This study's object is brick structures for multi-story residential construction. In such buildings it is necessary to arrange built-in protective structures for civil defense. As a result of prolonged temperature and humidity exposure, wetting and destruction of brickwork may occur. Solving this problem requires devising measures to isolate brickwork from external influences, as well as, if necessary, options for strengthening damaged structures.

One of the results of this work is the identification of principal damage based on analysis of the consequences of prolonged temperature and humidity exposure to complexly loaded brick structures (walls, partitions, columns) of a public facility. This is frost-related damage up to 40% of the initial cross-section, which is mainly associated with different porosity of the brick and the influence of atmospheric precipitation.

The next result of the work is proposals for increasing the bearing capacity of damaged brickwork using tie clips from rolled steel elements. A qualitative feature of the proposal is the recommendations for installing these clips, which allow them to be included in joint work with existing brick elements. This qualitative distinctive feature was confirmed by mathematical numerical modeling of the increase in the bearing capacity of reinforcement brick structures.

From a scientific perspective, different initial stress-strain states of brick structures and steel elements at the time of ensuring their joint operation were taken into account. After the installation of steel clips, the maximum compressive stresses in the brickwork decreased by 28.6%. The results could be applied when installing reinforcements with steel clips for damaged compressed brick structures

Keywords: protective structures, brick columns, frost damage, reinforcement, modeling, finite elements

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APPLYING MATHEMATICAL MODELING TO DETERMINE THE EFFICIENCY OF REINFORCING BRICK COLUMNS IN THE BUILT-IN CIVIL DEFENSE STRUCTURES WITH STEEL CAGES

Anton Hasenko
Corresponding author
Doctor of Technical Sciences, Associate Professor
Department of Highways, Geodesy, Land and Management**
E-mail: gasentk@gmail.com

Dmytro Usenko
Doctor of Philosophy (PhD)
Department of Chemistry and Physics**

Pavlo Semko
PhD*

Dmytro Ovsii
Doctor of Philosophy (PhD)*

*Department of Architecture and Urban Construction**
**National University «Yuri Kondratyuk Poltava Polytechnic»
Vitaliya Hrytsayenka ave., 24, Poltava, Ukraine, 36011

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1. Introduction

Under the conditions of martial law in Ukraine, the issue of expanding the fund of protective structures for civil defense of people [1] is acute. A fairly large number of dual-purpose structures that are built into existing public or residential buildings and are among the structures for civil defense of people have brick enclosing structures. To ensure the bearing capacity of such enclosing structures in accordance with DBN V.2.2-5:2023 "Protective structures for civil defense", it is necessary to carry out their reinforcement, which mostly comes down to the installation of steel frames or duplicate reinforced concrete elements. In addition, the need to reinforce brick structures with steel frames arises when the structures of buildings that are in an unfinished state and unpreserved form are damaged.

The principal damage to brickwork is frost damage, which is mainly associated with different porosity of bricks and the influence of atmospheric precipitation. That is why devising and examining effective measures to increase the bearing capacity of brick structures is a relevant issue.

2. Literature review and problem statement

In work [2], a well-known solution of using brick structures for vertical load-bearing elements of buildings and facilities is reported. In such buildings, according to modern requirements, it is necessary to arrange built-in protective structures for civil defense. It is shown that the popularity of brick structures is due to high strength, good thermal insulation properties, fairly high fire resistance, and durability [3]. According to the cited work, more than 20% of buildings are built of artificial stones (bricks). At the same time, the age of such buildings reaches 50 years. But the issues related to the gradual frost-induced destruction of brickwork during prolonged temperature and humidity effects during long-term operation of stone buildings [4] remained unresolved. Identification of major damage to brick structures is the first part of the problem. The main causes of damage to building structures are direct ingress of moisture, which leads to material degradation. Typical damages resulting from uneven settlements are inclined and cross-shaped cracks in the piers and blind walls; vertical cracks in the places of connection of longitudinal and transverse walls with possible falling of the walls outwards. Typical damages of brick structures due to imperfection of structural solutions are horizontal cracks in the walls, more often at the level of the bottom of window openings, lintels, or at the level of floor support; cracks in the places of laying of reinforced concrete lintels. Using non-destructive strength control methods, it is possible to determine the strength of exploited brick structures and determine their actual bearing capacity.

It should be noted that it is also worth taking into account the specified damages during the combined action of vertical and horizontal loads on the building [5]. The reason for this may be the difficulties associated with taking into account, in addition to the action of permanent loads from the self-weight of wall and floor structures, temporary loads on the floor, the weight of the snow cover, additional pressure from the action of the shock wave. Proposals for the effective inclusion of steel reinforcement elements in the joint operation of the formed composite structure are given in [6]. Devising effective methods for strengthening brick structures is the second part of the problem.

An option to overcome these difficulties may be numerical modeling of the behavior of building structures under the action of both static and dynamic loads, as well as temperature effects. This approach was used in [7] during finite element analysis of building structures in ScadSoft SCAD Office. During finite element analysis, the structure is divided into a large number of simple geometric elements (finite elements), each of which has its own properties (material, geometry). However, despite the large number of finite elements, the advantages of finite element analysis are the calculation of the behavior of each finite element depending on the loads and boundary conditions. Another positive feature of the analysis is the representation in the form of diagrams of deformations, stresses, displacements, and other parameters, which help engineers evaluate the structure [8]. Advanced computer-aided design (CAD) technologies are used to construct structural models.

Thus, finite element modeling [9, 10] may be an option for overcoming the difficulties in predicting the performance of damaged brick structures after reinforcement. ScadSoft SCAD Office has a fairly wide range of subroutines designed to model specific tasks. However, the construction of models for individual needs in this program is limited. Identifying an effective algorithm for finite element modeling of brick structures taking into account steel reinforcement elements and searching for a finite element modeling software package with arbitrary construction of models for one's own requirements is the third part of the problem. This, in turn, may be the basis for optimizing the structure and identifying weaknesses in order to ensure the safety and durability of buildings [11].

All this gives grounds to argue that it is advisable to conduct a study aimed at determining the effectiveness of reinforcement of brick columns in the built-in civil defense structures with steel collars by mathematical modeling.

3. The aim and objectives of the study

The aim of our work is to determine the effectiveness of reinforcing brick columns in the built-in civil defense structures with steel clips using mathematical modeling. This will make it possible to determine the actual load-bearing capacity of the formed composite structures, taking into account the different initial stress-strain states of their components.

To achieve this aim, the following objectives were accomplished:

– to perform an analysis of damage to brick complex-loaded deformed structures (walls, piers, columns) in a public facility that occurred after prolonged temperature and humidity effects as a result of the building being in an unfinished, unpreserved state;

– to devise proposals for effectively increasing the load-bearing capacity of brickwork by installing steel clips and including them in joint operation with damaged structures;

– to identify an effective algorithm for constructing finite element models of composite samples of spatially reinforced brick columns formed after reinforcement of damaged brick structures with steel clips, taking into account their different initial stress-strain states;

– to represent the results of finite element analysis of brick columns before and after reinforcement.

4. The study materials and methods

The object of our study is brick structures located in a public facility in the city of Poltava (Ukraine). According to the provided design drawings, the building was designed to be 5 floors high with a technical basement. Construction of the building stopped about 8 years ago. Over the entire period, the building was in an unpreserved state and was subject to environmental influences. The general view of the building facades at the time of the survey (summer 2024) is shown in Fig. 1.

External longitudinal load-bearing walls have a thickness of 51 cm (2 bricks). Internal longitudinal load-bearing walls have a thickness of 38 cm (1.5 bricks). The corners of the brick walls according to the drawings are reinforced with 3 VR1 100×100 mm through three rows of masonry. The partitions between the rooms are thick at 0.5 brick (12–15 cm). In fact, there are load-bearing brick walls of two floors (first and second) and reinforced concrete floor panels under the first, second and third floors. On the third floor, the walls are made above the lintels above the windows by 3 rows of bricks. The facade of the third floor is missing on one of the facades, as well as the internal walls and the elevator shaft's walls. The partitions are either partially missing or partially destroyed by unknown attackers.

The actual strength of the brickwork was determined during non-destructive tests conducted in accordance with DSTU B V.2.7-61:2008 (EN 771-1:2003, NEQ) "Building materials. Ordinary and facing ceramic bricks and stones. Technical conditions". The tests were conducted in accordance with DSTU B V.2.7-248:2011 "Wall materials. Methods for determining the ultimate strength in compression and bending". According to our results from determining the strength of the brickwork, it was established that the supporting structures of the building correspond to the technical condition III – unsuitable for normal operation, which requires devising measures to restore the design parameters, in particular the brickwork.

a

b

Fig. 1. General view of the facades at a public facility: *a* – main facade; *b* – side facade

Mathematical finite element modeling of the studied structures was carried out using the Software Package Femap 2020.2 with NX Nastran (Trial Version Siemens Digital Industries Software with personal activation code 2827301401535961 was used). The developer of the Femap software is Siemens Digital Industries Software. Nonlinear behavior of materials, primarily brickwork, was solved by the Newton-Raphson step-iterative method.

5. Results of mathematical modeling of brick columns reinforced with steel clips formed after reinforcement

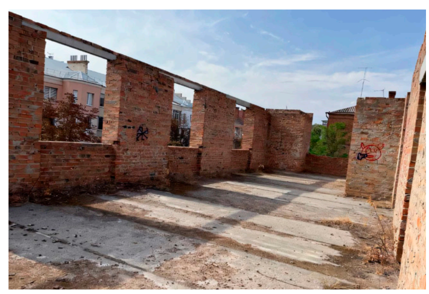
5. 1. Damage analysis of brick complex-loaded deformed structures (walls, piers, columns) in a public facility

The main factor that caused almost all damage is the incompleteness of the building structures of the facility under study, which led to prolonged exposure to precipitation and frost damage to brick (Fig. 2) and reinforced concrete structures. As is known, frost damage to brickwork is a process of damage to bricks and mortar in the masonry caused by repeated freezing and thawing of water that has penetrated the pores of the material. As a result, water, turning into ice, expands, creating internal pressure and gradually destroying the brick and mortar. Frost damage to brickwork is due to the different porosity of the brick (Fig. 3) and lack of protection from precipitation. The result of frost damage is a reduction in the cross-section of the walls (up to 60 mm) and a decrease in the strength of the brick. These factors in combination reduce the bearing capacity of the walls by up to 40%. According to Section 5 and Appendix B.3, as well as Table B.3.1 “Natural classification features of the technical condition of stone and reinforced stone structures” of DSTU 9372:2024, the technical condition of brick structures with such damage is assigned category III – unsuitable for normal operation. Therefore, the indicated damaged areas of brickwork require the development of reinforcement options.

a *b* *c*

Fig. 2. Damage caused by frost heave to brick wall structures: *a* – damage to the internal partition; *b* – damage to the internal load-bearing wall; *c* – damage to the external load-bearing wall

a



b

Fig. 3. Reasons for accelerated frost damage to brickwork: *a* – different porosity of the brick; *b* – lack of protection from precipitation

Based on a visual inspection of the surface of the brick walls and non-destructive testing of the strength of their individual fragments, a photo recording of the existing condition was performed (Fig. 2, 3). In addition, diagrams of the location of damage and defects in the brickwork were constructed, depicted on the scans of the internal and external walls. It was established that thawing, weathering and, as a result, destruction of the brickwork over the total depth (on both sides) is about 40% of the thickness. The main causes of frost damage to brick structures are different porosity of the brick, firing (over-firing) of individual bricks, and the influence of atmospheric precipitation. This percentage of damage corresponds to the category of technical condition III according to Table B.3.1 "Natural classification features of the technical condition of stone and reinforced stone structures" DSTU 9372:2024. No vertical or inclined force cracks were detected in the brick structures.

5. 2. Compiling proposals for the effective arrangement of steel frames for damaged brick elements

One of the most effective ways to strengthen brickwork in the case of local or general damage is to use external steel frames with subsequent internal concreting [12]. The technology involves the creation of a composite system "brick-steel-concrete" where all materials work together, compensating for the loss of strength of the original structure. The most typical variants of such reinforcements are implemented in the form of technological schemes R3 (reinforcement of columns) and R9 (reinforcement of openings). Scheme R3 provides for the restoration of vertical elements, allows integrating a brick column into a spatial rigid system through steel and concrete. Scheme R9 is aimed at local reinforcement of openings, where the main task is to stabilize the lintel zone. Both systems are based on the principle of transforming masonry into a composite element, which makes it possible to expand the bearing capacity of the structure without completely replacing the masonry. Practice shows that both schemes are effective for the reconstruction of old brick housing stock under conditions of limited access and impossibility of complete dismantling of structures.

Scheme R3 (Fig. 4, *a*) involves the sequential arrangement of a steel cage around a brick column that has suffered damage or partial loss of bearing capacity. The main goal is to restore the vertical stability of the element and reduce deformations under load.

The engineering and analytical model of this scheme shows that in the presence of a cage of rigid corners and ladders, the outer shell takes on part of the vertical forces, and the inner concrete core provides resistance to crushing and maintains the shape. Such a composite system has an increased bearing capacity and a significantly greater reserve of durability compared to restored brick.

According to the design solution, the reinforcement R3 is performed as follows:

1. Base preparation: the upper plane of the floor slab is cleaned to "live" concrete. A leveling layer of cement-sand mortar of the M100 brand is applied.
2. Installation of the cage: four steel corners L75 × 8 mm are mounted, which are placed at the corners of the column. They are installed using cement mortar and, if necessary, fixed with self-expanding dowels.
3. Corner bonding: to ensure spatial rigidity of the structure, "ladders" are welded between the corners on both sides – flat strips 8 mm thick and 100 mm wide. They are oriented both horizontally (at the level of 1/3 of the floor slab) and vertically – from opposite sides of the frame.
4. Anti-corrosion protection: all metal elements are treated in two layers with PF-115 paint on GF-021 primer in accordance with the requirements of ISO 12944-5:2020.
5. Restoration of masonry: after installation of the structure, damaged areas of bricks are selected, the surface is moistened, and the internal volume is filled with concrete of class C20/25 with compaction, or cement-sand mortar M200 with reinforcement with a mesh Ø8 mm of class VI with a cell of 100 × 100 mm.
6. Limitation: reinforcement is carried out exclusively in the absence of loads on the floors (snow, temporary, operational), which makes additional deformations impossible and ensures installation accuracy.

Scheme R9 (Fig. 4, *b*) is intended for local reinforcement of the area of openings in load-bearing or enclosing brick walls. The main goal is to reduce stresses in the lintels and prevent progressive destruction due to the concentration of forces around the opening.

According to the design solution, R9 reinforcement is performed as follows:

1. Preparation: on both sides of the wall, the damaged layer of brick is removed to a "live" state. Cleaning, moistening and preparation for laying the frame are performed.
2. Installation of the frame: on both sides of the opening, steel corners L75 × 6 mm are vertically mounted, which rest on a horizontal corner laid on the lower part on the M100 mortar on the floor slab.
3. Formation of "ladders": transverse bars with holes are inserted between the vertical posts, which are connected by ties. The upper part of the opening is fixed with a horizontal ladder, which forms a reinforced jumper welded to the vertical elements.
4. Welding: all connections are made with a welded seam with a leg of at least 5 mm in accordance with DBN V.2.6-198:2014.
5. Concreting: the internal volume of the opening is filled with concrete C20/25 or M200 mortar with Ø8 mm mesh reinforcement, which provides additional rigidity and stability.

Analytically proposed reinforcement systems make it possible to redistribute stresses to steel elements, reduce the risk of cracks opening in the jumper, and create an effective spatial structure that works for tension

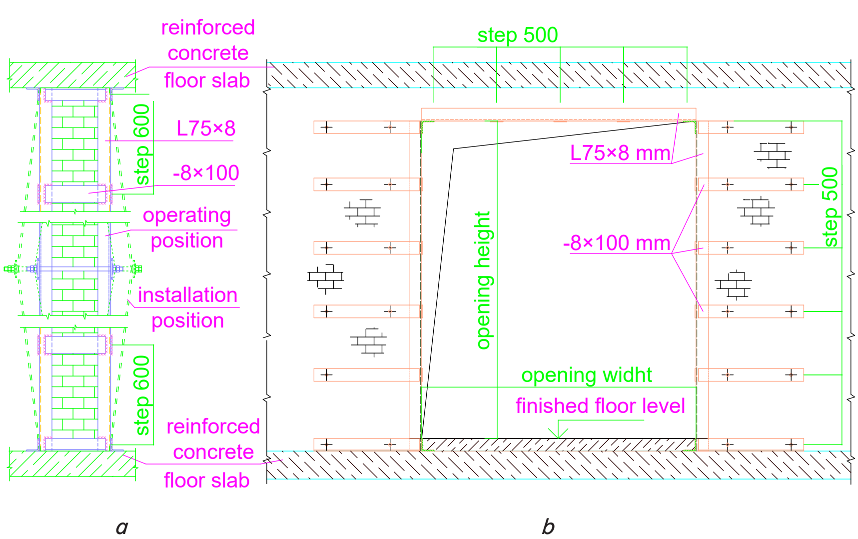


Fig. 4. General view of solutions for strengthening damaged elements: *a* — brick columns; *b* — brick structures along the perimeter of openings

and bending. This is especially true when reconstructing openings in the walls of frame houses where the inherent bearing capacity of the masonry is underestimated.

5. 3. Developing an effective algorithm for constructing finite element models of composite samples of spatially reinforced brick columns

The construction of a finite element model to determine the stress-strain state of numerical models of brick structures before and after reinforcement and their analysis in the elastic stage of work was performed using some techniques described below. The use of these techniques has made it possible to take into account the actual physical and mechanical properties and different stress-strain states at the time of ensuring the joint operation of the components of the composite structure.

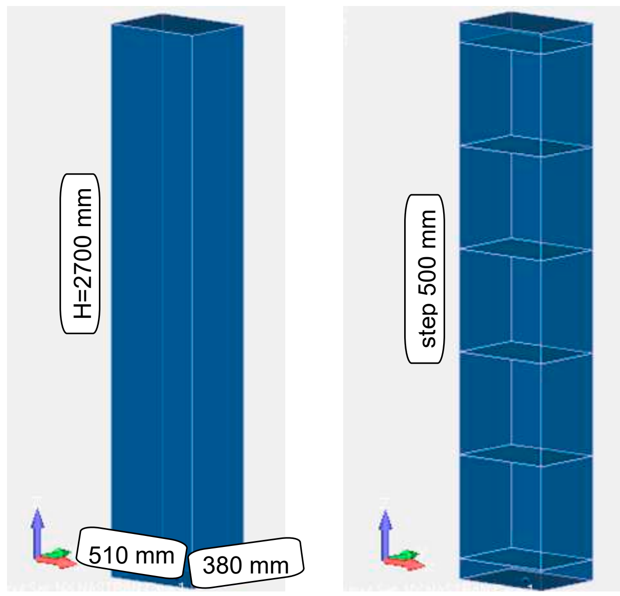
Initially, a flat cross-section of the studied brick masonry model was built using straight lines specified by the coordinates of the nodal points. The volumetric model of the structure (brick masonry) was formed by extending the flat boundary surface formed in advance along the specified straight lines to the required height of the model (Fig. 5, *a*). To specify steel reinforcement elements, it is necessary to first select the lines of their location in a solid body (brickwork – Fig. 5, *b*). To do this, the solid body was cut with planes, at the intersection of which lines were formed for the subsequent location of steel reinforcement elements on them (Fig. 6).

The model materials (characteristics of brickwork and reinforcing bars) were specified separately as isotropic. All material properties were specified as scalar quantities. The values of the physical and mechanical characteristics of the materials (Young's modulus of elasticity E and the coefficient of transverse deformations ν) and the deformation law (σ-ε) were taken according to the current regulatory documents. The third constant – the shear modulus G – was determined automatically from the known ratio between E and ν.

During the modeling of the structures, it was assumed that they would operate in the elastic-plastic stage. Therefore, when specifying the characteristics of the materials, bilinear dependences between load and deformations were taken into account. The steel work diagram was specified in a simplified form using the Prandtl diagram. It was assumed that critical (destructive) deformations in the brickwork (the beginning of the opening of cracks between the masonry composites) occur earlier than the steel strengthening area. Therefore, the steel work diagram was interrupted at the yield point.

The constructed three-dimensional model was "filled" with finite elements. The steel reinforcement elements – corners and strips – were divided into one-dimensional elements. These are those whose properties are determined along a straight line (Fig. 7).

The brickwork was divided into three-dimensional (volumetric) finite elements. The three-dimensional elements proposed in the NASTRAN database are divided into tetrahedra (a three-dimensional body with four sides and four corners – Fig. 8, *a*) and hexahedra (a three-dimensional body with five sides and five corners – Fig. 8, *b*). When modeling spatial bodies of regular geometric shape, finite elements in the form of a hexahedron are preferred. In addition, the choice of the type and size of three-dimensional finite elements was influenced by the time of constructing a three-dimensional finite element mesh, the required disk space for performing the NASTRAN calculation, the accuracy and convergence of the results obtained when calculating models divided by different finite elements.



a *b*

Fig. 5. Constructing the three-dimensional geometry of a brick column model: *a* — dimensions of the brick column; *b* — three-dimensional geometry of the brickwork cut by planes

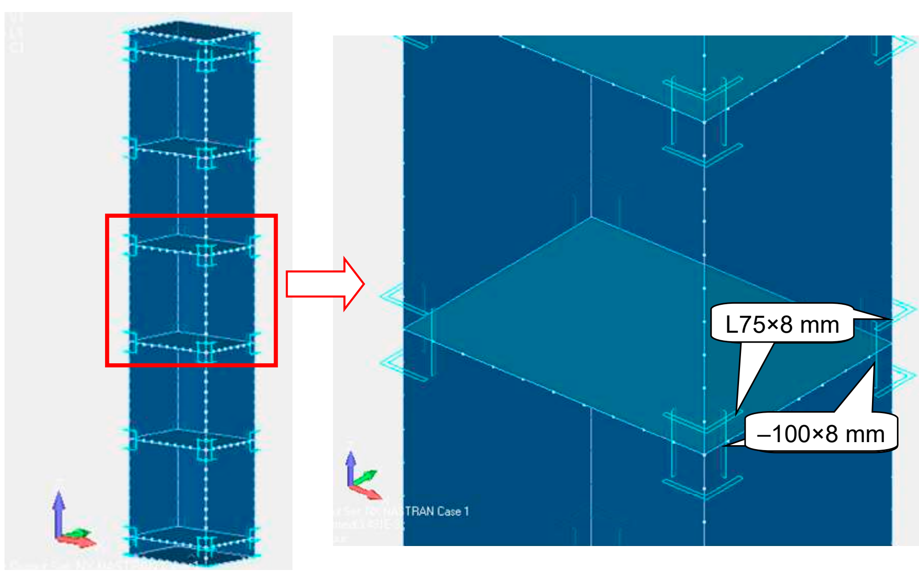


Fig. 6. Arrangement at the intersection of the planes of steel elements

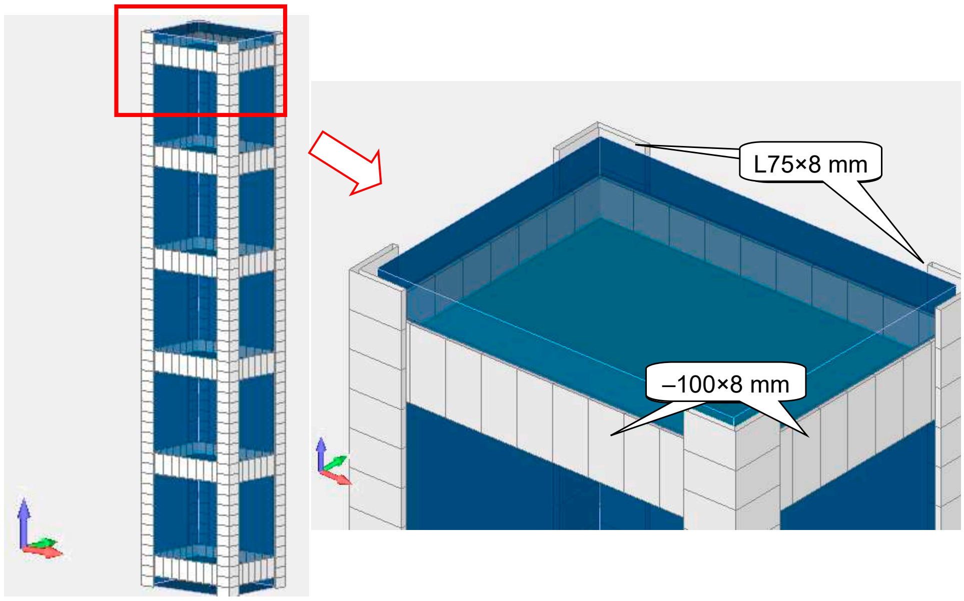
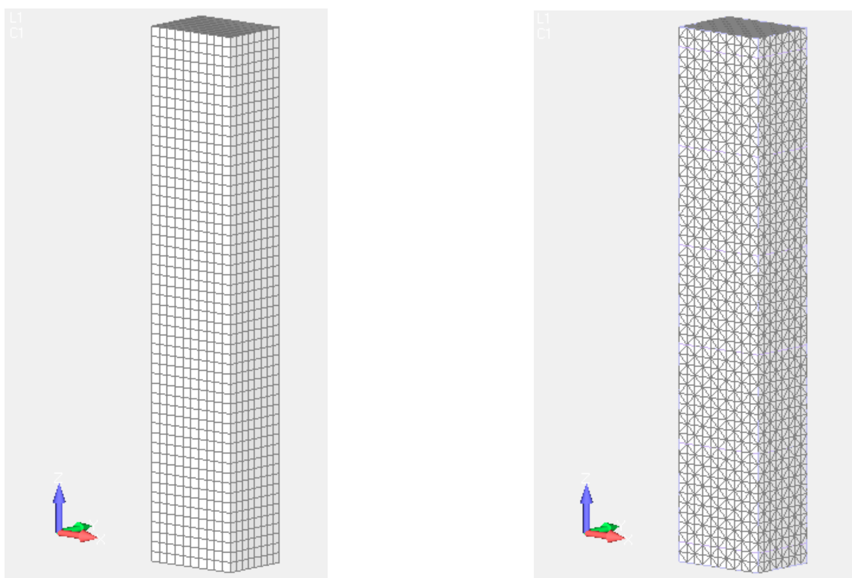


Fig. 7. Linear finite elements of steel reinforcement elements



a *b*

Fig. 8. Brickwork model, broken down into three-dimensional finite elements of the following types: *a* — Hex Mesh (4320 finite elements; 5445 finite element nodes); *b* — Tet Mesh (4320 finite elements; 5445 finite element nodes)

When calculating the model using the finite element method, a symmetrical mesh is of great importance since otherwise the distribution of stresses and strains will have an asymmetric appearance. To prevent this from happening, before dividing into finite elements, the model body was controlled to be cut in two symmetrical planes, as well as the properties of a specific linear or volumetric finite element were assigned using the window shown in Fig. 9. After dividing the body into finite elements, the mandatory union of coincident points (nodes of finite elements) formed as a result of cutting the body was achieved. As a result, a single body was formed with the union of coincident nodes of different materials – steel and brickwork (Fig. 10). For the given model, 432 coincident nodes were found.

During the numerical modeling of building structures, several types of finite element analysis were used:

A. Linear static analysis (Static) was performed primarily as a trial to control the correctness of the construction of the structure model. In the case of confirmation of the correctness of the model built, the following full calculation was performed.

B. Nonlinear static analysis (Nonlinear Static) is the main type of analysis, during which the previously specified functional dependences of the work of materials (σ-ε diagrams) were taken into account. The results of this type of analysis were used to compare the stress-strain state of load-bearing building structures both without damage and with them, as well as taking into account the reinforcement structures. The number of load stages from the start of the load to the maximum applied value is 10 with the option of displaying results at intermediate stages. The specified number of iterations at each stage is 5.

C. The stability calculation (Bucling) was carried out to determine the form of loss of stability of flexible elements of building structures, such as exposed bars of reinforcing frames, etc.

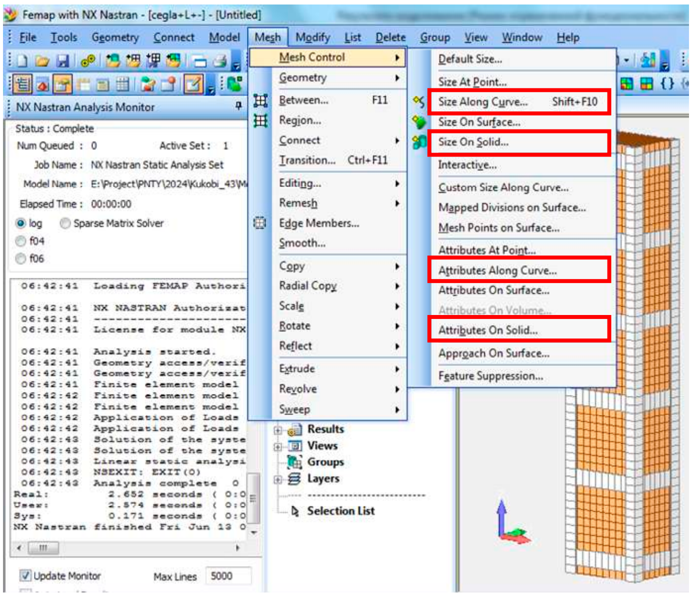


Fig. 9. Assigning properties to a specific linear or volumetric finite element

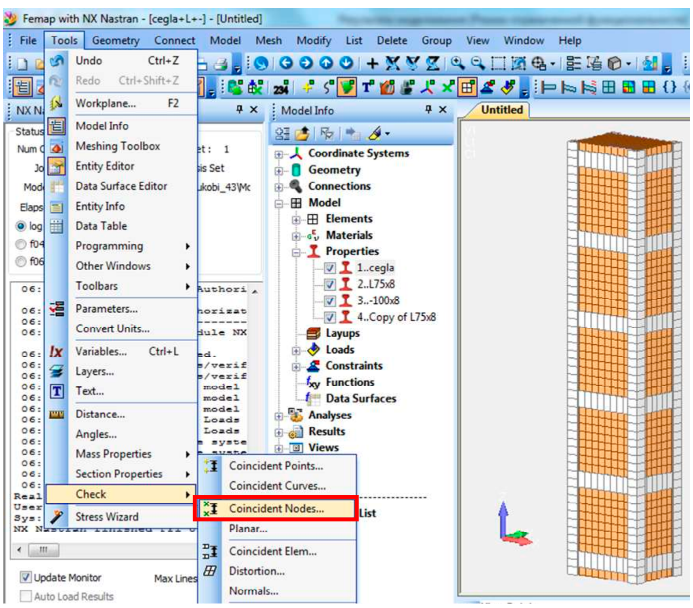
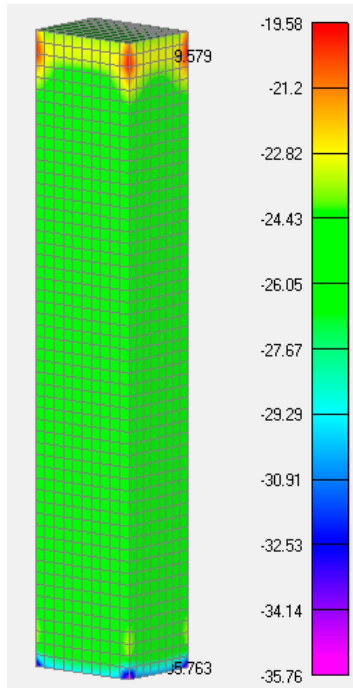


Fig. 10. Performing the joining of matching nodes of finite elements of brickwork and steel reinforcement elements

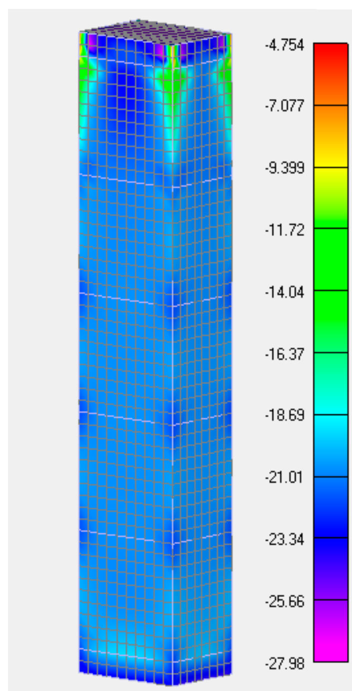
5. 4. Results of finite element modeling of brick columns before and after reinforcement

As a result of finite element analysis of reinforced complex-loaded deformed brick columns of buildings, stress distributions were obtained on the surface of the brickwork before and after reinforcement (Fig. 11), as well as along the length of the elements of the steel reinforcement cage (Fig. 12).

The stress distributions shown in Fig. 11, 12 allowed us to identify the locations of maximum stresses and design more effective reinforcement schemes. Finite element modeling makes it possible to perform technical and economic comparisons of the devised reinforcement options without conducting experiments under laboratory conditions or directly at the construction site. It was determined that after the installation of steel reinforcement cages, the maximum compressive stresses in the brickwork decreased by 28.6%. At the same time, the maximum stresses are concentrated near the supporting parts of the studied structure.



a



b

Fig. 11. Stress distribution on the surface of a brick column: *a* – before reinforcement (σ_{max} = –36 MPa); *b* – after reinforcement (σ_{max} = –28 MPa)

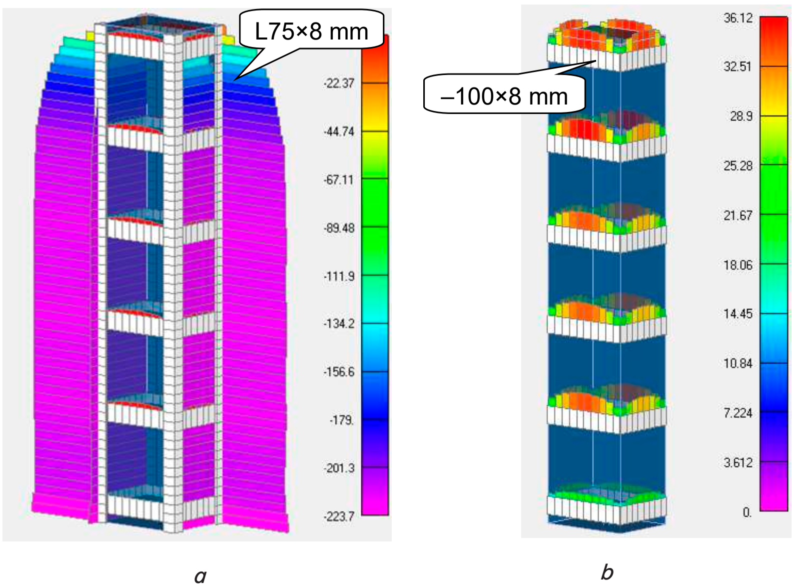


Fig. 12. Stress distributions along the length of steel reinforcement elements: *a* – corners of the cage (σ_{max} = –224 MPa); *b* – connecting strips (σ_{max} = 36 MPa)

reinforcement of building structures. The results obtained are advisable to apply when installing reinforcements with steel clips of damaged compressed brick structures.

The limitation inherent in this study is that, in addition to assessing the residual bearing capacity of reinforced structures, it is impossible to accurately identify the mechanism of destruction of brickwork.

The disadvantage of our study is the consideration of nonlinear operation of brickwork according to current regulatory documents, and not the actual fragment of the brickwork in operation.

This study in the future may take into account temperature stresses in steel reinforcement elements arranged by the thermal tension method. The difficulties that may be encountered in this case would be the specification of the actual temperature difference along the length of the steel reinforcement elements when constructing finite element models.

6. Discussion of results based on the mathematical modeling of damaged brick structures reinforced with steel frames

The result of the building being in an unconserved state explains the detected damage to brick structures in the form of frost damage (Fig. 2). The specified damage is explained by repeated atmospheric influences on the building in the form of rain or snow, as well as periodic freezing-thawing of accumulated moisture. Over time, the water, freezing, turned into ice, expanded and created internal pressure, gradually destroying the brick and mortar. Another factor contributing to the destruction of the brickwork was the different porosity of the brick, which was recorded by non-destructive strength testing (Fig. 3).

When devising proposals for effectively increasing the bearing capacity of the brickwork, a variant of installing external steel frames was described (Fig. 4). A qualitative feature of the proposal in comparison with known data [3, 5] are recommendations for the installation of these frames, which allows them to be included in joint work with existing brick elements. The effectiveness of our proposals is confirmed by mathematical modeling of the behavior of building structures, which was performed using the finite element method. The main goal of the modeling was to evaluate the bearing capacity, stiffness, and deformation characteristics of reinforced elements under various loading conditions. It was determined that after the installation of steel reinforcement frames, the maximum compressive stresses in the brickwork decreased by 28.6% (Fig. 11, 12). A feature of mathematical modeling is the identification of an effective algorithm for constructing finite element models of composite samples (Fig. 6–10). This algorithm allows for the most accurate formulation of the work of the components of the formed composite structures in the mathematical model. The conclusions from our study could be used to improve typical schemes and technological maps in the field of reconstruction and

7. Conclusions

1. Based on the results of our analysis of damage to complex-loaded brick structures (walls, piers, columns) on the example of a public facility with the possibility of installing civil defense protective structures, it was determined that the main damage to brick wall structures is their frost damage of up to 40%. This percentage of destruction is mainly due to the different porosity of the brick and lack of protection from precipitation. The specified damage occurred after prolonged temperature and humidity effects as a result of the building being in an unfinished, unpreserved state.

2. The use of steel clips to reinforce columns and corner systems on strips for openings is an effective engineering solution for restoring the operational suitability of brickwork. Both schemes are technologically accessible, allowing for quick reinforcement without dismantling structures while ensuring long-term stability.

3. An effective algorithm for constructing finite element models of brick samples reinforced with steel cages has been found, which allowed us to reproduce in the most accurate formulation the work of the components of the formed composite structures in the mathematical model. The nonlinear work of the brickwork was taken into account, as well as the uneven stress-strain state of the reinforcement elements and existing damaged brick elements.

4. Distribution diagrams were constructed relative to the main axes of stresses and deformations on the surface of the brickwork, as well as in any section of the models or directly in the steel reinforcement elements and their numerical values with an indication of the extrema. It was determined that after the installation of the steel reinforcement cages, the maximum compressive stresses in the brickwork decreased by 28.6%. At the same time, as expected, the maximum stresses are concentrated near the supporting parts of the studied structure.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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