ORIGINAL ARTICLE

Shear and Flexural Strength of Masonry Walls Made of Calcium Silicate Materials Made in Poland

Radosław Jasiński [1], Adam Piekarczyk [1], Łukasz Drobiec [2]

[1] PhD CEng, Silesian University of Technology, Department of Building Structures, Gliwice, Poland

[2] Assistant Professor, PhD CEng, Silesian University of Technology, Department of Building Structures, Gliwice, Poland

Abstract: In the article are presented the results of the shear and flexural strength of the masonry specimens with the thin joints made of 15 types of the calcium-silicate masonry units produced by 12 Polish manufacturers. The tests of initial shear strength of the masonry f_{vko} were carried out according to the PN-EN 1052-3 [12] standard (117 specimens). The dependence of the shear strength on the vertical holes percentage were considered as well. The article describes also the results of flexural strength tests (48 specimens) at failure in the plane parallel and perpendicular to the bed joints. The shear and flexural strength is compared with characteristic values proposed in the Polish NA to the PN-EN 1996-1-1 [10] code and national annexes of other European countries. On the basis of performed tests of mechanical parameters of the wall, the authors chose the optimal masonry element, which was used for testing walls subjected to compression, shearing and bending in the plane [16—18]. The results of these studies were partly presented at the international conference WMCAUS-2016 and published in [19]

Keywords: Calcium silicate units; initial shear strength; flexural strength

1. Introduction

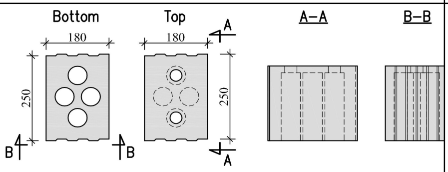
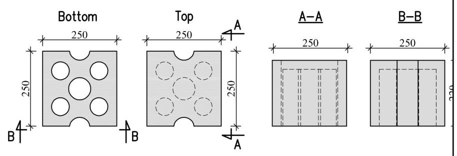
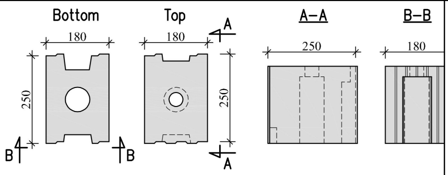
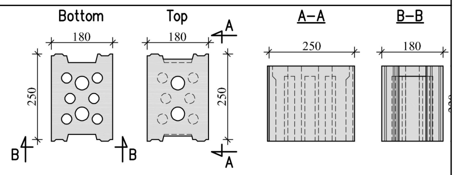
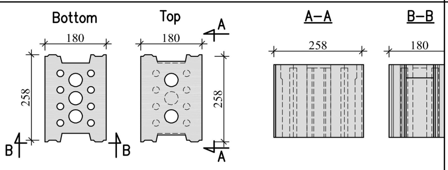
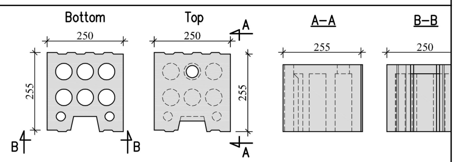
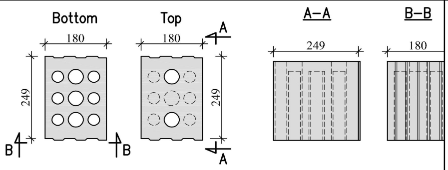
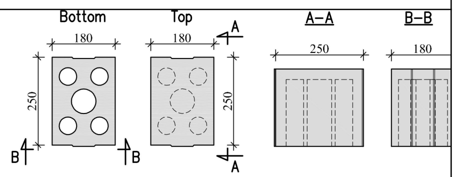
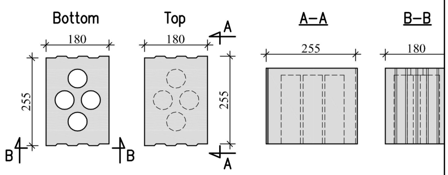
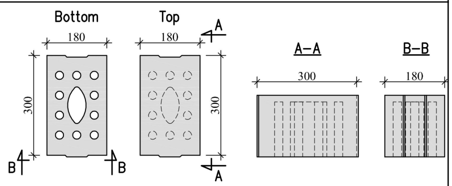
Parameters determining the usefulness of the wall as a material from which shear walls is shear strength f_v and stiffness K. Shear strength directly affects the wall's safety because it allows to determine the design shear capacity V_{Rd}. In turn, the stiffness of the wall affects the distribution of horizontal shear forces V_{Ed} and the bending moments of M_{Ed} within individual storeys. In addition, stiffness determines the movements of e_a, which, of course, limits the initial eccentricities affecting the values of N_{Rd}. In curtain walls loaded with wind of M_{Rd} load, the bending strength of f_x determines the strength of the wall. The complexity of the wall causes that it can not be unambiguously determined whether cracking and subsequent destruction will result from loss of adhesion of mortar to masonry elements in welded joints or in butt welds, it is necessary to determine strength in both directions: parallel and perpendicular to the plane of bed jounts. This publication presents the results of investigations of the properties of masonry made of silicate wall elements, of which over 20% of stiffening and screening walls are made in Poland. 12 Polish producers were selected for the research, whose production covers over 80% of the silicate elements market. Obtained results were referred to the provisions of European standards and available test results. The results of the compression test are included in the publication [1].

2. Masonry units

Specimens were made of 15 types calcium produced by 12 polish manufacturers. Overview of these elements is given in Table 1. The 6 masonry units of each type were taken randomly and subjected to compressive strength

doi: 10.18686/utc.v4i1.30

test according to PN-EN 772-1: 2001 [20] Results of masonry units compressive strength tests are given in Table 2 where values of mean compressive strength and coefficient of variation for each unit type are presented. Compressive strength values were converted into normalised compressive strength using shape factor δ in accordance with annex A in PN-EN 772-1: 2001 [20] standard. For each calcium silicate units type compressive strength class were determined according to annex D to PN-EN 771-2: 2006 [21]. Tested masonry units were assigned to the 15, 20 and 25 strength classes given in Table 2.

Unit number	Masonry unit	Unit number	Masonry unit
I	 N 18 250×180×220 mm	VIII	 6NFD 250×250×220 mm
II	 NP 18 250×180×220 mm	IX	 T18 250×180×220 mm
III	 5 NFD P+W 258×180×220 mm	X	 6 NFD w+w 255 × 250 × 220 mm
IV	 BP 18/24 249×180×240 mm	XI	 ½ BSD 180 (P+W) 250×180×220 mm
V	 N18/255 255×180×220 mm	XII	 MT 18 300×180×185 mm

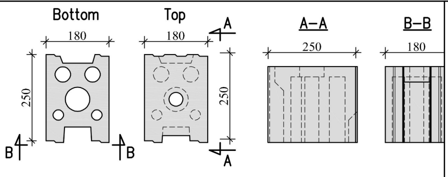
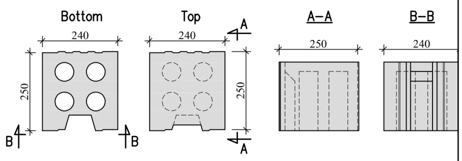
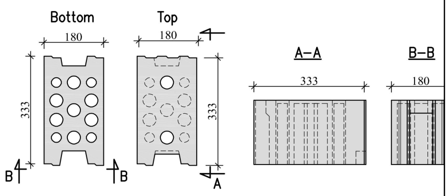
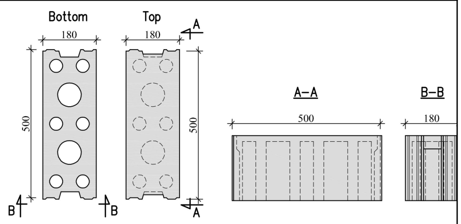
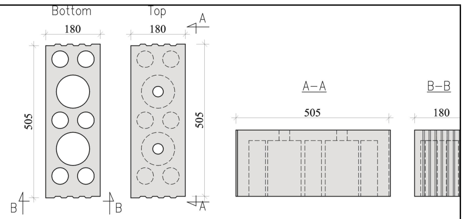
VI	 U18L 250×200×180 mm	XIII	 N24 250×240×220 mm
VII	 SILKA E18 333×180×199 mm	XIV	 BSD 180 500×180×220 mm
		XV	 N18/500 505×180×220 mm

Table 1. Tested masonry units

Unit number	Mean compressive strength, N/mm^2	Shape factor δ	Normalized compressive strength f_b, N/mm^2	Strength class	Unit number	Mean compressive strength, N/mm^2	Shape factor δ	Normalized compressive strength f_b, N/mm^2	Strength class
I	14.1	1.23	17.3	15	VIII	18.1	1.12	20.3	20
II	20.4	1.23	25.1	25	IX	22.9	1.23	28.2	25
III	19.7	1.23	24.2	20	X	16.7	1.12	18.7	15
IV	14.5	1.13	16.4	15	XI	17.7	1.23	21.8	20
V	22.0	1.23	27.1	25	XII	15.3	1.15	17.6	15
VI	15.0	1.	18.5	15	XII	13.7	1.13	15.5	15

		23			I				
VII	12.8	1.19	15.2	15	XIV	18.0	1.23	22.1	20
					XV	10.14	1.23	22.6	20

Table 2. Results of masonry units compressive strength tests

3. Shear walls. Characteristic initial shear strenght f_{vko}

To test the shear strength were used 14 types of masonry units uniform thickness t_u=180 mm. In accordance with the requirements of PN-EN 1052-3: 2004 [12] tried to do at least 9 elements. A total of were made and researched 117 test specimens. Due to the dimensions of the most studied masonry units according to PN EN 1052-3: 2004 [12] in the studies used shear elements of the B type – fig 1. Within each series specified initial characteristic shear strength of the wall according to PN-EN 1052-3: 2004 [12] procedure.

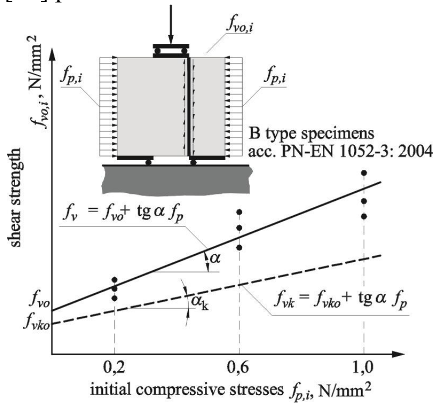


Figure 1. The shape of the specimens and the basic symbol

The test results are given in Table 3. In accordance with EN 1996-1-1: 2005 (EC 6) [5] regardless of the strength class of mortar characteristic shear strength $f_{vk,EC6}$ of masonry made for thin joints mortar is equal $f_{vk,EC6}$ = 0.4 N/mm². However, in the Polish National Annex in the table NA.6 PN EN 1996-1-1: 2013 (PN-EN) initial shear strength set $f_{vk,PN\text{-}EN}$ = 0,30 N/mm² it was at 30% less than recommended in the EC 6. In other countries in National Annexes of EC 6 friction coefficient have been set arbitrarily at tgα_k = 0.4. Comparison of test results obtained and the designated the characteristic values of the parameters contained in the Polish National Annex are summarized in Table 4.

No.	Series	$\frac{A_o}{A_{brutto}}100\%$ *	f_{vo} N/mm²	f_{vko} N/mm²	α deg	0,8tg α	α_k deg
1	I	21%	0.74	0.59	26	0.39	21
2	II	10%	0.37	0.29	43	0.75	37
3	III	15%	0.59	0.47	40	0.68	34
4	IV	24%	0.65	0.52	40	0.68	34
5	V	21%	0.38	0.31	39	0.64	32
6	VI	21%	0.51	0.41	50	0.95	44
7	VII	21%	0.56	0.45	45	0.81	39
8	VIII	27%	0.61	0.49	35	0.57	30
9	IX	16%	0.76	0.61	51	0.99	45
10	X	26%	0.70	0.56	34	0.53	28

11	XI	26%	0.70	0.56	35	0.56	29
12	XIII	20%	0.63	0.50	52	1.03	46
13	XIV	23%	1.04	0.83	26	0.40	22
14	XV	37%	0.49	0.39	28	0.43	23
Mean value m_x, N/mm^2:			0.62				
Standard deviation σ, N/mm^2:			0.171				
C.O.V V_x			0.27				

* – percent of the openings surface area as the ratio of the area of holes A_o and gross section area of masonry unit A_{brutto}.

Table 3. Summary of the test results

Initial characteristic shear strength of the all test specimens series was more than the value specified by Polish National Annex equal 0.3 N / mm^2. With results of the 14 series of different masonry units calculated characteristic strength of the wall shear according to the procedure given in Appendix D of Eurocode PN-EN 1990: 2004 from the relation

$$X_k = f_{vko} = m_x(1-k_nV_x) = 0.62(1-1.70\cdot 0.27) = 0.33\ \text{N/mm}^2 \quad (1)$$

where: m_x – mean value, V_x – coefficient of variation, k_n – statistic factor (table D1, PN-EN 1990:2004).

Figure 2a shows the results of the initial shear strength obtained in the each series of units. The figure also shows the characteristic shear strength calculated according to the equation (1), and the values specified by code. At the same thickness (t_u=180 mm) and the length of masonry (l_u≤300 mm), the most important factor affecting the large differences in shear strength was the degree of perforation of the bed surface by vertical holes. **Figure 2**b shows the comparison of the obtained shear strength as a function of the ratio of the area of holes A_o and gross section area of masonry units A_{brutto}. In order to better illustrate occurring trends in the graph also introduced inscribed the best fit polynomial least squares method.

Table 4. Comparison of the test results and code values

No.	Series	f_{vko} N/mm^2	$f_{vko,\,PN\text{-}EN}$ N/mm^2	$\frac{f_{vko}}{f_{vko,PN-EN}}$
1	I	0.59		1.97
2	II	0.29		0.98
3	III	0.47		1.56
4	IV	0.52		1.74
5	V	0.31		1.02
6	VI	0.41		1.36
7	VII	0.45	0,3	1.50
8	VIII	0.49		1.63
9	IX	0.61		2.03
10	X	0.56		1.88
11	XI	0.56		1.87
12	XIII	0.50		1.68
13	XIV	0.83		2.78
14	XV	0.39		1.29

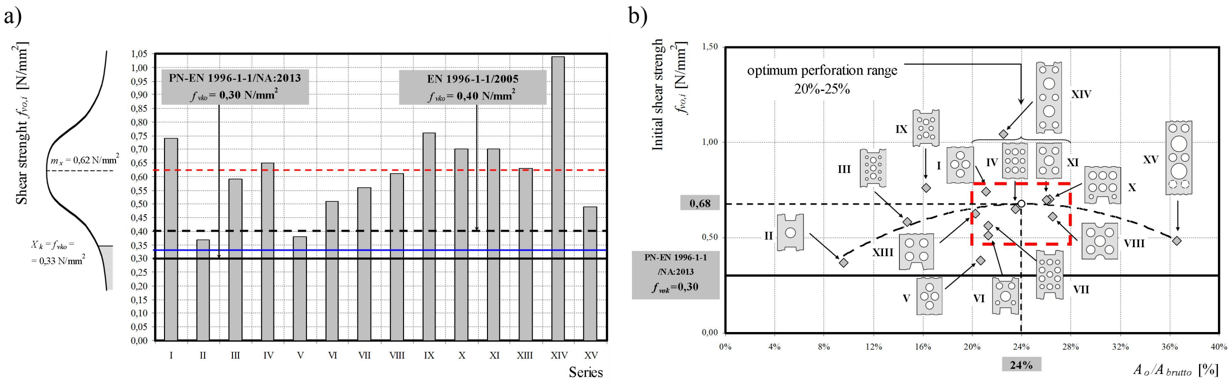


Figure 2. Test results of f_{vko}: a) a comparison with the values prescribed by the EN 1996-1-1: 2005 and EN 1996-1-1: 2013, b) as a function of the percentage area of openings

The maximum initial shear strength were saturated with openings in the range of 20% -25% and the hole diameter of not more than 40 mm (**Figure 2**, b), and the components do not have mounting brackets. The lowest initial shear strength was obtained at 10% saturation holes and 37%. At intermediate values A_o/A_{brutto} results suggest the presence of extreme of the function of shear strength in the range of 20% - 28% of the holes surface area. Qualitative estimate indicates that the saturation hole bed area of 24% of initial shear strength f_{vo} is about 0.70 N / mm^2.

Location of the holes did not have such importance because both series where the holes are arranged in a row (IV, X, XIII) and running bond (I, VIII, XI) have found similar strength values. It is noteworthy that that the elements of the second series, which showed the lowest value fvo the maximum compressive stress remained undamaged – Fig 3, a. Elements series XIV (max fvo) at the highest compressive stresses were completely destroyed – Fig 3, b. Although elements of the saturated holes at 20 - 25% have a higher shear strength, is the large compressive stress can dangerous brittle fracture.

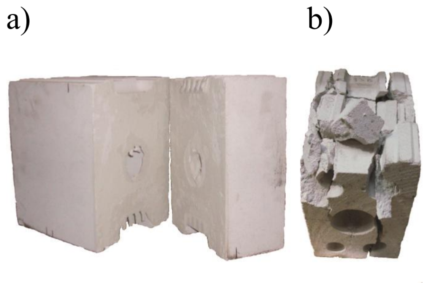


Figure 3. Failure patterns units at f_p = 1,0 N/mm^2: a) units II series, b) units XIV series

4. Characteristic flexural strength f_{xk1} and f_{xk2}

The flexural strength tests were carried out according to the PN-EN 1052-2 [11] standard. In PN-EN 1996-1-1: 2013 [10] standard there are two characteristic flexural strength fxk1 i fxk2, when the plane of masonry failure is parallel (Fig 4, a) and perpendicular (Fig 4, b) to the bed joints. The flexural strength of the masonry shall be determined on the basis of destructive testing of specimens supported along two linear supports and loaded also along two lines, the method called usually the four load points method – Fig 5.

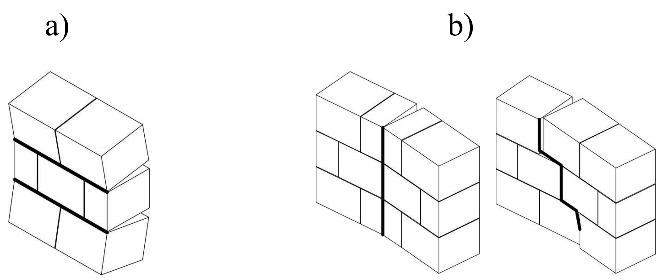


Figure 4. Flexural failure of masonry in plane: a) parallel, b) perpendicular to the bed joints

On the basis of maximum force at the moment of the specimen failure the flexural strength f_{xi} is calculated as the value of the greatest tensile stress on the assumption of linear distribution of stresses in the cross section subjected to pure bending. Flexural strength of a single specimen is calculated from the formula

$$f_{xi} = \frac{3F_{i,\max}\left(l_1 - l_2\right)}{2bt_u^2}, \qquad (2)$$

where: $F_{i,max}$ – maximum force, l_1 i l_2 – respectively spacing of supports and lines along which the load is applied, b i t_u – width and thickness of specimen.

Table 5 contains the mean flexural strength fx,mv made of the same calcium-silicate masonry units, mean value mx calculated for all tested specimens at a given plane of failure, standard deviation σ and coefficient of variation Vx.

Plane of failure parallel to the bed joints				Plane of failure perpendicular to the bed joints			
Unit number (series)	$f_{x1,mv}$, N/mm^2	Unit number	$f_{x1,mv}$, N/mm^2	Unit number (series)	$f_{x2,mv}$, N/mm^2	Unit number	$f_{x2,mv}$, N/mm^2
I	0.55	IX	0.18	I	0.44	IX	0.40
III	0.36	X	0.23	III	0.44	X	0.36
IV	0.19	XI	0.70	IV	0.27	XI	0.44
VI	0.39	XII	0.22	VI	0.42	XII	0.23
VII	0.70	XIII	0.42	VII	0.38	XIII	0.43
VIII	0.17	XIV	0.54	VIII	0.42	XIV	0.39
m_x, N/mm^2	0.39			m_x, N/mm^2	0.39		
σ, N/mm^2	0.204			σ, N/mm^2	0.068		

V_x	0.52	V_x	0.18

Table 5. Flexural strength tests results

Figure 5. Flexural strength test

The procedure for estimating the characteristic values for the design assisted by testing according to PN-EN 1990: 2004 [9] and formula (1) was used. The flexural strength of masonry when the plane of failure is parallel to the bed joints fxk1 was 0.05 N/mm2 and in case of failure in plane perpendicular to the bed joints fxk2 = 0.27 N/mm2. Due to the high variability of the flexural strength (Vx = 52%), the strength fxk1 was three times lower than the value in Polish National Annex to PN-EN 1996-1-1 [10] wherein fxk1,PL = 0.15 N/mm2 (Fig 6, a). Characteristic strength fxk2 = 0.27 N/mm2 is also lower than the value proposed in Polish standard fxk2,PL = 0.30 N/mm2 (Fig 6, b), although due to less variability of results (Vx = 18%), by only 10%. In Lithuanian studies [2], from the tests of four specimens obtained mean value fxk1,mv = 0.174 N/mm2 and coefficient Vx = 0.22, which according to formula (1) gives characteristic flexural failure fxk1 = 0.10 N/mm2 (kn = 1.83) also lower than the value in Polish standard. In aforementioned Lithuanian study five specimens with plane of failure perpendicular to the bed joints were tested. Mean flexural strength fxk2,mv = 0.178 N/mm2 and coefficient Vx = 0.26. According to formula (1) characteristic value fxk2 = 0.10 N/mm2. Therefore the characteristic value obtained from Lithuanian research is much lower than in the Polish National Annex.

a) b)

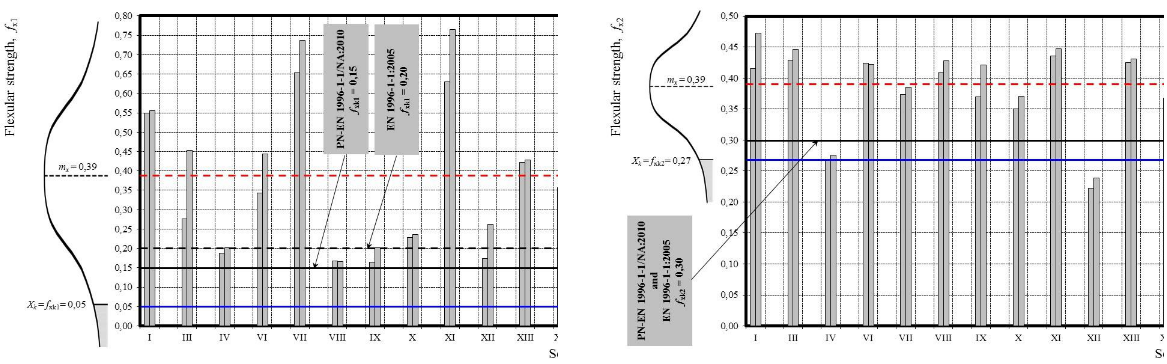


Figure 6. Tests results: a) flexural strength f_{x1}, b) flexural strength f_{x2}

5. Polish code arrangements against the arrangements of other European countries

5.1. Shear walls

According to the European standard EC-6 a characteristic initial shear strength of the walls of silicate units is equal f_{vko} = 0.40 N/mm^2. Identical values adopted in the National Annexes in the UK BS EN 1996-1-1 [3] and Austria ÖNORM EN 1996-1-1: 2006 [8]. In the German National Annex DIN EN 1996-1-1 [4] in the case of walls with joints thickness of 0.5 to 3 mm is assumed initial shear strength of the masonry of f_{vko} = 0.22 N/mm^2. The wide variation in shear strength was introduced in the legislation of the Russian СНиП II-22-81 [15], where he introduced the Mohr-Coulomb law. The shear strength labeled R_{sq} is in the range of 0.01 ÷ 0.25 N / mm^2 depending on the compressive strength of the mortar. However, in the Polish National Annex PN-EN initial shear strength of silicate units adopted at f_{vko} =0.30 N/mm^2. Due to the lack of applied research is allowed so the value adopted in the project version of the standard ENV 1996-1-1: 1995 [6].

5.2. Flexural strength

In EN 1996-1-1 standard the flexural strength of the masonry made of calcium-silicate masonry units and thin joints $f_{xk1,EN}$ is equal 0,20 N/mm^2. The flexural strength $f_{xk2,EN}$ is the same as in the Polish standard, which is 0,30 N/mm^2. In the National Annex to the German standard DIN EN 1996-1-1 [4] it is assumed that the strength $f_{xk1,D}$ = 0 except for infilling masonry made of large masonry units, were $f_{xk1,D}$ = 0.2 N/mm^2. The flexural strength $f_{xk2,D}$ according to DIN EN 1996-1-1 [4] is calculated depending on the masonry joint shear strength. In the Swiss standard SIA 266 [14] the flexural strength $f_{xk1,CH}$ in case of masonry made of calcium-silicate units is equal 0,15 N/mm^2. In the Finnish National Annex SFS-EN 1996-1-1:2009 [13] for masonry made of mortar with strength $f_m \geq 10$ N/mm^2 the flexural strength $f_{xk1,FIN}$ = 0.20 N/mm^2, when the compressive strength of calcium-silicate masonry units $f_b \leq 20$ N/mm2 and $f_{xk1,FIN}$ = 0.25 N/mm^2 when f_b = 25 N/mm^2. The flexural strength $f_{xk2,FIN}$ = 0.42 N/mm^2 for the masonry with unfilled vertical joints made of mortar with $f_m \geq 10$ N/mm^2 and masonry units with $f_b \leq 20$ N/mm^2 and $f_{xk2,FIN}$ = 0.53 N/mm^2 when f_b = 25 N/mm^2. Belgian National Annex NBN EN 1996-1-1: 2010 [7] for the masonry made of calcium-silicate masonry units group 1 with thin joints gives the flexural strength $f_{xk1,B}$ = 0.50 N/mm^2, while $f_{xk2,B}$ = 0.35 N/mm^2 for the masonry with unfilled vertical joints.

References

1. Jasiński R, Drobiec Ł, Pierkarczyk A. Mechanical properties of masonry walls made of calcium silicate materials made in poland. Part 1. Masonry properties and compressive strength. Procedia Engineering 2016, 161: 904–910.
2. Jonaitis B, Marčiukaitis G, Valivonis J. Analysis of the shear and flexural behaviour of masonry with hollow calcium silicate blocks. Engineering Structures 2009, 31: 827– 833.
3. BS EN 1996-1-1 Eurocode 6: Design of masonry structures. Part 1-1: General rules for reinforced and unreinforced masonry structures.
4. DIN EN 1996-1-1/NA: 2012-05 National Annex. Nationally determined parameters. Eurocode 6: Design of masonry structures. Part 1-1: General rules for reinforced and unreinforced masonry structures – German National Annex.
5. EN 1996-1-1: 2005 Eurocode 6. Design of masonry structures. Part 1-1: General rules for reinforced and unreinforced masonry structures.
6. ENV 1996-1-1: 1995 Eurocode 6. Design of masonry structures. Part 1-1: General rules for reinforced and unreinforced masonry structures.
7. NBN EN 1996-1-1: 2010 Eurocode 6: Design of masonry structures. Part 1-1: General rules for reinforced and unreinforced masonry structures – Belgian National Annex.
8. Önorm EN 1996-1-1: 2006 Eurocode 6: Bemessung und Konstruktion von Mauerwerksbauten. Teil 1-1: Allgemeine Regeln für bewehrtes und unbewehrtes Mauerwerk.
9. PN-EN 1990: 2004 Eurocode. Basis of structural design. (in Polish).
10. PN-EN 1996-1-1+A1: 2013-05/NA: 2014-03 Design of masonry structures. Part 1-1: General rules for reinforced and unreinforced masonry structures. (in Polish).
11. PN-EN 1052-2:2001 Methods of test for masonry. Part 2: Determination of flexural strength. (in Polish).
12. PN-EN 1052-3: 2004 Methods of test for masonry. Part 3: Determination of initial shear strength. (in Polish).
13. SFS-EN 1996-1-1: 2009 Eurocode 6: Design of masonry structures. Part 1-1: General rules for reinforced and unreinforced masonry structures – Finnish National Annex.
14. SIA 266: 2003 Masonry.
15. СНиП II-22-81: 2000 Каменные и армокаменные конструкции. (Unreinforced and reinforced masonry

structures) (in Russian).
16. Drobiec Ł. The effect of different strengthening systems on the cracking of spandrel walls made of calcium silicate units. Brick and Block Masonry – Trends, Innovations and Challenges. Taylor & Francis Group, London 2016, pp. 2055–2062.
17. Jasiński R. Research of bed joints reinforced masonry walls with openings made of calcium silicate units horizontally sheared. Brick and Block Masonry – Trends, Innovations and Challenges. Taylor & Francis Group, London 2016, pp. 230 –2311.
18. Piekarczyk A, Jasiński R. Distortions and the way of damaging masonry walls supported on Deflected Structural Elements. Taylor & Francis Group, London, CRC Press, pp. 1815–1822.
19. Jasiński R, Drobiec Ł, Pierkarczyk A. Mechanical properties of masonry walls made of calcium silicate materials made in poland. Part 2. Shear and flexural strength. Procedia Engineering 2016, 161: 911–917.
20. PN-EN 772-1: 2001/Ap1: 2002 Methods of test for masonry units. Part 1: Determination of compressive strength. (in Polish).
21. PN-EN 771-2: 2006 Specification for masonry units. Part 2: Calcium silicate masonry units. (in Polish).