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Experimental studies of the strength of masonry under axial and local compression

Abstract. Masonry is one of the traditional building materials that remains highly relevant in modern civil and industrial construction. Determining its strength characteristics, especially under compressive loads, remains an important scientific and technical task, since such forces prevail in load-bearing walls, columns, and other structural elements of masonry. The compressive strength of masonry is affected by numerous factors, including the strength and geometric properties of the units, their shape accuracy, the presence of voids, the mortar strength, the deformation characteristics of hardened mortar, the workability of the mortar mix, the bond strength between mortar and masonry units, the degree of joint filling, the bonding pattern, and the overall quality of workmanship. When determining the strength of masonry under local compression, the nature of the sample's destruction is taken into account, on the basis of which a corresponding kinematic scheme is developed that determines the main parameters that affect the strength of the masonry. One of the key issues is the lack of a unified approach to determining the geometric parameters of the samples used for testing. The objective of this study is: 1. to develop scientifically based recommendations for the optimal shape and size of standard samples that allow the most reliable assessment of the axial compressive strength of masonry based on test results; 2. to consider the case of local compression of walls by stamps located near the end face with a width less than the wall thickness.

Keywords: masonry, strength, compression, brick, mortar

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Introduction.

Masonry is one of the traditional building materials that remain highly relevant in modern civil and industrial construction. Determining its strength characteristics, particularly under compressive loads, remains an important scientific and technical task, since such forces prevail in load-bearing walls, columns, and other structural members of masonry.

A significant contribution to the formation of the principles of masonry structure's design was made in the works of L.I. Onyshchyk, which became the foundation for relevant research in the mid-20th century. At the same time, many scientific works indicate that the strength limit of masonry, determined by the formula of L.I. Onyshchyk, is underestimated compared to the actual experimental results [1–3] obtained during tests of brick columns with a cross-section of mainly 250×250 mm. In a number of cases, discrepancies of 2–4.5 times were found, indicating the need to improve existing approaches to determining the strength of masonry.

Abroad, it is usually determined based on the results of testing prisms, wall fragments, and wallettes. Prisms are samples with a height ranging from one to three heights of masonry elements, while wallettes are short wall fragments formed from several rows and at least three masonry elements wide. Among foreign researchers, Francis A.J. [18], Hamid A.A. [14], Ganesan T.P. [19], Wu F. [20], and others [8, 21–29] have made significant contributions to the study of masonry strength under compression. Their work is devoted to analyzing the influence of prism geometry, number of rows, joint thickness, mortar type, and Poisson's ratio. Researchers emphasize that in order to obtain reliable results, it is necessary to take into account the height-to-thickness ratio (*h/t*), the volume fraction of mortar, and the number of rows in the sample.

Therefore, samples with different shapes and geometric dimensions are used for experimental determination of masonry strength under compression, and the question of a master sample remains unresolved and requires further research.

Aspects of determining the strength of masonry under local compression are discussed in detail in the scientific works of Pinchuk N.M. [30], Shapoval S.L. and Klymenko E.V. [31–32], Mitrofanov V.P. and Dovzhenko O.O. [5]. When analyzing the strength of a structural element, the nature of its destruction is taken into account, on the basis of which a corresponding kinematic diagram is developed that determines the main parameters that affect the strength of the masonry (h/l_{loc}, f_k). The case of local compression of walls by stamps located near the edge with a width less than the thickness of the wall has not been studied.

Problem statement.

The purpose of the authors' experimental studies is to analyze the nature of destruction and limit load of brick masonry under axial and local compression in order to provide recommendations on: the shape and dimensions of samples for determining the strength of masonry under compression and methods for calculation under local compression.

Main material and results.

Two series of test samples were manufactured in the laboratory of the Department of Building Structures. The first one was for axial compression testing (Fig. 1) and included: three columns with cross-sectional dimensions of 510×510, 380×380, 250×250 mm, 1 m high; three pairs of half-brick-thick prisms with heights of three, five, and seven standard-size bricks, as well as a half-brick-thick wall fragment measuring 900×440 mm. The geometric parameters of the samples of the first series are given in Table 1. The marking with a letter indicates the type of test sample: C – column; W – wall; P – prism. The geometric dimensions are given in cm. Twin samples are marked as *a* and *b*. During the loading process, the deformed state of the masonry was studied using clock-type indicators with a scale of 0.01 mm, with a measurement base of 400 mm.

The second series involved testing the local compression of brick walls in the case of applying a load near the edge, not across the entire width of the wall cross-section along its length (Fig. 2), using platforms of various sizes: 150×250; 100×150; 100×100; 100×250; 150×100.

Table 1 – Geometric parameters of the 1st series test samples

№	Description	Width, mm	Length, mm	Height, mm
1	C-25.25.100	250	250	1000
2	C-38.38.100	380	380	1000
3	C-51.51.100	510	510	1000
4	W-90.12.44	120	900	440
5	P-25.12.21.5-a	120	250	215
6	P-25.12.21.5-б	120	250	215
7	P-25.12.36.5-a	120	250	365
8	P-25.12.36.5-б	120	250	365
9	P-25.12.51.5-a	120	250	515
10	P-25.12.51.5-б	120	250	515

The strength of bricks and mortar was determined using standard methods. The average strength of bricks in the first series f_b was 11.3 MPa, and mortar f_m was 8.56 MPa. For the second series f_b = 8.52 MPa, f_m = 4.45 MPa.

All test samples were mounted on a metal plate with loops for transportation to a 500-ton hydraulic press, where the tests were performed.

During testing, the first vertical cracks formed at a load of approximately: 0.9 N_u for a column with a cross-section of 250×250 mm; 0.8 N_u for a cross-section of 380×380 mm; 0.55 N_u for a column with a cross-section of 510×510 mm; 0.6 N_u for prisms and walls with dimensions of 900×440 mm. As the load increased, the length of the cracks grew, they spread both along the stone and along the mortar, and new cracks appeared.

The nature of the destruction of the column with a cross-section of 250×250 mm is shown in Fig. 3. Vertical cracks can be observed along the height of the column in combination with inclined cracks near the loaded and supporting planes, as well as crumbling of bricks in the lower part of the sample. Characteristic signs of destruction are present on four sides.

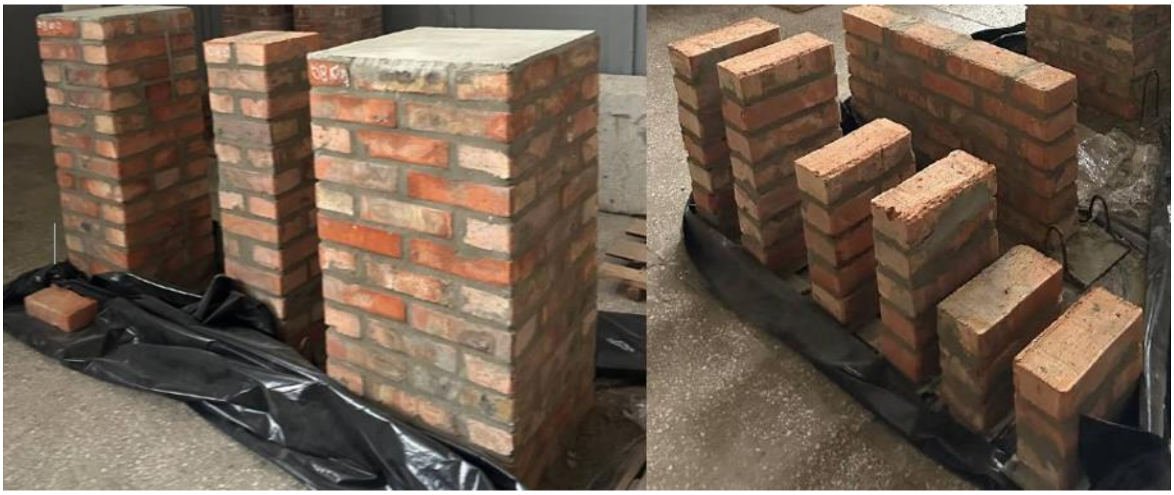


Figure 1 – Test samples for axial compression testing

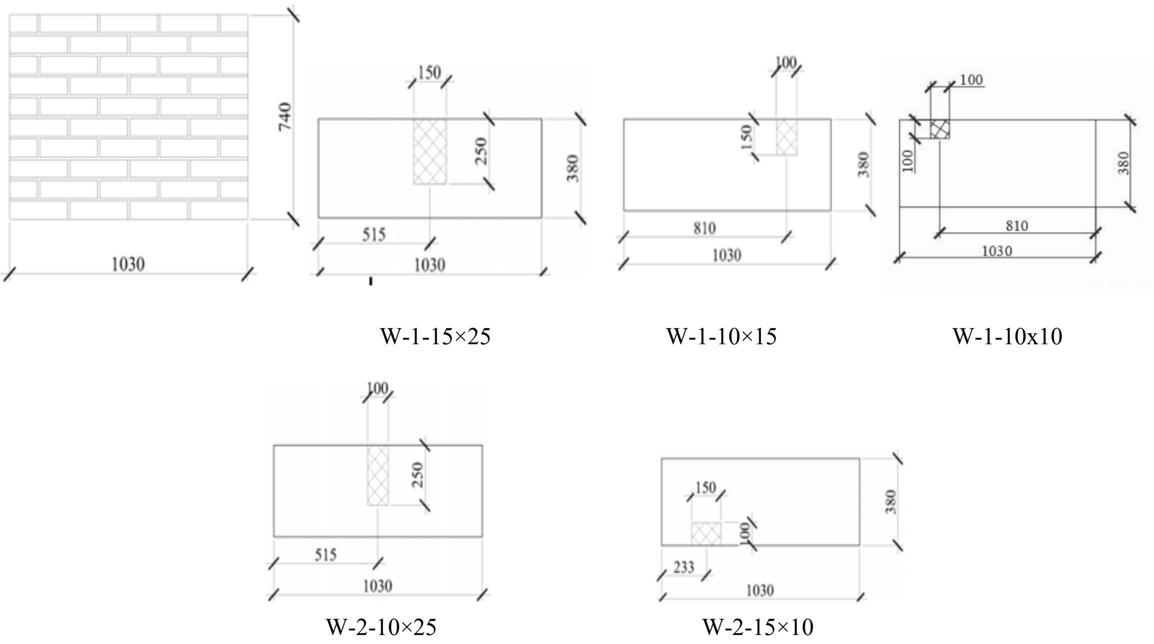


Figure 2 – Local compression cases for samples of the second series

Figure 3 – Masonry test column C-25.25.100 after testing

The destruction nature of the column with a cross-section of 380×380 mm is illustrated in Fig. 4. There are features of destruction similar to the previous sample, which are observed on two opposite edges of the test sample.

A column with a cross-section of 510×510 mm after testing is shown in Fig. 5. On one of its side faces, there is an inclined plane of destruction that extends both along the brick and along the mortar between the upper right and lower left corners of the face. On the other edge, two pyramids are visible, connected at their vertices in the middle of the column in height, combined with the separation of the side arrays. Vertical cracks are also present.

The results obtained by the authors confirm the data [1, 3, 4] (Fig. 6) regarding the presence of splitting cracks along the height of the test samples, compaction pyramids under the loading platform, crumbling of bricks within its limits, as well as local destruction in the corner areas of the elements.

Figure 4 – Masonry test column C-38.38.100 after testing

The nature of the wall destruction is shown in Fig. 7. On the front edges of the sample, there is a system of vertical and inclined cracks, areas with crumbling bricks. At the stage preceding the limit stage, one of the vertical cracks completely crossed the test sample and separated a column from it, which split in a plane perpendicular to the front edge.

Similar results were obtained in [7, 8] and others; almost all photos in Fig. 8 show the splitting of the wall parallel to the front edge.

Figure 5 – Masonry test column C-51.51.100 after testing

a

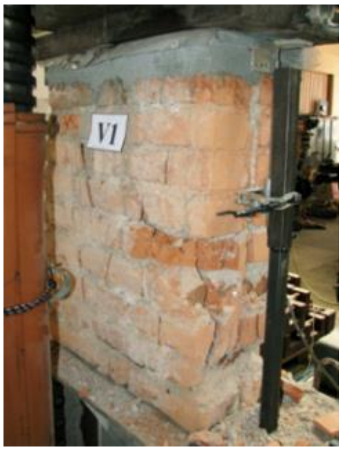
b

Figure 6 – The nature of the destruction of masonry columns under compression according to:
a – [4]; b – [1]

The nature of the destruction of the prisms is illustrated in Figures 9–13. The first two provide information on the results of testing samples with a height of three rows of masonry. More characteristic signs of destruction are shown in Fig. 10: crushing and delamination of bricks across the entire plane of the prisms; the presence of two wedges connected at the top in the middle of the sample height, the base of which is the supporting and loaded planes; a splitting crack in the plane of the element thickness.

Figure 7 – Test sample W-90.12.44 after testing

a



b

Figure 8 – The nature of wall destruction under axial compression in laboratory tests:
a – [6, 7]; b – [6]

Prisms with a height of five rows of masonry after destruction are shown in Fig. 11 and Fig. 12. Here, there are vertical and inclined cracks on the edges of the test samples, crumbling of bricks, and delamination of the outer layers.

The nature of the destruction of prisms with a height of 7 rows of masonry is shown in Fig. 13. The photo shows a broken plane of destruction on the front surface, delamination of the outer layers of masonry, vertical cracks, and crumbling bricks.

Figure 9 – Test sample P-25.12.21.5-a after testing

Figure 10 – Test sample P-25.12.21.5-b after testing

Figure 11 – Test sample P-25.12.36.5-a after testing

Figure 12 – Test sample P-25.12.36.5-b after testing

During testing of the prisms [8], it was established that initial cracking occurred in the middle part of the samples in terms of height. At this stage of loading, which was about 60% of the limit, the first vertical cracks formed in the central zone, passing through both the stone and the mortar joints.

Figure 13 – Test sample P-25.12.51.5-a after testing

According to the authors' interpretation, the occurrence of such cracks is caused by tensile loads arising in the composite structure of the masonry under the influence of the Poisson effect (Fig. 14).

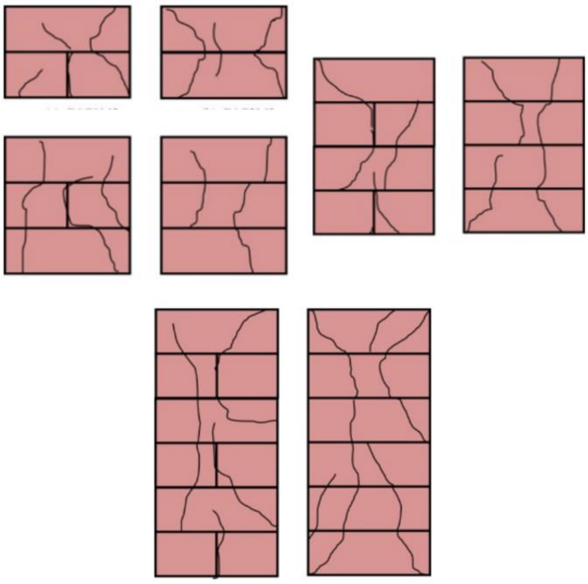


Figure 14 – The cracking pattern of prisms in [8]

With a further increase in load, intensive opening and development of existing cracks was observed, as well as the formation of new ones, which spread towards the upper and lower limits of the sample. In the areas of contact with the loading plates of the testing machine, the combined effect of tensile forces and friction forces between the clamping surfaces caused the formation of inclined cracks. For samples of smaller height, inclined cracks prevailed, which is explained by the reduced height of the area within which tensile forces act. The final stage of destruction occurred after the formation of inclined cracks in the brick elements of the upper and lower rows, which led to the fragmentation of the stones and the separation of individual vertical masonry columns, limited by previously formed vertical cracks.

In experiments [9–11], both destruction by splitting in the plane of the prism thickness and vertical cracks on the front surfaces of the samples were obtained (Fig. 15).

a

b

c

Figure 15 – The destruction nature of the test prisms according to: a – [11]; b – [10]; c – [9]

The theoretical compressive strength of brick masonry under short-term loading was determined using the formula by Onyshchyk L.I. [12]: $f_k = 3.66$ MPa.

According to the requirements of the norms [13], the characteristic value of masonry compressive strength can be calculated using the following equation:

$$f_k = K f_b^{\alpha} f_m^{\beta}. \qquad (1)$$

In our case $f_k = 5{,}2$ MPa.

The experimental determination results of the strength of test samples under axial compression are given in Table 2.

Among the columns, the highest load-bearing capacity was observed in the sample with a cross-section of 510×510 mm and a height of 1 m, which can be explained by its massiveness, operation under conditions of volumetric stress, and a reduction in the possibility of unevenness in the masonry structure affecting its resistance.

Testing of stone prisms showed that their resistance decreases as the *h/t* ratio of the samples increases. The highest load-bearing capacity was found in prisms with a ratio of *h/t* = 1.8 (three rows high), and the lowest in prisms with a ratio of *h/t* = 4.3 (seven rows high). The authors [8, 14, 15] made a similar assumption. At the same time, in [14], it is considered that the number of rows should be taken into account, rather than the *h/t* ratio.

Table 2 – Results of the 1st series experimental samples testing

No	Sample ID	N_u, kN	f_k, MPa
1	C-25.25.100	353.0	5.65
2	C-38.38.100	662.0	4.58
3	C-51.51.100	1961.3	7.54
4	W-90.12.44	594.3	5.5
5	P-25.12.2.5-a	204.0	6.8
6	P-25.12.21.5-б	158.9	5.3
7	P-25.12.36.5-a	143.2	4.77
8	P-25.12.36.5-б	149.1	4.97
9	P-25.12.51.5-a	136.3	4.54
10	P-25.12.51.5-б	131.4	4,38

The resistance of the wall sample is 5.5 MPa at a ratio of *h/t* = 3.67. In study [16], wall sections and wallettes made of clay bricks on a cement-sand mortar were tested. According to the data obtained, the resistance of the test samples increases with a decrease in the *h/t* ratio, similar to prisms. Similar results were obtained in [17].

Graphs showing the dependence of relative strains of masonry on the load level for columns with cross-sections of 250×250 mm, 380×380 mm, and 510×510 mm (Fig. 16–Fig. 18) were constructed based on the data from four indicators for each sample.

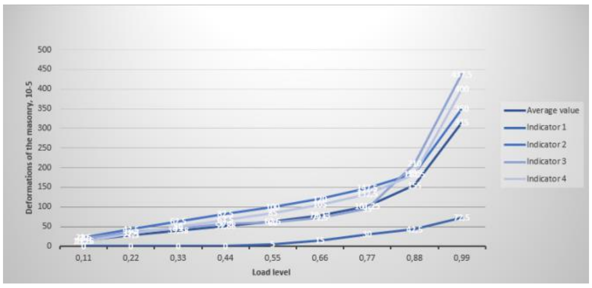


Figure 16 – Relative strain of brick masonry depending on the load level for a column with a cross-section of 250×250 mm (C-25.25.100)

The obtained strain values correspond to those described in [4], where for f_m= 5.96 MPa they are 0.0023, and in [9], where they reach a value of 0.0035.

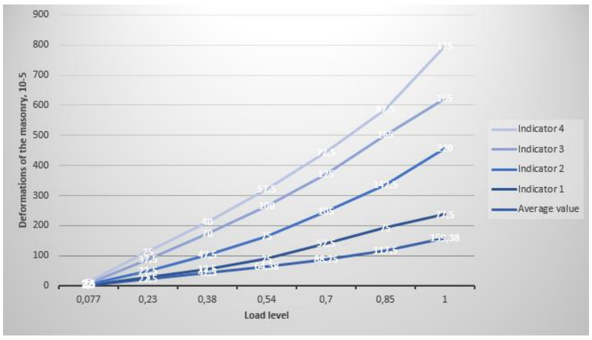


Figure 17 – Dependence of relative deformations of brick masonry on the load level for a column with a cross-section of 380×380 mm (C-38.38.100)

Distortions in deformation dependencies in the final stages of loading and the appearance of their plastic component, which suggests the feasibility of applying plasticity theory in the calculation of brick structures, were noted.

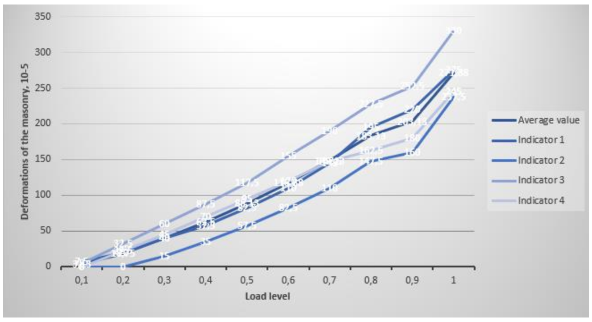
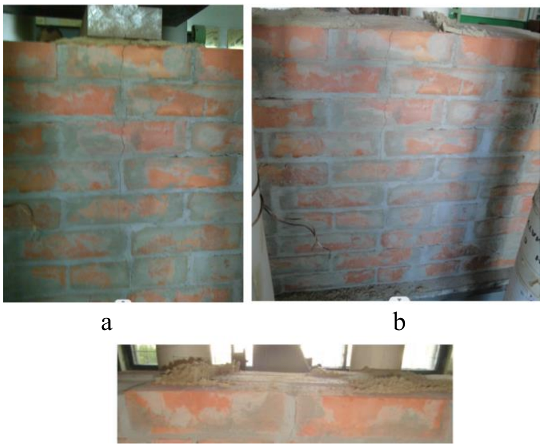


Figure 18 – Dependence of relative deformations of brick masonry on the load level for a column with a cross-section of 510×510 mm (C-51.51.100)

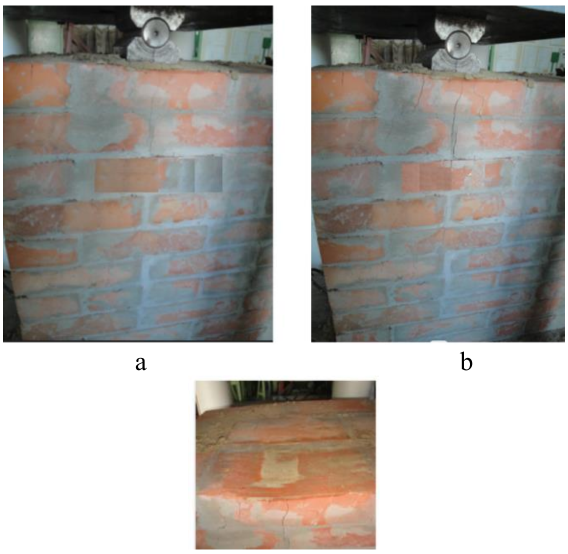
The nature of wall destruction during local compression is shown in Figures 19–23.



a b

c

Figure 19 – Test sample W-1-15×25: a – during testing; b – nature of destruction; c – load edge after testing

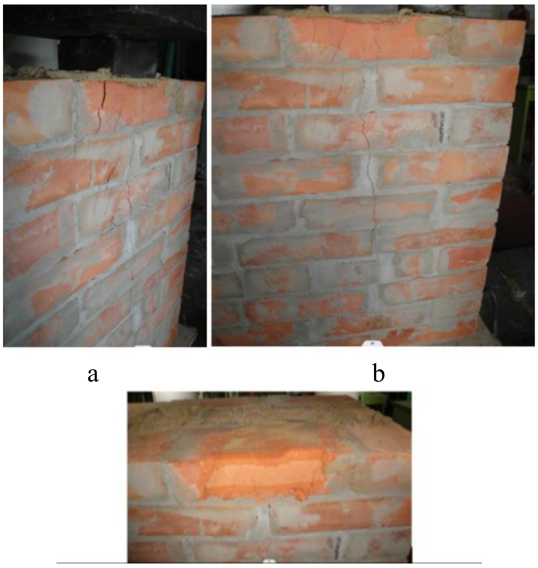


a b

c

Figure 20 – Test sample W-1-10×15: a – during testing; b – nature of destruction; c – load edge after testing

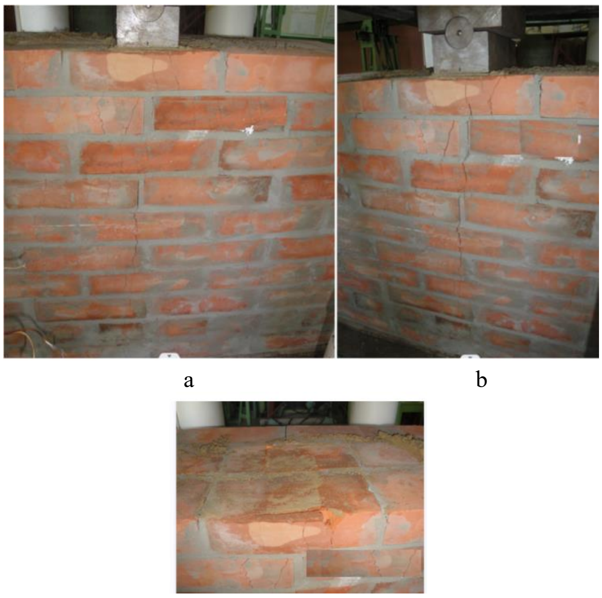
The marking of samples indicates the wall number and the dimensions of the loading area $l_{loc}\times b_{loc}$ in cm.



a b

c

Figure 21 – Test sample W-1-10×10: a – during testing; b – nature of failure; c – load edge after testing



a b

c

Figure 22 – Test sample W-2-10×25: a – during testing; b – nature of destruction; c – load edge after testing

When applying a load along the length of the wall using stamps whose width was less than the thickness of the wall, destruction was observed, in which a pyramid of compaction formed under the loading platform, which initiated the splitting of the sample along a plane extending to both front edges of the wall.

In one case, when the width of the loading area was greater than the length and the stamp was located close to the corner of the wall, the corner of the wall was cut off (Fig. 23).

Figure 23 – Test sample W-2-15×10:
a – during testing; b – nature of destruction

The compressive strength of brick masonry according to L.I. Onishchik's formula is $f_k = 2{,}67$ MPa, and according to formula (1) $f_k = 3{,}51$ MPa. The average result of the column tests is 3 MPa.

The results of the wall crush test are shown in Table 3. The main parameter of influence is the ratio l_{loc}/h, as it increases, resistance decreases.

Table 3 – Test results for the second series of samples

Sample ID	Stamp dimensions, mm		l_{loc}/h	$N_{u,\ test,}$ кН
	l_{loc}	b_{loc}		
W-1-15×25	150	250	0.20	228
W-1-10×15	100	150	0.14	219
W-1-10×10	100	100	0.14	156
W-2-10×25	100	250	0.14	224
W-2-15×10	150	100	0.20	96

Interpretation of results and their approval. Based on the results of the brick masonry testing for axial compression, the following can be proposed as reference samples: columns with a cross-section of 250×250 mm and a height of 1000 mm, a brick wall measuring 900×440 mm, or prisms five bricks high, the last two samples are half a brick thick.

The nature of masonry destruction under local compression allows us to assume that the dependencies obtained by the variational method can be used to calculate the splitting resistance.

Conclusions.

Three groups of samples were tested under axial compression, which are used to determine the compressive strength of masonry in different countries.

If columns are used as test samples, their cross-sectional dimensions are proposed to be 250×250 mm with a height of 1000 m. Alternatively, a wall with dimensions of 900×440 mm and a thickness of half a brick can be considered. When using prisms, it is advisable to use an element with a height of 5 bricks. The resistance values of the above samples show similar results, which are higher than the masonry strength obtained using the L.I. Onishchik formula.

When locally compressed by a stamp located near the front edge of the wall, with a width less than its thickness, the elements are destroyed with the formation of a compression pyramid under the stamp by splitting perpendicular to the front plane. The resistance of samples under local compression is greater than under axial compression. The main influencing factor is the ratio of the length of the loading area to the height of the wall.

In the stages preceding destruction, significant values of relative deformations of brick masonry are observed, which justify the possibility of applying the theory of plasticity in calculating the bearing capacity of masonry.

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Експериментальні дослідження міцності кам'яної кладки при місцевому та осьовому стисненні

Аннотація. Кам'яна кладка – це традиційний будівельний матеріал, який продовжує відігравати значну роль у сучасному цивільному та промисловому будівництві. Визначення її міцнісних характеристик, особливо при стискальному навантаженні, залишається актуальною дослідницькою проблемою, оскільки стискаючі сили є переважаючими в несучих стінах, колонах та інших конструкційних елементах кладки. На міцність кладки на стиск впливають численні фактори, включаючи міцність та геометричні властивості елементів, точність їхньої форми, наявність пустот, міцність розчину, деформаційні характеристики затверділого розчину, легкоукладальність розчинової суміші, міцність зчеплення між розчином та елементами кладки, ступінь заповнення швів, характер з'єднання та загальну якість виконання робіт. При визначенні міцності кладки при локальному стисканні враховується характер руйнування зразка, на основі якого розробляється відповідна кінематична схема, що визначає основні параметри, що впливають на міцність кладки. Одна з ключових проблем полягає у відсутності єдиного підходу до визначення геометричних параметрів зразків, що використовуються для випробувань. Метою цього дослідження є: 1. формулювання науково обґрунтованих рекомендацій щодо форми та розмірів стандартних зразків, що дозволить максимально достовірно оцінити осьову міцність кладки на стиск на основі результатів випробувань; 2. розгляд випадку локального стиснення стін штампами, розташованими біля грані, шириною меншою за товщину стіни.

Ключові слова: Кладка, міцність, стиск, цегла, розчин

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