International Journal for Computational Civil and Structural Engineering, 19(4) 48–68 (2023)

DOI:10.22337/2587-9618-2023-19-4-48-68

REPAIR OF MASONRY AFTER DYNAMIC IMPACTS. CALCULATION AND DESIGN METHODS

Oleg V. Kabantsev, Oleg A. Simakov

Department of Reinforced Concrete and Masonry Structures, Moscow State University of Civil Engineering (National Research University), Moscow, RUSSIA

Abstract: Civil engineers are encouraged to apply novel techniques, to improve and to adapt well-known methods amid the reality of modern life. An impressive number of restoration and strengthening techniques are developed for unreinforced masonry (URM) material well-known for centuries. Masonry may need restoration and strengthening due to errors made in the course of design, construction or long-term operation of buildings and structures. Besides, masonry needs strengthening in seismic areas. Strengthening of masonry structures, subjected to dynamic impacts during military operations, was initiated after the Second World War. Construction technologies advanced considerably over the last seventy years, and today shotcrete, a widely known strengthening technique, can be applied for a good reason. This article addresses shotcrete as a method for restoring masonry damaged by explosion impacts. Results of the laboratory testing of materials and parts of structures are provided together with improved methods of analysis. The methodology for computer-aided analysis of buildings is also presented, taking into account the staged nature of work and the ability of external shotcrete to support loads. Practical restoration of buildings is addressed in the conclusions section, and conclusions are drawn there.

Keywords: masonry restoration; shotcrete; fiber reinforced shotcrete; dynamic impacts; external reinforcement

ВОССТАНОВЛЕНИЕ КАМЕННЫХ КЛАДКИ ПОСЛЕ ДИНАМИЧЕСКИХ ВОЗДЕЙСТВИЙ. МЕТОДЫ РАСЧЕТА И ПРОЕКТИРОВАНИЯ

О.В. Кабанцев, О.А. Симаков

Национальный исследовательский Московский государственный строительный университет, г. Москва, РОССИЯ

Аннотация: Современные реалии требуют от инженеров в области строительства применение как новых техник, так и совершенствование и адаптацию уже известных методик. Для хорошо известного на протяжении столетий материала каменной кладки разработано значительное количество методов восстановления и усиления, необходимость которых обоснована ошибками проектирования, строительства или длительной эксплуатацией, а также усиление кладки в сейсмических районах. В то же время вопросами усиления конструкций из каменной кладки, получивших динамические повреждения в результате боевых действий, полноценно занимались только после второй мировой войны. За последние 70 лет строительные технологии значительно продвинулись, появилась возможность обоснованно применять хорошо известный метод усиления путем устройства аппликаций из торкрет-бетона. В настоящей статье рассмотрены вопросы применения современного торкрет-бетона для восстановления каменной кладки, разрушенной после взрывных воздействий. Приведены результаты лабораторных ипытаний материалов, фрагментов конструкций, а также скорректированные методики расчета. Также представлена методика компьютерного расчета здания с учетом этапности проведения работ и включении в работу внешней аппликации. В заключении приведен практический опыт восстановления зданий, сделаны выводы.

Ключевые слова: восстановление каменной кладки, торкрет-бетон, торкрет-фибробетон, динамические воздействия, внешнее армирование

1. INTRODUCTION

1.1. Review of the literature

Masonry has been widely used to make bearing structures of buildings for over 200 years. Masonry structures have served as frameworks of multi-storey buildings since the 50s of the 20th century. At present, although reinforced concrete structures and modular systems made of wood and metal have leapfrogged in development, masonry is still used to make bearing walls. Studies [1, 2] confirm that frameworks of numerous buildings and structures are made of masonry. Besides, a great number of such buildings and structures have more than two storeys. The analysis of masonry buildings shows their nearly uniform distribution over regions, except for northern areas, where the percent share of buildings with masonry bearing walls is somewhat lower.

Methods of design and analysis of masonry structures are based on a traditional masonry model viewed as a continuous medium with generalized ("effective") characteristics. The validity of this model for regular ("standard") operating conditions is confirmed by numerous studies [1-5]. However, it is extremely difficult, and in some cases impossible, to use this model to project the behavior of masonry structures subjected to inelastic deformations with different areas on the diagram.

The need to analyze the projected ability of masonry structures to support loads beyond the elastic phase of deformation is evident. It is explained by special conditions, such as seismic impacts, beyond-design soil deformations, versatile beyond-design loads and external impacts on bearing masonry structures during the term of operation. To analyze the ability of masonry structures to support loads beyond the elastic phase of deformation, a masonry model was developed. It represents masonry as a piecewise homogeneous composite material featuring discontinuous fields of adhesive interaction between composite material elements and different values of the modulus of elasticity [6-12]. The key element of this model is the mechanism of adhesive interaction between masonry materials (bricks/stone and mortar), which has its own mechanical characteristic R_{adh}. If neither contact zone of the composite material demonstrates adhesive interaction ($R_{adh}=0$), masonry materials interact in the "dry" friction mode, and masonry loses integrity, its most valuable property [13-15].

In the model [6-8], the most complex state of biaxial stress of masonry is schematically represented as interacting piecewise homogeneous elements of the composite material featuring different mechanisms of interaction (Figure A.1. - Figure A.3), where F is the generalized force parameter of interaction; N_i denotes shear forces.

A model of interaction between elements of a composite material in a vertical mortar joint is presented in Figure A.1. Interaction between bricks and mortar in a vertical mortar joint is determined by the lack of adhesion between these materials, because a microcrack emerges under the action of shrinkage stresses in the zone of contact between bricks and mortar.

Figure A.2 shows a model of interaction between elements of the composite material in a horizontal masonry joint under the action of compression stresses perpendicular to the joint

Figure A.3. shows a model of interaction between elements of a composite material in a horizontal masonry joint under the action of tensile stresses, perpendicular to the joint.

Analysis of the masonry model that represents a piecewise homogeneous composite material featuring discontinuous fields of adhesive interaction between composite material elements and different values of the modulus of elasticity confirms the crucial role of adhesive interaction between masonry materials in ensuring the integrity of masonry.

For a number of reasons, masonry structures need restoration and strengthening [3-5]. The main reasons are:

- errors made in the course of design;
- errors made in the course of construction;
- an increase in design loading;

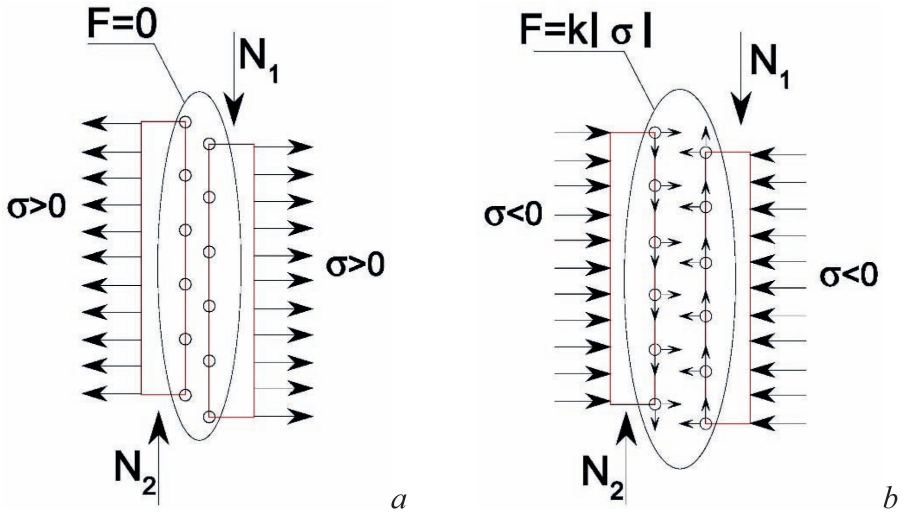


*Figure A.1. Model of interaction between masonry materials (bricks/stone and mortar): a - interaction in the absence of compression stresses perpendicular to the joint, (**$\sigma>0$**); b - interaction under compression stresses perpendicular to the joint, (**$\sigma<0$**). k - friction factor along the line of contact between bricks and mortar*

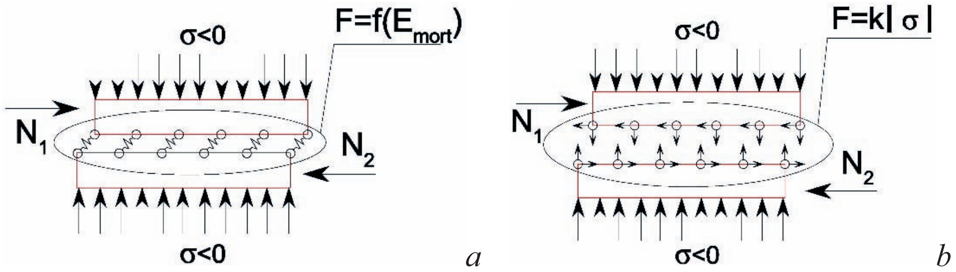


*Figure A.2. Model of interaction between masonry materials (bricks/stone and mortar) in a horizontal masonry joint under the action of compression stresses perpendicular to the joint (**$\sigma<0$**): a - when conditions of mortar strength and/or adhesion strength accompanying interaction between masonry materials are met; b - when conditions of the mortar strength and/or adhesion strength accompanying interaction between masonry materials are not met; k - friction factor along the brick and mortar contact line*

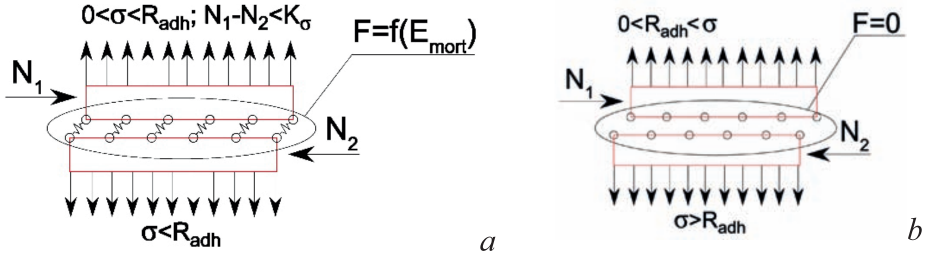


Figure A.3. Model of interaction between masonry materials (bricks/stone and mortar) in a horizontal masonry joint under the action of tensile stresses perpendicular to the joint ($\sigma<0$): a - when conditions of the mortar strength and/or adhesion strength accompanying interaction between masonry materials are met; b - when conditions of the mortar strength and/or adhesion strength accompanying interaction between masonry materials are not met; k is the mortar cohesion factor.

- structural collapse as a result of operation (beyond-design impacts; lack of repair work, in particular, lack of repair of insulation);
- other causes (accidents).

Methods of masonry restoration and strengthening are available for masonry structures in operation in traditional conditions triggering most widely spread types of damage and defects [16, 17]. These methods demonstrate good convergence with experimental results and the real behavior of strengthened structures. Besides, masonry failure under static loading and dynamic seismic impacts is also considered.

Masonry structures damaged by explosion impacts are clustered into an independent group. Explosive loading is the cause of damage types characterized by high-intensity local dynamic impacts (energy). Such impacts lead not only to the local damage of masonry, but can also cause disintegration of internal bonds between masonry materials, such as bricks and mortar, as well as disintegration of internal bonds between outer and inner layers of masonry structures. This kind of damage determines the need for a detailed masonry model in the form of a piecewise homogeneous composite material featuring discontinuous fields of adhesive interaction between composite material elements and different values of the modulus of elasticity. This model is used to analyze the behavior of damaged masonry structures.

No detailed scientific studies of masonry damage caused by explosive loading were conducted. There is no systematized information about the features, the structure and the characteristics of such damage in the research literature.

Presently, two main options are used to restore and strengthen masonry structures damaged by explosion impacts:

Option 1. The implementation of recommendations developed for the restoration of structures damaged during combat operations in the years of World War II [18, 19]. These recommendations have a "prescriptive" nature; they have no detailed verification of analysis, but they stem from practical experience and focus on large-scale application in case of limited mechanization, traditional technologies and construction materials. Evidently, the application of this principle of strengthening and restoration of damaged masonry structures is feasible in individual cases. The principle of masonry restoration and strengthening, that has no reliable methods of validation, cannot be recommended for large-scale use.

Option 2. Using techniques developed to increase the seismic stability of masonry by restoring its integrity. Two main principles are employed to improve masonry integrity: (1) the principle of increasing the number of internal bonds in masonry using a method of special elements introduced into masonry, for example [20]; (2) the principle of adding external structures that have the required bearing capacity. Different techniques are used to attach these structures to masonry, for example, composite materials [21] and shotcrete [20-23] serve as the external reinforcement for masonry structures.

Masonry restoration made according to option 2 is backed by research that serves as the basis for analysis of reinforced masonry structures and strengthening elements. In general, these methods of strengthening masonry structures can be considered similar in terms of the principles of restoration of masonry structures damaged by explosion impacts.

This one-sided shotcrete technology is the most technologically advanced method of improving the seismic stability of masonry structures.

The shotcrete method used to apply concrete to the surface of an existing structure is well known; it is based on a sophisticated technology. However, a century-long application of the shotcrete technology improved each principal component of this method. As a result, present-day shotcrete differs greatly from the initial technology. Today the shotcrete technology is optimal (in terms of parameters of shotcrete machines, composition of materials, new types and combinations of admixtures), and its efficiency is close to the maximum.

Considerable research is contributed to the application of shotcrete used to strengthen masonry structures of buildings in earthquake-prone areas [20, 24-26].

Studies of laboratory specimens and full-scale experiments have the following results:

1. An increase in the general stiffness of masonry that equals, at least, 20%. In this case, stiffness parameters depend on conditions of bonding between strengthening elements and existing masonry (bonding in the form of keys and micro-keys; adhesive bonding between shotcrete concrete and existing masonry).
2. A considerable (up to 3 times) increase in the total bearing capacity of shotcrete-strengthened masonry. The key condition for increasing the bearing capacity of a strengthened structure is strong bonding between shotcrete concrete and existing masonry (see point 1). According to the research findings, the most effective method of increasing bonding between shotcrete concrete and existing masonry is either the use of customized shotcrete compositions or mechanical surface preparation by making keys and micro-keys (joint pointing, making keys with pre-set dimensions). The effect of adhesion produced on bonding between shotcrete concrete and strengthened masonry, as well as the value of the bearing capacity varies in the range of 30-75% of the final value of the bearing capacity of a strengthened element.
3. The collapse mechanism typical for masonry strengthened using one-sided shotcrete differs greatly from the collapse mechanism typical for masonry that has no strengthening: masonry without strengthening or reinforcement is prone to brittle failure. Masonry strengthened using one-sided shotcrete is characterized by elasto-plastic deformation that triggers disintegration of bonds between shotcrete and masonry.
4. The recommended shotcrete thickness of 4-6 cm was identified in an experiment conducted before the practical application of shotcrete aimed at improving the seismic stability of existing buildings.

The practical development of methods aimed at increasing the seismic stability of masonry structures shows that problems solved to design earthquake-resistant masonry are totally different from tasks focused on restoration of masonry structures damaged by local high-intensity explosion impacts.

Given that explosion impacts cause complete destruction of masonry in certain parts of bearing structures, new masonry is needed to restore them, and special design solutions should be applied for the new masonry to support loads.

Evidently, there is a need to study interaction between strengthening structures, or one-sided shotcrete, and existing masonry, and to identify mechanisms of their interaction.

Analysis of a detailed masonry model, that represents a piecewise homogeneous composite material with discontinuous fields of adhesive interaction between composite material elements and different values of the modulus of elasticity, demonstrates the need to develop a shotcrete composition featuring high adhesive strength between shotcrete and existing masonry made of different types of bricks. This type of interaction is particularly important because the contact develops over the entire area of shotcrete.

1.2. Purpose, Objective and Summary of the Study Outlined in This Article

The world is being rocked by versatile armed conflicts, resulting in substantial damage to buildings and structures. Masonry buildings are the backbone of built-up areas in any populated locality. Therefore, such buildings are inevitably damaged by explosion impacts. Hence, the development of effective sophisticated methods of restoration and strengthening of masonry structures is highly relevant.

The purpose of this project is to develop an integrated research-based method of strengthening masonry bearing structures damaged as a result of explosion impacts. An integrated method is understood as a method and technology of masonry restoration, development of special compositions of materials, performance of research to check the effectiveness of the proposed method, identification of principal mechanical characteristics, development of a method of analysis of design solutions for restoration and strengthening of damaged structures.

One-sided shotcrete is chosen as the main strengthening method. It is highly mechanized, easy to implement, and it ensures a sufficient increase in the bearing capacity of masonry.

To achieve this goal, masonry damage, caused by explosion impacts, and earlier experimental studies were analyzed, key characteristics of materials were identified, the composition of the shotcrete material was developed, studies were conducted to identify characteristics of interaction between strengthening structures and masonry materials, and a method of analysis was refined in order to take into account the actual nature of damage to masonry as a result of explosion impacts. The composition, focused on masonry strengthening after dynamic impacts, was developed; its physical and mechanical properties, adhesion to the main types of bricks were studied. Methodological fundamentals of (1) analysis of masonry in multi-story buildings and (2) masonry strengthening techniques are developed.

2. MATERIALS AND METHODS

2.1. Theoretical fundamentals of modeling

2.1.1 Studies of masonry damage from explosion impacts

The following data characterize the explosion damage of one-storey and multi-storey buildings built in 1970-2010:

- materials: 250x120x65 (55) mm ceramic and silicate bricks; strength of bricks: 5-12,5 MPa; strength of cement-sand mortar: 2,5-10 MPa. The percentage of silicate bricks used to make bearing structures is high;
- building frameworks have longitudinal and transverse bearing walls;
- three types of building collapse patterns (figure 1).

a) *b)* *c)*

Figure 1. Collapse patterns typical for bearing structures of masonry buildings. Pattern 1: complete destruction of one floor (a); Pattern 2: Complete destruction of a large part of brickwork encompassing several floors and accompanied by destruction of adjacent parts of floor slabs (b); destruction of a part of a building (c)

Masonry damage from explosion impacts has the following features:

1. Exterior walls of buildings suffer from the greatest damage due to the lower accessibility of interior walls to impact factors.
2. Inclined and vertical cracking of intact brickwork in the areas adjacent to local damage (figure 2.a);
3. Types of hidden damage in intact brickwork:

3.1. Disintegrated bonds between the outer course and the brickwork (figure 2.b);

Disruption of adhesive interaction between basic elements of brickwork (mortar and bricks) in horizontal joints affecting large areas of walls subjected to explosion impacts. Research results show that few structures retain adhesive strength at the interface between masonry materials, and these structures can be neglected.

a) *b)*

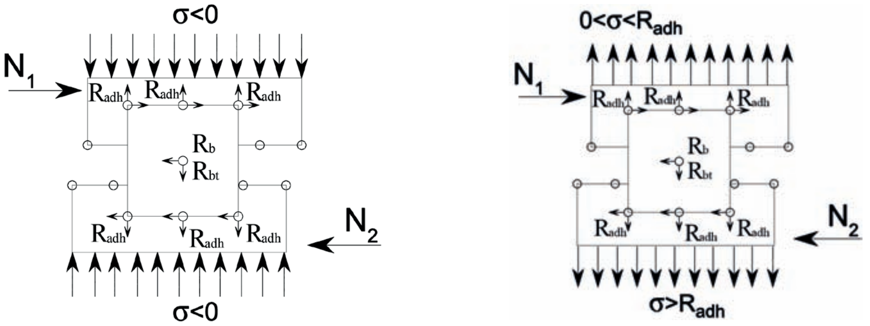
Figure 2. Brickwork destruction patterns characteristic for explosion damage; inclined cracking (a); disintegrated bonding along the outer course (b)

3.3 As a rule, large parts of brickwork feature disintegrated bonding between the outer course and the brickwork throughout the entire wall height. In this regard, the outer course cannot be taken into account during the analysis of further brickwork operation. Accordingly, the proposed strengthening method assumes that the outer course should be dismantled despite the absence of external damage.

2.1.2 Brickwork models

The analysis is made for a masonry model representing a piecewise homogeneous composite material with discontinuous fields of adhesive interaction between composite material elements and different values of the modulus of elasticity. The research of structures subjected to explosion damage proves that in case of disrupted adhesive bonding the model of interaction between masonry materials in horizontal masonry joints follows the patterns presented in Figure A.2.b and Figure A.3.b.

Adhesive interaction missing from existing masonry structures is needed to restore masonry structures damaged by explosion impacts. Towards this end, the shotcrete method is applied to ensure strong contact interaction with existing masonry structures (figure 5). Adhesive strength and other types of contact between shotcrete and existing masonry structures can ensure this type of interaction.



a) *b)*

Figure 5. Model of interaction between damaged masonry and shotcrete elements in compression and shear (a), tension and shear (b)

2.1.3. Methods of taking account of interaction between a shotcrete element and an existing masonry structure

The masonry model strengthened with one-sided shotcrete is implementable in the case of reliable interaction between a shotcrete element and existing masonry structures. This general condition is difficult to implement due to a large difference between stiffness values of masonry and shotcrete. This method ensures high adhesive strength at the interface between shotcrete and masonry without special actions aimed at adhesion improvement (dismantling of existing structures, etc.). In general, the mechanism of interaction between shotcrete elements and existing masonry has the following two components: the adhesion mechanism (the main mechanism) and interaction based on the shear of micro-keys (figure 6). Micro-keys emerge in existing masonry due to natural openings in areas of masonry joints.

a) *b)*

Figure 6. A model of interaction between shotcrete and masonry; adhesion mechanism (a), micro-key mechanism (b)

If adhesion is sufficient and micro-keys are in place (which is less important), the shotcrete method used to restore damaged masonry (1) serves as compensation for disintegrated internal bonds between masonry materials and (2) increases the bearing capacity of a masonry structure as a whole.

In general, the bearing capacity of strengthened masonry can be found using formula (3).

$$Q_f = Q + Q_{ad}. \tag{1}$$

where Q is the bearing capacity of a masonry specimen without strengthening; Qad is the bearing capacity of a strengthening element. Earlier studies [24] describe the general failure mechanism for masonry specimens strengthened with one-sided shotcrete: masonry specimens fail along unbonded joints in the area of contact between shotcrete and masonry, and an increase in the bearing capacity is limited by the value of Qad,max, determined using formula (2).

$$Q_{ad,max} = R'_{sq} 0{,}2 A_{micro-key}, \tag{4}$$

where Rsq' is the design shear strength of masonry along the unbonded joint;

A is the area where force is transferred; it can be approximated as 20% of the area of contact between shotcrete and masonry (taken as 0,2 in formula (2)).

2.4. Studying shotcrete materials

Properties of shotcrete are determined by the composition of shotcrete materials and the shotcrete technology used (coupled with the experience of a nozzleman). As for the shotcrete material composition, a special shotcrete mix is developed using the prior experience. It’s focused on brickwork strengthening, and the main emphasis is on its adhesive strength.

Special specimens were prepared for testing purposes. These were (1) slabs designated for strength testing and (2) joint-free masonry specimens used to test shotcrete adhesion to different masonry materials (silicate bricks, solid and hollow ceramic bricks, figure 7). Specimens were made at a construction site by a standard team of builders (figure 8).

Four prism-shaped specimens (figure 7), having dimensions of 70×70×280 mm, were made of a shotcrete slab to find the modulus of elasticity and the prism strength. Besides, cylinder-shaped specimens, that were 64 mm in diameter, were drilled using a diamond drilling machine to find the compressive strength.

a) *b)*

Figure 7. General view of specimens; specimens used to test properties (a), specimens used to test adhesion (b).

Figure 8. The manufacturing of specimens

The following results were obtained as a result of research (table 1):

- The modulus of elasticity of shotcrete is 25600 - 28000 MPa.

- The compressive strength of shotcrete exceeds 63 MPa.

Table 2. Prism-shaped specimens: testing results

№	Cross-sectional area cm^2	Size, cm^3	Mass, g	Density, g/cm^2	R (compressive strength), MPa	Eb (modulus of elasticity), ×103, MPa
1	50,28	1447,8	3118	2,154	46,68	28,0
2	50,73	1415,3	3052	2,156	43,60	26,2
3	54,87	1536,3	3306	2,152	37,28	25,9
4	51,73	1448,4	3126	2,158	40,48	25,6

Adhesive strength (adhesion) was found via a tearing force whose value was sufficient to detach a specimen, made of a cured composition, from the brickwork, made of different types of bricks. The force was applied to the specimen through a metal disk with an anchor (hereinafter referred to as a stamp) glued to the surface of the specimen.

Before testing five measurement points were prepared on each slab; the number of points was determined by the regulatory documents.

The preparation procedure included:

- grinding needed to smooth the surface;
- using a cutting tool to cut a layer of shotcrete to reach the masonry and to make a specimen with a diameter of 50 mm.

When the specimen was ready, metal stamps were glued to them using a high-strength fast-setting adhesive composition.

Adhesion tester was used to find the value of the tearing force in accordance with the operating instruction.

As a result of testing it was found that the “shotcrete-masonry" contact line did not collapse. Rather, masonry collapsed in the area adjacent to the contact line.

Adhesion testing results demonstrated the brickwork collapse (Figure 9), meaning that the adhesive strength exceeds the tensile strength of brickwork (the tensile strength of the interface between shotcrete and brickwork, identified in an experiment, is 0,9-1,2 MPa).

Figure 9. Testing adhesion between shotcrete and brickwork
The results can be presented as a diagram (figure 10).

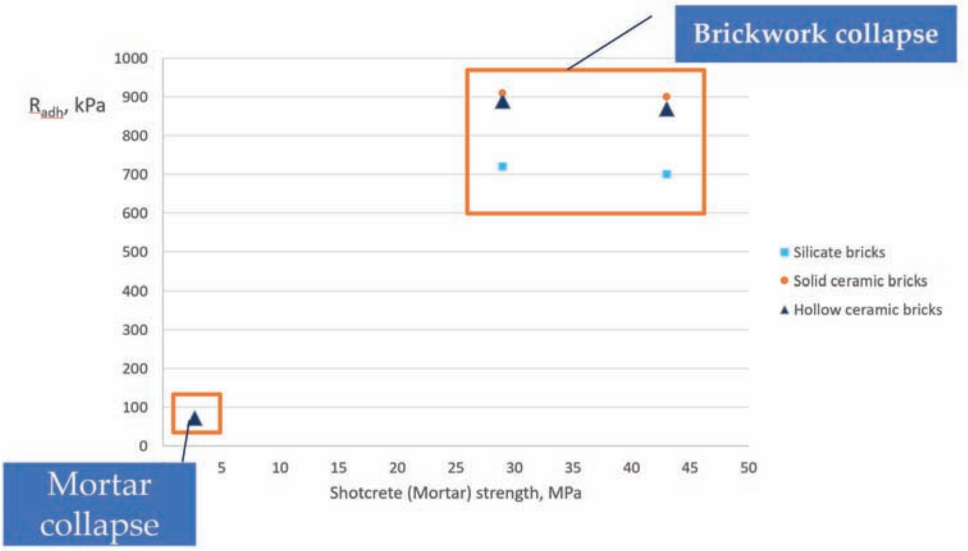


Figure 10. Testing adhesion between shotcrete and masonry.

2.5. Analysis of strengthening

The studies of adhesion between shotcrete and brickwork confirm the general principles of analysis conducted using formulas (1) and (2), namely, a limit on an increase in the bearing capacity of strengthened brickwork based on the strength of masonry materials rather than shotcrete.

Earlier experimental studies and numerical modeling serve as the basis for a masonry strengthening method applied to brickwork damaged by explosion impacts. This method employs a one-sided shotcrete technology that has the following stages (figure 11):

Stage 1. Installing temporary slab supports, starting from lower floors. These supports should take loads throughout the entire height of a building. Their ability to support loads needs to be controlled.

Stage 2. Dismantling the outer course. Dismantling masonry elements in the area of explosion damage. Performing masonry work to restore lost elements of masonry structures.

Stage 3. Installing local elements to strengthen wall intersection nodes.

Stage 4. Installing wall reinforcement elements in shotcrete areas. Shotcrete of exterior surfaces of walls (figures 7, 8).

Stage 5. Removing temporary slab supports, starting from upper floors (after shotcrete curing).

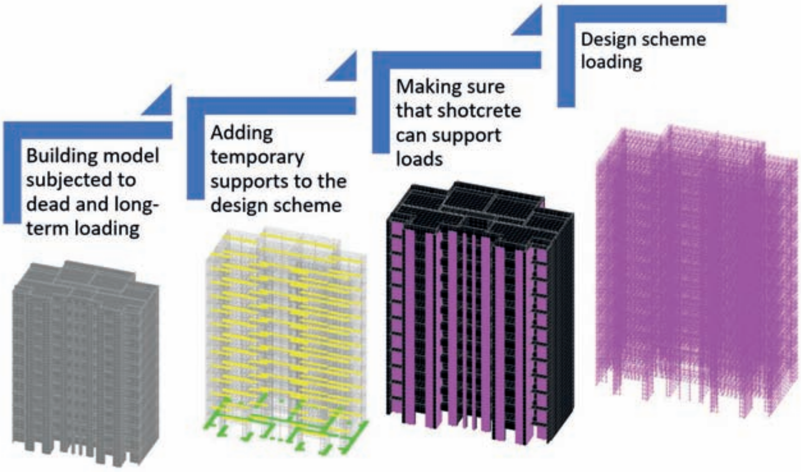


Figure 11. Strengthening of bearing structures in a multi-storey building: stages of computational modeling

Traditional single-stage methods of analysis of strengthening structures for existing buildings (including multi-storey buildings) cannot have accurate results because such methods do not take into account the staged nature of the stress-strain state development, including the ability of strengthening elements to take loads at final stages. In this regard, most reliable modeling results are obtained using MONTAGE software. It is a multi-stage technology of computational analysis implemented by SCad Office software package. The computation technology allows to identify stages of computation corresponding to stages of the stress-strain development in the structures being strengthened.

3. RESULTS

Masonry structures of multi-storey buildings damaged as a result of explosion impacts were investigated.

The following facts were identified in the course of the building examination (figure 12):

Foundations (in the limited serviceable condition):
- local collapse of the perimeter pavement;
- perimeter pavement cracking;
- vegetation growth; perimeter pavement sagging;
- moisture content increase in plinth structures due to damaged sills;
- local collapse of the finishing layer of the plinth;
- damaged finishing layer along the route of utility pipelines.

Exterior walls (in the emergency condition):
- damage and collapse of masonry walls of the engineering floor due to the dynamic impact;
- destruction of masonry and a layer of wall plaster on floors 7-10 due to thermal and dynamic impacts;
- damage and collapse of the main facade brickwork on floors 1-10 resulting from the dynamic impact;
- wall damage; a through hole in the gable facade on the level of the 10th floor;
- exterior walls do not meet the requirements for the thermal conductivity of materials according to the thermal analysis of structures.

Floor slabs (in the emergency condition):
- destruction and collapse of floor slabs from the 5th floor to the engineering floor of entrances 2 and 3, resulting from the dynamic impact;
- destruction of finishing layers resulting from the dynamic impact;
- cracks in joints of floor slabs, resulting from the dynamic impact.

The roof (in the emergency condition):
- destruction and collapse of bearing structures of the roof resulting from the dynamic impact;
- damage to the whole area of roof coating resulting from the dynamic impact;
- local absence of flashing;
- the minimum term of effective operation of building and roofing elements made of roll materials is 10 years for residential buildings.

Stairs (in the emergency condition):
- destruction and collapse of bearing structures of stairs and elevator shafts resulting from the dynamic impact;
- cracks along the joints between staircases and walls;
- spalling concrete steps of staircase structures;
- local destruction of the finishing layer.

Balcony slabs (in the emergency condition):
- destruction of balconies and extended enclosed balconies on floors 6-10 of entrance 2, resulting from the thermal impact;
- local destruction and collapse of structures of balconies and extended enclosed balconies resulting from the dynamic impact;
- concrete deterioration; spalling of facing panels of balconies and extended enclosed balconies due to the dynamic impact;
- damaged protective concrete layer of slabs of balconies and extended enclosed balconies;
- destruction of glazing of balconies and extended enclosed balconies as a result of the dynamic impact.

Entrance halls (in the limited serviceable condition):
- local destruction of the brickwork of entrance halls;
- locally damaged finishing layer of pit walls;
- concrete spalling; cracking steps of entrance lobbies and pits.

Figure 12. General view of the building described in this paragraph

The following actions are recommended in respect of the building's bearing structures judging from the defects and damages identified during the examination:

1. Restoration of damaged parts of bearing walls

The recommendation is to use materials similar to those that existing structures are made of, including silicate bricks M150 or better, and mortar M75 or better. It is recommended to reinforce the parts of masonry to be restored using 100x100 mm steel mesh B500, 4 mm diameter, to be installed every three rows.

Restored parts of walls are to be attached to existing walls by steel anchor rods embedded in the existing masonry using special chemical compositions or mounted in smaller diameter holes.

2. Strengthening bearing walls damaged by dynamic impacts

Exterior bearing walls should be strengthened using one-sided shotcrete with the thickness of 75-85 mm. B500 d5 mm mesh, 100x100 mm, is to be used as the reinforcement. The shotcrete material (whose tensile strength should not be below the tensile strength of brickwork) will stick to brickwork by means of adhesion. An additional layer of mesh should be applied to reinforce the outside corners. A cast-in-place belt should reinforce the upper part of the parapet.

The masonry is additionally reinforced with cast-in-place reinforced concrete pylons not less than 160 mm thick (the size of their section is to be determined in the course of the analysis).

Shotcrete can be applied through 350x50 mm holes in solid balcony slabs; holes should be spaced 700 mm apart. Reinforcement rods should be inserted into these holes.

One-sided shotcrete should be applied to masonry after the outer facing layer is dismantled.

It is recommended to use carbon fiber composite materials to reinforce internal bearing stairwell walls with diagonal cracks. In this case carbon mesh and special polymer cement mortars is the best option. The total reinforcement thickness is up to 25 mm.

3. Restoration of damaged parts of floor slabs and stair landings

Floor slabs and stair landings are to be restored by concreting damaged areas and applying new reinforcement selected according to the analysis.

Floor slabs should be restored by concreting destroyed parts that are 220 mm thick. Concreted parts should have cavities to prevent excessive loading. Both a floor slab and steel beams, such as channels or I-beams, can serve as bearing elements.

It is recommended to restore stair landings (if the integrity of their edges is preserved) using

B20-25 concrete and reinforcement bars; the thickness of a concrete layer should be, at least, 100 mm, and the reinforcement should be selected on the basis of analysis.

4. Restoration of partitions

Partitions should be made of hollow ceramic bricks 120 mm thick. Partitions should be perpendicularly attached to the bearing structures (bearing walls and floor slabs).

Given that the process of strengthening building frameworks is staged, analysis made for the transitory period should also be staged, and each stage should correspond to a certain part of structures being restored. In this case, staged analysis ensures the continuity of the stress-strain state (SSS) of model elements in the course of transition from one stage to another (MONTAGE software module implements the technology ensuring the stage-by-stage incorporation of elements into the model).

Analysis made for the principal term of building operation (standard analysis made for a building subjected to long-term operating loads) corresponds to an independent stage of comprehensive staged analysis taking into account the continuity of SSS that emerges at earlier stages.

Wind loads, acting on building frameworks, are analyzed at an independent stage, and the analysis thus performed should take into account the state of strain that emerges at earlier stages.

In total, five stages of analysis of building frameworks are identified (Table 2).

Principal solutions designed to strengthen the following building structures were developed as a result of modeling made according to the proposed method of analysis:

- strengthening of external bearing walls of a building using one-sided shotcrete;
- installation of monolithic reinforced concrete pylons along the building façade;
- wall restoration on floors 9 – 10,
- reinforcement of internal walls of stairwells by external carbon bonding (figure 13).

Table 2. Description of characteristic stages of analysis

Stage №	Stage analysis
1	Building framework generation mode. An existing building with restored masonry
2	Prevention of vertical displacements of elements simulating floor slabs
3	Mode of transitory analysis Dismantling of the outer facing layer; applying shotcrete for strengthening purposes
4	Mode of transitory analysis Removal of temporary supports from under the floor slabs
5	Mode of standard operation encompassing long-term operating loads and reduced values of long-term operating loads. Loads include the deadweight of structures, floors, partitions, enclosing structures, full values of operating loads, snow and wind loads.

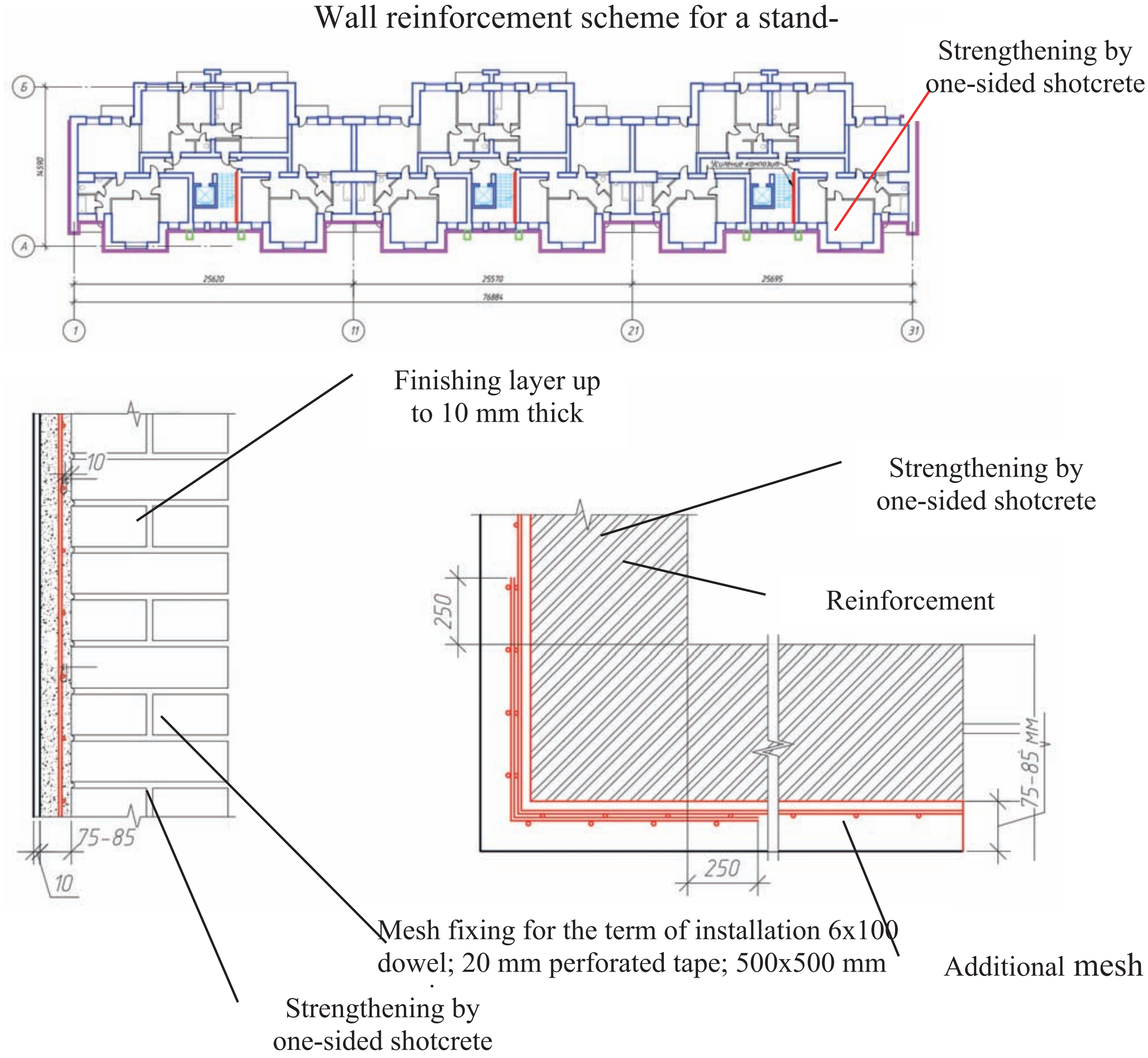


Figure 13. Key structural solutions aimed at strengthening bearing masonry walls

The shotcrete technology applied to strengthen bearing walls requires the following sequence of work performance:

1. Before shotcrete is initiated, spots to be shotcreted should be visually examined; inventory, scaffolding, machines and devices needed for safe work performance should be ready in the work performance area.
2. Defective spots should be cut out so that only strong and dense brickwork is left. Towards this end, boundaries of the spots to be repaired should be chalk marked and spots to be repaired should be cut out in straight lines along the contour by an angle grinder or a diamond saw to a depth of, at least, 10 mm.
3. A jackhammer should be used to remove loose spots to the depth of damage perpendicularly to the repaired surface. The quality of work should be checked by hammer testing.
4. To ensure the best adhesion, the surface should be treated using a high-pressure spray gun, at least, 500 bar, or a sandblaster.
5. The surface to be shotcreted should be cleaned of dirt and moistened.

6. The surface of the spots to be restored to the design dimensions should be shotcreted layer by layer; the thickness of one shotcrete layer is up to 100 mm. Shotcrete concrete rundown should be prevented, as this can lead to cavitation, and it is extremely difficult to detect and eliminate cavities. The thickness of one shotcrete layer should be checked by probing fresh layers in several spots using a thin metal rod.
7. The main layer of shotcrete with a thickness of 30 mm can be applied forty minutes after the restoration of damaged spots.
8. Accumulation of rundown deposits is not allowed in particular areas. They should be removed immediately after formation.
9. The surface to be repaired is to be smoothed.
10. The surfaces to be repaired should be moistened, or film-forming compositions should be applied.

The technology of the final stage of work (shotcrete) is shown in figure 14.

The result of the work is shown in figure 15.

Figure 14. Strengthening masonry walls of a multi-storey building

Figure 15. The strengthening of masonry walls of a multi-storey building

4. DISCUSSION

The explosion damage of bearing masonry walls greatly differs from the damage caused by design, construction or operational errors, for which a large number of solutions, methods of restoration and reinforcement are available. The greatest difficulty is the disintegration of bonding between brickwork materials, namely, mortar and bricks, including the destruction occurring at a considerable distance from the spot of impact. The most effective method is external shotcrete, which ensures compensation for internal bonds in masonry lost due to intensive dynamic impacts. To implement the concept of restoration of damaged masonry structures, a model simulating the behavior of masonry and reinforcement structures is developed together with a method of analysis of bearing structures of a building, which takes into account staged analysis corresponding to stages of strengthening and development by strengthening elements of the ability to support loads.

A composition was designed to strengthen the masonry. It adhesive interaction with all types of brickwork does not require supplementary structural solutions to increase adhesion. The composition was subjected to a exhaustive testing procedures, including those aimed at finding the adhesive strength accompanying interaction with different types of bricks.

The strengthening method, including the composition, the technology, as well as the algorithm of analysis, were pilot tested at a specific construction facility - a multi-storey residential building damaged as a result of explosion impacts.

5. CONCLUSIONS

The method of restoration of masonry structures damaged by dynamic explosion impacts is developed and justified. According to the novel method, damaged internal masonry bonds are compensated by exterior strengthening structures accompanied by a simultaneous increase in the bearing capacity of a masonry structure as a whole. Studies have proven that the most successful and technologically efficient solution to the problem of restoration is the shotcrete technology coupled with the necessary reinforcement.

The shotcrete technology ensures reliable interaction between the strengthening structure and damaged masonry via two mechanisms: interaction via adhesion and interaction via the shear of micro-keys. The value of the adhesive strength at the interface between shotcrete and masonry materials exceeds the tensile strength of both bricks and masonry mortar. The proposed technology ensures fast shotcrete and the required standard of quality.

This work was financially supported by the Ministry of Science and Higher Education of Russian Federation (grant # 075-15-2021-686). Tests were carried out using the research equipment of the Head Regional Shared Research Facilities of the Moscow State University of Civil Engineering

Author Contributions: Conceptualization, O.V.K.; methodology, O.V.K.; software, O.V.K. and O.A.S.; validation, O.A.S.; formal analysis, O.V.K. and O.A.S.; investigation, O.V.K. and O.A.S.; resources, O.V.K. and O.A.S.; data curation O.A.S.; writing—original draft preparation, O.V.K. and O.A.S.; writing—review and editing, O.V.K.; visualization, O.V.K. and O.A.S.; supervision, O.V.K.; project administration, O.V.K.; funding acquisition, O.V.K. All authors have read and agreed to the published version of the manuscript.

FUNDING

This research is funded from the grant issued by the National Research Moscow State University of Civil Engineering as a result of a competition among the lecturers for implementation of fundamental and applied scientific research (R&D) by the teams of NRU MGSU researchers.

Institutional Review Board Statement: Not applicable.
Informed Consent Statement: Not applicable.
Data Availability Statement: The data presented in this study are available on request from the corresponding author.
Conflicts of Interest: The authors declare no conflict of interest.

REFERENCES

1. **Page, A.W.** The biaxial compressive strength of brick masonry, *Proc. Inst. Civ. Eng.* 1981, *71*, pp. 893–906.
2. **Lourenço, P.B.** Computational strategies for masonry structures, Doctoral Thesis. Delft University, 1996.
3. **López, J.; Oller, S.; Oñate, E.** Cálculo del Comportamiento de la Mampostería Mediante Elementos Finitos. Barcelona, 1998.
4. **Geniev, G.A.** About the criterion of strength of masonry under flat stressed state. *Structural Mechanics and Analysis of Structures* 1979, *2*, pp. 7-11.
5. **Tyupin, G.A.** Deformation theory of plasticity of masonry. *Structural Mechanics and Analysis of Structures* 1980, *6*, pp. 28-30.
6. **Kabantsev, O.V.** Modeling nonlinear deformation and destruction of masonry under biaxial stresses. Part 1. *Applied Mechanics and Materials* 2015, 725-726, pp. 681-696.
7. **Kabantsev, O.V.** Modeling nonlinear deformation and destruction of masonry under biaxial stresses. Part 2. *Applied Mechanics and Materials* 2015, 725-726, pp. 808-819.
8. **Kabantsev, O.V.** Research fundamentals of the structural theory of masonry for the assessment of limit states of masonry structures in earthquake resistant buildings, Post-Doctoral Thesis. Moscow State University of Civil Engineering, Moscow, 2016.
9. **Vildeman, V.E.; Sokolkin, Y.V.; Tashkinov, A.A.** *Mechanics of inelastic deformation and fracture of composite materials,* Nauka: Moscow, Russia, 1997, 228 p.
10. **Kashevarova, G.G.; Zobacheva, A.Yu.; Dubinsky, S.I.** Modeling of the process of destruction of a brick masonry of buildings in full-scale and numerical experiments. *Structural Mechanics and Analysis of Structures* 2011, *1*, pp. 69-73.
11. **Kabantsev, O.V.** Discrete model of masonry under the biaxial stressed state. *Proceedings of TSASU* 2015, *4*, pp. 113-134.
12. **Kabantsev, O.V.; Tamrazyan, A.G.** Modeling of elastic-plastic deformation of a masonry under the biaxial stressed state. *International Journal for Computational Civil and Structural Engineering* 2015, *11*, pp. 87-100.
13. **Polyakov, S.V.; Safargaliev, S.M.** *Seismic stability of buildings with bearing brick walls*, Alma-Ata: 1988, 188 p.
14. **Polyakov, S.V.** *Studies on earthquake resistance of large-panel and stone buildings*, Moscow: 1962, 289 p.
15. **Polyakov, S.V.; Konovodchenko, V.I**. *Strength and deformations of vibrating brick panels at skew. Seismic stability of prefabricated large element buildings*, Moscow: 1963, pp. 131-148.
16. **Likhnenko, E.V.; Zhadanov, V.I.; Arkaev, M.A.; Adigamova, Z.S.** Modern methods of reinforcement of masonry structures with the use of composite materials when performing the capital repair of civil buildings. *Expert: theory and practice* 2021, *6 (15)*, pp. 37-44.
17. **Orlovic, R.; Mantegazza, D.; Naichuk, A.; Derkach, V.** Modern methods of repair and strengthening of stone structures. *Architecture, design and construction* 2010, *1 (44)*, pp. 86-87
18. **Shvedova, V.I.; Tumolskiy, A.P.; Molchanova, A.V.** *Application of Stakhanov's methods to rehabilitation works. General construction works*, Moscow, Leningrad: 1945, 88 p.
19. **Basov, M.A.** *Restoration of buildings destroyed by bombardment*, Moscow, Leningrad: People's Commissariat of the RSFSR, 1943, 88 p.

20. **Kabantsev, O.V.; Tonkikh, G.P.; Koshayev, V.V.** Experimental investigations of the bearing capacity of the masonry with cracks during cement mortar injection using the discharge-pulse technology. *Vestnik MGSU* 2011, *1*, pp. 127-135
21. **Tonkikh, G.P.; Kabantsev, O.V.; Granovsky, A.V.; Simakov, O.A.** Experimental studies of seismic reinforcement of masonry with the system of external reinforcement on the basis of carbon fiber. *Vestnik of TGSU* 2014, *6*, pp. 57-69.
22. **Tonkikh, G.P.; Kabantsev, O.V.; Koshayev, V.V.** Methodology of experimental studies on reinforcement of masonry buildings with reinforced concrete applications. *Earthquake-resistant construction. Safety of constructions* 2005, *6*.
23. **Tonkikh, G.P.; Kabantsev, O.V.; Koshayev, V.V.** Experimental studies of bearing capacity of masonry under main loads. *Earthquake-resistant construction. Safety of constructions* 2007, *6*.
24. **Tonkikh, G.P.; Kabantsev, O.V.; Simakov, O.A.; Simakov, A.B., Baev, S.M.; Panfilov, P.S.** Experimental study of seismic strengthening of masonry exterior concrete applications. *Earthquake-resistant construction. Safety of constructions* 2011, *2*.
25. **Tonkikh, G.H.; Simakov, O.A.; Kabantsev, O.V.; Bayev, S.M.** Experimental studies of masonry aseismic reinforcement using external concrete applications. *Earthquake-resistant construction. Safety of constructions* 2011, *2*.
26. **Kabantsev, O.V.; Simakov, O.A.; Neshchadimov, V.A.; Shtyrlov, D.A.** Strengthening bearing masonry walls of damaged multi-storey buildings. *Industrial and Civil Engineering* 2023, *7*, 29-35.

СПИСОК ЛИТЕРАТУРЫ

1. **Page, A.W.** The biaxial compressive strength of brick masonry, *Proc. Inst. Civ. Eng.* **1981**, *71*, pp. 893–906.
2. **Lourenço, P.B.** Computational strategies for masonry structures, Doctoral Thesis. Delft University, 1996.
3. **López, J.; Oller, S.; Oñate, E.** Cálculo del Comportamiento de la Mampostería Mediante Elementos Finitos. Barcelona, 1998.
4. **Гениев Г.А.** О критерии прочности каменной кладки при плоском напряженном состоянии // Строительная механика и расчет сооружений. 1979. №2. С. 7-11.
5. **Тюпин Г.А.** Деформационная теория пластичности каменной кладки // Строительная механика и расчет сооружений. 1980. №6. С. 28-30.
6. **Kabantsev, O.V.** Modeling nonlinear deformation and destruction of masonry under biaxial stresses. Part 1. *Applied Mechanics and Materials* **2015**, 725-726, pp. 681-696.
7. **Kabantsev, O.V.** Modeling nonlinear deformation and destruction of masonry under biaxial stresses. Part 2. *Applied Mechanics and Materials* **2015**, 725-726, pp. 808-819.
8. **Kabantsev, O.V.** Research fundamentals of the structural theory of masonry for the assessment of limit states of masonry structures in earthquake resistant buildings, Post-Doctoral Thesis. Moscow State University of Civil Engineering, Moscow, 2016.
9. **Вильдеман В.Э. Соколкин Ю.В., Ташкинов А.А.** Механика неупругого деформирования и разрушения композиционных материалов. М. : Наука, 1997. 228 с.
10. **Кашеварова Г.Г., Зобачева А.Ю., Дубинский С.И.** Моделирование процесса разрушения кирпичной кладки зданий в натурных и численных экспериментах // Строительная механика и расчет сооружений. 2011. – №1. – С. 69-73.
11. **Кабанцев О.В.** Дискретная модель каменной кладки в условиях двухосного напряженного состояния // Вестник ТГАСУ. 2015. № 4. С. 113-134.
12. **Кабанцев О.В., Тамразян А.Г.** Моделирование упругопластического деформирования каменной кладки в условиях двухосного наряженного состояния // International Journal for Computational Civil

and Structural Engineering. 2015. Iss. 3. Vol. 11. Pp. 87–100.

13. **Поляков С.В., Сафаргалиев С.М.** Сейсмостойкость зданий с несущими кирпичными стенами. – Алма-Ата: 1988. – 188 с
14. **Поляков С.В.** Исследования по сейсмостойкости крупнопанельных и каменных зданий. - М.: 1962. – 289 с.
15. **Поляков С.В., Коноводченко В.И.** Прочность и деформации виброкирпичных панелей при перекосе. // Сейсмостойкость сборных крупноэлементных зданий. - М.: 1963. - С. 131-148.
16. **Лихненко Е.В, Жаданов В.И., Аркаев М.А., Адигамова З.С.** Современные методы усиления каменных конструкций с применением композитных материалов при выполнении капитального ремонта гражданских зданий // Эксперт: теория и практика. 2021. № 6 (15). С. 37-44. doi:10.51608/26867818_2021_6_37
17. **Орлович Р., Мантегацца Д., Найчук А., Деркач В.** Современные способы ремонта и усиления каменных конструкций // Архитектура, дизайн и строительство. 2010. №1 (44). С. 86-87
18. **Шведова В.И., Тумольский А.П., Молчанова А.В.** Применение стахановских методов на восстановительных работах. Общестроительные работы. Москва, Ленинград, 1945 - 88 с.
19. **Басов М.А.** Восстановление зданий, разрушенных бомбардировкой. Москва ; Ленинград : Наркомзем РСФСР, 1943. - 88 с.
20. **Кабанцев, О.В.** Экспериментальные исследования несущей способности каменной кладки с трещинами при их инъецировании цементным раствором по разрядно-импульсной технологии [Текст] / О.В. Кабанцев, Г.П. Тонких, В.В. Кошаев, В.Я. Еремин, М.В. Тихонов // Научно-технический вестник МГСУ. – 2011. – №2 (т.1) . – С. 127-135
21. **Тонких Г.П., Кабанцев О.В., Грановский А.В., Симаков О.А.** Экспериментальные исследования сейсмоусиления каменной кладки системой внешнего армирования на основе углеволокна/ Вестник ТГАСУ 2014 г. № 6. С. 57-69. EDN: REJYWB
20. **Тонких Г.П., Кабанцев О.В., Кошаев В.В.** Методика экспериментальных исследований по усилению зданий из каменной кладки железобетонными аппликациями. Журнал «Сейсмостойкое строительство. Безопасность сооружений» №6, 2005 г.
22. **Тонких Г.П., Кабанцев О.В., Кошаев В.В.** Методика экспериментальных исследований по усилению зданий из каменной кладки железобетонными аппликациями. Журнал «Сейсмостойкое строительство. Безопасность сооружений» №6, 2005 г.
23. **Тонких Г.П., Кабанцев О.В., Кошаев В.В.** Экспериментальные исследования несущей способности каменной кладки при главных нагрузках. Журнал «Сейсмостойкое строительство. Безопасность сооружений» №6, 2007 г.
24. **Кабанцев О.В., Тонких Г.П., Тонких Г.П., Кабанцев О.В., Симаков О.А., Симаков А.Б., Баев С.М., Панфилов П.С.** Экспериментальные исследования сейсмоусиления каменной кладки наружными бетонными аппликациями. // Сейсмостойкое строительство. Безопасность сооружений. 2011. № 2.
25. **Кабанцев О.В., Тонких Г.П., Симаков О.А., Симаков А.Б., Баев С.М.** Повышение сейсмостойкости каменных конструкций односторонними аппликациями из торкрет-бетона//Аэропорты. Прогрессивные технологии. 2011. №2. С. 26-32.
26. **Кабанцев О.В., Симаков О.А., Нещадимов В.А., Штырлов Д.А.** Усиление несущих стен из каменной кладки поврежденных многоэтажных зданий // Промышленное и гражданское строительство. 2023. № 7. С. 29-35. doi: 10.33622/0869-7019.2023.07.29-35

Kabantsev Oleg — Doctor of Technical Sciences, Associate Professor, Professor of Departments of Reinforced Concrete and Stone Structures, National Research Moscow State University of Civil Engineering (NRU MGSU); 129337, Moscow, Yaroslavskoe Highway, 26; E-mail: ovk531@gmail.com

Simakov Oleg – Candidate of Technical Sciences, Associate Professor Departments of Reinforced Concrete and Stone Structures, National Research Moscow State University of Civil Engineering (NRU MGSU); 129337, Moscow, Yaroslavskoe Highway, 26; E-mail: simakov-ne@mail.ru

Олег Васильевич Кабанцев — доктор технических наук, доцент, профессор кафедры железобетонных и каменных конструкций, Национальный исследовательский Московский государственный строительный университет (НИУ МГСУ); 129337, г. Москва, Ярославское шоссе, д. 26; эл. почта: ovk531@gmail.com

Симаков Олег Александрович - кандидат технических наук, доцент кафедры железобетонных и каменных конструкций, Национальный исследовательский Московский государственный строительный университет (НИУ МГСУ); 129337, г. Москва, Ярославское шоссе, д. 26, эл. почта: simakov-ne@mail.ru;