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ANISOTROPY OF STRENGTH AND ELASTIC CHARACTERISTICS DURING COMPRESSION OF MASONRY OF HISTORICAL BUILDINGS

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Abstract
The article presents analytical dependences for calculating the compressive strength and elastic modulus of masonry made of ceramic solid bricks under axial uniaxial compression at arbitrary an-gles to horizontal mortar joints of masonry. Satisfactory agreement of experimental and theoretical values of masonry strength under compression at different angles to horizontal mortar joints is shown. A method for determining the basic variables included in the analytical equations of the computational model of the compressive strength anisotropy of masonry of existing structures, based on tests of specimens-prisms cut from masonry, has been developed and experimentally sub-stantiated. Comparative tests of the strength and elastic characteristics of masonry were carried out using specimens-prisms and standard specimens. It was found that the average values of the initial shear strength of masonry obtained on the specimens-prisms and standard specimens differed by no more than 8 %, and the compressive strength perpendicular to the plane of horizontal joints and the elastic modulus of masonry – by no more than 5 % and 1,2 %, respectively, which indicates the ap-plicability of the proposed method for assessing the strength and elastic characteristics of masonry of existing structures.

Keywords: masonry, ceramic brick, anisotropy, modulus of elasticity, compressive strength.

АНИЗОТРОПИЯ ПРОЧНОСТНЫХ И УПРУГИХ ХАРАКТЕРИСТИК ПРИ СЖАТИИ КАМЕННОЙ КЛАДКИ ИСТОРИЧЕСКИХ ЗДАНИЙ

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Реферат
В статье приведены аналитические зависимости для расчета прочности на сжатие и модуля упругости каменной кладки из керамического полнотелого кирпича при осевом одноосном сжатии под произвольными углами к горизонтальным растворным швам кладки. Показано удовлетворительное согласование экспериментальных и теоретических значений прочности кладки при сжатии под различными углами к горизонтальным растворным швам. Разработан и экспериментально обоснован метод определения базисных переменных, входящих в аналитические зависимости расчетной модели анизотропии прочности при сжатии каменной кладки существующих конструкций, основанный на испытаниях, вырезанных из тела образцов-призм. Выполнены сопоставительные испытания прочностных и упругих характеристик каменной кладки по образцам-призмам и стандартным образцам. Установлено, что средние значения начальной прочности на сдвиг каменной кладки, установленные на образцах-призмах и стандартных образцах, отличались не более чем на 8 %, а прочности на сжатие перпендикулярно плоскости горизонтальных швов и модуля упругости кладки – не более чем на 5 % и 1,2 % соответственно, что свидетельствует о применимости предлагаемого метода для оценки прочностных и упругих характеристик каменной кладки существующих конструкций.

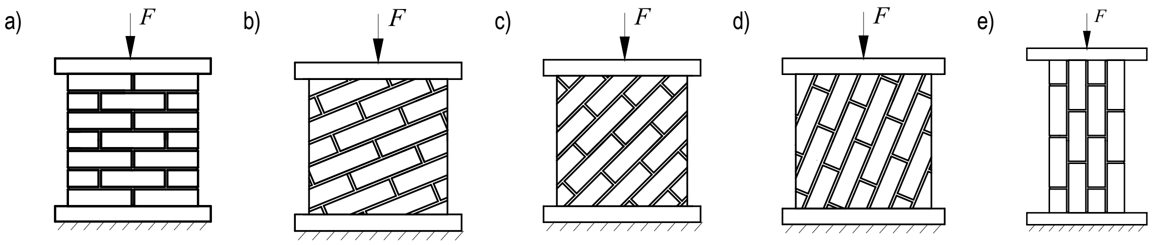
Ключевые слова: кладка, керамический кирпич, анизотропия, модуль упругости, прочность на сжатие.

Introduction

Most typical masonry structures work on compression perpendicular to the plane of horizontal joints of masonry. At the same time, there are a number of structures whose compression resistance can be determined by the compressive strength of masonry at other arbitrary angles to the plane of the support joints. Such structures primarily include vaults made of ceramic bricks of various kinds, arched or pointed arched lintels, which are widely distributed in masonry buildings and structures of cultural and historical value. Inspection of old buildings shows that most of these structures do not fit into the theoretical design schemes given in the methodological and regulatory documents due to the degradation of masonry, the loss of part of vertical supports, spring-loaded arches, ties or other elements. Under the action of loads or forced deformation, for example, with nonuniform foundation settlement, the geometric shapes of vaults and arches determine the direction of the force flows arising in them at different angles to the mortar joints of the masonry. As practice shows, the angle of inclination of the compressive force to the mortar joints of masonry in these structures depends on their shape, the ratio of the span to the rising height and is within 10° – 40°. A calculated assessment of the reliability of existing hold-down masonry structures is usually performed by checking the limit states of the bearing capacity by the method of partial coefficients. At the same time, the effects of impacts (the values of the main stresses and their trajectories) are established on the basis of calculations of structures by the finite element method using modern computing systems. Masonry in the calculation models is considered as a homogeneous, isotropic material, and the assessment of the resistance of structures to compression is based on the particular characteristics of the strength of masonry [1–3]. However, the solution of this problem is complicated by the absence in the current norms of the numerical values of the compressive strength of masonry at arbitrary angles to the plane of the supporting mortar joints, as well as full-fledged data on the anisotropy of its elastic characteristics.

Calculation model of the strength of masonry under compression at arbitrary angles to the supporting mortar joints

In order to experimental evaluation of the anisotropy of the strength and elastic characteristics of masonry, tests were performed on five series of specimens of masonry under the action of compressive force at angles to the plane of the support joints of equal 0°, 22,5°, 45°, 67,5°, 90° (figure 1) [7].



a) – series C-1 (θ = 0°); b) – series C-2 (θ = 22,5°); c) – series C-3 (θ = 45°); d) – series C-4 (θ = 67,5°); e) – series C-5 (θ = 90°)

Figure 1 – Schemes of specimens of masonry

The tasks of the tests included:

– identification of the pattern of cracking and fracture of experimental specimens of masonry;

– determination of compressive strength, as well as elastic modulus and Poisson's ratio of masonry, depending on the orientation of the direction of the compressive force to the supporting mortar joints.

Experimental studies have shown that at angles θ from 45° to 67,5° the cause of the fracture of the masonry is its shear in the plane of the supporting mortar joints. When the angle is

67,5° < θ ≤ 90°, the nature of the masonry fracture is determined by the compressive strength of the brick in the direction of the butt surface, and at 0° ≤ θ < 22,5° – the compressive strength of the brick in the direction of the support surface.

If the angle of inclination of the compressive force to the horizontal mortar joints differs from 0° and 90°, then tangential (τ) and normal compressive stresses (σ) arise in the mortar joints, the ratio of which varies depending on the angle θ (figure 2).

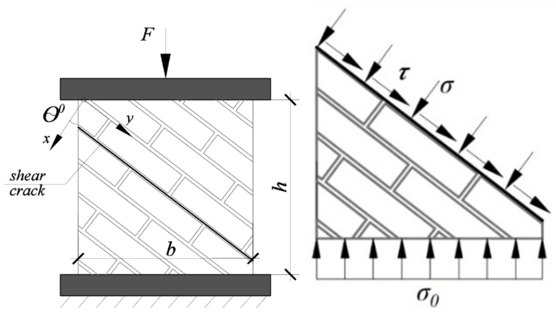


Figure 2 − Tangential and normal stresses in the supporting mortar joints of masonry

In accordance with figure 2, the values of compressive stresses in masonry at which shear cracks arise in the supporting mortar joints can be determined by the equation (1)

$$\sigma_{0,crc} = \frac{f_{v0}}{\cos\theta \cdot (\sin\theta - \cos\theta \cdot tg\varphi)}. \quad (1)$$

The value $\sigma_{0,crc}$, set by equation (1), should not exceed the value set by equation (2)

$$\sigma_{0,crc} = \frac{0,065 f_b}{\cos\theta \cdot \sin\theta}. \quad (2)$$

Experimental and theoretical studies show that during compression, the formation of shear cracks in mortar joints did not lead to immediate fracture of the masonry. At the same time, the ratio of the compressive strength of masonry f_θ to the values of compressive stresses $\sigma_{0,crc}$ depended on the angle of inclination of the trajectory of the compressive stresses to the plane of the supporting mortar joints (figure 3).

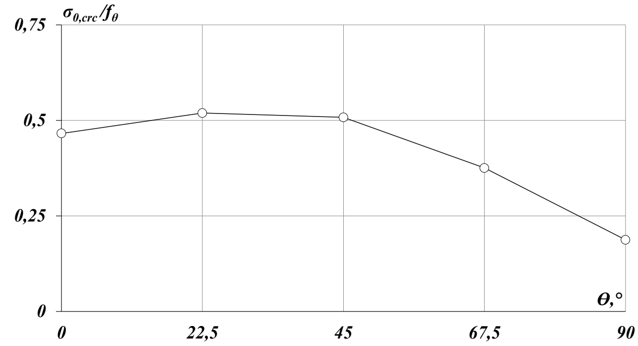


Figure 3 – Function « $\sigma_{0,crc} / f_\theta$ - θ »

The compressive strength of masonry at angles θ in the range of 37,5° – 67,5° can be obtained by multiplying the values of compressive stresses at which shear cracks arise in the supporting mortar joints of masonry $\sigma_{0,crc}$, by a dimensionless coefficient k , the value of which should be taken according to the empirical equation (3)

$$k = 0,252 \cdot \theta - 0,0024 \cdot \theta^2 - 4,097. \quad (3)$$

where θ – the angle of inclination of the supporting mortar joints in degrees.

Taking into account the correction factor k , the compressive strength of masonry at angles θ in the range of 37,5° − 67,5° is determined by the equation (4)

$$f_\theta = k \cdot \frac{f_{v0}}{\cos\theta \cdot (\sin\theta - \cos\theta \cdot tg\varphi)}. \quad (4)$$

The value f_θ , set by equation (4), must not exceed the values set by equation (5)

$$f_\theta = k \cdot \frac{0,065 f_b}{\cos\theta \cdot \sin\theta}. \quad (5)$$

If the values of the compressive strength of masonry f_θ at θ = 90° and 0° are known, then the compressive strength f_θ at angles 0° < θ < 37,5° and 67,5° < θ < 90° is determined by linear interpolation.

Figure 4 shows the results of calculating the compressive strength values of masonry f_θ ,exp depending on the angle of inclination of the supporting mortar joints θ according to the proposed calculation model f_θ ,calc, which are in satisfactory agreement with the experimental data f_θ ,exp.

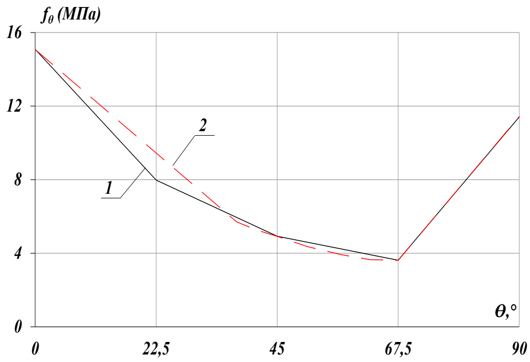
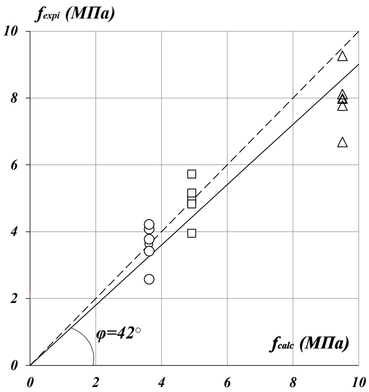


Figure 4 – Function of the strength of masonry f_θ on the angle of inclination of horizontal mortar joints θ



«△» – values for the angle θ = 22,5°; «□» – values for the angle θ = 45,0°; «○» – values for the angle θ = 67,5°

Figure 5 − Comparison of calculated and experimental values of compressive strength at the angle of inclination of the support joints θ

As an illustration of the reliability of the proposed computational model, figure 5 shows a comparison of the results of experimental $f_{\theta,exp}$ and theoretical $f_{\theta,calc}$ values of the compressive strength of masonry for all considered experimental specimens, and also in accordance with [1] the value of the coefficient of variation of the error vector is determined.

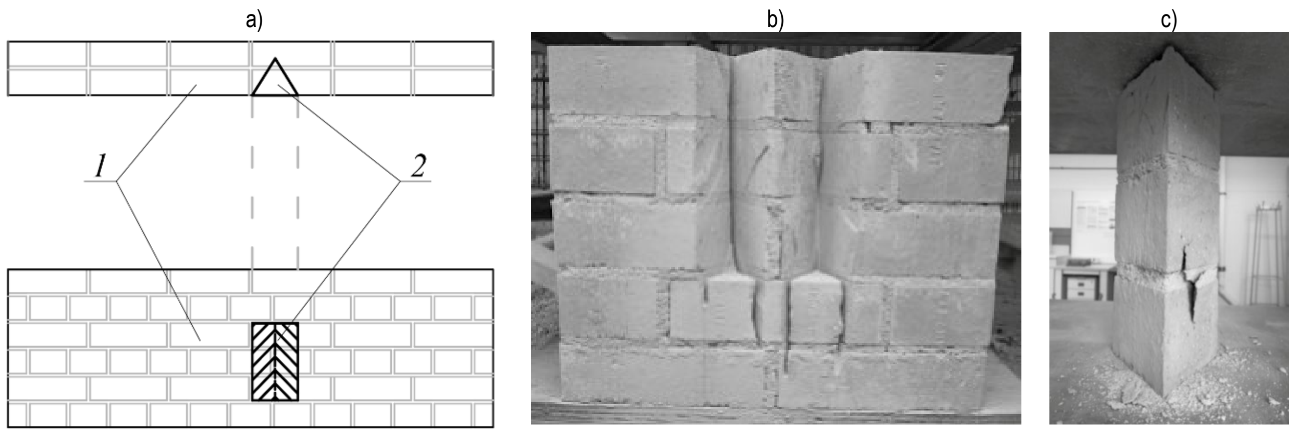
It follows from Figure 5 that the pairs of corresponding theoretical f_{calc} and experimental f_{expi} values of the compressive strength of masonry are located relative to a straight line, the angle of inclination of which to the X-axis was 42°. In this case, the value of the coefficient of variation of the error vector V_δ = 16,6 %. The results obtained indicate the reliability of the developed computational model.

Determination of strength and elastic characteristics of masonry of existing structures based on tests of specimens-prisms

For the analytical calculation of the compressive strength of masonry at arbitrary angles to the plane of the supporting mortar joints in accordance with the proposed calculation model, according to the results of the inspection of masonry structures, it is necessary to obtain the values of the following basic variables:

– value of the initial strength of masonry for shear f_{v0};
– coefficient of internal friction $tg\varphi$;
– normalised compressive strength of bricks f_b;
– compressive strength of masonry f_θ at θ = 0° and θ = 90°.

The degree of anisotropy of the compressive strength f_θ and the elastic characteristics of the masonry of existing structures can be estimated by the results of direct tests with a compressive load of specimens-prisms cut from the masonry. Two vertical incisions are made in the wall at an angle of 60° to its surface, which intersect in the masonry. This creates a prism with a base in the form of an equilateral triangle (figure 6).



«1» – masonry; «2» – test specimen
a) − scheme of specimens selection; b) – masonry after specimen-prisms selection; c) − compression test of the specimen

Figure 6 – Masonry specimen in the form of a triangular prism [8]

After removing the mortar from the horizontal joints in the upper and lower bases of the prism, the specimen is easily removed from the masonry. The advantage of the proposed method is also that the masonry structure has minor damage during the extraction of specimens, which is very important for objects of historical and cultural value. This method is feasible for wall masonry structures, from the body of which it is possible to cut specimens-prisms at an angle to the direction of horizontal mortar joints other than 90°. If the cutting of specimens-prisms from the masonry is possible only at an angle of 90° to the plane of the supporting mortar joints, then in this case the compressive strength and elastic modulus of masonry are determined on the basis of tests of prisms with a compressive load perpendicular to the plane of horizontal mortar joints, and the initial shear strength of masonry f_{v0} – by tests for prism shear (figure 7).

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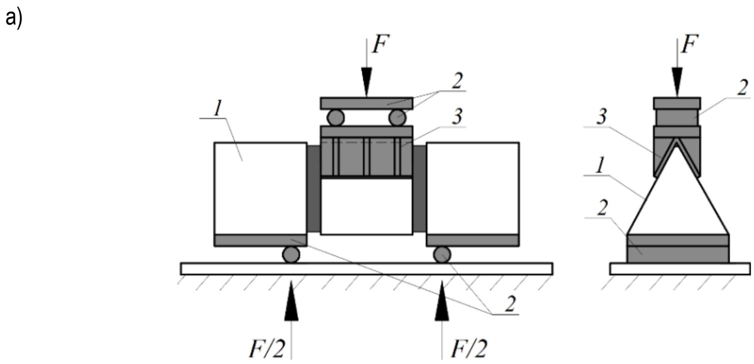

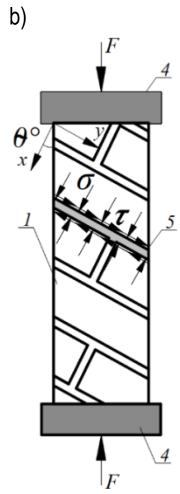

«1» – test specimen; «2» – set of plates and roller supports; «3» – triangular stamp for load transfer; «4» – stamp for load transfer; «5» – shear joint (shear crack)

a) – determining the value f_{v0}; b) – determining the value f_θ

Figure 7 – Schemes for testing specimens-prisms

In this case, the calculation of the anisotropy of the compressive strength of masonry is carried out in accordance with the proposed calculation model. The modulus of elasticity of masonry at angles to the supporting mortar joints E_θ is assumed to be equal to the product of the compressive strength f_θ by the value of the elastic characteristic K_E, the value of which is established according to experimental studies (figure 8).

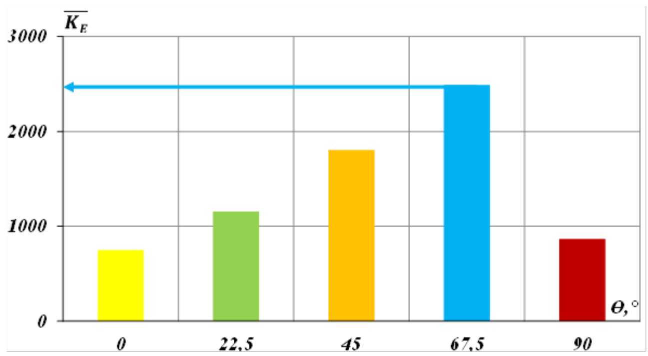

Figure 8 – Average values of the elastic characteristic $\overline{K}_E$ depending on the angle θ

Experimental studies have shown satisfactory agreement of the results of determining the compressive strength and elastic modulus of masonry specimens-prisms and standard specimens under the action of compressive force perpendicular to the plane of horizontal mortar joints. The difference in the average values of the compressive strength of masonry specimens-prisms and standard specimens did not exceed 5 %, and the elastic modulus – 1,2 %. The nature of the fracture of standard specimens and specimens-prisms at the angles of inclination of the direction of the compressive force to horizontal joints 0° < θ < 90° was the same. At the same time, the difference in the values of the compressive strength of the masonry, established by the two methods, was in the range of 30 % – 40 %, which indicates a more significant effect of tangential stresses on the compressive strength of the masonry standard specimens, compared with the specimens-prisms. The average values of the initial shear strength of masonry obtained on the specimens-prisms and standard specimens differ by 8 %, which indicates the applicability of the proposed method for assessing the shear strength of masonry of existing structures.

Conclusion

1. A computational model of the strength of masonry made of bricks under compression at arbitrary angles to horizontal mortar joints of masonry is proposed and experimentally substantiated, taking into account the initial shear strength of masonry, the coefficient of internal friction, the normalised compressive strength of bricks, the compressive strength of masonry perpendicular to the plane of horizontal joints.
2. A method for determining the anisotropy of compressive strength and elastic characteristics of masonry of existing structures has been developed and experimentally confirmed on the basis of tests of masonry specimens in the form of triangular prisms.

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