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INTENSITY OF DAMAGE IN THE AGING PROCESS OF BUILDINGS

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Predicting the aging process of residential buildings carried out using traditional technologies is necessary when planning refurbishment works in these buildings. The article presents a picture of the changes in the technical condition of a not refurbished building constructed in traditional technology, in the form of a function describing the aging process according to the PRRD (Prediction of Reliability according to Rayleigh Distribution) model developed by the author. The results of analyses of the relationships between the function of the intensity of damage and the function of unreliability, as well as the function of changes in the performance characteristics of a building which had not undergone refurbishment during the entire course of its use are presented. Three levels of damage intensity during subsequent years of using the building were determined: safe, critical and unacceptable intensity.

Keywords: technical condition, performance characteristics, service life

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1. INTRODUCTION

The aging process of residential buildings is an inevitable problem. Familiarity with the course of the damage process for the entire period a building is in use is helpful when planning refurbishment works. Studies on the topic of determining the service life of a building are being carried out. Various methods, among others Markov chains [1, 2], are applied for the mathematical description of the course of the damage process. The course of using a building is presented as a cycle, containing four operational statuses [1] or the damage process of a residential building encompassed in eight states [2]. Problems in the aging process are also solved by neuron networks [e.g. 3] or fuzzy sets [4]. The proposed model [5], based on Hamilton-Jacob-Bellman equations, specified a common building, maintenance and repair strategy, minimizing the total cost in an unspecified planning horizon. The result of studies on methods of modernization works on buildings [6] is the FMEM method, which combines the use of the emergency state and effects analysis. Identifying the likely emergency states makes it possible to plan modernization works, and, thanks to the limit state method, the longevity of the entire modernization activity can be assessed. Conclusions drawn from the methods of predicting the service life of the building [7] can be used both at the design stage of new buildings as well as for making decisions connected with the refurbishment of buildings [8-11]. The needs of building owners in all stages of the building life cycle are also being studied [12-13], so that the identification of needs can serve to determine the scope of building works. Studies on the assessment of the influence of seismic damages on the life of a building are also being carried out [14, 15]. There are many papers on the topic of the sustainable development of the life cycle of a building [e.g. 16-20]; they pertain mainly to the unfavourable influences of the building on changes to the environment.

The methodology proposed in the article supplements issues with a mathematic description of the aging process in the form of the relationship of the function of the intensity of damage in a building and changes in the performance characteristics of a building which had not been refurbished.

2. PRRD MODEL DESCRIBING THE AGING PROCESS OF A BUILDING

Buildings, during their use, are subjected to continuous destruction processes which take various courses. With the passing of time, the lowering of their performance characteristics takes place, with their partial return occurring as a result of repairs. In accordance with requirements set out by standards [21-24], a programme of the exposition of aging accounting for the most important mechanisms of degradation ought to be developed. The degradation model, understood as the distribution of the predicted use of a building [24], ought to be established accounting for the performance characteristics – time relationship, applying synthetization, modelling or interpolation/extrapolation. The degradation model ought to be calculated from the performance characteristics – time relationship, by substituting quantitatively specified performance requirements, expressed in the form of performance characteristics features or degradation indicators. The relationship between performance characteristics – time ought to be a nonlinear function of time according to standards [21-24].

The most frequently used mathematical model of the distribution of a measurable feature (length, angle, etc.), of any given good is the normal distribution. However, in cases when measurable features take on only positive values, the normal distribution can be merely an approximated model, whereas a more precise model should be sought in the class of variable distributions with positive values [25]. For modelling a situation in survival analysis, where the probability of a failure changes over time, as a distribution of the random variable of the time buildings are usable, the Weibull distribution is used. This distribution belongs to the family of asymmetrical gamma distributions. The Weibull distribution has been applied for many years, as a strength distribution as well as a distribution of the time of the proper operation and durability of analysed goods [26-28]. The density function f(t) of this distribution is described by the relationship:

$$f(t) = \alpha\beta^{\alpha}t^{\alpha-1}\exp(-(\beta t)^{\alpha}) \quad \text{for } t \geq 0, \tag{2.1}$$

where:

t – service life, α – scale parameter (actual number) α > 0, β – shape parameter (actual number) β > 0.

Parameter α of the distribution describes the behaviour of the probability of failure over time:

- for $\alpha < 1$ the probability of damage decreases with time, suggesting that the goods can have manufacturing defects and slowly undergo damage,
- for $\alpha = 1$ (exponential distribution) the probability is constant, indicating the fact that failures have the nature of external random events,
- for $\alpha > 1$ probability increases with time, suggesting that wear with the passing of time is the main reason behind failure.
- for $\alpha = 2$ (Rayleigh distribution), probability increases linearly with time.

The distribution parameter β is a coefficient characterizing the speed at which reliability disappears. After transformations, it can assume the formula describing the distribution function for the Weibull distribution:

$$F(t) = 1 - \exp\left(-(\beta t)^{\alpha}\right) \tag{2.2}$$

This distribution function is called the function of not survival, failure rate or unreliability function of an object F(t). Unreliability and failure-free operation are opposite events that exclude one another, thus the function of changes in reliability R(t) is described by the relationship:

$$R(t) = 1 - F(t)) \tag{2.3}$$

Transforming Formulas (2.2) and (2.3), the R(t) function describing the course of the process of changes in the performance characteristics in time t can be obtained:

$$R(t) = \exp\left(-(\beta t)^{\alpha}\right) \tag{2.4}$$

The Weibull distribution (for various parameters) creates a class of distributions covering exponential distribution as well as distributions with a monotonously increasing or decreasing function of damage intensity.

Especially important in the practice of assessing goods [26] is exponential distribution. This distribution is a particular example of the Weibull distribution, where the shape parameter $\alpha = 1$. The exponential distribution is applied very often [26-28] to assess the distribution of the time of proper operation, however the exponential model of the reliability distribution does not exist in reality. In the exponential distribution, significant approximations are accepted, assuming the negligible influence of wear processes. A characteristic feature of the exponential distribution is the constant intensity of damage for entire service life of the object. The most frequently applied description of changes in the reliability of technical equipment are relationships based on this distribution. Another specific example of the Weibull distribution, where the shape parameter is α=2, is the Rayleigh distribution [26]. This distribution occurs when the wear of the object with the passing of time is the main reason behind failure. It is the author's opinion that the choice of the Rayleigh distribution for modelling the aging process in buildings seems to be the most accurate. All buildings and their components undergo wear over the course of their use, with the Rayleigh distribution applied in cases when the wear of the building increases along with the passing of time. Literature also shows [26], that the Rayleigh distribution is applied in the case of complex objects to describe the variability of degradation processes of complex objects.

The general form of the function describing the course of changes in the performance characteristics in time t based on the Weibull distribution is expressed by relationship (2.4). In the Rayleigh distribution, parameters α and β are equal to:

$$\alpha = 2,\ \ \beta = \frac{1}{T}. \tag{2.5}$$

Assuming the above, it is suggested that the aging process of a building be determined by the PRRD (Prediction of Reliability according to Rayleigh Distribution) model [29] of changes in the performance characteristics of the i-th building component based on the Rayleigh distribution. The model can be written using the following relationship [29, 30]:

$$R_i(t) = \exp\left(-\left(\frac{t}{T_i}\right)^2\right) \tag{2.6}$$

where:

T_i – signifies the lifespan of element i.

Lifespans of building components are given in literature depending on the type of applied material-structural solution.

A building is made up of many interconnected components. Each component of a building has its function. Components which serve a structural function have the most important influence on the service life. Other auxiliary components influence the performance characteristics of a building to a lesser degree, with their influence resulting, above all, from the fact that damage to auxiliary elements can lead to changes in the parameters of basic components. In indicating the performance characteristics of the entire building, which is a set of components, the intensities of the influence of performance characteristics in the form of A_i weights of individual building components were accounted for [31]. Changes in the performance characteristics of a building $R_B(t)$ in time t are described by the relationship [32]:

$$R_B(t) = \sum_{i=1}^{m} [A_i R_i(t)] \tag{2.7}$$

where:

$R_i(t)$ – changes in the performance characteristics of component *i* in time t according to the PRRD model, A_i – weight of the i-th component, i – number of building component, m – number of all components.

The aging process, described based on the PRRD model, is shown in Figure 1. It was assumed that the building is constructed using traditional technology, the partition walls are masonry, made of solid brick on cement-lime mortar, the roof framework, ceilings and stairs, window frames and doors, as well as floors are all made of pine wood, the roof cover is made of ceramic roof tiles, and the plumbing from galvanized steel. For each of the 25 components, changes in the performance characteristics of the building were indicated in accordance with principle (2.6), and next for the entire building according to (2.7).

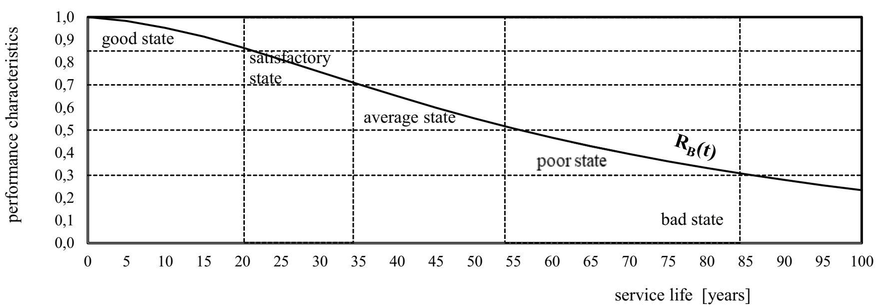

Fig. 1. Changes in performance characteristics of a building described by the PRRD model.

The performance characteristics of such a building decrease over the course of using a building. In the subsequent years or service, the technical condition of the building changes. A good condition changes to a satisfactory condition in the 22nd year of use, and average in the 35th year. A poor condition requires refurbishment to be carried out and begins in year 55, while bad from the 85th year of a building is in use.

The unreliability function F(t) is described by relationship (3). Making use of the assumptions regarding the description of changes in the performance characteristics, the function of the unreliability of component i of building $F_i(t)$ in the PRRD model is expressed by the formula:

(2.8) $$F_i(t) = 1 - \exp\left(-\left(\frac{t}{T_i}\right)^2\right)$$

The unreliability function of building $F_B(t)$ is described by the relationship:

(2.9) $$F_B(t) = \sum_{i=1}^{m}[A_i F_i(t)]$$

where:

F (t) – changes in the unreliability of component i in time t according to the PRRD model, A_i – weight of i-th component, i – number of building component, m – number of all components.

The $R_i(t)$ as well as $F_i(t)$ Functions are a description of the aging process of the i-th component in a building, the $R_B(t)$ and $F_B(t)$ functions show the aging process of the entire building.

3. INTENSITY OF DAMAGE

The reliability function is described by the Wiener Equation [25]:

(3.1) $$R(t) = \exp\left(-\int_0^t \lambda(t)\right)dt$$

Which disambiguates the relationships between reliability and damage intensity λ(t).

Often [e.g. 25, 26], a different definition of the intensity of damage λ(t) is given, described as the speed at which unreliability F(t) increases in relation to reliability R(t):

(3.2) $$\lambda(t) = \frac{dF(t)}{dt}\frac{1}{R(t)}$$

Using the above relationships, a formula describing the intensity of damage $\lambda_i(t)$ for building components according to the PRRD model was derived:

$$\lambda_i(t) = \frac{2t}{T_i^2} \tag{3.3}$$

where:

T_i – lifespan of element i.

In Figures 2-5, functions of the aging process of selected building components are presented.

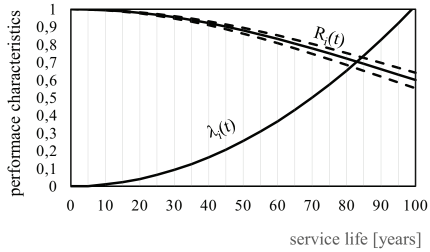

Fig. 2. Changes in the service properties and intensity of damage of masonry walls according to PRRD model.

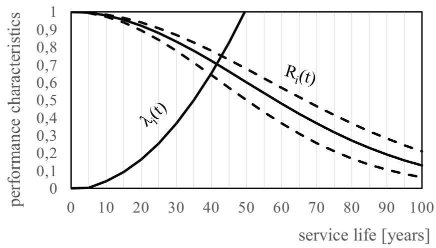

Fig. 3. Changes in the performance characteristics and damage intensity of wood ceilings

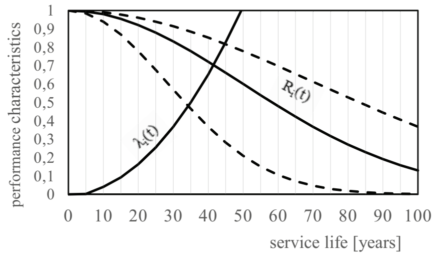

Fig. 4. Changes in the performance characteristics and damage intensity of plain roof tile

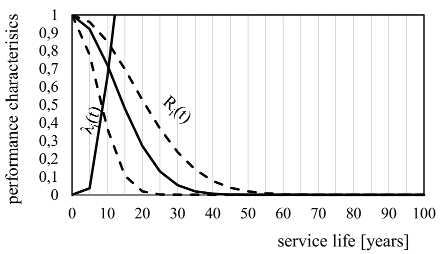

Fig. 5. Changes in the performance characteristics and damage intensity to gutters and downpipes

Using the damage intensity of building components, the damage intensity $\lambda_B(t)$ for the entire building was indicated, accounting for the role and function of each component of the building in the form of A_i weights. Changes in the intensity of damage in a building which had not undergone refurbishment, with given material-structural solutions, such as in pt. 2, are expressed by the relationship:

$$\lambda_B(t) = \sum_{i=1}^{m}[A_i \lambda_i(t)] \tag{3.4}$$

where:

A_i - weight of element i.

Changes in the damage intensity over time t of use for each of the assumed 25 building components were calculated according to Formula (3.4). The next stage was to indicate the intensity of damage for the entire building in time t, assuming the lack of refurbishment works. The results of calculations have been presented in Figure 6.

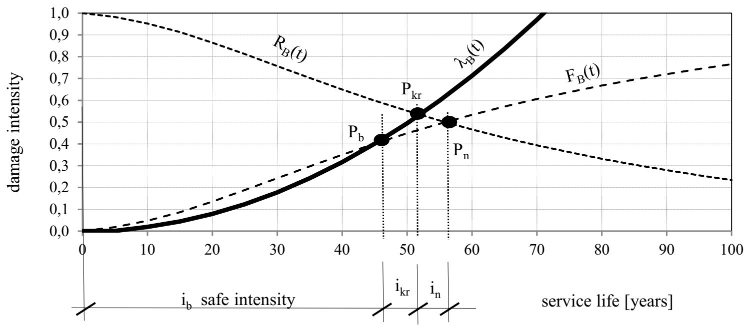

Fig. 6. Changes in the intensity of damage in an unrenovated building

It is assumed that the intensity of damage in a building which had not been refurbished is safe when the values of the intensity of damage in a building $\lambda_B(t)$ are lower than the value of the unreliability of the building $F_B(t)$. Safe intensity falls from the time a building is constructed to a term at point P_b. Point P_b implies the time when the intensity of damage to a building is higher than its unreliability. From the term P_p, the intensity of damage is assumed as critical, which increases constantly and reaches the critical level at term P_{kr}. Point P_{kr} is assumed at a term when the values of the intensities of damage are equal to the values of performance characteristics. In the following years of use, if refurbishment works are not undertaken, the intensity of damage in a building continuously increases. It is assumed that the intensity of damage reaches an unacceptable level from term P_n. Term P_n occurs when changes in the performance characteristics reach lower values than changes in the unreliability of a building. The intensity of damage of a building which had not been refurbished increases continuously over subsequent years of use. The accumulation of damage and its effects make it necessary to carry out refurbishment of the building at a term after crossing P_p.

4. SUMMARY

The presented methodology of describing changes in the intensity of damage, unreliability and performance characteristics over the course of the service life of a building is a diagnostic process of predicting the technical condition of a residential building.

The model of the distribution of the time during which a building operates properly presented as the prognosis of changes in the technical condition can be applied to solve problems occurring in practice.

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LIST OF FIGURES:

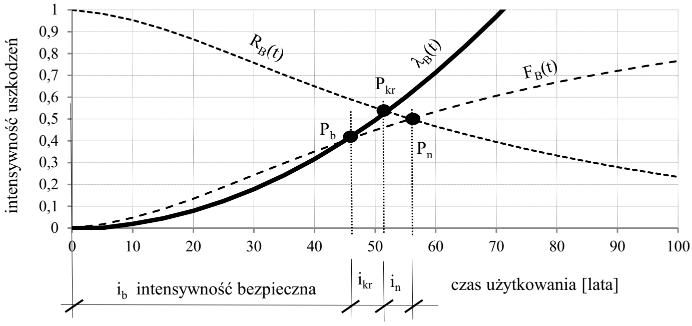
INTENSYWNOŚĆ USZKODZEŃ W PROCESIE STARZENIA BUDYNKÓW

Keywords: stan techniczny, właściwości użytkowe, cykl życia budynku

SUMMARY:

Obiekty budowlane podczas użytkowania podlegają ciągłym procesom destrukcyjnym o zróżnicowanym przebiegu. W miarę upływu czasu następuje obniżanie ich właściwości użytkowych, a częściowe przywrócenie następuje w wyniku napraw. Prognoza procesu starzenia budynków mieszkalnych jest potrzebna do planowania przedsięwzięć remontowych w tych budynkach. Do matematycznego opisu przebiegu procesu niszczenia mogą być stosowane różne metody, między innymi autorski model PRRD (Prediction of Reliability acording to Rayleigh Distribution). Według modelu PRRD można określić prognozy zmian właściwości użytkowych budynku w pełnym okresie jego użytkowania $R_B(t)$ oraz prognozy wzrostu zawodności tego budynku $F_B(t)$. Korzystając z zależności stosowanych w obiektach technicznych opisujących funkcję niezawodności elementów składowych obiektów wzorem Wienera, została wyprowadzona zależność określająca intensywność uszkodzeń $\lambda_i(t)$ dla elementów składowych budynku. Intensywność uszkodzeń $\lambda_B(t)$ dla całego budynku w modelu PRRD uwzględnia rolę i zadanie każdego elementu budynku w postaci wag A_i. Policzone zostały zmiany intensywności uszkodzeń w czasie t użytkowania dla każdego spośród przyjętych 25-u elementów składowych budynku.

Kolejnym etapem było wyznaczenie intensywności uszkodzeń dla całego budynku w czasie t, zakładając brak przedsięwzięć remontowych. Wyniki obliczeń przestawione są na rysunku 1.



Rys. 1. Zmiany intensywności uszkodzeń w budynku nieremontowanym

Intensywność uszkodzeń budynku nieremontowanego jest bezpieczna wtedy, kiedy wartości intensywności uszkodzeń budynku $\lambda_B(t)$ są niższe niż wartości zawodności budynku $F_B(t)$. Intensywność bezpieczna przypada od terminu wybudowania budynku do terminu w punkcie P_b. Punkt P_p oznacza termin, kiedy intensywność uszkodzeń budynku jest większa niż jego zawodność. Od terminu P_p intensywność uszkodzeń przyjmuje się za krytyczną, która stale rośnie i osiąga poziom krytyczny w terminie P_{kr}. Przyjmuje się punkt P_{kr} w terminie, kiedy wartości intensywności uszkodzeń są równe wartościom właściwości użytkowych. W kolejnych latach użytkowania przy braku przedsięwzięć remontowych intensywność uszkodzeń budynku stale rośnie. Przyjmuje się, że intensywność uszkodzeń osiąga poziom niedopuszczalny od terminu P_n. Termin P_n występuje wtedy, kiedy zmiany właściwości użytkowych osiągają niższe wartości niż zmiany zawodności budynku. Intensywność uszkodzeń budynku nieremontowanego stale rośnie podczas kolejnych lat użytkowania. Kumulacja uszkodzeń i ich skutki wymuszają wykonanie remontu budynku w terminie po przekroczeniu P_p.

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