INTERACTION BETWEEN STRUCTURAL CRACKS AND PLASTER DAMAGE: AN EXPERIMENTAL CAMPAIGN ON MASONRY PANELS

Chiara Calderini¹, Stefania Degli Abbati², Sergio Lagomarsino³, Riccardo Ginanni Corradini⁴, Valerio Piovanello⁵

ABSTRACT

The paper presents the results of an experimental test campaign carried out on masonry panels covered with a traditional three layers plasters. The tests aim is understanding the relationship between the mechanical behaviour of masonry and covering layers under seismic loads. The final goal is to provide a correlation between structural and non-structural damage in masonry walls of heritage buildings and to propose innovative intervention techniques for the repair of seismic damage. The laboratory tests are conducted in diagonal compression, on full-scale mock ups made with materials and techniques reproducing as far as possible historic masonry and artistic surfaces. The masonry reproduces quite well that of L’Aquila (Italy), for which many data are available, while frescos are defined on the basis of Italian tradition. In all experiments, pre-existing damage patterns on the covering are reproduced, in order to take into account typical decay conditions of heritage buildings. In particular, the detachment of plasters is simulated by mean of round paper wafer applied at the interface between masonry and plaster. The tests provide information on: the collapse load of the panels; the damage pattern of masonry and covering surfaces; the displacement capacity of covering in its damaging process.

Keywords: Historic masonry, Testing, Diagonal compression, Plaster, Seismic performance

1. THE PROBLEM OF SEISMIC DAMAGE TO ARTISTIC ASSETS

A comprehensive reliable risk assessment for historical monuments should regard not only their architectural and structural components, but also movable (paintings, statues, libraries…) and unmovable (frescos, stucco-works, pinnacles, battlements, banisters, balconies) artistic assets accommodated in. This latter is an unexplored [1-3] and critical issue, mainly own to the evidence that the seismic damage of artistic assets is often related to small damage levels of the housing structure. Their protection requires, thus, the definition of appropriate limit states and the development of suitable modelling strategies.

To this aim, it is useful to distinguish the different types of artistic assets in historic buildings, on the basis of their typical seismic behaviour [4]. Concerning immovable assets only, three main different classes may be recognized: the first one is that of artistic assets which are structural elements by themselves (caryatid, carved stone columns, carved stone arches,…); the second is that of artistic assets which are not structural elements but have an own seismic response (statues, altars, pinnacles,…); finally, the third one is that of artistic assets which are not structural elements but are strictly connected to structural elements (frescos, mosaics, stuccoes,…). In this paper, this latter class of assets is considered (Fig. 1).

¹ Assistant professor, University of Genoa, chiara.calderini@unige.it
² Research assistant, University of Genoa, stefania.degliabbati@unige.it
³ Full professor, University of Genoa, sergio.lagomarsino@unige.it
⁴ Il Cenacolo s.r.l., Rome, Italy, riccardo.ginanni@ilcenacolo.net
⁵ Il Cenacolo s.r.l., Rome, Italy, valerio.piovanello@ilcenacolo.net

2923
The main issue for the considered class of assets is the interaction between the behaviour of structural and non-structural elements; in particular, the interaction between the damage in the sustaining walls and the damage in the finishing surfaces (plasters and painted or frescoed surfaces) should be analysed. In the paper, preliminary results of an experimental campaign oriented to study these issues are presented. The research has different aims: the definition of proper limit states for finishing surfaces in relation to the damage of structure; the development of suitable modelling strategies for plasters and frescos under seismic actions; the definition of innovative intervention techniques for the reparation of seismic damage.

2. DESCRIPTION OF THE TEST CAMPAIGN

2.1. Aim of experimental tests
The results of a laboratory experimental test campaign carried out on masonry panels covered with a traditional plasters are here presented. The tests are conducted in diagonal compression, on full-scale mock-ups made up with materials and techniques reproducing as far as possible historic masonry and artistic surfaces. The masonry tries to reproduce that of L’Aquila (Italy), for which many data are available, while plasters are defined on the basis of Italian tradition. In all experiments, pre-existing damage patterns on the covering are reproduced, in order to take into account typical decay conditions of heritage buildings.

The tests provide information on both the behaviour of structural elements (masonry panels) and non-structural ones (coverings). In particular, the strength of masonry will be defined on the basis of the collapse load of the panels. Moreover, an approximate evaluation of the shear modulus will be provided. These parameters will be useful to calibrate models available in the literature and developed by the authors in past researches [5]. The results of the experiments will support the updating of mechanical parameters to be adopted in models and codes. Finally, the relationship between structural damage states and structural limit states will be analysed. Considering non-structural elements, the damage of covering surfaces will be analysed in terms of crack width and distribution during the tests. The crack pattern of coverings will be compared with that of masonry, by removing the plasters after the tests. Moreover the effect of pre-existing damage will be discussed. Finally, preliminary limit states will be defined on the basis of the data collected.

2.2. Description of tests and test set up
The laboratory tests are conducted in diagonal compression on eight masonry panels $90 \times 90 \times 36$ cm large, finished with three layers plaster; in all experiments, pre-existing damage patterns on the covering are reproduced through some round paper wafers applied at the interface between masonry and plaster.

The diagonal compression test is carried out with a procedure similar to that described in ASTM E 519-02 [6] and RILEM TC 76-LUM [7], in which a square masonry panel is subjected to a compressive force applied on one of its diagonals. In some cases, an edge load is applied in order to produce pre-compression stresses normal to bed joint planes (Fig. 2). The load on the specimen is
applied by a hydraulic jack action on steel shoe placed at the top corner and transmitted to a similar shoe at the bottom corner. The tests are performed with many cycles of loading and unloading, increasing the jack action gradually until the failure of the panel so as to identify the shear diagonal tensile strength $f_t$ and the shear modulus $G$, depending on the progress of cracking.

A system based on an infrared camera is used in order to follow in detail covering’s damaging process and to evaluate plaster’s damage pattern and displacement capacity. Furthermore, during the tests, the detachment of plaster process is identified by thermography.

Fig. 2 Diagonal test set up with (a) or without (b) the edge load applied in order to produce pre-compression stresses normal to bed joint planes

2.3. Technical realization of test mock-ups
The masonry panels are built in order to reproduce traditional rubble stone masonry walls of old buildings in L’Aquila. The cross-section is formed by two external leaves made of small-medium size stones (standard stone dimensions are about $18 \times 12 \times 12$ cm) and a central leaf made of smaller stones and mortar infill. The two external leaves are not connected through systematic cross-through stones; however, each panel is characterized by the random presence of some bigger stones which ensure a good cross-section connection. The face of the masonry panel is characterized by the presence of rough-hewn stones, quite small and not very stretched, while mortar joints are quite thick.

Fig. 3 Example of front (a) and cross-section (b) of masonry walls in L’Aquila

All the panels are built with lime stones and air lime mortar. The stones have been carefully chosen, in order to maximize the fitting and the interlocking between them. The remaining voids have been filled with mortar and small stones, roughly broken and then finished off with care and then hit it with the hammer until ensuring even better placing with the mortar joints. The stone/mortar volume ratio is about 1:1.5.
The stones used for the panels are made up of a sedimentary, carbonaceous, monomineralogic stone, characterized by different colouring changeable from dark grey to light grey. No particular textural characteristics are to be noticed, such as laminations or colour strings, while at a deep microscopic analysis it reveals to be quite thick. It has no vacuoles nor fossils but presents thin calcitic stripes, while on the surface there is a slight patina due to orange oxides. All the stones come from a quarry located in Vado Ligure, Savona, Italy.

The mortar used to build the masonry panels is a non magnesiac air lime mortar, made up of a normally seasoned non hydraulic patty and aggregate obtained by crushing and grinding the same limestone of stones. The non hydraulic patty is classified as CL 90-S referring to UNI EN-459-1:2002 [8]. The aggregate is calcareous and characterized by a grading which is variable from very fine to rough. Fig. 5 shows the grading curve that characterizes it, where x-coordinate represents mesh’s sieve and y-coordinate the crossing aggregate percentage.

Two types of air lime mortar are realized: the first one has a binder/aggregate ratio of 1 to 3, while the second one has a lower binder/aggregate ratio of 1 to 2.5, so that the air lime mortar results to be more fluid and capable to fill all the spaces between the stones. In order to create a perfect mixture, sand quarry and patty have been mixed for a long time.

The surface of each panel has been finished by a three layers lime plaster. Each layer has a different thickness and different aggregate grading (Table 1). The plaster has been realized by mixing the same patty and aggregate used for the panel construction.
Table 1 Features of lime plaster’s layers

<table>
<thead>
<tr>
<th>LAYER</th>
<th>THICKNESS</th>
<th>AGGREGATE DIAMETER (AVER.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner</td>
<td>Necessary to level panel’s surface</td>
<td>8 mm</td>
</tr>
<tr>
<td>Mean</td>
<td>1-1.5 cm</td>
<td>4 mm</td>
</tr>
<tr>
<td>Outer</td>
<td>2 mm</td>
<td>0.5 mm</td>
</tr>
</tbody>
</table>

In order to simulate a pre-seismic damage, one round paper wafer (φ = 20 cm) has been applied between the inner and the mean layer of plaster on one side of each panel (Fig. 6). The wafer has been alternately located in the centre of the surface (for half panels) and in an asymmetric position (for the other ones).

![Fig. 6 Location of round wafer on each panel’s single front: a) in the centre of the surface; b) in an asymmetric position](image)

Table 2 summarizes the features of each panel subjected to diagonal compression test.

Table 2 Summary of the features of the mock-ups

<table>
<thead>
<tr>
<th>PANEL</th>
<th>FEATURES OF LIME MORTAR</th>
<th>TYPE OF PLASTER</th>
<th>PAPER WAFER’S POSITION</th>
<th>TEST SET UP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AGGREGATE</td>
<td>BINDER</td>
<td>BINDER/AGGR. RATIO</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Calcareous</td>
<td>Non hydraulic patty</td>
<td>1:3</td>
<td>Central</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td>Traditional three layers plaster</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td>Central</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td>Asymmetric</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td>Central</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td>Asymmetric</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3. CHARACTERIZATION OF MASONRY

A set of tests have been performed in order to preliminarily characterize the masonry components.

3.1. Stones

In order to characterize the stones, the following tests have been performed: hydrostatics weighting test, whose aim is to obtain specific gravity; Point Load Test, whose aim is to obtain a preliminary classification of the stones. In particular, the specific weight has been obtained for six stone samples, 2927
which looked different in terms of colours and textures; the results are not very different for each type of stone and are similar to the standard values proposed in literature for limestone (2.6-2.8 g/cm³). Point Load Test has been performed in laboratory on various samples of different shapes, as the Recommendations ISRM (1994) suggest [9]. The main aim is to obtain the resistance to a point load \( I_{4(50)} \), which can be correlated both to the tensile strength \( (I_{8(50)} \) is about 0.80 times the direct tensile strength obtained from “Brasiliana test”) and to the compressive one \( (I_{9(50)} \) is about 20-25 \( C_0 \), where \( C_0 \) is the compressive strength). The results obtained are lower than the expected values for limestone (compressive strength: about 23 Mpa; tensile strength: about 1.3 Mpa). However, it is important to point out that since only few samples were tested, the reliability of this test is scarce (the aim was only to have a preliminary classification of the stones). For this reason, a more accurate mechanical characterization obtained through the sampling of some cores from the stone quarry is planned in the near future.

### 3.2. Air lime mortar

In order to define the exact mixture of the mortar before the masonry panels construction, different types of air lime mortars have been tested following the indications of UNI EN 1015-11:2007 [10]. In particular, 24 prismatic specimens (measuring 160 × 40 × 40 mm) have been realized by using different aggregate types and binder/aggregate ratio, as shown in Table 3.

<table>
<thead>
<tr>
<th>NUMBER OF SAMPLES</th>
<th>BINDER TYPE</th>
<th>AGGREGATE TYPE</th>
<th>BINDER/AGGREGATE RATIO</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>NON HYDRAULIC PATTY</td>
<td>CALCAREOUS AGGREGATE</td>
<td>1:2</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>3 parts of CALCAREOUS AGGREGATE + 1 part of RIVER SAND</td>
<td>1:2</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>CALCAREOUS AGGREGATE</td>
<td>1:3</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>3 parts of CALCAREOUS AGGREGATE + 1 part of RIVER SAND</td>
<td>1:3</td>
</tr>
</tbody>
</table>

One flexural and one compressive test have been performed each week on one sample of each type of mortar; the fourth week, the three last samples of each type have been tested in order to have a statistic result. The tests aim, on the one hand, is to evaluate the flexural and compressive strength of the mortar and the influence of different binder/aggregate ratio and aggregates; on the other hand, is to evaluate the ageing period and the expected increase of flexural and compressive strength. The results of the experimental tests on mortar specimens show that:

- The binder/aggregate ratio of 1:3 is better than the binder/aggregate ratio 1:2, even if the results are not so different;
- The presence of river sand does not affect the final resistance of the air lime mortar;
- The resistance of air lime mortar is quite low (compressive strength is about 7-8 kg/cm²; flexural strength is about 3-4 kg/cm²), but it slowly increases as evident in literature.

![Fig. 7](image.png)  
Flexural test (on the left) and compressive test (on the right) on mortar specimens

---

2928
3.3. Plan of collection and reprocessing of the masonry construction data

During panels construction, an easy and quick methodology for the collection of all the construction data has been tuned up. This methodology was based on the combination of an accurate photo-campaign of all leaves for each masonry panel, supported by the filling of a specific form to organize some extra-information which cannot be deduced by pictures. In particular, pictures of all the leaves for each masonry panel have been taken during the panel construction, together with a picture of each side of the panel. Each picture was then straightened up. The picture analysis allowed us to collect quantitative information on the masonry pattern such as the real dimensions of the used stones, the number of bigger or smaller stones, the number of empty spaces etc... The number of stone fragments (which cannot be deduced from the pictures because of the presence of mortar) was marked in the form, specifying their location in the face or in the cross-section of the panel.

The aim of this work was to deduce the real pattern of each masonry panel \textit{a posteriori}, in order to possibly establish a connection between the mechanical behaviour of the panel subjected to the diagonal compression test and its building characteristics.

4. CONCLUSIONS

Unluckily, at the moment, the results of the tests are not yet available since they will be performed on July 2012.

ACKNOWLEDGEMENTS

The results have been achieved in the project PERPETUATE (www.perpetuate.eu), funded by the European Commission in the Seventh Framework Programme (FP7/2007-2013), under grant agreement no 244229.

REFERENCES


2929