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Experimental Results of Shear Strength and Stiffness of Existing Masonry Walls

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ABSTRACT: This paper shows the results obtained during an experimental campaign of diagonal compression tests in Tuscany, in which a significant number of masonry panels was tested. The aims of this research are mainly two. On the one hand the authors compare medium values of shear strength and shear stiffness varying the knowledge level (LC1, LC2 and LC3) proposed in the recent Italian seismic code (OPCM 3431/05). On the other hand, the authors verify shear strength and stiffness range values, proposed by the OPCM 3431 code, for the masonry typology recurring most in the Tuscany region (Italy).

1 INTRODUCTION

The evaluation of masonry mechanical properties plays a prominent role in determining a building's seismic vulnerability and in designing seismic improvement and retrofitting interventions. In particular, the development of numerical analysis requires a knowledge of the shear and compressive strength and elasticity modulus of masonry.

The new Italian seismic code (OPCM 3431/2005, Annex 1 and 2) introduces, for existing masonry buildings, a new definition of structural safety which is based on the knowledge level of the building. In particular, it requires the carrying out, besides a geometric and structural detail survey, of exhaustive *in situ* investigations, in order to achieve the highest knowledge level of the masonry typology; this close examination includes diagonal compression or shear-compression tests for each kind of masonry in the building. However, the OPCM. 3431/2005 code provides a range value of mechanical parameters for some masonry typologies (Table 11.D.1, Annex 11.D). Moreover, it authorizes Regional Authorities to define a new range of values of mechanical properties of masonry typologies, recurring in a given area.

The paper proposed is related to this context. Indeed, the authors show the results obtained after an experimental campaign of diagonal compression tests in Tuscany (Italy), in which a significant number of masonry panels were tested. The authors, in collaboration with the Tuscany Regional Authority (Regional Seismic Department), have assembled a data-base in which the results of other diagonal compression tests, previously carried out in the same area, are included. (Vignoli 1999, Avorio et al. 2002)

2 DESCRIPTION OF EXPERIMENTAL TEST CAMPAIGN

An experimental campaign was carried out by the authors on the occasion of collaboration between the Department of Structural and Geotechnical Engineering and the Regional Seismic Department of the Tuscany Region from September 2004: all tests were carried out by the DELTA laboratory from Lucca, Italy.

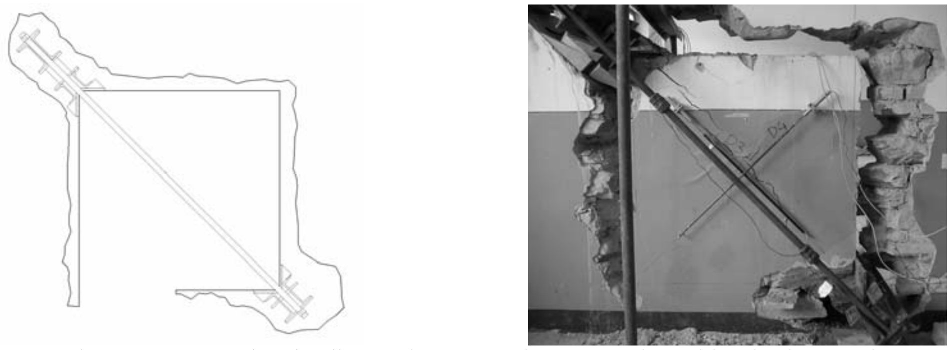

Figure 1 : Example of a diagonal compression test and cracking in the panel

One or more diagonal compression tests were carried out for each investigated building to determine shear strength and stiffness of the masonry panels. The test, in the laboratory version, is codified by the ASTM E 519-81 code and is usually performed on 1.20 x 1.20 m square panels characterized by a thickness included from 0.25 to 0.70 m.

For the in-situ test, the panel is obtained from the wall by means of four cuts made with a diamond wire or a circular saw; the only difference between the in-situ and laboratory test is the connection between the lower part of the panel and the wall. Numerical analyses have demonstrated that it is possible to neglect the influence of this connection.

The test tools consists of two L girders placed on the two edges of the panel connected with some diagonal steel bars and pressed by a hydraulic jack in order to have uniform pressure throughout the panel thickness. Four displacement transducers are placed on the four diagonals of the two sides of the panel in order to measure the diagonal displacements.

Tests were carried out with many cycles gradually, increasing the jack stroke until the breaking of the panel so as to identify a more realistic value for the shear breaking stress (τu) and to obtain the shear stiffness value (G) depending on the progress of cracking.

3 PROCESSING OF EXPERIMENTAL DATA

The aim of the processing of the data obtained is to find the values of the shear breaking stress and the shear stiffness characterizing the masonry. In particular it's possible to obtain diagonal and angular deformations from the displacements estimated by the four transducers placed on the panel's diagonals and from the maximum values of the load P_d registered by the pressure transducer for each cycle it's possible to find out the correspondent strain configuration in the middle point of the panel, using the elastic problem solution for a plate loaded in its plane.

The principal tensile strain value, relating to the maximum load borne by the panel during the last cycle, is the tensile strength due to the diagonal cracking of the masonry (f_t). OPCM 3431/2005 code proposes calculation of the shear stress τ_0 according to the Turnsek – Cacovic strength criterion (Turnsek and, Cacovic 1971):

$$\tau_0 = \frac{f_t}{1.5} \quad (1)$$

It is possible to obtain the G modulus identifying the inclination of a significant line tangent or secant to the curve $\tau - \gamma$ constructed with the shear stress and strain values. Nevertheless, the choice of the significant lines for each cycle is not univocal but depends on the operator. In particular the choice of the angular strain (γ) relating to the maximum shear stress (τ_{max}) is not univocal especially if there is great strain with constant loads. For this reason the authors suggest a procedure to identify univocally and automatically the shear modulus value for each load cycle. This procedure consists of rounding off the shear stress and strain curve with a triangular-rectangular diagram characterized by a subtended area equivalent to the examination curves having the same value as the dissipated energy correlated to the angular strain for each load cycle. In Fig. 2 the procedure, previously described, can be seen for a Sillano panel: in order to highlight the slope variation of each cycle, only the load cycles are reported.

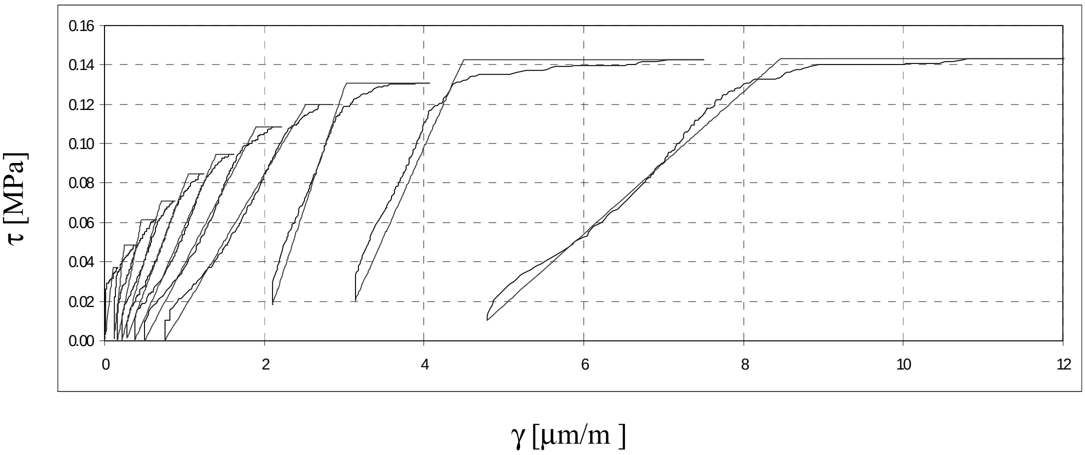

Figure 2 : Determination of the shear stiffness modulus for a Sillano panel

Looking at the shear stress and strain diagram it's possible to observe that the gradient of the lines of each cycle decrease as strain increases: it's possible to estimate a value of the shear stiffness modulus characteristic of the uncracked panel (G_{nf}) working out an average of the G modulus relating to the first load cycles when the panel is not yet cracked, a value characteristic of the cracked panel (G_f) regarding the values relating to the cycles in which the first cracks appear and, if necessary, a value characteristic of the breaking of the panel. In Table 1 the results of the experimental tests are shown.

Table 1 : Experimental results of the tests

Place	Panel	b x h x s	P_{max}	$f_t = 0.5\ P_{max}/A$	$\tau_u = f_t\ /1.5$	G_f	G_{nf}
		m	N	N/m^2	N/m^2	N/m^2	N/m^2
Filecchio di Barga, Italy	1	1.19 x 1.16 x 0.42	57000	5.7 x 10^4	3.8 x 10^4	113 x 10^6	301 x 10^6
	2	1.17 x 1.17 x 0.43	45000	4.4 x 10^4	3.0 x 10^4	177 x 10^6	3917 x 10^6
	3	1.18 x 1.18 x 0.47	72000	6.5 x 10^4	4.4 x 10^4	172 x 10^6	681 x 10^6
Forte dei Marmi, Italy	1	1.24 x 1.27 x 0.67	75000	4.5 x 10^4	3.0 x 10^4	109 x 10^6	452 x 10^6
Pieve S. Stefano, Italy	1	1.25 x 1.21 x 0.62	56000	3.6 x 10^4	2.4 x 10^4	74 x 10^6	436 x 10^6
	2	1.15 x 1.12 x 0.52	41000	3.5 x 10^4	2.3 x 10^4	78 x 10^6	364 x 10^6
Barga, Italy	1	1.21 x 1.21 x 0.50	43000	3.5 x 10^4	2.3 x 10^4	77 x 10^6	-
Sillano, Italy	1	1.19 x 1.24 x 0.49	120000	10 x 10^4	6.7 x 10^4	81 x 10^6	238 x 10^6
Subbiano, Italy	1	1.20 x 1.22 x 0.68	91000	6.0 x 10^4	4.0 x 10^4	86 x 10^6	394 x 10^6
San Godenzo, Italy	1	1.20 x 1.20 x 0.68	41000	3.8 x 10^4	2.5 x 10^4	45 x 10^6	227 x 10^6
	2	1.19 x 1.20 x 0.68	53000	4.8 x 10^4	3.2 x 10^4	71 x 10^6	164 x 10^6
Piancastagnaio, Italy	1	1.19 x 1.22 x 0.69	110000	9.1 x 10^4	6.0 x 10^4	291 x 10^6	547 x 10^6
	2	1.19 x 1.21 x 0.66	91000	7.7 x 10^4	5.1 x 10^4	28 x 10^6	207 x 10^6

4 COMPARING RESULTS WITH CHANGING LEVEL OF KNOWLEDGE

The OPCM 3431 code specifies that knowledge of the masonry building is very important in order to have an appropriate safety analysis. This knowledge can be obtained in different ways with improvement of the survey, of historical research and of experimental tests. These processes depend on the aims for the building and are related to just a part or the whole of the building depending on the size and importance of the improvement.

In particular, three knowledge levels are defined depending on the precision and the exhaustiveness of the tests carried out on the panel in order to evaluate the quality and the mechanical characteristics of the masonry. An LC1 knowledge level is achieved if limited in situ tests are carried out on material based on visual examinations of the masonry surface after the removal of the plaster. An LC2 knowledge level is achieved if extensive in situ tests are carried out on material properties that consist of the performance of tests to characterize the stone and the mortar or of double flat jack tests. An LC3 knowledge level is achieved if exhaustive in situ tests are carried out on material properties geared to obtaining quantitative information on material strength and stiffness with diagonal compression tests or vertical compression and shear tests.

The average values of the mechanical parameters are defined depending on the knowledge level obtained in terms of the values given by the 11.D.1 Table of the 11.D Annex of the OPCM 3431 code for each masonry typology. In addition, for the LC3 level, a distinction is made for the cases in which three panels (LC3a), two panels (LC3b) or only one panel (LC3c) are tested.

Furthermore, according to the knowledge level achieved, the OPCM 3431 code defines the value of a Confidence Factor (Table 2) to use in order to obtain the design values from the average ones.

Table 2 : Confidence Factor

Knowledge Level	Confidence Factor
LC1	1.35
LC2	1.20
LC3	1.00

The authors compared the design values to be used during safety checks for the tests carried out depending on the achieved knowledge level. Initially it was necessary to observe the masonry panel characteristics (Fig. 3) in order to identify a reference masonry between the typologies given by the 11.D.1 Table of the 11.D Annex of the OPCM 3431 code. In Table 3 there are the masonry typologies associated with each building investigated.

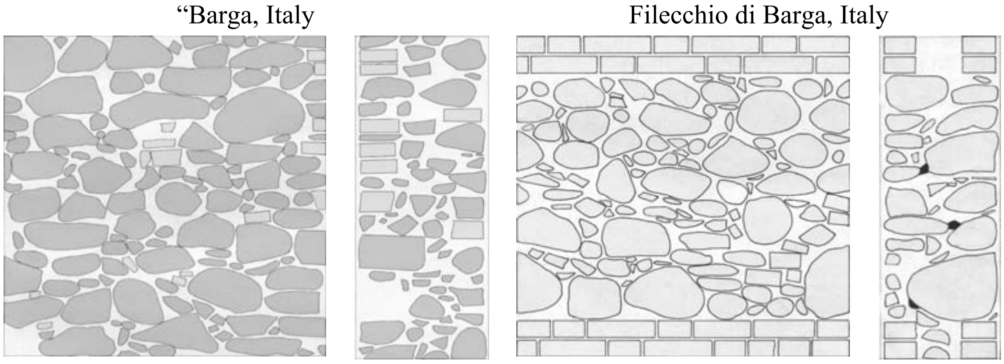

Figure 3 : Relief of some panels tested

Table 3 : Masonry typologies

Place	Masonry typology
Filecchio Barga, Italy	Random rubble stone masonry
Forte dei Marmi, Italy	Random rubble stone masonry
Pieve S. Stefano, Italy	Random rubble stone masonry
Barga, Italy	Random rubble stone masonry
San Godenzo, Italy	Random rubble stone masonry + horizontal course
Subbiano, Italy	Multiple-leaf hewn stone masonry
Sillano, Italy	Multiple-leaf hewn stone masonry + horizontal course
Piancastagnaio, Italy	Soft hewn stone masonry (tuff, calcareous stone, etc.)

Using the values proposed by the 11.D Annex of the OPCM 3431 code for the different masonry typologies, the authors obtained the average values of shear strength and stiffness for each building investigated (Table 4). It is important to remember that the design values depend on the adopted analysis method: for linear analysis it is necessary to use a safety factor equal to 2 in addition to the Confidence Factor.

Table 4 : Shear strength and stiffness values with changing knowledge level

Place	Design values					
	LC1		LC2		LC3	
	τ_u [N/m^2]	G [N/m^2]	τ_u [N/m^2]	G [N/m^2]	τ_u [N/m^2]	G [N/m^2]
Filecchio Barga, Italy	1.9×10^4	111×10^6	2.8×10^4	157×10^6	3.7×10^4	154×10^6
Forte dei Marmi, Italy	1.5×10^4	85×10^6	2.2×10^4	121×10^6	2.6×10^4	109×10^6
Pieve S. Stefano, Italy	1.5×10^4	85×10^6	2.2×10^4	121×10^6	2.4×10^4	76×10^6
Barga, Italy	1.5×10^4	85×10^6	2.2×10^4	121×10^6	2.6×10^4	77×10^6
San Godenzo, Italy	1.8×10^4	102×10^6	2.6×10^4	145×10^6	2.9×10^4	58×10^6
Sillano, Italy	3.1×10^4	151×10^6	4.3×10^4	205×10^6	5.2×10^4	81×10^6
Subbiano, Italy	2.6×10^4	126×10^6	3.6×10^4	171×10^6	4.3×10^4	86×10^6
Piancastagnaio, Italy	3.1	167×10^6	4.4×10^4	225×10^6	5.6×10^4	159×10^6

Looking at the data in Table 4 it is important to point out that the design shear strength values increase using a closer knowledge level. For LC1 and LC2 levels the results are obtained from the values given by the 11.D.1 Table of the 11.D Annex of the OPCM 3431 code while, for LC3 level, they are also calculated in terms of the number of the experimental tests according to the OPCM 3431 criteria.

In particular, an example will be analyzed referring to the “Fratelli Cervi” School in Filecchio di Barga which is the only building in which three tests on the same masonry typology (panel 1: $\tau_u = 3.8\times10^4$ N/m^2; panel 2: $\tau_u = 3.0\times10^4$ N/m^2; panel 3: $\tau_u = 4.4\times10^4$ N/m^2) were carried out. Using the criteria given by the OPCM 3431 code, it is possible to obtain an average value equal to 3.7×10^4 N/m^2 similar to the arithmetic average of the experimental tests. It is important to show that if two tests had been available the design value would have been less than 3.4×10^4 N/m^2, equal to the average of the extremity of the range given by the OPCM 3431 code. In fact, also in the supposition of having obtained the greatest values (3.8×10^4 e 4.4×10^4 N/m^2), the arithmetical average of the results would have been contained in the range. In addition, if only one test had been available, the design value would have been equally similar to the average of the extreme values of the range (3.4×10^4 N/m^2).

Analyzing the average and design shear strength values for a close knowledge level (LC3) it is possible to obtain a significant strength increase only if three tests are carried out. For one or two tests it is clear that, in terms of average strength, the same result for a lower knowledge level (LC2) is obtained and the increase of the design value is related only to the different Confidence Factor. This consideration shows that the performance of two experimental tests (referring to the LC3 knowledge level) is not convenient because, certainly in this case, they would give the same strength value as only one test.

5 CONTROL OF THE SHEAR STRENGTH AND STIFFNESS RANGE GIVEN BY THE OPCM 3431 FOR THE MASONRY TYPOLOGIES RECURRING MOST IN TUSCANY

In order to evaluate whether it is necessary to propose specific range values for strength and stiffness of the masonry typologies recurring most in Tuscany, the authors have compared the experimental results with the values given by the OPCM 3431 code. In this analysis the authors have referred to much more experimental data in order to have a more statistically representative sample. The results of other experimental campaigns carried out in Umbria and Tuscany have also been considered. (AA.VV 1999, Avorio et al. 2002, Borri et al. 2004)

The authors also identified the reference masonry typologies for these new panels. The experimental values of shear strength for each panel tested are grouped into masonry typology in order to be compared with the range given by the OPCM 3431 code. It is important to point out that, according to the reference code, the shear strength has been calculated using the Turnsek – Cacovic criterion.

5.1 Random rubble stone masonry

For this masonry typology the reference values given by the OPCM 3431 code are the following:

$\tau_0 = 2.0\times10^4 \div 3.2\times10^4$ N/m^2 Average shear strength for the masonry
$G = 115\times10^6 \div 175\times10^6$ N/m^2 Average shear stiffness modulus for the masonry

The experimental values possessed by the masonry typology on examination, are shown in the next graph in which they are compared with the threshold defined by the OPCM 3431 code.

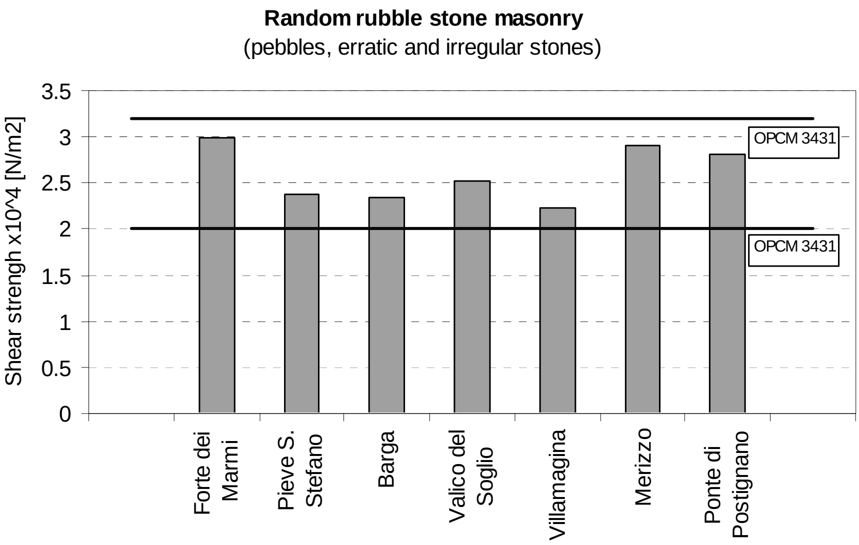

Figure 4 : Comparison between the experimental values and the threshold defined by the OPCM 3431

If horizontal courses are present, for this masonry typology, the OPCM 3431 code suggests multiplying the mechanical parameters by a corrective factor equal to 1.3 so the new range is:

$\tau_0 = 2.6\times10^4 \div 4.2\times10^4$ N/m^2 Average shear strength for the masonry
$G = 149.5\times10^6 \div 227.5\times10^6$ N/m^2 Average shear stiffness modulus for the masonry

The panels which can be associated with this masonry typology are shown in Fig. 5.

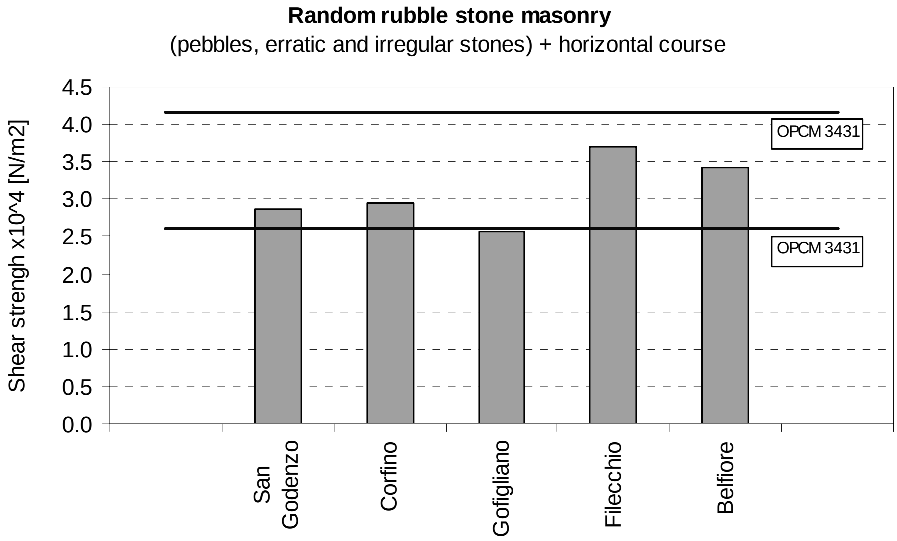

Figure 5 : Comparison between the experimental values and the threshold defined by the OPCM 3431

5.2 *Multiple-leaf hewn stone*

For this masonry typology the reference values given by the OPCM 3431 code are the following:

$\tau_0 = 3.5\times10^4 \div 5.1\times10^4$ N/m^2 Average shear strength for the masonry
$G = 170\times10^6 \div 240\times10^6$ N/m^2 Average shear stiffness modulus for the masonry

It is very difficult to identify this masonry typology and the authors also chose to consider panels that have lightly hewn stones in this category in order to distinguish them from masonry in which there are totally irregular pebbles or ashlars.

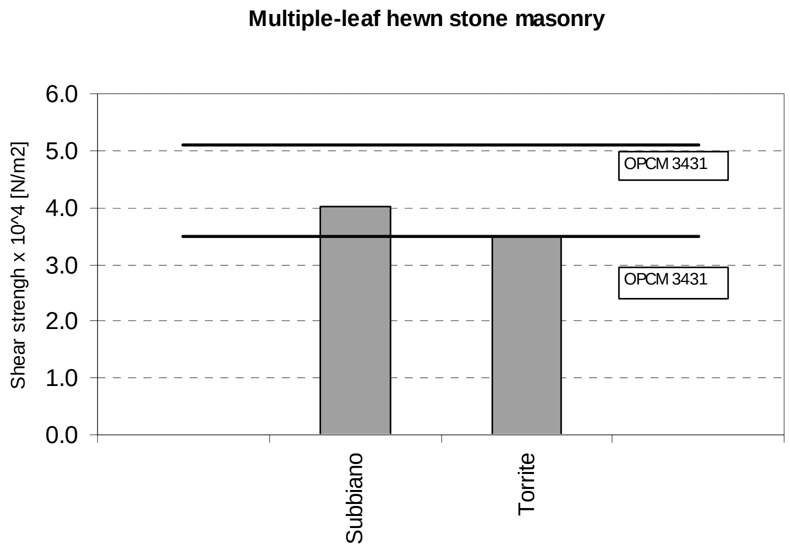

Figure 6 : Comparison between the experimental values and the threshold defined by the OPCM 3431

The values proposed in the OPCM 3431 code seem really representative of the masonry typologies tested and the experimental results are within the proposed ranges. Furthermore, the corrective coefficient related to the presence of horizontal course is well calibrated in particular if the bordering takes up the entire thickness of the panel. Only for a few buildings did the authors find results near the threshold of the proposed range. In these cases, as in the Torrite and Gorfigliano schools, the masonry has characteristics near the border line of the ranges.

6 CONCLUSIONS

The campaign of experimental tests carried out and the following elaboration points out many significant results. The diagonal compression tests, even if invasive, lead to direct knowledge of the most important mechanical parameters useful for safety checks.

The actions of the Tuscany Regional Authority allowed definition of a procedure for the performance and elaboration of these kinds of tests; in particular some detailed standards relating to the executive procedure have been written and they will be available, in a data-base including the test results, on the Tuscany Regional Authority website:
http://www.rete.toscana.it/sett/pta/sismica/index.htm.

The comparison between the design values for shear strength and stiffness modulus with changing knowledge level (LC1, LC2 and LC3) have pointed out that it is important to carry out an experimental campaign in order to use not so many preventive values in the structural checks and to have a significant advantage in satisfying the safety checks. In this context it would be appropriate to consider that the cutting out of the panel could disturb the masonry condition. This aspect, which is very difficult to evaluate, can be considered only if there are objective factors that can influence the results of the test (damage or excessive dampness caused by the water used during the cutting operation). The comparison between the experimental results and the values given by the OPCM 3431 code allowed the pointing out of the fact that the ranges are well calibrated for each masonry typology considered, ensuring the use of realistic values even for limited knowledge level (LC1 and LC2).

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