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Effects of Opening Shapes on Behaviour of Shear Walls Made of AAC Masonry Units

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Abstract. Stiffening walls in masonry structures give support against lateral forces, such as wind or earthquakes. These aspects in brick walls, which have very low compressive and shear strength, require further observations (Jasiński 2017). This paper demonstrates the author's own results from tests performed on ten masonry units made of autoclaved aerated concrete. The tests were performed in four series of two elements. The first series denoted as HOS-AAC included four elements (the reference elements) without openings, with the length $l = 4.43$ m, $h = 2.43$ m, and thickness $t = 180$ mm. The wall tests were performed under initial compressive stress values $\sigma_c = 0$ N/mm², 0.75 N/mm² and 1.0 N/mm². In remaining three series, we used walls (external dimensions $l = 4.43$ m, $h = 2.43$ m, $t = 180$ mm) with different opening shapes denoted by convention as A, B and C. The models were tested under different values of initial compressive stress $\sigma_c = 0.1$ N/mm², 0.5 N/mm² or 1.0 N/mm². The results were compared with test results for unreinforced walls without openings, tested under the same initial conditions. The failure mechanism and changes in cracking morphology were described. And the analysis was performed for parameters responsible for wall stiffness and changes in values of cracking and failure stresses.

1. Introduction

Stiffening walls in the building ensure the geometrical stability and restrain horizontal displacements [1]. They are extremely important for providing safety. This problem is particularly significant for multi-storey brick buildings which are built at the cost of minimum wall thickness and at minimum costs of construction. In case of brick buildings, the complex aspects and the introduction of new technologies require continuous tests to verify models of the wall strength and to introduce new aspects. However, with a few exceptions, [2, 3, 4] there are not too many tests on walls under monotonic loading. This paper presents selected tests on stiffening masonry walls made of AAC. The masonry was built in the technology of thin layer bed joints and uneven head joints. The walls were weakened as they had a single window opening of different width or a single door and window opening. The aim of this paper was to analyse the cracking morphology and the destruction mechanism and to determine the basic mechanical parameters concerning initial compressive stress during shear loading.



2. Test models and testing technique

Test models were prepared from AAC blocks ($f_b = 4.0 \text{ N/mm}^2$) with dimensions of $600 \times 240 \times 180 \text{ mm}$. They were produced by a Polish manufacturer, and bedded in masonry mortar of M5 type ($f_m = 6.1 \text{ N/mm}^2$). Compressive strength of masonry (PN-EN 1052-1:2000 [5]) was $f_{c,mv} = 2.97 \text{ N/mm}^2$ ($f_k = 2.48 \text{ N/mm}^2$), and modulus of elasticity was $E_{cm} = 2040 \text{ N/mm}^2$. Shear strength determined in accordance with PN-EN 1052-3:2004 [6], was $f_{vo} = 0.306 \text{ N/mm}^2$, and shear modulus for walls under diagonal compression, tested in accordance with ASTM E519-81 [7], was $G = 475 \text{ N/mm}^2$. The test models were divided into three series: HAS-AAC, HBS-AAC and HCS-AAC. All the models had the same external dimensions and height/length ratio $h/l = 2.43/4.43$. HAS-AAC walls with A-type opening had an opening that was 1.48 m long and 0.98 m high (figure 1a). The reinforced and unreinforced models were tested under two values of initial compressive stress $\sigma_c = 0.1 \text{ N/mm}^2$ and 1.0 N/mm^2 . HBS-AAC walls with B-type opening had an opening of the same height as the wall with A-type opening. But its length was extended to 2.66 m (figure 1b). The reinforced and unreinforced models were tested under two values of initial compressive stress $\sigma_c = 0.1 \text{ N/mm}^2$ and 0.50 N/mm^2 . HCS-AAC walls with C-type opening had a door opening that was 1.03 m long and 1.90 m high, while a window opening was 1.48 m long and 0.98 m high (figure 1c). The elements were tested under two value of initial compressive stress $\sigma_c = 0.1 \text{ N/mm}^2$ and 0.50 N/mm^2 . The reference models HOS-AAC had no openings, and their external dimensions were identical to the models with openings. The walls were tested under initial compressive stress values $\sigma_c = 0.1 \text{ N/mm}^2$, 0.75 N/mm^2 and 1.0 N/mm^2 .

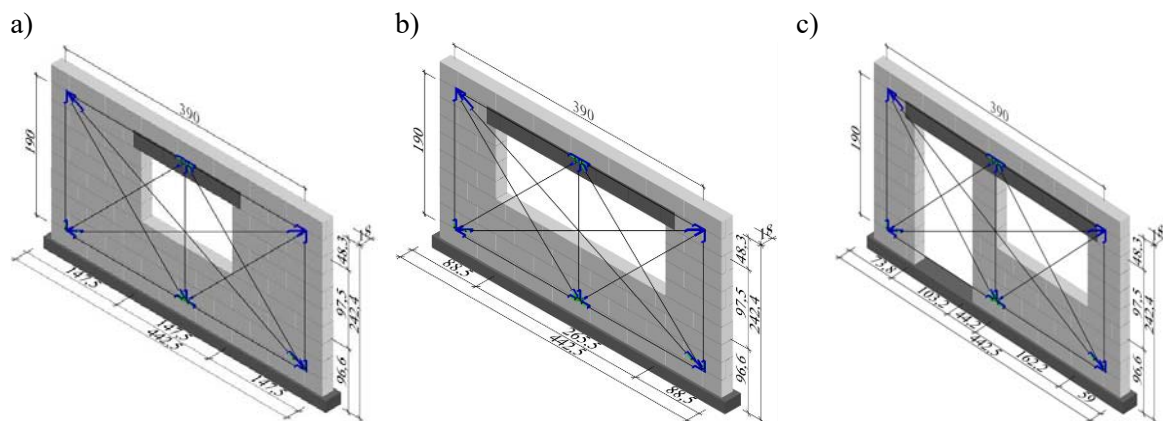


Figure 1. Geometry of models with openings: a) HAS-AAC walls with A-type opening, b) HBS-AAC walls with B-type opening, c) HCS-AAC walls with A-type opening

The test procedure was performed in the test stand [8, 9, 10, 11, 12] appropriate for walls with the maximum length of 4.5 m and the height of ca. 2.5 m. The stand provided the option of forcing horizontal shear force with the maximum capacity of 3000 kN and applying simultaneously vertical compressive load with the maximum force of 1250 kN. During the tests, measurements of the horizontal force, vertical compressive load, and shear strain and deformation of walls were made. As it was planned to measure stiffness of the whole wall, the size of the frame measurement system was chosen to include the maximum area of the wall, and at the same time to neglect edge disorders. The paper [12] describes in details the methodology of measurements of shear strain and deformation. The terms **general angle of shear strain** or **general angle of shear deformation** at the phase after cracking were used to describe the wall behaviour under horizontal loading. Partial values of general angle of shear strain were denoted as Θ_j . The average value of the **general angle of shear strain** of the masonry Θ , (at i^{th} level of loading) was determined as the mean arithmetic value of partial values

Θ_i Shear stress τ_i was determined as the ratio of horizontal loading H_i and the horizontal area of the masonry in accordance with the following relationship:

$$\tau_{v,i} = \frac{H_i}{A_h}. \quad (1)$$

General stiffness of a wall K_i was the ratio of the applied force H_i and the corresponding horizontal displacement u_i according to the following relationship

$$K_i = \frac{\tau_i}{\Theta_i} \frac{A_h}{h}. \quad (2)$$

The wall stiffness at the moment of observing first cracks was denoted as K_{cr} . Initial stiffness K_o was determined in the initial phase of loading at stress values $0 < \tau \leq 0,05\tau$. The measured force, at which the first crack was observed in the masonry units or mortar was considered as the cracking force H_{cr} . The corresponding stresses τ_{cr} , were defined as cracking stresses, and the angle Θ_{cr} was defined as the shear strain angle at the moment of cracking. The width of 0.1 mm was regarded as the minimum width of the crack, neglecting all previously observed micro-cracks. The measured force, at which the model was destroyed was considered as the destructive force H_u – an increase in force was not further recorded at increasing displacements. Stresses at the top edge of the wall, corresponding to the force H_u were regarded as failure stresses τ_{cr} , and the angle Θ_u as shear strain deformation angle. Because the testing accessories obstructed the access to the masonry face, I did not update the list of cracks, but only observed their behaviour (the place of formation, direction of propagation).

3. Test results

3.1. The cracking mechanism in the models

The cracking morphology was predominantly affected by initial compressive stress, and also by the shape and size of an opening, and the presence of reinforcement. In unreinforced walls with A-type opening, the development of cracks depended on the values of initial compressive stress. In the wall under compressive load up to 0.1 N/mm², first cracks appeared in the central part of a pillar from the side of support B (figure 2a). And in the wall under maximum compressive load of 1.0 N/mm², first cracks were observed in the lower part of the pillar and in the approximate mid-length of the spandrel area (figure 2b). In the wall with B-type opening having the length over 2.5 m, first cracks under minimum compressive stress were nearly horizontal through the masonry units and through head joints. They developed in the central part of the spandrel area (figure 2c).

First cracks in the wall under maximum compressive stress were also observed in head joints of the spandrel area. Cracks in the masonry units, from which the extreme pillar above the support B was made, appeared nearly simultaneously (figure 2d). The direction of cracks overlapped the diagonal section of the pillar running between the bottom corner of the masonry and the lintel support. In the wall with C-type opening under the minimum compressive stress, first cracks were developed in the lintel support from the side of the support A. At the same time, cracks in the bottom corner of the window opening, from the side of the support B, were observed (figure 2e). The cracks were running through joints towards the bottom corner of the door opening. In the wall with C-type opening under the maximum compressive load of 0.5 N/mm², first cracks were formed in the support of the window lintel, from the side of the support A (figure 2f). Minor cracks in the edge pillar above the support B were observed at the same time.

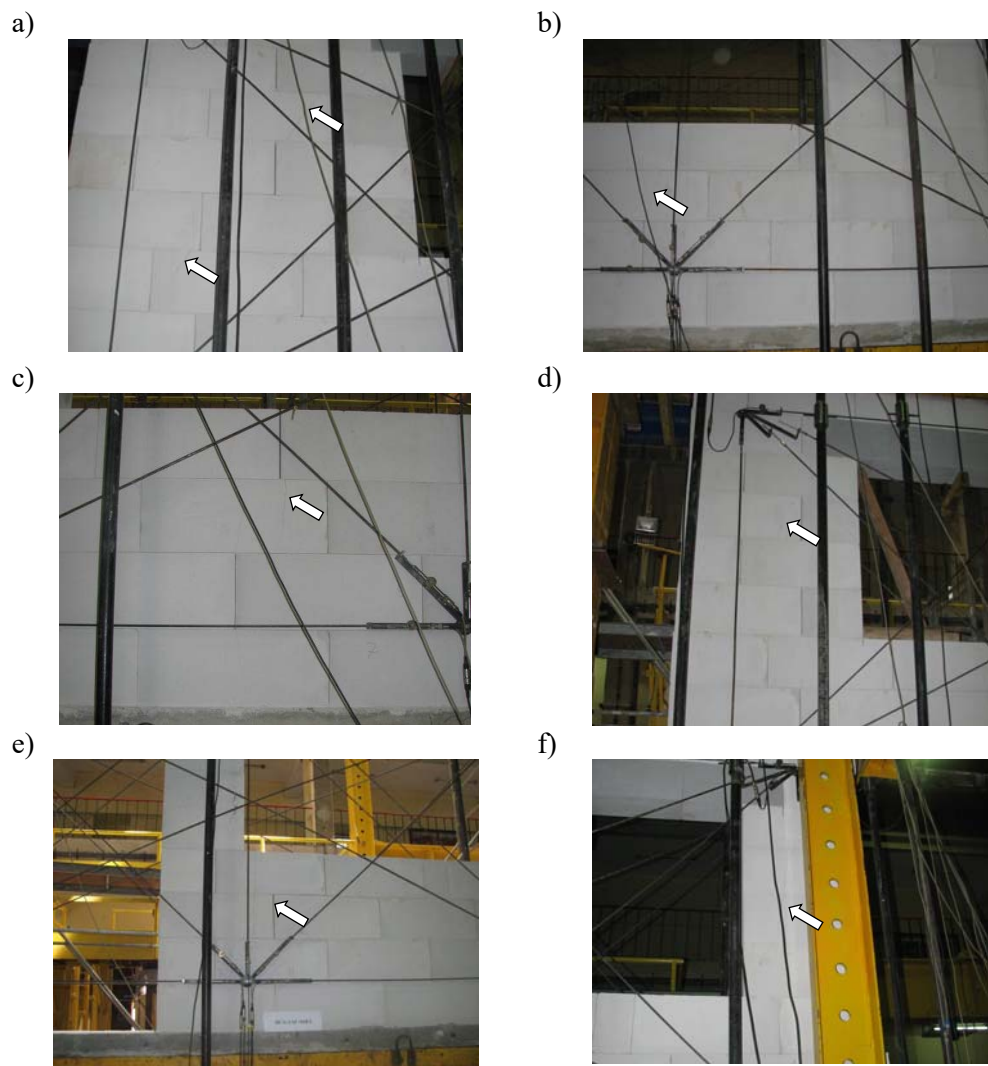


Figure 2. First cracks in the unreinforced walls with openings, made of autoclaved aerated concrete units: a) wall with A-type opening, initial compressive stress of 0.1 N/mm^2 , b) wall with B-type opening, initial compressive stress of 1.0 N/mm^2 , c) wall with C-type opening, initial compressive stress of 0.1 N/mm^2 , d) wall with D-type opening, initial compressive stress of 0.50 N/mm^2 , e) wall with C-type opening, initial compressive stress of 0.1 N/mm^2 , f) wall with C-type opening, initial compressive stress of 0.50 N/mm^2 .

The increasing horizontal loading caused the formation of primary and secondary cracks in the pillars between window openings and in corners of the openings in the AAC walls. No symmetry between cracks was found because the arrangement and the morphology of cracks were affected by the pillar position in relation to the opening and by values of initial compressive stress. The models under minimum compressive stress were destroyed slowly. The original and primary cracks reached the width of 5 mm , shear deformations of the walls were visible to the naked eye. Primary and secondary cracks were developing in the pillars. In the walls with A-, B- and C-type openings, the existing cracks in the pillars from the side of the support B covered nearly the whole length of the diagonal (figures. 3a, c, e). In the models with B- and C-type openings, the cracks were running through bed and head joints, whereas in the wall with A-type opening, the cracks were also noticed in the masonry units. The opposite pillars, from the side of the support A, in the wall with the smallest opening (figure 3a) and in

the walls with B-type (figure 3c) and C-type openings (figure 3e) were cracked at the height from the top edge of the wall to the spandrel area or from the lintel support to the bottom corner of the window opening. In the walls with door and window openings (C-type opening), the secondary cracks in the central pillar did not develop. They only covered the top masonry unit, and the additional cracks were noticed in the bottom part from the side of the door and window openings (figure 3e). The walls under the maximum compressive stress were destroyed rapidly because masonry units were diagonally cracked, and mainly because the masonry was crushed in the zone subjected to the highest compressive stress. Diagonal cracks caused by applied tension were generally observed in the pillar above the support B (the walls with B- and C-type openings – figures. 3d, f) and in the opposite pillar (the wall with A-type opening – figure 3b). Destruction caused by compression was found in the top layers of the masonry units, bottom areas of the opening corners (figure 3b), and the top part of the central pillar in the wall with C-type opening (figure 3f). In the spandrel areas of all the models with openings, the cracks were predominantly running through bed and head joints, and were formed near corners. However, in the walls with A-type opening, the damage was observed in the bottom corner of the opening subjected to compression.

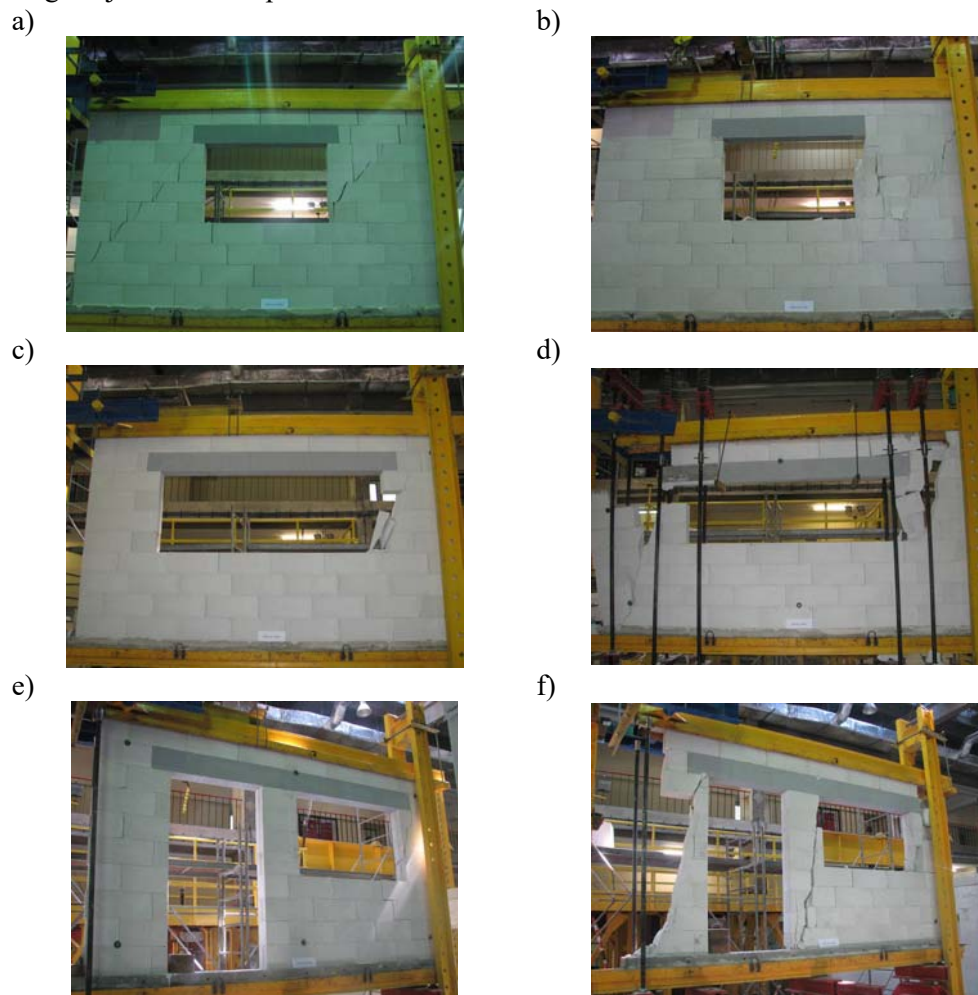


Figure 3. Models of unreinforced walls made of AAC masonry units at the moment of destruction: a) wall with A-type opening, compressive stress of 0.1 N/mm^2 , b) wall with A-type opening, compressive stress of 1.0 N/mm^2 , c) wall with B-type opening, compressive stress of 0.1 N/mm^2 , d) wall with B-type opening, compressive stress of 0.50 N/mm^2 , e) wall with C-type opening, compressive stress of 0.1 N/mm^2 , f) wall with C-type opening, compressive stress of 0.50 N/mm^2

3.2. Stress-strain relationships

Figure 4 illustrates the relationships between stress τ_i and strain θ_i for the unreinforced walls with A-, B- and C-type openings, from HAS-AAC, HBS-AAC and HCS-AAC series. The obtained test results are presented in Table 1. In Table 2, the obtained results are presented with reference to results obtained for the walls under minimum compressive stress. Until the moment of cracking, the relationships between stress and angle of shear deformation were proportional in all the tested walls. Initial compressive stress appeared to have the most significant effect. In the wall with A-type opening (figure 4a), compressed to the value of 0.1 N/mm², there was a slightly higher shear deformation after cracking. Also, shear stress increased. The destruction occurred at shear strain of 1.5-2.0 mrad. There was a clear increase in shear deformation when the maximum shear stress was applied. In the wall under initial compressive stress up to 1.0 N/mm², a non-linear increase in shear deformation to the value of ca. 3 mrad was noticed after cracking. The further increase in shear strain resulted in a clear decrease in shear stress. Like in the walls with A-type opening, in the walls with much longer B-type opening the stress-shear strain relationship (figure 4b) was strongly affected by the values of initial compressive stress. The lowest shear stress at an increasing shear strain was observed in the wall under minimum compressive stress. After cracking, the wall strength slightly increased and the destruction took place at deformation of 1.5 mrad. In the wall under maximum compressive stress up to 0.5 N/mm² there was a noticeable increase in cracking and failure stresses, but they occurred at lower values of strain and deformation of 1.0 mrad. The behaviour of the wall with C-type opening was considerably different when compared to the walls with A- and B-type openings (figure 4c). After cracking, there were considerably lower shear stresses and higher shear deformations. In the unreinforced wall under minimum compressive stress and in the reinforced walls, the values of stress and strain at the moment of cracking were similar. After cracking, there was a significant, nearly proportional increase in shear deformation. And the unreinforced elements were destroyed at shear deformation value of 3 mrad.

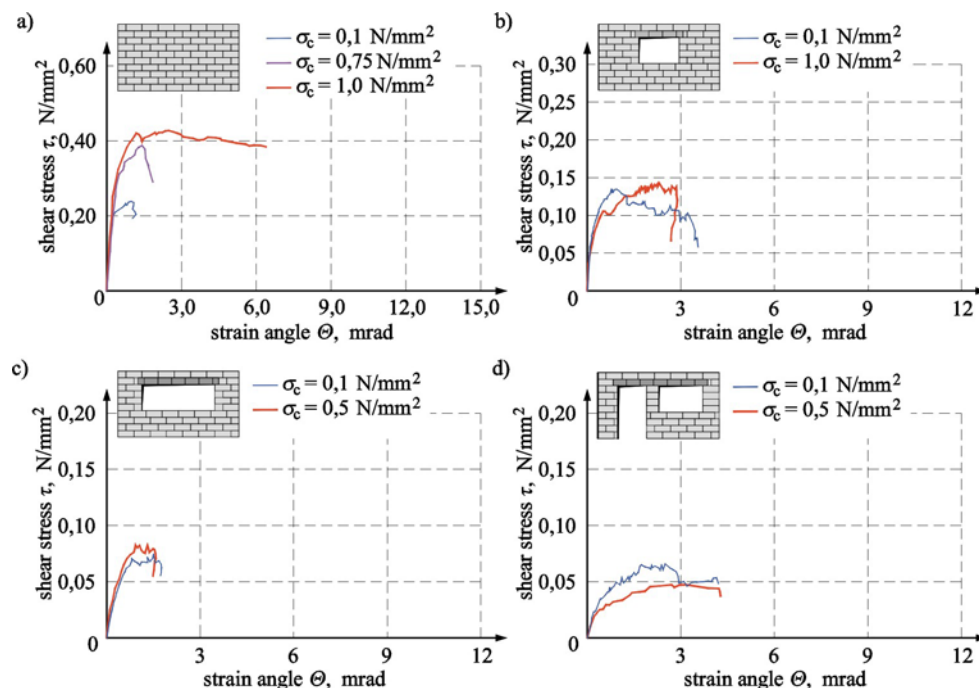


Figure 4. The relationship between stress-angle of shear deformation for all tested walls: a) walls without any opening, b) walls with A-type opening, c) walls with B-type opening, d) walls with C-type opening

Table 1. Test results for the walls with openings

Opening type	Series	σ_c N/mm ²	Stresses		Angles of shear strain (deformation)		Total stiffness	
			cracking	failure	cracking	failure	initial	at the moment of cracking
			τ_{cr} N/mm ²	τ_u N/mm ²	θ_{cr} mrad	θ_u mrad	K_o MN/m	K_{cr} MN/m
without an opening	HOS-AAC	0.1	0.196	0.235	0.281	0.97	932	229
		0.75	0.372	0.426	0.724	2.44	1168	169
		1.0	0.298	0.385	0.524	1.45	1541	187
		1.0*	0.11	0.25	0.651	2.72	379	75
A	HAS-AAC	0.1	0.110	0.136	0.424	0.774	669	85
		1.0	0.097	0.144	0.422	2.237	602	76
B	HBS-AAC	0.1	0.066	0.072	0.72	0.809	656	30
		1.0	0.072	0.084	0.65	0.927	282	37
C	HCS-AAC	0.1	0.025	0.054	0.453	4.088	229	18
		0.5	0.035	0.066	0.433	2.537	210	27

Table 2. Compared test results for walls and walls under minimum compressive stress

Opening type	Series	σ_c N/mm ²	Stresses		Angles of shear strain (deformation)		Total stiffness	
			cracking	failure	cracking	failure	initial	at the moment of cracking
			$\tau_{cr,\sigma}$	$\tau_{u,\sigma}$	$\theta_{cr,\sigma}$	$\theta_{u,\sigma}$	$K_{o,\sigma}$	$K_{cr,\sigma}$
			$\tau_{cr,\sigma=\min}$	$\tau_{u,\sigma=\min}$	$\theta_{cr,\sigma=\min}$	$\theta_{u,\sigma=\min}$	$K_{o,\sigma=\min}$	$K_{cr,\sigma=\min}$
without an opening	HOS-AAC	0.1	1	1	1	1	1	1
		0.75	1.90	1.81	2.58	2.52	1.25	0.74
		1.0	1.52	1.64	1.86	1.49	1.65	0.82
A	HAS-AAC	0.1	1	1	1	1	1	1
		1.0	0.88	1.06	1.00	2.89	0.90	0.89
B	HBS-AAC	0.1	1	1	1	1	1	1
		0.5	1.09	1.17	0.90	1.15	0.43	1.23
C	HCS-AAC	0.1	1	1	1	1	1	1
		0.5	1.40	1.22	0.96	0.62	0.92	1.50

4. Analysis of test results

4.1. Cracking and failure stresses

In the walls with A-type opening, subjected to an increasing values of initial compressive stress from 0.1 N/mm² to 1.0 N/mm², stress τ_{cr} decreased by 12% (figure 5a) and failure stress increased by 6% (figure 5b). For the models with B-type openings, the values of cracking stress in the wall under initial compressive stress up to 0.5 N/mm² increased by 9% in comparison to the models under minimum compressive stress. (figure 5c). At the moment of destruction, stress values increased by 17% when compared to the models under minimum compressive stress (figure 5d). In the walls with C-type opening, the effect of compressive stress was much stronger in comparison to the walls with A- and B-type openings. Cracking stress increased by ca. 40% (figure 5e). In case of failures stress τ_u , the values increased by 22% (figure 5f).

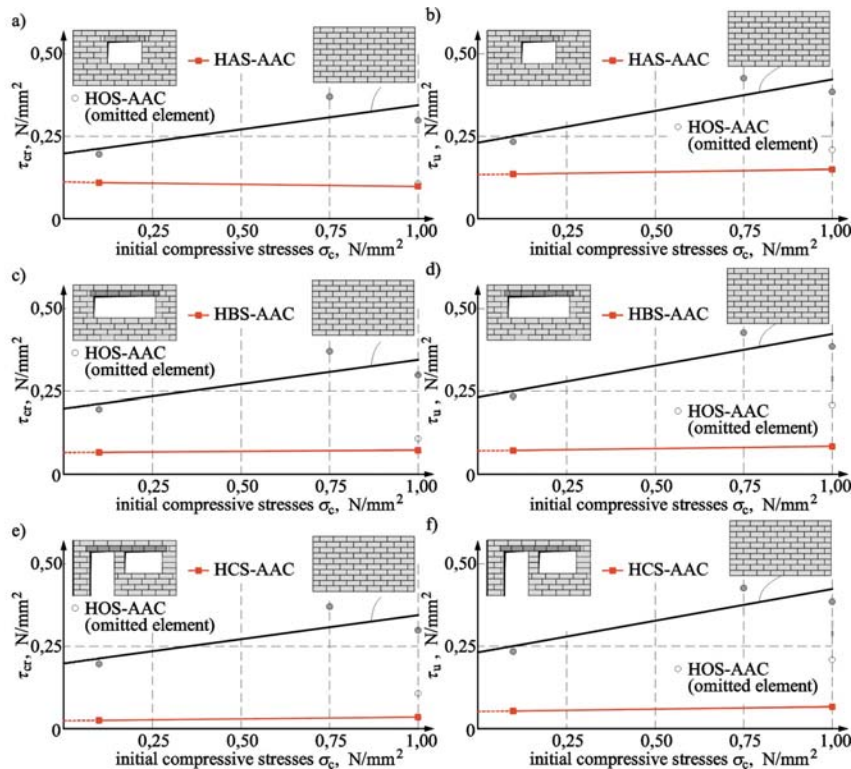


Figure 5. The obtained (cracking and failures) stress values for all test elements depending on the value σ_c and shape of the opening: a), c), e) cracking stresses – τ_{cr} , b), d), f) failure stresses – τ_u

4.2. Angles of shear strain and deformation

Values of the initial compressive stress also had an effect on angles of shear strain at the moment of cracking Θ_{cr} . In the unreinforced walls with A-type opening under initial compressive stress of 1.0 N/mm², there was not any increase in strain values in comparison to strain in the wall under minimum compressive stress. At the moment of destruction, there was nearly a 3-fold increase in Θ_u . In the walls with B-type opening, shear strain values were lower by 10% at the moment of cracking. At the highest compressive stress values, shear deformation was greater than in the wall under minimum compressive stress. In the walls with C-type opening, a tendency like in the models with B-type opening was shown at the moment of cracking. In the unreinforced wall, values of shear strain were lower by 4% and 42%. At the moment of destruction, shear deformation of all the walls was lower by 38% in comparison to the walls under minimum compressive stress.

4.3. Overall stiffness of the walls

In the wall with A-type opening under maximum compressive stress, stiffness at the moment of cracking K_{cr} was reduced by 11%. The initial stiffness K_o in the unreinforced element decreased by 10%. Also, in the wall with B-type opening under maximum compressive stress, initial stiffness K_o was higher by 23% in comparison to the unreinforced wall. No increase in stiffness was observed in the wall with plastic mesh type reinforcement. At the moment of cracking, stiffness K_{cr} was lower by 57% in comparison to the model under minimum compressive stress. Like in the walls with B-type opening, an increase in initial compressive stress caused an increase in stiffness K_{cr} in the models with C-type opening. Stiffness increased by 50%. The initial stiffness of the shear wall under initial compressive stress of 0.5 N/mm² was lower by ca. 8% when compared to the walls under minimum compressive stress.

5. Conclusions

The tests on unreinforced walls with openings, made of AAC masonry units demonstrated that:

- first cracks in the walls with openings were formed in the pillars between the openings, and then in the corners of window openings. Values of initial compressive stress and the size of openings were the most significant factor affecting crack morphology. In the walls in minimum compression, the stepped cracks were developed in bed and head joints. An increase in compressive stress eliminated the formation of stepped cracks. In the walls with A- and B-type openings, the cracks began in the bottom corner of the opening and propagated towards the bottom corner of the wall. In the models with C-type opening (door and window openings), the cracks were formed near the window opening and ran towards the bottom edge of the wall like in the case of the walls with A- and B-type openings. In the edge pillar, there were diagonal cracks running through the whole height of the wall.
- The tests performed on the walls with A-type opening led to the following conclusions:
 - shear stress at the moment of cracking τ_{cr} was decreasing at an increasing value of initial compressive stress σ_c from 0.110 N/mm² in the element in minimum compression to 0.097 N/mm², when $\sigma_c = 1.0$ N/mm²,
 - shear stress at the moment of destruction τ_u also depended on initial compressive stress σ_c . There was an increase in stress values from $\tau_u = 0.136$ N/mm² at $\sigma_c = 0.1$ N/mm², to $\tau_u = 0.144$ N/mm² at $\sigma_c = 1.0$ N/mm²,
 - shear strain at the moment of cracking Θ_{cr} in the wall model in minimum compression was equal to 0.424 mrad. No significant change was observed at an increasing value of compressive stress, in the element in the minimum compression, shear deformation at the moment of destruction Θ_u was 0.774 mrad. For the shear element at the highest initial compressive value of 1.0 N/mm², deformation was the greatest, equal to 2.237 mrad,
 - stiffness K_{cr} determined at the moment of cracking was changing within the range of 85 – 76 MN/m with the simultaneous increase in the value σ_c ,
 - The similar tendency was observed for initial stiffness K_o . For the element in minimum compression, $K_o = 669$ MN/m, and for the model compressed to the value of 1.0 N/mm², initial stiffness was equal to $K_o = 602$ MN/m.
- The tests conducted on the walls with B-type opening indicated that:
 - shear stress at the moment of cracking τ_{cr} was increasing at an increasing value of initial compressive stress σ_c from 0.066 N/mm² in the element in minimum compression to 0.072 N/mm², when $\sigma_c = 0.50$ N/mm²,
 - shear stress at the moment of destruction τ_u also depended on initial compressive stress σ_c . In the wall in minimum compression, there was an increase in stress values from $\tau_u = 0.072$ N/mm² to $\tau_u = 0.084$ N/mm² at $\sigma_c = 0.50$ N/mm²,
 - shear strain at the moment of cracking Θ_{cr} in the wall model in minimum compression was 0.72 mrad, whereas at the maximum compressive stress equal to 0.50 N/mm² shear strain decreased to the value of 0.65 mrad, in the element in minimum compression, shear deformation at the moment of destruction Θ_u was 2.02 mrad. For the shear element at the highest initial compressive value of 0.50 N/mm², deformation was the lowest, equal to 1.86 mrad,
 - stiffness K_{cr} determined at the moment of cracking was increasing at an increasing values of compressive stress. In the unreinforced models, stiffness was changing within the range of 30-37 MN/m with the simultaneous increase in the value σ_c ,
 - an increase in initial compressive stress reduced the initial stiffness K_o . In the unreinforced walls, stiffness was within the range of 656-282 MN/m.
- The tests performed on the walls with C-type opening led to the following conclusions:

- shear stress at the moment of cracking τ_{cr} was changing at an increasing value of initial compressive stress σ_c from 0.025 N/mm² in the element in minimum compression to 0.035 N/mm², when $\sigma_c = 0.50$ N/mm²,
- shear stress at the moment of destruction τ_u was increasing with an increase in initial compressive stress σ_c . In the unreinforced wall, at $\sigma_c = 0,1$ N/mm², the determined value was $\tau_u = 0.054$ N/mm², and at $\sigma_c = 0.50$ N/mm², the determined value was $\tau_u = 0.066$ N/mm²,
- shear strain at the moment of cracking θ_{cr} in the unreinforced model in minimum compression was 0.453 mrad, whereas at the maximum compressive stress equal to 0.50 N/mm² shear strain slightly decreased to the value of 0.433 mrad,
- In the unreinforced element in minimum compression, shear deformation at the moment of destruction θ_u was 4.088 mrad. For the shear element at the highest initial compressive value of 0.50 N/mm², deformation was lower, equal to 2.537 mrad,
- stiffness K_{cr} determined at the moment of cracking was increasing at an increasing values of compressive stress. In the unreinforced models, stiffness was changing within the range of 18-37 MN/m with the simultaneous increase in the value σ_c ,
- variability in the values of initial stiffness K_o was similar. In the unreinforced element in minimum compression, initial stiffness was equal to 229 MN/m and slightly decreased to 210 MN/m in the model in maximum compression up to 0.50 N/mm².

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