

Analysis of the calculation and experimental method for determining the bearing capacity of stone structures

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Abstract. The article presents the results of an experimental study of the stress-strain state of damaged stone columns. It includes an overview of the general research methodology and methods for addressing specific tasks. Detailed descriptions are provided of the strength testing methods for individual elements of brickwork, including bricks and cement-sand mortar. The article also introduces the technology for manufacturing and testing the eccentric compression of stone columns of various cross-sections. A matrix of the conducted experiment is presented, which includes levels and varying factors such as the depth of damage to elements, eccentricity of load application, and angle of inclination of the damage front along one of the principal cross-sectional axes. The experiment's results reveal the most adverse factor affecting load-bearing capacity. Additionally, a calculation and analysis of the safety margin are performed based on the examination of the materials used, which are not considered in calculating the load-bearing capacity of the damaged stone column.

1 Introduction

Stone structures have been widely used throughout history, being one of the oldest materials in the construction industry. During the industrialization period of construction, stone structures, which didn't meet the level of technological development and mechanization requirements compared to precast reinforced concrete, were rarely used, and research on their performance was almost completely discontinued. Nowadays, stone structures have found their optimal application both in enclosing and load-bearing structures. The optimal solution lies in combining these functions, especially with the use of effective insulation methods. However, the widespread adoption of stone structures is hindered by insufficient understanding of their behavior, inaccuracies in determining the parameters of stress-strain

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state (SSS), i.e., imperfections in their calculation. The main drawback in theoretical calculations lies in unaccounted factors (non-uniformity of masonry, real stress-strain state, material behavior diagrams, etc.) and a simplified empirical approach that does not describe the actual behavior of the structure. Structures built using stone masonry are considered composite materials. By composite, it is meant an artificially created, solid material consisting of two or more components, each of which is introduced into the composition to impart the missing properties necessary to achieve high strength and deformation characteristics.

According to European standards [1], the normative shear resistance (f_{vk}) is determined based on the test results of brickwork. The initial normative shear resistance (f_{vko}) of stone masonry (shear bond strength) is determined based on the test results according to EN 1052-3 or EN 1052-4. The normative shear resistance of stone masonry (f_{vk}) is based on mortar of general purpose if all joints are considered fully filled.

$$f_{vk} = f_{vko} + 0,4\sigma_d, \quad (1)$$

but not exceeding 0.065 times the compressive strength, f_b , or the tensile strength, f_{vkt} .

where f_{vko} – the initial normative shear resistance of stone masonry in the absence of compressive loading;

f_{vkt} – the boundary value f_{vk} ;

σ_d – the calculated compressive stress perpendicular to the shear force, computed as the average stress distribution within the compressed section of the cross-section under the respective combination of loads;

f_d – the reduced (normalized) compressive strength of stone (block) f_d according to 3.1.2.1 [1] in the direction of the shear force, i.e., when loading test specimens perpendicular to the horizontal joint.

The vertical shear resistance at the junction of two walls can be determined through appropriate tests on a specific object or by processing a database. In the absence of test results, the normative shear resistance of stone masonry (f_{vk}) is allowed to be taken as equal to the value of f_{vko} . If the joint is made according to 8.5.2.1 [1], then in this case, f_{vko} is taken when checking the shear strength of the wall intersection without considering temporary loading.

During calculating circular brick disks [2], it has been established that the greater the difference between the moduli of elasticity of the brick and mortar, the more unevenly distributed the tensile stresses are, with the peak located in the material with the lower modulus.

Assessing the works of domestic and foreign scientists, it should be noted the inadequacy of studying the issue of determining the failure criterion of brickwork as a whole.

For the first time, such a criterion was developed in the work [3] for stone masonry under plane stress conditions. This criterion more accurately reflects the physical phenomena occurring in the stone masonry up to failure. Naturally, the proposed methodology requires confirmation through experimental research.

As of today, both domestic [4] and international standards [5-11] for masonry design under uniaxial stress do not align with the modern level of knowledge in solid mechanics and evidently require revision.

In the works of B.R. Sinha, M.D. Loftus, R. Temple [12], P. Schubert, H. Glitza [13, 14], and L.I. Onishchik [5], methodologies for conducting experiments to determine the elastic constants of masonry (elastic moduli in the principal axes of orthotropy, shear modulus, Poisson's ratios) are provided. Additionally, data on the strength characteristics of masonry are presented in these works [16-18].

In their work [19], S. Fattal and F. Jokel examine four hypotheses regarding the failure of masonry. It is established that failure can occur due to: a) joint failure; b) critical normal stress; c) critical biaxial combination of principal stresses; d) critical tensile strain in the wall

plane. The authors draw the following conclusions in their study: 1) the failure of brick walls under the action of compressive loads may occur due to joint detachment or splitting; 2) the load-bearing capacity, in cases where failure is caused by splitting, can be predicted based on the criterion of the critical biaxial combination of principal normal stresses.

Our team [20] has also conducted research aiming to develop a calculation model for determining the residual bearing capacity of compressed stone elements with damaged cross-sections. Laboratory testing of 15 prototypes with pre-modeled damage revealed that parameters characterizing element damage eccentricity significantly affect carrying capacity, with the depth of damage in the cross section of the column identified as the most influential factor. The resulting calculation model, based on existing building codes, addresses both direct and oblique types of damages, providing a comprehensive approach to assessing structural integrity.

This paper [21] explores various analysis methods for historic structures and proposes guidelines to address the complexity of engineering problems in conservation and restoration projects.

In the paper [22] investigates analytical methods for estimating the bearing capacity of stone columns by comparing measured and estimated values from 36 full-scale field tests. It evaluates 15 analytical solutions using statistical approaches to rank them based on prediction accuracy, providing valuable guidance for designers and decision-makers in selecting reliable design methods for projects involving stone columns.

This study of our colleagues in Ukraine [23] addresses the degradation of reinforced concrete and metal structures in long-term operation by reviewing relevant literature and conducting field studies. It highlights modern methods and materials for strengthening damaged structures, presenting findings from visual and instrumental examinations of various load-bearing elements and providing recommendations for repair based on the actual technical condition of the building.

There was a separate research group [24-27] that using stone columns is an efficient method to increase the bearing capacity of soft soils, with research focusing on various design aspects to enhance effectiveness. Experimental and numerical studies have explored factors such as non-uniform diameters, granular blankets, and different loading conditions, highlighting improvements in bearing capacity and settlement reduction with specific reinforcement techniques such as geotextiles and geogrids. The findings underscore the significance of considering parameters like modified area ratio and bed soil cohesion in optimizing the performance of stone columns, while also indicating the impact of loading conditions on stress distribution between the columns and surrounding soil.

This paper [28] presents a numerical investigation into the effect of concentric inclined loading on the undrained bearing capacity of stone column groups, revealing insights into their performance under varying load conditions. The study [29-31] introduces a mechanistic model for predicting the strength of masonry columns reinforced with fiber-polymer composite jacketing, employing incremental plasticity theory and multi-surface yield criteria. Through computational implementation, the model demonstrates real-time and accurate solutions for compressive strength, validated against experimental data and compared favorably with existing standard-based formulas, offering a promising approach for analyzing reinforced masonry columns with minimal input parameters.

The study [32] investigates the bearing mechanism and failure mode of multi-layer geosynthetic-encased stone columns using compression tests under dynamic and static loading.

To nowadays research, numerous studies have been conducted on various aspects of elastic compression of stone columns of different cross-sections. However, limited research has been devoted to the eccentric compression of stone columns with various cross-sections.

Therefore, conducting additional research in this area is necessary to gain a deeper understanding of the behavior of stone columns under eccentric loading.

2 Methodology of the research

Using experimental methods and conducting physical tests to study the behavior of structures, determine the parameters of stress-strain state, and based on this, develop calculation methods for stone structures.

This work is dedicated to experimental and theoretical research on the strength of stone masonry under the action of local compressive forces, i.e., crushing.

Two most common cases of local application of compressive force were investigated: across the entire width of the wall section (Fig. 1); at the edge of the element across the entire width of the wall section (Fig. 2).

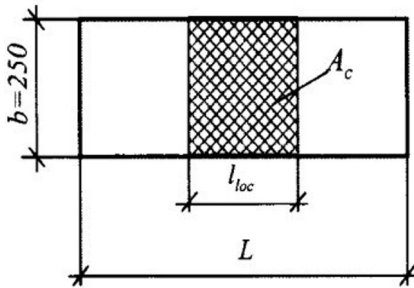


Fig.1. Load applied at the midpoint across the entire width of the wall section.

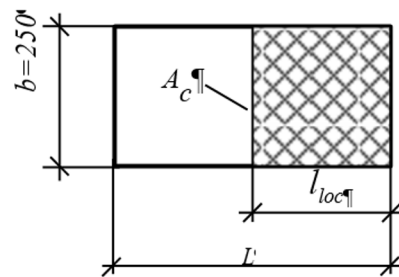


Fig.2. Load applied at the edge across the entire width of the wall section.

To conduct the physical experiment, experimental specimens were fabricated. Clay bricks of ordinary grade M100 and cement mortar in a 1:6 ratio were used for the column specimens. The specimens for testing columns under short-term compressive loads were placed under a press symmetrically with respect to the hinge axes and centered for uniform pressure distribution. Clock-type indicators (ICH-10) with a division value of 0.01 mm were used for deformation measurements, and 6PAO-LISI gauges with the same division value were used for deflection measurements. To obtain reliable data regarding brick deformation, strain gauges on paper base with a 50 mm base were adhered to the bricks. Data from the strain gauges were automatically recorded. The load was increased with a step of 1/20 of the expected ultimate load obtained through calculations with a delay of 5-6 minutes. At the time of testing, the age of the specimens was not less than 28-30 days.

The influence of local load application on a fragment of stone masonry was studied using experimental wall specimens. For such specimens, multi-row masonry with through bonding in the 6th row was used. The specimens were subjected to uniformly distributed pressure (over the loading area) through metal stamps. To create a hinge, the load on the stamp was centered through a 30mm diameter metal ball installed in a recess at the center. Two groups of measuring instruments were used on the specimens: the first one for recording vertical and horizontal deformations (clock-type indicators ICH-10 with a division value of 0.01 mm), and the second one for measuring deviations from the axis of the initial position in vertical displacement (6 PAO-LISI type deflection gauge). The load was also applied step by step, approximately at 1/20 of the calculated ultimate load and with intervals of 5-6 minutes. The failure criterion for the wall specimens was the inability of the tested specimen to withstand increasing force. At the time of testing, the age of the specimens was less than 28-30 days. The arrangement of clock-type indicators and strain gauges is shown in Figures 3, 4, 5.

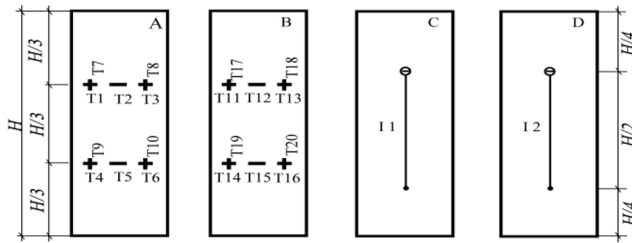


Fig.3. The arrangement diagram of measuring instruments on the faces of the columns is as follows: T1, T2, T3, T4, T5, T6, T11, T12, T13, T14, T15, T16 - transverse deformations; T7, T8, T9, T10, T11, T17, T18, T19, T20, I1, I2 - longitudinal deformations.

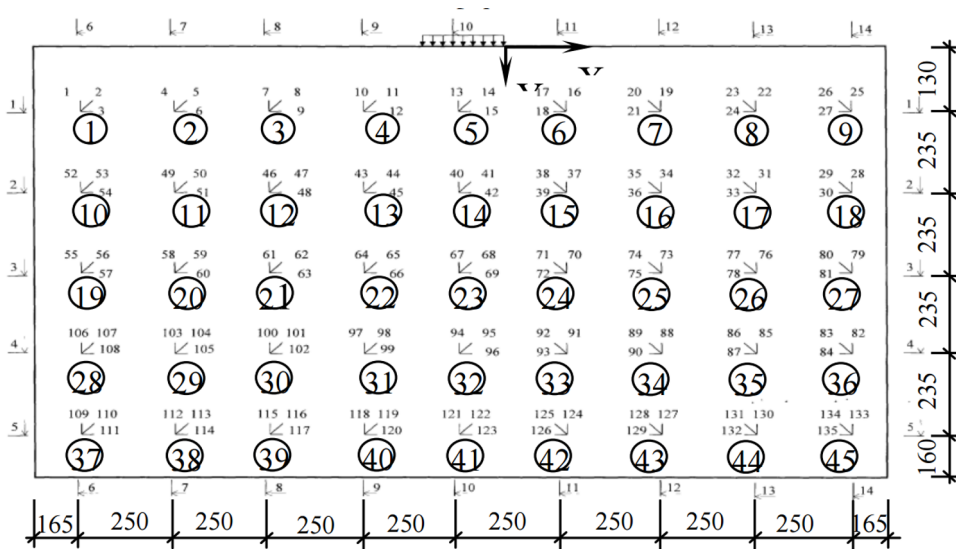


Fig.4. The arrangement diagram of strain gauges on the walls.

3 Results of the Research

As a result of testing stone columns under central compression, experimental values of the strength limit were obtained, and a comparison was made with normative data obtained using the formulas of L.I. Onyshchik. The results are shown in Fig. 7.

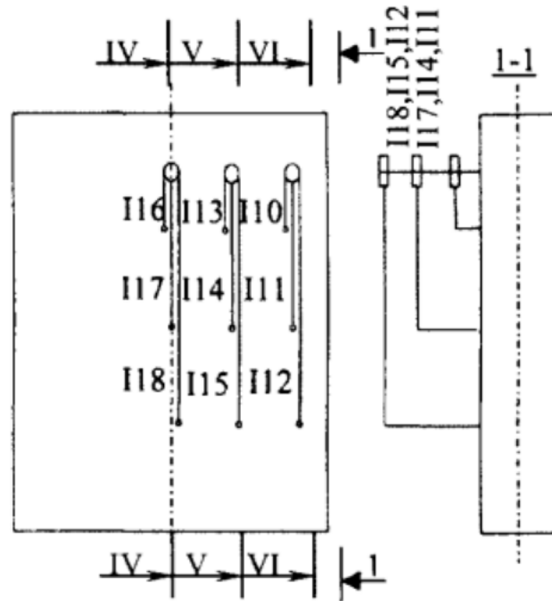


Fig.5. The arrangement diagram of clock-type indicators for determining transverse deformations.

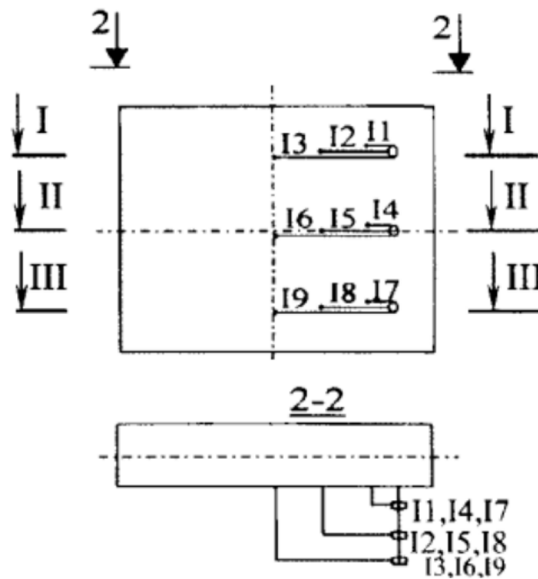


Fig.6. The arrangement diagram of clock-type indicators for determining longitudinal deformations.

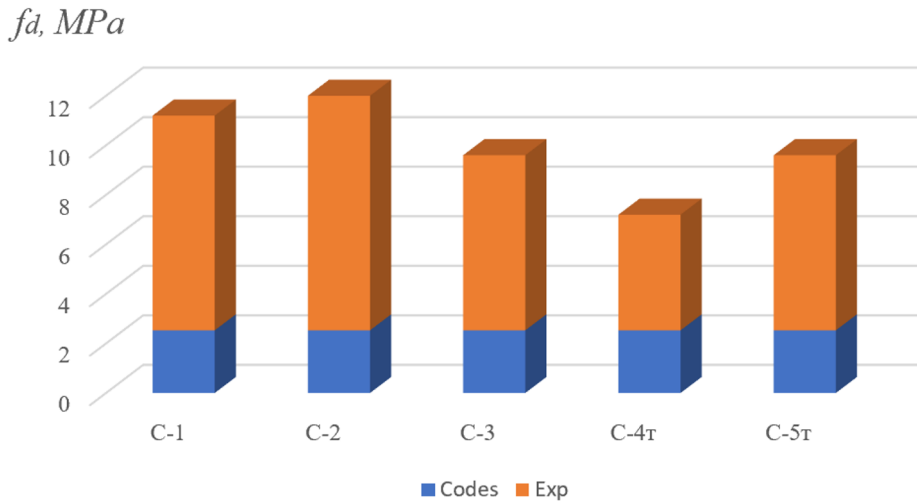


Fig.7. Graph comparing the calculated and experimental methods for determining the strength limit of stone masonry, C-1,C-2,C-3,C-4t, C-5t – samples.

4 Analysis of Research Results and Conclusions

During the research, brick masonry was considered as a monolithic heterogeneous elastic-plastic body consisting of bricks and mortar-filled joints. A particular feature of masonry work is the presence of complex stress states in both bricks and mortar, resulting in simultaneous off-center compression, bending, tension, shearing, etc. The main causes of such a state include the following factors: non-uniformity in the laying of mortar, differences in the deformation properties of bricks and mortar, the presence of vertical joints in the masonry, non-uniformity of bricks, incorrect brick shape. Research on the mechanical behavior of brick masonry is based on numerical solution of the bulk deformation and failure mechanics problem of heterogeneous bodies, taking into account structural failure for various cases of macro-heterogeneous stress-strain states. A representative volume of the heterogeneous medium or a volume element of periodicity is considered. It is assumed that the structural elements are isotropic and elastically brittle. The material behavior at the macro level is described by nonlinear constitutive relations of orthotropic media. The calculation of effective moduli and the construction of effective material functions describing the non-elastic deformation of the medium at the macro level are carried out based on establishing a relationship between calculated macro-stresses and specified macro-deformations.



Fig.8. Sample C1.3-6 after testing.

The analysis of the obtained results indicates an underestimation of the normative strength limit compared to the experimental data by 2.8-4.7 times. Observing the experiment (Fig.8) and the nature of the destruction revealed an almost linear dependence between stress and strain, unlike the normative one. The destruction started with the appearance of vertical cracks. During the testing of stone columns, brittle fracture was observed. In the upper rows, the destruction of the upper layer of stone was observed. The first cracks appeared at a stress of $N/N_u = 0.83 \dots 0.92$.

As a result of testing stone walls, it was found that the aspect ratio (length to height ratio) does not affect the strength limit of the sample.

The stone wall specimens were divided into 2 groups based on the loading scheme of the structures and the nature of the observed failures. For the first group of walls, two types of failure were identified: splitting-crushing and crushing-splitting. For the second group of walls, two types of failure were also identified: crushing and splitting. The load-bearing capacity of locally compressed masonry is largely influenced by the area A_{loc} through which local stress is transmitted. As the ratio I_{loc}/L increases, the angle between the inclined crack (which was characteristic for most specimens of the first group) and the vertical decreases.

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