Mechanical safety of reinforced concrete structures at all stages of the life cycle

Ivan A. Terekhov[1,*], *Nikolay* N. Trekin[2], *Emil* N. Kodysh[3], *Sergey* D. Shmakov[1]

[1] Russian University of Transport (RUT (MIIT)), 9, Obraztsova st., Moscow, Russia
[2] Moscow State University of Civil Engineering, Yaroslavskoye shosse, 26, 129337, Moscow, Russia
[3] JSC TSNIIPromzdaniy, building 2, 46, Dmitrov highway, Moscow, Russia

Abstract. Ensuring the mechanical safety of operated buildings at all stages of the life cycle is an urgent task. This is especially important when planning major repairs and reconstruction in buildings, as well as determining the period of safe operation from the moment of the survey, i.e. clarification of the remaining service life.

The total service life at the design stage is set by the customer and the general designer in accordance with the recommendations of GOST 27751-2014 «Reliability for constructions and foundations. General principles». Mechanical safety and durability are ensured when calculating structures using the limit state method, assigning protection measures depending on the operating conditions, as well as complying with the requirements of SP 255.1325800.2016 «Buildings and structures. Operating rules. General Provisions».

A method for preliminary assessment of the mechanical safety of buildings and their structures is proposed for consideration, which eliminates some of the shortcomings of existing methods for calculating the residual life by physical wear (damage) of building structures based on the results of a visual inspection, the basis of which is the dependence of the allowable safe operation period on the percentage of reduced bearing capacity. It is proposed to use the results of a visual inspection performed in accordance with GOST 31937-2011 «Buildings and constructions. Rules of inspection and monitoring of the technical condition».

Key words: mechanical safety, reinforced concrete structures, life cycle, allowable service life, building, inspection, defect, category of technical condition.

1 Introduction

A large number of operated buildings with reinforced concrete structures are approaching the standard (design) service life or exceeding it. At the same time, there are many examples when buildings are decommissioned ahead of schedule, mainly due to the emergency state of the structures. This discrepancy between the standard service life and the actual one indicates the irrational use of the resource of reinforced concrete structures, which leads to additional costs [1].

The work of reinforced concrete structures at any stage of the life cycle is subject to fundamental probabilistic laws.

* Corresponding author: terekhov-i@mail.ru

The random nature of the behavior of reinforced concrete structures is explained by the following:

- the use of idealized and simplified models in the calculation of structures that cannot take into account a number of acting factors due to their uncertainty;
- insufficient knowledge and complexity of physical and technological processes in the pre-operational stage of the operation of structures - during manufacture and installation;
- variability in the values of acting constant and temporary loads.
- insufficient consideration of specific loads and impacts.

The task of ensuring the reliability, mechanical safety and durability of structures is solved by developing the requirements of documents that standardize the quality of design, manufacture, installation and maintenance during operation.

When calculating the reliability and mechanical safety of reinforced concrete structures, it is recommended to take into account the time factor in direct form, which affects the stress-strain state of structures, as well as their strength and deformation characteristics.

The accumulation and development of damage can lead to the impossibility of the design to perform its functions at any stage of the life cycle - failure.

Ensuring the mechanical safety of operated buildings at all stages of the life cycle is an urgent task. This is especially important when planning major repairs and reconstruction in buildings, as well as determining the period of safe operation from the moment of the survey, i.e. clarification of the remaining service life.

2 Methods

Influence of the pre-operational stage of structures operation on their durability

The manufacture, transportation of structures and the erection of buildings is a complex system in which it is necessary to take into account the influence of temperatures, compression forces, friction, changing strength and physical and mechanical characteristics, dynamic and static effects of process equipment, lifting and transport mechanisms and means, reliability of interface nodes, accuracy of manufacturing and installation of frame elements, etc. [2].

Defects made during the manufacture of the structure can lead to its earlier failure. These include: surface defects of reinforced concrete structures (shells, cavities, voids), surface cracks, a decrease in the thickness of the concrete protective layer, deviation from geometric parameters and dimensions, a decrease in concrete strength relative to design values, violation of the technological process, and others.

Defects at the installation stage, arising from deviations from the requirements of the work design, can lead to additional eccentricities and forces, as well as a change in the stress-strain state (this is especially true for columns), which will cause a decrease in the bearing capacity and adversely affect the service life designs. Defects at this stage include: poor quality of welded and assembly joints, deviation from the design position of structures, concrete chips due to mechanical damage, cracks due to violations of the conditions for slinging structures, and others.

In [3] for precast concrete structures, the most common defects of the pre-operational stage were identified. For example, in 60% of cases, the welds of the support points of the crossbars on the consoles were reduced to 40-60% of the design values; in 20% of cases, the longitudinal and end seams between the floor slabs and coatings were not completely monolithic; in 5% of cases, the ribbed plates were not welded to the embedded parts of the crossbars.

Defects in the pre-operational stage of the structure may develop during the operation stage. At the same time, at the stage of operation, taking into account the conditions of its implementation, new defects may also form as a result of the negative impact of loads and the environment, as well as natural degradation processes of materials of building structures and violation of the rules of operation.

In regulations such as SP 63.13330.2018 «SNiP 52-01-2003 Concrete and reinforced concrete structures. General provisions», also contains requirements that when calculating structures for limit states, various design situations should be considered in accordance with GOST 27751-2014 «Reliability for constructions and foundations. General principles», including the stages of manufacturing, transportation, erection, operation, in case of emergency and fire [4-6]. The need to comply with these provisions is confirmed by a significant number of accidents during the construction period and affects the durability.

According to the results of the statistical data of the Ministry of Emergency Situations for the period 2014-2019. the average annual material damage as a result of an emergency is about 3 billion rubles. [7]. It was found that on average for the period 2017-2019. Since the number of victims of accidents has decreased by 47% compared with the data for 2008-2010, while the number of victims has increased by 11%.

It is characteristic that the causes of accidents that occurred in different regions are the same factors [8, 9]. Table 1 shows an analysis of the causes of accidents according to various sources.

Table 1. Analysis of the causes of accidents

	Percentage of causes of collapses, %		
	for the period from 1981-1990. according to [10]	according to [11] for industrial buildings	according to [12] for industrial buildings with a metal frame
Failure to comply with the technology of construction and installation works	**65**	**53**	**49**
Low quality building materials	20	4	15
Violation of operating conditions	11	38	26
Design errors	4	5	10

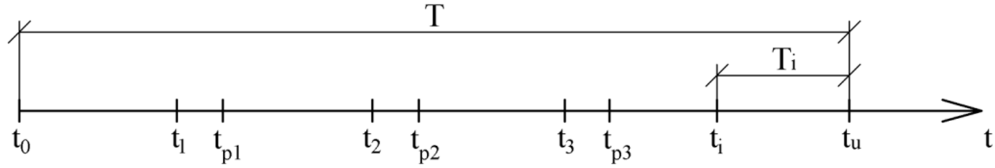
A high accident rate due to a violation of the technology of construction and installation works indicates the need to improve the quality of work, especially in the pre-operational period.

Provisions for calculating the remaining service life

The main indicators of durability that characterize the operating time of the structure before the onset of an emergency condition (Figure 1) are the total service life $T = (t_u – t_0)$ and the remaining service life $T_i = (t_u – t_i)$ [13].

The assessment of the total service life at the present time at the design stage is carried out in most cases on an enlarged basis and is advisory. Mechanical safety and durability are ensured by designing structures using the limit state method, as well as by assigning protection measures depending on operating conditions.

The recommended service life of buildings and structures, depending on their type and level of responsibility, is given in Table 1 of GOST 27751-2014. Determining the actual service life of buildings at the design stage is complicated by the fact that during this period planned repair and maintenance activities are carried out, the quality of which can significantly affect the duration of the service life.



t_0 is the initial period of time (date of manufacture or construction);
t_1, t_2, t_3, t_i – time of surveys;
t_{p1}, t_{p2}, t_{p3} - the time of the current or major repairs;
tu is the time of occurrence of the emergency state; T_i is the remaining service life;
Fig. 1. The duration of the reinforced concrete structure

Determining the remaining service life will prevent the occurrence of an emergency condition, as well as a more reasonable approach to the issue of planning current or major repairs in the building [14, 15].

In accordance with the theory of reliability, the calculation of the residual service life in general terms should be based on the provisions under which the structure will not fail during the period of operation from the moment of the survey.

1. The basic information for determining the residual service life of supporting structures is the results of the survey, which includes determining the actual category of technical condition, taking into account the operating conditions and the loading history for the period preceding the survey, performing a comparison with the data from the design documentation.

2. The failure of the structure is a consequence of the development of defects in it, which reduce the bearing capacity and performance.

3. The rate of development of defects and damage depends on the ability of the structure to resist these damages, which is laid down at the design stage and is provided at the operation stage.

4. When determining the remaining service life, it is necessary to take into account the combined impact of various adverse factors. The presence of several defects on one structure as a result of various loads and influences can worsen its technical condition and lead to failure.

Background to the development of a methodology for determining the service life between surveys

Experimental data on the operation of reinforced concrete structures at the stage close to the boundaries of the first and second limit states and, especially beyond them, are currently quite scarce. Researchers in the ongoing experiments on reinforced concrete structures - bending and eccentrically compressed, in most cases, studied the ascending section of the structural strength resistance. This is justified for establishing criteria for designing buildings and structures for operational loads. Due to the spread in the values of the physical and mechanical characteristics of materials, acting loads, operating conditions, etc. these parameters for designing are accepted taking into account the probabilistic spread and the required security. Therefore, the actual bearing capacity of structures, in the vast majority of cases, is higher than the calculated value.

The works [16] compare experimental data describing the operation of structures, including those in a special limiting state, with theoretical data obtained on the basis of calculations performed according to regulatory documents. The comparison results showed that in reinforced concrete structures there are strength reserves up to 30%, and deformability up to 50%.

The calculation substantiation of the criteria for assessing the technical condition of building structures is based on the study of the effect of a defect on the process of reducing the bearing capacity. As a result of the calculation, it is possible to obtain the values of the percentage of the bearing capacity reduced from the value provided for in the design, depending on the defect parameter.

Accepted percentages of reduced bearing capacity at the border of the transition of building structures with defects from a working state to a limited working state and from a limited working state to an emergency one are shown in Table 2.

Table 2. Percentage of reduced bearing capacity

	Technical condition category		
	workable	limited working capacity	emergency
Percentage of reduced bearing capacity	from 90 to 100% inclusive	75-90%	up to 75%

3 Results

Methodology for determining the operational safety of buildings and their structures

It is proposed to use the results of a visual survey [17] performed in accordance with GOST 31937-2011 «Buildings and constructions. Rules of inspection and monitoring of the technical condition».

The proposed method for assessing the operational safety of buildings and their structures eliminates some of the shortcomings of existing methods, and also allows you to determine the results of a visual inspection [18, 19]:

- allowable service life between inspections of buildings, depending on the category of technical condition of individual structures, taking into account the combined effect of defects located on the same structure;
- indicative terms before the overhaul of buildings.

However, if the results of a visual inspection are not enough to solve the tasks set, then it is necessary to conduct a detailed (instrumental) inspection and determine by calculation the actual bearing capacity of structures with all existing defects.

It is proposed to assign the allowable service life not according to the average operational safety of all structures, but according to the shortest allowable service life of the structure, i.e. the time interval between the inspection of all structures in the building. After the restoration of the bearing capacity of the structure, the period may be revised.

Defects that reduce the bearing capacity of the structure must be summed up. For example, the effect of cracks from reinforcement corrosion and mechanical damage in the compressed zone of plates should be summed up.

The summation of the influence of defects is proposed to be carried out taking into account the interaction matrices. If the total value of the percentage of reduced bearing capacity φi is in the range of 75-90%, then the structure is assigned a limited-operational state, if less than 75% - emergency (see Table 2).

It is recommended to sum up no more than two defects located in the same summation area, including defects of the same type (for example, inclined cracks).

The influence of each defect on the total percentage of reduced bearing capacity φi of one structure is determined by the formula:

$$\varphi_i = \varphi_{ogr} - \frac{\varphi_{ogr} - \varphi_{avar}}{U_{avar} - U_{ogr}} \cdot (U_{fact} - U_{ogr})\ , \% \qquad (1)$$

Where $\varphi_{avar} = 75\,\%$, $\varphi_{ogr} = 90\,\%$ - percentages of reduced bearing capacity in emergency, limited-operational technical condition, respectively;

U_{avar}, U_{ogr} - Criteria for assessing the emergency and limited-operational state;

U_{fact} - the indicator of the defect actually determined during the examination.

The total percentage of reduced bearing capacity for one structure is:

$$\varphi_{sum} = \left[100 - \psi_1 \cdot (100 - \varphi_1) - \psi_2 \cdot (100 - \varphi_2)\right] \cdot k_e\ , \% \qquad (2)$$

Where φ_{sum}, φ_1, φ_2 - percentage of the reduced bearing capacity of the building structure, taking into account the joint effect of defects, while $\varphi_1 \le \varphi_2$;

ψ_1, ψ_2, ψ_3 – combination coefficients taken equal $\psi_1 = 0.9$, $\psi_2 = 0.7$ (if there are two defects).

$k_e = k_{e1} \cdot k_{e2} \cdot k_{e3}$ - coefficient taking into account operating conditions.

A detailed principle of constructing the developed technique, taking into account the joint influence of defects, as well as operating conditions, is considered in the article [20].

If the structure is in working condition, as well as the actual loads and impacts that do not exceed the design ones, normal operation of the construction object is possible. In this case, the allowable service life is equal to the base one, equal to 10 years.

In case of a limited operational state of structures, buildings (structures), the allowable service life (t) is taken according to the schedule shown in Figure 2. The allowable service life obtained from the calculation results is rounded up to the nearest month.

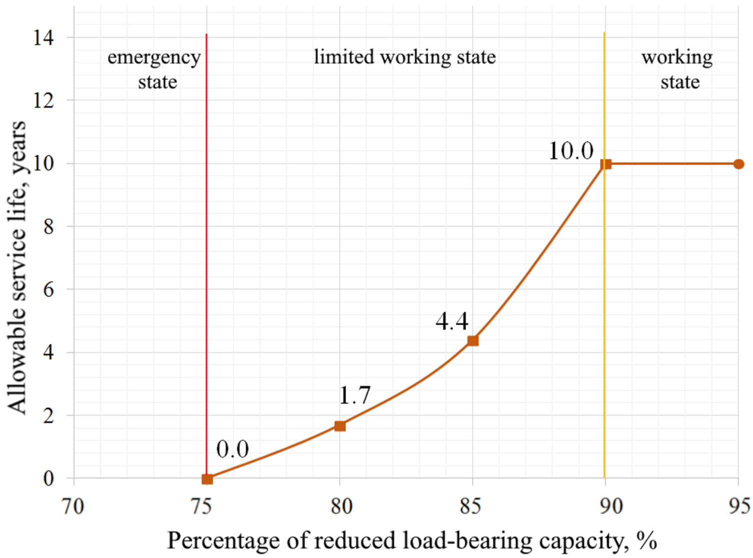


Fig. 2. Graph of allowable service life versus percentage of reduced bearing capacity

When determining the emergency state of structures using this method, it is necessary to immediately carry out emergency response measures, instrumental examination and develop measures for restoration or make a decision on demolition/dismantling.

If defects in building structures are detected during a visual inspection, the parameters of which exceed the assessment criteria corresponding to the emergency condition, in the absence of a danger of a sudden collapse of building structures, after emergency response measures and an instrumental (detailed) examination, it is allowed to assign an updated category of technical condition in accordance with GOST 31937 based on the actual state of the structure.

Forecasting the timing of the overhaul

The assessment of the state of the building is determined depending on the total percentage of reduced bearing capacity Φ:

$$\Phi = 100 - \frac{\delta_1(100-\varphi_1)+\delta_2(100-\varphi_2)+...+\delta_i(100-\varphi_i)}{\delta_1+\delta_2+...+\delta_i}, \quad (3)$$

where φ_1, φ_2, ... φ_i - percentages of reduced bearing capacity of certain types of structures, determined by the formula;

δ_1, δ_2, ... δ_i is the magnitude of the significance of individual types of structures.

$$\varphi_i = \sum_{k=1}^{k=n} \varphi_k \frac{F_k}{F_i}. \quad (4)$$

where φ_i is the average percentage of reduced bearing capacity of a particular type of structure;

φ_k – the percentage of reduced bearing capacity of a separate structure, determined by the results of a visual inspection according to formula (2);

F_k – dimensions (area or length) of the damaged area (m^2, m) or the number of damaged structures;

F_i – the dimensions of the entire structure (m^2, m) or the number of structures;

k – the number of damaged sections or structures with different percentages of reduced bearing capacity.

It is recommended that the values of the significance of structures be established on the basis of expert assessments that take into account the operational safety and socio-economic consequences of the destruction of certain types of structures, the nature of the destruction (development of plastic deformations or instantaneous brittle fracture).

For buildings and structures of various structural systems, due to the difference in the main structural elements that make up the system, it is advisable to introduce a differentiated approach to assigning significance values, taking into account the need to ensure the failure-free operation of the construction object.

The estimated life of the building before major repairs in years is determined by the formula:

$$t = \frac{t_{fact} \times ln(0,85)}{\ln(\Phi / 100)}, \tag{5}$$

where tfactis the service life of the building in years at the time of the survey.

4 Conclusions

1. It has been established that a high accident rate due to a violation of the technology of construction and installation works indicates the need to improve the quality of work in the pre-operational period.

2. The service life of individual structures between surveys and the building as a whole before major repairs can be entered into the information model, which will ensure operational safety, as well as lead to more rational planning of repair costs.

3. The proposed method for determining the operational safety of buildings and their structurestakes into account that defects that reduce the bearing capacity of the structure must be summed up.

4. This technique allows you to determine the allowable service life between surveys of buildings, depending on the category of technical condition of individual structures and the approximate time before the overhaul of buildings.

5. After detailed testing, this technique can be included in the regulatory documents.

References

1. S.B. Sborshchikov, P.A. Zhuravlev, *Life cycle of urban planning decisions: the organizational aspect of their reengineering*, Industrial and civil construction. 2021. No. 4. S. 33-39. DOI: 10.33622/0869-7019.2021.04.33-39.
2. E.A. Korol, M.N. Berlinova, *Features of the calculation of wall panels with a monolithic connection of layers at the stages of installation, transportation and operation*, Vestnik MGSU. - 2019. - T. 14. - No. 3 (126). - S. 367-375.
3. E.N. Kodysh, N.N. Trekin, *Analysis and systematization of the causes of defects in reinforced concrete structures of multi-storey frame buildings*, Prevention of accidents in buildings and structures. - M .: LLC "Veld", 2008. - S. 96-102.
4. A.I. Zvezdov, I. I. Vedyakov, K. P. Pyatikrestovsky, *The history of building design standards in Russia and the tasks of their improvement*, Industrial and civil construction. - 2018. - No. 11. - S. 28-34.
5. A.G. Tamrazyan, A.I. Dolganov, D.I. Kaleev, F.K. Zhikharev, Yu.N. Zvonov, S.E Zubareva, A. Ubysh, News of higher educational institutions. Technology of the textile industry. - 2017. - No. 4 (370). — S. 267-271.

6. V.I. Travush, V.I. Kolchunov, N.V. Klyueva, *Some directions of development of the theory of survivability of constructive systems of buildings and structures*, Industrial and civil construction. - 2015. - No. 3. - S. 4-9.
7. *Results of the activities of the Ministry of Emergency Situations of Russia* [Electronic resource]. EMERCOM of Russia [website]. - 2022. - Access mode: https://www.mchs.gov.ru/deyatelnost/itogi-deyatelnosti-mchs-rossii (date of access: 03/18/2022).
8. I.V. Beilezon, Yu. A. Belyaev, *Overview of accidents in buildings, structures, their parts and structural elements that occurred in 1988* (materials of the state inspection in the construction of the USSR State Construction Committee) – M.: Stroyizdat, 1989.
9. A.N. Dobromyslov, *Analysis of accidents in industrial buildings and engineering structures*, Industrial construction. - 1990. - No. 9. — P. 9-10.
10. *Accidents of buildings and structures on the territory of the Russian Federation in 2003* [Electronic resource]. IS "MEGANORM" [website]. - 2004. - Access mode: https://meganorm.ru/Data1/45/45817/index.htm (date of access: 03/20/2022).
11. A.I. Bedov, I.G. Terekhov, A.I. Gabitov, A.S. Salov, *AI Examination of industrial safety of buildings and structures: textbook*. allowance – M.: DIA Publishing House, 2022. – 435 p.
12. M. B. Permyakov, *Analysis of accidents in buildings and structures of industrial enterprises* [Electronic resource], Prevention of accidents in buildings and structures. - M .: Weld LLC, 2009. Access mode: https://www.pamag.ru/pressa/error-analyz (date of access: 03/20/2022).
13. G.A. Smolyago, N. V. Frolov, *Modern approaches to calculating the residual life of bent reinforced concrete elements with corrosion damage*, Bulletin of the Tomsk State University of Architecture and Civil Engineering. - 2019. - T. 21. No. 6. - S. 88-100.
14. V.A. Pshenichkina, K.N. Sukhina, V.S. Babalich, K.A. Sukhin, *Estimation of the residual life of load-bearing reinforced concrete structures of exploited industrial buildings*. — M.: Izd-vo ASV, 2017. — 176 p.
15. Tamrazyan A.G. *Methodology for the Analysis and Assessment of the Reliability of the State and Prediction the Service Life of Reinforced Concrete Structures* // Reinforced concrete structures. 2023. — V. 1. — No. 1. — P. 5–18.
16. N.N. Trekin, E.N. Kodysh, *Special limiting state of reinforced concrete structures and its regulation*, Industrial and civil construction. — 2020. — No. 5. — P. 4–9.
17. N.G. Kelasyev, E.N. Kodysh, N.N. Trekin, I.A. Terekhov, D.S. Shmakov, A.B. Chaganov, *Determination of the service life of structures, buildings and structures*, Industrial and civil construction. - 2020. - No. 2. - P. 12–17.
18. *Recommendations for assessing the reliability of building structures of buildings and structures by external signs* - M .: FSUE TsPP, 2001. - 100 p.
19. *Methodology for assessing the residual resource of the supporting structures of buildings and structures* [Electronic resource]. - FAU "FTsS", 2018. - 50 p. Access mode: https://www.faufcc.ru/upload/methodical_materials/mp34_2018.pdf (date of access: 03/13/2022).
20. N.N. Trekin, E.N. Kodysh, I.A. Terekhov, S.D. Shmakov, O.S. Shchedrin, *Methods for determining the operational safety of buildings and their structures*, Academia. Architecture and construction. - 2022. - No. 4. - P. 152-159.