INFLUENCE OF LOAD DIRECTION ON BEHAVIOUR AND MECHANICAL PARAMETERS OF CLAY-BRICK MASONRY WALLS UNDER CYCLIC COMPRESSION

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Abstract
The results of laboratory tests of masonry wallettes subjected to cyclic compression normal and parallel to bed joints are presented in this paper. The influence of the direction of loading on the $\sigma = \sigma(\varepsilon)$ relationship and basic mechanical parameters was analysed. The paper also describes the modes of failure of the tested elements.

Streszczenie
Artykuł przedstawia wyniki badań laboratoryjnych ścian murowanych poddanych cyklicznemu ściskaniu w kierunku prostopadłym i równoległym do spoin wspornych. Analizie poddano wpływ kierunku obciążenia na zależność $\sigma = \sigma(\varepsilon)$ oraz podstawowe właściwości mechaniczne. Artykuł przedstawia również postaci zniszczenia analizowanych elementów.

Keywords: **Brick masonry; Cyclic loading; Uniaxial compression tests.**

1. INTRODUCTION

Because of the material anisotropy, behaviour of masonry structures subjected to cyclic or dynamic loading depends strongly on the direction of the acting load with respect to the bed joints. In the analyses of the loaded structures the horizontal component of the dynamic load is usually very important. That is why it is crucial that mechanical parameters applied in calculations are determined for a direction of load both normal and parallel to the bed joints. This issue has already been discussed for monotonic static loads in e.g. [1, 2]. In addition to the load direction the load type is also an important factor determining the behaviour of the masonry. The main load types are: instantaneous – applied and acting in one cycle, dynamic and statically cyclic. This kind of research has been performed worldwide for many years, however, the results are unequivocal. The first to publish the results were *Abrams* et al. [3] who presented that the ultimate force in cyclic compression is 30% lower compared to static loading. *Oliveira* at al., *Al Schebani and Sinha*, *Senthivel and Sinha* [4-6] investigated strains of brick masonry walls under uniaxial cyclic load. The envelope of cyclic loading which they obtained in the tests was similar to the envelope obtained from monotonic loading tests. The problem of cyclic loading was discussed also by *Ciesielski*, e.g. in [7].

The influence of the direction (vertical, horizontal) and type (monotonic, cyclic) of loading on the modulus of elasticity is also an interesting and extremely important issue. Although there are results of the modulus of elasticity determined in the direction different from normal to the bed joints [2, 8-11], no comparison has been made between the values of the modulus of elasticity determined in cyclic and single-cycle tests. In the majority of the tests it has been shown that the modulus of elasticity of masonry walls compressed in the direction parallel to the bed joints (E_x) is about

70% of the value of the modulus of elasticity in compression normal to the bed joints (E_y).

The results of these tests do not comply and often are even in contradiction to one another. Currently, there are no standards concerning testing of masonry walls subjected to cyclic compression, neither static nor dynamic. The knowledge of the behaviour of masonry under such type of loading would allow better understanding of the processes taking place in masonry walls and, as a consequence, the occurring damages. The lack of unambiguous and direct recommendations for the assumption of mechanical parameters of masonry subjected to cyclic loading encourages deeper insight to and further investigation into this issue.

2. LABORATORY TESTS

In order to determine the behaviour and mechanical characteristics of masonry under cyclic loading and describe the influence of the type of loading on material degradation mode, experimental tests on 12 masonry wall specimens were carried out. Two test specimens, which differ in shape and overall dimensions (see Fig. 1), were used.

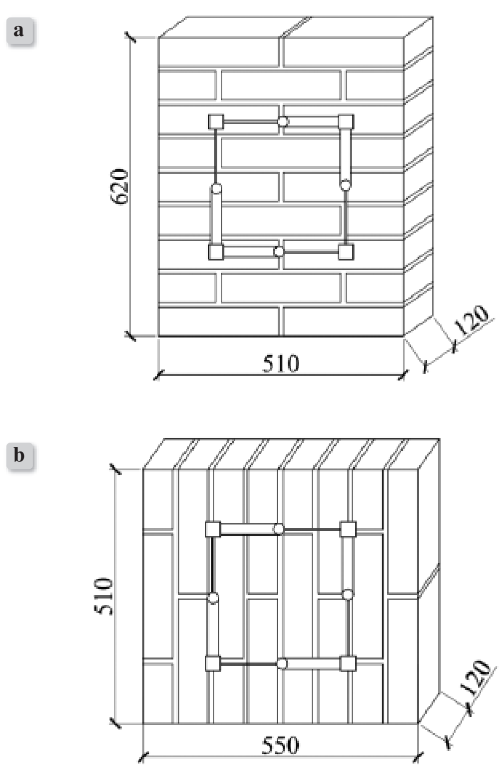

Figure 1.
Shape and overall dimensions of test specimens [mm]: a) model CV type; b) model CH type

The experimental investigations were performed on two types of test specimens made of clay brick of class "15" (f_b = 18.7 N/mm^2) and cement-lime mortar (1 : 1 : 6) class M5 (f_m = 6.8 N/mm^2). Material tests were performed to determine the mechanical properties of brick and mortar used in the research, as well as to control the homogeneity of the components used.

Elements of **CV** type were used to determine the compressive strength of masonry according to the method given in EN 1052-1:2001 [12]. In total there were tested: 6 specimens of **CV** type and 6 specimens of **CH** type. Masonry wallettes **CV** were subjected to axially compressive loads in direction normal to the bed joints, whereas models **CH** were compressed parallel to the bed joints. Three specimens of series **CV** and **CH** (reference specimens) were loaded statically in one cycle (indicated by "d") whereas the rest of the specimens were subjected to compressive cyclic loads (indicated by "c"). All specimens were built by qualified bricklayers.

On both sides of each wall a set of displacement measuring sensors was attached after locating the wallette in the testing machine (with range from 0 up to 6000 kN) – as in Fig. 2. The accuracy of these inductive sensors was 0.002 mm. To eliminate friction between the masonry specimens and the machine head a separator made of teflon (10 mm thick) was introduced.

Masonry walls, except for three series, were subjected to compressive cyclic loads. In the case of the elements of CV and CH types (specimens – prepared and tested in accordance to EN 1052-1 regulations) the first level of loading was 50 kN and in every following cycle it was increased by 50 kN. The loading speed was ca. 2 kN/s. During each cycle the loading was sustained for ca. 2-3 minutes and then the specimen was unloaded. The loading history for cyclically compressed masonry is graphically presented in Fig. 3.

3. TEST RESULTS

The main results of the presented investigations comprised values of cracking stresses σ_{cr}, ultimate stresses σ_u, corresponding strains ε_{cr} and ε_u, and the value of the instantaneous modulus of elasticity E; they are presented in Table 1. In column 8 the correlation between σ_{cr} and σ_u stresses and number of cycles up to failure for each tested specimen is shown. No visible difference between the values of the ultimate stresses of monotonically and cyclically loaded specimens was observed. The value of the modulus of elas-

Figure 2.
The masonry wallette type CV (a) and CH (b) with displacement measuring system – machine ready for testing

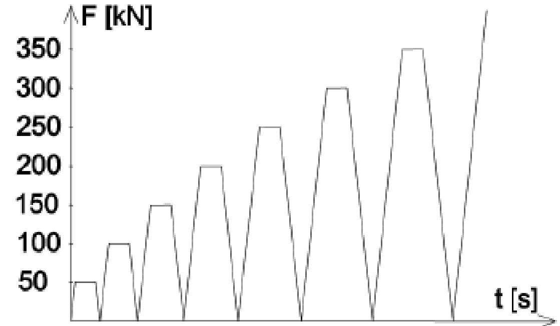

Figure 3.
Loading history diagram

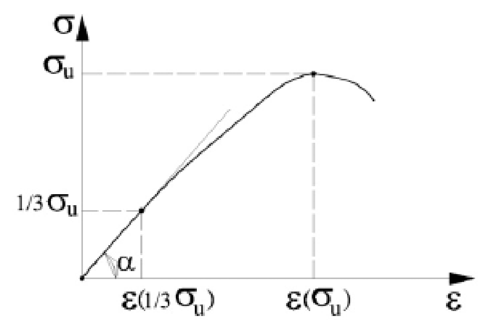

Figure 4.
Designation scheme the value of the modulus of elasticity

ticity (E) – basic material property, necessary for calculations of masonry structures – was determined as tangent of the inclination angle of the secant line of $\sigma(\varepsilon)$ relationship from $\sigma = 0$ to $\sigma = 0.33\sigma_u$, as shown in the scheme in Fig. 4.

Table 1.
Main results of investigations

Test specimen			σ_{cr} [N/mm^2]	σ_u [N/mm^2]	$\sigma_{u,mean}$ [N/mm^2]	ε_{cr} [$\times 10^{-3}$]	ε_u [$\times 10^{-3}$]	σ_{cr}/σ_u	E [MPa]	Number of cycles
direction of the loading normal to the bed joint	monotonic loading	CV-d-1	6.83	13.14	14.01	1.02	2.61	0.52	8182	1
		CV-d-2	7.31	14.92		0.93	2.54	0.49	7460	1
		CV-d-3	6.98	13.98		0.93	2.63	0.50	7208	1
	cyclic loading	CV-c-1	6.52	12.48	12.97	0.93	2.89	0.52	7627	16
		CV-c-2	7.34	14.57		1.04	3.29	0.50	7285	18
		CV-c-3	7.11	11.85		1.17	2.91	0.60	5751	15
direction of the loading parallel to the bed joint	monotonic loading	CH-d-1	2.67	11.49	12.15	0.35	2.41	0.23	7022	1
		CH-d-2	2.51	11.69		0.34	2.76	0.21	7014	1
		CH-d-3	2.72	13.26		0.34	2.54	0.21	7544	1
	cyclic loading	CH-c-1	2.39	11.11	11.64	0.49	3.34	0.22	4641	16
		CH-c-2	2.87	13.86		0.36	3.35	0.21	7498	18
		CH-c-3	2.28	9.94		0.47	3.69	0.23	4824	14

The first cracks in the elements compressed in the direction normal to the bed joints (**CV** type) appeared at the stress level σ_{cr} = 6.52-7.34 MPa. The ultimate stress σ_u of all the elements loaded in such manner (including monotonically loaded specimens) was similar and reached up to 11.85-14.92 MPa. It is worth mentioning that despite the difference in values of cracking stress σ_{cr} and ultimate stress σ_u between the specimens, the ratio of these stresses was very similar (0.49-0.60). Similar situation was observed in masonry walls loaded in the direction parallel to the bed joints. The ratio between the cracking stress σ_{cr} and the ultimate stress σ_u was also similar (0.21-0.23), although it was less than half the ratio obtained for compression in the direction normal to the bed joint.

As expected, the maximum value of the modulus of elasticity was reported in the masonry walls monotonically loaded in the direction normal to the bed joints (**CV-d** series, 7208-8182 MPa). When cyclic loading was applied, the value of the modulus of elasticity was reduced (**CV-c** series, 5751-7627 MPa). The influence of the loading scheme (cyclic or monotonic) was more pronounced in the masonry walls compressed parallel to the bed joints (**CH** series). The values of the modulus of elasticity in these tests decreased from 7014-7544 MPa to 4641-7498 MPa for masonry tested in one cycle (**CH-d** series) in comparison to the cyclically loaded walls (**CH-c** series).

The mean values of the cracking stress $\sigma_{cr,mean}$, ultimate stress $\sigma_{u,mean}$ and ultimate strain $\varepsilon_{u,mean}$ for each series of masonry walls are presented in Table 2.

Table 2.
Mean values of mechanical parameters from tests

series	σ_{cr} [N/mm^2]	$\sigma_{u,mean}$ [N/mm^2]	ε_{cr} [$\times 10^{-3}$]	$\varepsilon_{u,mean}$ [$\times 10^{-3}$]
CV	7.02	13.49	1.00	2.81
CH	2.57	11.89	0.39	3.02

The values of the mean ultimate stress $\sigma_{u,mean}$ of the specimens loaded in the direction normal and parallel to the bed joints do not significantly differ and their ratio is equal to:

$$\frac{\sigma_{u,mean,\mathrm{CV}}}{\sigma_{u,mean,\mathrm{CH}}} = 1.13 \quad (1)$$

These results differ from the results presented in [11] where the ratio of these two values was less than 1. On the other hand, other tests of masonry walls made of cellular concrete blocks [2] showed that the compressive strength of masonry loaded in the direction normal to the bed joints is by 30% higher than for masonry walls loaded in the direction parallel to the bed joints.

Huge differences were observed in case of the cracking stresses. Masonry walls compressed in the direction parallel to the bed joints cracked at the stress level of about 1/3 of cracking stress determined for masonry walls compressed in the direction normal to the bed joints:

$$\frac{\sigma_{cr,mean,\mathrm{CV}}}{\sigma_{cr,mean,\mathrm{CH}}} = 2.72 \quad (2)$$

Mean values of the instantaneous modulus of elasticity, depending on the loading scheme (monotonic, cyclic) and direction of the loading force (normal, parallel to the bed joint), are collectively presented in Table 3.

Table 3.
Mean value of the modulus of elasticity

the loading history	CV	CH
one cycle	$E_{y,d}$ = 7617 MPa	$E_{x,d}$ = 7193 MPa
many cycles	$E_{y,c}$ = 6887 MPa	$E_{x,c}$ = 5654 MPa

The value of the modulus of elasticity of masonry compressed in the direction parallel to the bed joints (E_x) was lower than the value of the modulus of elasticity of walls compressed in the direction normal to the bed joints (E_y), both in case of cyclic and monotonic loading:

$$\frac{E_{x,d}}{E_{y,d}} = 0.94 \quad (3)$$

$$\frac{E_{x,c}}{E_{y,c}} = 0.82 \quad (4)$$

This tendency (E_x/E_y < 1) complies with the reported results [2, 8, 9, 10], although the difference between the values of the moduli of elasticity tested under different directions of loading was higher and their ratio was equal to ca. 0.7 in those tests.

It is also worth to analyse the influence of the loading scheme. The obtained ratios between the moduli of elasticity under instantaneous and cyclic loading were equal to, respectively:

$$\frac{E_{y,c}}{E_{y,d}} = 0.90 \tag{5}$$

$$\frac{E_{x,c}}{E_{x,d}} = 0.79 \tag{6}$$

Modulus of elasticity of cyclically compressed masonry walls was equal to 90% of the value of the instantaneous modulus of elasticity when the direction of loading was normal to the bed joints and 79% when the direction of loading was parallel to the joints.

Typical stress-strain hysteresis determined for cyclic loading of specimens of **CV** and **CH** types is presented in Fig. 5. A significant influence of loading direction is observed. The degradation process in case of loading in parallel direction is, as expected, more significant. Unfortunately, the loading devices at the laboratory (force-controlled hydraulic test machine) did not allow to obtain the falling branches of σ-ε relationships. However, linking together the points of maximal stresses, the envelope curves (see Fig. 6 and Fig. 7) were obtained and it can be noticed that they have significantly non-linear shape.

In Fig. 6 and Fig. 7 yellow, orange and red lines represent the specimens loaded statically in one cycle. In case of models loaded in the direction normal to bed joints all envelopes of σ-ε curves are located below the curve depicting the relationship determined in a single-cycle test. For **CH** type specimens results for one wallette are above such lines (see Fig.7).

The comparison of the envelope of σ-ε curves (average relationships determined for all models of each series) of small specimens (**CV** and **CH** types) for both directions of cyclic loading is shown in Fig. 8. The significantly greater strain deformations (faster stiffness degradation caused by micro-crack appearance) of models loaded parallel to bed joints are observed.

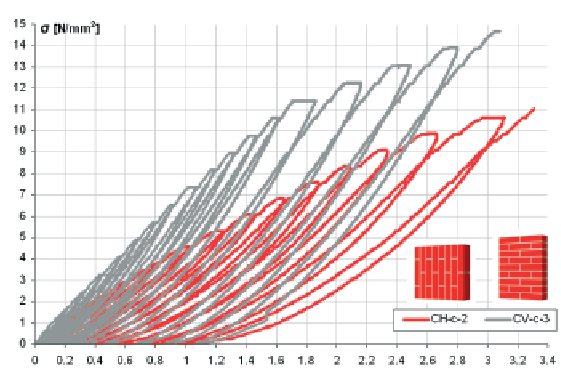

Figure 5.
Typical stress-strain hysteresis of CV and CH type models

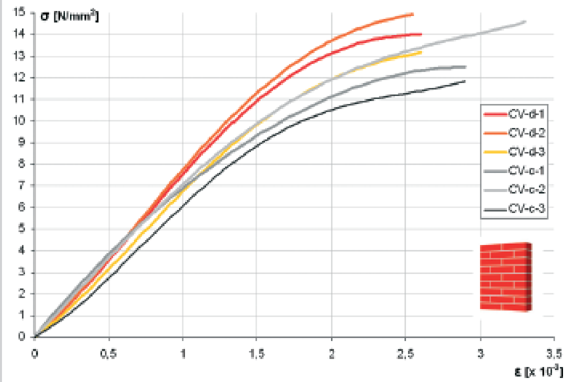

Figure 6.
Envelope of stress-strain curves of CV type models

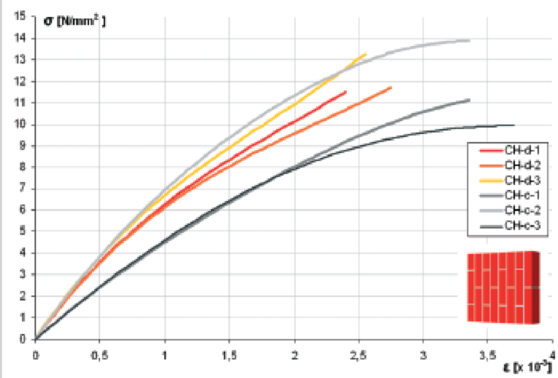

Figure 7.
Envelope of stress-strain curves of CH type models

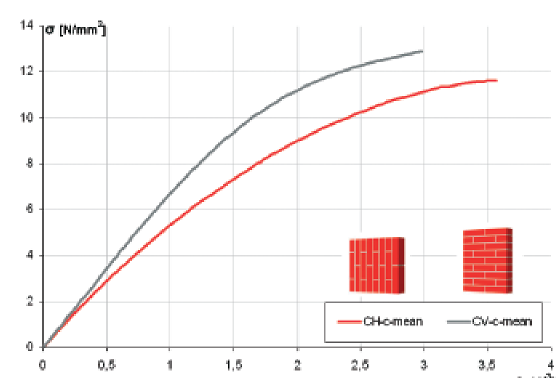

Figure 8.
Comparison of envelope of stress-strain curves for CV and CH specimens

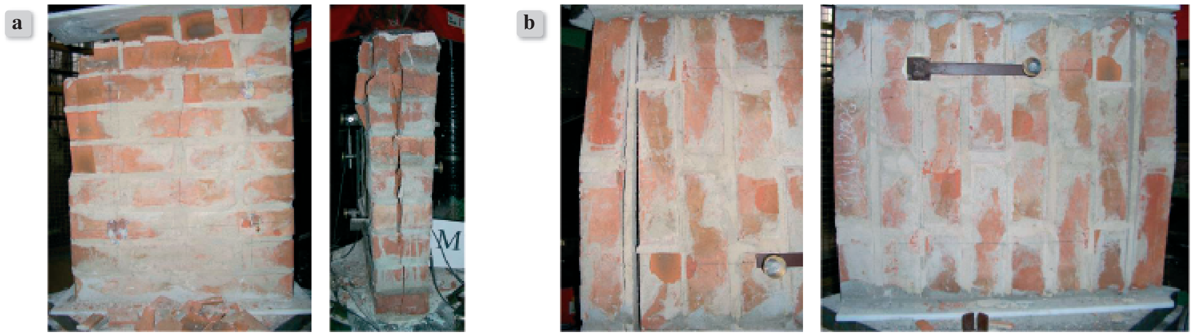

Figure 9.
Failure of a) CV type model b) CH type model

Failure of masonry wallettes loaded in the direction normal to bed joints occurred each time in a similar manner due to formation of vertical cracks and due to occurrence of cracks in the axis of the wall in longitudinal direction (Fig. 9a). The elements loaded in the direction parallel to bed joints fractured by delamination at bed joints (Fig. 9b). No significant difference was observed between the values of the ultimate stresses in the monotonically and cyclically loaded elements.

4. SUMMARY AND CONCLUSIONS

The outcome of the presented results of laboratory experiments carried out on 12 clay brick masonry walls of two types, loaded cyclically normal to the bed joint (models **CV**) and parallel to the bed joints (models **CH**), has revealed the following conclusions:

1. Failure of all tested specimens was brittle with the limited and very similar number of cycles – between 14 and 18 – regardless of shape, overall dimensions and loading direction.
2. A significant influence of loading direction on the stress-strain hysteresis in case of cyclic loading of specimens (**CV** and **CH**) was observed. The degradation process in case of loading in parallel direction was more significant. All envelopes of σ-ε curves for this type of specimens were located below the curve representing the relationship determined in a single-cycle test.
3. Despite visible differences between the values of cracking and ultimate stresses the ratio between these two values was similar.
4. The envelope of the σ-ε curves for the cyclically loaded elements is considerably more non-linear than the envelope for the statically loaded elements.
5. In case of walls loaded parallel to bed joints cracking appears at the stress level of about 20% of ultimate stress while the elements loaded normal to bed joints were cracked under stress level of about 50% of ultimate stress.
6. Masonry walls loaded in the direction parallel to the bed joints were cracked under stress level of 1/3 of the cracking stress of the elements loaded in the direction normal to the bed joints.
7. Direction of loading has an influence on the value of the modulus of elasticity. Masonry walls loaded in the direction parallel to the bed joints had lower values of the modulus of elasticity than the walls loaded in the direction normal to these joints.
8. Cyclically compressed masonry walls had lower values of the modulus of elasticity that the walls tested in a single cycle.
9. Because of the limited number of tested specimens all presented results and comments should be regarded mainly from qualitative point of view. At the moment it is difficult to formulate more general or quantitative conclusions. More test data, especially for other types of masonry units (hollow bricks and blocks) and mortar joints (thin bed joints) are needed.

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