

Kustikova Yu.O.



Kustikova
Yuliya Olegovna,

Candidate of Technical Sciences,
Associate Professor of the Department of Housing and Communal Services; Moscow State University of Civil Engineering (National Research University) (MGSU); 26 Yaroslavskoe shosse, Moscow, 129337, Russian Federation; ID RSCI: 706584, Scopus AuthorID: 57192558117, WoS ResearcherID: ABF-3524-2020, ORCID: 0000-0002-9671-1258; yulia.kustikova@yandex.ru

Problems in selecting durability indicators for elements of buildings and structures at the design, construction, and operation stages

Using residential buildings erected during the period of mass industrial housing construction as a case study, the article examines the impact of selecting an optimal combination of standard and design service lives for structural components, individual elements, engineering systems, and the building as a whole on ensuring its reliability throughout the entire life cycle. It is shown that a mismatch between the service lives of load-bearing and enclosing structures, finishing layers, internal engineering systems, and equipment leads to a premature decline in the facility's operational performance, an increased need for repairs, higher total costs, and reduced efficiency in the use of the housing stock. The necessity of an integrated assignment of durability indicators already at the design stage is substantiated, taking into account construction conditions, operational features, maintainability, accessibility of technical servicing, and the economic feasibility of the decisions made. Methodological approaches are proposed for selecting rational technical, organizational-technological, and economic solutions that ensure the required level of reliability of buildings and structures at the design, construction, and operation stages. A theoretical framework is presented that makes it possible to relate the durability of individual elements to the integral reliability of the building, assess the influence of service life on its functional stability, and provide a basis for improving design practice, regulatory requirements, and strategies for housing stock operation. Particular attention is paid to buildings of the first mass-produced series as the facilities that most clearly demonstrate the consequences of errors in assigning service lives. The practical significance of the results lies in the possibility of using them to substantiate major repairs, modernization, and reconstruction of the existing housing stock under current conditions.

Keywords: life cycle, reliability, durability, construction, technical operation, reliability indicators

In the second half of the twentieth century, the USSR launched housing construction on an unprecedented scale, which continued until the early 1990s. At the first stage, from the late 1950s to the mid-1960s, the task was to relocate citizens from basements and barracks. At the second stage, from the mid-1960s to the mid-1980s, mass housing construction was used to resettle residents of communal apartments. Finally, beginning in the mid-1980s, the main objective of housing construction was to increase the provision of comfortable and well-equipped housing for citizens.

At all stages, inexpensive and short-lived materials and products were used in the construction of residential buildings. This can be explained by two circumstances.

First, the pace and volume of housing construction were so high that extensive savings in financial resources became necessary. This was achieved through the use of simplified and unreliable engineering solutions in the design process and the application of construction materials with minimum cost.

Second, the construction of buildings and structures relied exclusively on products manufactured by domestic construction industry enterprises, whose technological base was largely archaic. This predetermined the production of a limited range of products, their low quality and, consequently, poor durability.

During the years of industrialized housing construction, a sufficiently large number of residential buildings were erected according to various stan-

dard designs, which combined both successful solutions in terms of operational reliability and extremely unsuccessful technical solutions. Examples of completely unsuitable technical solutions include three-layer reinforced concrete wall and roof panels with insulation layers made of reed boards (design service life: 10 years) and cement-fiber boards (design service life: 15 years). Another striking example of disregard for maintainability is heating panels, which are reinforced concrete blocks with heating system pipelines cast into them.

In Moscow, between 1959 and 1976, 5,081 prefabricated five-storey residential buildings were constructed, with a living area of 10.7 million sq m (approximately 15 million sq m of total floor area), which, at the time the renovation programme was launched, accounted for about 10 % of the city's housing stock [1]. In recent decades, Moscow has been implementing a large-scale renewal of residential development dating from the 1960s and 1970s, involving the demolition of five-storey apartment buildings and the construction of modern residential buildings in their place within the framework of the renovation programme [2, 3].

In buildings of the standard series P-32, P-35, and K-7, the external wall panels are self-supporting and have different structural designs. In P-35 series buildings, they are made of rolled thin-walled ribbed shell slabs assembled in pairs with 100 mm mineral wool slab insulation. In P-32 series buildings, vibro-brick panels with a thermal insulation layer of large-porous expanded clay concrete were used. In K-7 series buildings, suspended three-layer panels were

applied, consisting of two layers of cement-sand mortar and an intermediate thermal insulation layer made of foam glass or mineral wool slabs.

The intermediate floors in buildings of the P-35 and P-32 series are made of two reinforced concrete shells, with the upper shell supported along its longitudinal sides by the lower shell, with sound-insulating gaskets laid along the entire length of bearing. To improve the sound insulation properties of the floors, the lower shells were filled with quartz sand.

The external walls, sized to a single room, were made either of three-layer panels consisting of reinforced concrete layers and insulation, for which mineral wool slabs and cellular concrete were commonly used, or of single-layer panels made of concrete with light-weight aggregates, such as expanded clay, thermozite, and others.

From the standpoint of operational reliability, prefabricated buildings of the overwhelming majority of standard series cannot be regarded as efficient and reliable. This applies primarily to inter-panel and interblock joints and seams, as well as to the thermal insulation properties of external enclosing structures, which deteriorate significantly during operation due to the ageing of thermal insulation materials. Initially, extremely short-lived cement-reed and cement-fibre boards were used as insulation; these were later replaced by semi-rigid mineral wool slabs, and only in the 1980s did insulation layers in three-layer reinforced concrete panels begin to be made of foam plastic materials with substantially greater durability [4, 5].

Since a significant part of the currently existing housing stock was erected during the period of mass housing construction, the problem of the reliability of the apartment buildings comprising this stock is particularly acute today. In the course of major repairs, this problem should be addressed by minimizing the discrepancy between the residual service life of structures, elements, and systems that are not replaced during overhaul and the standard service lives of newly installed elements.

Over the years, domestic industry has mastered the mass production of a wide range of durable structures, materials, and products for construction, which makes it possible, in the design of buildings and structures, to focus on selecting their optimal combinations from the standpoint of durability. It should also be noted that the domestic market for construction materials still offers a sufficiently wide range of imported products.

Ensuring the normative values of individual reliability indicators and their rational combination makes it possible to adopt, in the design process, solutions that fully comply with the established reliability requirements. This can be achieved provided that alternative design solutions are developed using modern technical means and technologies.

An analysis of architectural and construction design practice makes it possible to assert that ensuring the required reliability of structures, elements, systems, equipment, as well as buildings and structures as a whole at the design stage is possible only if all evaluation indicators characterizing reliability are taken into account, various technical solutions are developed on their basis, and these solutions are comprehensively assessed, optimized, and subsequently selected.

At the same time, the formation of a set of evaluation indicators ensuring the reliability of buildings at the design stage is a conceptual issue of fundamental importance. The difficulty of solving this problem lies in the fact that all reliability evaluation indicators taken into account are deterministic, equally significant, and partially contradictory.

The deterministic nature of evaluation indicators means that their values may vary only within the permissible ranges established by regulatory documents.

Their equal significance implies mandatory compliance of all evaluation indicators, without exception, with the established regulatory requirements.

Contradictoriness is inherent not in all evaluation indicators, but only in some of them. At the same time, contradictions between indicators may be either strict, that is, antagonistic, or non-strict. An example of an antagonistic contradiction is the requirement contained in the design brief to ensure the minimum cost of constructing a building while simultaneously achieving the maximum level of comfort, including space-planning solutions, the quality of interior finishing, the level of engineering amenities, and other characteristics.

An example of a non-antagonistic contradiction between evaluation indicators is the relationship between the indicator characterizing the insulation of the internal spaces of the building being designed and the indicator characterizing its energy efficiency.

In the case where contradictions among all evaluation indicators without exception are non-strict, the formation and selection of the optimal (rational) solution are carried out within the area of agreement. This area is characterized by the fact that any solution chosen within it can be improved without reducing the values of the remaining evaluation indicators [6–9]. However, in the assessment and selection of reliable technical solutions in the design of buildings and structures, such a situation generally does not arise. Therefore, the task is not to choose the option that is best from the standpoint of reliability across the entire set of evaluation indicators, but rather to determine a solution that satisfies reliability requirements through an optimal combination of the values of these indicators.

In other words, each evaluation indicator, while remaining within the permissible range in quantitative terms, does not necessarily attain its absolutely best value; however, the combination of all indicators in their interrelation proves to be the most preferable for a particular project. In this formulation, the problem of selecting the best solution is addressed within the area of compromise, which is characterized by the principle of optimality according to which solution a is preferable to solution a' if the condition $x(a) \geq x(a')$ is satisfied. The mathematical model for selecting the best solution in the area of compromise is as follows [10]:

$$x^0 = \{x/x \in X, \{x^1/x^1 \geq x\} \cap X \neq \emptyset\}. \quad (1)$$

The search for the best solutions in the area of compromise is carried out on the basis of a specific algorithm and the corresponding principle of optimality [11].

To select the best solution at the design stage while taking into account the values of all reliability assessment indicators, we have proposed two methods, referred to as the computational method and the material method.

The computational method is based on varying the quantitative values of reliability assessment indicators within the intervals established by regulatory documents, taking into account constraint indicators in order to obtain their optimal combination. For example, the load reliability factor is successively varied within the range from 1.05 to 1.10 with a step of 0.01 while the values of the remaining assessment indicators are kept unchanged. In a similar manner, the material reliability factor is varied within the range from 1.15 to 1.50 using the same increment. The search for the best combina-

tion of assessment indicators is carried out using one of the well-known mathematical methods of combinatorics.

Combinatorics is a branch of mathematics that studies discrete objects, finite sets, and the operations of selecting, ordering, and enumerating their elements, including combinations, permutations, and arrangements.

Combinatorial problems are characterized by the fact that all objects under consideration, which in the present study are rational design options, consist of individual discrete elements, that is, reliability assessment indicators of design solutions, while the sets of these elements are finite.

In the course of combinatorial analysis, two main types of operations are performed: the selection of subsets and the ordering of the elements of a set [12]. This fully corresponds to the essence of the proposed method, which is based on the successive enumeration of admissible combinations of assessment indicators and the selection of the most preferable design solution.

The material-based method of ensuring the reliability of design solutions is based on the purposeful selection of such materials as make it possible, already at the design stage, to achieve high reliability indicators for structures, elements, and systems while simultaneously minimizing labor, financial, and material-technical costs. One example is the manufacture of reinforced concrete structures under both factory and on-site conditions using reinforcement made of different materials.

For conventional steel reinforcement (classes A400, A500, A600, and higher in accordance with CP 63.13330¹), the material-based method is implemented through the use of reinforcement of higher strength classes, which makes it possible to increase the design resistance and reduce the stress level under given loads; the use of reinforcement with improved ductility and crack-resistance characteristics, ensuring more reliable structural behavior in limit states; the introduction of anti-corrosion protection measures for reinforcement, including epoxy coatings, hot-dip galvanizing, and the use of stainless reinforcement, which significantly reduces the rate of corrosion damage during operation in aggressive environments; as well as an increase in durability due to a lower probability of corrosion-related damage.

The use of high-quality metallic reinforcement makes it possible to improve structural reliability without increasing dimensions and weight; however, it requires strict quality control of the material and compliance with technological requirements during fabrication and installation.

The use of composite reinforcement in design solutions (glass-fiber-reinforced polymer, basalt-fiber-reinforced polymer, and carbon-fiber-reinforced polymer reinforcement), regulated by CP 295.1325800.2017², represents one of the clearest examples of the implementation of the material-based method for improving reliability. The main advantages of composite reinforcement include high corrosion resistance, which prevents reinforcement deterioration in aggressive environments; low density, reducing the self-weight of structures; high tensile strength exceeding the corresponding values for steel reinforcement; and electromagnetic inertness.

Another illustrative example of the material-based method for selecting design solutions optimal from the standpoint of reliability assurance is the consideration of alternative uses of different concrete classes in the manufacture of reinforced concrete structures

under both factory and on-site conditions. In this case, concretes of different classes, substantially differing in properties and cost, may be used for the production of the same structure.

The long-term experience of constructing and technically operating prefabricated buildings erected during the period of mass industrial housing construction should be thoroughly analyzed, first, in the design of new buildings and structures and, second, in the technical operation of existing facilities in the course of repair works.

In the design of new construction projects, efforts should be made to minimize deviations of the standard (design) service lives of structures, elements, and systems from their average value by selecting the most durable elements subject to replacement during operation, while simultaneously providing a justified reduction in the standard service lives of non-replaceable elements.

Within the framework of current or major repairs, when replacing elements that are in an unsatisfactory technical condition or have exhausted their service life, it is necessary to take into account the residual service life of those elements whose replacement is not envisaged. In cases where the technical condition of non-replaceable elements in the repaired buildings does not comply with the regulatory requirements for technical operation, remedial measures should be provided for their rehabilitation without replacement.

The reliability of complex technical systems, which include buildings and structures, at all stages of the life cycle is determined by the durability of their constituent elements. In mathematical form, the reliability of a system consisting of m elements may be represented as follows [13]:

$$P(t) = \prod_{i=1}^m P_i(t) dt. \quad (2)$$

This reliability function is associated with the point indicator T and the integral indicator $\hat{T}$ of the durability of a building (structure), as well as with the γ -percent service life T_γ , which are determined by expressions (3)–(5):

$$T = \int_0^\infty \prod_{i=1}^m P_i(t) dt; \quad (3)$$

$$\hat{T} = \int_0^\infty \prod_{i=1}^m P_i(t) dt; \quad (4)$$

$$T_\gamma : \prod_{i=1}^m P_i(T_\gamma) = \gamma. \quad (5)$$

In principle, the relationship between the reliability of a complex system and the durability of its constituent elements raises no doubt. However, in cases where, at certain stages of the life cycle, requirements are imposed to ensure reliability in the form of specified quantitative parameters, the durability indicators of the elements must be determined analytically.

With a certain degree of approximation, it may be assumed that, provided the regulatory operating conditions of buildings and structures are observed, the service lives (durability) of their constituent elements follow a normal distribution.

In this case, if the parameters of the normal distribution are denoted by μ_i and σ_i , and their estimates by $\hat{\mu}_i$ and $\hat{\sigma}_i$, then the point estimate of the probability of failure-free operation of the system may be determined from expression (6) [14, 15]:

$$\hat{P}(t) = \prod_{i=1}^m \Phi[h_i(t)], \quad (6)$$

¹ SP 63.13330. Concrete and reinforced concrete structures.

² SP 295.1325800.2017. List of rules. Concrete structures reinforced with polymer composite reinforcement. Design rules. URL: <https://www.minstroyrf.gov.ru/docs/15269/>

where the Laplace function is given by:

$$\Phi(x) = \frac{1}{\sqrt{2n}} \int_{-\infty}^x \exp\left(-\frac{t^2}{2}\right) dt; \quad (7)$$

$$h_i(t) = \frac{\hat{\mu}_i - t}{\hat{\sigma}_i}, \quad i = \overline{1, m}. \quad (8)$$

The minimum reliability value of the system (building, structure), taking into account the durability of its constituent elements, is determined by expression (9):

$$P_q(t) \equiv \Phi\left\{h(t) - u_q \sqrt{1 + \frac{1}{2}h^2(t)}\right\}, \quad (9)$$

where u_q and $h(t)$ are tabulated values of the quantiles of the normal distribution corresponding to the levels q and $\hat{P}(t)$.

The above theoretical approaches should be taken as the basis for selecting optimal (rational) technical, organizational-technological, and economic solutions at all stages of the life cycle of buildings and structures. Their application makes it possible, already at the design stage, to substantiate such combinations of structural, technological, and operational solutions as ensure the required level of reliability, durability, maintainability, and economic efficiency of facilities. This approach is of particular importance during the construction of buildings and structures, when the quality of implementation of design solutions directly affects the achievement of the calculated reliability indicators and service life. Equally important is the application of these approaches in the course of technical operation, major repair, modernization, and reconstruction, since it is precisely at these stages that it becomes necessary to reconcile the residual service life of existing structures and systems with the standard service lives of newly introduced elements, materials, and engineering equipment. This creates the methodological prerequisites for making well-founded decisions aimed at improving the operational reliability of facilities, extending their effective service life, and reducing total costs throughout the entire life cycle.

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Проблемы выбора показателей долговечности элементов зданий и сооружений при проектировании, возведении и эксплуатации

В статье на примере жилых зданий, возведенных в период массового индустриального жилищного строительства, рассматривается влияние выбора оптимального сочетания нормативных и расчетных сроков службы строительных конструкций, отдельных элементов, инженерных систем и здания в целом на обеспечение его надежности в течение всего жизненного цикла. Показано, что несогласованность сроков службы несущих и ограждающих конструкций, отделочных слоев, внутренних инженерных систем и оборудования приводит к преждевременному снижению эксплуатационных качеств объекта, увеличению потребности в ремонтах, росту совокупных затрат и уменьшению эффек-

тивности использования жилищного фонда. Обоснована необходимость комплексного назначения показателей долговечности уже на этапе проектирования с учетом условий возведения, особенностей эксплуатации, ремонтпригодности, доступности технического обслуживания и экономической целесообразности принимаемых решений. Предложены методологические подходы к выбору рациональных технических, организационно-технологических и экономических решений, обеспечивающих требуемый уровень надежности зданий и сооружений на стадиях проектирования, строительства и эксплуатации. Приведен теоретический аппарат, позволяющий увязать долговечность отдельных элементов с интегральной надежностью здания, оценить влияние сроков службы на его функциональную устойчивость и сформировать основу для совершенствования проектной практики, нормативных требований и стратегий эксплуатации жилищного фонда. Особое внимание уделено зданиям первых массовых серий как объектам, наиболее наглядно демонстрирующим последствия ошибок в назначении сроков службы.

Практическая значимость результатов заключается в возможности их использования при обосновании капитального ремонта, модернизации и реконструкции существующего жилищного фонда в современных условиях.

Ключевые слова: жизненный цикл, надежность, долговечность, возведение, техническая эксплуатация, показатели надежности

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Об авторе: **Кустикова Юлия Олеговна** — кандидат технических наук, доцент кафедры жилищно-коммунального комплекса; **Национальный исследовательский Московский государственный строительный университет (НИУ МГСУ)**; 129337, г. Москва, Ярославское шоссе, д. 26; РИНЦ ID: 706584, Scopus AuthorID: 57192558117, WoS ResearcherID: ABF-3524-2020, ORCID: 0000-0002-9671-1258; yulia.kustikova@yandex.ru.

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