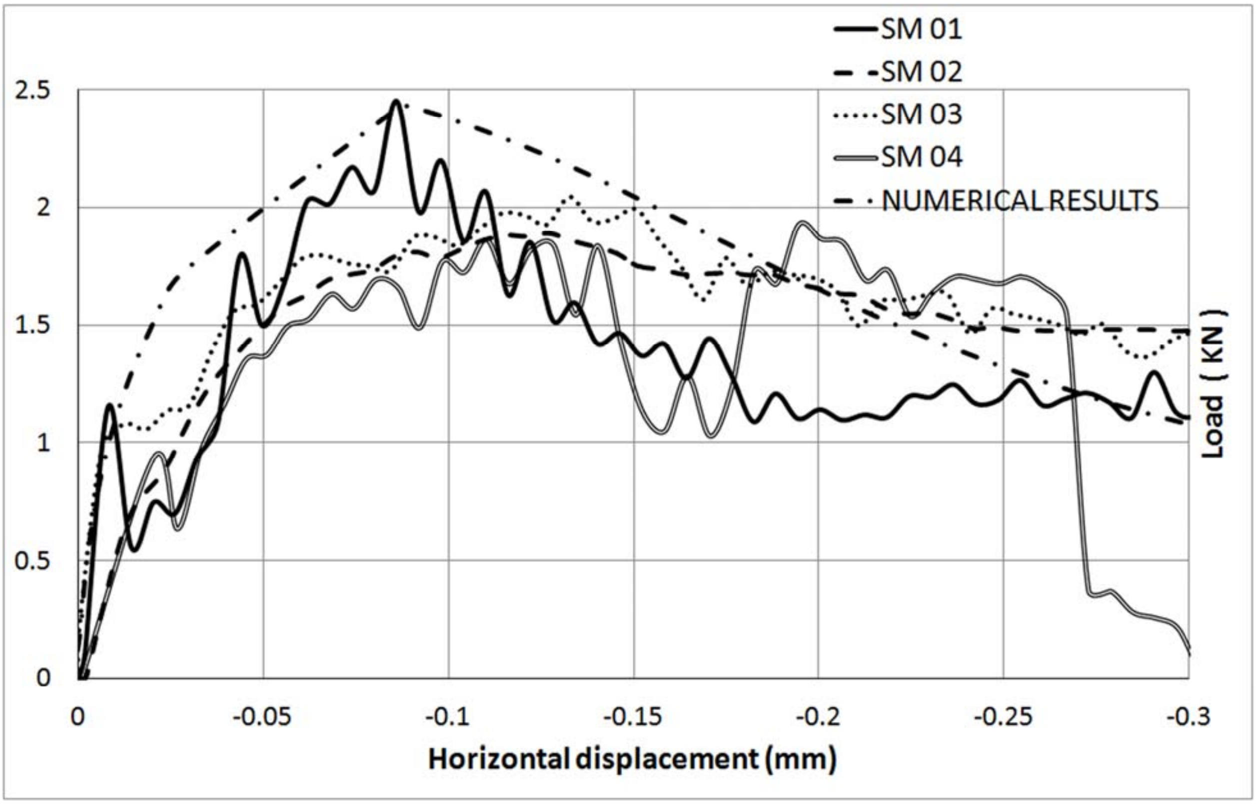

Figure 10. Comparison between numerical and experimental results.

CONCLUSIONS

An innovative preliminary design stage procedure for the pre-qualification of dehumidified repair mortars applied to historical masonry buildings has been described. Compression static tests are carried out on assembled specimens stone block-repair mortar, which specific geometry can test the detachment process of mortar in adherence with the historical masonry structures.

Through a rather fast laboratory procedure, this method supplies useful indication for selecting, from a range of alternatives, the product that is best in keeping with the mechanical characteristics of the historical material, thereby avoiding the errors associated with materials that are not mechanically compatible.

The methodology is currently being used at Sacro Monte di Varallo Special Natural Reserve (UNESCO heritage site) in Piedmont (Italy), where the stone masonry of the Chapels are subjected to rising damp effects due to capillary action or rain infiltrations. The study of the phenomena involved in the detachment process between the masonry stone and the dehumidified repair plasters is basic to plan a durable restoration work of the historical plasters of the Chapels at Sacro Monte di Varallo.

A numerical simulation based on the cohesive crack model was used to follow the experimental data. The evolutionary phenomena involved in the detachment process of mortar in a coupled stone block - mortar system are accurately analyzed by means of the experimental setup proposed. Through the cohesive crack model it was possible to interpret theoretically the above mentioned phenomena occurring at the interface between stone block and mortar. Therefore the mechanical behavior of the interface is characterized. The parameters obtained can be used for the analysis of a problem with different boundary conditions.

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REFERENCES

Fassina V., Favaro M., Naccari A. and Pigo M. 2002. Evaluation of compatibility and durability of a hydraulic lime-based plaster applied on brick wall masonry of historical buildings affected by rising damp phenomena. Journal of Cultural Heritage, 3: 45-51.

Collepardi M. 1990. Degradation and restoration of masonry walls of historical buildings. Materials and Strctures, 23: 81-102.

Grazzini A. 2006. Experimental techniques for the evaluation of the durability of strengthening works on historical masonry. Masonry International, 19: 113-126

Bocca P., Grazzini A. 2012. Experimental procedure for the pre-qualification of strengthneing mortars. International Journal of Architectural Heritage, 6 (3): 302-321.

Bocca P., Grazzini A. 2013. Mechanical properties and freeze-thaw durability of strengthening mortars. Journal of Materials in Civil Engineering, DOI:10.1061/(ASCE)MT.1943-5533.0000597.

Binda L., Saisi A., Ludwig N., Maierhofer C., Leipold S., Schaurich D. 1998. Combination of non-destructive testing methods for the characterisation of the moisture content and distribution in a historic brickwall. *In Proceeding of the 2nd Internationl Conference RILEM on Rehabilitation of Structures*, 112-129, Highett (Australia).

Tulliani J.M., Formia A., Sangermano M. 2011. Organic-inorganic material for the consolidation of plaster. Journal of Cultural Heritage, 12: 364-371.

UNI 6556: 1976. Prove sui calcestruzzi. Determinazione del modulo elastico secante a compressione. UNI (Ente Italiano Nazionale di Unificazione), Milan (Italy)

Cervenka J., Kishen J.M.C. and Saouma V. E.1998. Mixed mode fracture of cementious bimaterial interfaces; part II: Numerical simulations. Engineering Fracture Mechanics; 60: 95-107.

Barpi F., Valente S. 2002. Fuzzy parameters analysis of time-dependent fracture of concrete dam models. International Journal of Numerical and Analytical Method in Geomechanics, 26: 1005-1027.

Barpi F., Valente S. 2004. A fractional order rate approach for modeling concrete structures subjected to creep and fracture. International Journal of Solids and Structures, 41/9-10: 2607-2621.

Barpi F., Valente S. 2005. Lifetime evaluation of concrete structures under sustained post-peak loading. Engineering Fracture Mechanics, 72: 2427-2443.

Barpi F., Valente S. 2008. Modeling water penetration at dam-foundation joint. Engineering Fracture Mechanics, 75/3-4: 629-642; doi 10.1016/j.engfracmech.2007.02.008.

Barpi F., Valente S. 2010. The cohesive frictional crack model applied to the analysis of the dam-foundation joint. Engineering Fracture Mechanics; 77: 2182-2191

Barpi F., Valente S. 1998. Size-effects induced bifurcation phenomena during multiple cohesive crack propagation. International Journal of Solids and Structures, 35(16): 1851–1861.

Cornelissen H.A.W., Hordijk D.A., H.W. 1986 *Reinhardt Experimental determination of crack softening characteristics of normal and lightweight concrete*. Heron, 31: 45-56.

Alberto A., Antonaci P., Valente S. 2011. Damage analysis of brick-to-mortar interfaces. In *Proceedings of 11th International Conference on the Mechanical Behavior of Materials*, 1151-1156, Como Lake (Italy).

Bocca P., Grazzini A., Masera D., Alberto A.,Valente S. 2011. Mechanical interaction between historical brick and repair mortar: experimental and numerical tests. Journal of Physics, 305, 1-10.

Dassault System Simulia Corp. 2010. Providence, RI, ABAQUS, release 6.10.