Combined Cyclic Testing Procedures in Diagonal Compression on Hollow Clay Block Reinforced Masonry

(Procedimenti di prova combinati su muratura armata in blocchi laterizi soggetta a cicli di compressione diagonale)

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ABSTRACT

Information on ductility and strength degradation of reinforced masonry walls undergoing shear cycles can be achieved by means of different kinds of tests. Two nominally identical specimens were tested in cyclic diagonal compression. The tests were performed with either imposed distortion or imposed maximum load. A mutual relationship between the two tests seem to exist, based on the dissipated energy.

SOMMARIO

La degradazione della resistenza e della capacità di assorbimento di energia in elementi murari, sottoposti ad azioni cicliche nel piano dell'elemento stesso, può essere studiata sperimentalmente tramite prove di diverso tipo.

Le prove su provini gemelli sono state effettuate secondo due diverse modalità: a distorsione imposta ed a carico massimo imposto.

Sembra possibile individuare una relazione tra i due metodi di prova fondata sulla considerazione dell'energia dissipata.

1. INTRODUCTION

Cyclic tests on structural elements give information about available ductility, stiffness degradation, energy absorption and dissipation.

As far as reinforced masonry shear walls are concerned, two kinds of tests are usually performed: the racking test and the diagonal compression test |1,3| . The main difference between them can be seen in the restraints imposed on the specimen (Fig.1).

The racking test can be usefully performed on large size specimens: shear force and axial load applied to the element make testing conditions near to a realistic situation for a load-bearing wall. The undetermined restraints make it impossible to know stress conditions in the element. The available information pertains to the whole wall and can be expressed in function of the global drift corresponding to each value of the shearing force.

On the contrary loading and restraining conditions for the element under diagonal compression are very simple: stress conditions can be known at some extent for the central portion of the wall |5|. Therefore the specimen acts as a limited portion of shear wall in a structure and the test can give information about strain and stress behaviour of masonry regarded as a material.

When cyclic tests are performed, different procedures can be followed obtaining constant load cycles, constant displacement cycles, gradually increasing displacement cycles (with constant or variable increment) and random cycles.

Cyclic tests on shear walls are usually performed under different increasing limits of distortion. The degradation in resistant and ductile characteristics can be related to imposed distortion, number of cycles and level of loading. But further information can be achieved by performing a series of cycles, each one reaching the maximum attainable load. Such a load decreases in subsequent cycles due to strength degradation.

As a consequence of the above considerations on different testing conditions, a couple of nominally identical reinforced masonry elements was tested under cyclic diagonal compression according to both testing procedures (either imposed distortion or imposed load) in order to get information about strength and ductility response of the same structural element.

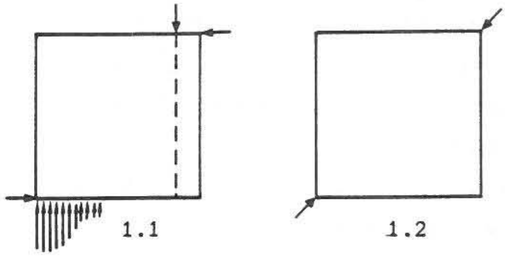


Fig. 1.1 - Standard ASTM racking test

1.2 - Diagonal compression test

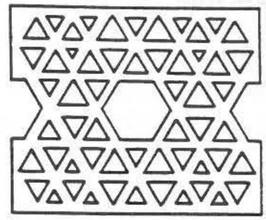


Fig. 2 - Clay block (coring pattern)

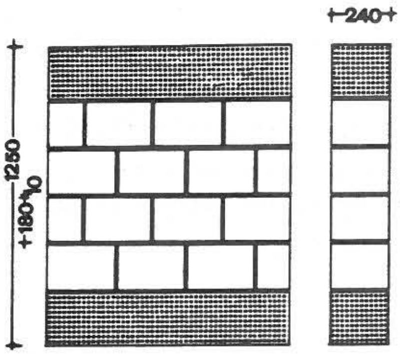


Fig. 3.1 - Reinforced masonry wall

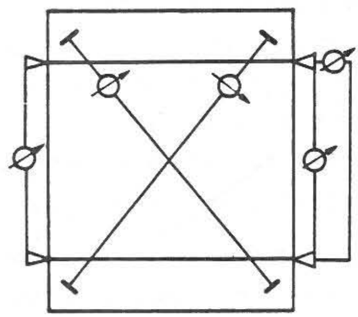


Fig. 3.2 - Gauge lengths

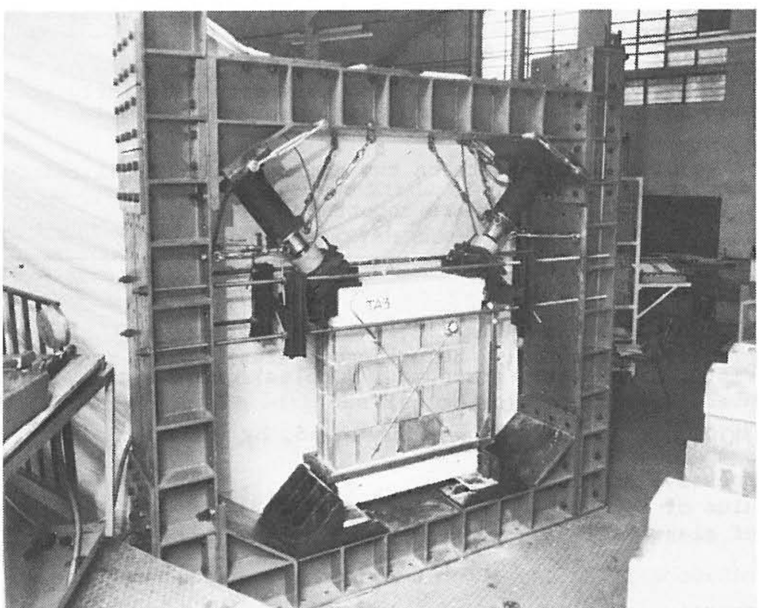


Fig. 4 - Testing equipment

2. SPECIMEN CHARACTERISTICS

The elements were made of vertically perforated clay blocks. The block coring pattern particularly suited the requirements of presenting pockets and holes for housing vertical bars. The pattern provides a relatively high compression strength perpendicularly to the holes (Fig.2).

Vertical reinforcement was made up by deformed bars. Horizontal bed mortar joints were reinforced with a galvanized continuous wire truss.

Block dimensions and reinforcement spacings led to choose the element size as Fig.3 shows. A reinforced masonry portion is embraced in upper and lower R.C. beams, preventing local rupture under the load and providing anchorage for vertical bars.

Reinforcement percentages are 0.4‰ (horizontal) and 1.3‰ (vertical), computed on the gross area.

Strength characteristics of all components (blocks, mortar, reinforcing bars) are collected in Table 1 and 2.

The following reference tests were performed on blocks and masonry prisms in order to determine the mechanical properties of masonry:

(a) Tests on blocks:
- compression test;
- splitting (brazilian) test;
- compression test perpendicularly to coring direction;

(b) Tests on masonry prisms:
- compression test;
- splitting (brazilian) test on 590x580x240(mm.) masonry prisms;
- compression test perpendicularly to coring direction.

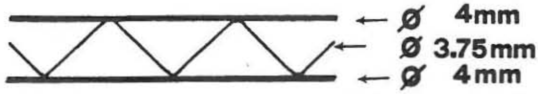
Here only the results of the tests on two nominally identical reinforced masonry specimens (named TA3 and TA4) are reported.

TABLE 1 - MASONRY

UNITS (hollow clay blocks)	
Nominal dimensions 180 x 240 x 285 (mm) - 49% coring	
Mean compressive strength (// holes)(gross area)	= 52.3 N/mm^2
Characteristic compressive strength (// holes)(gross area)	= 42.6 N/mm^2
Mean compressive strength (⊥ holes)	= 3.5 N/mm^2
CEMENT MORTAR 1:0:3 (cement:lime:sand, by volume)	
Mean compressive strength	= 12.1 N/mm^2
Mean modulus of rupture	= 2.6 N/mm^2
Modulus of elasticity	= 13400 N/mm^2
MASONRY	
Mean compressive strength (// holes)	f_{me} = 11.8 N/mm^2
Mean tensile splitting strength	f_t = 0.6 N/mm^2

TABLE 2 - REINFORCEMENT

i) vertical - Ø 10 mm deformed bars/300 mm	
yield point	= 490 N/mm^2
strength	= 719 N/mm^2
ii) horizontal - galvanized continuous wire truss Ø 4 mm	
strength	= 600 N/mm^2



3. TEST SET-UP

The element undergoing diagonal compression was inserted in a rigid steel testing frame (Fig. 4). The element resting on a corner, was alternatively loaded along either diagonal, by means of hydraulic jacks.

The gauge length arrangement was chosen according to the following hypotheses on the distortion of the element.

Upper and lower R.C. beams were assumed to be rigid, so that only the length changes of the vertical sides were measured. The element can be thought of as a strut parallel to the compressed diagonal: information about stiffness variation along this direction is of evident interest. Finally the overall behaviour is synthesized by the drift between upper and lower sides.

Loading measurements were obtained through load cells set between element and jack. Strain measurements (Fig.3) were consistent with the above mentioned assumptions.Therefore dial gauges were set on the vertical sides of the element and a couple of dial gauges and a couple of transducers were placed along both diagonals. Drift values were determined by means of both a dial gauge and a transducer.

When performing loading cycles two kinds of diagrams were automatically plotted: horizontal drift versus diagonal load and length change along one diagonal versus applied diagonal load.

4. RESULTS

Test results are here given with the aim of emphasizing the different information rising from both kinds of test.

4.1. Cyclic test at imposed distortion (Fig.5)

The test on specimen TA3 was performed under imposed distortion, that is imposed displacement between top and bottom side of the wall. According to the previous condition, the loading programme consisted of:

- 5 loops (1st to 5th) considerably below the "elastic" limit with 0.1 mm

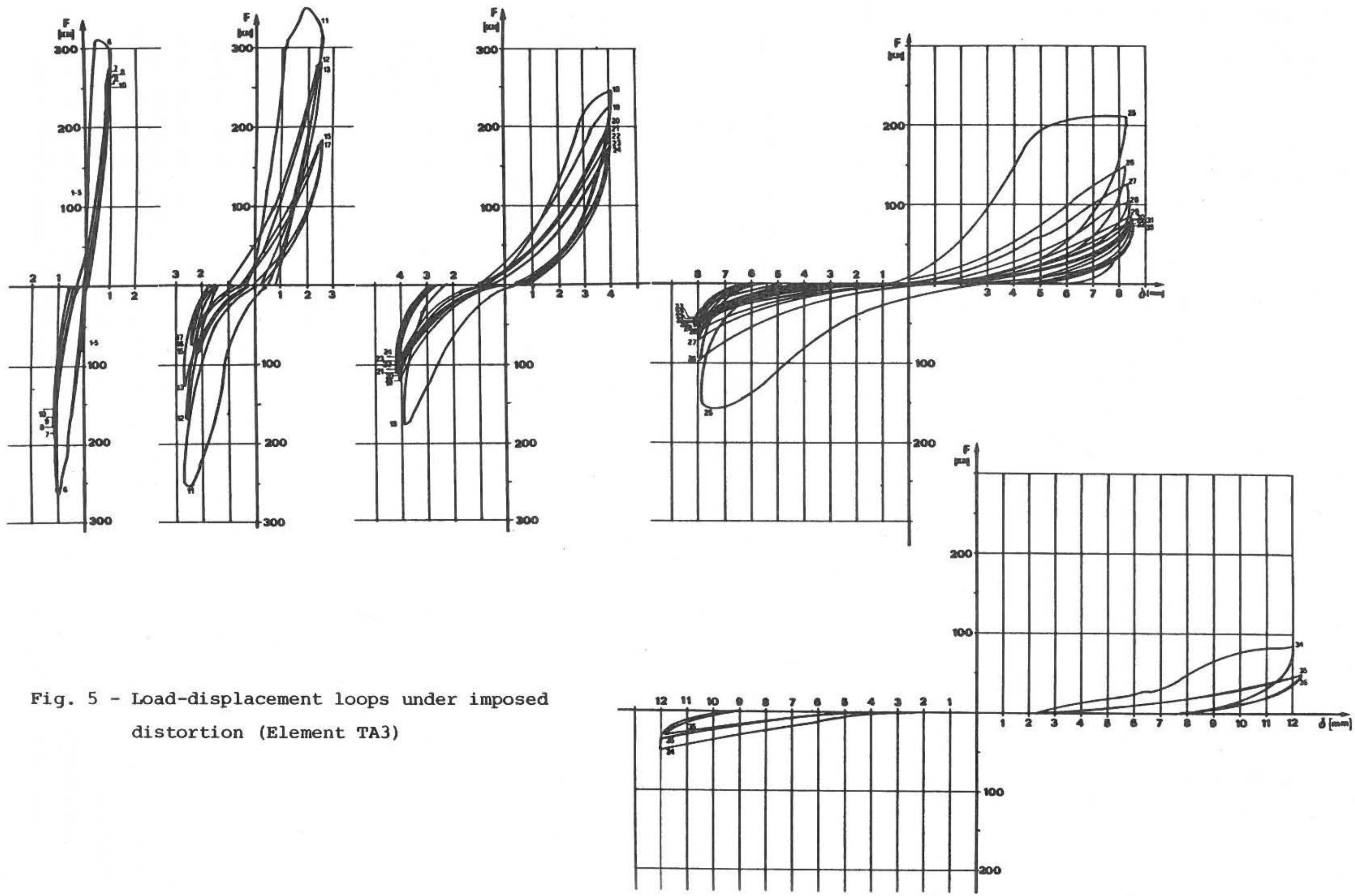


Fig. 5 - Load-displacement loops under imposed distortion (Element TA3)

maximum imposed displacement, in order to determine the deformation parameters in the uncracked linear elastic field.

- 5 loops (6th to 10th) with 1 mm limit displacement corresponding to manifest cracking across the tensioned diagonal in the 1st half-loop of the series;
- 7 loops (11th to 17th) with 2.5 mm maximum displacement;
- 7 loops (18th to 24th) with 4 mm maximum displacement;
- 9 loops (25th to 33th) with 8 mm maximum displacement;
- 3 loops (34th to 36th) with 12 mm maximum displacement;

Figure 5 plots cyclic diagonal load versus horizontal relative displacement. Some comments can be made on the shape of the loops. 1st to 5th loops signify essentially linear behaviour.

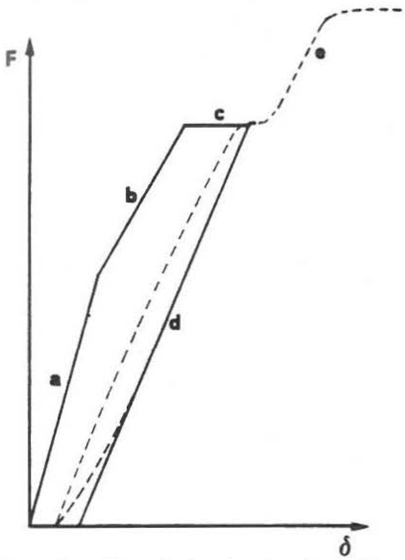


Fig. 6 - Approximate broken line for loops at first cracking

The ascending branch of the 6th loop can be easily considered as a bilinear curve where (Fig. 6):

- line (a) coincides with the previous series of elastic loops;
- line (b) shows a stiffness decrease rising from spread cracking inside the blocks.

The horizontal branch (c) signifies evident cracking across the tensioned diagonal. The descending branch (d) represents the experimental unloading curve to a great extent; the slopes of line (b) and (d) are comparable with each other.

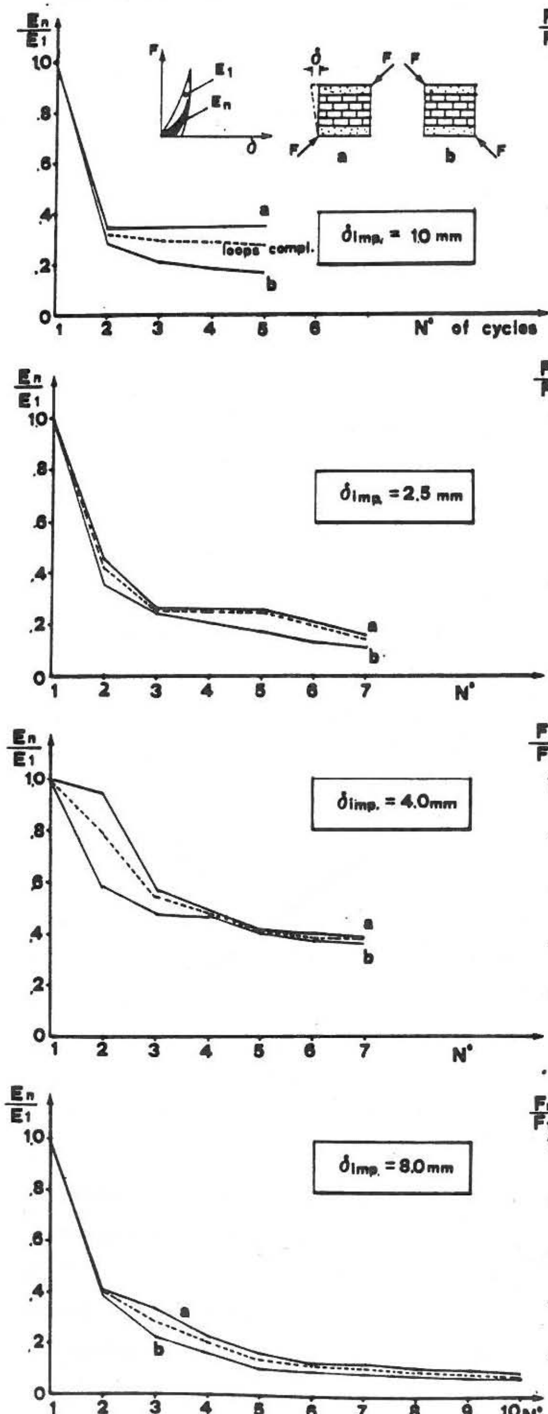
After cracking the wall can sustain higher load, as branch (e) shows.

In the subsequent loops (7th to 10th) the ascending branch slope and the attained load decrease little by little involving less and less enclosed areas. The same behaviour can be noticed in the other series of loops.

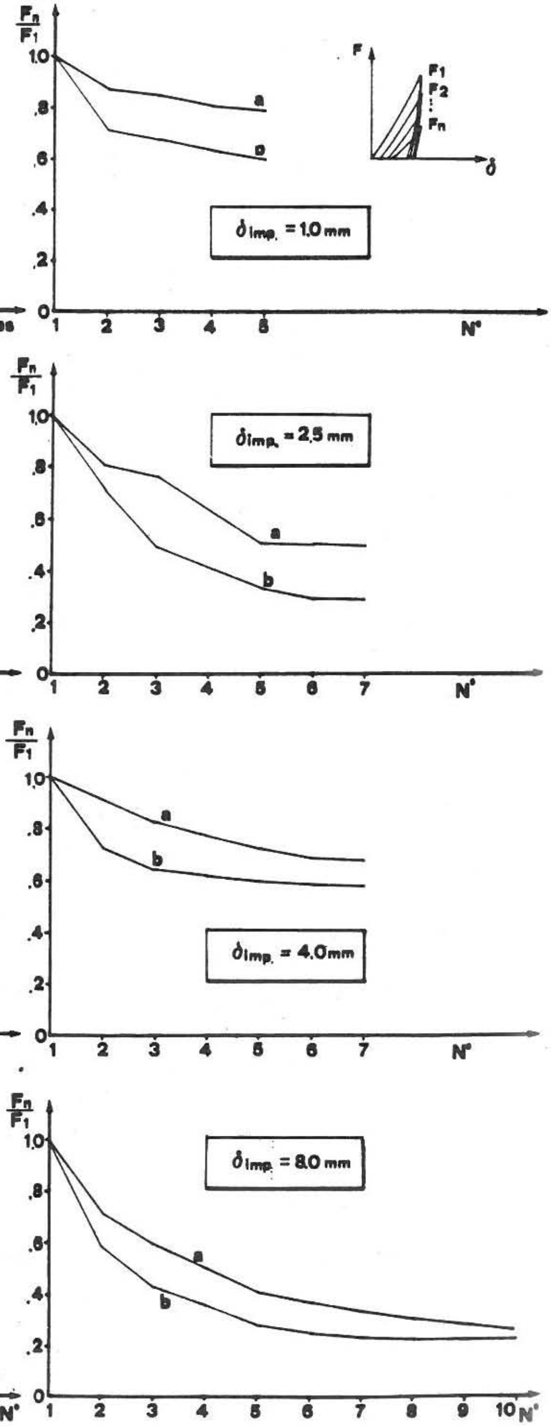
Experimental results can be handled in order to show the maximum attained load degrading with the number of loops performed under the same limit distortion.

Figure 7.2 plots the attained diagonal load (made dimensionless to the load in the first loop of the series) versus the number performed loops. In general 5 loops seem to be sufficient for defining an asymptotic value of the attained load.

But a more meaningful parameter is the energy dissipated during loading and subsequent unloading: its variations point out the degrading behaviour of the

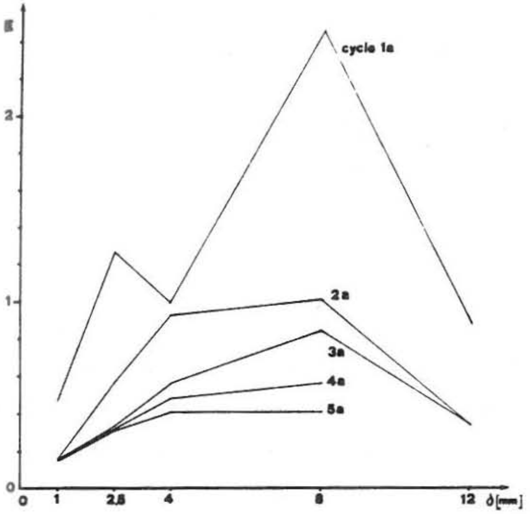


7.1



7.2

Fig. 7.1 E_n/E_1 ratio versus the number of performed loops.
7.2 F_n/F_1 ratio versus the number of performed loops.



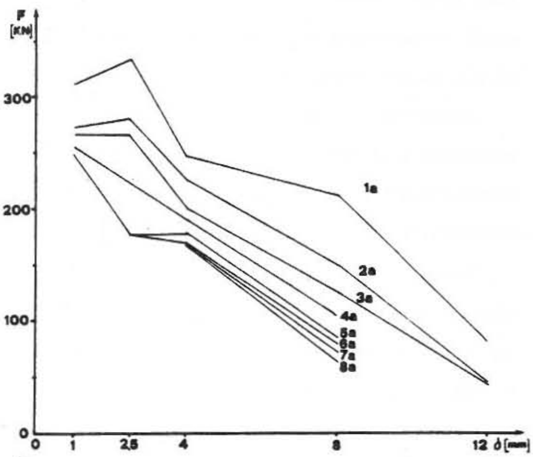
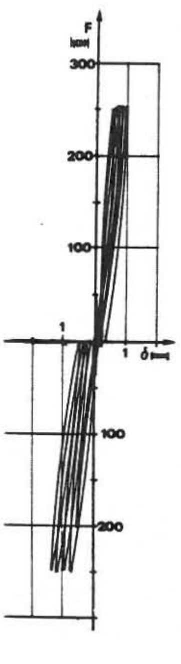
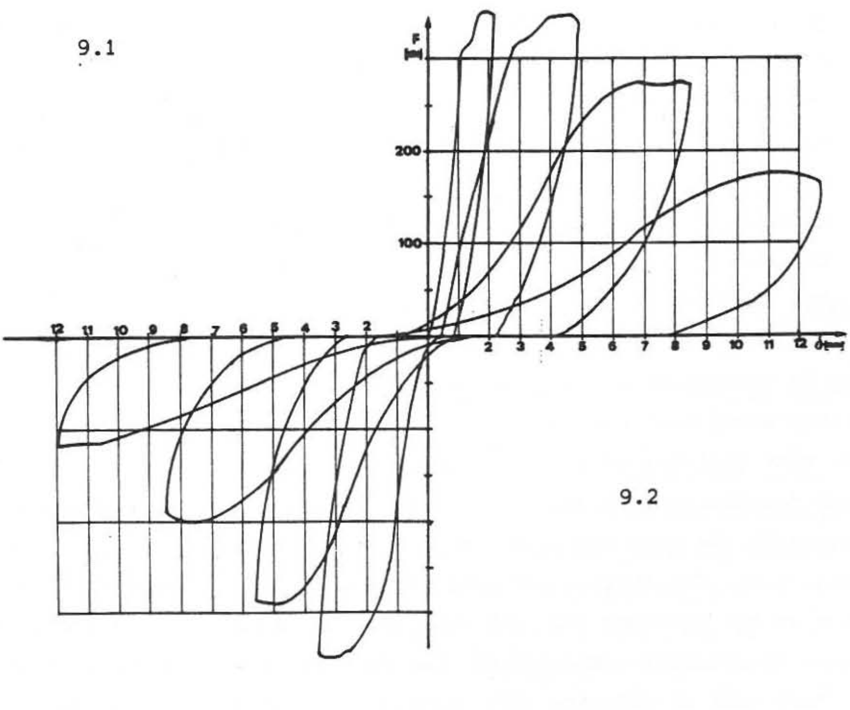


Fig. 8.1 - Dissipated energy 8.2- Attained load
Each curve refers to the i-th loop and different limit distortions

Figs. 9.1 and 9.2 - Loops for element TA4. Test with imposed maximum load





specimen.

The dissipated energy was assumed to be proportional to the enclosed area of the loop: Fig. 7.1 displays the decrease in dissipated energy made dimensionless with reference to the first loop versus the number of loops. For earch imposed limit distortion 3 curves are plotted: they refer to half-loops or to complete loops.

Figures 7.1 and 7.2 allow to notice strong decrease in attained load and dissipated energy subsequent to the first loop. But this trend does not seem to be confirmed for 4 mm imposed displacement and particularly for (a) loops. This derives from the non-attainement of the wall carrying capacity.

A more comprehensive representation of the test is given in Figure 8.1 where the dissipated energy was not made dimensionless. The plotted curves refer only to (a) loops ((b) loops show the same trend).

Each broken line in Fig. 8.1 joins points representing the dissipated energy value for loops with the same ordinal number within each series (of loops). Therefore each curve does not denote the actual loading procedure. The 1st loop broken line is generally increasing up to 8 mm deflection (Fig. 8.1). Energy decrease at 4 mm displacement is closely connected with the testing procedures. In fact under 4 mm imposed displacement the maximum attained load in the 1st loop did not reach the load carrying capacity and that is confirmed in Fig. 8.2.

4.2 Cyclic test at imposed maximum load (Fig. 9).

The following testing procedure was carried out for specimen TA 4:

- 4 loops below the elastic limit up to the load corresponding to 0.1 mm horizontal relative displacement;
- 1 loop with such a maximum load as to cause spread cracking inside the blocks.

The attained load belongs to branch (b) in Fig. 6. The same load was imposed in the subsequent 4 loops alternatively along both diagonals (Fig. 9.1), the test finished after 4 more loops with decreasing attained load coinciding with the load carrying capacity (Fig. 9.2). The testing procedure does not allow to represent the wall degradation as for specimen TA3. The experimental diagrams can be plotted in the H-γ plane (horizontal component of diagonal load versus angular distortion).

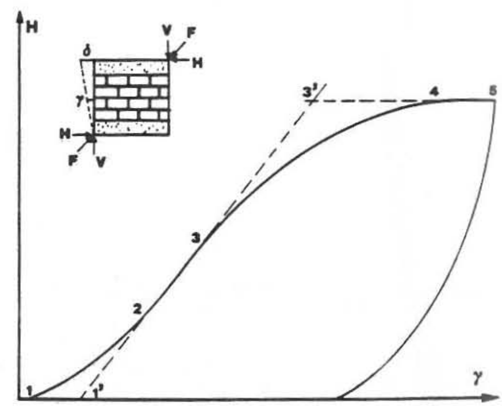


Fig. 10 - Appriximate loop for tests with maximum imposed load

Each half of complete loop consists in general of (Figure 10):

- branch 1-2 corresponding to the closing of the previously opened cracks perpendicular to the compressed diagonal. This branch would not exist if the closing occurred during the former unloading. The 1-1' branch signifies the phenomenon of the crack closing.
- branch 2-3 nearly linear. In experimental diagrams this branch is partly curvilinear and reaches the maximum load (branch 3-4).
- branch 4-5 nearly horizontal, with increasing distortion under contant load.

The unloading process follows.

The loading branch can be approximately considered as bilinear (1'-3'-5) and point 3' can be assumed as corresponding with the attainment of the maximum load.

If all the loops with cracked tensioned diagonal are taken into account and superimposed in such a way as to have all the 1' points coinciding with the origin of the $H - \gamma$ plane, Figure 11.1 is obtained. Two interpolating straight lines for 3' points can be drawn for (a) and (b) loops respectively. Both lines find an horizontal upper bound corresponding to the maximum attainable load for the uncracked or slightly cracked wall. Each line defines a domain. A loading process that starting from the origin of the $H - \gamma$ plane with a straight line reaches the border of the domain, determines the value of the maximum attainable load for that loop.

The slope of 1'-3' branch is proportional to the wall stiffness and depends on the previous loading process. The load history can be related to the dissipated energy. A relationship between the above quantities was determined.

Being :

G the shear modulus of the current cycle;

G' the shear modulus of the wall with spread inner cracking;

E the progressively dissipated energy;

the G/G' ratio was plotted versus E as Figure 11.2 shows.

The diagrams of Figs 11.1 and 11.2 fully describe the history of the element TA4 (imposed maximum load test).

Similarly the experimental results of element TA3 (imposed deformation test) can be handled so that the Figs 12.1 and 12.2 can be obtained.

The comparison between Figs 11 and 12 points out a difference in the total dissipated energy for the two specimens. Such a difference can be due to various reasons as the variability of the characteristics of the two nominally identical specimens, the loading history, the importance of the final degradation. A further difference can be noticed between the $H-\gamma$ domains of the Figs 11.1 and 12.1, in spite of the nominal identity of the specimens.

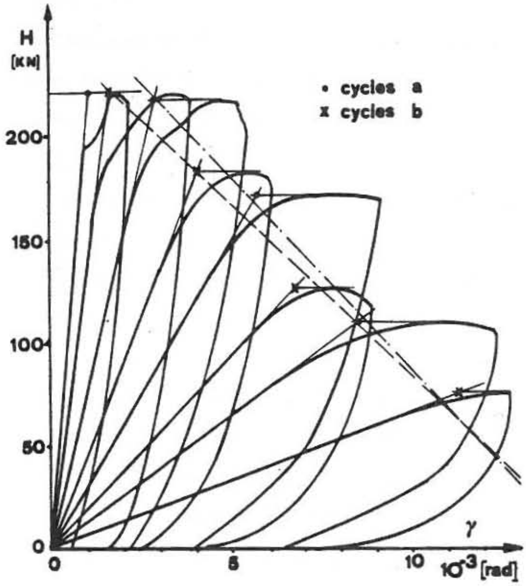


Fig. 11.1 - Loops for element TA4
(imposed load test)

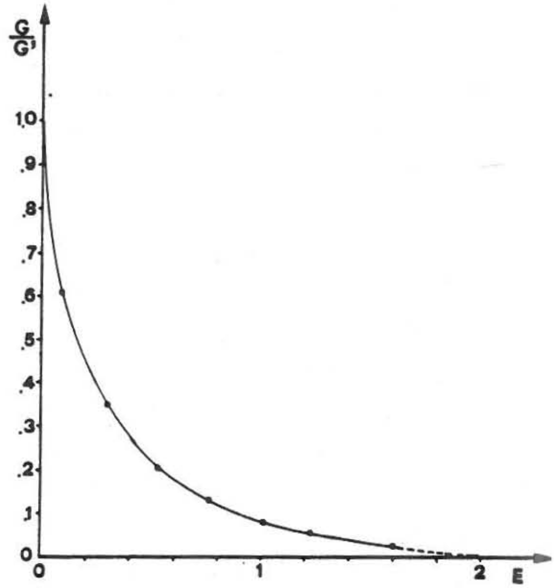


Fig. 11.2 - Shear modulus (G) versus dissipated energy (E)

G shear modulus of the current cycle;
G' shear modulus of the wall with spread inner cracking;
E progressively dissipated energy.

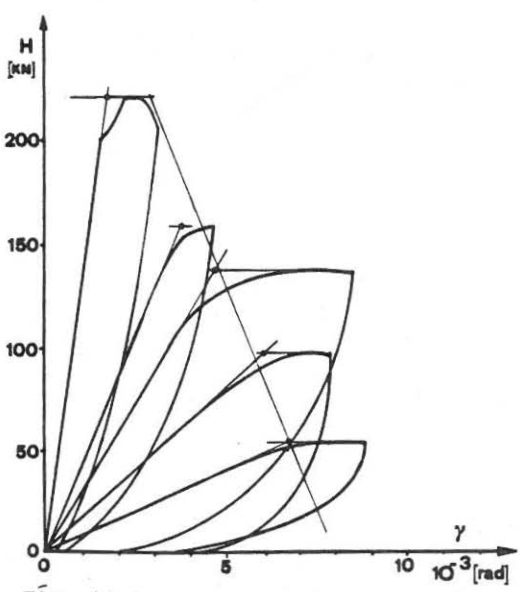


Fig. 12.1 - Loops for element TA3
(imposed distortion test)

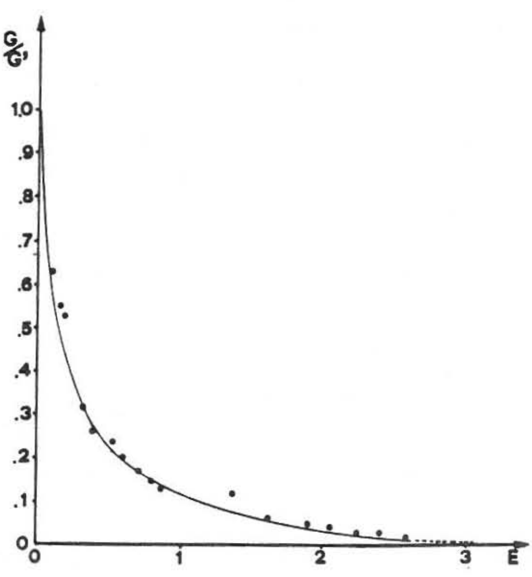


Fig. 12.2 - Shear modulus (G) versus dissipated energy (E)

G shear modulus of the current cycle;
G' shear modulus of the wall with spread inner cracking;
E progressively dissipate energy

Another representation of the experimental results can be plotted in the H-E_{tot} plane (Fig. 13), being: H the horizontal component of the maximum attainable diagonal load in a certain cycle; and E_{tot} the total dissipated energy in the whole loading process up to the same cycle.

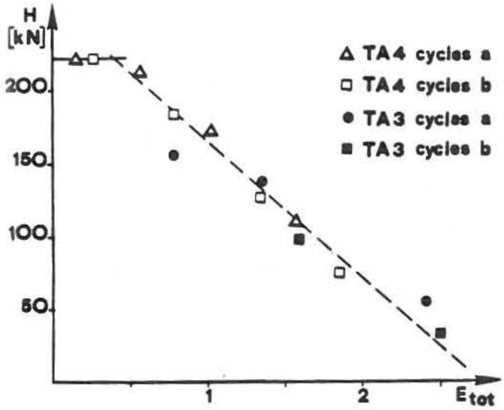


Fig. 13 - Horizontal component of the maximum attainable diagonal load versus total dissipated energy.

The experimental points define a domain in H-E_{tot} plane (dashed line in Fig. 13). The experimental points in Fig. 13, that derive from both tests, seem to fall into only one line, thus defining one value of the total dissipated energy in both cases. For a certain cycle, being known the dissipated energy E up to that phase of the loading process, by means of a diagram of the kind shown in Fig. 11.2, the G/G' ratio is determined and so the slope of the ascending branch of the subsequent cycle is found. In the H-E_{tot} plane this loading stage defines the value of the maximum attainable load in that cycle. The subsequent unloading stage determines the dissipated energy of the same cycle. This energy added to the previous energy value gives the value for determining the slope of the subsequent cycle, following the above illustrated procedure.

The complete interpretation of the behaviour of the wall seems to be possible, but some questions are still unanswered:

1) is it possible to define one curve relating the G/G' ratio to the total dissipated energy E in function of the masonry characteristics and independently of the loading history?
2) in a certain cycle after reaching the respective maximum load how long is the branch with increasing deformation under constant load?
3) how can be the unloading stage described?
4) diagrams of the kind shown in Figs 11.1 and 12.1 are drawn omitting the branch above named 1-1' (see Fig. 10), corresponding to the crack closing; its contribution is essential for evaluating the total distortion of the wall. Is it possible to find a relationship between the length of the 1-1' branch and the slope of the interpolating lines in Figs 11.1 and 12.1?

These considerations draw the attention to the need of further experimental research.

5. CONCLUDING REMARKS

The performed tests lead to the following conclusions:

1. Sufficient ductility can be given to masonry shear walls (analogous to the ductility usually assigned to R.C. shear walls). Low reinforcement percentages and relatively low bar spacings (both vertically and horizontally) allow masonry shear walls to show ductile behaviour under in-plane seismic actions. This possibility was previously found in |5|.

2. Two different cyclic testing procedures were compared. A mutual relationship based on the dissipated energy could exist. This would allow the definition of a standard cyclic testing procedure. Two kinds of information would derive:
   - ductility values to be used in the design of masonry shear walls under seismic actions with the methods of the equivalent static actions,
   - cyclic models for reinforced masonry elements, to be used in finite element quasi-static or dynamic analyses for a more precise determination of the overall ductility.

The results are still insufficient to the complete definition of the masonry shear wall behaviour under cyclic actions. The determined relationship between both testing procedures seems to deserve further research.

AKNOWLEDGEMENT

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