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RELIABILITY ANALYSIS FOR NON STANDARD MASONRY SYSTEMS UNDER SEISMIC LOADING

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SUMMARY

The paper concerns the analysis and experimental characterization of a number of *non-standard* masonry types that are commonly present in Calabria (Italy), a region at a high seismic risk. In order to assess the structural reliability and to design the retrofitting interventions for such indigenous constructive types it is important to know the local techniques and to carry out a specific on-site experimental investigation.

The attention has been focused on a number of towns in the district of Cosenza. Here, a survey has been carried out in order to detect and classify the structural features of the local residential housing. A significant element observed was the large presence of buildings made of a *non-standard* masonry that doesn't meet law requirements and mostly dated back to the first half of the XIX century, a period in which hollow bricks (usually employed for curtain or enclosure walls) available on the market at a low cost were diffusely used in substitution/combination of the ancient materials in the construction of traditional bearing masonry walls.

After surveying and classifying the different types (elements, textures, structural configurations…), the masonry elements and the materials have been experimentally investigated (by testing samples taken on site and manufactured in laboratory), as here specified:

Mortars: composition of the mixture; chemical and mechanical properties (tensile and compressive strength).

Hollow clay/concrete blocks: dimensional features; defects; mechanical properties (compressive strength in the two directions–parallel and perpendicular to the holes).

Masonry panels with clay/concrete blocks: uniaxial and diagonal compression tests (compressive and tangential strength).

The collected data have been processed and compared with the Italian and European laws, collecting the necessary information for an assessment of the structural reliability convenient for the local context, and defining the most suited strategies of rehabilitation/retrofitting for the seismic risk. In fact, for economical and practical reasons, it is not acceptable a systematic carpet-substitution of the existing residential housing. Trough this research work it was possible to collect the necessary information for an assessment of the structural reliability convenient for the local context, and to define the most suited kind of

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rehabilitation/retrofitting for the seismic risk (in fact, for economic and practical reasons, it is not acceptable a systematic carpet-substitution of the existing residential housing.

INTRODUCTION

The province of Calabria, as well as many Italian areas, is characterized by a high seismic activity (fig. 1) and by a great number of traditional masonry buildings endowed with a high vulnerability.

The research work presented has been carried out in this geographical context, and is aimed at the experimental mechanical characterization of a number of *non-standard* masonry types that are frequently encountered in this territory.

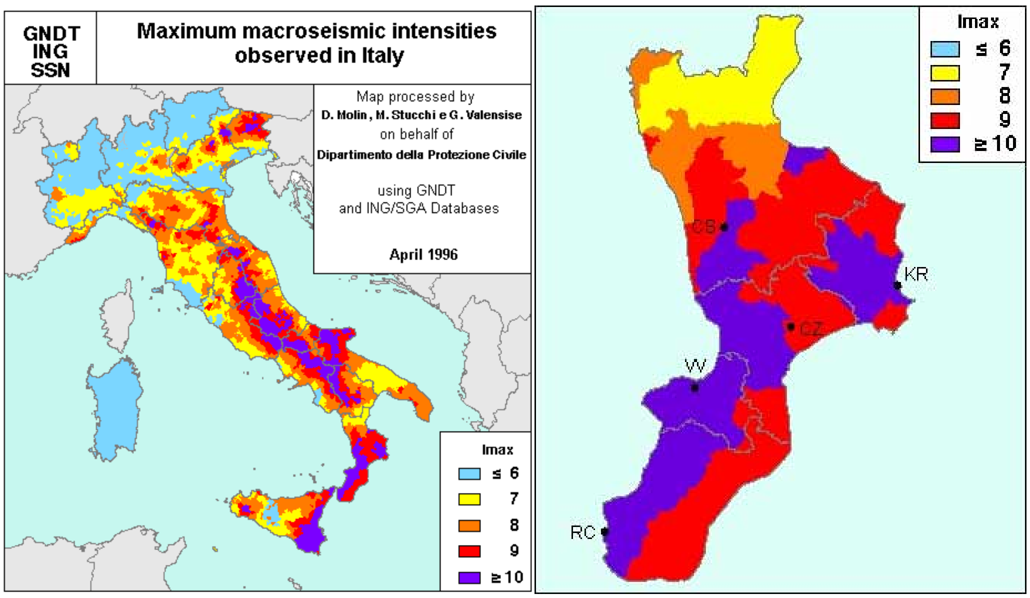

Figure 1. Maximum macroseismic intensity observed in Italy at 1996, and detail of region Calabria.

By nature, masonry is a complex composite material: only in a very few historical types the blocks arrangement is systematically ordered, whereas in most case buildings have been intensely re-shaped to accommodate the usage exigencies, resulting in very irregular geometries, coexistence of miscellaneous and heterogeneous materials (that are often recycled stuff), different stratified constructive techniques. The mechanical and physical parameters turn out to be very scattered, hard to be identified, and a prediction of the structural response of the building (but even of the very single masonry panel) is indeed a difficult task. It should also be remembered that the structural elements, types and constructive techniques are changeable in the different geographic areas. It is not unusual to encounter situations severely below the norm because of the materials used and the structural configurations.

These reasons altogether can give explanation for the lack of a general purpose tool to be actually used in the safety assessment of existing masonry buildings under seismic loading. On the other hand, the assessment of the structural reliability of existing buildings is an urgent matter, considering the great diffusion of vulnerable masonry constructions.

A crucial element that has to be included in these analysis, as well as in the design of the retrofitting interventions, is a specific on site experimental investigation over the indigenous constructive types, aimed at the knowledge of local techniques and types and at the mechanical characterization of materials and structural elements.

The attention has been here focused on a number of towns in the District of Cosenza (Acri, Bisignano, Corigliano Calabro, San Demetrio, Luzzi, Rose e Montalto), where, first of all, an extensive survey has been carried out in order to detect and classify the structural features of the local residential housing. A significant element detected was the large presence of buildings made of a *non-standard* masonry not meeting law requirements. These types are mostly dated back to the first half of the XX century, a period in which hollow bricks that are usually employed for curtain or enclosure walls (in particular, hollow clay units with 21 holes and hollow concrete blocks), were increasingly available on the market at a low cost and were diffusely used in substitution or combination of the ancient materials (stone rubble, solid bricks…) in the construction of traditional bearing masonry walls.

After surveying and inventorying different types (elements, textures, structural configurations…), masonry elements and materials have been experimentally investigated (by testing samples both taken on site and manufactured in laboratory), in order to provide the information to be used in the reliability assessment and in the selection of the most appropriate intervention lines. In fact, it is evident that a systematic substitution of all these typology is not economically and practically sustainable.

The experimental tests have been organized according to the following scheme:

hollow clay units and concrete blocks: definition of the geometrical and dimensional features, defects, mechanical properties (compressive strength in a direction parallel and perpendicular to the holes); mortars: composition of the mixture; definition of chemical and mechanical properties (tensile and compressive strength); masonry panels with clay/concrete units: uniaxial and diagonal compression tests for the determination of the characteristic compressive and tangential strength. The collected data have been processed and critically compared with the Italian and European in force laws (Table 1).

Table 1. Law references.

D.M. 26/01/96	C.5	Requirements of blocks to be used in seismic areas.
D.M. 20/11/87	1.2	Requirements of materials (mortars, brick and concrete blocks)
	2.3.1.1	Determination of the characteristic strength of masonry on the basis of the units.
	All.1	Experimental determination of the characteristic strength of stone and brick units.
	All.2	Experimental determination of the characteristic strength of masonry.
UNI 8942	1	Clay units for masonry buildings: glossary, classification.
	3	Clay units for masonry buildings: testing methods.
UNI EN 196-1		Experimental testing methods for cements: mechanical strength.
Eurocode 6	3.1	Clay units (EN 771-1); concrete blocks (EN 771-3) and related testing methods and instructions (EN 772-1).
	3.2	Mortars: types, classification (EN 998-2); determination of the compressive strength (EN 1015-11*).
	3.6	Determination of the mechanical charcteristics of non reinforced masonry: experimental testing (EN 1052-1); on the basis of the mechanical parameters of units and mortar (par. 3.6.2.2-3-6-2-6).

*Alternative to EN 196-1, that is the law here followed.

CHARACTERS AND EVOLUTION OF THE TRADITIONAL CONSTRUCTIVE TECHNIQUES IN CALABRIA: "NON STANDARD" MASONRY TYPES

In Calabria, according to the popular constructive tradition, masonry elements were usually built with stone rubble, sometimes staggered by solid bricks courses. Solid brick elements were also used for quoins, lintels, openings' jambs and wherever a fair scarfing was required in order to guarantee an effective box-like overall behaviour. Instead, monuments and important dwellings were rather built using more valuable and expensive materials (like stone ashlars): indeed, a typical feature of popular architecture is the inclination to use cheap materials, easily available on site, and accordingly the specific technologic solutions adopted are the strict consequence of this "optimisation" need. Later on, when even stone rubble began to lack and conversely either the industrial manufacturing of artificial clay blocks spread on a serial and larger scale and the workmanship cost increased, the constructive models started to change as well. Hollow clay units, much less expensive and more easy to be laid, soon began to be used in combination with solid blocks (or even as a substitute) both in new constructions and in readapting old buildings.

Moreover, starting from the first half of 20th century, mixed structure buildings (a sort of transition element towards the fully framed building - with external masonry walls and internal framed structure) knew a great success and diffusion in Italy, thanks to the dissemination of the new reinforced concrete technology (fig. 2).

Figure 2. The evolution of the traditional bearing masonry in Calabria: some examples of "non standard" masonry types.

With regard to this particular structural type, an investigation has been carried out in the north of Calabria, in the district of Cosenza (and in particular in the cities of Acri, Bisignano, Corigliano Calabro, San Demetrio, Luzzi, Rose, Montalto). As previously outlined, a large number of buildings have been detected in which *non-standard* masonry types are used. Such types have been here defined *non-standard*, in the sense that they do not meet in-force law requirements with regard to the aseismic prescriptions for structural masonry systems (for the geometrical, dimensional and mechanical properties of the components and the arrangement sets).

Indeed, during the briefly mentioned transformation process of the building practices, the complete absence of a reference standard, a previously assessed experience or constructive rules, together with a certain speculative impulse, have determined a proliferation of buildings characterized by an incorrect use of techniques and materials, and by a poor quality and executive accuracy.

For the materials and the masonry arrangements that have been observed during the surveys, no experimental data or reference literature existed at all. In order to appraise the structural reliability of these buildings and define the most suited kind of rehabilitation/retrofitting techniques for the seismic risk, all the necessary information was to be retrieved on site.

The aim of the research work here presented is just to provide the reference data for the safety assessment, by examining a significant population of buildings on which acquiring a sufficiently exhaustive typological and technological knowledge for the inventory of the indigenous materials and constructive systems) and performing a specific experimental laboratory program for the mechanical characterization of the constituents and the different masonry specimens.

CLASSIFICATION AND MECHANICAL CHARACTERIZATION OF THE COSTITUENTS

In the territory and in the age considered, the use of stone rubble is still present, especially in the basement floor, but very often different masonry types have been observed, made with a miscellaneous combination of traditional solid bricks, various hollow blocks (in particular, brick units with 21 holes and hollow

concrete units many of which are no longer manufactured) and mortars, with a considerable variability in morphology and nature of the constituents and in the arrangement patterns of the walls.
First of all, the characterization of the most used binders has been performed, taking representative samples of the mortars (in order to identify and reproduce their composition) and retrieving samples of the blocks (being elements no more manufactured and marketed, a widespread search in the local brickyards has been performed).
After that, an experimental investigation for the geometrical and mechanical characterization has been carried out, classifying and evaluating the different elements according to the law requirements.
With regard to the geometrical and dimensional parameters, the following aspects have been evaluated both for hollow brick units and for hollow concrete units : shape, dimensions, incidence of holes, defects. In a second phase, the units have been subjected to compressive tests, following all the actual direction of the loads.
Mortars have been experimentally tested as well: their composition has been analysed, and the physical and chemical properties of the ingredients have been determined. After that, the most representative mixtures have been reproduced, casting a number of specimens on which the compressive and flexural tests have been performed.

Hollow brick units and hollow concrete blocks

Among the different types of hollow brick units (fig. 3) with 21 holes that have been observed during the surveys, the two most recurrent types have been considered: from now on they will be denoted with the labels *FA* and *FB*. The dimensions of both are *25cm x 25cm x 12cm*. Also in the case of concrete units (fig. 3) two types of blocks have been examined, called: *BA* and *BB*. The samples have been characterized with respect to their dimensions, geometry and mechanical parameters, according to the law prescriptions (table 1). A part of the samples retrieved and analysed in this phase has been later used for the preparation of the masonry specimens to be tested successively tested under compression (in particular the *FA* brick units and *BA* concrete blocks).

Figure 3. Examples of hollow brick and concrete units observed in the masonry buildings.

Geometrical classification

In tables 2 and 3 the structural masonry units have been classified with respect to the norms (table 1): UNI 8942 - part 1 [1] (on the basis of the position under way, the manufacturing technology, the incidence of holes); DM 20/11/87 [2] (on the basis of the hole incidence and the average normal section of the single hole); EC 6 [3] (on the basis of the total volume, hole area, internal hedge thickness; EN 771-1 and 3).

Table 2. Classification of the 21 holes brick units.

	Type FA	**Type FB**
Dimensions	*25 cm x 25 cm x 12 cm*	*25 cm x 25 cm x 12 cm*
Hole percentage φ	**50,95 %**	**47,20 %**
UNI 8942 classification	**BSB 00-21** (semi-solid blocks with horizontally laid holes)	**BSB 00-21** (semi-solid blocks with horizontally laid holes)
DM 87 classification	**Hollow units**	**Hollow units**
EC 6 classification (EN 771-1)	**2 b**	**2 b**

Thirty units belonging to the class FA have been visually inspected, with a particular attention to the incidental presence of defects (cracks, burr, chipping, protrusions, …). Then for ten samples taken from this set, linear dimensions, thickness of internal hedges have been measured and the shape and the profile have been examined and judged (with regard to the planarity of the faces, straightness, orthogonality of the edges.

For these ten samples and for more ten samples belonging to the class FB, the hole incidence φ and the average area of single holes f have been determined. Among these geometrical parameters, particularly significant is the hole incidence φ, since, according to the Italian law D.M. 26/01/96 [2] it qualifies the masonry unit to be used in a seismic area: only elements endowed with a sufficiently limited hole incidence (that is to say, the solid and semi-solid ones) will be in fact admitted for structural uses. More specifically, according to this norm both the masonry unit classes we have examined should be considered hollow on the basis of the hole percentage and average area of single holes. Therefore, strictly speaking, they could not be used for the construction of structural masonry in a seismic area. Moreover, the examined units have revealed a number of additional deviations from the geometrical prescriptions even with respect to the classification in the class of hollow units provided in the law (the thickness of the internal and external hedges was insufficient).

Hence, masonry walls built with such elements are already out-of-rule because of the inadequacy of the blocks used. The situation is even worsened if we consider the arrangement of the units in the panels (see the related section).

A similar analysis has been performed for the concrete units: ten BA samples and ten BB blocks have been examined, determining the hole percentage, they have been classified according to the in-force standards (summarized in table 3). This case is quite different: in fact they are to be considered semi-solid units, and their use for structural purposes is admitted in seismic areas by the Italian law. Only one deviation from the standards has indeed been traced: the average normal section of the single holes, that is double then the limit value.

Table 3. Classification of the hollow concrete units.

	Type BA	Type BB
Dimensions	*40 cm x 20 cm x 20 cm*	*40 cm x 20 cm x 20 cm*
Hole percentage φ	**42,23 %**	**31,59 %**
UNI 8942 classification	**BSB 00-21** (semi-solid blocks with horizontally laid holes)	**BSB 00-21** (semi-solid blocks with horizontally laid holes)
DM 87 classification	**Semi-solid units**	**Semi-solid units**
EC6 (EN 771-3) classification	**2 a**	**2 a**

Compressive tests

Compressive tests on the hollow brick units have been performed according to the rule UNI 8942–3 and to DM 20/11/87 – att. 1 [1]. For the test, 26 samples of 21 holes brick units of the FA type (average dimensions *25cm x 25cm x 12cm*) have been used. Among these, 10 samples have been tested in the direction orthogonal to the holes on the long face (*type a* test – fig. 4-a); 6 have been tested under compression in the direction orthogonal to the holes on the short face (*type b* test – fig. 4-b); 10 have been tested under compression in the direction parallel to the holes (*type c* test – fig. 4-c), so that all the possible situations encountered in the real cases have been represented. It is necessary to point out that according to the law prescriptions, at least 30 samples should be tested in order to determine the characteristic strength f_{bk}. For the practical difficulties highlighted in the preliminary remarks, it was not possible to retrieve such a numerous population of samples, hence, for the computation of the characteristic values, we refer to the coefficient provided by UNI laws, that are applicable for the actual number of samples (*n=10* for *type a* and *type c* tests; *n= 6* for *type b* test).

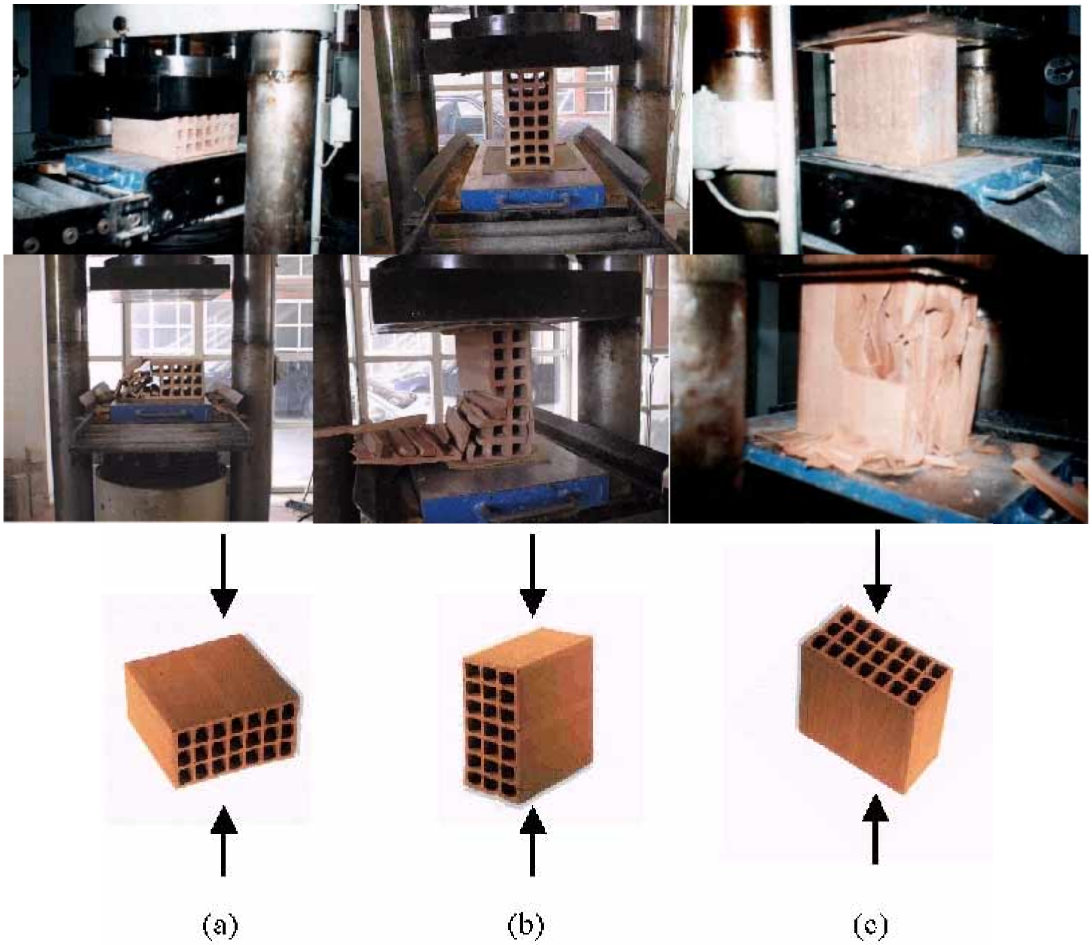

Figure 4. Compressive tests on hollow brick units: a) direction orthogonal to the holes on the long face; b) direction orthogonal to the holes on the short face; c) direction parallel to the holes.

The results obtained are shown in table 4. It is worth observing that the brick units belonging to the type FB, which are characterized by a sligthly lower hole incidence (closer to the threeshold required for a classification as a semi-solid block according to D.M. 20/11/87 [2]) have exhibited significanlty higher strength valueshan the FA type. With regard to to concrete blocks (fig.5), the compressive test was performed following the EN 771-3 standard. Ten samples from the type BA and six from the type BB have been used (average dimensions: *20 cm x 40 cm x 20 cm*).

Table 4. Characteristic strength f_{bk} for brick and concret units.

f_{bk} (N/mm^2)	Type FA	Type FB	Type BA	Type BB
Compression orthogonal to holes (a)	3,03	7,66	-	-
Compression orthogonal to holes (b)	3,56	-	-	-
Compression parallel to holes (c)	12,69	14,82	13,89	10,06

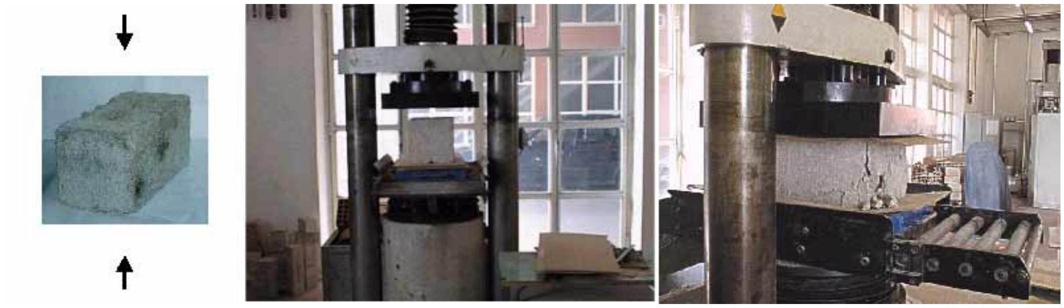

Figure 5. Compressive tests on hollow concrete units.

Data interpretation according to Italian law D.M.16/01/96 [4]

As previously pointed out, this law allows the use of only semi-solid and solid elements for building in bearing masonry in seismic areas, and fixes a minimum threshold also for their characteristic compressive strength f_{bk}. The masonry units examined in this research work have already revealed some dimensional and morphologic deviations: in the previous section has been highlighted that only concrete units can actually be classified as "semi-solid", whereas the brick 21 holes units are to be considered as strictly "hollow" (only according to the UNI 8942 [1] classification both units are comprised in the class of semi-solid units- type B). At this point, the characteristic compressive strengths experimentally measured have been compared with the minimum indicated by the D.M. 16/01/96 [4], in order to assess if the different types of units could be – at least approximately associated to a specific resistance class (Table 5).

Table 5. Comparison between the experimental values for the f_{bk} of the brick and concrete units and the law limits (DM 16/01/96 [4].

f_{bk} (N/mm^2)	Type FA	Type FB	Type BA	Type BB	law limits (for semi-solid units)	
					Direction of loads	Direction normal to loads
Compression orthogonal to holes (a)	**3,03***	7,66	-	-	$f_{bk} \geq 5$ N/mm^2	$f_{bk} \geq 1.5$ N/mm^2
Compression orthogonal to holes (b)	**3,56***	-	-	-	$f_{bk} \geq 5$ N/mm^2	$f_{bk} \geq 1.5$ N/mm^2
Compression parallel to holes (c)	**12,69**	14,82	13,89	10,06	$f_{bk} \geq 5$ N/mm^2	$f_{bk} \geq 1.5$ N/mm^2

* Out of range value.

For the hollow brick units, the actual position of the holes with respect to the vertical loads has been taken into account. For the FA type, the only case in which the recorded values turn out to be compatible with the requirements is case (c), that is to say, when units are placed with vertical holes within the wall (such a position is almost never encountered: brick units turn out to be systematically positioned with horizontal holes! Only in one case they are vertical, but always in combination with horizontal ones – see following section). Hence, the reason that makes the irregularity so severe for masonry walls built with type FA brick units is not so much the morphologic inadequacy of the blocks themselves (that is quite small), but rather the wrong placement: if a different, correct arrangement (with always vertical holes) would have realized, the mechanical strength would have been acceptable. Different is the case of type B units: although they are irregular with regard to the hole percentage (ϕ =*47,20%*, that is out of range but not so far from the limit value) they are endowed with a good characteristic strength irrespectively of the hole direction. Whatever their orientation in the masonry panel is, the limits provided by the Italian law D.M. 16/01/96 are complied with. The irregularity for masonry built with blocks can be judged as less severe.

Unfortunately, the survey carried out in the territory has revealed that type FA brick unit is indeed the most commonly used. The concrete units, classified as semi-solid, are always used with vertical holes. Moreover the experimental compressive tests (table 5) exhibit values that are completely within the prescribed range: these walls are potentially suitable for a use in seismic areas.

Mortars: composition and classification according to Italian and European laws (D.M.20/11/8t [2]; EC 6 [3])

The analysis of the constructive techniques has revealed that the mortars used were basically of two types: the first composed of sand and cement, the second with sand, cement and a small amount of hydraulic lime. For both, the usual water/cement ratio was *0,5*, pretty higher than the recommended value (with a consequent decrease in the resulting mechanical strength). In fact, in the building practice, a more fluid mixture was preferred in order to compensate the absorption of the water by the blocks (which were not systematically moistened, as a correct rule would suggest). In order to characterize the typical mortars and investigate at the same time the effect of the water content on the final strength, tests for the determination of the compressive and the tensile strength have been performed on three types of mortar, different either for the ingredients or for the water/cement ratio (table 6). For the preparation of the mixtures, ingredients and their proportion have been tuned in order to reproduce as much as possible the actual situation: Portland cement 325; hydraulic lime; quarry sand on which no preliminary cleaning or washing has been performed.

Table 6. Ingredients and proportions for the 3 mortar types.

# sample (40mmx40mmx160mm)		**Ingredients**							
		Sand		Portland Cement 325		Hydraulic lime		Water	
		Kg	Volume fraction	Kg	Volume fraction	Kg	Volume fraction	Liters	Water/cement
MORTAR A	3	2,34	3,76	0,5	1	-	-	0,27	0,8
MORTAR B	3	2,34	3,76	0,5	1	0,25	0,5	0,42	0,8
MALTA C	3	2,34	3,76	0,5	1	-	-	0,18	0,5

The types A and B are the most widespread (in particular the mortar A, that has been indeed used in the preparation of the masonry specimens). A characterictic feature of the mortar B is the presence of a small amount of hydraulic lime aimed at reducing the shrinkage. Mortar C has been prepared with the same ingredients as mortar A, but with a lower water/cement ratio, in order to assess its influence on the mechanical strength. Preparation, maturing and execution of tests has been done in accordance with the prescriptions of UNI EN 196-1 (September 1996).

Table 7. Average compressive strength and classification of the mortars according to DM 20/11/87 and EC6.

	Average compressive strength *N/mm²*	**DM 20/11/87**	**EC 6**
MORTAR A	7,39	M3	M5
MORTAR B	6,72	M3	M5
MORTAR C	10,5	M2	M10

For each type 3 prismatic samples have been prepared, and they have been tested under bending (in order to indirectly measure the tensile strength - Spinelli 2001 [5]). The results, for the sake of brevity, are left out. The 6 semi-prisms obtained are then been tested under compression, always following the mentioned law. Results are shown in table 7. A comparison between mortar A and mortar C confirms that to a higher water/cement ratio follows a lower mechanical strength. The lowest values at all (both in tension and in compression) are attained for mortar B. This could be explained, besides that with the high water/cement ratio, by the addition of the lime, that furtherly involves a reduction in the cement content. In figure 6 the average compressive strengths are compared with the indication of the laws (D.M. 20/11/87 [2]; EC 6 [3]) for the classification of mortars.

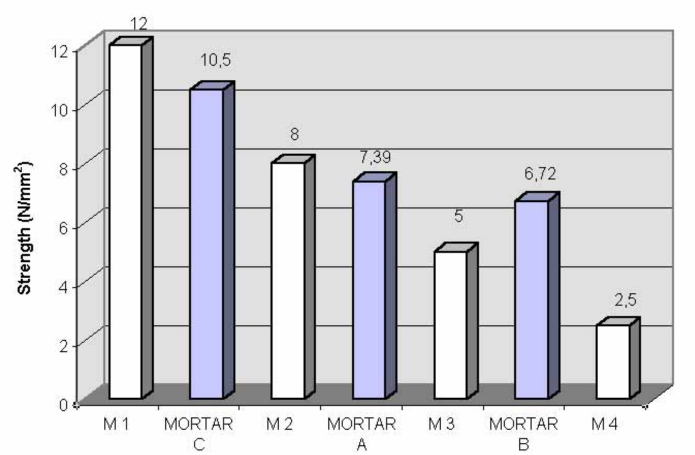

Figure 6. Comparison between experimental strengths and standard-law mortar classes.

CLASSIFICATION AND MECHANICAL CHARACTERIZATION OF MASONRY TYPES

After the analysis of the constituents (masonry units and mortars), a morphologic and typological investigation on the *non-standard* masonry types has been performed, inventorying the most common masonry arrangements. There are no literature references about these types, which are severely irregular and defective with respect to law requirements: hollow blocks, not qualified for a structural use, are inopportunely used and they are even placed with horizontal holes. Moreover, the multiple walls were realized simply placing units side by side (with no scarf joints), leaving an empty space between the wythes, with no vertical grouting: the negative consequences on the transversal solidity of the panel are unavoidable. The different types observed, in which miscellaneous combinations of solid bricks, hollow brick/concrete units, mortars (type A or B) are present, nave been inventories and classified (table 8).

Table 8. Classification of non standard masonry types.

	Unit type	Hole orientation	thickness	main use	transversal discontinuity
PP 50	Solid brick (P)	-	*50 cm*	Ground floor	YES
PP 38	Solid brick (P)	-	*38 cm*	1st floor, ground floor	YES
PSP 38 A	21 holes brick unit (SP)	Horizontal (A)	*38 cm*	1st floor and up	NO
PSP 38 B	21 holes brick unit (SP)	Both vertical and horizontal (B)	*38 cm*	1st floor and up	NO
PSP 25 A	21 holes brick unit (SP)	Horizontal (A)	*25 cm*	2nd floor and up	NO
PPSP 38 A	Solid brick (P) + 21 holes brick unit (SP)	Horizontal (A)	*38 cm*	1st floor	NO
PC 60 C	Concrete blocks (C)	Vertical (C)	*60 cm*	Ground floor	YES
PC 40 C	Concrete blocks (C)	Vertical (B)	*40 cm*	Ground floor, 1st floor	YES
PC 30 C	Concrete blocks (C)	Vertical (B)	*30 cm*	1st floor and up	YES

Table 9. Type and dimension of masonry specimens.

Masonry type		specimen	Width, thickness, height
PSP 38 A		1	*52,6cm x 37,7cm x 41,8cm*
PSP 38 B		2	*52,5cm x 38cm x 43,6cm*
		3	*52cm x 37,6cm x 43cm*
PPSP 38 A		4	*51,5cm x 37cm x 44,5cm*
		5	*52,5cm x 37cm x 44,3cm*
PSP 25 A		6	*51,8cm x 25cm x 43,4cm*
		7	*52cm x 25cm x 43,3cm*
PC 40 C		8	*42,5cm x 40cm x 44cm*
		9	*41,8cm x 40,2cm x 44cm*

At this point, the most representative masonry types have been selected, and for them a set of specimens has been reproduced in laboratory (as much accurately as possible) for the execution of uniaxial compressive tests. For the brick masonry, 7 specimens have been prepared belonging to 4 different structural types and using: type A mortar; solid bricks (whose features are later specified); type FA hollow brick units. The preparation of the specimens and the execution of he tests has been made in accordance with the norm EN 1052-1, except for some dimensions of the specimens (height and width), limited by the specific available press. With regard to the masonry composed of concrete units, 2 specimen have been built using type BA blocks and a type A mortar. Also in this case the reference law is EN 1052-1, and there is a deviation in the dimension of the specimens. In table 9 the different types, the dimensions, number and features of the specimens are listed.

Uniaxial compressive tests

In table 10 and in figure 7 the results of the experimental testing is summarized for the 9 specimen, in terms of: ultimate stress for the single specimens (σ_u); average ultimate stresses for the different masonry types ($\sigma_{u,media}$); average longitudinal and tangential elasticity modulus *E* and *G*; characteristic compressive strength f_k processed both following the European law EC 6 (EN 1052-1) and the Italian law (DM 20/11/87). It has to be remarked that for each type only two specimens were available, therefore for the determination of the f_k according to EN 1052-1, we referred to point 10-a. The values computed according to DM 20/11/87 are to be only considered as indicative, since it should be used at least 6 experimental data. With this premise, we can anyway notice that the application of D.M. 20/11/87 87 leads to higher values (in the case of concrete block masonry, the difference is quite important). In table 10 and figure 3 are also reported the experimental compressive strengths measured on a "reference" masonry panel (labelled PP 12) built according using solid brick units (dimensions: *25cm x 12cm x 5cm*; characteristic strength f_{bk} = *18,88 /mm²*) and a M3 mortar, with one wythe, running bonds (bricks are staggered ½ one from the other), with the aim of presenting a comparison between the non standard masonry and the an ideal example realized according to a correct and good constructive rule (experimental data are reported from a previous investigation - Spinelli [5]).

Table 10. Experimental results for uniaxial compressive tests: reference solid brick panel and non standard masonry.

Type	Specimen	σ_u *N/mm²*	$\sigma_{u,media}$ *N/mm²*	f_k (EN1052-1) *N/mm²*	f_k *(DM 87)*** *N/mm²*	E *N/mm²*	G *N/mm²*
PSP 38 A	1	2,50	-	2,10	- *	3530	1412
PSP 38 B	2	2,62	2.65	2,20	2,50	3887	1555
PSP 38 B	3	2,68					
PPSP 38 A	4	2,42	2,61	2,10	2,45	4856	1942
PPSP 38 A	5	2,80					
PSP 25 A	6	2,80	2,86	2,40	2,70	3084	1233
PSP 25 A	7	2,92					
PC 40 C	8	7,82	7,70	6,40	7,40	7205	2882
PC 40 C	9	7,58					
PP 12			16,74	13,95	16,17	10060	4024

* for PSP 38 A only one specimen was available, and f_k, could not be computed.

**computer on the base 2 samples.

Some comments

Examining the experimental results (Tab. 10) it can be noticed that, among the non standard brick masonry types (that are the most irregular and defective) the PSP 25 A type - maybe unexpectedly - has exhibited the best behaviour. Possibly, that could be explained by a better constructive quality: a greater homogeneity in the arrangement and smoother stress distribution (this is indeed confirmed by the uniformity of the displacements recorded by the transducers during the test). The other types are instead characterized by the coexistence of very heterogeneous materials (different strengths, different geometries and orientation, …) possibly causing a stress intensification and an early collapse in correspondence of the weak elements (typically, courses of the hollow brick units placed with horizontal holes). Maybe, when using miscellaneous blocks, the intention was that of obtaining a more valuable and strong masonry (the use of solid bricks, let's remember, was an additional cost that could be suffered only for a strict necessity- where the loads were higher). The only effect, instead, was that of increasing the stiffness of the wall (as it is shown by the values of the secant elastic modulus in table 10- that is actually higher).

The concrete block masonry are instead the more effective. Not only they better comply with the seismic laws, but they have also exhibited satisfactory experimental results, even if compared with the ideal solid brick panel (PP12).

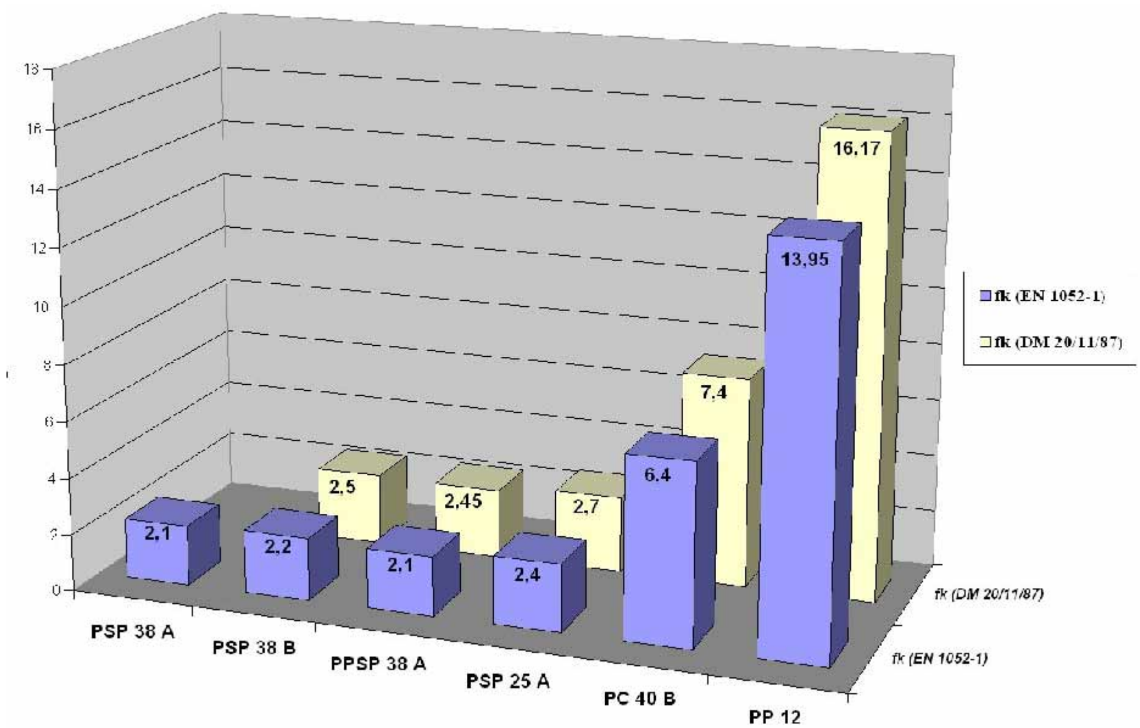

Figure 7. Characteristic compressive strengths according to EN 1052-1 and D.M. 20/11/87 for non standard masonry types and the reference panel.

CONVENTIONAL DETERMINATION OF MASONRY STRENGTH

According to D.M. 20/11/87 and EC6, the masonry characteristic compressive strength, besides then experimentally, can also be "conventionally" determined, on the basis of the strength of the components (block and mortar) by some tables and formulas.

One of the objective of the research work was indeed to verify the possibility to take such conventional values as a significant reference for the safety assessment for the examined masonry types. Hence, the procedures suggested have been applied, entering in the formulas or in the tables with the actual constituents' parameters, deducing the conventional masonry strengths and comparing them with the experimental ones. In table 11 and in figure 8 the comparison is shown for both the reference solid brick panel PP 12 and for the other masonry types.

While reading the table, it is necessary to keep in mind that the application of the conventional calculus proposed by the italian law is really representative only for one of the examined masonry types (except the PP12 panel, of course): the PC40 C type. In fact, this is the only one that complies with almost all the law requirements (solid or semi-solid masonry units; horizontal and vertical joints fully filled up with mortar) and is besides characterized by a homogeneous and regular texture (only one block type, always placed in the same way. the latter condition is necessary in order to provide a univocal value for the block strength to be used for entering the table. In all the other case, strictly speaking, no conventional estimate is possible, but the masonry strength can only be experimentally assessed. More representative can be considered the values calculated following the EC6 procedure on the basis of the mortar characteristic strength and the normalized block strength (even the ones placed with horizontal holes), but a required condition, also in this case, is that the vertical joint is completely filled up with mortar, that is true only for PC 40 C panels.

Table 11. Conventional f_k for masonry based on the parameters of the components.

	D.M.87				EC 6			
	Conventional values			Experimental data	Conventional values			Experimental data (EN 1052-1)
	Blocks	Mortar	Masonry		Blocks	Mortar	Masonry	
Type	f_{bk}* N/mm^2	*classe*	f_k N/mm^2	f_k N/mm^2	f_b** N/mm^2	f_m N/mm^2	f_k N/mm^2	f_k N/mm^2
PP 12	18,88	M3	6,78	16,17	13,78	7,39	5,44	13,95
PC 40 C	13,90	M3	5,71	7,40	15,29	7,39	5,49	6,40
PSP 25 A	3,03	M3	2,20	2,70	2,87	7,39	1,20	2,40
PSP 38 A	3,03	M3	2,20	-	2,87	7,39	1,20	2,10
PSP 38 B	3,03	M3	2,20	2,50	2,87	7,39	1,20	2,20
PPSP 38 B	3,03	M3	2,20	2,45	2,87	7,39	1,20	2,10

* Characteristic strength of the block calculated according to DM.
** Normalized strength of the blocks calculated according to EC 6.

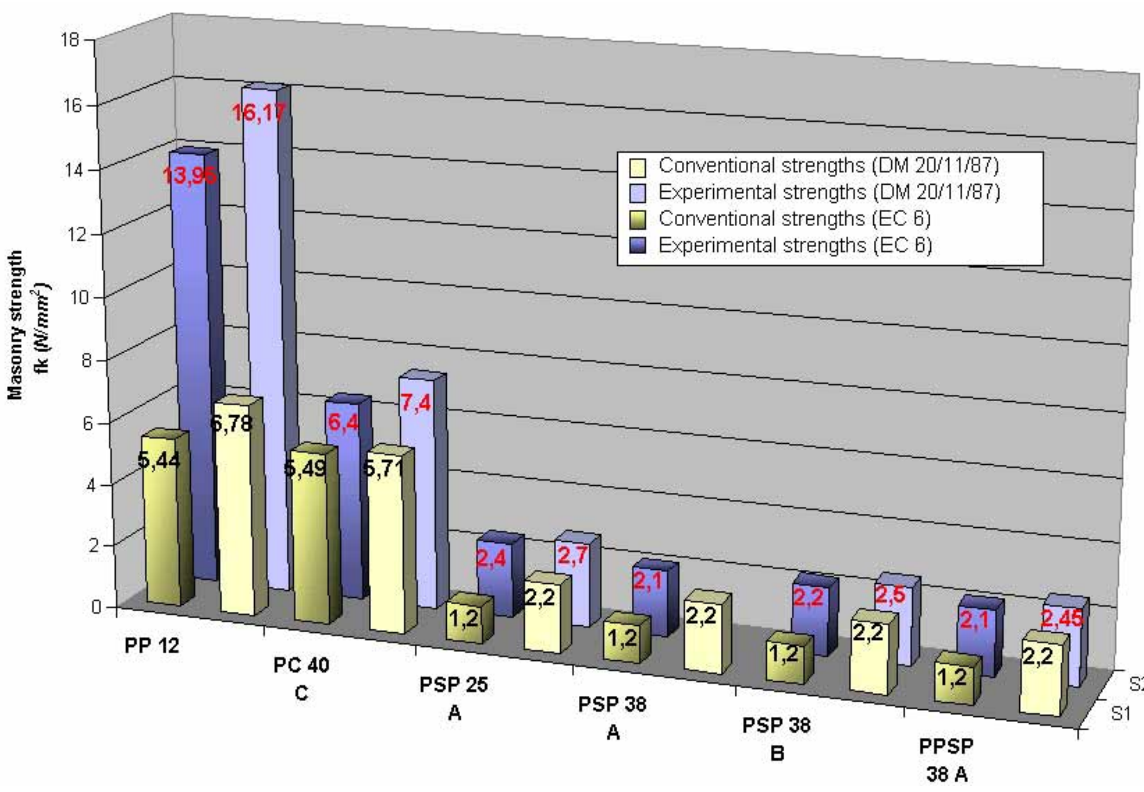

Figura 8. Comparison among experimental and conventional the characteristic strengths for PSP 25 A and PMC 40 B.

Conventional values have been determined all the same, also for the other masonry types (where appropriate, the lowest f_{bk} among the different blocks has been considered), in order to verify if such a method could at least represent an approximate reference. The conventional values, both calculated according to l'EC 6 and DM 20/11/87 are in all cases significantly lower then the experimental ones. Hence, despite all the limits and inaccuracies, the method seem to have very large safety margins, and in the absolute lacke of any experimental information (as it actually happens in contexts like the one analysed), they can be represent the only practical reference for a large scale safety assessment.

CONCLUSIONS

The presented research work is aimed at the knowledge of a number of non standard masonry types widely used in the province of Calabria: in such a context, an investigation in the territory and an experimental mechanical characterization are the only way to evaluate the structural reliability on a large scale. The experimental results and their interpretation have identified which are the less reliable masonry types (pointing out – one more time – that a fundamental element is a good quality of the execution). Besides, it has been found that the conventional methods suggested by the Italian and European laws for the determination of characteristic masonry strength on the basis of that of the constituents can represent – even in cases so far from the ideal conditions conjectured by the norms, a useful reference for the safety assessment.

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