Збірник наукових праць. Галузеве машинобудування, будівництво
Academic journal. Industrial Machine Building, Civil Engineering
http://journals.nupp.edu.ua/znp
https://doi.org/10.26906/znp.2025.65.4213

UDC 624.04:620.1

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Reliability of Buildings and Structures: General Requirements, Terms, and Indicators

Abstract. Modern buildings and structures, with their increasing complexity in design and operation, are transforming into unique engineering systems, the failure of which can lead to significant material, moral, and human losses. Ensuring their reliability is one of the most critical problems in the modern construction industry. This article systematizes the key provisions of reliability theory as applied to construction objects. The main terms, such as dependability (failure-free operation), durability, maintainability, and storability, are considered, and quantitative reliability indicators are analyzed. The evolution of calculation methods is investigated, charting the transition from outdated deterministic approaches (the allowable stress method) to modern probabilistic methodologies, which are based on the concept of limit states. The dynamics of reliability over the object's life cycle are discussed, highlighting the typical "bathtub curve" phases of burn-in, normal operation, and wear-out. The article identifies the key challenges in the practical application of modern probabilistic methods, particularly the gap between advanced theoretical models and the lack of systematized empirical data on failures, which is necessary for the accurate calibration of national standards.

Keywords: reliability, durability, limit states, reliability indicators, building structures, structural safety.

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Received: 09.11.2025 Accepted: 28.11.2025 Published: 26.12.2025

Introduction.

The reliability of buildings and structures is one of the most important problems of modern construction, which has become particularly acute in recent decades. This is due to the growing complexity of modern objects, which may have many elements with complex interdependencies, where failure can lead to large material losses, as well as to the loss of human lives. Reliability theory, which is the science of methods for assessing and creating systems with specified reliability indicators, plays an essential role in addressing this challenge.

The reliability theory for buildings differs significantly from the reliability theory for machines and other equipment, which is due to several unique features. Firstly, building structures have significantly longer service lives, which are measured not in years, but in decades and centuries. This circumstance complicates the accumulation of credible technical and economic information about the behavior of structures throughout their full life cycle. Secondly, there is a need to assess the technical condition of heterogeneous structures that are operated in different conditions and modes but are of different ages. This requires complex statistical models to reproduce the processes of the object's functioning.

Thirdly, the reliability of buildings is associated with "mixed responsibility." This means its assessment depends not only on the economic consequences in the event of failure but also on the probability of a negative impact on human health, including injuries and fatalities. The fourth difference lies in the limited possibility of using structural redundancy as an effective means of increasing reliability. The fifth feature is the significant complexity of analyzing moral obsolescence, which determines the moment of modernization or replacement of the object, in contrast to equipment with a short service life (5–10 years).

The sixth difference is due to the low maintainability of many building structures. Their elements often have a sequential connection and rigid interdependence, which makes it impossible to quickly restore or replace individual parts with interchangeable blocks, as is common in other branches of technology. Another feature is the significant influence of the property of storability on durability and dependability, as destructive changes can occur at the stage of long-term storage and transportation of materials. A final distinction lies in the significant importance of non-mechanical failures, not directly related to damage, such as failures of the internal environment created by enclosing structures (e.g., the microclimate in a residential building).

The totality of these differences requires the separation of building reliability into a distinct section of construction science that operates with specific terms and indicators. It should be noted that reliability is a broader concept than strength, rigidity, or stability. For example, reinforced concrete slabs that are strong according to their initial characteristics may deform beyond permissible values due to increased creep over several years of operation. Thus, strength is only one aspect of reliability, not its synonym.

Analysis of Recent Research and Publications

In modern construction science and practice, reliability concepts are in a process of dynamic evolution. A fundamental change in calculation methodology, reflecting a growing understanding of the probabilistic nature of loads and material properties, was the transition from the outdated "allowable stress method" to the modern "limit state method".

The allowable stress method, which was dominant until the 1950s, was based on a simple deterministic inequality: $\sigma \leq [\sigma]$ $\sigma \leq [\sigma]$ where the maximum stress σ must be less than an allowable stress $[\sigma]$. This allowable stress was determined by dividing the material strength by a single, lumped "factor of safety." This approach was purely deterministic and could not account for the separate and random variability of different loads and material properties.

In contrast, the limit state method, which appeared in the second half of the 20th century, is probabilistic in its nature and allows for the quantitative consideration of uncertainties. Its basis is a probabilistic approach to the calculation of loads and resistances, which is now reflected in all modern structural standards. This global shift in engineering philosophy was not arbitrary; it was the result of decades of theoretical development.

The foundational principles were established by pre-normative bodies, most notably the Joint Committee on Structural Safety (JCSS) in its Probabilistic Model Code.

These probabilistic principles were then formalized in key international and regional standards. The International Organization for Standardization codified this approach in ISO 2394:2015, General principles on reliability for structures, which provides the framework for risk- and reliability-informed decision-making. In Europe, the definitive standard became EN 1990:2002, Eurocode 0: Basis of structural design, which establishes the principles and requirements for safety, serviceability, and durability for the entire suite of Eurocodes. The superiority of the limit state method over the allowable stress method is now well-documented in contemporary research, demonstrating more economical and consistent structural safety.

The Ukrainian construction industry is part of this global harmonization. This approach has found its reflection in the Ukrainian regulatory framework, particularly in the State Building Codes (DBN). Relevant documents, such as DBN V.1.2-14:2018, System of ensuring reliability and safety of construction objects. General principles for ensuring reliability and structural safety of buildings and structures are the practical embodiment of these theoretical concepts. This standard implements the probabilistic approach, notably by introducing consequence classes (CC1, CC2, CC3) to differentiate reliability requirements based on the object's importance and potential damages.

Modern scientific publications, particularly the works of Lantukh-Liashchenko, analyze the development of reliability theory in Ukraine specifically within the context of adapting these European standards (Eurocodes). This analysis confirms that the Ukrainian construction industry is aligning its standards with European principles, which require deep probabilistic modeling. This advanced methodology is being actively applied in Ukrainian research to various structural challenges, including the reliability of steel trusses and bridges.

Definition of unsolved aspects of the problem

The review of recent publications confirms a clear and necessary global transition, which Ukraine is actively participating in, from outdated deterministic methods to a modern, probabilistic design philosophy. The adoption of standards like DBN V.1.2-14:2018, which are harmonized with the Eurocodes, represents a significant advancement in the theoretical basis for structural design.

However, this transition exposes a critical and presently unsolved problem: the significant gap between the adopted methodology and the empirical data required to properly implement it. Probabilistic methods, by their very nature, are data dependent. The partial safety factors and load combination factors used in limit state design are not arbitrary; they are calibrated to achieve a specific "target reliability index" β = 3.8 for a 50-year reference period for consequence class CC2). This calibration, in turn, requires robust statistical models of loads and material resistances, which must be based on a large volume of "credible technical and economic information" and "complex statistical models," as noted in the introduction.

While Ukraine has adopted the methodology of the Eurocodes, it has not yet established a corresponding, systematic, and national framework for the collection and analysis of failure data. As the conclusions of the original analysis state, the "main unresolved problem is the lack of systematized and credible information on failures," and this "lack of an empirical basis complicates accurate calculations and forecasting".

Therefore, the unsolved aspect is this data-methodology gap. Without a national empirical database, Ukrainian engineers and regulators are largely compelled to adopt the target reliability levels and partial safety factors prescribed by the Eurocodes. These factors, while well-researched for Western Europe, may not be optimized for local Ukrainian construction practices, material supply chains, or specific environmental load conditions. This creates a disconnect that hinders the full, localized, and economically optimized application of the very standards that have been adopted.

Problem statement and research methods

The purpose of this article is to systematize the terminological apparatus, analyze the quantitative reliability indicators, and review the modern calculation methods for ensuring the viability of construction objects. The specified specificity of the industry shapes the approach to the entire life cycle of the object, its operating conditions, and the quality of execution at each stage.

Thus, the task of this article is to systematize the theoretical foundations of reliability and review the main terms. The research method employed is a systematic analysis and review of foundational academic literature, international and national standards, and key theoretical concepts to provide a holistic, consolidated overview of reliability in construction, thereby establishing a clear basis for future analysis and the enhancement of structural safety.

Main material and results

Reliability is a complex property of an object that, depending on its purpose and operating conditions, combines several distinct properties. These are all interconnected, but their relative significance may change based on the object's function. Reliability is the concept that allows an object to maintain, within defined limits, the values of all parameters that characterize its ability to perform its required functions in specified operating modes and conditions. This complex property is best understood by defining its primary components.

The Comprehensive Properties of Reliability

Dependability is the ability of an object to continuously maintain a working state over a certain time or operating period. For non-repairable objects, such as foundations or primary load-bearing elements of slabs, dependability is the defining property, as their failure necessitates complete dismantling or replacement.

Durability, in contrast, is the property of an object to maintain its working capacity until a limit state is reached, while allowing for interruptions in operation for the duration of repairs. Durability is the main property for objects subject to be repaired, such as facades or roofs. Ensuring their working capacity requires systematic measures to prevent and detect damage.

Maintainability is the property of an object that consists in its adaptability to technical maintenance and repair to maintain or restore a working state. It includes components such as technological adaptability (the possibility of control and inspection), accessibility for replacement, simplicity of dismantling, and interchangeability of elements.

Storability is the ability of an object to retain the values of its dependability and durability indicators during and after long-term storage and transportation. This property is critical for building materials and products, as physical and chemical processes (e.g., oxidation, the effect of solar radiation) can act on them, changing their structure and protective properties even before the start of operation.

Safety and Survivability are also critical. Safety is the ability of an object not to pose a threat to human life and health, while survivability is the ability to maintain limited working capacity in the presence of defects or damage that were not foreseen by the operating conditions (e.g., progressive collapse resistance).

The loss of system quality can be partial or complete. This loss is called a failure - an event consisting in the disruption of the object's working state. It is important to distinguish between the failure of an element and the failure of the object. If there is no redundancy in the object, the failure of one element can cause the failure of the entire system. However, the failure of one three-layer wall panel, for example, does not necessarily mean the failure of the building as a system, although it may lead to a decrease in the efficiency of its operation.

The transition of an object to a limit state (hranychnyi stan) means that its further use for its intended purpose is unacceptable, or the restoration of its state is impractical. For non-repairable objects, the limit state may occur because of failure, reaching a predetermined service life, or moral obsolescence.

Quantitative Indicators of Reliability

Quantitative reliability assessment is carried out using indicators that reflect the measure of an object's inherent properties. The main indicator of dependability is the probability of reliable operation, or the reliability function, which is defined as the probability that the object will operate reliably in the time interval from 0 to t:

$$P(t) = P(0,t) = P\{T > t\} = 1 - F(t) \qquad (1)$$

where T is the random operating time of the object until failure, and F(t) is the distribution function of the random variable T.

Hence, the opposite concept-the probability of failure - is derived, which describes the probability that the object will fail during a given time:

$$Q(t) = Q(0,t) = P\{T \le t\} = F(t) \quad (2)$$

Thus, the relationship between reliability and failure probability is:

$$Q(t) = 1 - P(t) \quad (3)$$

To determine the probability of failure, the failure rate (λ(t)) is often used, which characterizes the probability of a failure occurring at time t on the condition that no failure has occurred before this moment. It is related to the failure probability density function f(t) and the reliability function P(t) by the relationship:

$$\lambda(t) = f(t) / P(t) \quad (4)$$

where f(t) is the derivative of the distribution function

For repairable objects, the indicator means time between failures (MTBF) is used, which is calculated as the ratio of the operating time to the average number of failures.

Table 1 – Nomenclature of reliability indicators.

Nomenclature of indicators	Dependability	Durability	Maintainability	Storability
Main	P(t), Tm	TM	Vm	Tмy
Additional	λ(t), ω(t)	Tтp	Hв (vo)	-
Established	tγ	tγ	-	tγ
Note: where Tmp - mean restoration time, Vm - mean storability time, Tmy - mean time between repairs, tγ - failure stream parameter, Hв(vo) - probability of restoration within time vo.				

Methods for Calculating the Reliability of Building Structures

As reviewed, calculation methods have evolved from a simple deterministic approach to the more complex, probabilistic limit state method, which has become the foundation of modern design.

The limit state method is based on the concept that the forces, stresses, or deformations arising in the structure from external influences should not exceed its load-bearing capacity. This is expressed by the general inequality:

$$N \le \Phi \quad (5)$$

where N is the design force (effect) arising in the structure, and Φ is its design load-bearing capacity (resistance).

The key difference of this method is the use of probabilistic factors, known as partial safety factors. The design load F is determined as the normative (or characteristic) load F, multiplied by the reliability factor for load Υ*f*:

$$F = Fn \times \Upsilon f. \quad (6)$$

This Υ*f* factor accounts for the possible unfavorable deviation of the actual load from its normative value. Similarly, the load-bearing capacity of the structure Φ is also calculated considering probabilistic factors. It is related to the normative material resistance through the reliability factor for material γm.

$$R = Rn / \gamma m \quad (7)$$

This γm factor accounts for the possible deviation of material strength from its normative value. Thus, the limit state method effectively separates the uncertainties associated with loads from those associated with materials, which is a significant advancement over the single "factor of safety" in the allowable stress method.

The values of these factors are not arbitrary. They are directly linked to the "mixed responsibility" concept and are selected based on the consequence class (CC) of the structure, as defined in standards like DBN V.1.2-14:2018 and EN 1990. A high-consequence structure (e.g., a hospital, Class CC3) requires higher reliability factors (e.g., γ*f*=1.1×γ*f*, CC2) than a low-consequence structure (e.g., a storage building, Class CC1), ensuring a consistent and appropriate level of safety.

Furthermore, combination factors (ψi, or γl and γt) are used to calculate the forces from different types of loads (permanent, sustained, and short-term) when they act simultaneously. For the main load combinations Cm, the following ratio is used:

$$Cm = Pd + \left(\gamma l1Pl1 + \gamma l2Pl2 + \cdots\right) + \\ + \left(\gamma t1Pt1 + \gamma t2Pt2 + \cdots\right) \quad (8)$$

where Pd is the permanent load, Pli are sustained loads, and Pti are short-term loads, multiplied by their respective combination factors. The general formula for calculating the reliability of a structure, incorporating all these factors, can be written in an expanded form:

$$N\left(\sum Fni\gamma fi\psi i\gamma n, \Lambda, \Omega\right) \le Rn\gamma m\Phi\left(\Omega, \Lambda\right)\gamma c \quad (6)$$

where ψiis the load combination factor, Λ and Ω are geometric characteristics, γn is the reliability factor for the structure's importance (related to consequence class), and γc is the operating conditions factor.

Dynamics of Building Reliability over the Life Cycle

The reliability of an object is not a static characteristic; it changes over time. After construction is completed, the object has an initial reliability N0, which begins to decrease from the first day of operation. This dynamic is well-illustrated by the failure rate curve, commonly known as the "bathtub curve". This curve (Figure 1) describes the change in failure rate λ(t)over the life of an object and is divided into three periods.

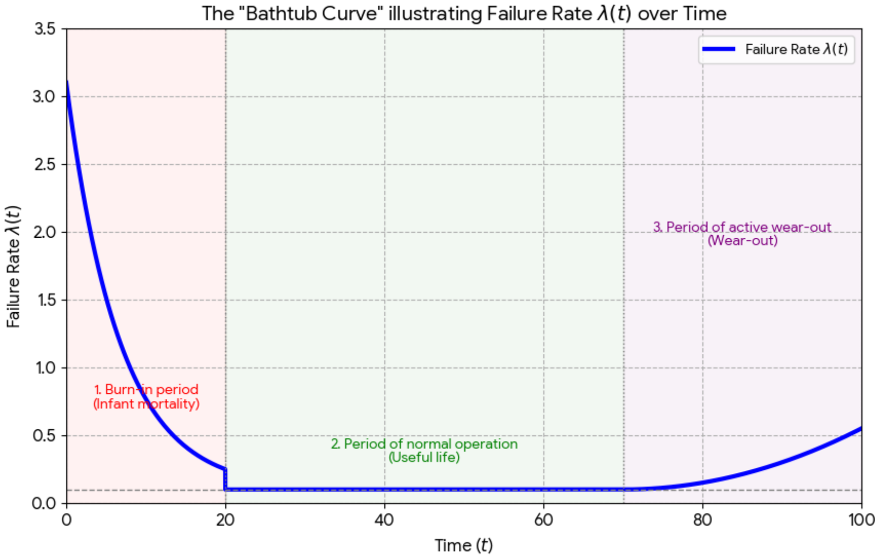

Figure 1 – The "bathtub curve" illustrating failure rate λ(t) over time.

Burn-in period. At this initial stage, the failure rate is high but rapidly decreases. This is associated with the detection and elimination of "infant mortality" failures-technological defects related to manufacturing, transportation, and assembly. In buildings, there are failures like leaks or freezing at poorly executed wall joints, which are typically identified and remediated early.

Period of normal operation. After the initial defects are eliminated, the failure rate stabilizes at a low, relatively constant level. Failures during this "useful life" period are considered sudden or random, often associated with accidental load concentrations or unforeseen phenomena not accounted for in the design.

Period of active wear-out. When elements begin to reach their average service life, the failure rate begins to increase rapidly. This is caused by natural and cumulative degradation processes: material aging, wear, fatigue, and corrosion.

This dynamic demonstrates that the causes of failures change throughout the object's life cycle. Failures at the burn-in stage are most often a consequence of poor-quality control or design flaws, whereas failures at the wear-out stage are caused by natural, unavoidable degradation processes. Understanding this life-cycle dynamic is essential for planning maintenance, repair, and replacement, forming the basis of modern life-cycle civil engineering.

Conclusions

Summarizing the presented materials, it can be concluded that the reliability of buildings and structures is not a static characteristic, but a complex, comprehensive property that is far broader than the traditional concepts of strength and stability. The unique specificity of construction objects-manifested in their extremely long durability, low maintainability, and high cost of failure (mixed responsibility) requires the application of a specialized reliability theory that differs from analogous fields of engineering.

The analysis showed that construction science and practice have successfully adopted probabilistic approaches, which is reflected in the necessary and complete transition from outdated deterministic calculations (the allowable stress method) to the modern limit state method. Thanks to this method, which is based on the use of partial safety factors for loads and material properties, it has been possible to significantly increase the accuracy and validity of design decisions. This probabilistic methodology is now codified in modern Ukrainian regulatory documents, particularly DBN V.1.2-14:2018, which harmonizes domestic standards with European and international principles and confirms the industry's transition to a more risk-oriented design philosophy.

At the same time, this analysis has identified that significant challenges exist for the full implementation of probabilistic reliability theory. The main unresolved problem is the lack of systematized and credible information on structural failures, which creates a critical gap between the advanced theoretical models and their practical implementation. The lack of a national empirical database complicates accurate, localized calculations and the forecasting of structural behavior during operation.

Therefore, further research must be directed not only at the refinement of theoretical models but also at the creation of effective national systems for collecting and analyzing operational and failure data. This will allow for the solving of the multi-criteria optimization problem: balancing initial investment costs with long-term maintenance costs, while ensuring a precisely calibrated and consistent level of safety for structures of all consequence classes.

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Suggested Citation:

APA style	Klimov, M., Valovoi, O., & Valovoi, M. (2025). Reliability of Buildings and Structures: General Requirements, Terms, and Indicators. *Academic Journal Industrial Machine Building Civil Engineering*, *2*(65), 52-58. https://doi.org/10.26906/znp.2025.65.4213
DSTU style	Klimov M., Valovoi O., Valovoi M. Reliability of Buildings and Structures: General Requirements, Terms, and Indicators. *Academic journal. Industrial Machine Building, Civil Engineering*. 2025. Vol. 65, iss. 2. P. 52–58. URL: https://doi.org/10.26906/znp.2025.65.4213.

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Надійність будівель і споруд: загальні вимоги, терміни та показники

Аннотація. Сучасні будівлі та споруди зі зростаючою складністю проєктування й експлуатації трансформуються в унікальні інженерні системи, відмова яких може призвести до значних матеріальних, моральних і людських втрат. Забезпечення їхньої надійності є однією з найважливіших проблем сучасної будівельної галузі. У статті систематизовано ключові положення теорії надійності стосовно об'єктів будівництва. Розглянуто основні терміни, зокрема безвідмовність, довговічність, ремонтопридатність і збережуваність, а також проаналізовано кількісні показники надійності. Досліджено еволюцію методів розрахунку, що відображає перехід від застарілих детермінованих підходів (методу допустимих напружень) до сучасних імовірнісних методологій, заснованих на концепції граничних станів. Обговорено динаміку надійності протягом життєвого циклу об'єкта з виокремленням характерних фаз «ванної кривої»: періоду припрацювання, нормальної експлуатації та зносу. Визначено ключові проблеми практичного застосування сучасних імовірнісних методів, зокрема розрив між розвиненими теоретичними моделями та браком систематизованих емпіричних даних про відмови, необхідних для точної калібровки національних нормативних документів.

Ключові слова: надійність, довговічність, граничні стани, показники надійності, будівельні конструкції, конструктивна безпека.

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Надіслано до редакції:	09.11.2025	Прийнято до друку після рецензування:	28.11.2025	Опубліковано (оприлюднено):	26.12.2025