Mechanical properties of masonry as required for the seismic resistance verification

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ISSN 1330-3651
UDC/UDK 620.172.21:691.421-478

MECHANICAL PROPERTIES OF MASONRY AS REQUIRED FOR THE SEISMIC RESISTANCE VERIFICATION

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Preliminary notes

Despite the extensive use of masonry in different types of construction, this material has not been investigated as much as other materials. Results obtained from different sources are general and for each particular use its characteristics have to be determined separately. Although the stress state in masonry is very complex and cannot be easily simulated in experiments, the properties obtained by simple experiments that investigate the basic failure modes of masonry could be used for a more accurate prediction of its non-linear behavior and failure. The outlined extended testing of masonry mechanical properties in plane has been necessary for obtaining the parameters needed for the non-linear numerical analysis of the masonry behavior under in-plane lateral loading. Presented data could be used as initial required values for masonry as used in Croatia. They represent the main input data for any further analysis of masonry buildings made of hollow-clay blocks and they could be used as a good reference for designers, brick industry and masonry builders in Croatia.

Keywords: *hollow-clay units, masonry, mechanical properties, simple tests*

Mehanička svojstva ziđa za provjeru seizmičke otpornosti

Prethodno priopćenje

Primjena opeke i opečnih blokova je jako raširena u građevinarstvu. Istraživanja mehaničkih svojstava opeke kao materijala i ponašanja ziđa pri djelovanju horizontalnih opterećenja u ravnini nije dovoljno istražena, a rezultati iz drugih izvora su obično generalni i ne mogu se direktno primijeniti te se za svaku pojedinu primjenu trebaju posebno odrediti. Ziđe je anizotropno i za svaku nelinearnu analizu njegova naponskog stanja je potreban niz podataka o mehaničkim svojstvima do kojih se teško dolazi. U radu su izložena proširena istraživanja mehaničkih svojstava glinenih zidnih elemenata i ziđa određena primjenom jednostavnih metoda ispitivanja, na primjeru šuplje blok-opeke kakova se često koristi u Republici Hrvatskoj. Prikazani rezultati mogu se koristiti za složene nelinearne proračune ponašanja ziđa izloženog djelovanju vertikalnog i horizontalnog opterećenja.

Ključne riječi: *jednostavna ispitivanja, mehanička svojstva, šuplja blok-opeka, ziđe*

1 Introduction
Uvod

Simple experiments can determine basic mechanical properties of masonry walls, which by their nature are anisotropic. Structural masonry element, a wall, consists of mortar and masonry units and its mechanical properties depend on mechanical properties of its elements. This paper presents test results of the masonry made of hollow clay blocks and lime-cement mortar as used in Croatia, performed according to EN 1996-1-1:2005 [1]. Standard tests of mechanical properties are extended by examining the horizontal compressive strength of masonry, thus modulus of elasticity and ultimate strain, tensile strength and shear modulus of masonry that are also needed for numerical verification. The properties of masonry walls for out of plane loading are not included.

The purpose of this study is to get a basis for numerical analysis of masonry walls and masonry infill panels as are often used in Croatia. They could be used as good reference for designers, brick industry and masonry builders.

2 Properties of masonry units
Svojstva zidnih elemenata

The hollow clay unit type V5 ($l_u \times w_u \times h_u$=250×190×190 mm) produced by a local manufacturer was chosen, cut into quarters ($l_u \times w_u \times h_u$=190×125×95 mm) and tested in compression in accordance with the norm HRN EN 772-1:2004 [2] and in tension in accordance with [7].

Masonry unit can be classified as Group 2 in accordance with the norm EN 1996-1-1:2005, [1, 8]. The hollow clay blocks, shown in Fig. 1, consist of 54,4 % voids.

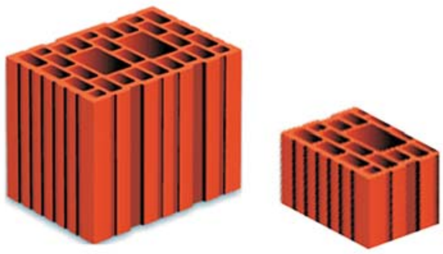

Figure 1 *The V5 and the cut masonry unit*
Slika 1. *V5 i izrezani zidni element*

Table 1 *Test results of masonry units*
Tablica 1. *Rezultati ispitivanja zidnih elemenata*

Sample No. (i)	Vertical compressive strength $f_{mu,c,i}$ / N/mm^2	Horizontal compressive strength $f_{h,mu,c,i}$ / N/mm^2	Tensile strength $f_{mu,t,i}$ / N/mm^2
1	13,3	2,3	0,7
2	13,3	2,0	0,8
3	13,3	2,1	0,7
4	12,6	2,0	0,7
5	13,0	2,0	0,9
6	12,8	1,9	0,9

The test results for tensile, horizontal and vertical compression strength are given in Tab. 1.

The average values of compressive and tensile strength are $f_{mu,c}$=13,0 N/mm^2, $f_{hmu,c}$=2,0 N/mm^2 and $f_{mu,t}$ =0,8 N/mm^2 with a standard deviation S=0,29 N/mm^2, S=0,14 N/mm^2, S=0,11 N/mm^2 and coefficients of variation V=2 %, V=7 % and V=13 %, respectively. The mean normalized compressive strength is calculated in accordance with Appendix A of the norm HRN EN 772-1:2004 [5] as

$$f_{\mathrm{b}} = 1,2 \cdot \delta \cdot f_{\mathrm{mu,c}} = 1,2 \cdot 0,93 \cdot 13,0 = 14,5 \tag{1}$$

and

$$f_{\mathrm{bh}} = 1,2 \cdot \delta_{\mathrm{h}} \cdot f_{\mathrm{hmu,c}} = 1,2 \cdot 1,27 \cdot 2,0 = 3,1 \tag{2}$$

in N/mm^2, where δ is the masonry unit shape factor.

3 Properties of mortar
Svojstva morta

For construction of the masonry wallets, the lime-cement mortar (general purpose) with a volume ratio of cement, lime and sand 1:1:5 was used.

In accordance with the norm HRN EN 1015-11:2000 [3] obtained compressive strength was f_{m}=5,02 N/mm^2, tensile strength f_{mt}=1,27 N/mm^2 and therefore the mortar can be classified in Class M5.

4 Vertical compressive strength of masonry
Tlačna čvrstoća zida u vertikalnom smjeru

The tests were carried out on four unreinforced masonry wallets in accordance with the norm HRN EN 1052-1:2004 [4].

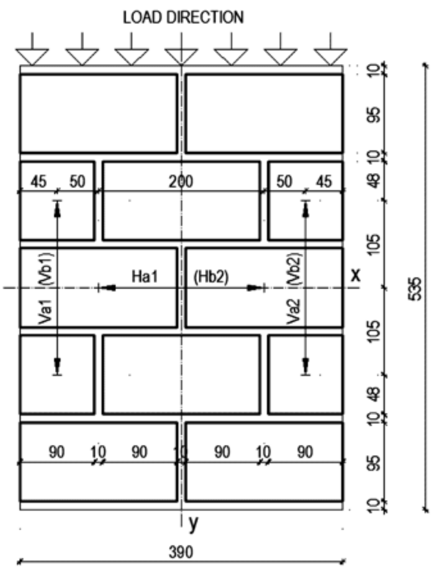

Figure 2 Front (back) side of the test specimen. Units are mm.
Slika 2. Prednja (stražnja) ploha ispitnog uzorka. Jedinice su mm.

The mortar was evenly applied to the bed and head faces of masonry units and carefully kept out of masonry unit voids. Four LVDT-deformation sensors were placed in vertical (V_{a1}, V_{b1}, V_{a2} and V_{b2}) and two in horizontal direction (H_{a1} and H_{b1}).

The scheme of the test specimen is shown in Fig. 2.

There was a brittle failure of the samples with multiple vertical cracks extending from the middle towards the ends of the sample. The collapse was accompanied by intense cracking sound.

The compressive strength was calculated using the Eq. (1) of the norm HRN EN 1052-1:2004 [4]

Figure 3 The test sample after failure in compression
Slika 3. Ispitni uzorak nakon sloma u tlaku

$$f_{i,\max} = \frac{F_{i,\max}}{A_i} \tag{3}$$

and is shown in Tab. 2. The average value of compressive strength of masonry wallets is f_i=2,0 N/mm^2 with standard deviation of S=0,1 N/mm^2 and the coefficient of variation of V=6,1 %.

Table 2 The compressive strength of samples in vertical direction
Tablica 2. Tlačna čvrstoća uzoraka u vertikalnom smjeru

Sample No. (i)	Ultimate load $F_{i,\max}$ / kN	Area A_i / mm^2	Compressive strength f_i / N/mm^2
1	91,0	48750	1,9
2	105,0	48750	2,2
3	96,0	48750	2,0
4	95,0	48750	1,9

The mean value of characteristic compressive strength of masonry was calculated as f_{k}=1,7 N/mm^2, according to Tab. 2 and the Eq. (3) of the norm HRN EN 1052-1:2004 [4]

$$f_{\mathrm{k}} = \frac{f}{1,2} \tag{4}$$

or

$$f_{\mathrm{k}} = f_{i,\min}. \tag{5}$$

The relation of normal strain to normal stress was linear up to the ultimate stress, as presented on the graph in Fig. 4.

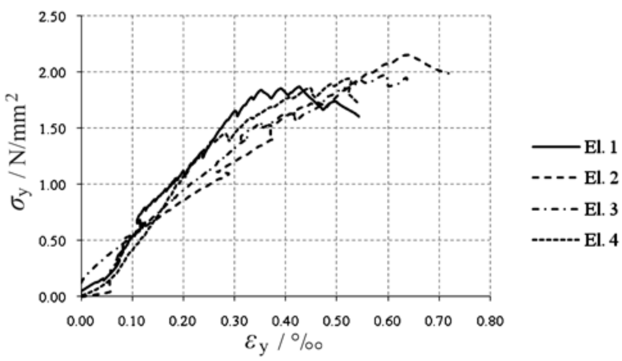

Figure 4 Relationship between normal strain and normal stress
Slika 4. Odnos normalnog naprezanja i deformacije

The modulus of elasticity was determined as the secant modulus according to the Eq. (2) of the HRN EN 1052-1:2004 [4] as follows

$$E_i = \frac{F_{i,\max}}{3\varepsilon_i A_i} \tag{6}$$

and is shown in Tab. 3.

Table 3 *Normal strains and secant modulus of elasticity*
Tablica 3. *Normalne deformacije i sekantni modul elastičnosti*

Sample No. (i)	Ultimate normal strain $\varepsilon_{i,\mathrm{u}}$ / ‰	Normal strain ε_i / ‰	Modulus of elasticity E / N/mm^2
1	0,54	0,13	4978
2	0,72	0,16	4487
3	0,63	0,15	4527
4	0,54	0,14	4640

The average value of modulus of elasticity of masonry in vertical direction was rounded up to 100 N/mm^2 to E=4600 N/mm^2.

By applying the values of transverse and longitudinal strains at a third of the maximum stress, the Poisson's ratio was determined by

$$\upsilon_i = -\frac{\varepsilon_{i,\mathrm{q}}}{\varepsilon_i}, \tag{7}$$

as shown in Tab. 4.

Table 4 *Poisson's ratio*
Tablica 4. *Poissonov omjer*

Sample No. (i)	Longitudinal strain ε_i / ‰	Transversal strain $\varepsilon_{i,\mathrm{q}}$ / ‰	Poisson's ratio υ_i /-
1	-0,13	0,008	0,06
2	-0,16	0,008	0,05
3	-0,15	0,008	0,05
4	-0,14	0,007	0,05

The values of measured longitudinal and transverse strains are given in Tab. 3 and the calculated Poisson's ratio of the masonry is $\upsilon = 0{,}05$.

5 Horizontal compressive strength of masonry
Tlačna čvrstoća ziđa u horizontalnom smjeru

In order to determine the properties of masonry in horizontal direction the tests were carried out on three unreinforced masonry wallets in accordance with the norm HRN EN 1052-1:2004 [4]. The samples were produced in the same manner as samples in the previous section. The mortar was applied to the bed and head faces of masonry units and carefully kept out of masonry unit voids. Leveling layer of mortar was applied to the top and bottom surfaces of the masonry wallets. The tests were conducted after 28 days.

Four LVDT-deformation sensors were placed in vertical direction (V_{a1}, V_{b1}, V_{a2} and V_{b2}). Applied vertical force during testing was measured by force transducers. Dimensions of the sample and arrangement of the sensors are shown in Fig. 5.

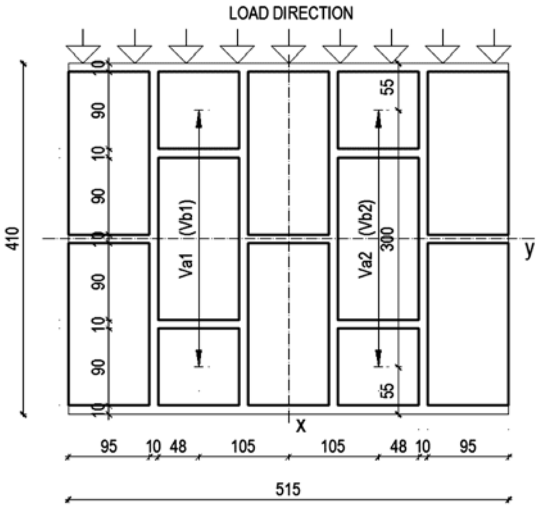

Figure 5 *Front (back) side of the test specimen. Units are mm.*
Slika 5. *Prednja (stražnja) ploha ispitnog uzorka. Jedinice su mm.*

There was a sudden brittle failure with multiple vertical cracks through the connection between the mortar and the masonry unit. In addition, the compressive failure occurred in the blocks leading to the collapse of the sample.

Due to the sudden break of the test samples only basic information necessary for calculating the mechanical properties was collected.

The terms by which the mechanical properties were determined are identical to those described in Chapter 4.

Table 5 *The compressive strength of samples in horizontal direction*
Tablica 5. *Tlačna čvrstoća uzoraka u horizontalnom smjeru*

Sample No. (i)	Ultimate load $F_{\mathrm{h},i,\max}$ / kN	Area $A_{\mathrm{h},i}$ / mm^2	Compressive strength $f_{\mathrm{h},i}$ / N/mm^2
1	73,2	66875	1,1
2	71,0	66875	1,1
3	74,4	66875	1,1

The average value of compressive strength in horizontal direction of masonry wallets is f_h=1,1 N/mm^2 and the mean characteristic value is f_{hk}=0,91 N/mm^2.

Table 6 *Normal strains and secant modulus of elasticity*
Tablica 6. *Normalne deformacije i sekantni modul elastičnosti*

Sample No. (i)	Ultimate normal strain $\varepsilon_{\mathrm{h},i,\mathrm{u}}$ / ‰	Normal strain $\varepsilon_{\mathrm{h},i}$ / ‰	Modulus of elasticity $E_{\mathrm{h},i}$ / N/mm^2
1	0,48	0,18	2054
2	0,51	0,20	1813
3	0,51	0,20	1854

The mean value of the modulus of elasticity was identified to E_h=1900 N/mm^2 and the Poisson's ratio was not determined.

6 Initial shear strength of masonry
Početna posmična čvrstoća ziđa

In order to determine the characteristic initial shear strength f_{vk0} and the characteristic angle of internal friction tanΦ_k, by following the guidelines of norm HRN EN 1052-3:2004 [5], twelve test samples were produced from the same mortar and masonry units, as shown in Fig. 6. The tests were conducted after 28 days, in series of four samples with corresponding normal stresses $f_{n,p}$=0,2 N/mm^2, 0,6 N/mm^2 and 1,0 N/mm^2, where n designated the series number (n = 1, 2 and 3).

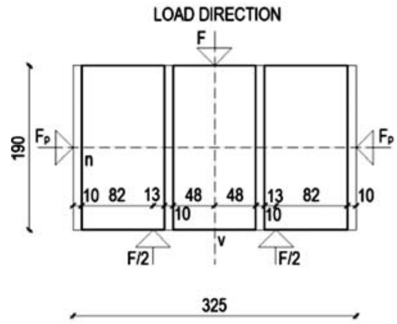

Figure 6 *The test specimen scheme*
Slika 6. *Shema ispitnog uzorka*

During the execution of experiments, the ultimate shear load $F_{i,\max}$ and corresponding normal load $F_{i,p}$ were observed. After each experiment, the form of collapse was analyzed in order to accept or reject the test, because not all failure modes of the masonry units are allowed to happen.

Figure 7 *The test specimen during testing*
Slika 7. *Ispitni uzorak tijekom ispitivanja*

The breakdown of samples in every series occurred at the contact of mortar and masonry unit and mostly on just one side only, as shown in Fig. 8a.

The results of two samples from different series were discarded because there was a breakage and dismantling of masonry unit, which is irregular according to Appendix A of norm HRN EN 1052-3:2004 [5] as shown in Fig. 8b.

Mean values of test results of the three series are shown by the means of diagram in Fig. 9.

By using the linear regression curve and linear extrapolation the initial shear strength was determined as f_{v0}=0,47 N/mm^2 and the angle of internal friction tanΦ=0,46.

The characteristic values in accordance with the norm HRN EN 1052-3:2004 [5] were obtained as

$$f_{vk0} = 0,8 \cdot f_{v0} = 0,38 \tag{8}$$

in N/mm^2 and

$$\tan\Phi_k = 0,8 \cdot \tan\Phi = 0,37. \tag{9}$$

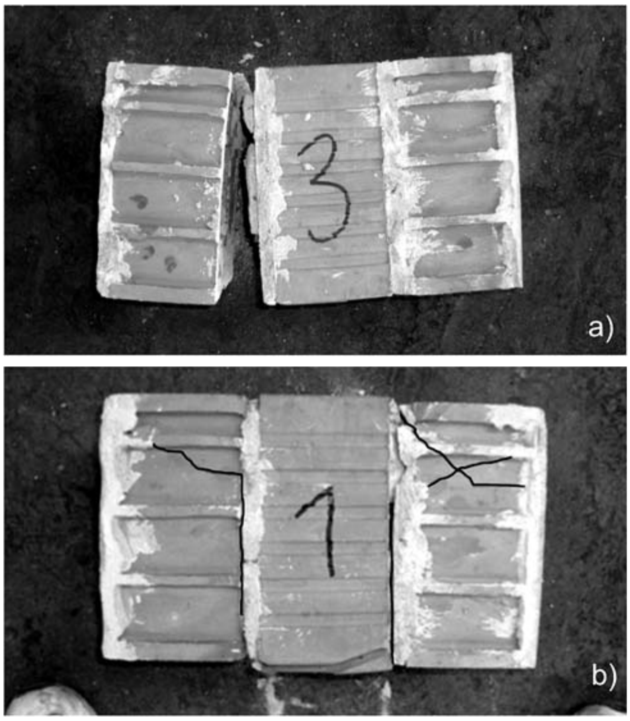

Figure 8 *a) regular and b) irregular failure of test specimen (masonry unit on the right)*
Slika 8. *a) pravilni i b) nepravilni slom ispitnog uzorka (zidni element na desnoj strani)*

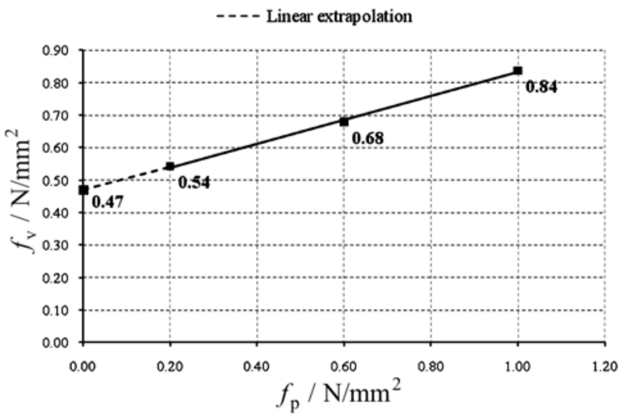

Figure 9 *Mean values of shear strength at different normal stresses*
Slika 9. *Srednje vrijednosti posmične čvrstoće pri različitim normalnim naprezanjima*

7 Tensile (shear) strength of masonry
Vlačna (posmična) čvrstoća zida

Tensile and shear strength of masonry was determined on four square samples of unreinforced masonry wallets by applying the diagonal tensile test in accordance with [6] and [9]. The samples were produced vertically and mortar was applied to the bed and head faces of masonry units and carefully kept out of masonry unit voids. Leveling layer of mortar was applied to the top and bottom surfaces of the masonry wallets. Before testing the sample was placed diagonally at an angle of 45 degrees towards horizontal with a special support. The tests were conducted after 28 days.

A total of four LVDT-deformation transducers were used to measure the deformation and one force transducer was used for measuring the force. Two LVDT-deformation sensors were placed in vertical (V_{a1} and V_{b1}) and two in horizontal direction (H_{a1} and H_{b1}).

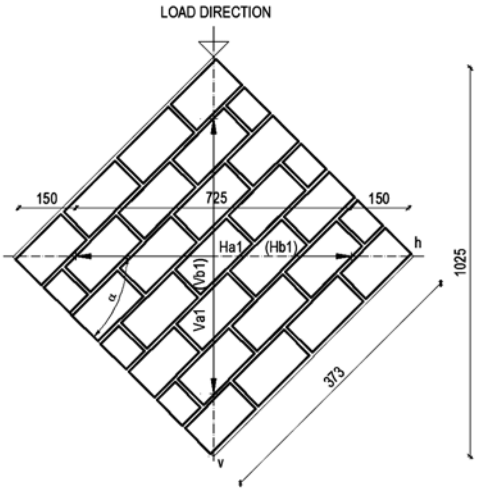

Figure 10 *Front (back) side of the test specimen. Units are mm.*
Slika 10. *Prednja (stražnja) ploha ispitnog uzorka. Jedinice su mm.*

The position of the test sample and arrangement of the sensors are shown in Fig. 10.

The loss of bearing capacity of the test samples occurred by sudden onset of irregular vertical cracks through the entire sample. The crack passed in part through the masonry unit and partly through contact of mortar and masonry unit as shown in Fig. 11 and the loss of adhesion and horizontal tensile strength of masonry units occurred.

During testing, a sensor was destroyed due to sudden fracture. This was prevented in other attempts by supporting the sample from the sides (see Fig. 12).

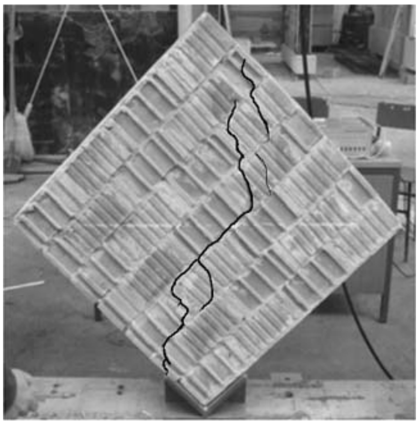

Figure 11 *Failure of the test sample*
Slika 11. *Slom ispitnog uzorka*

Figure 12 *Total separation of the test sample*
Slika 12. *Potpuno razdvajanje ispitnog uzorka*

The tensile and shear strength of masonry wallets were calculated by using the Eq. (3.12) of [4] and the Eq. (2) of [9]

$$f_{\mathrm{t}} = \frac{2F_{i,\max}}{\pi\sqrt{2}t_{\check{s}}l_s} \tag{10}$$

and

$$f_{\mathrm{v}} = \frac{F_{i,\max}}{\sqrt{2}t_{\check{s}}l_s} \tag{11}$$

and presented in Tab. 7.

Table 7 *The tensile and shear strength of samples*
Tablica 7. *Vlačna i posmična čvrstoća ispitnih uzoraka*

Sample No. i	Ultimate load $F_{i,\max}$ / kN	Tensile strength $f_{\mathrm{t},i}$ / N/mm^2	Shear strength $f_{\mathrm{v},i}$ / N/mm^2
1	49	0,24	0,38
2	42	0,21	0,32
3	32	0,16	0,25
4	35	0,17	0,27

The average tensile and shear strength of the test specimens were f_{t}=0,19 N/mm^2 and f_{v}=0,31 N/mm^2 with a standard deviations of S=0,04 N/mm^2 and S=0,06 N/mm^2 and coefficients of variation of V=19 %, respectively.

The mean values of characteristic strengths were calculated by using Eq. (3) of norm HRN EN 1052-1:2004 [2] which were

$$f_{\mathrm{k}} = \frac{f}{1,2} \tag{12}$$

or

$$f_{\mathrm{k}} = f_{i,\min} \tag{13}$$

as f_{tk}=0,16 N/mm^2 and f_{vk}=0,25 N/mm^2.

By this test method one can determine shear and normal deformation as well. As shown in Fig. 12 the relation between the shear strain and shear stress was linear up to the failure and the relation of tensile stress to tensile strain was nonlinear.

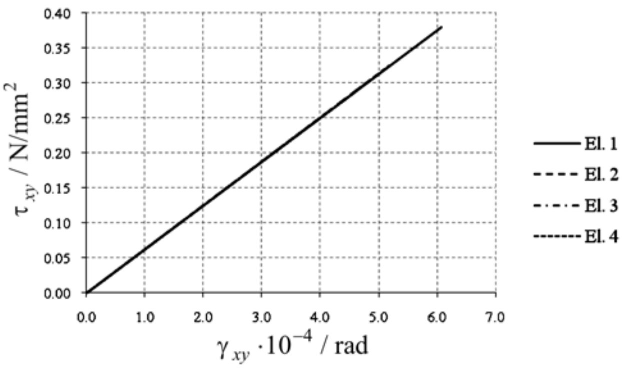

Figure 13 *Relationship between shear strain and shear stress*
Slika 13. *Odnos posmičnog naprezanja i posmične deformacije*

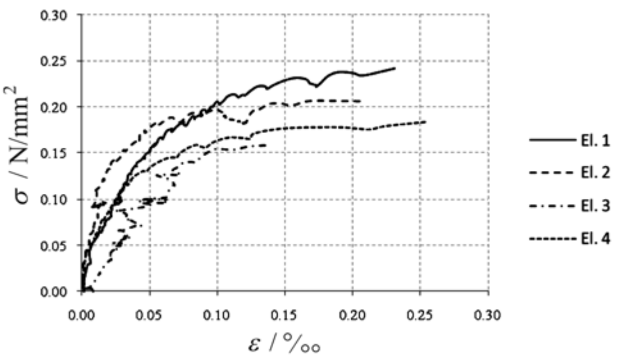

Figure 14 *Relationship between tensile strain and tensile stress*
Slika 14. *Odnos vlačne deformacije i vlačnog naprezanja*

In accordance with [9], shear strain was determined by using the following expression

$$\gamma_{yx} = \left(\tan\alpha + \frac{1}{\tan\alpha} \right)\left(\frac{\delta_{\mathrm{h}} + \delta_{\mathrm{v}}}{2d} \right) \tag{14}$$

where d=1025 mm is the length of diagonal of the masonry wallet, δ_{v} and δ_{h} are vertical and horizontal diagonal extension respectively and α=45° is the angle of masonry wallet towards horizontal according to Fig. 10.

The shear modulus was calculated by using the Hooke's law for shear

$$G_{yx} = \frac{\tau_{yx}}{\gamma_{yx}}, \tag{15}$$

where τ_{xy} was calculated according to Eq. 11 and Tab. 7.

Table 8 *The shear modulus, the diagonal normal and shear strains*
Tablica 8. *Modul posmika, dijagonalne normalne i posmične deformacije*

Sample No. i	Ultimate diagonal strains		Shear strain $\gamma_{yx,i}$ / rad	Shear modulus $G_{yx,i}$ / N/mm²
	$\varepsilon_{\mathrm{dh},i,\mathrm{u}}$ / ‰	$\varepsilon_{\mathrm{dv},i,\mathrm{u}}$ / ‰		
1	0,23	0,30	$6{,}1\times10^{-4}$	626
2	0,21	0,47	$5{,}2\times10^{-4}$	626
3	0,14	0,34	$4{,}0\times10^{-4}$	626
4	0,25	0,47	$4{,}3\times10^{-4}$	626

The average value of shear modulus of masonry was rounded up to 100 N/mm² to G_{xy}=600 N/mm² as was the case with the modulus of elasticity.

8 Conclusion
Zaključak

The results of experimental investigation of the mechanical properties of masonry and its constituent elements are given as were performed by the use of simple experimental methods. Masonry wallets were tested in-plane using Croatian/European norms and guidelines from [6] and [9].

The test results can be classified, as in the following table, with respect to type of the test and number of samples.

Table 9 *A set of mechanical properties obtained for masonry wall tests*
Tablica 9. *Skup dobivenih mehaničkih svojstava za zidne prizme*

Test method	Number of samples	Mechanical property and value
Vertical compression	4	f_{k}=1,7 N/mm² E=4600 N/mm² υ=0,05 ε_{u}=0,61 ‰
Horizontal compression	3	f_{hk}=1,1 N/mm² E_{h}=1900 N/mm² $\varepsilon_{\mathrm{h,u}}$=0,50 ‰
Horizontal sliding	12	f_{vk0}=0,38 N/mm² $\tan\Phi_{\mathrm{k}}$=0,37
Diagonal tension	4	f_{tk}=0,16 N/mm² f_{vk}=0,16 N/mm² G_{yx}=600 N/mm² $\gamma_{yx,\mathrm{u}}$=4,9×10^{-4}rad $\varepsilon_{\mathrm{dh,u}}$=0,21 ‰ $\varepsilon_{\mathrm{dv,u}}$=0,40 ‰

The meaning of symbols can be found in Tab. 13. Through the execution of experiments it has been noticed that hollow clay masonry blocks are very brittle and they could affect the outcome of test, i.e. cause an incorrect failure type. These were in our case most often vertical cracks and crushing of hollow clay masonry units.

Additional problems that arose were: (a) sudden failure of masonry at the moment at which it would be wise to remove the equipment that might be damaged like in the abrupt diagonal tension failure of the samples; (b) the importance of the quality of workmanship could be decisive, as mortar could infill the voids of masonry block and influence the results.

The mechanical properties of the constituent elements of masonry, mortar and masonry units, are shown in the following tables.

Table 10 *A set of mechanical properties obtained for masonry units*
Tablica 10. *Skup dobivenih mehaničkih svojstava za zidne elemente*

Test method	Number of samples	Mechanical property and value
Vertical compression	6	f_{b}=14,5 N/mm²
Horizontal compression	6	f_{bh}=3,1 N/mm²
Splitting tension	6	f_{bt}=0,7 N/mm²

Table 11 *A set of mechanical properties obtained for mortar*
Tablica 11. *Skup dobivenih mehaničkih svojstava za mort*

Test method	Number of samples	Mechanical property and value
Compression	6	f_{m}=5,02 N/mm²
Bending	3	f_{mt}=1,27 N/mm²

To represent the interdependence of some of the above parameters of masonry, it is useful to observe the law of orthotropic behavior of materials in plane stress condition, with a note that it is elastic state:

$$\begin{Bmatrix} \varepsilon_y \\ \varepsilon_x \\ \gamma_{yx} \end{Bmatrix} = \begin{bmatrix} \frac{1}{E_y} & -\nu_y \frac{1}{E_x} & 0 \\ -\nu_x \frac{1}{E_y} & \frac{1}{E_x} & 0 \\ 0 & 0 & \frac{1}{G_{yx}} \end{bmatrix} \begin{Bmatrix} \sigma_y \\ \sigma_x \\ \tau_{yx} \end{Bmatrix} \tag{16}$$

with

$$\nu_y E_y = \nu_x E_x . \tag{17}$$

In Eq. 16 and Eq. 17, y designates the direction perpendicular to bed joints and x the direction parallel to the bed joints. Therefore, according to Eq. 17 and the Tab. 9

$$\nu_x = \nu_y \frac{E_y}{E_x} = 0,05 \times \frac{4600}{1900} = 0,12 \tag{18}$$

the Poisson's ratio in horizontal direction is υ_h=0,12, thus the orthotropic elasticity matrix is filled.

Ratios of individual parameters obtained in this study are shown in Tab. 12. The values of individual strength are presented graphically in Fig. 15, from where it is clearly seen how compressive strength of masonry unit in vertical direction dominates. The weakest strength is the tensile strength of masonry, owing to low adhesion between mortar and masonry units and then initial shear strength or cohesion follows.

The outlined extended testing of the masonry mechanical properties in plane has been necessary (as shown in the work [10]) for obtaining the parameters needed for the non-linear numerical calculation of the masonry. Presented data could be used as initial required values for numerical analysis of masonry as used in Croatia.

***Table 12** Mathematical relations between parameters*
***Tablica 12.** Matematički odnosi među parametrima*

Parameters	Mathematical relation	Ratio / %
f_{bh}/f_b	$f_{bh}=0,21\cdot f_b$	21
f_{bt}/f_b	$f_{bt}=0,05\cdot f_b$	5
f_{hk}/f_k	$f_{hk}=0,65\cdot f_k$	65
f_{tk}/f_k	$f_{tk}=0,09\cdot f_k$	9
E_h/E	$E_h=0,41\cdot E$	41
G_{yx}/E	$G_{yx}=0,13\cdot E$	13
$\varepsilon_{hu}/\varepsilon_u$	-	82
$\varepsilon_{dh,u}/\varepsilon_{dv,u}$	-	53
υ/υ_h	-	42

The nonlinear properties of masonry are dependent upon the amount and loading type and input data can be obtained only by experiment. Taking into account the wide range of variation of mechanical properties of masonry, the testing of masonry is one of the basic aspects of seismic resistance verification of masonry structures. Using the data obtained by testing will make the results of seismic resistance verification more accurate.

Although the stress state in masonry is very complex and cannot be easily simulated in experiments, the properties obtained by simple experiments which explore the basic failure modes of masonry could be used, by means of failure theories, for a more accurate prediction of its loss of bearing capacity.

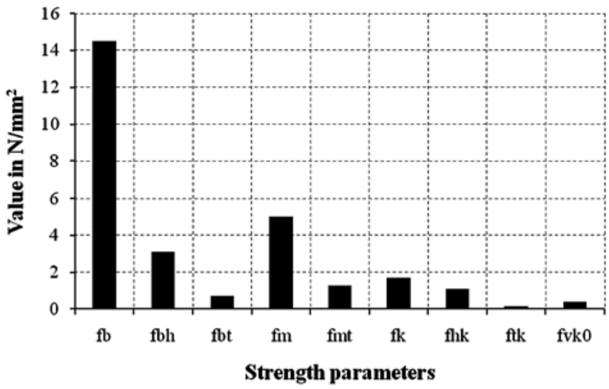

***Figure 15** Relationship between individual strengths*
***Slika 15.** Odnosi između pojedinih čvrstoća*

Acknowledgments
Zahvale

The research presented in this paper is part of the research project "Seismic design of infilled frames" supported by the Ministry of Science, Education and Sport of the Republic of Croatia and its support is gratefully acknowledged.

9 Notation
Oznake

The meaning of important symbols and indices used in this work is given in alphabetical order in the table below.

***Table 13** List of important symbols used in Latin characters*
***Tablica 13.** Popis bitnih simbola u latinici*

Symbol	Units	Meaning
E	N/mm^2	modulus of elasticity in vertical direction
E_h	N/mm^2	modulus of elasticity in horizontal direction
f_b	N/mm^2	normalized mean vertical compressive strength of masonry unit
f_{bh}	N/mm^2	normalized mean horizontal compressive strength of masonry unit
f_{bt}	N/mm^2	tensile strength of masonry unit
f_k	N/mm^2	mean vertical characteristic compressive strength of masonry
f_{hk}	N/mm^2	mean horizontal characteristic compressive strength of masonry
f_{tk}	N/mm^2	mean horizontal characteristic tensile strength of masonry
f_{vk}	N/mm^2	mean horizontal characteristic shear strength of masonry
f_{vk0}	N/mm^2	mean characteristic initial shear strength
f_m	N/mm^2	compressive strength of mortar
f_{mt}	N/mm^2	tensile strength of mortar
G_{yx}	N/mm^2	shear modulus
x,y	-	horizontal, vertical direction

Table 14 *List of important symbols used in Greek characters*
Tablica 14. *Popis bitnih simbola s grčkim znakovljem*

Symbol	Units	Meaning
Φ_k	-	mean characteristic angle of internal friction
$\gamma_{yx,u}$	rad	ultimate shear strain
ε_u	‰	ultimate vertical normal strain
$\varepsilon_{h,u}$	‰	ultimate horizontal normal strain
$\varepsilon_{dv,u}$	‰	ultimate diagonal strain in direction of compression diagonal
$\varepsilon_{dh,u}$	‰	ultimate diagonal strain in direction perpendicular to compression diagonal
ν	-	Poisson's ratio for vertical direction
ν_h	-	Poisson's ratio for horizontal direction

10 References
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