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To cite this article: Adam Piekarczyk 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **471** 052017

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The Influence of Compressive Stress on the Load-Bearing Capacity of Masonry Subjected to Vertical Displacements

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Abstract. The paper describes the results of tests of masonry wallets made of solid clay bricks with joints of normal thickness (10 specimens) and filled vertical joints and autoclaved aerated concrete (AAC) blocks with thin joints and unfilled vertical joints (5 specimens). The specimens made of clay bricks were 1290 mm wide, 1415 mm high and 250 mm thick, while the specimens made of AAC blocks had the width of 1250 mm, the height of 1510 mm and the thickness of 240 mm. The tests were carried out in a specially designed steel test stand with which the masonry specimens were monolithised. The force applied along the vertical edge of the specimens and causing the vertical displacements was carried out by means of hydraulic cylinder. The masonry specimens were tested without participation of vertical compressive stresses perpendicular to the bed joints σ_c or the tests were carried out after initial compression, which induced stress in the wall with mean values from 0.3 to 1.5 N/mm² for solid clay brick specimens and 0.9 N/mm² in walls made of AAC blocks. The compressive loads were implemented using four pairs of tensioned steel tendons equipped with springs to compensate the influence of masonry displacements. The deformation angles of masonry were also investigated. Deformation angles were calculated based on changes in the length of the system of measuring bases placed on both surfaces of the specimens. The compressive stresses σ_c influenced the values of the mean shear stress $\tau_{cr,\sigma}$ (force inducing vertical displacements divided by the area of the vertical cross-section of the specimen) at which the first oblique crack appeared. The $\tau_{cr,\sigma}$ stress was always greater than the stress $\tau_{cr,0}$ at which the first crack occurred in the specimens tested without compression. The ratio $\tau_{cr,\sigma}/\tau_{cr,0}$ for solid clay brick specimens ranged from 1.38 to 2.24, depending on the stress value σ_c and 2.18 for masonry made of AAC blocks. Compressive stresses also influenced the increase of the masonry deformation angles at the moment of the first cracking $\theta_{cr,\sigma}$ in relation to the deformation angle $\theta_{cr,0}$ of the specimens tested without compression. This effect was proportional to the increase of τ_{cr} so that the mean modulus of deformation was about 1630 N/mm² for clay brick walls. In the case of specimens made of AAC blocks a ratio of stress to angles of deformation G_{cr} equal to 631 N/mm² when the tests were not accompanied by compressive stresses ($\sigma_c = 0$) and 461 N/mm² when $\sigma_c = 0,90$ N/mm². Similar results were obtained in the case of the effect of the compressive stress σ_c on the increase of shear stress τ_u and the accompanying deformation angles θ_u at the maximum force inducing vertical displacements of masonry specimens obtained in tests.

1. Introduction

Vertical displacements of masonry walls may result from the displacements of adjacent structural members, most often deflections of floors on which walls were erected, as well as movements of foundations [1-5]. The displacements of structures supporting or adjacent to the load-bearing or non-



load-bearing masonry walls may result from improper preparation of subsoil, for example inadequate or uneven subsoil compaction, changes in groundwater conditions connected with land drainage or additional drainage as a result of deep excavation in the vicinity, swelling or subsoil contraction caused by vegetation, washing subsoil away due to failure of plumbing or rainwater system, loss of ground stability, additional ground subsidence caused by the construction of buildings next to the existing buildings, compaction of subsoil and increased loads due to vehicle traffic and continuous or discontinuous deformations of the ground caused by mining exploitation.

Investigations of masonry walls subjected to vertical displacements have been conducted in the Department of Building Structures of the Silesian University of Technology for over 20 years. The results of the tests are presented, among others, in [6-14].

2. Materials, specimens and tests program

2.1. Materials

Masonry specimens were made of solid clay brick and blocks made of autoclaved aerated concrete with a tongue and groove. The mean compressive strength of bricks determined on whole bricks f_B was 28.8 N/mm² (coefficient of variation $\nu = 6.4\%$), the compressive strength examined on cylindrical cores 60 mm in diameter and 120 mm high cut from bricks was 23.2 N/mm² ($\nu = 5.8\%$). The normalized compressive strength of bricks f_b determined according to PN-EN 772-1 [15] on the basis of tests of whole masonry units was equal to 23.3 N/mm². The nominal length of the AAC blocks was 624 mm, the nominal width was 240 mm, while the nominal height was 249 mm. Mean compressive strength of AAC blocks determined on six whole blocks was 3.05 N/mm² ($\nu = 5.9\%$), while the mean strength determined in accordance with standard [15] based on tests of samples cut from blocks was equal to 2.66 N/mm² ($\nu = 8.0\%$). The normalized compressive strength of AAC blocks f_b was 3.11 N/mm².

In specimens made of solid clay brick, cement-lime mortar with a cement:lime:sand ratio 1:1:6 by volume was used, that is mortar type F class M5 according to PN-B-10104 [16] standard and Polish National Annex to PN-EN 1996-1-1 standard [17]. The mean compressive strength tested on halves of samples obtained from flexural strength tests in accordance with PN-EN 1015-11 [18] was equal 9.47 N/mm² ($\nu = 10.0\%$). Compressive strength of this mortar tested on cylindrical samples with a diameter of 60 mm and a height of 120 mm was 7.03 N/mm² ($\nu = 7.2\%$). In masonry specimens made of AAC blocks system mortar for thin joints was used with mean compressive strength tested according to [18] standard equal to 18.8 N/mm² ($\nu = 9.0\%$).

2.2. Specimens

The masonry specimens made of solid clay brick had a total length of approximately 1290 mm, a height of about 1415 mm and a thickness of 250 mm. The bed and head joints had a nominal thickness of 10 mm (figure 1a). The specimens made of AAC blocks had a total length of about 1250 mm, a height of approximately 1510 mm, a thickness of 240 mm (figure 1b), thin 3 mm bed joints and unfilled head joints.

2.3. Tests program

The specimens were tested with the accompanying compressive stresses σ_c normal to the bed joints plane and without compression ($\sigma_c = 0$). In the case of specimens made of solid clay brick, two walls were tested without participation of σ_c and also two compressed with stresses of 0.3, 0.6, 0.9 and 1.5 N/m². In total 10 specimens made of solid clay brick were investigated. In the case of AAC blocks masonry, a total of 5 specimens were tested, i.e. 3 without compressive stresses and 2 with participation of σ_c stress equal to 0.9 N/mm². Specimens were marked as N-XX/Y or SN-XX/Y, where N represents solid clay bricks masonry and SN AAC blocks specimens, XX indicate the value of compressive stresses σ_c (XX = 00, 03, 06, 09 and 15) and Y is the number of specimen (Y = 1, 2 or 3).

a)

b)

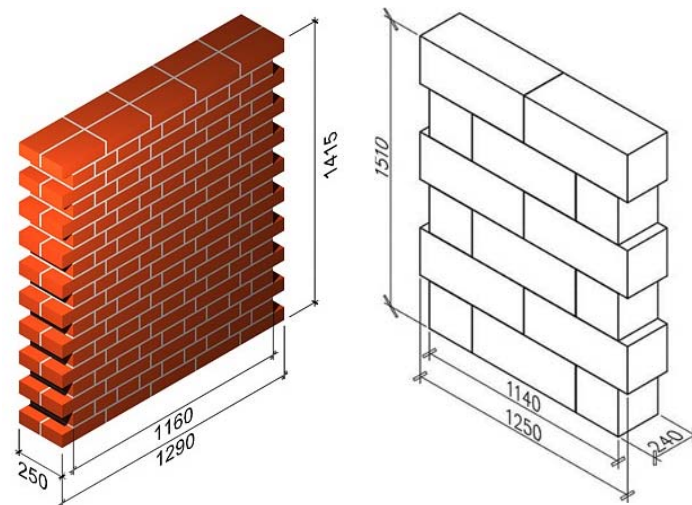


Figure 1. Specimens made of: a) solid clay bricks, b) AAC blocks

3. Test stand and testing procedure

3.1. Test stand

The steel test stand shown in figure 2 was specially designed and constructed for testing of masonry walls subjected to simultaneous vertical displacements and compressed. Specimens were monolithised with the external and central column using aggregate concrete. The vertical displacements were induced by force F by means of hydraulic jack with range up to 3000 kN and transmitted to the wall via the central column. The vertical reaction R was transferred to the external column and further to the laboratory floor. The horizontal reactions S were transmitted by means of two ties to a special retaining construction and to the second external column and then through steel tension members to the laboratory floor. The vertical compressive stress σ_c were generated by means of four pairs of steel rods with a diameter of 45 mm tensed by the force N_c . The force from the rods was transferred to the specimen via steel springs whose function was to compensate masonry displacements during the tests, so that they do not affect the value of compressive stress σ_c . The stress σ_c was introduced into the specimen monolithised with test stand at the F and S forces equal to zero.

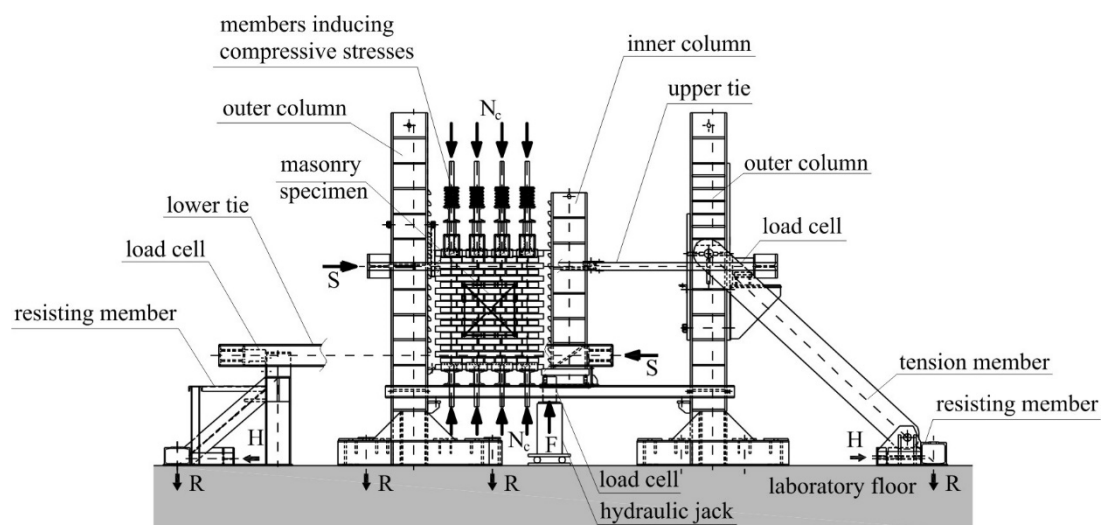


Figure 2. Test stand

3.2. Testing procedure

The static scheme of the test is shown in figure 3. In the middle part of the wall, beyond the external areas (close to the edges of specimen), where the distribution of stresses is very uneven, the configuration of vertical stress σ_y , horizontal stress σ_x and tangential stress τ similar to that shown in figure 3b can be assumed.

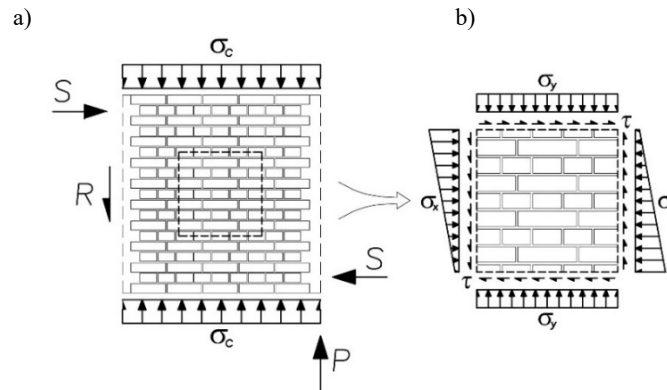


Figure 3. Static scheme of: a) loads of masonry specimen, b) stresses in the central part of the wall

Deformations of the wall represented by deformation angles θ (figure 4b) were determined based on changes in the length of the measurement bases in the form frame shown in figure 4a. Measurement frames with a side length of 600 mm were fixed to both surfaces of each specimen. The measuring bases were equipped with a total of 12 displacements transducers with a reading accuracy of 0.002 mm.

The tests were carried out with the control of force F pushing the central column in one cycle until failure. A situation where it was impossible to achieve a higher value of force F was accepted as a moment of failure of masonry specimen.

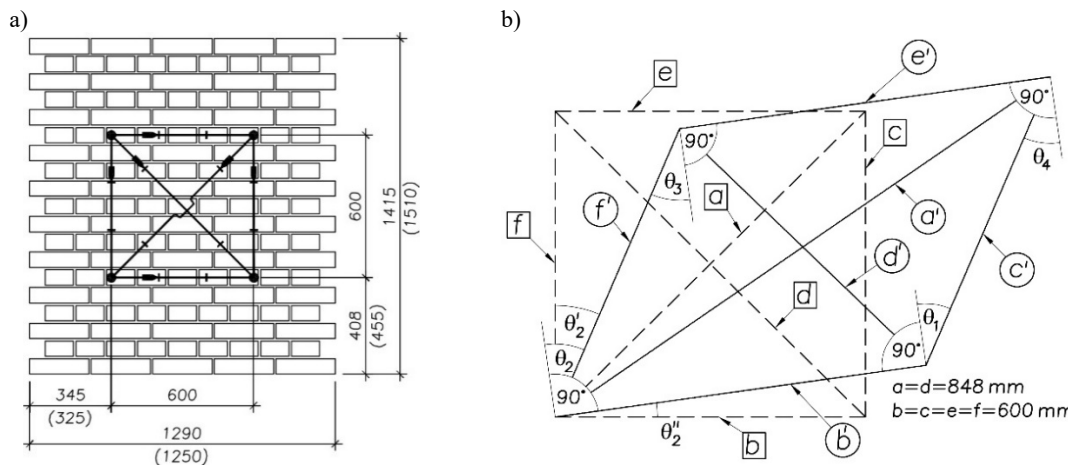


Figure 4. Scheme of: a) arrangement of measurement bases and displacements transducers (in brackets dimensions for AAC blocks specimens), b) determining the deformation angles θ

4. Test results and discussion

Table 1 presents partial test results, i.e. mean values of shear stresses at which the walls were cracked $\tau_{cr,mv}$, mean ultimate shear stresses $\tau_{u,mv}$ and accompanying stresses τ_{cr} mean values of deformation angles $\theta_{cr,mv}$. Averaged shear stresses were determined by dividing the appropriate values of F_{cr} and F_u

forces by the area of vertical cross-section of specimens equal to 0.354 m² for clay brick specimens and 0.362 m² for specimens made of AAC blocks.

Table 2 presents the ratios of mean values of shear stresses accompanying the cracking of specimens tested with participation of compressive stresses to shear stresses obtained in the case of specimens, where $\sigma_c = 0$ ($\tau_{cr,mv,\sigma}/\tau_{cr,mv,0}$). Similarly, the ratios of mean deformation angles ($\theta_{cr,mv,\sigma}/\theta_{cr,mv,0}$) and mean values ultimate shear stresses ($\tau_{u,mv,\sigma}/\tau_{u,mv,0}$) are summarized. Additionally, the ratios of mean ultimate shear stresses to mean shear stresses accompanying the occurrence of cracks ($\tau_{u,mv}/\tau_{cr,mv}$) at individual values of compressive stress σ_c are presented.

Table 1. Partial results of tests

Specimen	σ_c N/mm ²	$\tau_{cr,mv}$ N/mm ²	$\tau_{u,mv}$ N/mm ²	$\theta_{cr,mv}$ mm/m
1	2	3	4	5
Solid clay brick masonry				
N-00	0	0.58	0.66	0.361
N-03	0.3	0.80	0.94	0.480
N-06	0.6	0.92	1.21	0.560
N-09	0.9	1.10	1.37	0.629
N-15	1.5	1.30	1.70	0.876
AAC blocks masonry				
SN-00	0	0.15	0.18	0.247
SN-09	0.9	0.33	0.52	0.731

Table 2. Comparison of tests results

Specimen	σ_c N/mm ²	$\tau_{cr,mv,\sigma}/\tau_{cr,mv,0}$	$\theta_{cr,mv,\sigma}/\theta_{cr,mv,0}$	$\tau_{u,mv,\sigma}/\tau_{u,mv,0}$	$\tau_{u,mv}/\tau_{cr,mv}$
1	2	3	4	5	6
Solid clay brick masonry					
N-00	0	1.00	1.00	1.00	1.14
N-03	0.3	1.38	1.33	1.42	1.18
N-06	0.6	1.59	1.55	1.83	1.32
N-09	0.9	1.90	1.74	2.08	1.25
N-15	1.5	2.24	2.42	2.58	1.31
AAC blocks masonry					
SN-00	0	1.00	1.00	1.00	1.20
SN-09	0.9	2.20	2.96	2.89	1.58

Figure 5 shows the relation between shear stress τ_i and deformation angles θ_i . These dependencies can be considered linear in the range shear stresses from 0 to τ_{cr} . After diagonal cracking, especially in the case of heavily compressed specimens, the plastic nature of these relations is revealed, where the increment of the deformation angles θ_i is much faster than the stress τ_i increase. After cracking, there is also visible phenomenon of hardening of masonry, the degree of which expressed by the ratio $\tau_{u,mv}/\tau_{cr,mv}$ depends on the value of compressive stresses accompanying the vertical displacements of specimen edge. In the case of the tested masonry without compression, the hardening degree, i.e. the stress ratio $\tau_{u,mv}/\tau_{cr,mv}$, was 1.14 for clay brick specimens and 1.20 for specimens made of AAC blocks (Table 2, column 6). The degree of hardening in the case of masonry made of AAC blocks tested with the compressive stress $\sigma_c = 0.9$ N/mm² increased to 1.58, while for clay brick specimens the ratio $\tau_{u,mv}/\tau_{cr,mv}$ increased to 1.32 when the tests were accompanied by compressive stresses values of 0.6 N/mm², while at higher compressive stresses there was no further increase in the degree of hardening.

Compressive stresses σ_c influenced the values of the mean shear stresses accompanying the cracking $\tau_{cr,mv}$ and mean ultimate stresses $\tau_{u,mv}$ and the mean values of deformation angles

accompanying the cracking of masonry $\theta_{cr,mv}$, which is clearly evident from the graphs shown in figure 5 and the test results summarized in tables 1 and 2 (columns 3, 4 and 5). The higher compressive stresses σ_c accompanied the vertical displacement of the edge of specimen, the higher the stresses $\tau_{cr,mv}$, $\tau_{u,mv}$ and angles $\theta_{cr,mv}$ were obtained.

In the case of clay brick specimens, when compressive stress σ_c was equal to 1.5 N/mm^2 , the mean shear stress at cracking $\tau_{cr,mv}$ was obtained 2.24 times greater, mean deformation angle $\theta_{cr,mv}$ was 2.42 times higher and mean ultimate shear stress $\tau_{u,mv}$ was 2.58 times greater than for specimens tested without compression. In the case of masonry made of AAC blocks testes with compressive stress equal to 0.9 N/mm^2 , the mean stress $\tau_{cr,mv}$ was 2.20 times higher, mean angle $\theta_{cr,mv}$ was 2.96 times greater and mean stress $\tau_{u,mv}$ was 2.89 times higher than for specimens tested with $\sigma_c = 0$.

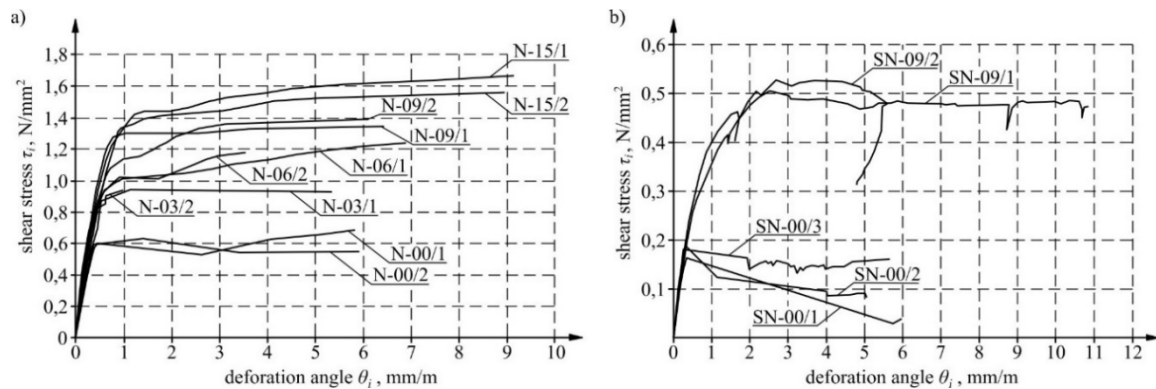


Figure 5. Relationship between shear stresses and deformation angles obtained for: a) masonry made of clay bricks, b) masonry made of AAC blocks

According to the theoretical description of the shear walls, accepted by Müller and Mann – described in [19], [20] and [21] – the state of stresses occurring at the interface between masonry unit and mortar joints is analysed. Then, a repetitive fragment of the masonry is mentally cut out with a height of $2y$ and a width of $2x$, which is affected by shear stress τ and normal to the plane of the bed joints σ_y . In accordance with the authors of the papers [8] and [22], such separated fragment of wall is additionally influenced by shear stress $\Delta\tau$, which value depend on the external stress normal to the plane perpendicular to the bed joints σ_x and $\nu\sigma_y$ stress resulting from the confinement of lateral masonry deformations (see equation (5)). Simplifying the present state of stress, it is assumed that there is no contact between the vertical head face of masonry units and mortar in head joints, which means that the stresses are transmitted only through the bed joints of masonry.

There are four stress ranges differing in the observed cracking mechanism depending on the value of compressive stress σ_c . At low stress σ_c the adhesion between the masonry unit and mortar may break due to tension (line “1” in figure 6 and figure 7, equation (1)). With a slightly higher compressive stress, the adhesion between masonry unit and mortar joint can be broken due to shearing (line “2” in figure 6 and figure 7, equation (2)). If the stress σ_c is greater, the cracking will occur when the masonry units tension strength is exceeded by the principal stress (curve “3” in figure 6 and figure 7, equation (3)). With very high compressive stress, mainly vertical cracks are formed passing through masonry units, related to the masonry failure due to compression (line 4” in figure 6, equation (4)).

Line „1”

$$\tau = (f_t + \sigma_c) \frac{x}{2y} + \Delta\tau. \quad (1)$$

Line „2”

$$\tau = (f_v + \mu\sigma_c) \frac{1}{1 + \mu \frac{2y}{x}} + \Delta\tau. \quad (2)$$

Curve „3”

$$\tau = \frac{f_{tb}}{\alpha} \sqrt{1 + \frac{\sigma_c}{f_{tb}} + (\sigma_x + \nu \sigma_c) \left(\frac{1}{f_{tb}} + \frac{\sigma_c}{f_{tb}^2} \right)}. \quad (3)$$

Line „4”

$$\tau = (f_b - \sigma_c) \frac{x}{2y} + \Delta\tau. \quad (4)$$

Additional shear stress $\Delta\tau$

$$\Delta\tau = (\sigma_x - \nu \sigma_c) \frac{2y}{x}. \quad (5)$$

where: f_t – adhesion between masonry unit and mortar due to tension (assumed f_{xk1} according to table. NA.8 in [17]),

μ – coefficient of friction ($\mu = 0,4$ according to NA.4.1 in [17]),

x – length of the masonry unit,

y – height of the masonry unit,

f_v – adhesion between masonry unit and mortar due to shearing (assumed f_{vk0} according to table NA.6 in [17]),

f_b – compressive strength of masonry unit (minimum strength was assumed for a given strength class declared by the manufacturer; $f_b = 20 \text{ N/mm}^2$ for clay brick and $f_b = 3 \text{ N/mm}^2$ for AAC blocks),

f_{bt} – tensile strength of masonry units (assumed $f_b = 0.035f_b$),

σ_x – compressive stress normal to the plane perpendicular to the bed joints,

α – factor taking into account the influence of the shape of masonry units on the value of maximum shear stress (assumed $\alpha = 2$ for clay bricks and $\alpha = 2,5$ for AAC blocks),

ν – the masonry Poisson's ratio (assumed $\nu = 0,2$).

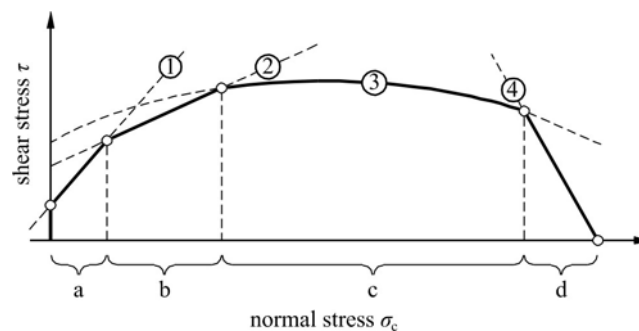


Figure 6. The Müller-Mann criterion modified by the influence of compressive normal stresses σ_x

Figure 7 shows the results of tests, that is the shear stress accompanying the appearance of cracks τ_{cr} (red and blue dots) depending on the stress value σ_c , which mean values are summarized in table 1. In figure 7 the cracking criterion lines described by the equations (1), (2) and (3) are also plotted. Criterion lines were determined based on strength classes of masonry units and mortar, tensile strength of masonry units assumed as 3.5% of compressive strength of clay bricks and AAC blocks and characteristic values of masonry mechanical parameters according to PN-EN 1996-1-1 [17]. The test results demonstrate higher shear stress values τ_{cr} than the cracking criterion lines, which leads to the conclusion that criterion lines sufficiently well describe the relationship τ - σ . It can be assumed that if the mechanical parameters of masonry based on which the cracking criterion lines were determined resulted from laboratory tests, then the conformity of the test results (values of τ_{cr} stresses) with

criterion lines would be better. It should also be noticed that in the case of masonry made of AAC blocks in the compressive stress range from 0 to 1.5 N/mm², only one curve describes the cracking criterion, i.e. curve “3” as evidenced by the cracking pattern of specimens showed in figure 8e and 8f.

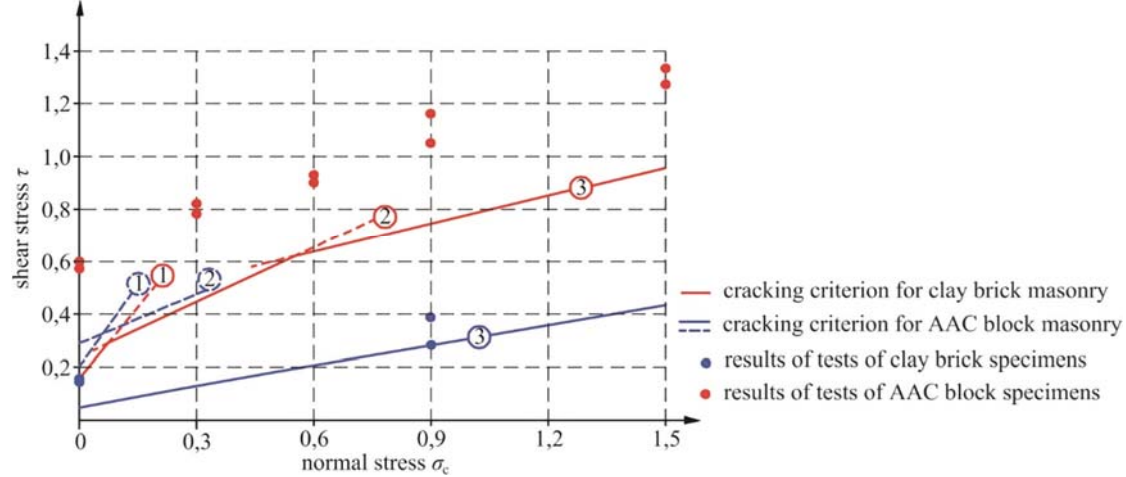


Figure 7. Tests results and the corresponding modified Müller-Mann criterion

Figure 8 shows the cracking pattern of specimens made of solid clay bricks and AAC blocks tested at different values of accompanying compressive stress σ_c . Cracking patterns correspond to the mechanism of cracking described above by formulas (1) to (5). In the case of specimens made of clay bricks at low σ_c values, most of the cracks passed through the head and bed joints of the masonry (figures 8a and 8b). When $\sigma_c = 0.9$ N/mm² and 1.5 N/mm² (figures 8c and 8d) almost all cracks passed through the masonry units. In the case of specimens made of AAC blocks, the cracking mechanism describes the curve “3” (see figure 7 – blue continuous line) in indeed the cracks passed through the masonry units, which was determined by the low tensile strength of AAC blocks. At the compressive stress equal to 0.9 N/mm² much more cracks were observed and cracks had a more vertical course. Locally the spalling of masonry units surface was observed, as well.

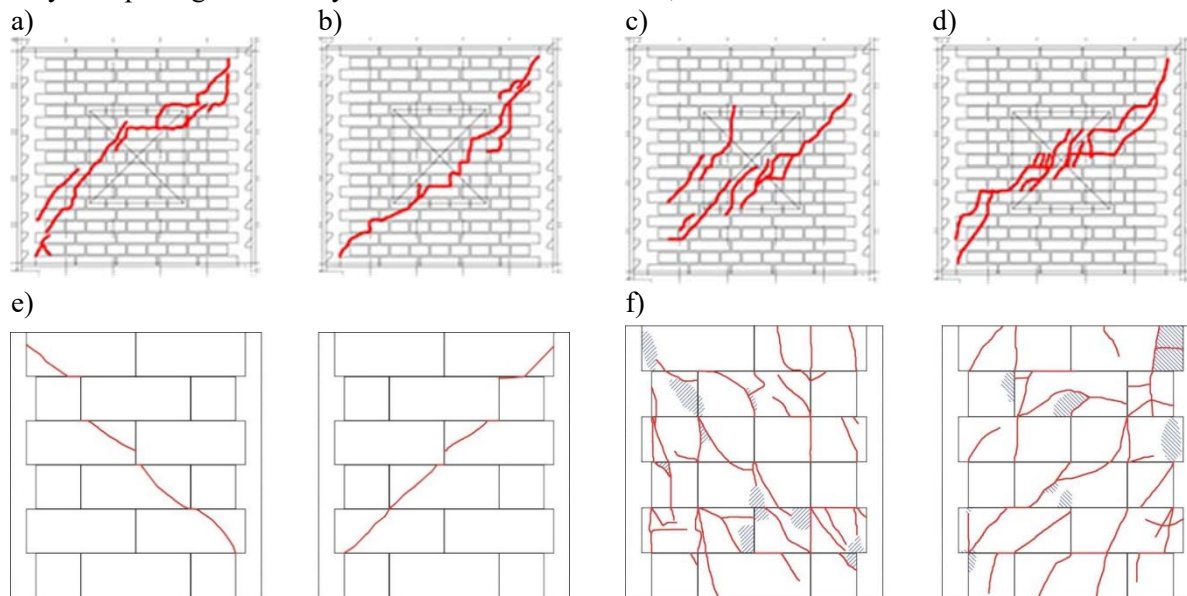


Figure 8. Cracking pattern of masonry subjected to vertical displacements made of clay brick with the participation of compressive stress with the following values: a) 0, b) 0.3 N/mm², c) 0.9 N/mm², d) 1.5 N/mm² and made of AAC blocks at stress σ_c equal to: e) 0 and f) 0.9 N/mm²

5. Conclusions

Based on the results of experimental research and theoretical analysis of masonry walls made of clay bricks and AAC blocks subjected to vertical displacements with simultaneous compression in the direction perpendicular to the masonry bed joints for a given number of specimens and the accepted range of compressive stress σ_c , the following conclusions can be drawn:

- compressive stress σ_c has a positive effect on values of shear stress τ_{cr} occurring at the moment of masonry cracking; the mean shear stress $\tau_{cr,mv}$ with a compressive stress of 1.5 N/mm² was 2.24 times higher for clay bricks masonry and 2.20 times higher for masonry made of AAC blocks than the mean stress $\tau_{cr,mv}$, when $\sigma_c = 0$,
- stress σ_c influenced the values of the ultimate shear stresses τ_u obtained in the tests; the greater the compression accompanied the vertical displacements of the masonry, the greater shear stress τ_u obtained; $\tau_{u,mv}$ stress at $\sigma_c = 1.5$ N/mm² was 2.58 times higher in the case of clay bricks masonry than at σ_c equal to 0, while for the specimens made of AAC blocks at $\sigma_c = 0.9$ N/mm² mean value of ultimate shear stress was 2.89 times higher than for masonry tested without compression,
- deformation angles occurring at the moment of cracking of masonry θ_{cr} were the higher the greater was compressive stress σ_c ; in the case of clay bricks, the mean angle $\theta_{cr,mv}$ at $\sigma_c = 1.5$ N/mm² was 2.42 times higher than at $\sigma_c = 0$, while for AAC blocks specimens at $\sigma_c = 0.9$ N/mm² mean deformation angle $\theta_{cr,mv}$ was 2.96 times higher than in the case of specimens tested without compression,
- compressive stress also changes the nature of the τ - θ relationship, at low values of σ_c equal to 0 or 0.3 N/mm², the masonry behaved like a brittle material and the mean ultimate shear stress $\tau_{u,mv}$ was not much higher than the mean shear stress occurring at the moment of masonry cracking $\tau_{cr,mv}$, in the case of clay bricks masonry, at $\sigma_c = 0$ the ratio $\tau_{u,mv}/\tau_{cr,mv}$ was 1.14, while for the masonry made of AAC blocks $\tau_{u,mv}/\tau_{cr,mv} = 1.20$; at high compressive stresses the more plastic nature of the masonry was revealed and there was observed a significant hardening effect of masonry after cracking, where the degree of hardening expressed by the ratio $\tau_{u,mv}/\tau_{cr,mv}$ at the compressive stress $\sigma_c = 1.5$ N/mm² in the case of clay bricks masonry was equal to 1.31 and for specimens made of AAC blocks at $\sigma_c = 0.9$ N/mm² the degree of hardening equal to 1.58 was obtained.

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