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Juocevičius [1] V., Kudzys [2] A.

[1] Department of Reinforced Concrete Structures,
Vilnius Gediminas Technical University,
Sauletekio 11, Vilnius,
E-mail: virgaudas.juocevicius@constructus.lt
[2] Institute of Architecture and Construction of
Kaunas University of Technology,
Tunelio 60, LT-44405, Kaunas, Lithuania.
E-mail: asi@asi.lt

ON TIME-DEPENDENT RELIABILITY OF SUSTAINABLE STRUCTURES

Peculiarities of sustainable reliability predictions for load-carrying structures of buildings, construction and civil engineering works are discussed. The quantitative probabilistic parameters of the structural safety and durability of members and their systems are formulated and applied. A new strategy for probability-based quality predictions of sustainable structures is presented. The safety prediction is meant for particular members (sections, connections) exposed to action effects. Contrary to this prediction, the durability issues for whole structural members (slabs, beams, columns, walls) as auto-systems representing their multi-criteria failure mode are considered. The methods of conventional resistance and transformed conditional probability design in practical calculations of reliability parameters of sustainable structures and works are presented. It is recommended to calibrate the target reliability index of sustainable structures considering not only the consequences of failure of the members but also their functional working classes.

Introduction. Coating materials may effectively slow down steel or concrete corrosion and wood purefaction processes, but they cannot be acknowledged as everlasting protective measures for structures exposed to aggressive environmental conditions. Besides, these materials cannot preserve the structure form degradation due to mechanical injuries caused by wind storms, avalanches and earthquake motions. Therefore, the design on durability of structures is indispensable in up-to-date sustainable construction.

Irrational structural solutions and unexpected damages or accidents are categorically inadmissible for sustainable buildings. Dangerous failures may be caused not only by irresponsibility of designers and builders, but also due to the absence of perfectly and fully formulated recommendations and directions presented in design and construction codes. Traditionally, the structural design of buildings and works is based on their performance, safety and cost factors. However, it is more expedient to base sustainable structural engineering on new models including the integrated life cycle design [1].

Design codes must help engineers to found and construct rational structures requiring small quantities of resources and being distinguished by excellent technical and economical properties. However, many structural engineers and researchers doubt the durability of deteriorating structures and works designed by the available deterministic methods of partial safety factors (in Europe) or load and resistance factor (in the USA and other countries). Shortcomings of the deterministic methods are obvious since it is inadmissible to disregard changes in probability distributions of member resistances and action effects during the design working life of structures.

A wide range of applied durability issues of deteriorating steel, concrete and wood structures can be neither formulated nor solved by the deterministic analysis methods. Only probabilistic approaches allow us to assess all uncertainties caused by inherent random variabilities, insufficient data and/or impressive knowledge of structural performance parameters. The probabilistic parameters obtained enable us to make an easier and more accurate assessment and selection of optimal concepts and economical decisions of buildings.

Ravesloot et al. [2] defined the sustainability of buildings as the creation of technology that ensures the same environmental quality for future generations. However, it may be translated into practice using the sustainable reliability prediction of structures. The sustainable structural design of buildings may be better apprehensible when the strategies for structural reliability prediction are formulated and applied. The sustainable durability prediction of structures must consider all extreme situations which are likely to occur during both pre-use and use (service) lives. Besides, the time-dependent quality of structures may be closely defined only by quantitative durability parameters using available probabilistic approaches, concepts and methods [3, 4, 5].

In spite of rather developed modern concepts, approaches and methods of reliability, hazard and risk theories, it is difficult to implement the probability-based methods in design practice. It may be explained by the absence of unsophisticated and rather easily apprehensible recommendations and computational algorithms in the sustainable durability prediction of structures. The intention of this paper is to recommend some new strategies and methodological approaches on the probabilistic integrated safety and durability prediction in sustainable structural design practice.

Safety margin process of members. Particular members as starting design objects of load-carrying structures are physically impalpable (cross-) sections and butts. Dangerous stresses of particular members are caused by permanent g, sustained $q_1(t)$ and extraordinary $q_2(t)$ live, snow $s(t)$ and wind $w(t)$ loads and other actions. All service loads which do not belong to sustained actions may be treated as extraordinary live load components. An overloading of members during severe service and climate actions may provoke a failure of structures. Therefore, the requirements of design codes should be satisfied at all sections along structural members (beams, slabs, columns).

According to Rosowsky and Ellingwood [6], the annual extreme sum of sustained and extraordinary occupancy live action effects $S_q(t) = S_{q_1}(t) + S_{q_2}(t)$ can be modeled as an intermittent process and described by a Type 1 (Gumbel) distribution with the coefficient of variation $\boldsymbol{\delta} S_q = 0.58$, characteristic S_{qk} and mean $S_{qm} = 0.47 S_{qk}$ values.

It is proposed to model the annual extreme climate (wind and snow) action effects by Gumbel distribution law with the mean values equal to $S_{wm} = S_{wk} / \left(1 + k_{0.98} \boldsymbol{\delta} S_w\right)$ and $S_{sm} = S_{sk} / \left(1 + k_{0.98} \boldsymbol{\delta} S_s\right)$ [4, 7, 8, 9, 10, 11]. The coefficients of variation of wind and snow loads depending on the feature of a geographical area are equal to $\boldsymbol{\delta} w = 0.2 - 0.4$ and $\boldsymbol{\delta} s = 0.3 - 0.7$. Presented data allow us to model extreme service and climate action effects as intermittent rectangular wave renewal processes. These time-variant intermittentaction effects belong to persistent design situations in spite of the short period of extreme events being much shorter than the design working life of structures.

According to probability-based approaches (design level III), the time-dependent safety margin as the performance of deteriorating particular members may be presented as follows:

$$Z(t) = g[\boldsymbol{\theta}, \mathbf{X}(t)] = \theta_R R(t) - \theta_g S_g - \theta_{q_1} S_{q_1}(t) - \theta_{q_2} S_{q_2}(t) - \theta_w S_w(t) \tag{1}$$

where $\boldsymbol{\theta}$ is the vector of additional variables characterizing uncertainties of models which give the values of resistance R, permanent S_g, sustained S_{q_1} and extraordinary S_{q_2} service or snow and extreme wind S_w action effects of members (Fig. 1, a). This vector may represent also the uncertainties of probability distributions of basic variables.

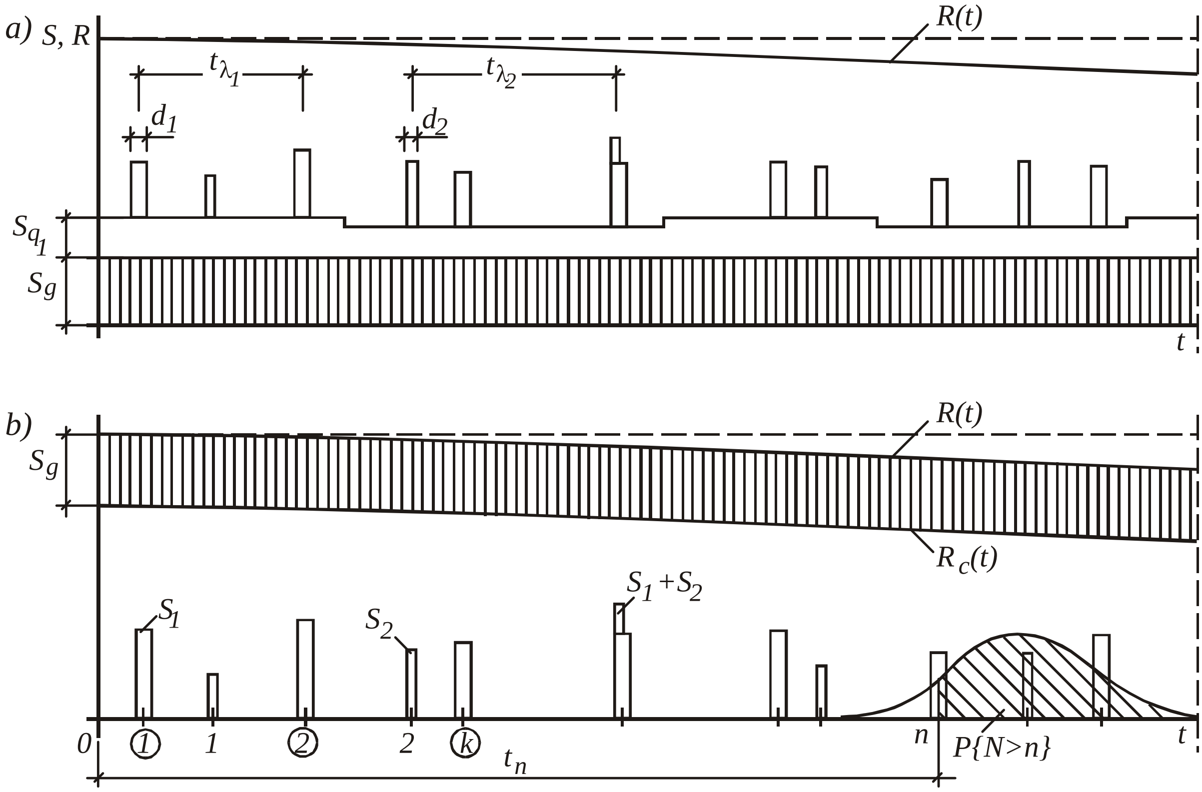

Fig. 1. Real (a) and conventional (b) models for safety analysis of particular members (sections) of deteriorating structure

Probability distributions of material properties are close to a Gaussian distribution [4, 7, 8, 12]. Therefore, a normal distribution or a log-normal distribution may be convenient in resistance analysis models [4, 9, 13, 14]. The permanent action effect S_g can be described by a normal distribution law [4, 8, 11, 13, 15]. Thus, for the sake of design simplifications, it is expedient to present the expression (1) in the form:

$$Z(t) = R_c(t) - S(t) \tag{2}$$

where the component process

$$R_c(t) = \theta_R R(t) - \theta_g S_g \tag{3}$$

may be considered as the conventional resistance of members which may be modeled by a normal distribution;

$$S(t) = \theta_q S_q(t) + [\theta_w S_w(t)] \tag{4}$$

$$S(t) = \theta_s S_s(t) + [\theta_w S_w(t)] \tag{5}$$

are the joint processes of two annual extreme action effects when floor and roof structures, respectively, are under consideration. The components in square brackets belonging to the wind action effect are used in design analysis of redundant systems. The action effect $S_s(t)$ in Equation (5) is caused by extreme snow loads.

Survival probability of particular members. It is expedient to divide the service life cycle of deteriorating particular members into the initiation, t_{in}, and propogation, t_{pr}, periods of time [9]. The member resistance process is:

$$R(t) = \eta_{l.d} R_{in} \varphi(t) \tag{6}$$

where R_{in} is its resistance at the initiation period the value of which may be revised using data of extreme execution loads and engineering (site) inspection measures [16]; $\eta_{l.d} = R_{in,l.d} / R_{in}$ is the factor of latent defects; $\varphi(t)$ is the resistance degradation function [17].

When variable action effects may be treated as rectangular renewal pulse processes, the time-dependent safety margin (2) may be expressed as the finite rank random sequence as follows:

$$Z_k = R_{ck} - S_k, \; k = 1, \; 2, \; ..., \; n-1, \; n \tag{7}$$

There

$$R_{ck} = \theta_R R_k - \theta_g S_g \tag{8}$$

$$S_k = \theta_q S_{qk} + \theta_w S_{wk} \text{ or } S_k = \theta_s S_{sk} + \theta_w S_{wk} \tag{9}$$

are the resistance and action effect of members at *k*-th cut of this sequence; 2 is the number of sequence cuts as critical events (situations) during design working life, t_n, of members (Fig. 1), where $\lambda = 1/t_\lambda$ is a mean renewal rate of these events per unit time when their return period is t_λ.

In design practice it is expedient to use the conventional bivarite distribution function of two independent extreme action effects. The mean and variance of this function may be respectively calculated by the formulae:

$$S_{km} = \theta_{1m} S_{1km} + \theta_{2m} S_{2km} \tag{10}$$

$$\boldsymbol{\sigma}^2 S_k = \theta_{1m}^2 \boldsymbol{\sigma}^2 S_{1k} + S_{1km}^2 \boldsymbol{\sigma}^2 \theta_1 + \theta_{2m}^2 \sigma^2 S_{2k} + S_{2km}^2 \sigma^2 \theta_2 \tag{11}$$

When R_{ck} and S_k are statistically independent, the instantaneous survival probability of the member at *k*-th extreme event, assuming that it was safe at the events 1, 2, …, $k-1$, is:

$$\boldsymbol{P}_k = \boldsymbol{P}\{R_{ck} > S_k\} = \int_0^\infty f_{R_{ck}}(x) \; F_{S_k}(x) \; dx \tag{12}$$

where $f_{R_{ck}}(x)$ and $F_{S_k}(x)$ are the density and cumulative distribution functions of R_{ck} by (8) and S_k by (9), respectively.

The cuts of random sequences of safety margins of members must be considered statistically dependent. The time-dependent survival probability of members may be calculated by Monte Carlo simulation and the numerical integration methods. However, it is more reasonable to use the method of transformed conditional probabilities. When the resistance is a non-stationary process, the partial survival probability of members may be written in the form:

$$P_i = P\left\{\bigcap_{k=1}^{2} (Z_k > 0)\right\} = \prod_{k=1}^{2} P_k \left[1 + \rho_{21}^{x_2}\left(\frac{1}{P_1} - 1\right)\right] \times ...... \times \left[1 + \rho_{k,k-1...1}^{x_k}\left(\frac{1}{P(Z_1 > 0 \cap ... \cap Z_{k-1} > 0)} - 1\right)\right] \times ...$$
$$... \times \left[1 + \rho_{n,n-1...1}^{x_n}\left(\frac{1}{P(Z_1 > 0 \cap ... \cap Z_{n-1} > 0)} - 1\right)\right] \tag{13}$$

where $\boldsymbol{P}_k$ is the instantaneous survival probability by (12); $\rho_{kl} = Cov(Z_k, Z_l)/(\boldsymbol{\sigma} Z_k \times \boldsymbol{\sigma} Z_l)$ is the factor of auto-correlation of rank sequence cuts the transformed value of which is $\rho_{k,k-1...1} = (\rho_{k,k-1} + ... + \rho_{k1})/(k-1)$; $Cov(Z_k, Z_l)$ and $\boldsymbol{\sigma} Z_k$, $\boldsymbol{\sigma} Z_l$ are the auto-covariance and standard deviations of these cuts;

$$X_k = P_k\left[4.5/\left(1-0.98\rho_{k,k-1...1}^{1/3\rho}\right)\right]^{1/2} \tag{14}$$

is the bond index of this factor.

When the member resistance may be treated as a stationary process, the expression (13) obtains the following form:

$$\boldsymbol{P}_i = \boldsymbol{P}\left\{\bigcap_{k=1}^{n}(Z_k > 0)\right\} = \boldsymbol{P}_k^n\left[1+\rho_{kl}^3\left(\frac{1}{\boldsymbol{P}_k - 1}\right)\right]^{n-1} \tag{15}$$

Survival probability of structural members. Contrary to the traditional structural safety analysis, time-dependent safety prediction issues should be considered not for particular members (sections, connections), but for structural members (slabs, beams, columns, walls) as auto-systems representing their multi-criteria failure mode due to various actions and responses of their components (Fig. 2).

Foundation piles may lose their bearing capacity like geotechnical supports or compression columns (Fig. 2, a). Only reaching the limit states in both bars of two-bar hangers means the failure of auto-systems (Fig. 2, b). Continuous beams have two normal and one oblique design sections as particular members representing the mixed auto-systems (Fig. 2, c).

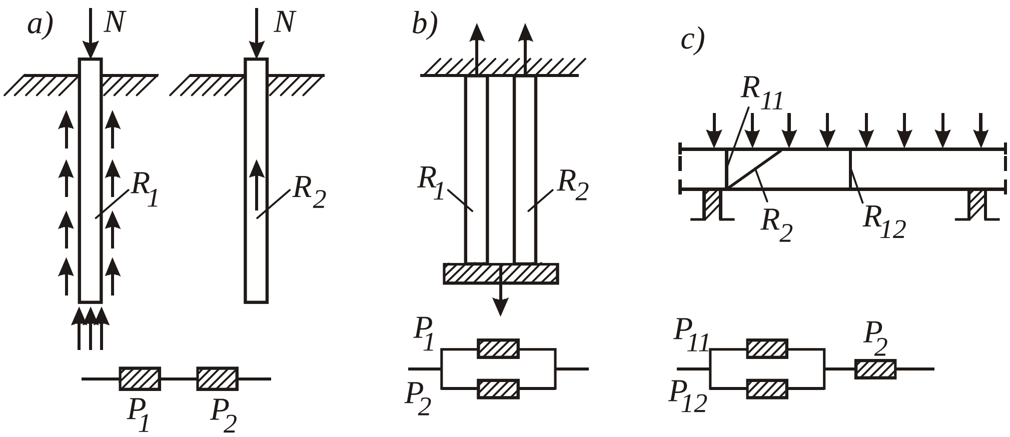

Fig. 2. Structural auto-systems: a) single pile, b) two-bar hanger, c) continuous beam

According to the method of transformed conditional probabilities, the total survival probability of structural members as series, parallel and mixed systems (Fig. 2) may be respectively calculated by the Equations:

$$\boldsymbol{P}_{ser} = \boldsymbol{P}\{Z_1 > 0 \cap Z_2 > 0\} = \boldsymbol{P}_1\boldsymbol{P}_2\left[1+\rho_{12}\left(\frac{1}{\boldsymbol{P}_{1/2}}-1\right)\right] \tag{16}$$

$$\boldsymbol{P}_{par} = \boldsymbol{P}\{Z_1 > 0 \cup Z_2 > 0\} = \boldsymbol{P}_1 + \boldsymbol{P}_2 - \boldsymbol{P}_1\boldsymbol{P}_2\left[1+\rho_{12}\left(\frac{1}{\boldsymbol{P}_{1/2}}-1\right)\right] \tag{17}$$

$$\boldsymbol{P}_{mix} = \boldsymbol{P}\{(Z_1 > 0 \cup Z_2 > 0) \cap Z_3 > 0\} = P_{par}P_3\left[1+\rho_{3,21}\left(\frac{1}{P_{3/par}}-1\right)\right] \tag{18}$$

where $\boldsymbol{P}_{1/2}$ and $\boldsymbol{P}_{3/par}$ are the greater value from the probabilities $\boldsymbol{P}_1$, $\boldsymbol{P}_2$ and $\boldsymbol{P}_3$, $\boldsymbol{P}_{par}$; $\rho_{3,21} = (\rho_{32} + \rho_{31})/2$ is the transformed coefficient of correlation.

According to the concept of performance service period [18], not only the performance, but also the survival probability value of particular members are time dependent random variables. In this case, a probabilistic design of structural auto-systems on sustainable safety and durability are, to a large extent, similar.

According to international design codes and standards, the reliability differention of structures is based on their consequences classes (CC) by considering the human life, economic, social and environmental consequences of failure or malfunction. The reliability classes RC1, RC2 and RC3 are associated with three consequences classes CC1, CC2 and CC3. However, the methodology of sustainable durability predictionrequires to take into account repair and replacement abilities of structural members. Therefore, the three functional working classes FC1, FC2 and FC3 of members must be considered. The functional working life t_f of structures is the time at which they can still be suitable for service with repair and/or adaptations [19]. Easily repairable or replaceable members belong to the class FC1. The members of the class FC2 require a great deal of effort in erection, repair and replacement technologies. Irreparable members can be ascribed to the class FC3 the durability requirement and relevant target reliability index for which must be the highest (Fig. 3).

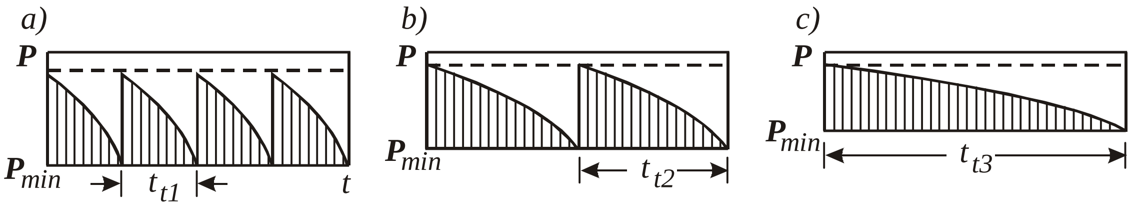

Fig. 3. Models for durability design of members the functional working classes of which are FC1 (a), FC2 (b) and FC3 (c)

Table I

Target reliability index $\beta_{\min}$ of structural members for a 50-year reference period

Consequences class	Functional working class		
	FC1	FC2	FC3
CC1	3.1	3.3	3.8
CC2	3.3	3.8	4.3
CC3	3.8	4.3	4.7

The target reliability index $\beta_{\min}$, as basis in sustainable durability and safety predictions, must be related to the consequences and functional working classes of structural members (Table 1). The values presented in the Eurocode EN 1990 [13] correspond to the members of the functional working class FC2. It is expedient to correct these directions. Besides, the index $\beta_{\min}$ may be reduced for existing or overloaded structures under construction since premature failures cannot be any longer caused by rough human design and construction errors. The comparison of members with different technical service lives allows designers to achieve a higher quality and economy of structures.

Conclusions. The time-dependent reliability prediction, as one of the main design tasks in structural engineering, is indispensable in order to guarantee time-dependent performance of structures and works. The strategy of this prediction should be based on the concepts of the integrated safety prediction of particular members (sections, connections) and the total survival probability prediction of structural members (slabs, beams, columns, walls) as auto-systems representing their multicriteria failure mode. For the sake of simplifications of probabilistic time-dependent safety analysis of particular members exposed to extreme action effects, it is recommended to use their conventional resistances and safety margin sequences with correlated cuts. The partial and total time-dependent survival probabilities of members may be calculated by the unsophisticated method of transformed conditional probabilities.

The probability-based methodology represents quite a realistic way to reveal the sustainability of members and their technical service life as the main durability parameter of deteriorating sustainable structures. The presented methodology of design on time-dependent reliability helps engineers to determine rational structural solutions and balancing reliability of sustainable structures fulfilling recommendations of design codes and standards. The target reliability indices of sustainable structures must be calibrated taking into account not only their consequences but also functional working classes.

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