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BRIDGES AND TUNNELS: THEORY, RESEARCH, PRACTICE

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RELIABILITY ASSESSMENT OF BRIDGE STRUCTURES

Purpose. The main purpose of the work was to analyze the methods for assessing bridge reliability, compare the approaches of Ukrainian state building codes with European standards for determining reliability, and provide recommendations for improving the regulatory framework of Ukraine. **Methodology.** The article is devoted to the study of bridge reliability as a key aspect of their design and operation. The theoretical foundations of structural reliability theory are considered, with the theory being based on a probabilistic approach to safety assessment taking into account the random nature of loads and material resistance. **Findings**. In the first section of the article, based on the theory of multiplication of probabilities for dependent events, it is shown that the reliability of a structure can be represented as the product $P(t)=P_0 \cdot P_t(t)$, where P_0 is the reliability at the operation start moment, and $P_t(t)$ is a function that characterizes the change in reliability over time and satisfies the condition $P_t(t)=1$ at $t=0$. The second section considers finding the reliability P_0, which is equal to the probability that the generalized load E will be less than the generalized resistance R. It has been proven that if the failure rate of the structure remains unchanged, increasing its initial reliability P_0 has very little effect on the residual service life (i.e., the time it will operate before becoming inoperable). **Originality**. The work shows that the failure rate function (risk function) $\lambda_{fr}(t)$, which characterizes the structural degradation processes, does not depend on the initial reliability P_0 but is determined only by the functional dependence on $P_t(t)$. This, in turn, leads to the fact that the residual service life of the structure depends mainly not so much on the initial reliability P_0 as on the degradation function $P_t(t)$. **Practical value.** Current domestic standards overestimate initial reliability, which can lead to a significant increase in material costs without a corresponding increase in its operating life. Therefore, it is recommended to consider the possibility of amending the DBN and harmonizing it with the requirements of the Eurocode, taking into account the real conditions for ensuring the reliability of structures.

Keywords: structural reliability; normal distribution law; safety index; random variable; generalized load; generalized resistance

Introduction

In the early stages of bridge construction, structures were given massive configurations in order to make them stronger and more rigid, based on the assumption that the larger the cross-section, the stronger the element. Over time, the understanding of the principles of construction changed. The development of mathematics, physics, mechanics, and materials science contributed to the emergence of the permissible stress method, which began to be used for structural calculations. Today, the main method is the limit state design method. This method is based on probabilistic indicators of load and material resistance. The papers (Євсейчик, & Медведєв, 2017; Башкевич, Євсейчик, Медведев, & Янчук, 2021; Medvediev, Kharchenko, Stakhova, Yevseichyk, Tsybulskyi, & Bekö, 2024) laid the foundation for the basic methods of probabilistic structural calculations.

In the current DBN (ДБН В.1.2-14:2018, 2018), in which the basic principles of structural reliability calculations have become normative, there are certain inconsistencies between (ДБН В.2.3-22:2009, 2009; ДСТУ 9181:2022, 2022) and (ДСТУ-Н Б EN 1990:2002, 2013).

In modern design, considerable attention is paid to the service life and residual capacity of bridges. In papers (Лантух-Лященко, 1999; 2019a; 2019b; Євсейчик, & Медведєв, 2017; Башкевич, Євсейчик, Медведев, & Янчук, 2021; Medvediev, Kharchenko, Stakhova, Yevseichyk, Tsybulskyi, & Bekö, 2024), the condition of structures is analyzed, and methods for assessing and predicting the technical condition and residual capacity are presented.

The purpose of this article is as follows:

• to show that the remaining service life of bridges depends not so much on the initial (design) reliability of the structure P_0 at the time of commissioning but on the rate of degradation of the structure over time;

• to show that for a given level of structural reliability, the sufficiency of the calculated load and resistance values depends on the coefficients of variation and margin.

Purpose

The main purpose of the work was to analyze the methods for assessing bridge reliability, compare the approaches of Ukrainian state building codes with European standards for determining reliability, and provide recommendations for improving the regulatory framework of Ukraine.

Methodology

The theory of reliability for building structures is a theory of safety calculation that takes into account the probabilistic nature of loads and structural resistance. Therefore, in order to be able to use the mathematical apparatus of this theory, we will give the basic definitions.

A failure is an event that consists in a violation of the operability of a structure, i.e., a complete or partial loss of its quality.

Failures, depending on the causes of their occurrence, are divided into *sudden* and *gradual*. Sudden failures are associated with design errors, hidden defects in materials or construction work, or operational violations. Gradual failures are caused by irreversible physical and mechanical changes: corrosion, creep, material fatigue, etc.

Let us denote by T the time of operation of a structure before its failure. That is, T is the time of failure-free operation of a structure. Obviously, T is a random variable.

The reliability of a structure is defined as the value (function) $P(t)$, which is equal to the probability that no failure will occur in the structure during the time from 0 to t, i.e.

$$P(t)=P\{T>t\}. \qquad (1)$$

In other words, reliability is the probability of failure-free operation of a structure over a period of time from 0 to t.

Along with the reliability function $P(t)$, we will consider the failure probability function

$$V(t)= P\{T<t\}. \qquad (2)$$

Functions (1) and (2) determine the probabilities of opposite events, therefore

$$P(t)+V(t)=1. \qquad (3)$$

Let us set the following problem (Medvediev, Kharchenko, Stakhova, Yevseichyk, Tsybulskyi, & Bekö, 2024): let the structure operate without failure until time t_0. What is the probability that it will not fail during the time interval from t_0 to t? As shown in (Лантух-Лященко, 1999; 2019a; 2019b; Євсейчик, & Медведєв, 2017; Башкевич, Євсейчик, Медведев, & Янчук, 2021; Medvediev, Kharchenko, Stakhova, Yevseichyk, Tsybulskyi, & Bekö, 2024), the conditional probability we are looking for is

$$P(t_0, t)=P(t)/P(t_0), \qquad (4)$$

where $P(t_0)$ is the reliability of the structure at time t_0.

From (4) it also follows that

$$P(t_0, t_0)=1. \qquad (5)$$

If we take t_0 as the initial time, i.e., consider t_0=0, then formula (4) can be written as

$$P(t)=P_0P_t(t), \qquad (6)$$

where P_0 is the reliability at the start of operation t_0=0 (it can be called the design reliability of

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the structure), and the function $P_t(t)=P(0, t)$ and according to (5) satisfies the initial condition

$$P_t(t)=1, \text{ at } t=0. \qquad (7)$$

Bridges, according to (ДСТУ-Н Б EN 1990:2002, 2013), are classified as structures with responsibility class CC2, for which the design reliability is a number very close to unity ($P_0 \approx 0{,}9993$ … 0,9995), therefore, on the graphs, the dependencies $P(t)$ and $P_t(t)$ practically coincide. To emphasize which of these functions is being considered, the point from which the graph begins is marked with P_0 or 1, respectively.

The time function $P_t(t)$ characterizes how the reliability of a structure changes (decreases) over time and is used to determine the residual life of the structure.

Let us define another function that is very important in reliability theory. To do this, let us set the following problem (ДСТУ-Н Б EN 1990:2002, 2013): the structure operated without failure from 0 to time t. What is the probability that it will fail in a small interval of time from t to $t + \Delta t$. Using formula (4), we can show (Лантух-Лященко, 1999; 2019a; Євсейчик, & Медведєв, 2017) that the probability we are looking for is equal to

$$V(t, t+\Delta t)=\lambda_{fr}(t)\Delta t, \qquad (8)$$

where the function $\lambda_{fr}(t)$ (failure rate) is a function of failure intensity (density) (Лантух-Лященко, 1999; 2019a; Євсейчик, & Медведєв, 2017) and is equal to

$$\lambda_{fr}(t) = -\frac{1}{P(t)} \cdot \frac{dP}{dt}. \qquad (9)$$

In other words, $\lambda_{fr}(t)$ is the probability that the structure will fail in the next small time interval if it has been operating without failure before that. Based on this probabilistic meaning of the failure rate function $\lambda_{fr}(t)$, it is often called the risk function.

Taking into account (6), formula (9) takes the form

$$\lambda_{fr}(t) = -\frac{1}{P_t(t)} \cdot \frac{dP_t}{dt}. \qquad (10)$$

From equation (10) it follows that the risk function (and therefore the residual life of the structure) does not depend on the design reliability P_0 and is determined only by the time function $P_t(t)$. Indeed, if conditions are not created to reduce the intensity of degradation of structural elements, then no matter how large (i.e., close to 1) the value of P_0 is, the reliability $P(t)$ will quickly decrease to its critical value.

From equation (9), after integration with taking into account the initial condition (7), we obtain

$$P(t) = P_0 \mathrm{e}^{-\int_0^t \lambda_{fr}(t)dt}. \qquad (11)$$

If we assume that the risk function does not change over time, i.e., $\lambda_{fr}(t)=\lambda_0$=const, then from formula (11) we obtain the well-known exponential law of reliability

$$P(t) = P_0 \mathrm{e}^{-\lambda_0 t}. \qquad (12)$$

This law is widely used in reliability theory. It is quite simple, easy to use, and, most importantly, has a so-called characteristic property. It consists in the fact that the probability of failure-free operation in the interval (t_0, $t_0+\tau$) does not depend on the beginning of this interval, but depends only on its length τ. The exponential law (12) works very well, but only in the case of sudden failures. Whereas in the case of gradual failures, the risk function cannot be considered a function that does not depend on time. As the construction material degrades, the risk function will gradually increase, and the use of the power law (12) can lead to significant errors in determining reliability.

Thus, the task of determining the reliability of a building structure can be divided into two parts:

• determining the design or initial reliability P_0 at the operation start moment of the structure;

• determining the time function $P_t(t)$, which characterizes the change in reliability over time.

Findings

Let us divide all calculated values into two main groups: generalized load E, which includes the parameters of external forces, and generalized resistance R, which includes the geometric and physical parameters of the materials of the structure itself. If we assume that E and R are deterministic values, then the calculation of the structure strength (or safety) consists in checking the inequality

$$R>E. \qquad (13)$$

However, as practical experience shows, both forces and geometric parameters and strength characteristics of materials have significant dispersion (scattering), the neglect of which can lead to significant errors in determining the area of safe behavior of the structure. That is, the generalized load E and the generalized resistance R for any moment in time during the operation of the structure must be considered random values. The task of reliability theory is to calculate the probability of fulfilling condition (13) with a predetermined accuracy.

Let us introduce a random variable S (Євсейчик, & Медведєв, 2017), which is called the strength reserve and is equal to the difference

$$S=R-E. \tag{14}$$

Then the design reliability P_0 is the probability that the random variable S will be greater than zero, i.e.

$$P_0=P\{R-E>0\} = P\{S>0\}. \tag{15}$$

Here, S, E, and R are defined at time t=0.

In most problems, it can be assumed that the generalized resistance and load have normal distribution laws. Then the random variable S will also be distributed according to the normal law with parameters

$$\mu_S = \mu_R - \mu_E;\ \ \sigma_S = \sqrt{\sigma_R^2 + \sigma_E^2}, \tag{16}$$

where μ_R, μ_E are mathematical expectations, and σ_R, σ_E are the standard deviations of resistance and load, respectively. Then it is easy to show (Башкевич, Євсейчик, Медведев, & Янчук, 2021) that the reliability (15) will be determined by the formula

$$P = 0.5 + \Phi(\beta), \tag{17}$$

where the function $\Phi(x)$ – $\Phi(x) = \frac{1}{\sqrt{2\pi}} \int_0^t e^{t^2/2} dx$ is the Laplace function, and the parameter β is called the safety characteristic:

$$\beta = \mu_S / \sigma_S. \tag{18}$$

As can be seen from Figure 1, which shows the distribution density function of the safety margin P_S, the value β determines the number of standards that fall within the interval from S=0 to $S=\mu_S$.

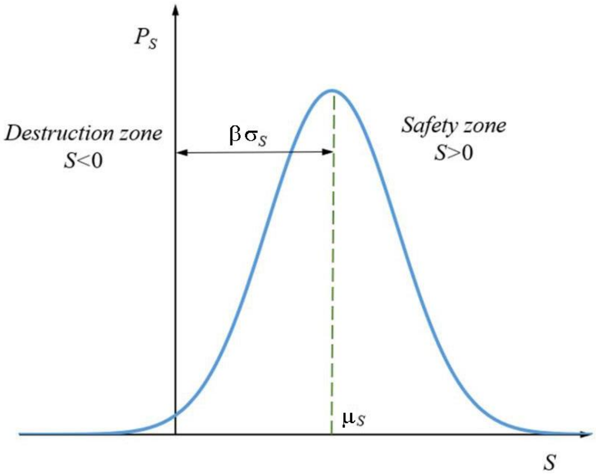

Fig. 1. Density of strength reserve distribution

Taking into account (16), the safety characteristic can be represented as:

$$\beta = \frac{\mu_R - \mu_E}{\sqrt{\sigma_R^2 + \sigma_E^2}}. \tag{19}$$

Let us introduce a deterministic value called the reserve coefficient:

$$\gamma = \mu_R / \mu_E. \tag{20}$$

Then (19) takes the form:

$$\beta = \frac{\gamma - \mu_E}{\sqrt{\nu_E^2 + \gamma^2 \nu_R^2}}, \tag{21}$$

where $\nu_R = \sigma_R / \mu_R$; $\nu_E = \sigma_E / \mu_E$ are the coefficients of variation of the values R and E, respectively.

The formula for determining the safety characteristic (21) has an advantage over formula (19) because the coefficients of variation can be estimated even with insufficient statistical information regarding the strength of the structure and the load.

According to the requirements of (ДСТУ-Н Б EN 1990:2002, 2013), the design reliability of the bridge must be at least 0,99928. This level of reliability, as follows from (17), corresponds to a safety factor of β=3.8. For more critical structures, a higher value of β is selected. Obviously, the higher the safety factor selected (assigned), the more expensive the structure will be.

According to current standards (ДБН В.2.3-22:2009, 2009), probabilistic calculation is replaced by a reliability criterion, which consists in fulfilling inequality (13)

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$$R_d \geq E_d. \qquad (22)$$

where R_d and E_d are absolute calculated values of generalized resistance and load, which have the same reliability as the safety factor S. This means that the number of standards that separate the values R_d and E_d from the corresponding mathematical expectations μ_R and μ_E is equal to β, i.e.

$$E_d = \mu_E + \beta\sigma_E; \quad R_d = \mu_R + \beta\sigma_R. \qquad (23)$$

It can be shown that the calculation of the structure according to criterion (22), where the calculated values are determined by the relations (23), leads to a significantly increased reliability than according to formulas (17) and (19). For this purpose, let us denote the number of standards in formulas (23) by β*. Then, from (22) it is easy to obtain

$$\beta^* \leq \frac{\mu_R - \mu_E}{\sigma_R + \sigma_E}. \qquad (24)$$

Then, taking into account the inequality

$$\sigma_R + \sigma_E > \sqrt{\sigma_R^2 + \sigma_E^2}, \qquad (25)$$

from (24) we obtain

$$\beta^* \leq \frac{\mu_R - \mu_E}{\sigma_R + \sigma_E} < \frac{\mu_R - \mu_E}{\sqrt{\sigma_R^2 + \sigma_E^2}} = \beta. \qquad (26)$$

From relation (26) it follows that the number of standards for the calculated values (23) must be less than the safety characteristic β in (19). And the calculation according to formulas (23) where β*=β leads to an overestimated value of reliability P_0 according to (17).

As an example, let us consider a special case where the coefficients of variation of the generalized resistance and load have the following values:

$$\nu_E = 0.3,\ \nu_R = 0.135. \qquad (27)$$

Let us assume that the number of standards in formulas (23) is equal to β*=3.8. Then, from inequality (24) for the reserve coefficient (20), we obtain

$$\gamma \geq 4.4. \qquad (28)$$

Taking into account (28) for the safety characteristic (21), we have

$$\beta \geq 5.1. \qquad (29)$$

It is obvious that such values of β lead to a significantly higher reliability of the structure than when β=3.8.

On the other hand, if we assume that the safety characteristic is equal to β*=3.8 from (21), we obtain γ≈3. Then, from inequality (26) at γ≈3 we have

$$\beta^* \leq \frac{\gamma - 1}{\nu_E + \gamma\nu_R} \approx 2.8. \qquad (30)$$

Therefore, to ensure a reliability level of P_0=0,99928, which corresponds to a safety factor of β=3.8, the number of standards β* in the formulas for determining the calculated values R_d and E_d must be selected at variation coefficients ν_E=0.3, ν_R=0.135 no more than β=2.8.

As can be seen from Fig. 2, the maximum number of standards β^*_{max} at which condition (22) holds true is determined by the equality

$$R_d = E_d. \qquad (31)$$

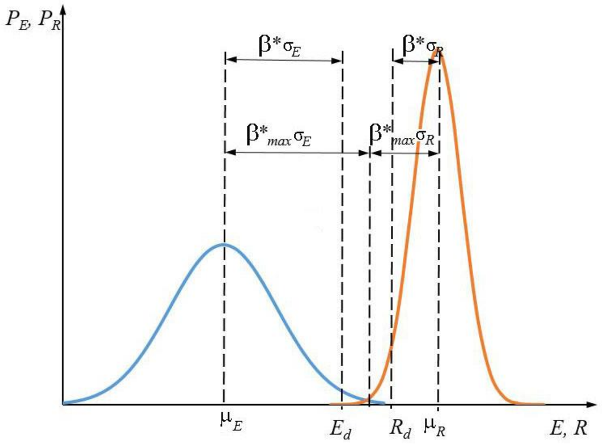

Fig. 2. Distribution function
of random variables E and R

Using (19), (20), and (23) from condition (29), we can obtain that

$$\beta^*_{\max} = \beta \leq \frac{\sqrt{\gamma^2 + \delta^2}}{\gamma + \delta}, \qquad (32)$$

where $\delta \leq \nu_E / \nu_R$.

Thus, instead of the reliability criterion in the form of inequality (22), equality (31) can be used, provided that the number of standards in the calculated values (23) is determined from condition (32).

Originality and practical value

The work shows that the failure rate function (risk function) $\lambda_{fr}(t)$, which characterizes the structural degradation processes, does not depend on the initial reliability P_0 but is determined only by the functional dependence on $P_t(t)$. This, in turn, leads to the fact that the residual service life of the structure depends mainly not so much on the initial reliability P_0 as on the degradation function $P_t(t)$.

Conclusions

The main factor determining the service life of a structure (total or residual) is not so much its initial (or design) reliability P_0 as the rate of its degradation, which is determined by the time functions $P_t(t)$ or $\lambda_{fr}(t)$. In other words, if the failure rate of the structure remains unchanged, increasing its initial reliability P_0 has very little effect on the residual service life (i.e., the time it will operate before becoming inoperable). Current domestic standards overestimate initial reliability, which can lead to a significant increase in material costs without a corresponding increase in its operating life. Therefore, it is recommended to consider the possibility of amending the DBN and harmonizing it with the requirements of the Eurocode, taking into account the real conditions for ensuring the reliability of structures.

Compliance with the reliability criterion in the form of inequality $R_d \geq E_d$ guarantees that for a given number of standards $\beta*$ for the calculated values E_d and R_d ($\beta*$ is usually specified), the reliability of the structure β will exceed the number of $\beta*$. This can lead to the creation of an additional reliability margin, which, firstly, may be inappropriate and, secondly, will definitely lead to a significant increase in the cost of construction. Therefore, the use of the limit case $R_d = E_d$ can be proposed as a reliability criterion. In this case, the number of standards for calculated values is related to the reliability of the structure by the ratio $\beta^*_{\max} = \beta\left(\sqrt{\gamma^2+\delta^2}\right)/(\gamma+\delta)$. Thus, using the above equalities, we can select all the necessary parameters of the distribution of random variables E and R to ensure a predetermined level of reliability of the structure.

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ОЦІНЮВАННЯ РІВНЯ НАДІЙНОСТІ МОСТОВИХ КОНСТРУКЦІЙ

Мета. Основною метою роботи було аналізування методів оцінювання надійності мостів, порівняння підходів українських державних будівельних норм із європейськими стандартами до визначення надійності, а також надання рекомендацій для вдосконалення нормативної бази України. **Методика.** Статтю присвячено дослідженню надійності мостів як ключового аспекту їхнього проєктування та експлуатування. Розглянуто теоретичні основи теорії надійності будівельних конструкцій, яка базується на ймовірнісному підході до оцінювання безпеки з урахуванням випадкового характеру навантажень і опору матеріалів. **Результати.** У першому розділі статті на основі теорії множення ймовірностей для залежних подій показано, що надійність конструкції можна представити як добуток $P(t) = P_0 \cdot P_t(t)$, де P_0 – надійність на момент початку експлуатації, $P_t(t)$ – функція, яка характеризує зміну надійності з часом і задовольняє умові $P_t(t) = 1$ при $t = 0$. У другому розділі розглянуто знаходження надійності P_0, яка дорівнює ймовірності того, що узагальнене навантаження E буде менше ніж узагальнений опір R. Доведено, якщо інтенсивність відмов конструкції залишається незмінною, то підвищення її початкової надійності P_0 дуже мало впливає на величину залишкового ресурсу (тобто час її роботи до переходу в непрацездатний стан). **Наукова новизна.** У роботі показано, що функція інтенсивності відмов (функції ризику) $\lambda_{fr}(t)$, що характеризує процеси деградації конструкції, не залежить від початкової надійності P_0, а визначається лише функціональною залежністю від $P_t(t)$. Це, в свою чергу, призводить до того, що залишковий ресурс конструкції залежить в основному не стільки від початкової надійності P_0, скільки від функції деградації $P_t(t)$. **Практична значимість.** Сучасні вітчизняні норми завищують початкову надійність, що може призвести до суттєвого збільшення матеріальних витрат без відповідного збільшення ресурсу її роботи. Тому рекомендується розглянути можливість щодо внесення змін до ДБН і гармонізувати з вимогами Єврокоду, з урахуванням реальних умов забезпечення надійності конструкцій.

Ключові слова: надійність конструкцій; нормальний закон розподілу; характеристика безпеки; випадкова величина; узагальнене навантаження; узагальнений опір

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