BUILDING STRUCTURES, BUILDINGS AND CONSTRUCTIONS

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THE TECHNIQUE OF EXPERT EVALUATION AND FORECAST OF ACTUAL RELIABILITY OF BUILDING STRUCTURES OF OPERATED BUILDINGS AND ENGINEERING CONSTRUCTIONS

Problem statement. Existing approaches to assessing reliability of building structures are based on the model which involves exponential distribution. Such a model can be applied only for the systems with abrupt failures. However, failures in building systems are usually caused by the wear.
Results. The analysis of the correctness of calculations and forecasting reliability of building structures is performed using exponentiation distribution. Wrongfulness of the use of the models for assessment of reliability of building structures which are currently operated and have cumulative wear is shown with examples. An approach involving the linearization method is proposed.
Conclusions. The approach proposed is straightforward to use, takes into account the changes in structure carrying capacity and does not contain inaccuracies and errors peculiar to the methods designed on the exponential distribution models.

Keywords: reliability, building structures, exponential model.

Introduction

The problems of assessing, calculating and forecasting reliability of building constructions, newly constructed and operated buildings are a concern for almost all engineers and scientific workers whose job involves designing, calculating, developing and advancing designs of bearing constructions as well as of building envelopes.

Big achievements in designing calculating methods of reliability parameters and assessment of probability of failure-free performance of building constructions were made by Russian and Soviet scientists such as A. G. Roytman, L. S. Avir, V. A. Rogonsky, V. D. Raizer, B. M. Kolotilkin, G. A. Poryvay, L. M. Pukhonto, A. N. Dobromyslov, A. P. Melchakov, V. S. Utkin, K. A. Piradov and some others. However, some of the approaches set forth by them have a number of defects which hamper a wide use of these techniques.

It is also noteworthy that the problems of assessing reliability and forecasting the remaining life and changes in the categories of technical conditions of building constructions in this new 21^{th} century are still in focus. Simple engineering techniques are now demanded not only by scientific workers but also by those dealing with servicing of buildings and engineering structures of various purpose in their day-to-day activities.

A system of monitoring building constructions and engineering structures presently introduced as the major tool includes forecasting the condition which is not possible without simple and handy methods of assessing reliability and remaining life.

1. Approaches to assessing reliability of building constructions

The authors of [1] attempted to systematize and describe the four major levels of methods for assessing reliability:

- *calculation methods with partial reliability coefficients.* Reliability is assessed in a deterministic manner, separately for each limit state. A needed security level is attained by the system of partial reliability coefficients exposed to various scattering effects and reduced to normative values that are defined to be characteristics (fractiles or quantiles). In practice, this method was inappropriately called “the method of limit conditions”;
- *first-order reliability theory and the method of moments*. Reliability is assessed using approximate methods of the reliability theory that consider a chosen point of a limit state surface in the space of basic variables and involves some kind of simplification of the limit state equation as well as of distribution functions. Safety is measured using a so-called safety index, or equivalent operation failure probability;

- *reliability theory*. Reliability is assessed using ‘accurate’ methods of the reliability theory for the entire system or for some of its elements with a full consideration of the distribution of basic variables and limit state equations. Safety is measured using the operation failure probability;
- *optimized methods of the reliability theory*. Sizing of the sections of a bearing structure is performed with respect to the economic data so that the average value of all the expenses incurred over the operation period considering all possible expenses in case of a failure is as low as possible. Other optimization strategies maximize the profits from servicing this construction. The main too for safety estimation is a chosen objective function.

As noted in [1], “in the foreseeable future, practical calculations of most constructions will be performed in accordance with the standards based on the methods of Level 1, i. e. using partial reliability coefficients. The methods of the higher levels can be used for top-priority buildings. The methods of Level 2 are intended for fostering rational bases of the standards that utilize the methods of Level 1. Levels 3 and 4 can further be used in scientific research exclusively”.

2. Analysis of the exponential model

Most domestic and foreign researchers dealing with the problems of reliability and durability of building constructions use the following exponential model regardless of the used level of approach to reliability calculations

$$P(t) = \exp(-\lambda \cdot t), \quad (1)$$

where $P(t)$ is a probability of failure-free performance (or, in other words, reliability) of the construction; λ — a constant of a wear of the construction over the entire period of its service (or an averaged wear value), 1/year; t is a current time, years.

It is suggested that a wear constant of the construction should be determined [2] using the ratio

$$\lambda = \frac{1}{T_0}, \quad (2)$$

where T_0 is an average time of failure-free performance of the structure.

The relation between a probability of failure-free performance $P(t)$ and a failure probability $Q(t)$ according to the main principles of the probability theory can be written as

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

The analysis of the formulas (1)—(3) shows that by the moment of the completion of failure-free performance of the construction T_0 the value of the probability of failure-free performance will be $P(t)$=exp (–1) = 0.3679. According to the formula (3), a failure probability will be $Q(t)$ = 0.6321. So, paradoxically, by the moment of the completion of failure-free performance, a failure probability is 1.7 higher than a probability of failure-free performance.

In [3] there are following data on values of failure probability that are to be accounted for in calculations:

- $10^{-5}…10^{-7}$ — in case of a failure without preliminary indications (massive failure, loss of resistance, deterioration of the base);
- 10^{-4} — provided that the limit bearing capacity is attained with preliminary indications (fluidity of a stretched zone during bending, subsidence of the base);
- $10^{-2}…10^{-3}$ — in case a building becomes unsafe to use without losing its bearing capacity so that no further service is possible.

The author of [1] introduces standard values of reliability obtained in the experience of servicing buildings and a table of such values is presented (Table 1). The value P_0 should be regarded as an initial reliability of a construction element, $P(t)$ is reliability of the element by the end of its service life.

Table 1

Standard reliability values according to [1]

Construction name	P_0	$P(t)$
Self-bearing elements of building envelopes	0.95	0.85
Elements of statically indefinite system which if fails does not result in an abrupt failure of the system	0.99	0.95
Bearing elements with gradual failures (floor, columns, frameworks)	0.999	0.99
Top-priority constructions with abrupt failures	0.9999	0.999

The values of limit probability of failure [3] presented in a number of works and standard values of probability of failure-free performance (reliability) [1] indicate a fairly high degree of similarity of values (with respect to (3)). The values of reliability presented in Table 1 by the moment of the end of failure-free performance are almost 3 times higher than the analogy value calculated using the formulas.

Assuming the time T_0 of the construction servicing (regulated by the standards [4]) before its major repairs to be an average time of its failure-free performance, let us determine the period when a regulated reliability value can be attained by the end of failure-free performance period. The calculation results are in Table 2. To compare the obtained results, a similar calculation was performed for a case where the complete service life was chosen as a period of failure-free performance [5]. The calculation results are in Table 3.

Table 2

Calculation values of continuity of failure-free performance of building constructions

Construction name	Service time before the major repairs [4], years	Regulated reliability value by Table 1	Calculation period of attaining the regulated reliability value, years
Strip concrete foundation	60	0.99	0.60
Large-panel walls with a heating layer	50	0.85	8.13
Ordinary stone walls (brick ones with the thickness of 2—2.5 bricks)	40	0.99	0.40
Concrete monolith floors	80	0.95	4.10

The analysis of calculation periods when regulated reliability values are attained (see Table 2 and 3) yields the following conclusions:

– For all of the above bearing and self-bearing constructions whose regulated reliability value of a probability of failure-free performance is 0.95—0.99. The used exponential model of the (1) type incorrectly describes the process, for constructions operate no longer than 8 years (from 0.4 to 7.69 years) before they fail. Further, for all of the constructions, according to the model under investigation, comes a period with unacceptably large failure probability;

– The above period of failure-free performance of bearing and self-bearing constructions in practice shows good agreement with the running-in period that is generally accepted to last for 1 to 10 years;
– Claddings (sheet walls) are safe to use for 8.13 to 16.25 years, which roughly corresponds to their service life prior to major repairs of sealed joints of sheet walls using non-hardening (8 years) and curable (15 years) mastics [4].

Table 3

Calculation values of continuity of failure-free performance of building constructions

Construction name	Service time before the major repairs [4], years	Regulated reliability value by Table 1	Calculation period of attaining the regulated reliability value, years
Strip concrete foundation	150	0.99	1.51
Large-panel walls with a heating layer	150	0.85	16.25
Ordinary stone walls (brick ones with the thickness of 2—2.5 bricks)	125	0.99	1.26
Elements of concrete and steel carcasses (columns, girders, beams, frameworks)	150	0.99	1.51
Concrete monolith floors	150	0.95	7.69

3. Examples of the application of the exponential model

To prove the preliminary conclusions made according to the results of the performed calculations (see Table 2 and 3) about inaccuracies of the ratio (1) used, we are going to discuss the technique described in [6].

The technique suggested by the authors [6] is designed entirely on the exponential model like in (1). In appendices [6] there are examples of emergency risk assessment and safe lives of buildings and constructions. The study was aimed a thorough investigation of a public building (hospital) with the actual service life of 0 years long. The results of the calculations performed by the authors [6] suggest that safe life of the building under investigation is 6 years long, while the limit service life, provided that there are no repair-and-renewals to the building for the purposes of risk-reduction, is 49 years long.

In another example, we have a monolith concrete dam of a structure under service "Weir of the River Nyazya Dam" (Chelyabinsk Region) with the actual service life of 34 years.

The main defects and damages of the elements of the dam structure:

– base for the foundation of thrust walls … not found;
– foundation plate of the duct … not found;
– retaining wall of the splout … vertical crack of 4—5 mm of width, water filtration through construction joints;
– a foundation plate of the downstream floor … displacement;
– thrust walls of the downstream floor … vertical crack up to 30 mm of width;
– a foundation plate of the upstream floor … concrete failure;
– thrust walls of the upstream floor … concrete failure due to vegetation;
– splay wall of the bypass channel … concrete disintegration;
– concrete bridge … failure of beam joints, no gaskets in places of beam bearing;
– gallery … not found.

According to the results yielded by means of the calculation methods [6], the structure under investigation (weir of the dam) at the moment of study had a physical deterioration of 90.6 %.

In accordance to the standards [7], the limit wear value of concrete constructions of foundations, abutments, beams and walls is 70—80 %.

The major signs of wear are:

– for the foundations … propagation of through cracks in the walls, failure of the base, deformations of the foundations;
– for the walls … deformations of walls, displacement, cracks and failure of joints;
– columns and abutments … cracks all through the column in the stretched zone, through cracks in the base of the column and on the top level of the console, delamina-

tions of the protective layer of concrete all through the column, corrosion and at times break of the reinforcement, bending of the column;

– concrete beams … cracks through the entire length and height of the beam in the middle of the span in the stretched zone, indication of gradual damping, exposure and strong corrosion of the reinforcement, in places break of the reinforcement, large dents and spalls in concrete of the stretched zone.

Having analyzed the presented list of actual damages of the constructions and of the damages of constructions with a 70—80 % limit wear, according to the standards [7], it can be inferred that most constructions investigated by the authors of [6] of the structure show no evidence of defects, while some of the defects do not agree with the 70—80 % level of physical deterioration [7]. It is also to be noted that most of the detected defects and damages of the structure are confined to minor constructions and coatings and do not affect the major bearing constructions (most of the foundations, concrete bridge, gallery).

Therefore, the above example indicates that the exponential model like in (1) used in the calculation [6] yields far too overrated results in the estimation of physical deterioration as well. Besides, in the tables [7] of the limit wear of all the constructions, their replacement is suggested in the approximate list of operations. The performed [6] analysis of the defects and damages points out the necessity of repairs and renewals to the coating of the thrust walls of the upstream floor (upstream floor is a waterproof coating of a channel in an upstream pool which is adjacent to a water-retaining structure and intended for lengthening filtration routes), which corresponds to a wear of 10—20 %.

It is also to be noted that using of the exponential model like in (1) makes sense only in systems with abrupt failures [8]. It is unacceptable, as noted in [8], to use this model in systems with gradual or deterioration failures.

4. Suggested solutions

The suggested approach to the assessment of actual reliability of building structures that are long into their operation stage is based on the method of linearization proposed by V. P. Chirkov [9]. Since, according to the values of initial and limit reliability indicators (probabilities of failure-free performance) given in Table 1, their divergence is minimal (especially in case of bearing elements of structures), it is assumed that a graph of a curvilinear function on the area under examination can be replaced by a linear dependence of a reliability indicator depending on a service time. The suggested linear model has its flaws, however it is widely recognized that it is most convenient to use in assessment calculations and expert evaluations.

Schematically, graphs of dependences of reliability on the bearing capacity and of continuity of a standard service on reliability are presented in Fig. 1 and 2.

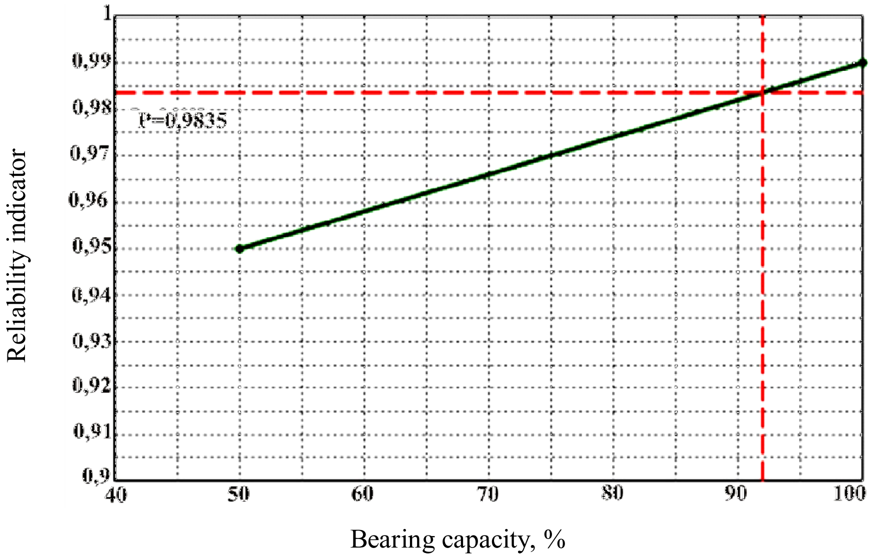

Fig. 1. Dependence of a reliability indicator on bearing capacity

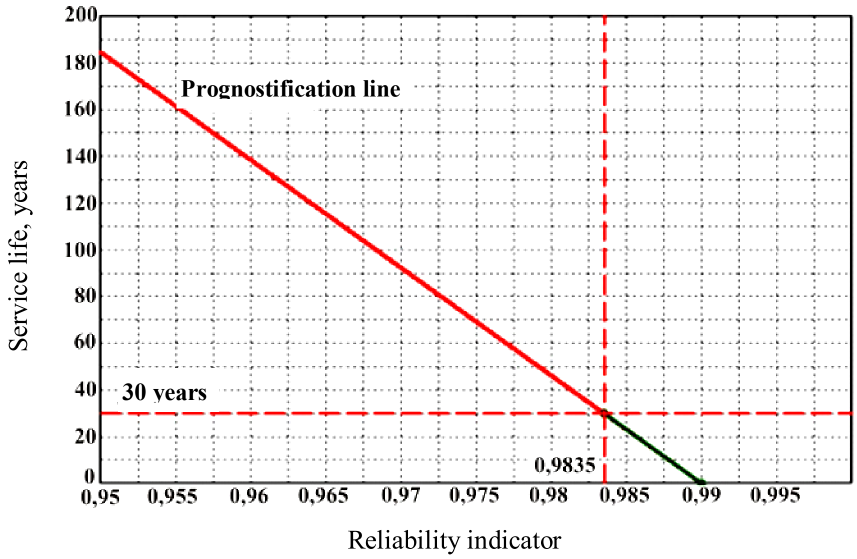

Fig. 2. Evaluation of a residual service life using the reliability indicator

The point of this technique is as follows:

- by the completion of construction works and launch of operation, a reliability value is accepted to equal the value of P_0 as suggested in Table 1, with a bearing capacity being known (a design bearing capacity);
- by the completion of servicing, a reliability value is accepted to equal the value of $P(t)$ as suggested in Table 1, with its bearing capacity being accepted with respect to an unacceptable decrease in bearing capacity (according to the regulations [10] or [11]);
- by the completion of the observation with use of instrumental research, an actual bearing capacity or its decrease percentage is determined;
- further, using available values, a linear graph of a dependence of reliability indicators on the bearing capacity is designed, by means of which an actual reliability of a construction element under examination is defined at the point of the research;
- using the obtained reliability values at the initial time moment that correspond to the time of the research and the limit value of reliability of a construction element. Depending on a service time, a linear graph is designed using which a residual service life of a construction element is defined.

Taking into consideration an actual decrease in bearing capacity of a building structure allows one not only to get a more accurate estimation of a reliability level of a construction being serviced but also to determine a rate of change in the reliability indicator.

Conclusions

1. Based on the above analysis of the model designed using the exponential distribution, we found that its application in calculations of reliability and evaluation of a residual service life of building structures and systems should be restricted or additionally justified, for there is a chance error results may emerge. The boundary of the application of this model can be a running stage of structures varying from 1 to 10 years from the completion of erection of a building or beginning of its service.
2. The suggested method based on the method of linearization facilitates expert evaluation of reliability indicators (probabilities of failure-free performance) of some construction elements and their residual service lives.
3. Unlike the existing technique, while developing this method for reliability assessment and evaluation of a residual service life of building structures of buildings being ser-

viced, limit values of failure probabilities and acceptable reliability indicators of building structures both at the moment of the beginning and completion of service have been properly accounted for.

4. Unlike the existing method, this approach, above all, accounts for changes in actual bearing capacity of building constructions being serviced as well as for limits of a possible decrease in bearing capacity.
5. This method is applicable as a basis for expert evaluations of reliability and residual service life of a structure being serviced.

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