MECHANICAL CHARACTERIZATION OF DIFFERENT TYPOLOGIES OF MASONRY MADE WITH THIN SHELL/WEB CLAY UNITS

Paolo Morandi[1], Guido Magenes[2], Luca Albanesi[3]
[1] Post-Doctoral Research Fellow, University of Pavia and EUCENTRE, Italy, paolo.morandi@unipv.it
[2] Associate Professor, University of Pavia and EUCENTRE, Italy, guido.magenes@unipv.it
[3] Assistant researcher, EUCENTRE Pavia, Italy, luca.albanesi@eucentre.it

ABSTRACT
Being pushed by market competition, the masonry industry improved the thermal properties of masonry units and developed new, faster and more economical technologies of construction. As a result of such development, hollow masonry units with large percentage of voids, thin shells and webs are produced. Nevertheless, clay units with thin webs/shells, could potentially represent a source of weakness and brittleness when used in structural masonry walls, either under prevailing vertical loading or under seismic actions. In this paper, a part of an experimental research on the evaluation of the mechanical characteristics of different typologies of masonry made with thin shell/web clay units is reported. The results of the mechanical characterization tests have shown that the different typologies of masonry considered in this research seem to have adequate properties required for a load-bearing material and are suitable to be used as structural masonry when seismic loading is not a concern. Moreover, some critical aspects related to the test procedures have also been discussed.

KEYWORDS: thin shell/web hollow clay units, masonry specimens, characterization tests, unit strength and stiffness

INTRODUCTION
The effort of clay unit producers to implement innovative solutions regarding the sustainability and energetic efficiency of masonry products leads to the development of clay units with very thin webs and shells aimed to improve the thermal and acoustic insulation properties. Nevertheless, clay units with thin webs/shells, could be a source of weakness and brittleness when used in structural masonry walls subjected either to prevailing vertical loads or in the case of shear cyclic excitations, especially if the construction is accomplished using thin layer mortar bed-joints. For these reasons some structural codes of the past, like the Italian masonry code DM 20/11/87 [1] and the ENV version of Eurocode 8 [2], had included a prescription on the minimum thickness of the webs and of the shells for load-bearing units in order to provide a simplified criterion that, along with the limitation of the void ratio, should guarantee a sufficient robustness of the elements. Currently, in the Italian Annex of EC6 [3] and in the draft of the Italian technical norms for constructions (NTC08 [4]), the minimum thickness of clay unit webs and shells for structural use is set equal to 7 and 10 mm, respectively.
Few researches have attempted to find a quantitative criterion to evaluate the robustness of masonry units (see for instance Tomazevic and Weiss [5]) from a structural point of view, and little information is available on the structural behaviour of masonry built with thin shell/web clay units.

In this context, an experimental campaign has been carried out at the laboratory of the Department of Civil Engineering and Architecture of the University of Pavia, with the aim of evaluating, in the first instance, the mechanical characteristics (*i.e.*, strength and stiffness) of different types of masonry made with thin shell/web hollow clay units (thickness of the shells and of the webs being ≥ 6.5 and ≥ 5.0 mm, respectively). Masonry typologies built with general purpose mortar and with thin layer bed-joints have been considered in this study, adopting different types of masonry units, *i.e.* plain, tongue-and-groove as well as mortar pocket clay units with holes volume ratio between 45 and 55%. Vertical and lateral compression tests on units, flexural-compression tests on mortar, vertical and diagonal compression tests on masonry wallets and tests for the determination of the initial shear strength on small sub-assemblages (triplets) have been performed.

THIN SHELL/WEB CLAY UNIT MASONRY TYPOLOGIES

In this work, five masonry typologies consisting of a combination of different thin shell/web vertically perforated clay units and various types of mortar have been considered, as summarized in Table 1. The nominal thickness of the tested masonry typologies was equal to 350 mm.

Four types of lightweight clay blocks with volume ratio of holes between 45 and 55% and thickness of the shells and webs being ≥ 6.5 and ≥ 5.0 mm respectively, have been adopted. For all typologies the webs parallel to the wall plane are continuous and rectilinear with interruptions only in the grip holes. The first type is a “plain” (parallelepiped) unit (P800 TS, length = 250 mm x width = 350 mm x height = 190 mm) with a nominal percentage of voids of about 45% and a declared gross dry density of 880 kg/m^3, the second type is a tongue-and-groove unit (P700 TS, 235 mm x 350 x 245 mm) with a nominal void ratio of about 50% and a gross dry density of 830 kg/m^3, while the third type (P700 TS Plan, 235 x 350 x 235 mm) is identical to the P700 TS except that it is rectified on the bed-joint surfaces allowing its use with thin layer mortar. Finally, the fourth block type is a mortar pocket unit (IP35SS DPE, 227 x 348 x 233) having a volume ratio of holes equal to about 55%, a declared density of 700 kg/m^3 and rectified bed-joint surfaces. The four typologies of clay units are shown in Figure 1.

General purpose mortar resulting in a thickness of the mortar joints between 5 and 15 mm and thin layer mortar bed-joints with a nominal mortar joint thickness between 0.8 and 1.0 mm have been used in the construction of the masonry specimens. Two different supplies of M10 (nominal 10 MPa mean compressive strength) pre-mixed general purpose mortar provided by the same manufacturer have been used for the masonry typologies T1 and T2, whereas for typologies T3, T4 and T5 two types of M10 pre-batched thin-layer mortar provided by different producers have been adopted; the thin layer mortar type 2 is fibre-reinforced with sufficiently long fibres aimed at limiting the penetration of mortar in the holes of the units. The same type of mortar used for the bed-joints has also been adopted to fill the mortar pockets. A determined amount of water set by the recommendations of the manufacturers has been placed in the mixture.

During the construction of the masonry specimens, before the placement of the mortar bed-joints, the clay units of typologies T1 and T2 have been dipped in water up to saturation in order to prevent excessive water absorption by the units in contact with the bed-joints that could affect the mechanical characteristics of the mortar. The thin layer mortars of type 1 and type 2 have been declared by the manufactures as “hygroscopic” and therefore the masonry specimens of the typologies T3, T4 and T5 have been realized with non-saturated units.

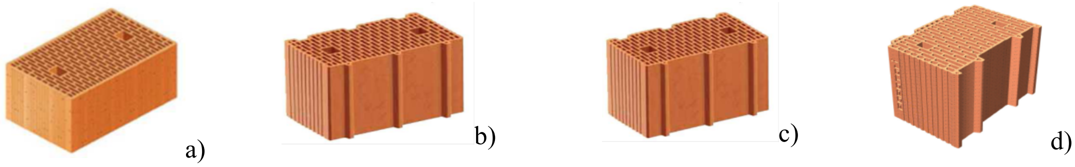


Figure 1: a) P800 TS, b) P700 TS, c) P700 TS Plan, d) IP35SS DPE

Table 1: Tested masonry typologies

Masonry typology	Type of unit	Type of mortar bed-joint	Type of head-joint
T1	P800 TS	General purpose – type 1	Fully filled with general purpose mortar
T2	P700 TS	General purpose – type 2	Unfilled tongue and groove
T3	P700 TS Plan	Thin layer – type 1	Unfilled tongue and groove
T4	P700 TS Plan	Thin layer – type 2	Unfilled tongue and groove
T5	IP35SS DPE	Thin layer – type 1	Filled mortar pocket

PERFORMED TESTS OF MECHANICAL CHARACTERIZATION

A series of tests on clay units, on mortars and on masonry assemblages have been performed in order to quantify the main mechanical properties of the masonry.

Tests for the determination of dimensions (length, width, height of the units; thickness of webs and shells; area of holes; value of combined thickness of webs and shells in percentage of the overall width), of net volume and percentage of voids by hydrostatic weighing and of net and gross dry density of masonry clay units have been performed according to the European Standards. The standards prescribe tests on 10 units with exception of the determination of the combined thickness of webs and shells for which only three units need to be subjected to measurements. Moreover, experiments for the evaluation of the compression strength of the units in the load-bearing direction (*i.e.*, under vertical compression) and perpendicular to the load-bearing direction (*i.e.*, under lateral compression) have been executed, following the recommendations of EN 772-1 [6], EN 771-1 [7] and the Italian norms for constructions (NTC 2008 [8] and the Circolare Ministeriale [9]). Accordingly, tests of vertical compression on 30 units and tests of lateral compression on 10 units have been carried out. The surfaces of the units subjected to the vertical compression tests in contact to the steel plates of the compression testing machine were rectified (*i.e.*, P800 TS and P700 TS were ground by the manufacturer for the purpose of the test, whereas P700 TS Plan and IP35SS DPE were already produced with planar surfaces). In order to study the variation of the compression strength of the units as a function of the surface preparation methods, the blocks P800 TS and IP35SS DPE were also tested with the surfaces capped with a layer of about 10 mm of high strength gypsum (with a compression strength > 30 MPa). In the case of the lateral compression tests, the faces of all types of units were capped with gypsum to compensate the irregularities of the tongue and groove perforations and of the mortar pockets.

Tests for the determination of flexural and compressive strength on the hardened mortar have also been carried out according to EN 1015-11 [10]. Three 40x40x160 mm prisms of mortar have been sampled for each supply, cast in rectified steel molds; the specimens have been cured for seven days in a polyethylene bag and for the subsequent 21 days in the laboratory room at a relative humidity of about 65% with a temperature of about 20°C. After 28 days, flexural tests (single point load) on the prisms up to failure have been executed; subsequently, the two parts obtained from the bending test have been subjected to compression test on a loaded area of 40 x 40 mm.

Vertical compression tests on six masonry wallets of typology T1, T2, T3 and T4 have been carried out in accordance to EN 1052-1 [11]; the bearing surfaces have been capped with a layer of high strength gypsum and the specimens have been instrumented with six displacement transducers (*i.e.*, one horizontal and two vertical transducers for each face) in order to measure the deformations. Monotonic vertical load has been applied to the specimens with a constant rate calibrated to reach failure in 15 to 30 minutes from the beginning of the test. The scheme of this test is shown in Figure 2a.
Moreover, wallets of typologies T1, T3 and T5 have been subjected to diagonal compression tests on approximately square masonry specimens as illustrated in Figure 2b). The specimens were placed into a compression testing machine and the loads were applied by means of steel angles. A plywood board was inserted between the steel angles and the corners of the masonry panels appropriately capped with a layer of gypsum to avoid stress concentration; the length of the contact side on each angle was about 1/8 of the length of the side of the panels (12 cm). Displacement transducers were applied on both sides to measure deformations along the diagonals. Three loading-unloading cycles have been performed at different levels of force.
Finally, tests for the determination of the initial shear strength in the plane of horizontal mortar bed-joints (f_{vi}) have been carried out, according to EN 1052-3 [12]. Specifically, for each of the typologies T1, T2, T3 and T4, three samples made up by three units (triplets) have been tested in the direction parallel to the bed-joints at each of three increasing levels of compression (equal to 0.2, 0.6 and 1.0 MPa, respectively) in the direction orthogonal to the bed-joints. A suitable test set-up has been developed in order to allow the execution of the shear test at different levels of precompression. A gypsum topping of about 1.0 cm has been applied in the regions of support and force application with the aim to ensure even contact surfaces. Three displacement transducers at each side of the assemblages have been placed, one to measure the lateral dilatancy (normal to bedjoints) and two to measure the relative displacements of the units parallel to the bed-joints. The layouts of a triplet with the installed instrumentation and the details of the test set-up are illustrated in Figure 2c) and Figure 2d), respectively.
The dimensions of the wallets and of the assemblages along with the number of specimens tested in vertical compression, in diagonal compression and in shear, are reported in Table 2. Only two panels of typology T3 have been subjected to diagonal test, since not very significant results on masonry with ungrouted head-joints were found in past experimental campaigns. No vertical compression and initial shear strength test on typology T5 has been conducted, because results close to those on typology T3 were expected, being the two types of masonry built with the same mortar and units with similar nominal characteristics.

Table 2: Tests on masonry wallets and assemblages

Masonry typology	Test	Dimensions of specimens [mm]			Number of specimens
		Length	Width	Height	
T1	Vertical compression	510	350	990	6
	Diagonal compression	1030	350	990	6
	Shear strength (on triplets)	250	350	590	9
T2	Vertical compression	470	350	1265	6
	Shear strength (on triplets)	235	350	755	9
T3	Vertical compression	470	350	1175	6
	Diagonal compression	940	350	940	2
	Shear strength (on triplets)	235	350	705	9
T4	Vertical compression	470	350	1175	6
	Shear strength (on triplets)	235	350	705	9
T5	Diagonal compression	908	348	932	6

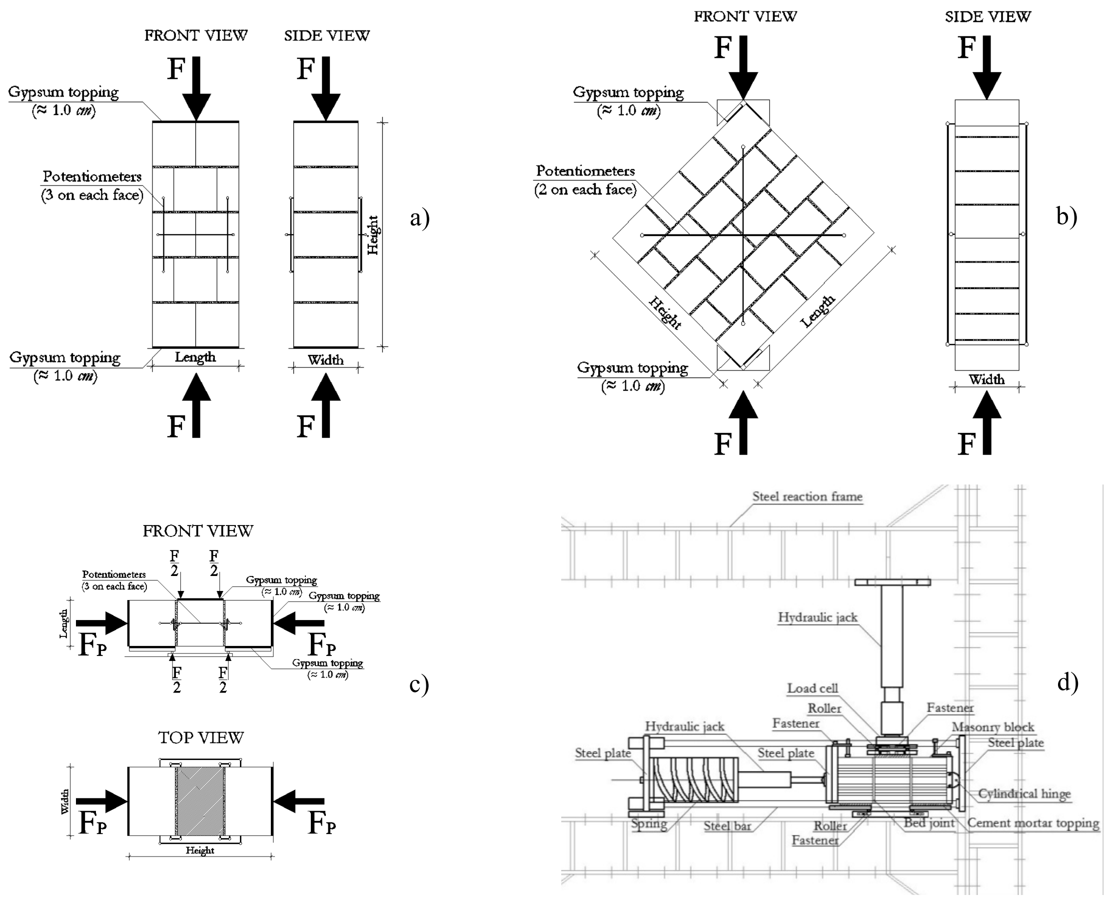


Figure 2: a) Vertical compression test on wallets; b) Diagonal compression test on panels, c) Initial shear strength on triplets; d) Details of the recently developed shear test set-up

RESULTS AND CRITICAL ASPECTS OF THE EXPERIMENTAL TESTS

The dimensions, the maximum areas of the holes, the minimum thickness of the shells and webs and their combined thickness, the dry density and the percentage of voids of the four different types of clay units have been measured according to the European standards and the results are reported in Table 3. Following the classification of Eurocode 6 part 1.1 (EC6) [14], all studied masonry blocks belong to Group 2 except the IP35SS DPE unit which belongs to Group 3, since the thickness of the webs and shells is lower than the corresponding limit value, equal to 5 and 8 mm respectively. Nevertheless, in accordance with the Italian Annex of EC6, none of the units here considered could be used as load-bearing element since the requirements related to minimum values of thickness for webs and shells, set equal to 7 and 10 mm, respectively, are not fulfilled.

The values of the compressive strength parallel and perpendicular to the holes of the units (*i.e.*, under vertical and lateral compression) are reported in Table 4. The majority of the units has shown a nearly explosive failure, not only due to the spalling of the shells but also distributed in the inner parts of the units; in the case of lateral compression tests, the spalling of the shells with tensile failures of the webs orthogonal to the shells has been observed. The compression strength f_b and f'_b is computed as the maximum force over the gross area of the loaded surface of the unit (*i.e.*, length x width for vertical compression and width x height for lateral compression). For design applications, EC6 provisions make use of normalized values of compression strength

($f_{b,norm}$ and $f'_{b,norm}$) which can be obtained as a function of the air-dry conditioning regime and of a shape factor depending on the dimensions of the specimen. According to the Italian norms, instead, characteristic values of strength are used for design and have been computed as 0.7 times the mean value obtained from 10 specimens in the case of lateral compression and as the 5% fractile of a normal distribution in the case of vertical compression. As expected, the vertical compression strength of P800 TS units has been found to be larger with respect to the other block types, thanks to their higher density and smaller percentage of voids, with almost equal values between the uncapped and the capped specimens. P700 TS and P700 TS Plan units have shown to possess similar values of vertical strength. Conversely, the vertical strength of IP35SS units has resulted to be very low in the case of uncapped specimens. Apparently, the causes of such small value of strength are attributable to the irregularities that were present on the faces even though the units were supposed to be perfectly planar for the use with thin layer bed-joints. The tests have been subsequently repeated topping the faces of the units, resulting in much higher values of vertical compression strength. The lateral compression strength of the different types of masonry blocks has shown to be similar (with mean values of about 3.0 MPa), except for the P700 TS Plan units which have resulted in a lower value.

Table 3: Measures of the dimensions of the clay units, area of holes, thickness of webs and shells, combined thickness, dry density and percentage of voids

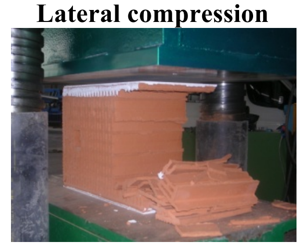
Type of unit	Dimensions [mm]			Max area of holes [mm^2]	Max area of gripholes [mm^2]	Minimum shell thickness [mm]	Minimum web thickness [mm]	Combined thickness [%]		Dry density [kg/m^3]		Percentage of voids [%]
	l	w	h	mean value	mean value	mean value	mean value	x	y	gross	net	
P800 TS	242	342	186	268	1244	9.0	5.5	17.1	43.5	995	1850	46
P700 TS	230	348	244	409	1660	9.0	5.0	17.5	35.8	850	1810	53
P700 TS Plan	231	348	234	416	1654	9.0	5.0	17.3	33.9	850	1830	53
IP35SS DPE	222	347	234	385	923	6.5	5.0	17.4	29.5	765	1740	56

Table 4: Vertical and lateral compression tests on units

Type of unit		Vertical compression		Lateral compression	
		f_b	$f_{b\,norm}$	f'_b	$f'_{b\,norm}$
P800 TS	Mean value [MPa]	19.2 (20.4)*	20.0 (21.2)*	2.9	3.3
	Standard deviation [MPa]	1.24	-	0.50	-
	Coeff. of variation [%]	6.5	-	17.4	-
	Characteristic value [MPa]	17.2	-	2.0	-
P700 TS	Mean value [MPa]	11.7	13.3	2.8	3.2
	Standard deviation [MPa]	1.17	-	0.72	-
	Coefficient of variation [%]	10.0	-	25.8	-
	Characteristic value [MPa]	9.8	-	2.0	-
P700 TS Plan	Mean value [MPa]	10.2	11.6	2.0	2.3
	Standard deviation [MPa]	0.82	-	0.45	-
	Coefficient of variation [%]	8.0	-	22.6	-
	Characteristic value [MPa]	8.9	-	1.4	-
IP35SS DPE	Mean value [MPa]	6.5 (14.9)*	7.3 (16.8)*	3.1	3.5
	Standard deviation [MPa]	1.05 (2.54)*	-	1.01	-
	Coefficient of variation [%]	16.2 (17.0)*	-	32.5	-
	Characteristic value [MPa]	4.8 (10.7)*	-	2.2	-

Vertical compression

Lateral compression



* The results of units capped with gypsum are reported in brackets.

The results of the flexural and compression tests on mortar are summarized in **Error! Not a valid bookmark self-reference.**. The flexural strength f_{fl} has been calculated as $1.5 \cdot F_{max} \cdot l/(b \cdot d^2)$, being F_{max} the maximum force, l the distance between supports (=100 mm), b and d the dimensions of the section of the prism (40 mm). Both type 1 and type 2 general purpose mortars have provided values of compressive strength smaller than the value declared by the manufacturer (that is 10 MPa), being even half in the case of type 1. The values of compression for thin layer mortar have resulted to be larger than 10 MPa, and particularly high for mortar of type 1. A ratio between the compressive and the flexural strength of about 4.5-5.0 and of about 3.2 has been found for the general purpose and for the thin layer glue-mortars, respectively.

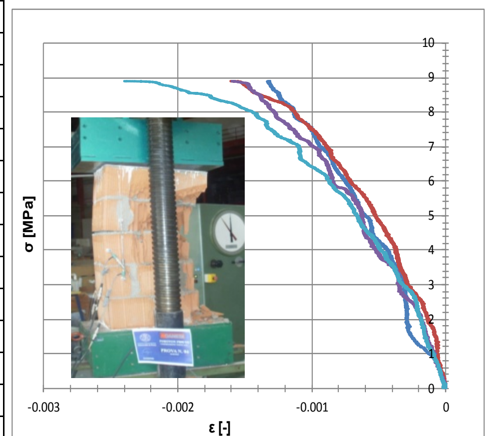
Table 5: Flexural and compressive strength tests on mortar

Type of mortar	Flexural test		Compressive test	
	f_{fl} [MPa] (mean value)		f_m [MPa] (mean value)	
G. P. – type 1	1.1		5.0	
G.P. – type 2	1.5		7.4	
Thin layer – type 1	5.6		17.8	
Thin layer – type 2	3.3		10.5	

As reported in Table 6, the compression strength of the masonry specimens has resulted to be rather high for the typology T1, characterized by very strong units; the masonry typology T4 has shown a value of compression strength about 70 % larger than the typology T3, although only the type of thin layer mortar has been varied. It appears that the fibre-reinforced mortar (thin-layer – type 2), even though possessing a much lower value of strength (obtained mean value of 10.5 against 17.8 MPa) allows to achieve a significant increase in the compressive strength of masonry. The length of the fibres has apparently allowed to efficiently limit the penetration of mortar in the holes of the units and to guarantee a minimum thickness of the mortar bed-joints, thus avoiding the concentration of high vertical stresses on limited parts of the webs, that instead has probably occurred in the case of the typology T3. Finally, the masonry typologies T2 and T4 have shown similar values of strength (6.9 and 6.7 MPa), although they were constructed with two different types of mortar (general purpose and thin layer bed-joints). Vertical cracks on the sides of the wallets and spalling of the shells have mainly occurred in the masonry typologies T1 and T2, whereas failures at the centre of the panels have primarily occurred for T3 and T4. The characteristic values of compressive strength (f_k) have been computed according to the requirements of EN 1052-1 and have been compared with the values evaluated according to the empirical expressions of EC6: $f_k = K \cdot (f_{b,norm})^{0.7} \cdot (f_m)^{0.3}$ for general purpose mortar, and $f_k = K \cdot (f_{b,norm})^{0.7}$ for thin-layer mortar, which involve the normalized mean compression strength of the units ($f_{b,norm}$), the mean compression strength of the mortar (f_m) and a coefficient K (equal to 0.45 for Group 2 units with general purpose mortar and equal to 0.70 for Group 2 units with thin-layer mortar). In comparison with the values of f_k obtained by the experiments, the application of the expressions from EC6 has provided a safe-side estimation of the experimental strength for the typology T1, T2 and T4, whereas has given an overestimation of the strength for the typology T3. The elastic modulus E has been computed as $F_{max}/(3 \cdot \varepsilon_m \cdot A)$, where F_{max} is the maximum force at failure, ε_m is the mean value of the deformations measured on the four vertical transducers in the point corresponding to 1/3 of the maximum force and A is the cross sectional area of the wallet. The ratio between the elastic modulus and the characteristic value of compression strength, set equal to 1000 in the EC6 provisions, has been found to be higher for the masonry made up by general purpose mortar (1403 and 1333 for T1 and T2, respectively) in comparison with the masonry with thin-layer bed-joints (1060 and 914 for typology T3 and T4, respectively).

Table 6: Compression strength *f* and elastic modulus *E* of masonry wallets; σ-ε curve and picture at failure on a specimen of typology T1

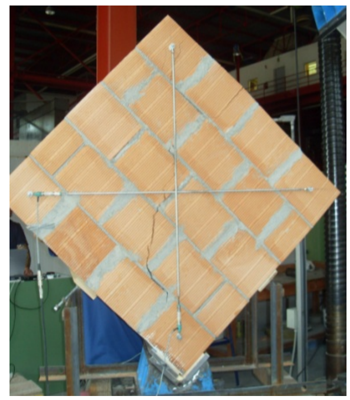
Masonry typology		*f* (from tests)	*f* (from EC6)	*E*
T1	Mean value [MPa]	9.5	-	10800
	Standard deviation [MPa]	1.3	-	1268
	Coefficient of variation [%]	13.3	-	11.7
	Characteristic value [MPa]	7.7	5.9	-
T2	Mean value [MPa]	6.9	-	7600
	Standard deviation [MPa]	0.6	-	1522
	Coefficient of variation [%]	8.3	-	20.0
	Characteristic value [MPa]	5.7	5.0	-
T3	Mean value [MPa]	4.0	-	3500
	Standard deviation [MPa]	0.3	-	495
	Coefficient of variation [%]	7.0	-	14.1
	Characteristic value [MPa]	3.3	3.9	-
T4	Mean value [MPa]	6.7	-	5300
	Standard deviation [MPa]	0.4	-	534
	Coefficient of variation [%]	5.7	-	10.1
	Characteristic value [MPa]	5.8	3.9	-

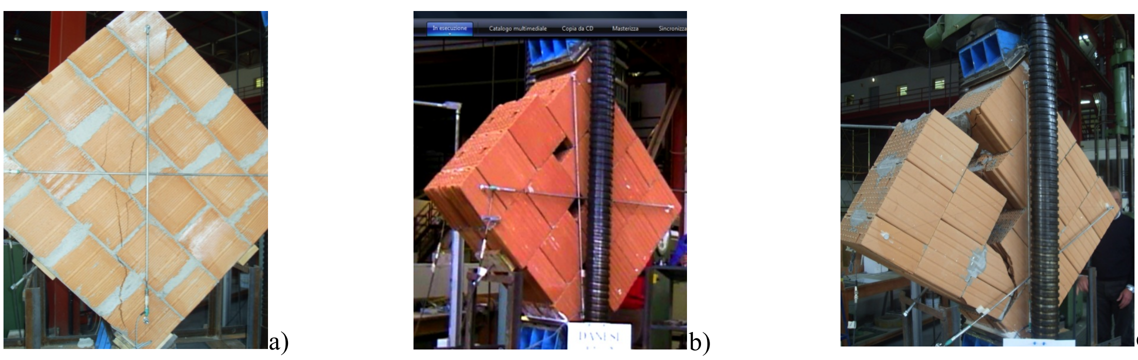


The diagonal tests represent one of the most common procedures to estimate the strength of masonry due to diagonal cracking; the parameter that is derived from this test is typically the tensile strength, which can be used for shear strength calculations. The tensile strength associated to diagonal cracking, f_t , can be evaluated as $F_{max}/(t\cdot(H+L))$, where F_{max} is the force at failure, t is the thickness and H and L are the height and the length of the specimen. Such estimate correlates the applied load to the diagonal principal tensile stress assuming a linear homogeneous elastic medium. If the results of the diagonal compression tests are used within a shear strength formulation as proposed in the EC6: $f_{vm}=f_{v0}+0.4\sigma_v$, the criteria to derive an estimate of the shear strength at zero normal stress (f_{v0}, $\sigma_v=0$) are not unique. Some codes, such as the Italian Commentary to the NTC08, allow the direct conversion of the results of diagonal test into values of shear strength, without however specifying how to convert the failure load into f_{v0}. In this work the value of f_{v0} was calculated as $(F_{max}\cdot cos\beta-0.4\cdot F_{max}\cdot sen\beta)/(L\cdot t)$, where $\beta=arctan(H/L)$ (Magenes et al. [15]). As shown in Figure 3, approximately vertical cracks through the units from the top to the bottom corner of the panels have mainly manifested in T1 (fully filled head-joints), whereas a step-wise cracking along the joints distinguishes the behaviour of T3 (dry head-joints); the typology T5 (mortar pocket head-joints) has instead manifested a mixed behaviour between T1 and T3 with cracks through the units and step-wise cracking along the joints. With reference to Table 7, a very low value of strength f_t has been obtained from the tests on typology T3, being about 10 times smaller than the strength corresponding to typology T1 (general purpose mortar bed and head-joints) since the tensile strength of the mortar bed-joints was reached without the occurrence of diagonal cracks in the units. An intermediate value has instead been found for the case of masonry with mortar pocket units (T5). Therefore, for the specimens with ungrouted head-joints the suitability of the diagonal compression test for the evaluation of the shear strength at zero normal stress seems doubtful, since the failure mechanism is essentially given by tensile failure of bedjoints. The mean elastic shear modulus *G* (secant at $0.33 \cdot \tau_{max}$) has been obtained from the deformation measurements and assuming isotropic behaviour. As shown in Table 7, very small values of *G* have been obtained for T3 and T5; for T1 a ratio of *G*/*E* (from the tests) of about 0.17 has been found, indicating for these types of masonry a strong discrepancy with the value of 0.4 proposed in the EC6 .

Table 7: Diagonal compression tests on masonry specimens; picture at failure

Typology		f_t	f_{v0}	*G*
T1	Mean value [MPa]	0.41	0.34	1851
	Standard deviation [MPa]	0.05	0.04	302
	Coefficient of variation [%]	11.4	11.4	16.3
	Characteristic value [MPa]	0.30	0.25	-
T3	Mean value [MPa]	0.042	0.036	182
	Standard deviation [MPa]	0.007	0.006	16
	Coefficient of variation [%]	16.7	16.7	8.5
	Characteristic value [MPa]	-	-	-
T5	Mean value [MPa]	0.17	0.14	703
	Standard deviation [MPa]	0.02	0.01	75
	Coefficient of variation [%]	10.9	9.8	10.7
	Characteristic value [MPa]	0.13	0.11	-





a) b) c)

Figure 3: Different failure mechanisms from diagonal tests for: a) T1; b) T3; c) T5

Referring to the triplet tests for the evaluation of shear strength, three different levels of precompression (0.2, 0.6 and 1.0 MPa) have been applied each on three specimens; the shear strength under zero compression (f_{v0}) has been computed as the intersection of the line resulting from a linear regression of the nine points showing the shear strength (f_{vi}) in function of the compression stress (f_{pi}) with the vertical axis. The tangent of the angle between this line and the horizontal axis represents the friction coefficient in a Coulomb type criterion as the strength formulation of the EC6 reported previously. The characteristic values have been found multiplying the mean values by 0.8 as per EN 1052-3. Table 8 shows that the largest values have been found in the case of masonry typology T1, whereas for typology T3 the lowest values have been identified. In all cases, with the exception of T3, the experimental obtained characteristic shear strength at zero compression (f_{v0}) has resulted to be larger than the corresponding values given in the EC6 provisions. The experimental strength on the T3 masonry triplets with thin layer mortar bed-joints of type 1 has been found to be 1/2 of the value proposed in the European code. The values of f_{v0} computed from the diagonal compression tests have resulted to be very different from the ones obtained from the tests on triplets. It should be noted that, in the shear strength expression of EC6, f_{v0} should be multiplied by 0.5 in the case of masonry with unfilled head-joints with adjacent faces of the masonry units closely abutted together. For all masonry typologies, a value of the friction coefficient $tan\alpha$ larger than given in EC6, set equal to 0.4 in the expression for the evaluation of the characteristic shear strength of masonry, has been obtained. In the majority of the cases, cracks across one or both the head-joints of the triplets with sliding of the units have occurred and, in the case of general purpose mortar joint specimens, the failure has befallen in the mortar/unit interface on one or two faces of the element, as reported in Table 8.

Table 8: Results of the initial shear strength tests and comparison with EC6; picture at failure

		From tests		From EC6	
Typology		**f_{v0} [MPa]**	**$tan\alpha$**	**f_{v0} [MPa]**	**$tan\alpha$**
T1	Mean value	0.69	0.77		
	Characteristic value	0.55	0.62	0.20	0.40
T2	Mean value	0.42	0.82		
	Characteristic value	0.34	0.66	0.20	0.40
T3	Mean value	0.18	0.65		
	Characteristic value	0.15	0.52	0.30	0.40
T4	Mean value	0.56	0.68		
	Characteristic value	0.45	0.55	0.30	0.40

CONCLUSIONS

The results of the mechanical characterization tests have shown that the different typologies of masonry constituted by vertically perforated clay units with thin webs/shells considered in this research have properties that could in most cases be adequate for use as a load-bearing material at least when seismic loading is not a concern. However, particular attention should be devoted to the choice and the construction of a proper thin layer mortar capable to guarantee a minimum thickness and a uniform distribution on the bed-joints without penetrating in the holes, in order to obtain sufficient levels of shear and compression strength avoiding stress concentration on limited parts of the elements, that could be particularly significant and dangerous with units having thin webs/shells. In this regard, the fibre-reinforced mortar used (thin-layer – type 2), despite its lower strength compared to the traditional glue mortar (thin-layer – type 1), has allowed to attain a significant increase in the shear and in the compressive strength of masonry.

The application of the EC6 for the evaluation of the strength parameters on the different masonry types has provided safe-sided estimations of the experimental resistance with the exception of the typology T3 realized with thin layer mortar of type 1.

The presented study has also shown that for units with sufficiently parallel and planar faces, the vertical compression strength of the unit measured with and without capping result to be very similar and the type of surface preparation seems to have little influence, as reported for the case of P800 TS units. Nevertheless, if the block shows irregularities on the bed-joint faces, as in the case of IP35SS DPE masonry units, the tests should be performed capping the elements to avoid an inconsistent evaluation of the unit strength.

The values of shear strength (f_{v0}) evaluated from diagonal compression tests have been found to be very different by the values of shear strength at zero compression directly measured trough initial shear tests on triplets, since they are estimated with experimental tests that can provide

two different failure mechanisms. This is particularly true for the masonry types with ungrouted head-joints, for which unrealistically low values of shear strength have been obtained from diagonal compression tests, once more evidencing doubts related to the applicability of this test procedure to masonry specimens made up by units with unfilled head-joints and to the validity of the related results, as already underlined in other studies (*i.e.*, Morandi and Magenes [16]). In a future phase of the present research, shear-compression tests on large wall specimens will be carried out, from which more references regarding the shear strength properties of the masonry assemblages will be available.
The results of the characterization here discussed also represent useful preliminary parameters to study the applicability of such types of masonry in the case of seismic actions.

ACKNOWLEDGEMENTS
The research upon which this work is based has been carried out at the University of Pavia and at EUCENTRE Pavia, and it is sponsored by ASSOPLAN whose financial support is gratefully acknowledged.

REFERENCES

1 Ministero dei Lavori Pubblici, Norme tecniche per la progettazione, esecuzione e collaudo degli edifici in muratura e per il loro consolidamento, D.M. del 20/11/87, Gazzetta Ufficiale 5/12/1987, n. 285 - S. 1987.
2 CEN (1995) Eurocode 8: Design provisions for earthquake resistance of structures – Part 1-3: General rules – Specific rules for various materials and elements, ENV 1998-1-3:1995, Brussels; Belgium.
3 Italian National Annex of Eurocode 6 (2010): Design of masonry structures – Part 1-1: General rules for reinforced and unreinforced masonry structures, EN 1996-1-1:2005.
4. Draft of the New Technical Norms for Constructions (2012).
5 Tomaževič, M., Weiss, P. (2012) "Robustness as a criterion for use of hollow clay masonry units in seismic zones: an attempt to propose the measure" Materials and Structures: Volume 45, Issue 4, pp 541-559.
6. EN 772-1 (2011): Methods of test for masonry units – Determination of compressive strength.
7. EN 771-1 (2011): Specifications for masonry units – Clay masonry units.
8 D.M. 14/01/2008 (2008): Norme Tecniche per le Costruzioni, G.U. 14 Febbraio 2008.
9. Circolare del Ministero delle Infrastrutture e dei Trasporti del 02/02/2009 n.617 - Istruzioni per l'applicazione delle Nuove norme tecniche per le costruzioni.
10. EN 1015-11 (2007): Methods of test for mortar for masonry – Determination of flexural and compressive strength of hardened mortar.
11. EN 1052-1 (2001): Methods of test for masonry – Determination of compressive strength.
12. EN 1052-3 (2007): Methods of test for masonry – Determination of initial shear strength.
13 EN 1015-3 (2007): Methods of test for mortar for masonry – Determination of consistence of fresh mortar (by flow table).
14 CEN (2004) Eurocode 6 - Design of masonry structures, Part 1-1: Common rules for reinforced and unreinforced masonry structures, EN 1996-1-1:2005, Brussels, Belgium.
15 Magenes, G., Calvi, G. M., Gaia, F., (1996) "Shear tests on reinforced masonry walls" Report RS-03/96, Dipartimento di Meccanica Strutturale, University of Pavia.
16 Morandi, P., Magenes, G., (2009) "Risposta sismica nel piano di pareti murarie in blocchi in laterizio alleggerito", Atti del XIII Convegno di Ingegneria Sismica ANIDIS, June 28-July 2 2009, Bologna, Italy.