Technology for reinforcing strip foundations of reconstructed brick buildings based on computer modeling

Ilyas Galiev¹, Ruslan Ibragimov¹[0000-0001-8879-1190], Azat Ashrapov¹ and Oleg Radaykin¹

¹Kazan State University of Architecture and Engineering, Kazan, Russia
E-mail: galiev-ih@kgasu.ru

Abstract. When resolving the issue of the foundations strengthening and reconstructed buildings foundations, it is necessary to consider the ground part of the building or structure as a whole. The foundations are the soil foundation under them. It is necessary to solve simultaneously the problem of reducing the sensitivity of a building or structure to uniform precipitation of foundations and to restore the spatial rigidity of the building.

In order to study this issue, a numerical experiment was developed – modeling and calculation of the reconstructed brick building bearing capacity based on varying the thickness of the brick wall.

The analysis of stress-deformed state portion of the structure revealed that the greatest deformation of the elements is obtained in the overlapping area bearing elements and the edge beam in the location area. The relative displacements study of the finite elements nodes showed convergence with field observations of the foundation beam deformation at the object.

Keywords: reconstruction, renovation, strengthening of foundations, underground construction.

1 Introduction
Modern civilization recognizes the potential of cultural heritage in the form of historic brick buildings. Hence there is need for their conservation and efficient use as one of the most important resources of the global economy. The loss of cultural property of this kind is irreplaceable and irreversible. Any loss of a historical building inevitably affects all areas of life of present and future generations, leads to ruptures of historical memory, impoverishment of society as a whole. The preservation of this kind of architectural and historical valuable objects is the basis of the development of civilization.

The main causes of physical deterioration, destruction of historic buildings of bricks in the world are technogenic [1], seismic [2, 3], biological effects [4]. The reason is usually the result of human activity: irrigation works, redevelopment and construction of the monument area, internal restructuring in order to adapt various operational measures.

The organization of parking lots, administrative and other premises, and access roads should be involved during the construction of new facilities, the reconstruction of old buildings and, in general, when planning the development of the territory. As for the new construction, this issue is quite well studied and there are many different ways of building objects with the use of the underground space. However, in cases where new construction is not planned for parking or other required premises, there is a need to maintain existing buildings, and in cramped conditions, in the
absence of free space, it is necessary to create sufficient amount of additional space. This issue becomes especially relevant and difficult [5, 6].

Sometimes the only solution is to arrange multi-level underground premises under existing buildings and structures.

Currently, there are various ways to reconstruct buildings with an increase in useful underground space [7, 8].

When laying soils with high deformability at the base of buildings, or if necessary, increasing the useful area of buildings due to additional underground floors, the method of "replacing existing buildings on new foundations" is used [10]. At its core, the method is a device for replacing and / or unloading structures.

The method of transplanting reconstructed buildings to new foundations is difficult to implement due to the tightness of the workspace, the limited methods, machines and equipment for implementation [11], the danger of a critical situation (excessive deformation or collapse of the building) [12, 13], the presence of unforeseen factors in underexplored (hidden) soil conditions [14], hidden defects and damages in the structures of the reinforced building, etc. In addition, the whole process requires constant monitoring of deformations and load-bearing elements of the building and quality control of work [15, 16].

In the matter of strengthening soils and foundations, the study one cannot be limited to their standing. It is necessary to consider the ground part of a building or structure, the foundations are a soil base under them as a single whole. With such an approach, it is often found out that it is impossible to do without reinforcing the foundation or foundations. It is necessary to solve simultaneously the problem of reducing the sensitivity of a building or structure to uniform the precipitation of foundations and to restore the spatial rigidity of the building, disturbed by the appearance of cracks, banks, etc. The sensitivity of the reconstructed building to uneven precipitation can be reduced by means of steel belts arranged by slabs, knocked out in foundations or walls [17].

![Figure 1](image1.png)

**Figure 1.** A fragment of a historic brick wall, supported by a new foundation.

In the production of this type of work it is little known about load transfer from the host to improve reinforcing structures to structures gain. Strengthening structures, in turn, can be either temporary intermediate (emergency, transfer, transfer) structures dismantled when the main foundation is installed [18, 19]; or permanent – included in the work according to the constant scheme and remaining in the general design for the period of further operation of the building [20, 21]. In this regard, the problem of improving the transmission nodes of reinforced structures, the number and pitch of reinforced beams is relevant. For example, in the study of shear wall deformation of the edge beam in the form of bending wall by up to 7 mm sill and shelf inclination to 6 mm were
discovered. In addition there are small areas unfilled with concrete; and cracks with an opening width of up to 0.3 mm at the points of load transfer and at the border with the metal (figure 1). In order to study this issue, a numerical experiment has been developed.

Purpose of the article is the modeling and calculation of the reconstructed brick building bearing capacity based on varying the thickness of the brick wall.

2 Materials and methods
Finite-element modeling of building structures using the LIRA-SAPR-2018 software package – the structural analysis software is comprehensive software package that benefits from BIM technology. The software is intended for the analysis and design of building and mechanical engineering structures of different purposes. The software for numerical analysis of structures' strength and stability and computer-aided design process was adopted for modeling a typical historical building of the mid-19th century.

A typical brick administrative building built in the middle of the 19th century was used as an experimental model.

2.1 Short description of the object
The House of the merchant Lisitsyn is located in Kazan on Pushkin Street. It was built in the XIX century. Since its construction, it has undergone many changes. The building was originally two-story. Later it was completed in length and a three-story stone outbuilding was attached perpendicular to it from the yard.

The complexity of the work was compounded by the presence of factors [22-23] influencing the conditions for the reconstruction of the facility: heavy traffic of public transport and pedestrians in the immediate vicinity of the work site, an extensive network of existing underground utilities to be suspended or reassigned; cramped storage conditions for materials, as building density exceeds the norm in accordance with Russian Standard 81-35.2004.

The structural scheme of the existing reconstructed building is frameless. The spatial rigidity and stability of the building is ensured by the work of load-bearing walls, staircase walls, connected by floor structures.

The overall dimensions of the building are 26.5×36 m, the height of the building is 10 m, the floor height is 3 m. The building has a basement floor, 3.5 m high. The supporting structures are brick walls of variable thickness reaching 0.9 m at the 1st floor level. A rubble foundation’s depth is nearly 3.5 m.

2.2 Production technology
Implementation of the proposed solutions was carried out at a real facility on Pushkin St. in Kazan. Before the work was carried out, the measures were taken to increase the rigidity of the structural system of the entire building, namely: in the levels of floors, monolithic belts were connected, interconnected by floor disks. On top of the foundations of the building hanging part, on a non-shrinking mortar, a metal belt (foundation beam) of C-beams, which are pulled together by through studs, was installed in a special stub. The second stage of the work is associated with the installation of temporary hanging structures. To do this, bored reinforced piles to a depth of 8.5 m were made at a distance from 0.9 m to 1.5 m from the walls of the building, and a monolithic reinforced concrete grillage was arranged on top of the piles. Directly under the metal belt, I-beams were installed in drilled through holes with a pitch of about 1 m, supporting the load-bearing wall through the C-beam, and a grillage served as their support. After wedging all the structures, welding and strengthening the heavy concrete, we started to develop the soil inside the building, as well as under the foundations to the level of -3.800 m. The old foundations and loose sections of brick walls were dismantled. A new monolithic reinforced concrete shallow foundation was laid under the contour of suspended walls of fine-grained concrete until the metal belt was completely filled. After the concrete foundation had gained strength, they started the phased dismantling of
temporary structures, while the load was transferred from the building to the newly completed foundations. In the process of carrying out technological work, the supporting building structures were monitored by the Federal State Educational Institution “Kazan State University of Architecture and Engineering”. Special devices and beacons were installed in characteristic places to measure the vertical and horizontal displacements of building elements. During the work, constant measurements and analysis of their readings were made.

One of the features of the arranged underground area in an existing building is the use of small-sized construction equipment [24, 25]. A Wacker Neuson mini excavator with a bucket volume of 0.08 m$^3$ and a dump truck with a loading capacity of 800 kg and a bucket volume of 334 m$^3$ were used at the facility (figure 2).

Figure 2. A fragment of a wall made of historical brick, based on temporary foundations and the work of small-sized equipment.

2.3 Experiment simulation
The following elements are highlighted in the developed model (figure 3):

- a section of a brick wall with overall dimensions of 0.51×2.8×3.25 (h) m (the size of the final element is 0.125×0.1275×0.2 m). Elastic modulus E = 10000 t/m$^2$, Poisson's ratio $\nu = 0.2$, specific gravity of the material $\rho_0 = 1.8$ t/m$^3$;

- a randbeam from C-beam №30u according to Russian standard 8240-89, pushed into a wall at the level of the basement floor, modeled from a core element combined in nodes with the final elements of a brick wall;

- transverse beams brought under a randbeam - I-beam №40 according to the Russian standard 8239-72*. Rigid inserts are included for communication with the foundation beam and rod elements;

- the grillage on top of the piles was adopted from monolithic reinforced concrete with a density of 2.5 t/m$^3$, dimensions 500×400 (h) mm;

- piles - a core element, material - reinforced concrete with a density of 2.5 t/m$^3$, with a diameter of 300 mm; pile pitch adopted 1.2 m.
- soil - as a soil condition at this stage of the experiment, plastic sandy loam specified by the finite element KE271-276 was adopted. At this stage of the experiment, the soil conditions are approximated by the coupling elements at the ends of the piles.

Rigid inserts are added for tying points of application of loads in the places of mating of rod elements.

Figure 3. 3D-model.

2.4 Load collection
To carry out calculations during the design development, we present the load collection algorithm using the example of the building under development (table 1).

The loads are collected with the following data: the density of the brickwork of the walls of the building is 1800 kg/m$^3$, the wall thickness is 0.51 (+0.1275 $n$) m, the standard values of the floor loads and the load safety factors $\gamma_f$ for the weight of building structures are taken according to Russian standard code of rules 20.13330.2016.

The geometric dimensions and heights are taken as follows:
- the distance between the piles along the axes: along the wall – 1.2 m (const), across the wall 1.75 (+ 0.1275 $n$) m;
- wall height (one floor) 3 m (const);
- wall thickness 0.51 (+ 0.1275 $n$) m;
- cargo floor area of 3 m$^2$ per meter of running wall (const);

“$n$” is the number of iterations.

The load area of 1 linear meter of the external wall is 3 m$^2$, then the linear load will be $P_1 = 2994 \times 3 = 8982$ kg/m.

The application of loads is carried out in the nodes of the final elements of the wall, the size of which is 0.2 m, therefore the load from the floors is $P = 8982 \times 0.2$ m = 1796.4 kg/m = 1.8 t/m.

The surface area of the final elements of the walls is 0.1275 $\times$ 0.2 m, therefore, the load on the nodes from the weight of the wall is $7068.6 \times 0.2/5 = 242.7$ kg = 0.24 t.

After applying the loads, we set the connections (fixing conditions) for the support nodes: at the ends of the piles, at the ends of the wall section and at the level of overlap along the wall section, the restriction of horizontal movements.
### Table 1. Load collection.

| Type of load                                      | Normative load, kg/m² | Load Reliability Factor | Estimated load, kg/m² |
|--------------------------------------------------|------------------------|-------------------------|-----------------------|
| **Permanent:**                                    |                        |                         |                       |
| From the mass of the floor slab (δ = 0.2 m, ρ = 2500 kg/m³) (from 3 floors) | 3×500                  | 1.1                     | 1650                  |
| Heater – expanded clay γ = 600 kg/m³, 150 mm      | 0,15×600=90            | 1.3                     | 117                   |
| Cement and sand screed 50 mm                      | 0.05×1800=90           | 1.3                     | 117                   |
| Roof structure                                    | 100                    | 1.1                     | 110                   |
| Floor loads for office buildings (from 3 floors)  | 3×200                  | 1.2                     | 720                   |
| Total constant per 1 m² of overlap (coverage)     | 980                    |                         | 2714                  |
| **Temporary:**                                    |                        |                         |                       |
| Snow                                             | 200                    | 1.4                     | 280                   |
| Total:                                           | 3048                   |                         | 2994                  |
| Loads per linear meter of walls (δ = 0.51 m, ρ = 1800 kg/m³, h = 10-3 = 7 m - on the edge of the top of the wall of the 1st floor) | 6426 kg/m            | 1.1                     | 7068.6 kg/m           |
|                                                  |                        |                         | (13860 kg/m²)         |

### 3 Results

Analyzing the stress-strain state of the construction site (figure 4.), it was found that the greatest deformations are received by the elements in the zone of abutment of the floor and the elements in the zone of the location of the beam.

![Figure 4. Stresses in the elements.](image-url)
With a wall thickness of 510 mm, the relative displacements of nodes located on the lower and upper boundary of the foundation beam were \(-9.394\) - \(-8.08\) = \(-1.314\) mm, that is, C-beam № 30 was crushed by 1.314 mm.

When analyzing the diagram of moments, it was found that the maximum values of the bending moment are 1.57 t·m.

When rolling beams made of C245 steel, the cross section of the beams is taken according to the required moment of beam resistance during bending, it is determined from the condition:

\[
W_{rec} = \frac{M_{max}}{R_y \cdot \gamma_c}. \tag{1}
\]

\[
R_y = 24 \text{ kN} / \text{cm}^2 = 2400 \text{ kg} / \text{cm}^2. \tag{2}
\]

\[
W_{rec} = 1570\text{kg} \times 100\text{cm} / 2400\text{kg} / \text{cm}^2 / 0.9 = 72.7\text{cm}^3. \tag{3}
\]

According to the assortment of rolling C-beams, with these efforts, C-beam number 16 is sufficient.

For cross beams \(W_{rec} = 5260\text{kg} \times 100\text{cm} / 2400\text{kg} / \text{cm}^2 / 0.9 = 243.5\text{cm}^3\), according to the assortment of rolling I-beams, with these efforts, I-beam No. 22 is enough.

With a wall thickness of 640 mm, the relative displacements of nodes located on the lower and upper boundaries of the foundation beam were \(-9.77\) - \(-8.71\) = \(-1.06\) mm, that is, C-beam № 30 was crushed by 1.06 mm.

When analyzing the moment diagram, it was found that the maximum values of the bending moment were 1.79 t·m.

When rolling beams made of C245 steel, the cross section of the beams is taken according to the required moment of beam resistance during bending, it is determined from the condition \(W_{rec} = 1790\text{kg} \times 100\text{cm} / 2400\text{kg} / \text{cm}^2 / 0.9 = 82.9\text{cm}^3\).

According to the assortment of rolling C-beams, with these efforts, C-beam number 16 is sufficient.

For cross beams \(W_{rec} = 5750\text{kg} \times 100\text{cm} / 2400\text{kg} / \text{cm}^2 / 0.9 = 266.2\text{cm}^3\), according to the assortment of rolling I-beams, with these efforts, I-beam No. 22 is enough.

With a wall thickness of 770 mm, the relative displacements of the nodes located on the lower and upper boundaries of the foundation beam were \(-10.58\) - \(-9.63\) = \(-0.95\) mm, that is, C-beam № 30 was crushed by 0.95 mm.

When analyzing the diagram of moments, it was found that the maximum values of the bending moment were 1.71 t·m.

The required moment of beam resistance during bending is determined from the condition \(W_{rec} = 1710\text{kg} \times 100\text{cm} / 2400\text{kg} / \text{cm}^2 / 0.9 = 79.2\text{cm}^3\).

According to the assortment of rolling C-beams, with these efforts, C-beam number 16 is sufficient.

For cross beams \(W_{rec} = 6180\text{kg} \times 100\text{cm} / 2400\text{kg} / \text{cm}^2 / 0.9 = 286\text{cm}^3\), according to the assortment of rolling I-beams, with these efforts, I-beam No. 24 is enough.

With a wall thickness of 900 mm, the relative displacements of the nodes located on the lower and upper boundaries of the foundation beam were \(-11.23\) - \(-10.50\) = \(-0.73\) mm, that is, C-beam № 30 was crushed by 0.73 mm.

When analyzing the moment diagram, it was found that the maximum values of the bending moment were 1.75 t·m.

The required moment of beam resistance during bending is determined from the condition \(W_{rec} = 1750\text{kg} \times 100\text{cm} / 2400\text{kg} / \text{cm}^2 / 0.9 = 81\text{cm}^3\).

According to the assortment of rolling C-beams, with these efforts, C-beam number 16 is sufficient.

For cross beams \(W_{rec} = 6590\text{kg} \times 100\text{cm} / 2400\text{kg} / \text{cm}^2 / 0.9 = 305.1\text{cm}^3\), according to the assortment of rolling I-beams, with these efforts, I-beam No. 27 is enough.

However, for the given loads, the beam wall is crushed. To prevent local deformation of the channel wall, it is necessary to provide additional reinforcements in the form of a contraction
double row of the beams between each other, or reinforce with a stiffener, the upper end of which should be cut to the belt or in any other way.

The selected sections in beams, when modeled in an article with wall thickness, are presented in table 2 and in figure 5.

Table 2. Dependence of the thickness of the simulated wall on the section of beams.

| №  | The thickness of the simulated brick wall, mm | Foundation beam section | Cross beam section |
|----|---------------------------------------------|-------------------------|--------------------|
| 1  | 510                                         | C-beam №16              | I-beam №22         |
| 2  | 640                                         | C-beam №16              | I-beam №22         |
| 3  | 770                                         | C-beam №16              | I-beam №24         |
| 4  | 900                                         | C-beam №16              | I-beam №27         |

Figure 5. Selected sections in beams.

The further direction of the study is aimed at modeling soil conditions, increasing the varied parameters, as well as calculating the complexity of the production of the presented works during the reconstruction of buildings.

4 Conclusions
1. When modeling a reconstructed brick building in the LIRA PC, the closest to the real behavior of the structure is the adoption of randbeams as core elements connected in nodes with the finite elements of the wall. To attach the points of application of loads in the places of interfacing of the rod elements, it is possible to use rigid inserts.

2. The calculation results showed that when varying the thickness of the brick section of the outer wall from 510 mm to 900 mm with a pitch of 128 mm, the following section of the foundation beam is sufficient - C-beam №. 16 for all thicknesses; cross-section of the transverse beam: I-beam No. 22, No. 22, No. 24, No. 27, respectively.

3 The relative displacements analysis of the nodes of the finite elements showed convergence with field observations of the foundation beam deformation at the object.

References
[1] Yuan H, Gao X, Qi W 2019 Modeling the fine-scale spatiotemporal pattern of earthquake casualties in cities: Application to Haidian District, Beijing International Journal of Disaster Risk Reduction, 34, pp 412-422. doi: 10.1016/j.ijdrr.2018.12.010
[2] Xin R, Yu C, Chen J and Jiang L 2010 Discussion on the typical seismic strengthening
techniques of masonry building walls after Wenchuan earthquake, *International Conference on Mechanic Automation and Control Engineering*, Wuhan, 2010, pp 1126-1129. doi: 10.1109/MACE.2010.5536620

[3] Xiao H J and Liu W D 2010 Experiment of the existing capacity of masonry blocks of in service historical preserved buildings, *Architectural Structure*, vol. 40, no. 11, pp 112-114.

[4] Brambilla G, Lavagna M, Vassavrellis G 2019 Environmental benefits arising from demountable steel-concrete composite floor systems in buildings. *Resources, Conservation and Recycling* 141 pp 133-142. doi: 10.1016/j.resconrec.2018.10.014

[5] Arkadiy Larionov, Yulia Larionova 2016 Prospects for Underground Parking Lots Arrangement at the Construction of Moscow Region Residential Property *Procedia Engineering*, Vol. 1652016, pp 1328-1331. doi: 10.1016/j.proeng.2016.11.859

[6] Joana M, Ricardo G, Luis M, Samuel N 2019 Combining embodied and operational energy in buildings refurbishment assessment *Energy and Buildings* 197 (15), pp 34-46. doi: 10.1016/j.enbuild.2019.05.033

[7] Donatello C, Amedeo F, Mauro De Luca P, Adriano M 2019 Estimating direct and indirect losses due to earthquake damage in residential RC buildings *Soil Dynamics and Earthquake Engineering*, 126, 105801. doi: 10.1016/j.soildyn.2019.105801

[8] Thomas Cz, Fernanda L 2020 Automated digital modeling of existing buildings: A review of visual object recognition methods *Automation in Construction*, 113, 103131. doi: 10.1016/j.autcon.2020.103131

[9] Alicia A, Jorge P, Rafael S, Rocío E 2020 Acoustical retrofit of existing residential buildings: Requirements and recommendations for sound insulation between dwellings in Europe and other countries worldwide *Building and Environment*, 74, 106771. doi: 10.1016/j.buildenv.2020.106771

[10] Shabiev S 2016 The Ecological City Planning Aspects of the South Ural State University Main Building Complex Reconstruction *Procedia Engineering*, 150, pp 1978-1982. doi: 10.1016/j.proeng.2016.07.201

[11] Ibragimov R, Fediuk R 2019 Improving the early strength of concrete: Effect of mechanochemical activation of the cementitious suspension and using of various superplasticizers *Construction and Building Materials*, 226, pp 839-848. doi: 10.1016/j.conbuildmat.2019.07.313

[12] Mangushev R, Osokin A 2017 Construction of Deep Foundation Ditch under a Reconstructed Multi-storey Building on the Main Avenue of St. Petersburg *Procedia Engineering*, 189, pp 622-629. doi: 10.1016/j.proeng.2017.05.099

[13] Yozo F, Dionysius M S, Yoshiki I, Tomonori N, Tuskasa M 2019 Research and Implementations of Structural Monitoring for Bridges and Buildings in Japan *Engineering*, 5(6), pp 1093-1119.

[14] Dachuan S, Yafeng G, Rui Guo 2019 Life cycle assessment of white roof and sedum traygarden roof for office buildings in China *Sustainable Cities and Society*, 46, 101390. doi: 10.1016/j.scs.2018.12.018

[15] Ibragimov R A, Korolev E V, Deberdeev T R, Leksin V V, Solovev D B 2018 Energy parameters of the binder during activation in the vortex layer apparatus *Materials Science Forum*, 945 MSF, pp 98-103. doi: 10.4028/www.scientific.net/MSF.945.98

[16] Charles Th, Alain B, Marion S 2019 Building rehabilitation life cycle assessment methodology-state of the art *Renewable and Sustainable Energy Reviews*, 103, pp 408-422.

[17] Ibragimov R A, Bogdanov R R 2017 The influence of a complex modifying agent on the hydration and structure formation of self-compacting concrete *ZKG International* 70(4), pp 44-49.

[18] Khalid M, Umberto A, Hyerin L, Jaume A Performance-based engineering and multi-criteria decision analysis for sustainable and resilient building design *Structural Safety*, 74, pp 1-13. doi: 10.1016/j.strusafe.2018.03.005
[19] Min-Koo K, Qian W, Heng Li 2019 Non-contact sensing based geometric quality assessment of buildings and civil structures: A review Automation in Construction, 100, pp 163-179. doi: 10.1016/j.autcon.2019.01.002

[20] Marini A, Passoni C, Belleri A 2018 Life cycle perspective in RC building integrated renovation Procedia Structural Integrity, 11, pp 28-35. doi: 10.1016/j.prostr.2018.11.005

[21] Joblot L, Paviot T, Deneux D, Lamouri S 2019 Building Information Maturity Model specific to the renovation sector Automation in Construction, 101, pp 140-159. doi: 10.1016/j.autcon.2019.01.019

[22] Kokoshin S, Ustinov N, Kirgincev B 2016 The use of Flexible Tubular Elements of the Overhaul and Tunnels Reconstruction Procedia Engineering, 165, pp 817-828. doi: 10.1016/j.proeng.2016.11.780

[23] Prepis A, Johnson D, Bianchi A, Gödicke H, Šurdić B, Hoxha G, Montanes F, Mills A, Wik S 2005 Protection and Preservation of Cultural Heritage in KOSOVO Consolidated Summary, International Donors Conference, UNESCO UNMIK Council of Europe European Commission, Paris, 41 p.

[24] Prepis A 2018 The values of the World Heritage and the younger generation, Heritage and Modern Times, vol. 1, no. 3 (3), pp 7-19.

[25] Prepis Alkiviadis 2002 Management and Preservation of Archaeological Sites, In: Z. Ahunbay U. Izmirlilig (ed.): Management and Preservation of Archaeological Sites, 4th Bilateral Meeting of ICOMOS Turkey ICOMOS Greece, 29 April-2 May, Side, Antalya / Turkey, pp 13-18.