SYNTHESIS REPORT
FOR PUBLICATION

CONTRACT N“ : BREU -0575
PROJECT N° : BE - 4001

TITLE : **INDUSTRIAL DEVELOPMENT OF REINFORCED MASONRY BUILDINGS**

PROJECT COORDINATOR : - National Technical University of Athens
Laboratory of Reinforced concrete
(LRC/ NTUA) - GR

PARTNERS :

- Consorzio Poroton Italia (CPI) - I
- Impressa Edile Vigni Vittorio (VIVI) -1
- Philippou S.A. (PHIL) - GR
- Hellenic Technodomiki S.A. (HETE) - GR
- University of Padua (UPAD) - I
- University of Pavia (UPAV) - I
- Technical University of Darmstadt (THD) - D

STARTING DATE : 01.04.1992 DURATION : 48 MONTHS

PROJECT FUNDED BY THE EUROPEAN COMMUNITY UNDER THE BRITE/EURAM PROGRAMME

DATE : SEPTEMBER 1996

INDUSTRIAL DEVELOPMENT OF REINFORCED MASONRY BUILDINGS

ABSTRACT

Reinforced masonry (R. M.) constitutes a construction system which may be used as an alternative to conventional R.C. structures in low- and medium-rise buildings. Within a research project financed by the European Union, reinforced masonry construction system was thoroughly investigated. The project included the development of bricks and mortars adequate for R.M. construction, the experimental investigation of local transfer mechanisms along interfaces, analytical modelling of R. M., full scale tests on subassemblages and scaled buildings, study of constructional problems through the construction of full scale houses and drafting of Recommendations for design and construction of R.M. buildings. In this paper, a brief presentation of the major tindings of this project is given.

1.- INTRODUCTION

Reinforced masonry is made of vertically perforated masonry units and mortar, whereas horizontal and vertical distributed reinforcement is placed in bed joints and vertical holes respectively. The construction system of reinforced masonry may present several advantages, when compared to R.C. low- and medium-rise buildings, namely:

- **Improved habitability, since** both thermal and acoustic insulation may be ensured by using appropriately designed bricks without any use of additional insulating materials. Reinforced masonry improves also fire resistance both because of the considerable thickness of walls and because of the absence of inflammable insulating materials.
- **Improved behaviour** of the building under service conditions thanks to the crack control offered by the reinforcement distributed within masonry walls. Thus, habitability and mechanical characteristics of R.M. structures are not affected by cracking.
- **Improved seismic behaviour:** Reinforced masonry buildings exhibit a good behaviour against seismic actions thanks to their stiffness, their ductility and their box-action (a guarantee against collapse). Moreover, the seismic behaviour of R.M. buildings does not depend on sophisticated (thus oversensitive) detailing of small critical zones, as it is the case for R.C. structures (e.g. beam-column joints).

  The use of distributed reinforcement within the masonry walls, offers considerable ductility, thus allowing for a higher number of storeys to be built as compared to plain masonry buildings. Finally, the distributed reinforcement ensures a satisfactory out-of-plane behaviour to the walls.
- **Facilitation of construction process and reduced cost** compared to reinforced concrete structures, since both skeleton and sophisticated detailing are avoided.

In order to investigate various aspects of this R.M. «poly-system», a BRITE/EURAM project was financed by the E.U. and it was carried out jointly by Industrial Partners and Universities in Greece, in Italy and in Germany. In what follows, a general description of the project is given, as well as some of the most important results obtained.

2.- TECHNICAL DESCRIPTION

The project was organised into seven tasks which aimed at the investigation of various aspects related to the development of appropriate materials, to the behaviour and design of R. M., as well as to constructional problems. The various steps of the research programme are mentioned here below:

Development of materials appropriate for reinforced masonry structures

The starting point of the development of reinforced masonry construction system was the development of bricks, mortars and grouts which should ensure adequate mechanical and physical properties to R.M. The relevant mechanical properties are compressive and tensile strengths, as well as moduli of elasticity, whereas the physical properties are related to thermal and acoustic insulation, hygric protection and fire resistance of masonry. Furthermore, a special geometry of bricks is needed to accommodate horizontal and vertical reinforcement. Several . production trials were needed (industrial scale) for the development of appropriate bricks, whereas a large number of trial mixes were considered for mortars and grouts, in order to select the most appropriate ones for the research work. The major topic of durability "(mainly, the corrosion of steel reinforcement embedded in bed joints of masonry) was thoroughly investigated and it has led to the selection of the appropriate mortars and grouts.

Structural models

The development of analytical models was sought, -describing the behaviour of reinforced masonry under various actions. This target was to be achieved step by step, as follows: Constitutive laws for bricks, mortar and unreinforced masonry were to be experimentally investigated. On the other hand, all mechanisms of force transfer along cracks in R.M. (namely, friction, dowel action, pullout/push-in of horizontal and vertical reinforcement) were to be experimental y investigated, whereas models were developed for each mechanism. All this basic information was to be used as input to analytical models describing the overall behaviour of reinforced masonry, whereas appropriate full scale tests on subassemblages would provide the necessary data for calibration, completion and correction of the analytical models. Finally, the analytical models would serve as a basis for the derivation of simplified engineering models adequate for the every day design of reinforced masonry.

Analysis of reinforced masonry buildings

This' topic was oriented towards the needs of every day analysis of R.M. buildings. The validity and the field of application of several practical methods of analysis were checked on the basis of parametric analyses and test results (to be obtained from testing a scaled model of a complete R.M. building on an earthquake simulator). The calibration of the practical methods of analysis would be based on extensive parametric work using sophisticated methods of analysis.

Studies on production and construction problems

The aim of this part of the research was to investigate economical and feasibility aspects related to R.M. construction, as compared to R.C. buildings. To this purpose, two sets of two houses (one made of R.C., the other made of R. M.) were constructed in Italy and in Greece, representative of small residential houses.

These buildings serve also other parts of the project. In fact, they are adequately monitored for in-situ durability and habitability tests, whereas full scale tests for the identification of dynamic characteristics of the buildings are to be carried out.

Recommendations

The final aim of this project is the drafting of recommendations for design, construction and maintenance of R.M. buildings, based on the information of all previous research topics. A subsequent considerable input to the relevant Eurocodes is anticipated.

3.- SOME SELECTED RESULTS

3.1.- Development of materials

(a) Bricks: The bricks to be used in R.M. construction had to satisfy a set of requirements related to their geometry, as well as to their mechanical and physical properties. For example, the bricks should have vertical holes of sufficient dimensions for the accommodation of vertical bars, combined with a large number of small vertical holes in order to ensure insulation properties, as well as thick and continuous shells and webs to ensure satisfactory mechanical properties, whereas their weight should not exceed certain limits for construction reasons. On the other hand, the bricks should *have* sufficient strength both parallel and perpendicular to the holes, whereas walls built with such bricks should have physical characteristics (e.g. thermal conductance and transmittance, sound insulation properties) such that to ensure satisfactory habitability parameters.

Several alternative bricks were designed both in Italy (by Consorzio Poroton Italia, CPI) and in Greece (by Philippou S.A., PHIL) and they were experimentally produced by the respective firms. A large number of small scale tests (both on bricks and wallets) allowed for the selection of one brick per country, which were subsequently produced in the quantities required for the extensive experimental work described in the following sections. Fig. 1 shows those bricks, whereas Table 1 summarises some of their characteristics. It should be mentioned that one additional production trial was made by PHIL near the end of the project, aiming at further improvement of the greek brick. The improved characteristics of this brick are included in Table 1.

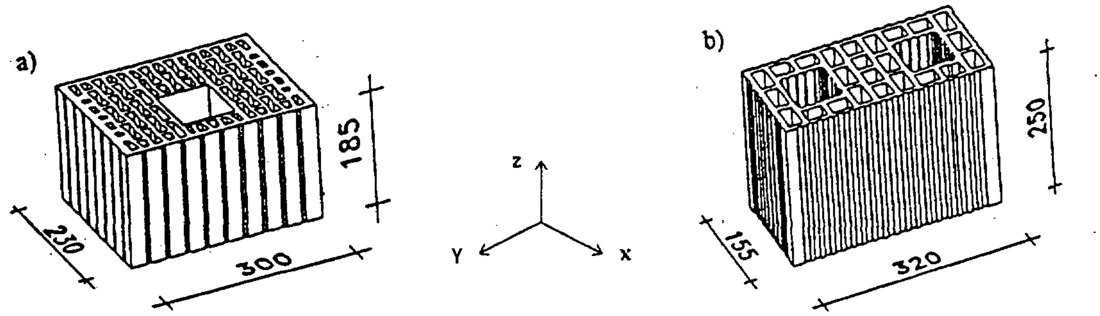


Fig. 1: Geometry of (a) italian and (b) greek bricks developed for the needs of the project.

Table 1: Some characteristics of the bricks developed for the needs of the project

(a) Brick developed in Greece

Physical and geometrical characteristics	Mechanical characteristics
Dimensions : 320x 155x 250 [mm] Cross section : 320x 155 [mm] Weight :9.8 kg Percentage of holes : 55% Net dry density :1720 kg/m³ Water absorption : 15% Web thickness: 8-10 [mm] Dimensions of big holes: 65x65 [mm] **Final production trial** Dimensions: 320x1 55x200 [mm] Weight: 10,4 Kg Percentage of holes: 50% Mean compressive strength (parallel to holes): 14,5MPa Web thickness: 11-12 mm Dimensions of big holes: 70x70 [mm]	**Mean compressive strength** • parallel to the holes f_c = 8.50 MPa . perpendicularly to the holes (direction X) f_c = 2.20 MPa . perpendicularly to the holes (direction Y) f_c = 1.15MPa **Characteristic compressive strength** • parallel to the holes f_{ck} = 6.45 MPa . perpendicularly to the holes (direction X) f_{ck} = 1.67 MPa • perpendicularly to the holes (direction Y) f_{ck} = 0.82 MPa **Reformational characteristics** • parallel to the holes E = 7527 MPa ν = 0.28 . perpendicularly to the holes (direction X) E = 1172 MPa ν = 0. 12 . perpendicularly to the holes (direction Y) E = 1046 MPa

(b) Brick developed in Italy

Physical and geometrical characteristics	Mechanical characteristics
Dimensions: 185x300x230 [mm] Cross section: 185x300 [mm] Weight: 11,10 Kg Net dry density: 1574 Kg/m³ Thermal conductivity A (W/m"C): 0,34 Thermal transmittance (W/m²°C): 0,93	**Mean compressive strength** • parallel to holes: 15,72 MPa • perpendicular to holes: 2,26 MPa **Characteristic compressive strength** . parallel to holes: 11,83 MPa . perpendicular to holes: 1,58 MPa **Mean tensile strength** (due to bending): 9,97 MPa **Characteristic tensile strength: 8,62** MPa

It should be mentioned that acoustic and thermal tests carried out both on wallets and on full scale walls, made of the selected bricks, as well as fire tests and permeability to rain water tests performed on wallets have shown a satisfactory behaviour, complying with the respective European or National Standards.

(b) Mortars and grouts

Mortars (for laying the bricks) and grouts (to fill the vertical holes containing reinforcement) have to. be workable enough, they have to exhibit satisfactory mechanical properties (compressive strength and adhesion to bricks), whereas at the same time they should ensure sufficient protection against corrosion to the reinforcement embedded in them. In addition. mortars have to be consistent enough, while grouts have to be fluid enough to fill the reinforced vertical holes.

A large numbers of mixes were designed and investigated both at the Nat. Tech. univ. of Athens and at the Univ. of Padua. Since several mixes were able to satisfy the requirements of strength, consistency and workability, the efforts in both Universities focused on the durability properties of mortars and grouts. Thus, five mixes (3 mortars and 2 grouts) were selected in Greece and six mortars mixes were selected in Italy, in order to evaluate their durability properties. Long term and accelerated durability tests were carried out on specimens shown in Fig, 2.

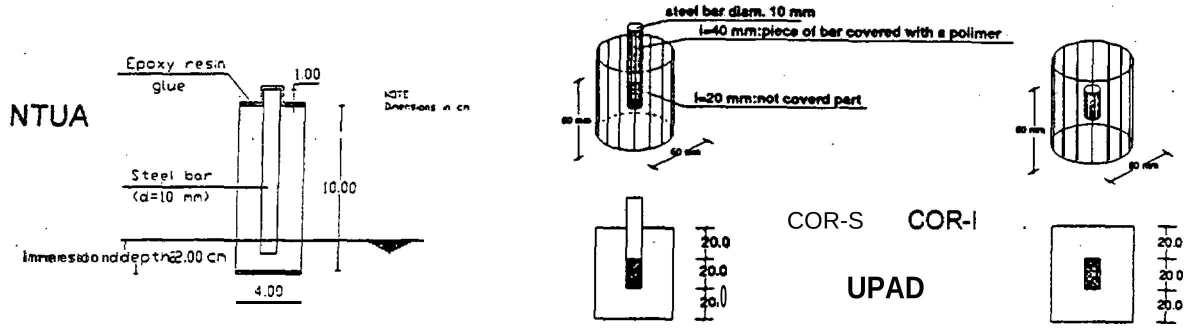


Fig. 2: Specimens used for durability tests

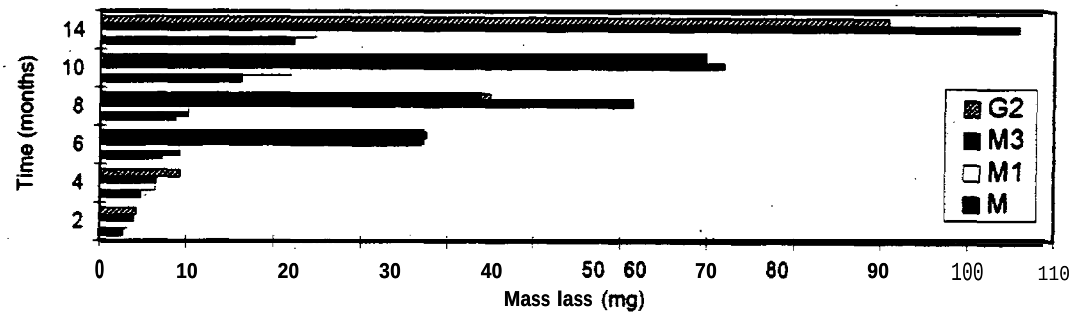


Fig.3: In-time development of mass loss of steel embedded in mortars and grouts tested in corrosive environment HzG-air (M 1 = C:L:S:W= 0,79:0,21:4,76:0,64 [by mass], M3= 1,0:0,0: 4,5: 0,75) [results obtained at the Nat.Tech. Univ. of Athens]

There was a good agreement between the results obtained in the two Universities: It was observed that in corrosive environment without chloride ions, lime cement mortars (with a low lime content though) show better behaviour than cement mortars (compare M 1 and M3 in Fig. 3). In case of corrosive environment with chloride ions, it was proved that the behaviour of mortars can be substantially improved in case inhibitors are added.

On the basis of the experimental results, the mixes shown in Table 2 were selected for further use within the project.

Table 2: Characteristics of mortars and grout selected for use within the project.

(a) Greece

Material	Mix proportions (per volume)	slump (mm)	Density (gr/mm³)	Mean com pressive strength (MPa)	Mean tensile strength (N/mm²)	Modulus of elasticity (N/mm²)	Poisson's ratio
Mortar	C:L:S:W= 1:0,25:4: 1,30	160,3 (25 strokes) 145 (15 strokes	2,05	11,86	1,91	12699	0,256
Grout	C:S:W=1:3:1,10 (+super-plasticiser 170 per cement weight)	205 (25 strokes) 182,5 (15 strokes	2,05	19,74	3,23	17915	0,239

(b) Italy

Mix proportions (per weight)	Compressive strength (N/mm²)	Tensile strength (N/mm²)
C:L:S:W=0,8:0,2:3 :0,65	21,16	4,68

3.2.- **Load transfer mechanisms**

As it is well known, the behaviour of reinforced masonry after cracking is governed by the mechanisms of load transfer along cracks, namely: The clamping effect of horizontal and vertical reinforcement crossing a crack, the friction along the compressed zone of a crack, as well as dowel action of both horizontal and vertical reinforcement. The experimental investigation and the modelling of those local mechanisms is necessary for the development of models describing the overall behaviour of R. M.” elements when subjected to monotonic or cyclic actions beyond cracking and beyond yield.

Within this project, all the above mechanisms were thoroughly investigated. Tests were carried out at the Nat. Tech. Univ. of Athens, as well as at the Univ. of Padua, using the materials developed in the respective countries (see §2 above).

Fig. 4 shows in a schematic way the geometry of specimens used for the investigation of load transfer mechanisms, as well as the testing arrangement. In what follows, the main findings of this part of the research are briefly presented and commented.

3.2.1.- Friction

In case mortar used to construct masonry is of considerably lower strength than bricks, cracks which appear in masonry normally pass through mortar joints. For comparable strengths of the constituent materials or for mortar stronger than bricks, cracks cross also bricks. Thus, friction along a crack can be mobilised either along a mortar-brick joint or along a crack within a brick. Both cases were experimentally investigated.

(a) Friction along a crack within a brick

As shown in Fig. 4A, two cases were considered, namely that of a vertical crack and that of a crack inclined by 45°. A normal compressive stress (0,05, 0,15 or 0,30 N/mm²) was constantly applied on the crack during shear testing. Tests have proved (see also Table 3) that:

(i) The greek bricks have exhibited lower friction coefficients (as well as lower frictional resistance) than the italian ones. This is attributed both to the higher compressive strength of the italian brick (almost three times higher than for the greek brick), as well as to their more pronounced micro-roughness.

(b) The mobilised frictional resistance depends on the inclination of the crack in respect with the longitudinal axis of the holes. In fact, during the pre-cracking procedure of the bricks, it was observed that the inclined cracks were more rough than the vertical ones, having a macro-roughness in addition to the micro-roughness.

(c) The normally observed tendency of the friction coefficient to decrease with increasing normal stress is recorded in this case too.

(d) As indicated by the values appearing in the last column of Table 3, there is an inherent scatter of the mechanism. In fact, the values of the maximum friction coefficient are very scattered for both types of bricks and for both types of tests carried out within the project.

Table 3: Summary of results on the mechanism of friction along a crack within a brick

Designation of specimen	Normal stress σ_0 (N/mm²)	Maximum friction coefficient μ_{max}	Extreme values of μ_{max}
Greek brick vertical crack	0,05 0,15	2,63 1,75	1,4-4,2 1,0-3,3
Greek brick oblique crack	0,05 0,15	1,88 1,23	1,2-2,6 0,1-2,5
Italian brick vertical crack	0,05 0,15 0,30	4,18 3,07 2,08	1,8-7,8 1,9-4,8 0,8-2,8
Italian brick oblique crack	0,05 0,1’5 0,30	,2,28 2,10 0,95	1>0-3,8 0,6-6,4 0,4-2,0

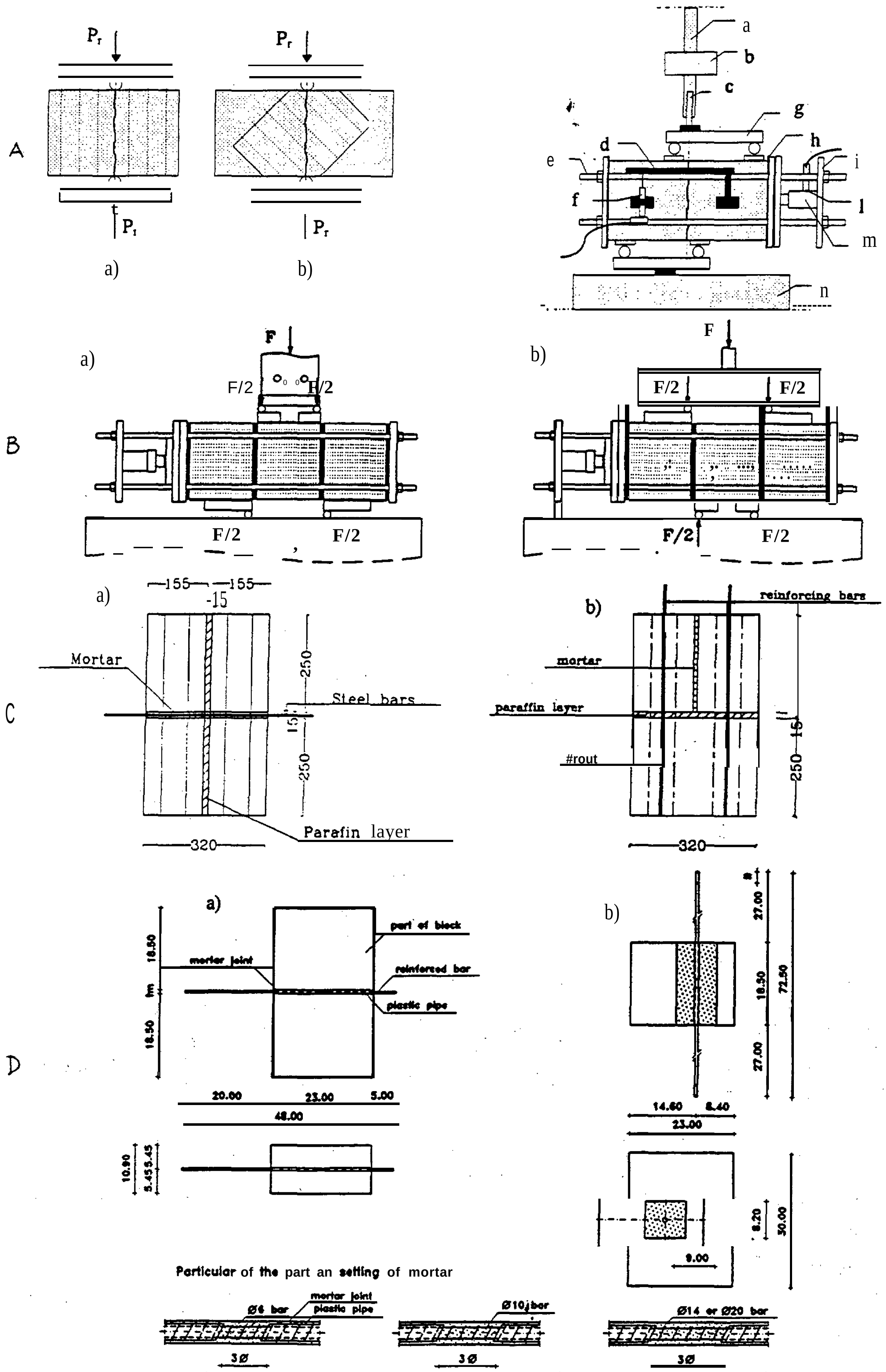


Fig. 4: Geometry of specimens and testing arrangements for the investigation of load transfer mechanisms along cracks within R.M.

(b) Friction between brick and mortar along a bed joint

This mechanism was investigated both in Italy and in Greece, using the bricks produced in the respective country. **As shown in** Fig. **4B,** the specimen was consisting of three bricks laid with mortar, thus forming two joints. The testing procedure was the following: Initially, a normal stress was applied to the joints, up to a predetermined value (0,05, 0,15 or 0,30 N/mm^2). This stress was kept constant during testing, whereas shear displacements were imposed to the specimen (either monotonically or cyclically),

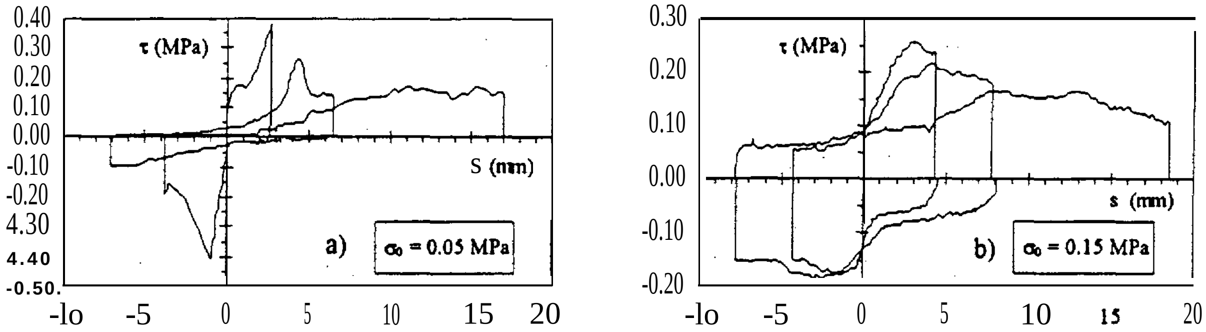


Fig. 5: A typical shear stress vs. shear displacement curve (tests earned out in Italy).

Fig. 5 shows a typical frictional stress vs. shear displacement curve. The interfaces between perforated bricks and mortar present some peculiarities which explain the differences in their behaviour when compared to the behaviour of interfaces within R.C. members. In fact, during construction of the specimens (in vertical position, as in real structures), mortar is inevitably entering the perforations of bricks, thus creating mortar dowels which expectedly alter the behaviour of the specimen, involving also bricks. The following two features are attributed to the mortar dowels:

(a) The ups and downs of the shear stress vs. shear displacement curves after the attainment of maximum shear resistance, As soon as the shear resistance of a mortar tooth is reached, the shear resistance of the specimen is reduced until new mortar dowels are mobilised and the resistance increases again.

(b) The damage observed on the bricks during testing: The action of mortar dowels leads either to horizontal or to vertical splitting of bricks. It seems, however, that after failure of the mortar teeth and/or of the, brick region adjacent to them, a residual shear resistance is still mobilised.

The obtained test results allow for the role of various "parameters to be evaluated: As expected, for both series of tests, the maximum mobilised friction coefficient is decreasing for increasing normal stress (Fig. 6). The same holds true for the residual friction coefficient, which

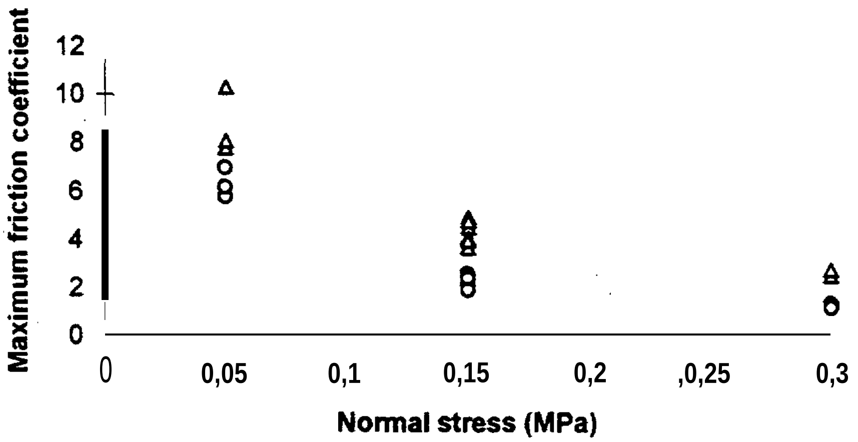


Fig.6 :Maximum friction coefficients as a function of the normal stress (Δ italian, o greek tests)

corresponds to the stabilised friction stress (after the attainment of the maximum resistance). It is however observed that the higher mechanical properties of the mortar in ease of the italian tests has led to higher maximum friction coefficients (Fig. 6). Nevertheless, this feature is not observed for the residual friction coefficients which are comparable for both series of tests.

3.2.2.- **Dowel action of horizontal and vertical reinforcement**

3.2.2.1 .- Dowel action of horizontal reinforcement

The mechanism was investigated using the specimen shown in Fig. 4C(a). Two deformed reinforcing bars were placed in the bed joint of each specimen, either 6mm or 10mm in diameter. Shear displacements were imposed to the bars, either monotonically increasing or cyclic.
All specimens failed due to crushing of mortar under the bars, whereas a plastic hinge was formed in the bars. In case of 10mm bars, local crushing of the brick shell was recorded. Splitting cracks in the bricks have also opened under the bars. After the completion of tests, the bars were taken out of the specimens and their deformed shape was examined. The formation of plastic hinges in the bars, in both sides of the vertical joint was apparent. Fig.7 shows shear force vs. shear displacement curves for monotonic loading.

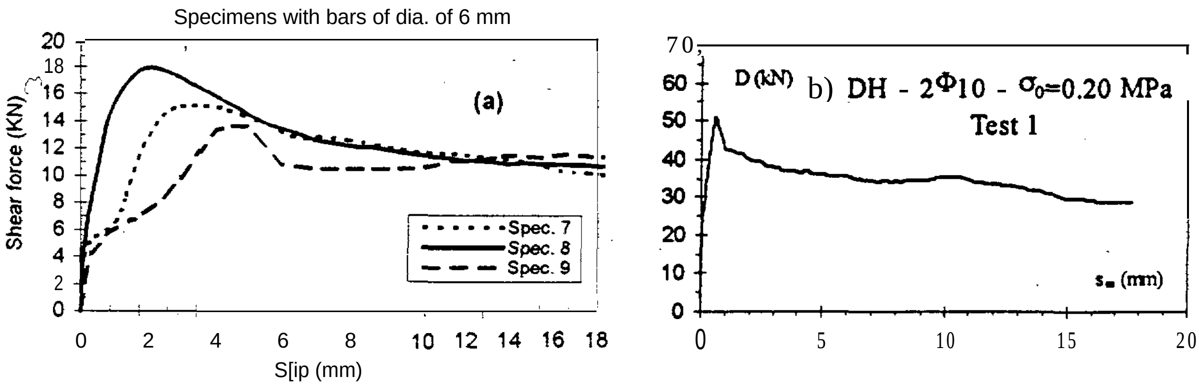
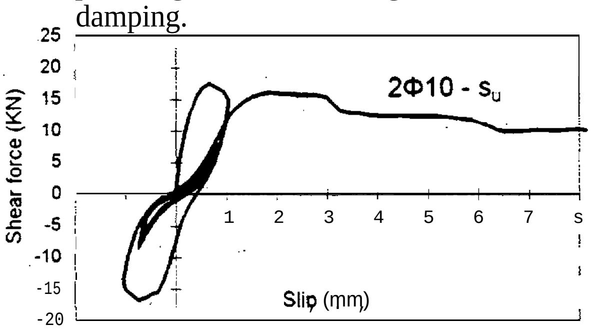


Fig. 7: Shear force vs. shear displacement curves for monotonic loading.

The behaviour of specimens presents some features common to all of them. A linear elastic behaviour up to a shear force which in some cases reaches 80% to 90% of the maximum shear resistance is recorded. In some cases, an early abrupt decrease in stiffness is observed, which is nevertheless followed by a subsequent increase. The second part of the ascending branch is however less steep than the first one, This kinking of the ascending branch may be attributed to local crushing of the mortar under the bar. The shear slip at which the maximum resistance is attained is rather scattered.
In Fig. 8, a typical hysteresis loops diagram is given. The cyclic behaviour of specimens presents all features common to shear sensitive systems. In fact, there is a pronounced response degradation with cycling, which is however quite scattered. The response during the third cycle is varying between 30°/0 and 80°/0 of that of the first cycle. In addition, there is a very pronounced pinching effect, resulting in limited area of the hysteretic loops and hence in low hysteretic damping.



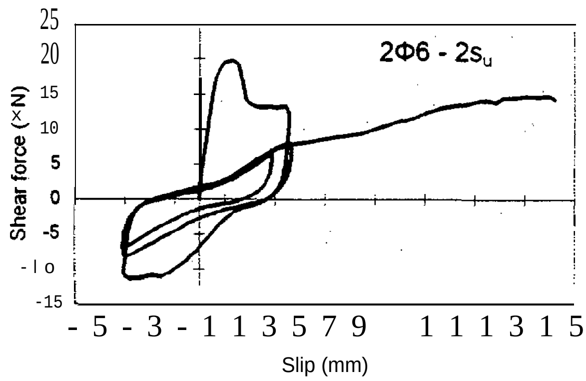


Fig. 8: Typical hysteresis loops

3.2.2.2.- **Dowel action of vertical reinforcement**

As shown in Fig. 4C(b), two reinforcing bars were placed in the vertical holes of the bricks, The vertical holes were subsequently grouted using a cement grout. The bars introduced to the vertical holes were 10mm or 12 mm or 14 mm in diameter deformed bars. All specimens were

subjected to imposed displacements (either monotonic or cyclic) whereas the main investigated parameter was the bar diameter.
All specimens exhibited a rather brittle behaviour, which is illustrated also in the shear force vs. shear displacement cures., This is attributed to the fact that the failure was due to fracture of the webs of the bricks due to the local compression excerted by the composite material «bar+grout». This fracture was initiated in the vicinity of the sheared joint and it was extended up to the external faces of the specimen.
The following can be observed, on the obtained shear force vs. shear displacement curves for monotonic and cyclic loading:

- The response of all specimens increases linearly with the imposed displacement, practically up to the attainment of the maximum response, which corresponds to a rather small shear displacement (of the order of 1mm).
- The ascending branch is followed by a rather steep falling branch (associated with fracture of the webs of the bricks), whereas stabilisation occurs at a low shear response value.
- It seems that the mobilised maximum shear response does not depend much on the bar diameter. This is attributed to the fact that failure is due to the fracture of the bricks and not to yielding of reinforcing bars.
- It is believed that the pronounced brittleness of the behaviour of these specimens is due to the high compressive strength of the grout.
- Regarding the cyclic behaviour, all remarks made for dowel action of the horizontal reinforcement (see § 3.2.2.1) are valid for vertical reinforcement as well.

3.2.3- **Pullout/Push-in of horizontal and vertical reinforcement**
Local bond-local slip tests were carried out using the specimens of Fig. 4D. Deformed bars 06, 010 or 014 were used; having a limited embedment length of 3 times the bar diameter. Satisfactory local bond conditions were observed (see Fig. 9a), since the mobilised bond response was approximately equal to 1/3 of the' compressive strength of the surrounding mortar (as it is the case also for bars embedded into concrete). Nevertheless, a rather unfavorable behaviour was observed under cyclic conditions (see Fig. 9b), in which case the bond response degradation during the third loading cycle was very high.

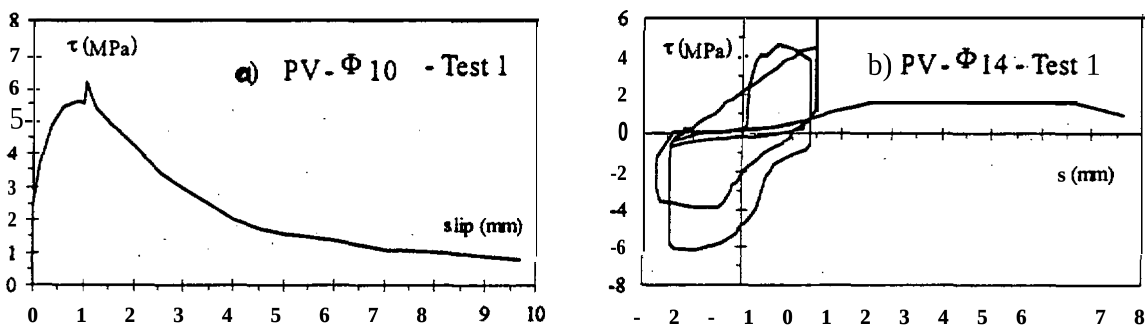


Fig. 9: Local bond-local slip for vertical bars: (a) Under monotonic actions, (b) Under cyclic actions.

3.3.- **Modelling**
In order to develop models able to describe the overall behaviour of R.M. walls subjected to in-plane actions, a systematic work was carried out at the Universities of Padua and Pavia, as well as at the Nat. Tech. Univ. of Athens. Non-linear hysteretic models were developed (univ. of Padua), whereas a previously available experimentally-based formalistic model was appropriately calibrated Univ. of Pavia). On the other hand, the so-called stereostatic model which was previously developed at NTUA was improved, whereas the models developed on the basis of testing on the load transfer mechanisms were introduced to the model to predict the in-plane behaviour of R.M. walls. The models were successfully used to predict the behaviour of full scale subassemblages which were tested within the project (see $3.4).

3.4.- Testing of full scale subassemblages

In this part of the project, extensive full scale testing of reinforced masonry subassemblages was performed. In total 22 full scale subassemblages were tested at the Nat. Tech.Univ. of Athens, at the Univ. of Pavia, at the Univ. of Padua and at the Tech. Univ. of Darmstadt. All specimens were subjected to a predetermined value of vertical load (held constant throughout testing) and subsequently subjected to cyclically imposed horizontal displacements at their top. The aim was to investigate the effect of various parameters on the strength and ductility characteristics of full scale walls and subassemblages. The parameters which were investigated are the following: The. aspect ratio of walls (it varied between 0,50 and 1,50), the percentage of horizontal and vertical reinforcement (it varied between $1/2\rho_{min}$ and $2\rho_{min}$, where ρ_{min} is the reinforcement which is required to reinstate the cracking resistance of the plain masonry), the normal stress due to vertical loads (equal to 0,20 or to 0,40 N/mm^2), the presence of flanges (or transverse walls), as well as the presence of openings on the walls. Fig. 10 shows the geometry of the subassemblages which were tested at the four Universities and summarises the values of the investigated parameters for all specimens. It should be noted that all specimens were adequately instrumented to record continuously their deformations and force response. In addition, strain gauges were placed on the horizontal and vertical) reinforcing bars of the specimens, in order to measure their strains (thus, also their stresses) during testing. Crack pattern and crack openings were also recorded during testing. Fig. 1 I shows some typical hysteretic loops obtained from testing full scale walls, whereas some of the obtained results are mentioned here below:

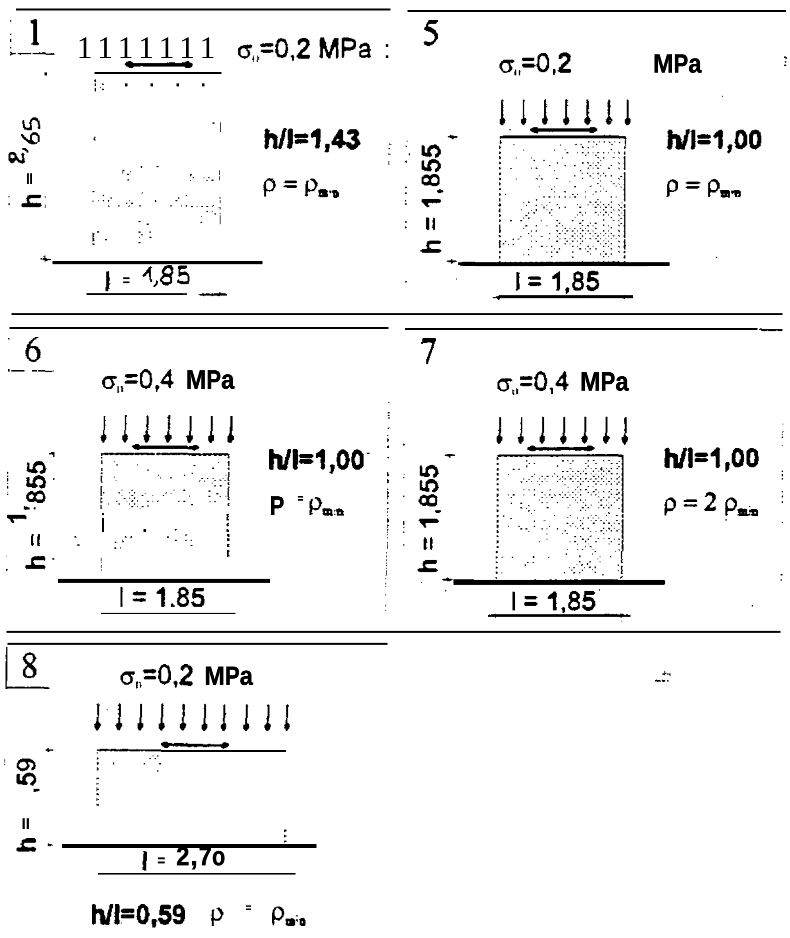


Fig. **10.1:** Test specimens of NTUA

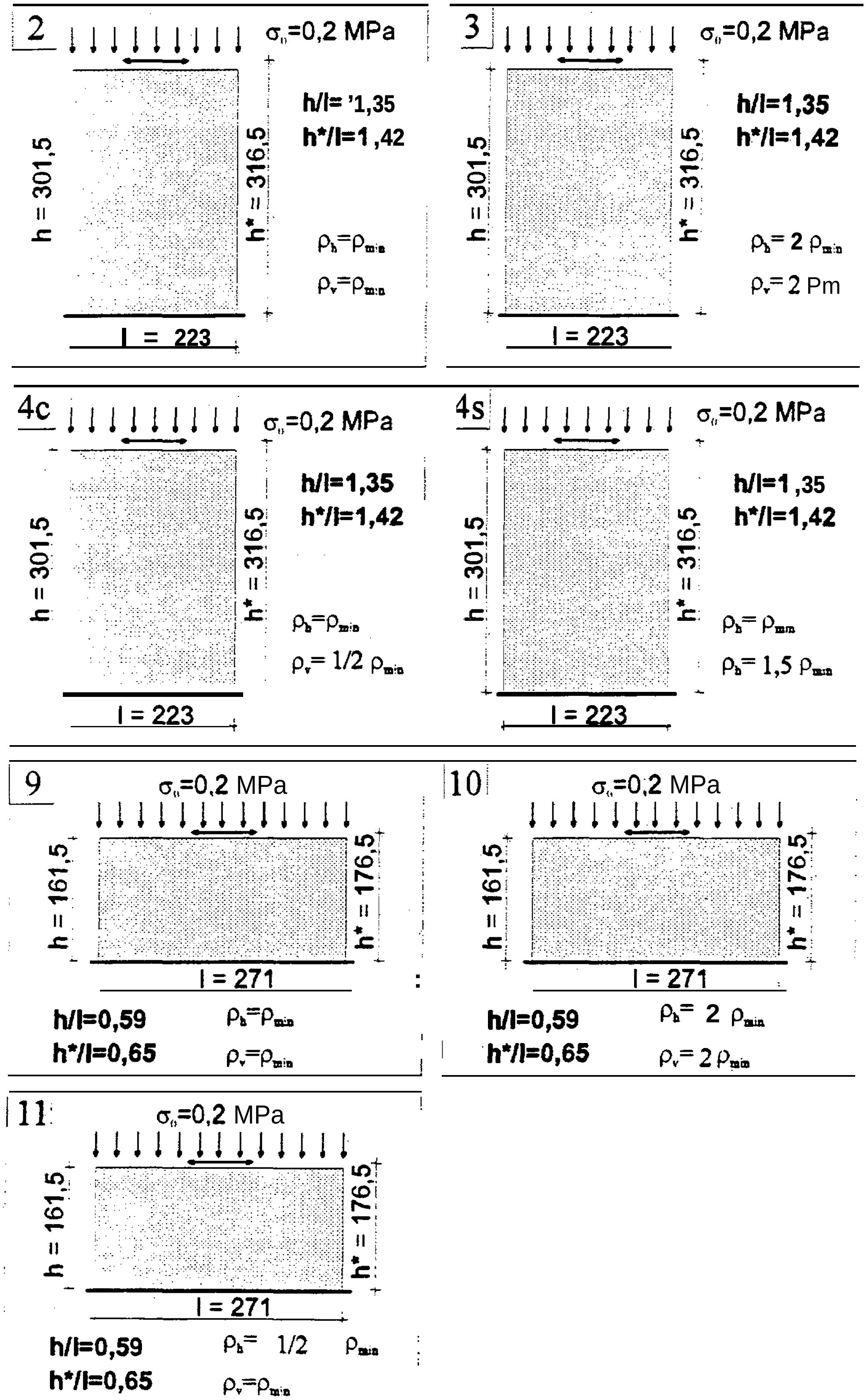


Fig. 10.2: Test specimens of UPAV (h* denotes the height at the point of application of' the horizontal load)

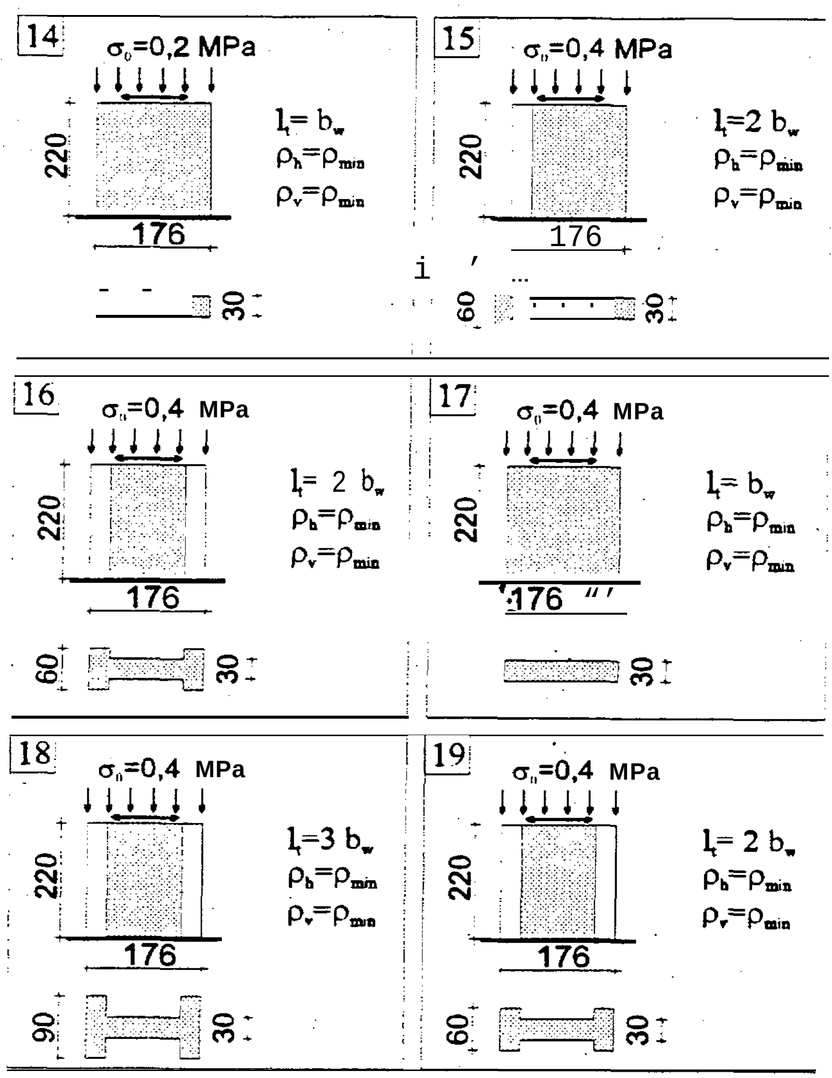


Fig. 10.3: Test specimens of UPAD

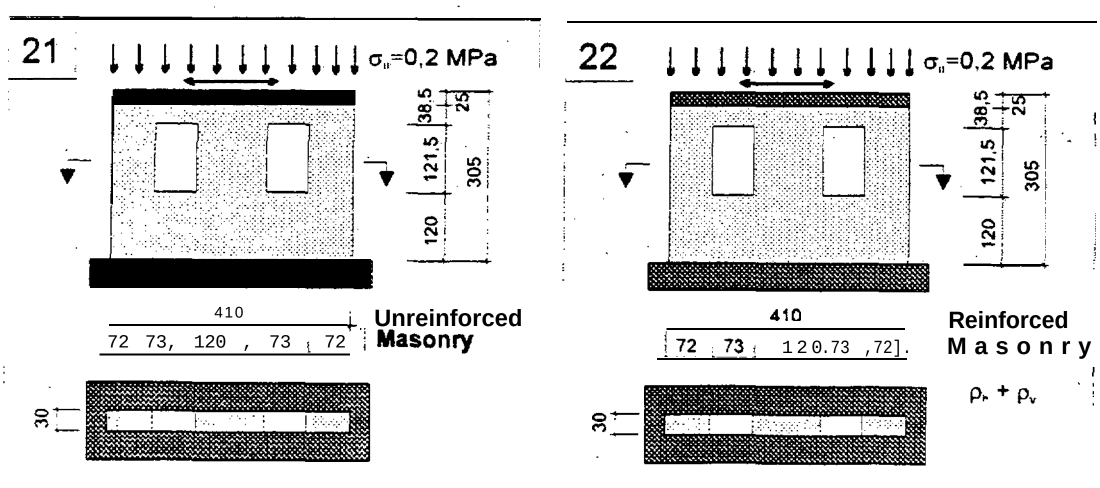


Fig. 10.4: Test specimens of THD

The effect of aspect ratio: It was proved that, as it was expected, the maximum shear resistance of walls was increasing with decreasing aspect ratio. The same holds true for the horizontal deformations of the walls, whereas their ductility was decreasing with the aspect ratio. Nevertheless, even for aspect ratios as low as 0,50, a displacement ductility not smaller than 3,0 was observed.

The effect of vertical stress: It was observed that the increase of vertical stress from 0,20 N/mm^2 to 0,40 N/mm^2 has led to an increase (by approximately 10%) of both cracking and ultimate resistance of walls. On the contrary, the ductility of walls was negatively affected by increasing vertical loads.

The effect of reinforcement: In general, the increase of reinforcement ratio leads to an improvement of the behaviour of walls in terms of cracking and ultimate resistance, as well as in terms of ductility. This is valid, however, only in condition that the reinforcement ratio does not impair the strength of masonry units used to construct the walls. In fact, in case a wall is over-reinforced, premature failure of bricks may occur, thus leading to decreased resistance and ductility. A favourable effect of the distributed reinforcement was observed also on the cyclic behaviour of walls which exhibit smaller response and stiffness degradation as reinforcement ratio was increasing. The experimental results have also shown that by modifying the reinforcement ratio, one may affect the mode of failure of a wall. In fact, a rather squat vertically under-reinforced wall may be forced to fail in flexure, whereas a vertically over-reinforced slender wall may fail in shear.

The effect of flanges: A substantial increase (of the order of 30%) was observed in the ultimate resistance of walls with flanges equal to three times the thickness of the wall. This increase in strength was smaller for smaller flange lengths. It was also observed that there is a considerable increase of ductility when flanges are provided to the walls, provided that there is sufficient bonding berween the wall and the flanges.

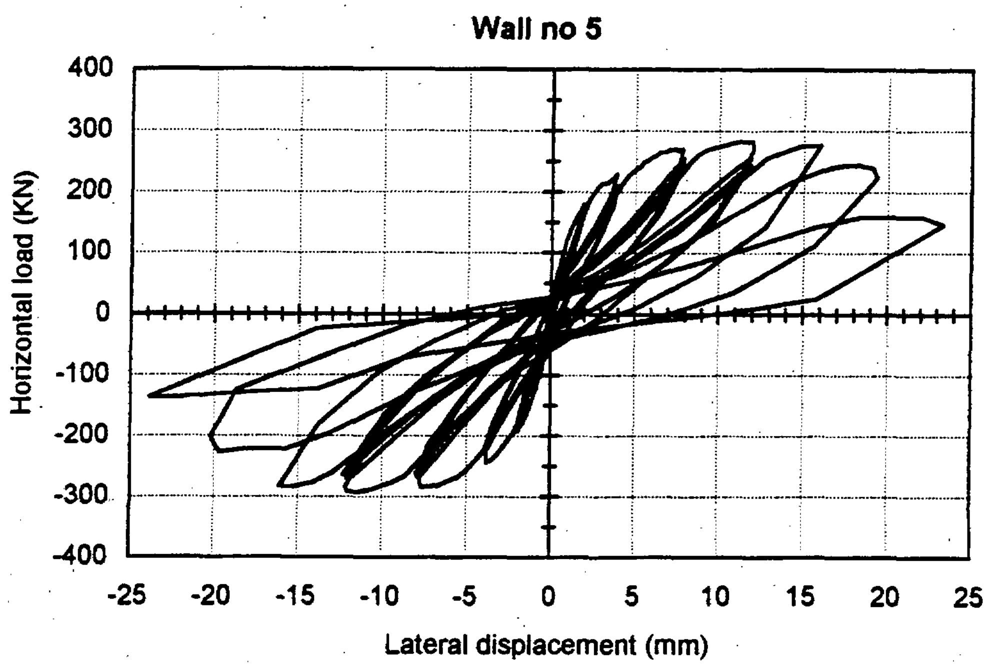


Fig. 11: Typical hysteretic loops obtained from testing full scale walls.

After the completion of tests, the obtained results were compared with the predictions made before testing using the models developed, as mentioned in the previous section. In some cases, the models were proved to be able to predict some of the major characteristics of the walls (such as cracking and ultimate resistance), whereas in other cases correction of the models and calibration was needed to fit the experimental results.

A very important tool for checking both the experimental results obtained from testing full scale subassemblages and the validity of methods of analysis is the testing of one scaled reinforced masonry building on an earthquake simulator. The model building, appropriately constructed, has been fixed on the earthquake simulator, and has been dynamically tested. Analytically predicted structural characteristics of the building are experimentally confirmed. Destructive tests are actually carried out.

3.5.- Analysis of buildings

Two aspects related to the analysis of reinforced masonry buildings were considered, namely the selection of suitable methods to be applied for the calculation of action effects (used in the design process) and the formulation of refined nonlinear cyclic models to be used in dynamic analyses with in-time integration (applied to evaluate the behaviour factor of R.M. buildings).

Within the context of seismic analysis of buildings, several approaches are commonly used, most of them based on linear elastic assumptions. A study was undertaken with the aim to evaluate those methods. The study consists in a critical comparison and discussion of the results that can be obtained applying various methods for the analysis of the same building. These methods included approaches of varying complexity from very simplified methods to refined three-dimensional linear finite element analyses. To this purpose, four buildings (two to three storey high) were selected as representative of R.M. building construction in Italy and Greece. The buildings were analysed using pier-type methods, two-dimensional linear elastic equivalent frame, three dimensional linear elastic equivalent frame and two- or three-dimensional linear elastic finite element method.

The following main conclusions were drawn on the basis of the analytical work:

- In general, equivalent frame methods seem to be more reliable, especially in what concerns the calculation of moments and axial forces. Two dimensional analysis can be applied, provided that there is no considerable eccentricity of the seismic force with respect to the centre of stiffness.
- The way in which the walls are bonded at their intersections should be taken into account. In case the masonry units are bonded at wall intersections, during the analysis an effective flange length" should be taken into account.
- Equivalent frame methods offer the possibility of calculating action effects also on horizontal elements (e.g. ring beams) thus allowing for strength verification of these elements as well.
- The pier type methods seem to be conservative for single- or two-storey buildings, provided that the piers are considered as free cantilevers. For more than two-storey buildings, it seems that these methods may underestimate the bending moments on the piers, especially in case of weak coupling (by ring beams only).

3.6.- Construction and testing of buildings

As mentioned in the Introduction, two small full scale buildings (one made of reinforced masonry, the other made of reinforced concrete) were constructed both in Italy and in Greece. The houses of each set (Fig. 12) were identical in geometry, whereas they were designed for the same actions and for the same insulation parameters. The reasons for the construction of these experimental houses are the following: Identification of constructional problems related to the construction of R.M. and formulation of alternative solutions to the problems. Comparison of costs and time. needed for the construction of a conventional R .C. and a R.M. structure. In-situ measurements of habitability parameters (such as acoustic and thermal insulation), as well as in-situ durability tests. Finally, in-situ measurements of the dynamic characteristics of the buildings and (static) testing of the buildings under conventional seismic loads.

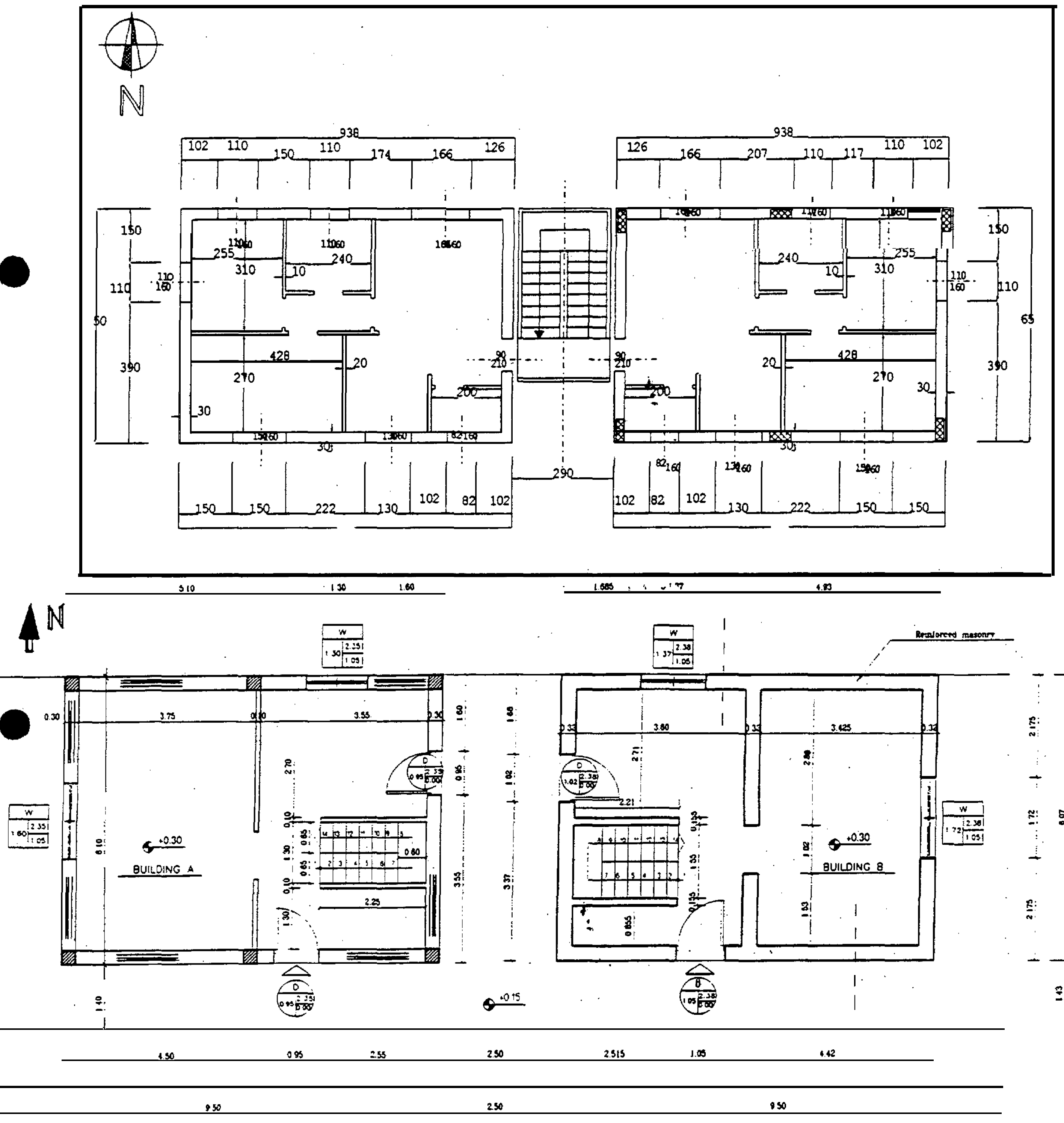
To this purpose, the buildings were appropriately instrumented. Although measurements will continue to be taken from the buildings in the years to come, one may say that thermal and sound insulation tests have shown a similar behaviour of the two buildings of each set, whereas no sign of steel corrosion is observed two years after the construction of the R.M. buildings.

3.7.- Recommendations

This is the final part of the project, which summarises the conclusions of all parts of the research work. It contains guidance about the characteristics (geometrical, mechanical and physical) of the materials to be used for R.M. construction, about the methods of analysis and verification of reinforced masonry elements, about the behaviour factors to be applied in seismic design and last but not least about the solution of constructional problems.

4.- CONCLUSIONS

On the basis of the research work carried out within the project, it was proved that reinforced masonry is a construction system which may offer sufficient strength against normal actions, as well as against seismic actions, provided that it is conceived and designed appropriately and that adequate materials are used. Furthermore, reinforced masonry can ensure satisfactory habitability conditions, if made using materials having properties similar to those investigated within the project. Finally, reinforced masonry is durable enough, provided of course that it is appropriately constructed (using materials that offer a favorable environment to the embedded reinforcement) and maintained.



R.C. building R.M. building

Fig. 12: Plan of the experimental houses built (a) in Italy, (b) in Greece

ACKNOWLEDGMENTS
This research project was financed by the European Union" within the framework of BRITE/EURAM Projects, Project No BE-4001, Contract No BREU-0575.