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Safety parameters analysis for assessing the stone structures' strength

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Safety parameters analysis for assessing the stone structures' strength

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Abstract. This article presents a comprehensive analysis of methods for assessing the safety of construction structures with a focus on partial coefficients and the variability of material strength. The study aims to enhance the methodology for determining the compressive strength of masonry structures by incorporating reliability theory and probabilistic approaches. Key scientific contributions include defining the role of fractional safety factors and analyzing their impact on structural design resistance. Practical value is demonstrated through solutions for assessing the design strength of brickwork, crucial for the safety of massive walls and pillars in existing buildings. The research highlights methods for evaluating material variability, particularly for bricks and mortar, and its implications for structural safety. The proposed methodology integrates theoretical insights with practical application, offering a detailed approach to determining design resistance and optimizing safety assessments. Key conclusions propose strategies for addressing structural variability and improving reliability, which are essential for modern construction projects.

Keywords: Masonry structures, compressive strength, partial safety factors, probabilistic methods, structural reliability, non-destructive testing, building renovation, material variability.

1. Introduction

The characteristic properties of stone houses, such as strength, durability, and aesthetic appeal, have made them a popular building structure for many centuries. One of the advantages of brick as a building material is its effective ability to create a variety of architectural forms and details. This allows architects and builders to create unique buildings with different styles and

character. In modern architecture, brick remains a popular choice for construction due to its aesthetics, environmental friendliness, and weather resistance.

To ensure long-term operation, repair, and restoration are mandatory processes for buildings and structures. In addition, requirements for comfort, energy efficiency, and safety of buildings are constantly changing. Legislative requirements for buildings change over time and they need to be updated to meet new safety and efficiency standards. Building codes require the installation of new fire systems and increased environmental insulation standards. There is also always the need to adapt the home to new functions or requirements.

The reliability of brick building structures is critical to the safety and protection of the interests of users. Resistance to various external influences and durability make them a popular choice for the construction of houses and buildings. Properly constructed brick buildings can last for decades without significant signs of wear or damage.

Today, various approaches are used to improve the seismic resistance of masonry structures, such as the use of reinforced concrete, additional strengthening of foundations, and the use of special diaphragms and frames. Robust structures reduce the risk of injury and property destruction during earthquakes [1 – 5]. For masonry structures with special functional requirements such as vibration insulation, sound insulation, energy efficiency, reliability plays an important role in meeting the functional requirements [6].

2. The research methodology

The research methodology integrates both well-established and novel approaches to assess the safety of masonry structures. For established methods, standard procedures from EN 1996-1-1 (Design of masonry structures) and EN 1990 (Basis of structural design) were utilized to determine compressive strength and safety factors. Probabilistic models, such as Monte Carlo simulations, were implemented to evaluate the variability of material properties and to estimate the probability of failure under different scenarios. These methods have been cited extensively in prior studies [8, 11]. Statistical analysis is applied to process the experimental data. Parameters such as mean strength, standard deviation, and coefficients of variation are calculated. These are used to derive the partial safety factors for the materials. Furthermore, reliability theory is applied to evaluate structural safety, and partial coefficients are adjusted based on the probabilistic distribution of loads and resistances.

The methodology also includes a detailed review of historical construction practices to understand the material composition and construction techniques used in the studied masonry structures. This is crucial for developing correction factors specific to older buildings.

Growing interest in the use of probabilistic methods for assessing the safety of monolithic and brick structures indicates a constant search for more accurate and reliable ways to ensure the safety of construction sites. Scientific sources offer detailed analyzes and methods for using probabilistic approaches to assess the safety of monolithic and brick structures under conditions of seismic activity and other loads [1 – 3].

Traditional safety assessment methods are usually based on deterministic approaches that consider only the physical parameters of structures and loads. However, in recent years it has been discovered that this approach does not always take into account all possible risks and uncertainties that may arise during the operation of buildings. The use of probabilistic methods makes it possible to take into account these uncertainties, as well as to take into account the stochastic nature of loads and material properties. For example, for monolithic and brick structures, stochastic modeling methods can be used, such as the Monte Carlo method, Monte

Carlo methods using random fields, stochastic analysis methods and others. [8 – 12]. The use of probabilistic methods helps in identifying potential vulnerabilities in structures and developing more effective safety improvement strategies. By considering risks and uncertainties in advance, better informed decisions can be made regarding the design, construction and operation of construction projects. Scientific works [10, 11, 12 – 14] explore models to assess the possibility of destruction of unreinforced masonry structures and determine criteria for their reliability.

Also, in accordance with European standards, methods have been developed to assess the probability of failure of monolithic structures during seismic loads. [6, 7, 13, 14]. These studies take into account various aspects affecting the reliability of structures, including material characteristics, loading conditions, technological features, and other factors. Research [13] considered a model of a technical system over a certain time interval and analyzed ways to increase the competitiveness of construction products [14]. Experimental studies of masonry walls and compressed parts under local overload are investigated in [4, 17, 18, 22].

In Ukrainian regulatory documents, masonry testing is considered according to the general principles established by standards [15] based on approaches similar to European standards [22]. In particular, masonry testing is conducted on sample specimens to determine their compressive strength. The selection of samples is regulated by standards to ensure representativeness.

For the calculation of masonry strength, partial safety factors are applied, taking into account the variability of material properties, particularly the strength of bricks and mortar. The use of ultrasonic testing, radiography, and other methods allows for the assessment of the masonry condition without damaging structural elements. Statistical models, such as the Monte Carlo method, help account for the stochastic nature of loads and material properties to predict failure probabilities.

To ensure the objectivity and reproducibility of results, at least 10,000 iterations are performed in the Monte Carlo method. This number allows for obtaining stable statistical indicators. When higher accuracy is required, the number of iterations increases depending on the available computational resources. The extent to which the simulation result approximates the true value is determined by the following parameters: confidence interval, confidence level, and variance. These values are considered for achieving precise and stable results. The exact sample size is determined empirically through a convergence analysis—results are evaluated over several sets of iterations, and the process continues until the assessment stabilizes.

The Monte Carlo method allows for modelling various scenarios of masonry structure operation. Loads can be grouped based on their impact and nature. This approach enables the adaptation of results to real-world conditions. Figure 1 presents a diagram illustrating operational scenarios for analysis. In particular, under accumulative effects (combined effects), loads overlap but do not create new effects. For example, constant load and wind. Amplified effects occur when the interaction of factors leads to nonlinear intensification of the effect or critical failure. For instance, thermal expansion and vibrations that cause cracks. This representation is convenient for analysis as it reflects the essence of the impact on the structure: either loads simply add up, or their interaction creates a new, dangerous effect.
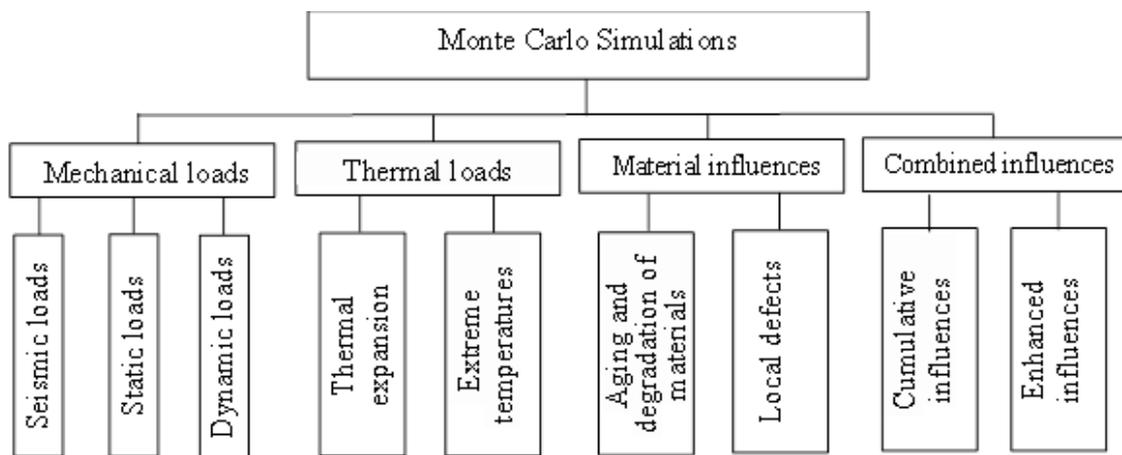
Figure 1. Diagram illustrating operational scenarios

Chart in Figure 2 illustrates the convergence of the Monte Carlo method as the number of iterations increases. The x-axis represents the number of iterations (logarithmic scale), and the y-axis shows the estimated value. As the iterations grow, the estimate stabilizes around the expected mean (0), indicating improved accuracy.

The use of probabilistic methods helps to obtain more accurate and objective assessments of the safety of structures and take into account risks during operation under various conditions and scenarios.
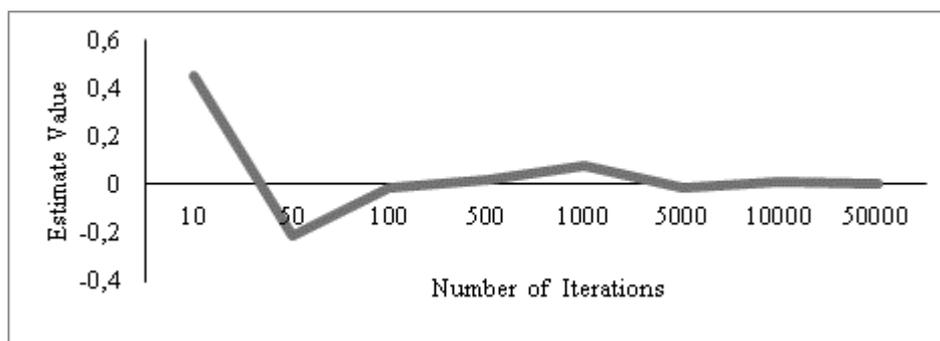

Figure 2. Convergence of Monte Carlo Method

3. Results and discussion

The purpose of the article is to improve the methodology for assessing the mechanical properties of masonry for building renovation using the results of individual brick-and-mortar tests. Testing brick samples cut from a building structure is one of the most effective methods for

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determining the strength of brick in an existing building. This approach allows you to obtain direct data on the strength of the brick material, taking into account all its features and possible defects. For testing, brick samples are usually selected from different places of construction to ensure objectivity under conditions of different loads and use. Brick samples can be subjected to different types of testing, including tensile, compression, bending, and other types of tests [1, 3, 5].

Removing large enough and representative brick samples from an existing building can be challenging [7], especially in the case of massive brick walls or pillars. Cutting out these samples may harm the building structure and degrade its load-bearing capacity, which is unacceptable from the point of view of preserving the building.

There are alternative methods for assessing the strength of brick structures that are less invasive and harmful to the building. These alternative methods are useful for assessing the strength of masonry structures without the risk of damaging the building elements. They allow you to obtain information about the strength and structural properties of a structure while maintaining its integrity and integrity. The use of techniques such as ultrasonic testing or radiography helps determine the strength and structural properties of a brick without damaging it [4]. The present study examines the feasibility of using ultrasonic non-destructive testing to evaluate the condition of a brick wall.

An important aspect to consider when researching bricks and mortars that were used in the past for construction is how they differ from modern ones. Even if the samples have similar compressive strength, this does not mean that their properties and composition fully correspond to the materials used in real structures. For example, the composition of raw materials, the quality of the sand-limestone mixture, and other components may vary due to changes in technologies for extracting and processing materials.

Typically, the smallest masonry samples are cut into cylindrical or cubic shapes. This ensures uniformity and standardization of the samples for subsequent material strength testing. In some cases, a correction factor of 1.8 [6] may be applied to cylindrical samples tested in compression perpendicular to the joints. This factor accounts for the effective reduction in material strength due to the uneven load distribution caused by the presence of joints. The factor is based on empirical data and numerical models.

Cylindrical samples can exhibit different interactions between material layers, particularly due to mortar joints, which create abnormal stress concentrations. Material heterogeneity and the method of load application result in an effect where the strength of cylindrical samples is reduced compared to cubic ones. The correction factor value of 1.8 compensates for this effect, aligning the results with standardized values. This value was obtained based on studies involving repeated testing of various sample types and analysis of the results. Reference [7] note that these values are determined by comparing actual test results with model predictions.

Standards [15] and [22] indicate that correction factors may vary depending on material properties, sample shapes, and testing methods. The correction factor of 1.8 for cylindrical samples should be applied in cases of compression testing perpendicular to the joints. It accounts for the effective reduction in material strength due to the uneven distribution of loads caused by the presence of joints. The value of the correction factor may vary depending on the specific testing conditions, sample type, material and structural characteristics, as well as the standards used for evaluation. The value of 1.8 is typical for testing cylindrical samples under compression perpendicular to the joints, but in other cases, different correction factors may be applied to account for differences in shape, loading conditions, or material properties.

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Specimens cut from masonry constructed with weak mortars may be particularly susceptible to damage during transport to the laboratory. Therefore, it is necessary to protect these samples to avoid any accidental damage and preserve them to obtain the most objective test results.

There is no point in examining damaged wall fragments for strength. Various research methods give an error in determining the average strength of brickwork in the range of 10 – 20% [12, 21].

Accurate determination of the average masonry compressive strength and the coefficient of variation of masonry strength requires statistical analysis of test results [22]. After testing each sample, its compressive strength is calculated. This can be done, for example, by dividing the maximum load the sample can withstand by its cross-sectional area. The average compressive strength of masonry is determined as the arithmetic mean of the strength of all samples.

To determine the characteristic value of masonry compressive strength using a 5% quantile in the case of a normal distribution, there is a formula:

$$f_k = \mu + 1.645 \cdot \sigma, \tag{1}$$

where:

μ – average value (mathematical expectation) of the strength distribution;

z – 5% quantile of the standard normal distribution (a value that corresponds to a 5% probability);

σ – standard deviation of the strength distribution.

The 5% quantile has specificity in the context of statistical distribution. It corresponds to the lowest 5% of values in a standard normal distribution, where the mean is distributed using a regular bell curve. Accordingly, 95% of the values are to the left of the 5% quantile, making it a practical application for defining an upper limit or threshold that can only be exceeded 5% of the time by random selection. In a normal distribution, the 5% quantile corresponds to $z \approx 1.645$, so we add this value to the mean to get the 5% quantile.

The standard deviation σ can be calculated as $\sigma = CV\mu$, where CV – the coefficient of variation of strength and μ – is the average strength of the masonry. The characteristic value can also be expressed as:

$$f_k = \mu \cdot (1 + z \cdot CV), \tag{2}$$

CV – the coefficient of variation in the strength of brickwork.

This expression is convenient to use in practice because it is based on basic statistical concepts and does not require complex calculations. Using a standard normal distribution and a 5% quantile yields an easily interpretable value: this is the strength value that is expected to be exceeded only 5% of the time.

The expression of the characteristic value (1) assumes that the strength of the masonry is distributed according to a normal law. However, this is not always confirmed. The compliance of the data with a normal distribution must be checked. There are several methods that can be used to check whether data follows a normal distribution [8]. To obtain reliable results, it is important to have sufficient data. Having at least three samples available for such assessments is generally recommended. In the case of a lognormal distribution of masonry compressive strength, the characteristic value can be determined using the quantile of the lognormal distribution. If the parameters of this distribution are known, the characteristic value can be determined.

For a lognormal distribution, the characteristic value is defined as the exponent of the mathematical expectation of the test logarithm plus a certain number of standard deviations of the logarithm:

$$f_k = e^\mu + z \cdot \sigma, \tag{3}$$

where:

μ – average value (mathematical expectation) of the logarithm of the distribution;

σ – standard deviation of the logarithm of the distribution;

z – quantile of the lognormal distribution corresponding to the given probability.

To determine the compressive strength of masonry in the case of a lognormal distribution, it is expressed as follows:

$$f_k = f_m e^{0.5 \cdot V_f f_f}, \tag{4}$$

f_k – compressive strength of masonry,

f_m – average strength of masonry,

V_f – masonry strength coefficient of variation,

f_f – factor depending on the sample size.

The value of the factor f_f is found in the EN 1990 standard [7], which defines the general principles for the design of structural structures.

f_m – average strength of masonry:

$$f_m = \frac{\sum_{i=1}^{n} f_i}{n} \tag{5}$$

As indicated in [14], the sensitivity coefficient $\alpha R = 0.8$ for $n \to \infty$ the partial coefficient γM can be expressed as follows for a normal distribution:

$$\gamma M = \frac{1}{\alpha R} \cdot \frac{1}{\gamma_{Rd}} \cdot \eta_d \beta V_f, \tag{6}$$

γ_{Rd} – model error coefficient,

η_d – conversion factor depending on the type of test method,

β – reliability level index,

V_f – coefficient of variation of masonry strength.

For a normal distribution, it is possible to express the partial safety factor γM using the sensitivity factor αR. According to the EN 1990 (Eurocode 0) standard, which sets out general principles for the reliability of structures, this expression is related as follows:

$$\gamma M = \alpha R 1. \tag{7}$$

When $\alpha R = 0{,}8$ (value specified in EN 1990 for $n \to \infty$), the partial safety factor γM is: $\gamma M = 1/8 = 1.25$.

This means that for large values the partial safety factor γM is equal to 1.25. This coefficient considers the difference between the average and the actual value.

The general dependence of the reliability coefficient γM is expressed:

$$\gamma M = \beta \eta_d V_f \cdot \frac{1}{\gamma_{Rd}} \cdot \frac{1}{\alpha R}, \tag{8}$$

γ_{Rd} – model error coefficient,

η_d – conversion factor depending on the type of test method,

β – reliability level index,

V_f – masonry strength coefficient of variation.

The EN 1990 standard [7] recommends the value of the coefficient γ_{Rd} for designed building structures to be equal to 1.0, and for existing building structures to be equal to 1.1. This coefficient takes into account the model error associated with the heterogeneity of materials, imperfection of analytical models, and other factors. The use of the γ_{Rd} coefficient makes it possible to compensate for these errors and provide a more conservative approach to the design and safety

assessment of building structures. The error when testing masonry samples may depend on various factors, such as their size, shape, type of loading, quality of material and others. The minimum error is observed when using large enough samples to better reproduce the characteristics of the material and avoid scale effects. On the other hand, the maximum error may occur when very small or irregularly shaped specimens are used, where the test results may be distorted due to incorrect reproduction of the actual operating conditions of the material. The error value η_d during testing of masonry samples can vary over a wide range from 1.1% to 1.2% or even wider.

Determining the coefficient γM in the case of a limited number of samples is very important for an adequate assessment of the strength of masonry structures, especially historical ones, where only a limited set of samples is available. Obtaining a reliable value of this coefficient allows us to provide an adequate assessment of the reliability of the building and make informed decisions on the safety and stability of structures. A combination of non-destructive and destructive tests may be one of the methods for assessing the strength of masonry and the coefficient of variation of this parameter, but it is not always the main one. The basic method may vary depending on the specific conditions, resource availability, scope of work and other factors [4, 8].

If sufficient numbers of destructive test specimens can be obtained, this may be the definitive method for determining the strength of masonry. Non-destructive methods can be used as an additional means to obtain information about the condition of a structure and confirm the results of destructive tests. If the partial reliability factor γM is determined from a limited amount of data from a small sample, its value may be exaggerated compared to values determined from broader or more current data that take into account current standards and practices. This may occur for several reasons, including limited sample representation, differences in test conditions or methodology, and changes in construction materials or technologies [8].

The values of the partial safety factor γM can be in a wide range. Typically designs, γM values range from 0,8 to 1,2.

Optimization of the safety factor γM through the reliability formula is based on the principles outlined in the EN 1990 (Eurocode 0) standard [9]. According to this standard, the design resistance of a material is defined as the ratio of its characteristic strength to the safety factor γM. Excessively high safety factors can lead to unjustified costs for structural reinforcement, so a balance between the strength reserve and economic feasibility is achieved through cost and risk analysis. The higher the probability of failure, the higher the safety factor γM should be, and conversely, if the failure probability is minimal, the factor can be reduced to an economically justified level. Figure 3 shows the balance between reinforcement costs and expected failure costs for various values of the safety factor γM.

The reinforcement costs at $\gamma M = 1.1$ are the lowest (11,000 UAH/m^2). The expected failure costs (failure probability × repair cost) are the highest (2,500 UAH/m^2). The sum of these costs results in total costs of 13,500 UAH/m^2, which is equal to the costs at $\gamma M = 1.2$. At $\gamma M = 1.2$, reinforcement costs are slightly higher (12,000 UAH/m^2), but the expected failure costs significantly decrease (1,500 UAH/m^2), which also yields total costs of 13,500 UAH/m^2. Therefore, the $\gamma M = 1.2$ factor is safer since the failure risk is reduced to 3%. This is the optimal choice between cost-efficiency and reliability (Figure 3).
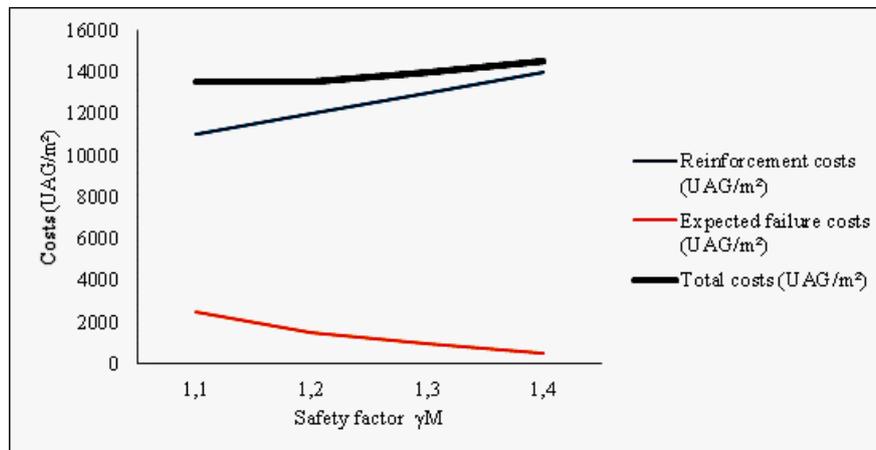
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Figure 3. Balance between gain costs and expected failure costs.

For masonry, a strength variation coefficient V_f, of approximately 0.1 or less is typically used. The coefficient of variation indicates the degree of variability in the strength of a material: the lower the value of the coefficient of variation, the smaller the difference between different strength values, and vice versa. Material characteristics, standard requirements, preliminary research and experience, as well as specific design and construction conditions are taken into account. Coefficient are determined for the desired level of reliability. The latter depends on the nature of the building, its functional purpose, customer requirements and other factors. The accuracy of measurements and parameter estimates and the risks associated with a specific project are also taken into account.

An alternative testing approach is to estimate the compressive strength of a structure based on testing of brick-and-mortar specimens. This approach can be effective when there is no ability or resources to test large numbers of samples taken from a structure. Assessing the strength of bricks and mortar provides a general understanding of the strength of the materials in a structure and will determine their potential to create strong building components.

However, it is important to consider that the strength of a structure depends not only on the strength of individual materials, but also on their interaction and the way in which they are connected to each other. Therefore, assessing the strength of a structure based on individual brick and mortar tests can only be a first step, and a full assessment requires additional testing on a large number of samples taken from the structure.

Standard [15] gives an expression for the dependence of the compressive strength of a wall:

$$f_k = K \cdot f_B^{0.7} \cdot f_M^{0.3}, \tag{9}$$

f_k – compressive strength of the wall;

f_B – compressive strength of the material (for example, brick);

f_M – environmental factor that takes into account the influence of various factors on the strength of the wall (for example, operating environment, quality of construction, compressive strength of the mortar)

K – coefficient that depends on various factors affecting the strength of the wall, and is determined in accordance with the relevant regulations and standards.

In Figure 4, we see a nonlinear dependence of masonry strength on the strength of mortar and bricks.
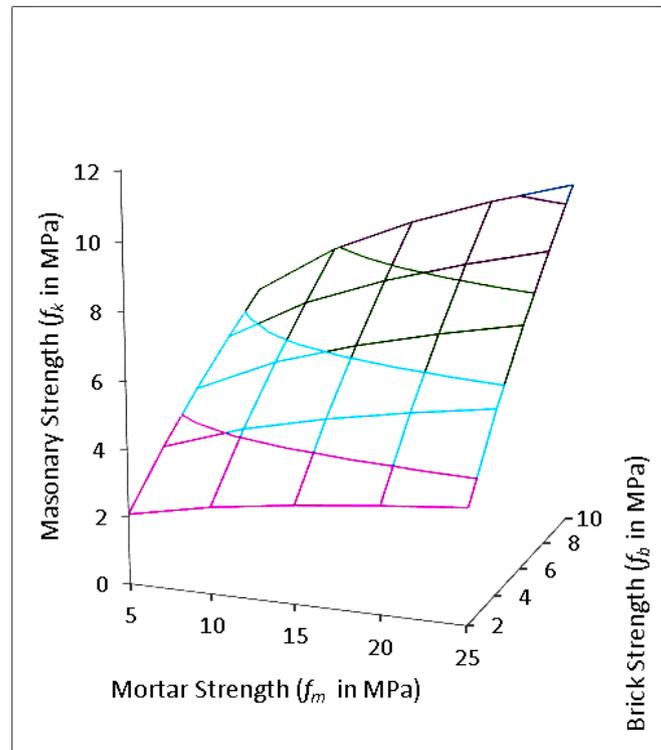

Figure 4. Dependence of masonry strength (f_k) on the strength of brick (f_b) and mortar (f_m).

By testing brick and mortar samples for compression in the laboratory, the average strength values of these materials are obtained. After this, using formula (9), the characteristic masonry compressive strength can be calculated using the average strength values of brick and mortar. This expression, given in EN 1996-1-1, is empirical as it is based on experimental results and relies on brick-and-mortar compression tests.

The coefficient K in expression (9) is assigned to ensure that the final result of calculating masonry strength will be in megapascals (MPa), as is usually convenient for measuring the strength of materials in construction. The choice of K factor depends on the units in which the average strength of brick and mortar is measured, and the desired unit of measurement for the final result.

According to EN 1996-1-1, for masonry without longitudinal joints, the value of the K factor is specified separately for different types of bricks and mortar, since these values can vary depending on the properties of the materials and construction methods. For example, K=0.55. For masonry with longitudinal joints, K=0.44 is recommended. For older masonry buildings, correction factors or alternative methods for determining structural strength are usually used, since their properties and construction conditions may differ significantly from modern buildings. Such correction factors can be taken into account to determine the value of the K factor in the formula given in the EN 1996-1-1 standard to take into account the features and disadvantages of older masonry structures.

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It is justified to use average values of brick-and-mortar strength to estimate the compressive strength of masonry, since the lack of accurate data on the variation of these parameters makes it difficult for them to be more fully included in the calculations.

We can consider (9) as a function that determines the dependence of the compressive strength of masonry f due to random variables: the compressive strength of brick f_B and the compressive strength of mortar f_M. This function allows you to evaluate the strength of masonry based on the properties of its constituent materials. The relationship between these parameters makes it possible to predict the strength of brickwork based on the properties of its constituent components.

Let the parameters f_B and f_M be random independent variables and have a lognormal distribution. The average value of the natural logarithm $ln(f)$ is determined by the formula:

$$mean\left(\ln\left(f_k\right)\right) = \ln\left(K\right) + u \cdot mean\left(\ln\left(f_B\right)\right) + w \cdot mean\left(\ln\left(f_M\right)\right), \tag{10}$$

mean( ) – average value,

K, u, w – constants,

f_B – compressive strength of brick,

f_M – compressive strength of the mortar.

We use the deviations σ of the natural logarithm $ln(f_k)$ to estimate the distribution of the wall's compressive strength f_k. It is convenient to use the natural logarithm to calculate the mean and standard deviation. So,

$$\sigma = \left(\left(u\sigma_{f_B}\right)^2 + \left(w\sigma_{f_M}\right)^2\right)^2 \tag{11}$$

or

$$std\left(\ln\left(f_k\right)\right) = \left(\left(u \cdot std\left(\ln\left(f_B\right)\right)\right)^2 + \left(w \cdot std\left(\ln\left(f_M\right)\right)\right)^2\right)^{\frac{1}{2}} \tag{11a}$$

std( ) – standard deviation,

σ_{f_B} – standard deviation of brick strength,

σ_{f_M} – standard deviation of the strength of the mortar,

u, w – constants.

The value of σ helps to evaluate the level of distribution of the wall's compressive strength f_k relative to the average value, which can be useful for further analysis and decision making.

If the values of the constants, as well as the coefficients in front of $ln(f_B)$ and $ln(f_M)$ are given, then the standard deviation and average value of the random variable $ln(f_k)$ can be calculated using formulas (10), (11).

Scientific sources [7, 8, 19] describe experimental tests of samples made of stone walls. According to the standard [16] the constants $u = 0.7$, $w = 0.3$ are set. The value of the constant K was obtained in the interval [0.26, 0.65], and the average value $mean(ln(f_k) = 0.43$.

Using the known values of $ln(f_k)$, $ln(f_B)$, $ln(f_M)$ the value of the constant K can be calculated using the inverse problem. For a higher value of the compressive strength of brickwork, the value of K will be greater. The value of K has great variability since there are different qualities of masonry workmanship. Manufacturing processes can vary depending on many factors, such as the quality of materials, technology, work conditions and others.

The coefficient of variation in brick strength can be calculated as the ratio of the standard deviation to the average brick strength.

$$\ln\left(f_B\right) = \mu + \sigma Z. \tag{12}$$

μ – average value of the logarithm of brick strength,

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σ – standard deviation of the logarithm of brick strength,

Z – the value of an ordinary ordinary random variable.

The coefficient of variation of masonry strength V_f is determined:

$$V_f = \left(\left(uV_{f_B}\right)^2 + \left(wV_{f_M}\right)^2\right)^{\frac{1}{2}},$$ (13)

Table 1. Contribution of each component

Parameter	Coefficient
Brick Strength Variation (V_{fB})	0,1
Mortar Strength Variation (V_{fM})	0,12
Overall Variation (V_f)	0,079

V_{fB} – coefficient of variation of brick strength;

V_{fM} – coefficients of variation of solution strength.

The resulting solutions can be useful for analyzing walls and supports. Knowing the compressive strength of masonry due to the strength of bricks and mortar allows one to analyze the strength of walls and supports in buildings. This helps assess the ability of structures to support loads and determine the need for efforts or modifications.

In [8] it is noted that the quality of masonry production is important for the coefficient of variation. Workmanship, for example, includes such aspects as the uniformity of brick placement, the quality of the mortar and its compression, and the quality of the joints. Defects in the manufacture of masonry lead to uneven load distribution and changes in the strength of the structure, which in turn increases the variation in strength.

Other parameters also affect the coefficient of variation of masonry strength. For example, the difference in the quality of materials (brick and mortar), operating conditions of the building, as well as the characteristics of the masonry itself (thickness, size, shape). To objectively determine the coefficient of variation of masonry strength, all these aspects should be taken into account.

Coefficients of variation of masonry strength determined in experimental tests on samples removed from the structure V_f = [0.12, 0.24]. Calculation using expression (13) gives the interval V_f = [0.10, 0.25]. Average values of V_f, obtained from experimental studies [9, 11, 20], and calculations using equation (13) $V^*_{f,\,ave}$ = 0.178, $V_{f,\,ave}$ = 0.166. The difference between $V^*_{f,\,ave}$ and $V_{f,\,ave}$ is 7%.

For example, five samples were selected with corresponding mean strength values, standard deviations, and calculated 5% quantile values. The values for each sample were determined based on the mean strength and standard deviation. The analysis of the coefficient of variation is conducted using the formula $V_f = \sqrt{u^2 V_{fB}^2 + w^2 V_{fM}^2}$, where V_{fB} and V_{fM} are the coefficients of variation for brick and mortar strength, and u=0.7, w=0.3 are given constants. It was determined

that the overall coefficient of variation V_f accounts for the contribution of each component (Table 1). The results of the calculations are presented in the Table 2 and Figure 5.

Table 2. Results of the calculations

Sample	Mean Strength (μ, MPa)	Standard Deviation (σ, MPa)	5% Quantile Strength (MPa)
1	10,5	0,8	11,816
2	11	0,7	12,1515
3	9,8	0,9	11,2805
4	10,2	0,85	11,59825
5	10,7	0,75	11,93375

According to EN 1998-1 (Eurocode 8) [15], the assessment of structural strength should be based on tests of bricks and mortar at three different locations on the site under consideration. It is recommended that at least five brick samples and ten test samples be taken from each location.
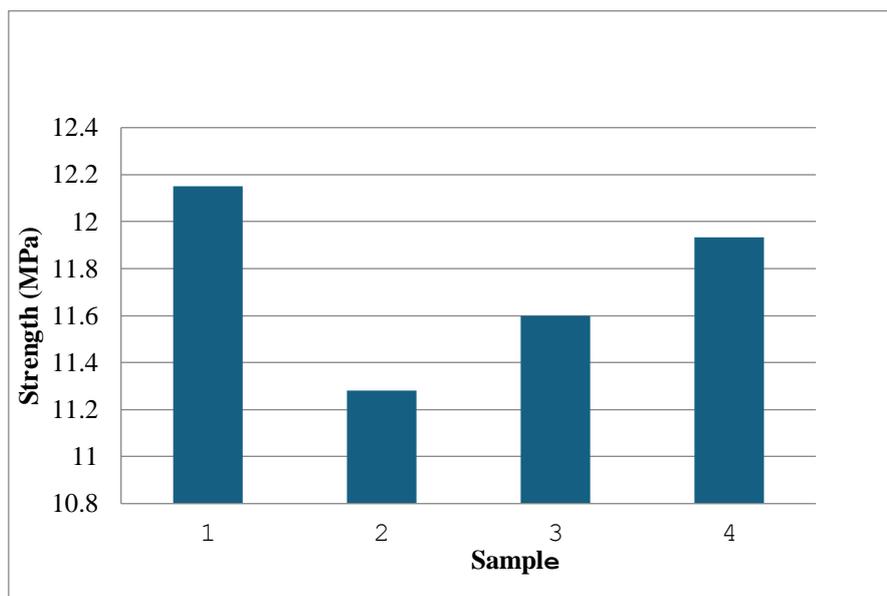

Figure 5. 5% Quantile Compressive Strength

In the process of determining the compressive strength of masonry from the strength of brick and mortar, high coefficients $\gamma M \geq 2.5$ should be assumed because the samples must be representative of all layers of the structure.

The axiom of the unacceptability of a zero probability of failure in reliability theory assumes that no system can be absolutely reliable, that is, there cannot be a system for which the probability of failure is zero. This axiom is key in reliability theory for scientific and practical reasons [14]. The probability of failure is one of the most important parameters of a building

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structure, especially from the point of view of safety and reliability. This indicator assesses the likelihood that a structure will fail to perform its function or will deteriorate within a certain time. This concept is very important for the design and evaluation of construction projects, especially in critical areas such as infrastructure, construction of structures, bridges, power plants and so on. The probability of failure helps to assess risks and make effective decisions during the construction and operation of buildings and structures.

Various methods are used to determine the probability of failure, including analytical calculations, expert judgment, statistical models, and empirical data from preliminary observations. It is also important to consider the probability of failure in the context of the influence of various factors, such as loading, operating conditions, materials, and construction technologies.

The use of probabilistic methods makes it possible to assess the risks of structural failure taking into account various factors, such as material properties, loading conditions, technological aspects, and other uncertainties. Reliability theory provides a mathematical basis for assessing the probability of failure of a structure depending on various factors and helps to carry out engineering analysis and make informed decisions on its design, construction, and operation [14].

The use of reliability theory and probabilistic risk management methods makes it possible to increase the safety and reliability of construction projects, reduce the likelihood of emergency situations and minimize possible losses. The expression for calculating the probability of failure P_f using an integral reflects the idea of calculating the probability of failure as the probability that the quality function $g(X)$ takes a value less than or equal to zero [15]

$$P_f = P\left[g(X) \leq 0\right] \int_{g(X) \leq 0} f(x) dx, \tag{14}$$

$f(x)$ – multidimensional function of variables x, reflecting the probability density of the distribution of these random variables.

X – vector of basic random variables,

$g(X)$ – quality function.

Figure 6 shows the distribution of the quality function $g(x)$. The probability density function $f(x)$ is integrated into the appropriate domains. The values in the X vector are random variables that characterize the properties of the system or process. The expression $g(X)$ is a quality function that determines whether the requirements are met. Integration occurs over the region where $g(X) \leq 0$. That is, the quality requirements are not met. Thus, there is a possibility of system or process failure.

The vector F of random events of structural failure includes the condition $g(x) \leq 0$. The building has failed if the quality function $g(x)$ takes a value less than or equal to zero. Vector F represents the failure event of each specific case (or combination of random variables) represented by the vector. The building did not fail and survived if its ability to withstand loads (resistance) is greater than or equal to the force acting on the building (action effect).

$$g(x) = R(x) + E(x), \tag{15}$$

random variables:

$R(x)$ – resistance, $E(x)$ – effect of actions.

The resistance of a building takes into account all the factors that ensure its strength and stability, such as the quality of materials, design features and technical condition.
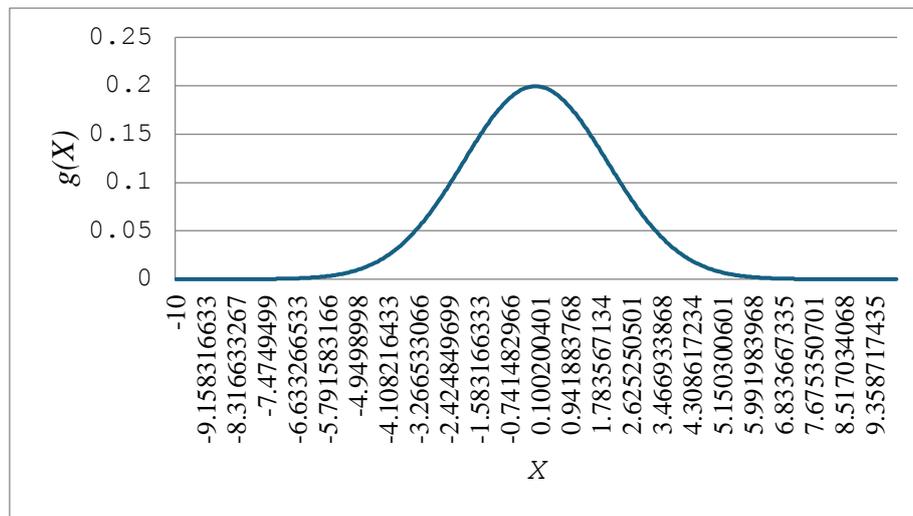
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Figure 6. Distribution of the quality function *g(x)*.

Action effect is a force or action that is applied to a building, such as wind force, snow load, seismic forces, etc. Thus, if the difference between the resistance and the effect of the actions is greater than or equal to zero, then the building retains its stability and strength when internal or external loads are applied:

$$g(x) = R(x) - E(x) \geq 0. \tag{16}$$

The design resistance of the structure is determined: for masonry structures such as brick walls, the design resistance includes the strength of the brick and mortar, and also takes into account parameters such as wall geometry, type of joints, etc.

$$R_d = R\left(\eta \frac{X_k}{\gamma_M} : a_d \right), \tag{17}$$

$R(\ )$ – function that determines the resistance of the structure taking into account the input parameters,

η – partial safety factor,

X_k characteristic value of the effective load (including the strength of brick and mortar),

γ_M – partial safety factor for the material,

a_d – additional safety factors or correction factors that take into account various aspects, such as changes in operating conditions, imperfections, standard deviations.

The formula for the dependence of the characteristic value of the effective load has the form:

$$X_k = f_B f_M, \tag{18}$$

f_B – brick strength,

f_M – mortar strength.

Expression (17) takes into account the need to ensure a balance between the load and the resistance of the structure for safety and reliability in operation. The compressive strength of masonry X_k in expression (17) is a material parameter that determines the resistance of a wall or pillar. Calculated value of masonry compressive strength f_d:

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$$f_d = \eta \frac{f_k}{\gamma_M} \qquad (19)$$

f_d – calculated value of masonry compressive strength,

η – partial safety factor, selected to ensure the level of structural reliability in accordance with accepted building standards,

f_k – characteristic value of masonry strength,

γ_M – partial safety factor for the material.

Design and operations optimization considers various structural failure scenarios and their likelihood to help make better decisions during the repair and replacement of building components. The probability of failure parameter allows for changes in operating conditions and wear and tear of the building structure over time. This allows regular inspections and maintenance to be planned to ensure the safety of the building throughout its life cycle. The value of the partial safety factor M and methods for determining the compressive strength of brickwork f_k are described in the scientific source [11]. However, these studies are intended for structures built more recently.

The absence of standards defining the strength of structures built a long time ago makes it quite difficult to analyze and assess their reliability. The study [11] recommends calculating the value of the safety factor γ_M taking into account the classes associated with the control of execution, the type of mortar and bricks provided for in the project. This parameter determines the difference between the design strength of the structure and the actual strength of the wall. For the analysis of older structures, the safety factor should be calculated based on the test results, taking into account the uncertainty due to the limitations of the selected research methods. In the process of analyzing the strength of brickwork, it is possible to take into account the uncertainties associated with changes in the properties of materials over time, uneven distribution of loads, and the influence of external factors. Conservative approaches involve general assumptions and safety margins to reduce risk.

4. Conclusions

The integration of probabilistic methods significantly improves the reliability and accuracy of masonry structure assessments, particularly for renovations and modernization.

The failure probability parameter (P_f) enhances risk prediction and long-term maintenance planning.

Optimization of the safety factor γM through cost and risk analysis allows achieving a balance between economic efficiency and structural reliability. Excessively high γM values can lead to unjustified reinforcement costs, while excessively low values increase the risk of structural failure. This approach is crucial in cases with uncertain material properties.

Conservative approaches mitigate uncertainties associated with limited sample data and material variability.

Probabilistic models, such as the Monte Carlo simulation, help account for stochastic factors in load and material properties, improving safety margins.

Non-destructive testing techniques reduce risks associated with invasive sampling, preserving structural integrity.

The study demonstrates the practical value of combining theoretical modeling with experimental testing, leading to more informed decision-making in construction safety management.

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