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Review of existing in experimental testing of masonry structures subjected to horizontal loads

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Abstract: The quasi-static cyclic test on masonry panels are more diffused for the evaluation of the seismic performances of masonry. The proposed paper shows the first results of a wide analysis of experimental tests, reported in the international technical literature, in order to identify the procedures more usually used and emphasized the principal aspects that stand to the execution of cyclic tests on masonry wall. In the second part of the paper it is reported an example of numerical simulation of some experimental Italian masonry tests, using a sophisticate finite elements code.

1 INTRODUCTION

The evaluation of the effects produced by seismic actions on masonry structures constitutes an important question for experimental and numerical research.

The techniques of experimental research on masonry elements, usually used in the laboratories, are:
1-tests quasi static (cyclic and non cyclic);
2-tests based on pseudodynamic method;
3-tests on shaking table.

Cyclic tests are, among the shear tests on walls the most diffused technique for its simplicity of realization. They, based on the application of predetermined loading histories (forces, displacements or deformations) by means of hydraulic jacks, do not consent a faithful reproduction of structural behaviour under seismic action, but they aim to rich, in a simple and easily performed way, the principal aspects that mostly characterized the structural response.

For this purpose two approaches can be followed in order to carry out an experimental program: the first one tends to simulate as closely as possible the actual service condition of structures both in terms of boundary conditions and in term of loading such that results to be directly used in design can be provided. The second one tends to give an experimental base for a theory which holds for more general cases than the experimental ones. In the latter case especially the tests have to be performed with clear procedures such that a numerical simulation can be easily developed.

However, the first way, though more used up to date, not always has leaded to good results since the introduced restraint conditions sometimes do not significantly represents the actual ones which vary as element cracking grows. Moreover loading histories seldom represent the real distributions of plastic excursions due to earthquake. The second way appears more promising, because the development of a complete theory for interpreting the mechanical behaviour of masonry structures under monotone and cyclic loading consents an applicability more extensive. Nevertheless, the international experimental researches seldom allow a simple numerical simulation because on the test model are present the actions of the boundary structures not easily estimated.

The proposed paper shows the first results of a wide analysis of experimental tests, reported in the international technical literature, in order to identify the procedures more usually used and emphasized the principal aspects that stand to the execution of cyclic tests on masonry wall; it can be an useful reference to start and to present the experimental researches, exactly as a protocol of communications that contain all the informations and data necessary to evaluate the results and to make numerical analyses. In the second part of the paper it is reported an example of numerical simulation of some experimental Italian masonry tests, using a sophisticate finite elements code.

2 EXPERIMENTAL EVALUATION

The main phases of an experimental research on masonry are the planning out of the experimental program, the realization of preliminary tests on the basic materials and the design of tests on specimens selecting the boundary conditions, the loading history and the behavioural parameters to evaluate.

It has to be noted that, in this paper, the word "specimen" identifies the walls subjected to final full-scale (or eventually reduced-scale) tests, whereas the preliminary tests are carried out on "components" or "small-sized composite elements".

The planning out of the experimental program (see Figure 1) requires the choice of the specimens' dimensions and loading method on the basis of the available testing facilities; on the other hand the specimens' dimensions (height, width, thickness) shall be chosen in such a way as to ensure that the behaviour under testing load simulates the behaviour in actual conditions.

EXPERIMENTAL PROGRAM
- OBJECT
  - UNREINFORCED MASONRY
  - REINFORCED MASONRY
  - RETROFITTED MASONRY
- SPECIMENS' DIMENSIONS
  - FULL SCALE
  - REDUCED SCALE
- LOADING METHOD
  - SEISMIC LOADS
    - STATIC OR QUASI-STATIC
      - MONOTONIC
      - CYCLIC
      - NON CYCLIC
    - PSEUDODYNAMIC
    - DYNAMIC (SHAKING TABLE)
  - NON SEISMIC LOADS

Figure 1. Experimental program

With regard to the characteristics of the specimens another thing to be considered is the aspect ratio; the choice of this parameter is connected with the design of tests on specimens and with the failure modes to be achieved and studied (see Calvi and Magenes (1991)).

In this section the main aspects of an experimental program direct to the evaluation of the in-plane seismic behaviour of unreinforced masonry using cyclic loading modality are reported.

The first phase is the execution of the preliminary tests. The purpose of the preliminary tests (see Figure 2) is to determine the main mechanical parameters of the materials used for the manufacturing of the specimens, in order to provide the basic information that make it possible to compare and assess the experimental results obtained on the specimens in different research centers, and to execute numerical simulations of the tests.

The preliminary tests are usually classical monotone tests. It is useful that all tests are carried out according to RILEM guide-lines (1988). Particularly tests on mortar should be carried out at 28 days and again at the same time as those on the masonry specimens (RILEM 1988).

The elastic modulus may be determined from the stress-strain curve as tangent or secant modulus. The secant modulus is most commonly used and is easier to determine; the points on the curve used for determining secant modulus are variable and some codes (EC6 1988) indicate the loading levels for this evaluation.

Another important aspect is the effect of anisotropy: the evaluation of elastic parameters in two orthogonal directions is useful for the determination of medium values of masonry elastic moduli.

PRELIMINARY TESTS
- COMPONENTS
  - COMPRESSION
  - TENSILE
    - DIRECT
    - INDIRECT (SPLITTING TEST)
    - BENDING (MODULUS OF RUPTURE)
  - ELASTIC MODULUS
  - POISSON'S RATIO
  - WATER ABSORPTION
- SMALL-SIZED COMPOSITE ELEMENTS
  - PRISMS
    - COMPRESSION
    - DIRECT TENSION ON MORTAR JOINT
    - TENSILE OR SHEAR
      - DIAGONAL COMPRESSION
      - RACKING TEST
    - STRESS-STRAIN CURVE
    - ELASTIC MODULUS
    - POISSON'S RATIO
  - TRIPLETS
    - SHEAR
      - COEFFICIENT OF FRICTION
      - COHESION

Figure 2. Preliminary tests

BOUNDARY CONDITIONS
- RESTRAINT CONDITIONS
  - RESTRAINED ROTATION AT ONE END
  - RESTRAINED ROTATIONS AT BOTH ENDS
- LATERAL LOAD
  - UNIAXIAL (LOADING-UNLOADING)
  - BIAXIAL
- AXIAL LOAD
  - CONSTANT
  - VARYING
  - BALANCED
  - ECCENTRIC
  - AXIAL-SHEAR RATIO

Figure 3. Boundary conditions

ASTM standards provides two methods to evaluate shear or diagonal tensile strength on prisms: racking test (ASTM 1980) and diagonal compression test (ASTM 1974); during the preliminary tests it is proper to use the second test method which is easier to perform and provides however reliable data. Some useful considerations about the carrying out modality and limits of the shear tests on triplets are reported in Atkinson et Al. (1989) and in Calvi and Magenes (1991).

An accurate description of the boundary conditions (see Figure 3) in another important aspect to make it possible the comparison of the experimental results among various research centers.

The choice of boundary conditions with restrained rotations at both ends of specimen is nearer to structural behaviour of masonry buildings with rigid slabs. The application of constant axial load is preferable, even if it is very difficult (Faella et Al. (1991)), because the variation of axial load affect the evaluation of some behavioural parameters.

The lateral and axial load and the reactions have to be transmitted in such a way as to produce a reasonably uniform transfer along the specimen, and far enough from the zone under study to avoid any uncontrollable effects on the stress distribution.

In some circumstances it is necessary to fit in some devices which are able to evaluate the part of applied lateral load that is borne by friction in the testing apparatus.

The main aspects to be considered when planning out a cyclic loading history are reported in Figure 4.

- CYCLIC LOADING HISTORY
  - CONTROLLING PARAMETER
    - FORCE
    - DISPLACEMENT (ROTATION)
    - DEFORMATION
  - CYCLES CHARACTERISTICS
    - SHAPE
      - SYMMETRIC
        - SINUSOIDAL
        - TRIANGULAR
        - TRAPEZOIDAL
      - ASYMMETRIC
      - ALTERNATE
      - NON ALTERNATE
      - INCREASING CONTROLLING PARAMETER
      - CONSTANT CONTROLLING PARAMETER
    - FREQUENCY
    - AMPLITUDE
    - NUMBER
      - ALL CYCLES
      - CYCLES WITH CONSTANT AMPLITUDE

Figure 4. Cyclic loading history

The choice of cyclic loading history is a very important problem in the analysis of seismic behaviour of masonry elements. In fact, the use of a cyclic history characterized by a few cycles with large excursions and many cycles with small excursions, similar to real seismic history (Cosenza and Manfredi (1990)), attends the direct evaluation of seismic behaviour. On the contrary, the adoption of different cyclic history requires the introduction for the use of experimental results in seismic design.

- BEHAVIOURAL PARAMETERS
  - GLOBAL FORCES
    - SHEAR
    - AXIAL FORCE
  - GLOBAL DISPLACEMENTS
    - HORIZONTAL
    - VERTICAL
    - ROTATIONS
  - DEFORMATIONS
    - LOCAL VALUE
    - GLOBAL VALUE
  - RESPONSE CHARACTERISTICS
    - FAILURE MODALITY
    - SHAPE OF HYSTERETIC MODEL
    - CRACKING PATTERNS
    - DUCTILITY CAPACITY
    - ENERGY ABSORPTION
    - DAMAGE EVOLUTION
      - STIFFNESS DEGRADATION
      - STRENGTH DEGRADATION

Figure 5. Behavioural parameters

Whereas several papers do not report the cyclic loading rule, some examples of this one are reported in Luders and Hidalgo (1988), Nishi et Al. (1988), Larbi and Harris (1990). Some useful considerations about the planning out of the loading rule are reported in Alexander et Al. (1974).

It has to be said that the displacement at the top of the specimen is the most used controlling parameter in the experimental programs reported in the scientific literature. It is useful to carry out a preliminary monotone lateral displacement increase test before carrying out the cyclic tests, in order to define the largest and the intermediate values of cycles amplitude (ECCS 1986).

The main behavioural parameters to evaluate during the test on specimens are reported in Figure 5.

In order to obtain an accurate evaluation of the behavioural parameters the acquisition data system has to able to make a sufficient number of readings to determine definitely the load-displacement curve for all cycles (shape of hysteretic model).

3 NUMERICAL SIMULATION

The masonry is a material strongly not homogeneous for its two-phase macroscopic nature and therefore its mechanical properties are conditioned by geometric and strength material characteristics and by the modalities of construction. This circumstance joined to the extreme diversity of the used materials and of the constructive typologies, when vary times and places of realization, makes more articulate the model of masonry structures.

Moreover the mechanical properties are dependent by the inclination of the principal stress directions because masonry is a material strongly anisotropic for the presence of blocks and mortar that individualize preferential strength directions. This anisotropy is not difficult to model for masonry structures with regular blocks, but instead the model is more complicated for masonry with irregular structure, very frequently used in the traditional building.

Masonry shows a clear non linear behaviour under load due to the modest tensile strength of constituent materials and to the state of coercion that is present between blocks and joints of mortar because of their different deformability; both the circumstances cause wide phenomena of microcracking that are present only for modest states of stresses. To this progressive cracking are to be added phenomena of sliding to the interface between blocks and mortar, which extension depends by the bond between blocks and mortar that is conditioned by the building modality.

Because of these considerations it is possible to observe that the model of mechanical behaviour of the masonry can be made with different levels of difficulty for what concern the model of the materials and of the structure; the choice is conditioned by different levels of load and by the knowledge of experimental parameters required for the models.

In general the masonry can be treated in three different ways:

- material homogeneous and isotropic characterized by medium properties;
- material homogeneous and ortotropic or anisotropic;
- material two-phase constituted by blocks and mortar.

The homogeneous and isotropic model is the most simple to define because it requests few experimental parameters easily valuable and it is adapt for masonry structures with irregular blocks. For conditions of loads prevalently axial the principal compression directions are practically vertical and then generally orthogonal to the joints of mortar; in this case the influence of the anisotropic nature of the material is not significant on the mechanical behaviour of masonry and then is sufficient to identify the strength and deformability characteristics in such direction. For masonry elements subject to a bending and shearing stress, and to compression as well, the calculus is more complex and articulate and is necessary an approach with finite elements using medium parameters that consider the different mechanical behaviour in the various directions.

For the use of a ortotropic or anisotropic model is necessary to introduce strength and deformability parameters dependent by the inclinations of the principal stress directions respect to the run of blocks and mortar.

The introduction of a two-phase model that considers the strength and deformability characteristics of constituent materials and takes in account the real dimensions of blocks and mortar joints, appears more logical with reference to the macroscopic two-phase nature of masonry. This approach, in effect, only apparently gives results more reliable, in fact the utilization of a model so refined requests the introduction of many parameters, some of them particularly difficult to determinate (bond between blocks and mortar) and others practically impossible to estimate (geometrical characteristics for walls with irregular elements). In spite of that, the approach two-phase with bidimensional and tridimensional models is indispensable for the knowledge of local behaviour of masonry that otherwise would be missed with the use of an homogeneous equivalent model. Therefore these models, that bear remarkable computational onus, are to use when local phenomena govern the problem, for example in case of concentrated loads or when aiming to provide local behaviour models from which obtain correlations between homogeneous equivalent parameters and strength and deformability properties of constituent elements.

The simulations done in order to provide some examples, have interested the experiences led in Italy by Benedetti (1985) on tuff panels and by Bernardini and others (1979) on brick panels. In both cases, for what concerns load, the specimens are interested by axial effort and horizontal load at top, while for what regards the conditions of boundary, the panels are bound to rotation at both sides.

The instruments of tests, reported in figures 6 and 9, are very similar because in both cases the top boundary is granted by the presence of a rigid beam connected at the bottom by two bars; such kind of boundary involves an axial load variable respect the value set at the beginning of the test; because the bars react in a variable way by means of the rigid rotation of the panel. Such event has influenced the results of the numerical simulation since without knowing the law of variation of axial load, it has been preferred to consider it constant and equal to the starting value.

For what concern the characterization of the mechanical properties, the masonry has been structured as a homogeneous equivalent material, using for it the criterion of yielding of Kupfer and the criterion of cracking of Hilleborg (Abaqus 1990).

For what concerns such question the characteristics provided by the testers are not exhaustive, since the knowledge of the elastic modulus E in orthogonal direction towards joints of mortar, already determined in the preliminary tests, is not sufficient.

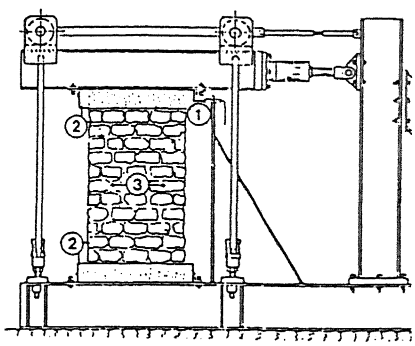


Figure 6. Experimental set-up (Benedetti (1985))

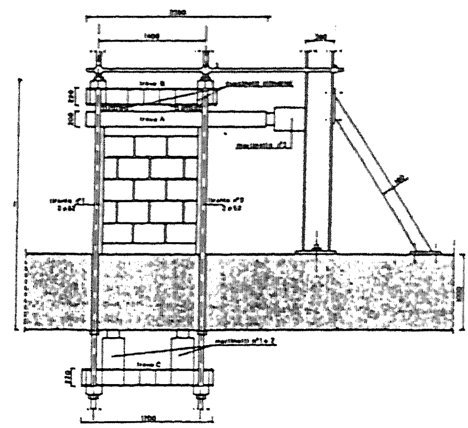


Figure 9. Experimental set-up (Bernardini (1979))

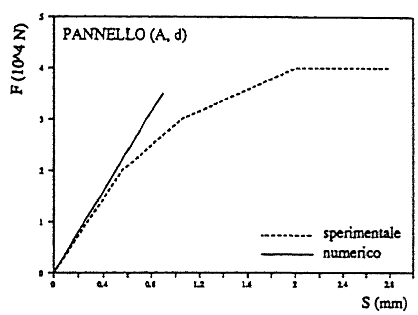
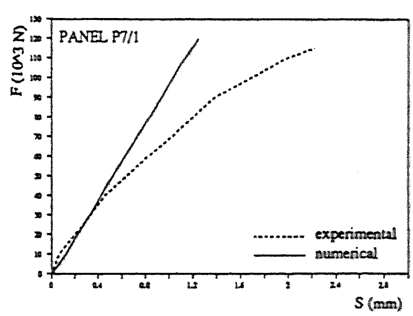


Figure 7.



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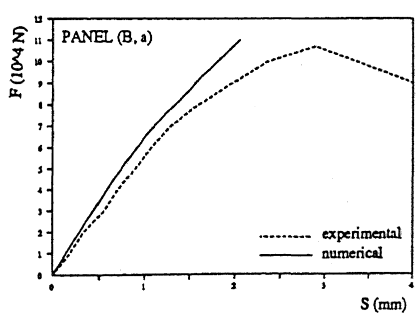

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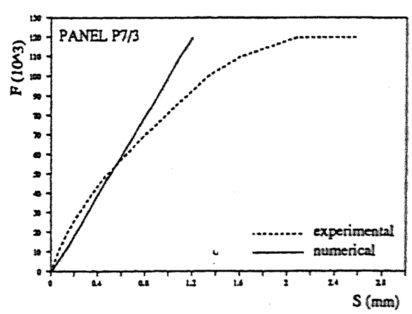

Figure 11.

In fact the intrinsic anisotropy of masonry and the regime of bending-shearing stresses involve a change of the mechanical characteristics in function of the principal directions of stresses. And so, whenever it is taken into account a homogeneous equivalent material it is necessary to introduce a reduced elastic modulus.

That considers, even in approximate way, of the effects of the anisotropy. In the simulations performed it is been adopted, without more precise elements, a medium elastic modulus value equal at 60% of the elastic modulus in orthogonal directions of the joints of mortar.

The comparison between the experimental results is reported in fig. 7, 8, 10, 11 for what concerns panels (B,a) and (A,d) of the tests of Benedetti and panels P7/1 and P7/3 of the tests of Bernardini.

4 CONCLUSIONS

This study has allowed to identify the procedures mainly adopted in international community for what concern the cyclic tests on masonry walls and to show the principal characteristics of this tests that both represent the classification criteria of a wide report that is about to be established in order to be able to compare the results obtained from different researchers and to provide a framework for a codification of test modalities on masonry walls.

The analysis of the experiences made has allowed to identify two points that seems to be of great importance with regard to application of load:

-the vertical load appears in most of cases variable and its increase is not controlled, but it is due to reaction of boundaries structures; such event makes difficult enough the evaluation of some mechanical characteristics that depend by the level of normal stress, and more the numerical simulation of tests shows some problem, as already seen in the example given, due to the undetailed knowledge of the law of variation of normal stress ;

-the horizontal load is applied with laws vary different from each other that mainly almost every times don't coincide with the effective distribution of seismic cyclic, and that vary often seems to be not useful to the development of theoretical model of damaging.

The numerical simulation made not always provided satisfactory results and this is due either to the natural difficulty to model a material so heterogeneous such the masonry and to two principal characteristics:

-they missed evaluation of anisotropy characteristics of masonry wall mainly in terms of elastic parameters; in both cases it is provided by the authors only the value of elastic modulus relative to a load directions orthogonal to the mortar and it seems so difficult due to make an appraisal of the elastic modulus when the principal compression direction bend just like it occurs for the present horizontal load;

-the missed knowledge of the law of variation of axial stress that in both cases tends to increase when horizontal loads increases with a substantial stability effect.

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