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Work of masonry under the combined action of vertical and horizontal loads: an analysis of experimental studies

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The characteristic damage of masonry walls under the combined action of vertical and horizontal loads has been analyzed. Possible schemes of masonry destruction are considered. A diagonal shear is identified as a typical case of the destruction of piers under seismic impacts. The closeness of the loading conditions of the piers of the bearing walls under the action of the seismic force to those that arise in the frame when it is skewed is noted. The article considers the results of experimental studies of masonry specimens on the skew as models of the operation of piers under seismic impacts. The nature of destruction is analyzed, determining factors of influence. Based on the analysis of known experiments, proposals are presented for a kinematically possible scheme for the destruction of masonry walls, which is proposed as a base for the calculation

Keywords: diagonal shear, damage, seismic influence, scheme of destruction

Робота кам'яної кладки при сумісній дії вертикальних і горизонтальних навантажень: аналіз експериментальних досліджень

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Проаналізовані характерні пошкодження кам'яних стін при сумісній дії вертикальних і горизонтальних навантажень. Розглянуто можливі схеми руйнування кладки. Особливу увагу приділено міжвіконним простінкам, котрі є однією із найбільш напружених й уразливих конструкцій цегляних будівель з точки зору сейсмостійкості. Виділено діагональний зсув як характерний випадок руйнування простінків при сейсмічних впливах. Наголошено на близькості умов завантаження простінків несучих стін при дії сейсмічної сили до тих, які виникають у каркасі при його перекосі. Розглянуто результати експериментальних досліджень кам'яних зразків на перекіс як моделей роботи простінків. Проаналізовано характер руйнування, визначальні фактори впливу: матеріал кладки, міцність каменю і розчину, внутрішнє і зовнішнє армування кладки, підсилення розчинними і бетонними аплікаціями, перехресними та горизонтальними залізобетонними смугами, вуглеволокном, діагональними металевими тяжами та інші. На основі аналізу відомих експериментів надані пропозиції щодо кінематично можливої схеми руйнування кам'яних простінків, котру запропоновано як базову для розрахунку варіаційним методом у теорії пластичності, розробленим у Національному університеті «Полтавська політехніка імені Юрія Кондратюка» для розрахунку міцності бетонних і залізобетонних, кам'яних та армокам'яних елементів при зрізі, місцевому стисненні та продавлюванні. В стадії руйнування простінок розділяється на чотири жорсткі диски: два клини під вантажною площадкою і два диски, окреслені зсувними ділянками клинів і площиною розколювання, котра з'єднує їх вершини. Клини рухаються назустріч один одному, а два інших диски віддаляються один від одного в напрямку, перпендикулярному до площини розколювання

Ключові слова: діагональний зсув, пошкодження, сейсмічний вплив, схема руйнування

Introduction

Ensuring seismic resistance is always one of the main tasks in the design and construction of buildings and structures in earthquake-prone areas. Recently, the applicability of this problem for Ukraine has significantly increased in connection with the frequent cases of earthquakes in Europe, including with a large number of human victims and significant material damage.

New seismic zoning maps ZSR-2004, put into effect in the norms [1] since 2006, provide for an increase in the proportion of territories subject to seismic effects. According to them, at this time, approximately 15% of the territory of Ukraine is earthquake-prone with design seismicity of more than 7 points.

The size of economic losses from seismic effects established as a result of the analysis for buildings with different structural schemes (with the same seismicity of the site) [2] indicates that buildings with masonry walls that are widespread in Ukraine are the most vulnerable to seismic effects and belong to the least seismic-resistant type. This is due, in particular, to the increased mass of structures and the presence of a large number of joints and seams, which leads to significant damage to building elements.

Review of the research sources and publications

The results of recent studies [3 – 8] show that buildings with bearing masonry walls receive the following typical damages from the action of seismic loads: inclined and cruciform cracks in the piers of walls and unpierced walls; vertical cracks at the junction of the longitudinal and transverse walls with possible falling out of the walls; horizontal cracks in the walls, often at the level of the bottom of window areas, lintels or at the level of support of the floor; cracks in the places where reinforced concrete lintels were laid; cracks of a chaotic direction in the walls, which are a combination of the above (Fig. 1).

Definition of unsolved aspects of the problem

Currently, there is no methodology for calculating masonry structures under the combined action of vertical and horizontal forces, which would be based on a common theoretical basis.

Problem statement

To create a reliable method for assessing the bearing capacity of masonry walls under the combined action of vertical and horizontal loads and informed decision-making regarding their effective reinforcement, it is necessary to analyze the nature of the destruction of structures and the results of their physical modeling in the experiment. The data obtained will serve as the basis for creating design diagrams of elements in assessing their strength.

Basic material and results

Tumanov A. [9], based on the results of experimental studies, proposed a classification of cracks observed in masonry walls under the combined action of vertical and horizontal forces. The main types are:

- main vertical cracks that divide the surface of the walls into separate vertical blocks;
- limiting inclined cracks that define the boundaries of an inclined compressed strip (destruction area);
- microcracks, the accumulation of which leads to crushing of the masonry;
- cracks in the tensile zone;
- cracks that characterize a shear of compressed masonry in inclined compressed strips.

The proposed classification of cracks can be considered as a criterion for the implementation of individual schemes of masonry destruction: displacement in the horizontal plane, diagonal shear, failure beyond the tensile zone, and crushing (Fig. 2).

a)

b)

c)

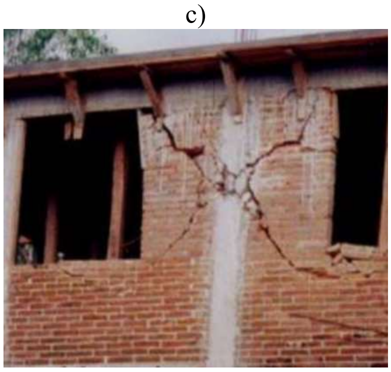


Figure 1 – The nature of the destruction of masonry walls under seismic effects:
a – a diagonal cracks [3];
b – a vertical crack at the junction of the longitudinal and transverse walls [7];
c – a cruciform crack in the wall [8]

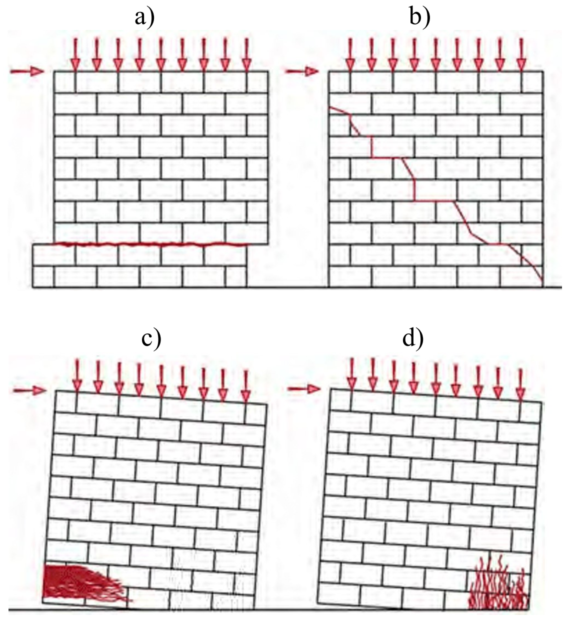


Figure 2 – The nature of the destruction of masonry under the combined action of vertical and horizontal loads:
a – displacement in the horizontal plane;
b – diagonal shear;
c – failure beyond the tensile zone;
d – crushing

One of the most vulnerable structures of masonry buildings in terms of seismic resistance are piers, cases of destruction are shown in Fig. 3 [10].

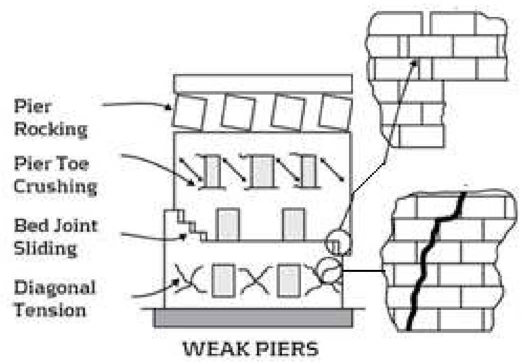


Figure 3 – Cases of destruction the piers under seismic effects

The width of the piers to a certain extent affects the location of the cracks (Fig. 4).

The most typical damage to walls is the formation of inclined and X-shaped cracks, which propagate mainly along the joints of the masonry, starting at the corners of the holes and other places where the walls weaken (change in stiffness). If the crack crosses the stones, then this is a sign of their insufficient strength, the layering of the masonry indicates a weak bond of the mortar to the stone. The value of crack opening can be different and is the main sign when assessing the degree of damage to a wall element.

According to [12], the piers of bearing walls under the action of a seismic force are under loading conditions that are close to those that arise in the frame when it is skewed.

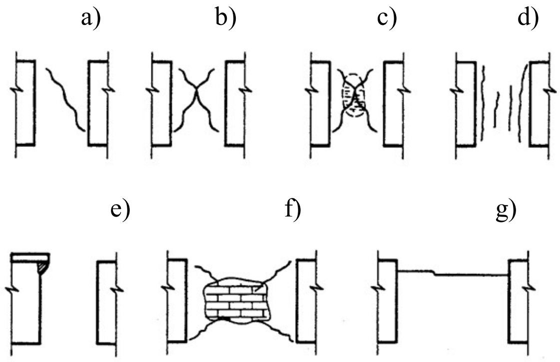


Figure 4 – Schemes of cracks location in the piers during earthquakes:
a – e – damage in relatively narrow piers;
f, g – the same in relatively wide piers [11]

In the first stage of deformation of the masonry (Fig. 5), when the seismic forces are small, the piers work together with the above-window chord over the entire contact area. The vertical load is transferred from the upper to the lower piers at all levels along all horizontal sections.

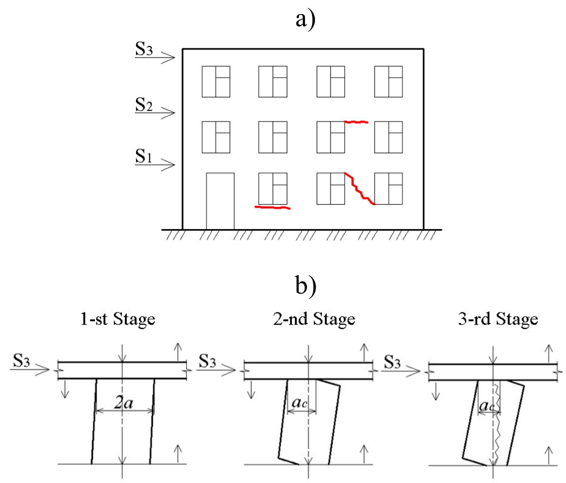


Figure 5 –The work of the piers of bearing walls under the action of horizontal seismic force:
a – characteristic damages;
b – stages of deformation of the piers

In the second stage, cracks form in the tensile zones of the horizontal section of the walls at the levels of the upper and lower parts of the window area adjacent to them, and the contact between the masonry is broken. At this stage, the transfer of vertical and horizontal loads in the mentioned sections is carried out only along with the length $a_c < 2a$ (where a is half the width of the pier). With an alternating horizontal load, the bond in the masonry is broken along the contact between the top of the pier and the bottom of the chord due to the formation of cracks.

The third stage is characterized by a further reduction in the length of the compressed zone and the formation of a diagonal crack in the pier. One and the same pier on different floors of a building may be at different stages of deformation, which is associated with a change in the values and ratio of vertical and horizontal forces, as well as with possible differences in the strength and stiffness of the piers.

So, an experimental study of the work of piers for the combined action of vertical and horizontal loads can be carried out when testing masonry samples on the skew, first performed by Dmitriev A. in 1940 in the laboratory of masonry structures CRIIS [13]. He tested fragments of vibrational masonry walls from hollow ceramic stones. Since 1948 Polyakov S. studied the features of work of filling in frame-stone buildings: 57 samples with frame and continuous filling were tested. Since the publication of the monograph by Polyakov S. [14], many authors have carried out experimental studies of the strength and deformability of fragments of masonry made of bricks of various types, limestone, and other materials when skewed without frame framing. In most cases, the specimens were tested with a concentrated load applied along with one of their diagonals (Fig. 6). To prevent crushing of the loaded corners of the masonry, the latter were reinforced with steel or reinforced concrete bearing elements. With this test scheme, the strength indicators of the samples are influenced by the length of the support areas (l_{loc}), through which the load is transferred to the sample.

Various methods of increasing the bearing capacity of elements under the combined action of vertical and horizontal forces were investigated.

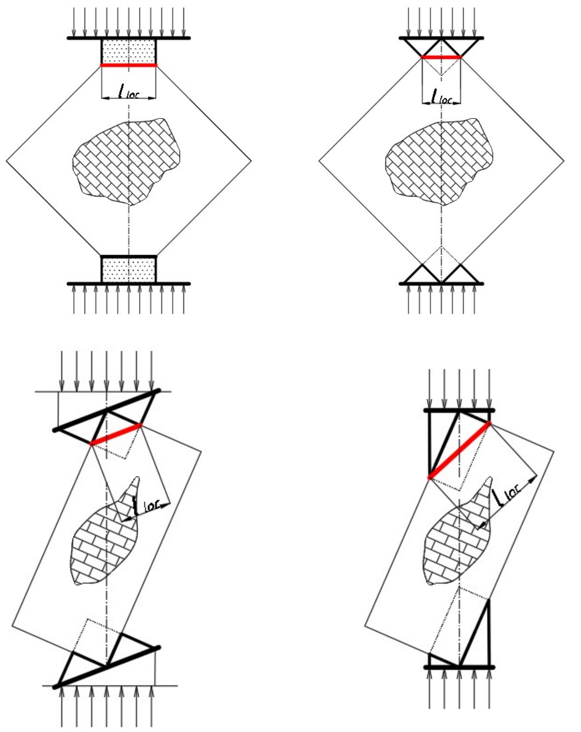


Figure 6 – Schemes used by researchers when testing masonry specimens for deformation during the application of a load along the diagonal

Known experiments with vibrational masonry panels with sides dimensions 1060×1060, 1120×1120, 800×800, 800×1200, and 800×1600 mm [15] without reinforcement and with reinforcement with vertical bars and wire meshes through three courses of masonry, which did not increase the strength of the samples. The desired result was achieved with external reinforcement, and here the distance between the moment of the formation of a diagonal crack and the destruction of the element significantly increased.

Kabantsev A. and Tonkikh P. [16] manufactured and tested 7 series of experimental samples with dimensions 1060×1060×250 mm from solid brick with strength f_b = 10 MPa on cement-sand mortar with strength f_m = 7.5 MPa: control samples without reinforcement and reinforced with one or two sides. Carbon fiber FibARM Tape 230 and FibARM Tape 240 and binder FibArm Resin 230+ and FibArm Resin 530+ were used as reinforcement elements [15]. The use of an external reinforcement system made it possible to increase the bearing capacity of the masonry by 30 – 100%, depending on the strength of the carbon fiber, area, thickness, and a number of reinforcement layers. The destruction of these samples, in contrast to those reinforced with reinforced concrete and concrete applications, which are applied according to the usual technology and by the concrete shotcrete method [16], occurred along a diagonal crack outside, brittle, almost instantly after reaching the ultimate loads.

During the tests Derkach V. of unreinforced samples with dimensions of 500×500×140 mm made of bricks with strength f_b = 15 MPa [17] the moment of formation of diagonal cracks coincided with the moment of destruction. At the same time, depending on the strength of the mortar, the following mechanisms of destruction were observed: splitting along the diagonal, in which the trajectory of the crack passes both along with the stones and along individual vertical and horizontal joints of the masonry (with a mortar with compressive strength f_m = 7.9 –10.9 MPa); splitting along the diagonal, in which the critical crack has a stepped trajectory and passes only along the horizontal and vertical joins of the masonry; displacement along the horizontal joints of the mortar (the last two types of destruction were observed when using a mortar with strength f_m = 3.1 MPa).

The experiments of Demchuk I. [18] were carried out on masonry samples with dimensions of 500×500×65 mm for the manufacture of which solid and hollow (18%) bricks were used on standard mortars with compressive strength f_m = 3.1, 7.9, and 10.9 MPa. The results obtained indicate a decrease in the shear strength of the masonry f_{vv} at the mortar strength f_m = 3.1 MPa.

Gasiev A. [12] produced and tested 3 series of samples with dimensions 1030×965×250 mm using a brick of average strength f_b = 12.5 MPa on a mortar with strength f_m = 7.5 MPa: control samples and reinforced with a sheet of carbon fiber brand MBRACE FIB CF230 / 4900.200g / 5.100m with one and two sides of the specimen along its extended diagonal. The bearing capacity in the first case of external reinforcement increases by about 1.5 times, and in the second by 2 times.

In the work of Izmailov Yu. [19], the results of experimental studies of the strength of four series of samples on the action of static and pulsating loads directed along the diagonal are presented. Both traditional masonry and vibrational brick elements were used. Strengthening was carried out by applying a plaster layer from a high-strength mortar to the side surfaces or reinforcing the plaster layer with steel meshes. Vibrations and the presence of plaster layers on the lateral surfaces of the samples increase the strength of the masonry up to 2 times; reinforcement postpones destruction from the moment of cracking, creating conditions for the development of plastic strain. Destruction of brick elements occurred along a diagonal crack, which spread along the joins, vibrational brick samples collapsed along a bandaged section; the destruction of the reinforced vibrational brick samples occurred along an inclined compressed strip. The effect on the resistance of the masonry was also analyzed by reinforcement with steel diagonal ties or during preliminary compression.

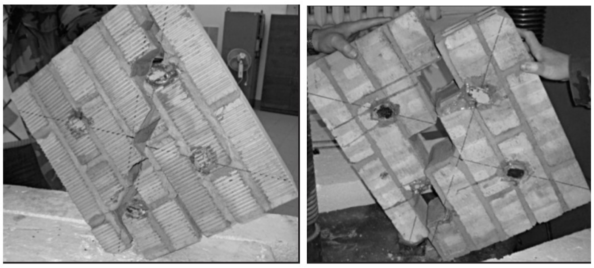
Experimental studies by Kadam S. and Singh Y. [6] included tests of six series of samples with strength characteristics of brick f_b = 21.06 MPa and mortar f_m = 3.72 MPa. The first two series had three reinforced masonry piers with dimensions of 700×700×115 mm (single-layer) and 700×700×230 mm (two-layer). Samples 3 – 6 series were reinforced from the outside (in one and two planes) with welded wire meshes located in a layer of concrete. Destruction of unreinforced specimens occurred behind a jagged diagonal crack and was sudden and externally brittle. The authors propose to consider this failure as a combination of diagonal shear and horizontal displacement. The behavior of reinforced specimens depended on their thickness, intensity, and method of reinforcement. The destruction began with the formation of a diagonal crack, the development of which was restrained for a certain time by reinforcement, which promoted more plastic failure in comparison with the samples without reinforcement. For specimens reinforced in one direction, the failure was accompanied by cracks that were localized along the edges of the specimen. At large displacements, there was a significant local crushing of the concrete adjacent to the welded mesh, which was torn in some places. For specimens reinforced in two directions, failure occurred along a crack that propagated along the length of the compressed diagonal of the specimens. At the last stage of loading, local crushing of the masonry in the places of load application was observed. The increase in the shear strength of the reinforced specimens in comparison with the reference was in the range of 0.57 – 1.48 MPa.

In the experiments of Dong K., Sui Z., Jiang J., Zhou X. [20], solid brick and ordinary mortar were used to make samples with dimensions of 2100×1560×240 mm and 1560×1560×240 mm (a total of 11 piers were tested). Three samples without reinforcement served as reference, the other 8 were reinforced with reinforced cross and horizontal strips from a solution 250 mm wide. The experiment varied: the strength of the mortar of masonry and reinforcement strips, their thickness, the reinforcement ratio of the strips, the location of the reinforcement (on one or both sides), as well as the value of the vertical load. For the value of samples, a brick with dimensions of 240×115×53 mm with f_b = 10 MPa and a mortar with f_m = 1 MPa, 2.5 MPa, and 10 MPa for unreinforced elements were used. For reinforcement strips with a thickness of 40 mm and 60 mm, a mortar with f_m = 2.5 MPa, 5 MPa, and 10 MPa was taken, respectively. The strips were reinforced with steel bars 6 – 12 mm in diameter. To simulate the work of the walls of the first floor of a seven-story building, a vertical load of 0.516 MPa was applied, the third – 0.4 MPa, and the seventh – 0.21 MPa. In the reference specimens, the first diagonal crack appeared in the center of the wall. It spread mainly along with horizontal and vertical layers of mortar, while in some places it crossed the brick. Sometimes a second diagonal crack could appear perpendicular to the first. Reinforced specimens collapsed from shear-compression along diagonal and vertical cracks, the latter appearing in unreinforced zones of the wall. When the maximum bearing capacity was reached, the strips retained their integrity and prevented the collapse of the samples during failure. The cracking load for the reinforced elements increased by 20 – 40%, and the ultimate load by 40 – 65%. An increase in the reinforcement ratio of the strips, the level of vertical stresses, and the strength of the mortar increased the shear resistance, while an increase in the ratio of the thickness to the width of the element, on the contrary, decreased it. The reinforcement increased the plastic properties of the masonry by 1.6 times with one-sided reinforcement and 2.8 times with two-sided reinforcement.

In the experiments of Mustafaraj E. and Yardim Y. [5], 6 specimens with dimensions of 1200×1200×250 mm was used with an average strength of a brick f_b = 24.03 MPa and mortar f_m = 5.68 MPa in compression. The samples were reinforced with a fiberglass mesh on both sides of the wall, followed by a layer of mortar. The test procedure was carried out in accordance with ASTM [21].

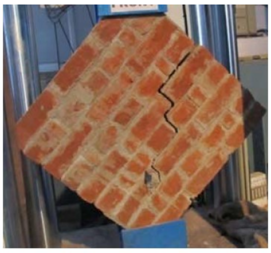
In the control unreinforced samples, destruction occurred along the compressed diagonal, mainly behind the mortar joins. However, in some cases, a combination of displacement along mortar horizontal joins over a length of about 500 mm was observed with a diagonal crack that propagated exclusively through he mortar joints. Specimens reinforced with fiberglass were destroyed along the compressed diagonal, their strength increased by an average of 1.3 times, while the plastic characteristics of the masonry increased.

So, analyzing the experimental studies of masonry on the skew, which can be considered as a simulation of the operation of masonry piers with the combined action of vertical and horizontal seismic forces, it should be noted that the most characteristic variant of failure (Fig. 7) is a diagonal shear in accordance with the classification (a crack can be stepped – extends only along vertical and horizontal mortar joins or rectilinear – crosses both the seams and the stone). Local crushing of masonry at the supports is also observed [16].



according to [17]

according to [12]



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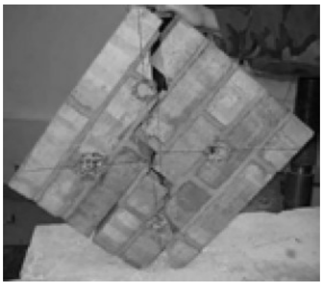

according to [3]

according to [5]

Figure 7 – Diagonal shear of masonry in experimental studies on the skew

Undoubtedly, the most complete data on the nature of deformation and destruction of masonry under the shear can be obtained experimentally. However, experiments require significant costs, and most importantly are parametrically limited, therefore, numerical calculations are an effective addition to physical experiments. A correct mathematical model is a tool for analyzing the influence of the selected parameters and their combination on the stress-strain state of the masonry. As a computational model, it is proposed to use the variational method in the theory of plasticity [22], which is widely used in calculations of concrete and reinforced concrete structures with a shear failure scheme [23 – 26]. And the failure obtained in experiments serves as a justification for the accepted kinematically possible failure scheme.

In the theoretical model, at the stage of destruction, the pier is divided into four hard disks: two wedges under the loading area (in the general case, the wedges should be non-sided) and two hard disks indicated by the shear sections of the wedges and a splitting plane that connects the tops of the wedges.

The wedges move towards each other; the other two disks move away from each other in a direction perpendicular to the splitting plane. There are four unknowns in the problem: two angles of inclination of the sections of shear of the wedges to the vertical, the ratio of the speeds of movement of hard disks, and the ultimate load.

Conclusions

In the experiments performed, the nature of the destruction of masonry samples was investigated when they were skewed, the effect of the masonry material, the strength of the stone and mortar, the internal and external reinforcement of the masonry, its reinforcement with mortar and concrete applications, cross, and horizontal reinforced concrete strips, carbon fiber, diagonal steel tension bar on strength of elements were revealed under the combined action of vertical and horizontal loads.

The analysis of the material under consideration made it possible to propose a substantiated kinematically possible scheme for the failure of masonry elements when skewed, which will serve as the basis for using the method for calculating the strength of such structures by the variational method in the theory of plasticity, developed at National University «Yuri Kondratyuk Poltava Polytechnic».

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