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Research paper

The Model of Failure for Exploited Brick Buildings in the Conditions of an Unevenly Deformed Base

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Abstract

The article proposes a model of failure for exploited brick structures and buildings in the conditions of an unevenly deformed base as a function of time. This model includes the corresponding models of the structural element, loads and effects, the base model, the material model, the environmental impact model, and the phenomenological model of damage accumulation. The author has constructed the distribution function of the generalized force influence on brick buildings in the conditions of an unevenly deformed base. Based on the results of experimental studies, the mechanisms of destruction of brickwork in conditions of a single-axial stress state are formulated. A solution has also been proposed that makes it possible to determine the coefficients of the elastic base for a layered base with any number of layers with different deformation characteristics. The laws of the distribution of such brick parameters are obtained: compressive strength, flexural strength, length and height, also the possibility of applying the normal distribution law for the properties of the materials of the exploited structures is shown. In the damage accumulation model, it is suggested that the criterion for the technical state of a brick element is to take a set of numerical parameters of cracks in the material: the width of crack opening, the length and density of cracks. The aggregate of these numerical parameters is a quantitative integral characteristic of the degradation process. The connection of the above parameters with reliability makes it possible to assess the reliability of the element in the crack resistance, depending on the exploiting time. The reliability assessment of an element is formulated as a search for the probability of the non-exceeding of the limiting state by the controlled parameter, after which the probability of non-extinction by the generalized parameter is determined. The proposed model can serve to predict the resource of the «building-base» system at all stages of the life cycle.

Keywords: *model of failure; reliability assessment; brick buildings; probabilistic model; deterministic model; degradation.*

1. Introduction

Buildings and structures made of bricks in the process of long-term maintenance undergo the simultaneous action of loads and impacts, different in their type and intensity. The combination of impacts leads to a reduction of the durability of buildings and structures. To assess the reliability of buildings and structures subject to degradation processes during operation, it is necessary to take into account features that are not reflected by deterministic models.

These features are:

- variability of mechanical characteristics of materials and structural sizes;
- variability of mechanical characteristics of the base of a building (structure);
- probabilistic nature of force and non-force impacts;
- the influence of the time factor on the properties of materials and the nature of the external environment impact.

The parameters listed above are not constant in time. Thus, the probabilistic approach to determining the level of reliability is due to the fact that all the strength and deformation characteristics of the "base – foundation – construction" system, as well as all loads and effects on the system are random variables or random processes. Therefore, for a more correct assessment of the failure of degrading building structures made from brick, probabilistic methods should be used. At the moment, there is a need to develop mechanisms for assessing the technical condition of brick buildings and structures, one of the components of which is the development of a model of failure. Moreover, the model should be applicable for assessing the state of exploited buildings, which are already subject to degradation processes of various types and intensities, as a rule. It is obvious that the assessment of the technical condition of the building must correlate with its stress-deformed state.

The aim of the study is to create a model of failure of brick structures and buildings that are resting on unevenly deformed bases. According to [1], the theoretical model should include all the main parameters that characterize it and which are considered as random variables. The general model of failure for the considered type of limiting state is, in general, a combination of the following:

-models of impacts on structures;

-the model of the behavior of a construction that takes into account the effects of impacts;

-models of load-bearing capacity, describing the carrying capacity of the influence effects;

-models of properties and structure of materials and geometric models;

-models of environmental impact on brickwork materials;

-models of damage accumulation in brickwork.

2. Main Body

2.1. Models of Impacts on Structures

Loads and other external influences acting on the structure are the most uncertain quantities and have a high level of stochasticity. The building (structure) is usually affected by several loads, each of which has its own peculiarities [2 - 4]. When assessing the reliability of brick buildings, the loads and impacts, regulated by existing design standards, must be taken into account. According to the type of loads, these classes of loads and impacts are distinguished:
– the own weight of the structures F_G.
– load from people and equipment (payload) F_q.
– climatic effects (snow load F_S, wind load F_W, external temperature effects F_T).
– impacts due to ground motion (precipitation) F_D.
The distribution functions of random loads and impacts can be adopted in accordance with the following distribution laws (Table 1):
- the own weight of the constructions F_G is the normal distribution law, characterized by the mathematical expectation of μ_G and the mean-square deviation σ_G; the value of the own weight of the constructions can be adopted as deterministic due to its small variability;
– useful load on overlap F_q is a double exponential law of distribution of Gumbel, characterized by the mathematical expectation of μ_q and the mean-square deviation σ_q;
– snow load F_S is also the law of distribution of Gumbel, characterized by the mathematical expectation of μ_S and the mean-square deviation σ_S;
– wind load F_W is the law of distribution of Gumbel, characterized by the mathematical expectation μ_W and the mean-square deviation σ_W;
– the temperature effects F_T can be taken in accordance with the normal distribution law, characterized by the mathematical expectation of μ_T and the mean-square deviation σ_T;
– the effects of the uneven shrinks F_D can also be taken in accordance with the normal distribution law, characterized by the mathematical expectation of μ_D and the mean square deviation σ_D.
The author has constructed the distribution function of the generalized force action on brick buildings in the conditions of an unevenly deformed base [5].

Table 1: Statistical parameters of load distributions

Type of load	The designation	Units	Average value	Variation coefficient V_x	The distribution law
Constant load	*G*	kN	*G*	0,1	Normal
Payload (50 years)	*Q*	kN/m^2	*0,6Q*	0,35	Gumbel
Snow load (50 years)	*S*	kN/m^2	$0,7S_0$	0,5	Gumbel
Wind load	*W*	kN/m^2	$0,75W_0$	0,35	Gumbel
Temperature impact	*T*	C^o	*T*	0,15	Normal
Uneven settlement impact	*D*	kPa	*P*	0,59	Normal

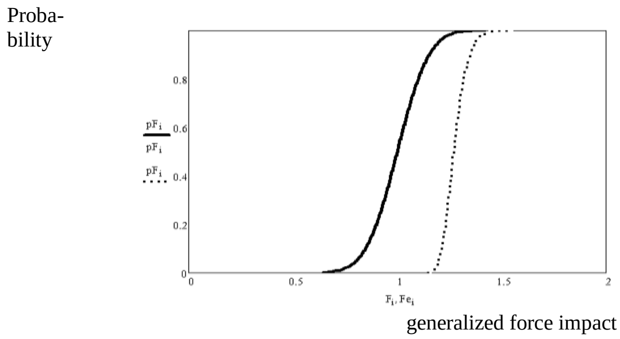


Fig. 1: Graphs of distribution functions of the generalized force

2.2. Model of a Structural Element

The model includes the schematization of its geometric dimensions and the use of any deformation hypotheses, which are usually of a deterministic nature.

Regarding the process of destruction, it is possible to determine some function of the main stress components and to relate it to a certain strength criterion k, which depends on stretching, compression or shear:

$$F(\sigma_1, \sigma_2, \sigma_3) \leq k, \quad (1)$$

where $\sigma_1 \geq \sigma_2 \geq \sigma_3$ are the main stresses.
G.A. Geniev developed criteria for the strength of masonry, which are based on three mechanisms of destruction adopted in the work [6]:
- destruction due to fragmentation, manifested in uniaxial and biaxial uneven or uniform compression.
- destruction due to tearing, manifested in uniaxial and biaxial uneven or uniform stretching.
- destruction due to shearing, manifested in mixed biaxial stressed compression-extension states.
According to the results of the author's experimental investigations [7], the following mechanisms for the destruction of brick masonry in the conditions of a uniaxial stress state are formulated:
- destruction of the avulsion;
- destruction of shift (shear);
- destruction of fragmentation;
- destruction of brick material;
- destruction of the solution material.

2.3. Base Model

A base model with two coefficients of rigidity of the elastic base was adopted. The basis of this model is the solution obtained by Vlasov V.Z. and Leontiev N.N. [8] and based on a simplified assumption about the nature of the stressed and deformed state of the base. The coefficients of rigidity of the elastic foundation C_1 and C_2 that determine the relationship between the load at the boundary of the base and the displacements of the boundary of the base, were obtained using the variation principle of Vlasov V.Z. under the assumption that the greatest contribution to the work of the internal forces of the base is made by normal stresses and shear stresses on horizontal platforms.
The values of the coefficients C_1 and C_2 depend on the correct choice of the lateral distribution function of vertical displacements, which is difficult even for a single-layered base, since such a choice uniquely determines the distribution of normal stresses on horizontal areas, which is unknown in advance. In most cases, a distribution is obtained that differs a lot from that recommended by the normative document DBN B.2.1-10-2009 "Bases and foundations of structures" [9] and is determined by the relation:

$$\sigma_{zp} = \alpha p_0, \quad (2)$$

where α is the coefficient taken by [1];

p_0 is the additional vertical pressure on the base or the average pressure below the foot of the foundation for b <10 m;
b is the width of the foundation.
In the case of a layered base, specifying a continuous function of the lateral distribution of vertical displacements leads to stress jumps on the boundary between the layers, which in fact are absent.
A solution was proposed in the work [10] that makes it possible to determine the coefficients C_1 and C_2 for a layered base with any number of layers with different deformation characteristics, while the distribution of normal stresses along the depth of the base is completely consistent with the distribution recommended by DBN B.2.1 -10-2009 [9].
As a model of the foundation, a linearly deformed half-space is subsequently used, deformation characteristics are the deformation modulus E and ν. The shear modulus G equals $G = \frac{E}{2(1+\nu)}$. These values can vary from layer to layer. The total energy of deformation of the base was obtained in the following form:

$$\Pi = \sum_{n=1}^{r}\frac{1}{2}\int_x\int_y\int_0^{0,2b}\left[\begin{array}{l}\sigma_{z(n)}\varepsilon_{z(n)} + \\ +\tau_{zx(n)}\gamma_{zx(n)} + \tau_{zy(n)}\gamma_{zy(n)}\end{array}\right]dxdydz_n - \int_x\int_y qw(x,y)dxdy. \qquad (3)$$

Here $\varepsilon_{z(n)}$, $\gamma_{zx(n)}$, $\gamma_{zy(n)}$ are deformations in the n^{th} layer of the soil;
$\sigma_{z(n)}$, $\tau_{zx(n)}$, $\tau_{zy(n)}$ are stresses within each layer.
Considering (7) as the functional $\Gamma\left(w, \frac{\partial w}{\partial x}, \frac{\partial w}{\partial y}\right)$, we obtain a differential equation that connects the load on the surface of the base with the displacements of its boundary:

$$-2t\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2}\right) + C_1 w(x,y) = q; \qquad (4)$$

where C_1 и $C_2 = 2t$ determine the stiffness parameters of the layered base;
w_0 are the displacements.
The values of C_1 and C_2 take on values [10], which completely coincide with the corresponding values obtained by Vlasov V.Z. (for one layer of thickness 0.2b and the even distribution of compressive stresses along the thickness):

$$C_1 = \frac{E_0}{(1-\nu^2)0{,}2b}; \quad C_2 = \frac{E_0 \cdot 0{,}2b}{6(1-\nu_0)}. \qquad (5)$$

Analysis of the ratios for C_1 and C_2 shows that these values depend on the size of the foundation. As the sizes increase, C_1 decreases, and C_2 increases; i.e. deflections of the foundation will increase with increasing distribution properties of the base.

2.4. Material Model

Consider the types of distribution of various characteristics of brickwork materials. Standards for materials set certain requirements for the characteristics of building structures, wherein the requirements of standards are followed only with a certain probability. It should be noted that these standards relate only to building materials in the factory manufacturing stage.
In particular, the distribution laws for the parameters of the silicate full-bricks of grade M150 [11] were determined: compressive strength, bending strength, geometric deviations of the brick along the length and height, and also obtained all the statistical characteristics of these parameters (Table 2), sample of n = 350 size.

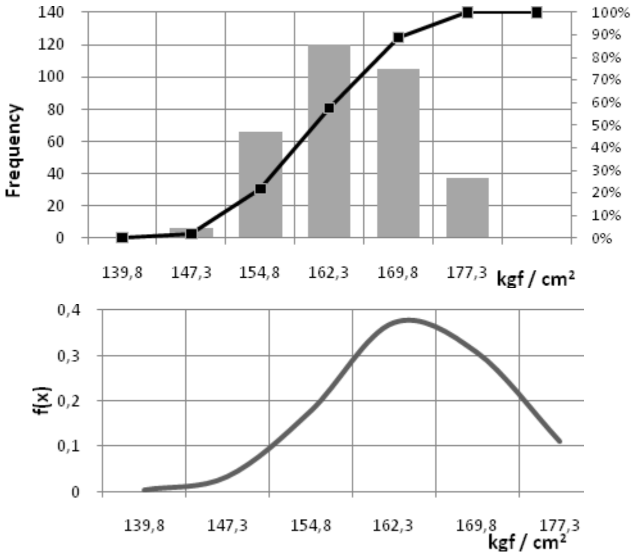


Fig. 2: Histogram and graph of distribution density of the strength of bricks on compression

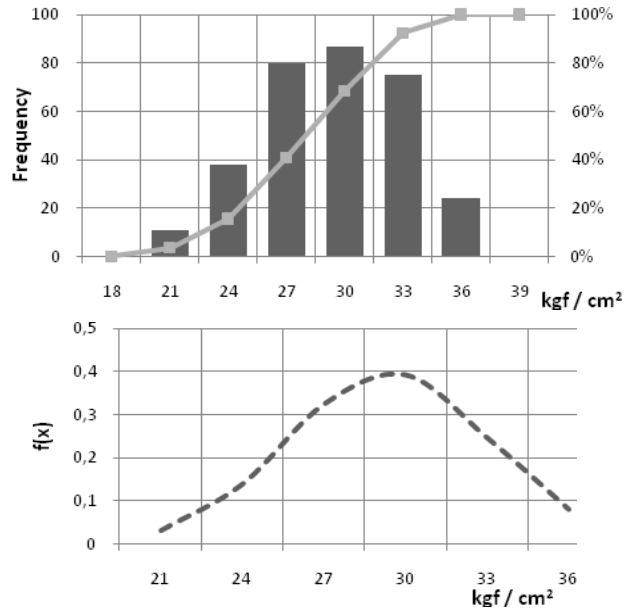


Fig. 3: Histogram and graph of distribution density of the strength of bricks for bending

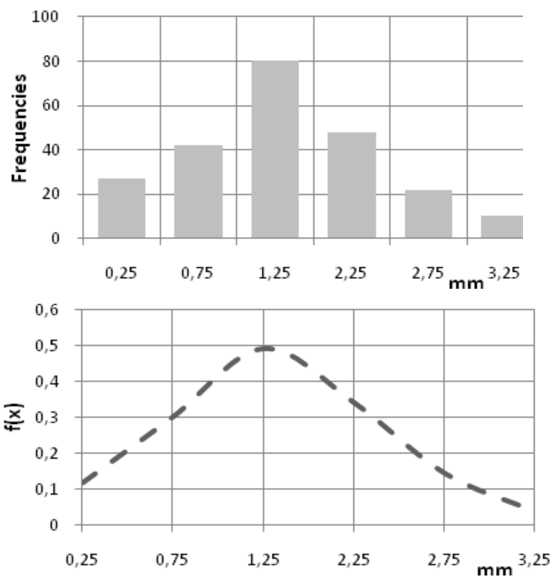


Fig. 4: Histogram and graph of distribution density of geometric deviations of brick length

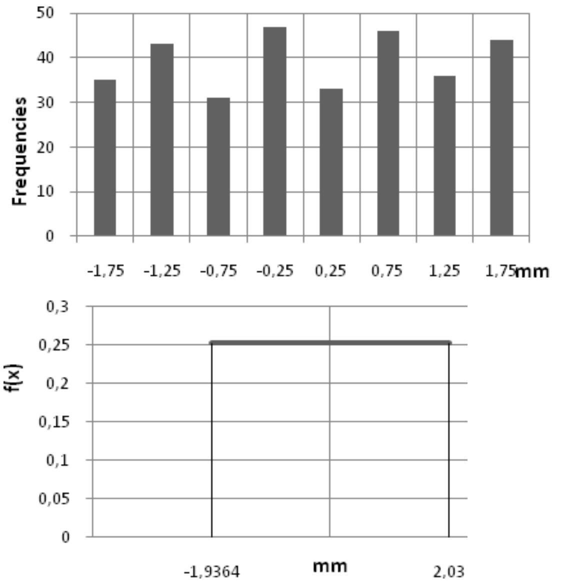


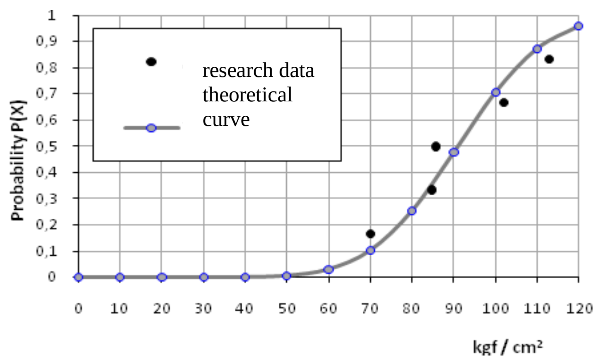
Fig. 5: Histogram and graph of distribution density of geometric deviations of brick height

Table 2: Statistical parameters of load distributions

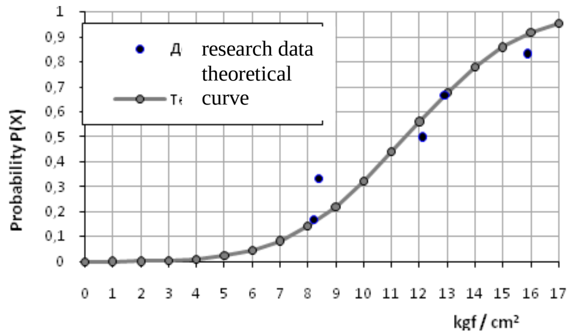
Brick parameters	The distribution law	Selective average $\overline{y_в^*}$	Selective mean square $\sigma_в^*$	Variation coefficient v, %
Compressive strength	normal	168,244 kgf/cm^2	7,37 kgf/cm^2	4,38
Flexural strength	normal	29,37 kgf/cm^2	3,7 kgf/cm^2	12,598
Length	normal	1,545681 mm	0,75072 mm	48,569
Height	normal	0,0468 mm	1,145 mm	24,4658

2.5. Model of the Impact of the Environment on the Materials of Brickwork

The possibility of the applicability of a normal distribution for exploited brickwork materials can also be justified by the following considerations. As a result of brick samples of masonry buildings testing, values that are satisfactorily described by the normal distribution curve were obtained [12]. A sample of 63 values was considered.



a)



b)

Fig. 6: Comparison of the experimental data and the theoretical distribution curve for the brick testing: a) for compression; b) for bending

2.6. Model of Damage Accumulation in Brickwork

Among the prerequisites for applying the theory of reliability is the collection, systematization and analysis of statistical data related to this or that aspect of the work of building structures. Not all operational factors can be reproduced in the laboratory, so they can be studied only on the buildings in use (structures, constructions). It should be noted that up to the present time there are no materials that would link the condition of the brick walls of the exploited building with statistical analysis of existing damages when finding the parameters distribution laws that characterize the state of the specified structures.

It is suggested that as the criterion for the technical state of a brick element is considered a set of numerical parameters of cracks in the material: the width of the crack opening, the length of cracks, the density of cracks. The aggregate of the given numerical parameters represents a quantitative integral characteristic of the degradation process.

The scientific idea is to find the connection between the above parameters (width, length, density) and reliability, because the actual cracking process completely reflects the deformation properties of the brick elements. The cracking formation model can be used to estimate the resource of an element. The construction of an element reliability model based on the crack resistance depending on the exploiting time can be formulated as a search for the probability of non-exceeding of the limiting state by a controlled parameter, and then the probability of non-extinction by the generalized parameter is determined.

By a generalized parameter is meant such a criterion that determines the degree of the operability of a structure (system) over a set of monitored parameters.

Let's write down the main provisions of the proposed reliability model:

1) in terms of the parameter of the crack opening width:

$$P_{f1}(T_{ef}) = \text{Prob}\{w_k^{cr} - w_{k(t)} \geq 0\}; \quad (6)$$

2) in terms of the crack length parameter:

$$P_{f2}(T_{ef}) = \text{Prob}\{l_k^{cr} - l_{k(t)} \geq 0\}; \quad (7)$$

3) in terms of the parameter of crack density:

$$P_{f3}(T_{ef}) = \text{Prob}\{d_k^{cr} - d_{k(t)} \geq 0\}. \quad (8)$$

The condition of the limiting state is written in the form:

1) in terms of the parameter of the crack opening width:

$$w_k(t) \leq w_k^{cr} \quad (9)$$

2) in terms of the crack length parameter:

$$l_k(t) \leq l_k^{cr}, \quad (10)$$

3) in terms of the parameter of crack density:

$$d_k(t) \le d_k^{cr} . \tag{11}$$

In this case, w_k, l_k, d_k, k depend on the stress level N/N_u.
The generalized parameter is written as:

$$P_{\Sigma}(t) = \frac{\sum_{i=1}^{n} k_i \left[Par_i(t) \right]}{\sum_{i=1}^{n} k_i} \tag{12}$$

where k_i are weight coefficients;
$Par_i(t)$ – relative values of primary parameters, which are determined by the formula:

$$Par_i(t) = \frac{\left[P_i(t) - P_u \right]}{\left(P_n - P_u \right)}, \tag{13}$$

where P_u is the maximum permissible value of the parameter;
P_n is the normative value of the parameter;
$P_i(t)$ are the measured values of the given parameter, that correspond to the operating time t.
On the example of one of the surveyed buildings, a statistical evaluation of the degradation parameters was obtained [13] (Table 3).

Table 3: Statistical parameters of load distributions

Parameters of degradation	The distribution law	Range	Selective average $\overline{y}_в^*$	Selective mean square $\sigma_в^*$	Variation coefficient v, %
Width of opening of cracks, mm	bimodal	0,1…0,9	0,348	0,169	0,4856
		1…2,5	1,625	0,455	0,28
Length of cracks, m	bimodal	0…3	1,133	0,477	0,42
		3…5	1,4167	0,5525	0,1251
Density of cracks, m/m^2	normal	0…0,006	0,002679	0,00132	0,4927

3. Conclusions

The model of failure is proposed for exploited brick structures and buildings in the conditions of an unevenly deformed base in a function of time. This model includes the relevant models of the structural element, loads and effects, the base model, the material model, the environmental impact model, and the phenomenological model of damage accumulation. The proposed model can be an effective apparatus for managing the technical condition of exploited brick buildings and structures. The model can serve to predict the resource of the «building – base» system at all stages of the life cycle.

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