Chapter 24
On Stochastic Method for Scale-Structural Failure Estimating and Structure Durability at Safety Operational Loading

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Abstract This work is devoted to the problem of creation of reliability criterion taking into account technogenic and anthropogenic factors in relation to the assessment of pipeline operation safety. There are proposed relations for the function of the structure failure probability through the failure probability of its similar structural elements. The structural element durability is found taking into account the results of the analysis of the probability of metal failure at a certain level of accumulated defects. Assuming that the failure probability should not exceed its acceptable value (the criterion of structural reliability), the relation for finding the structure life is written. The classification of damaging factors at destruction of structural elements of product pipelines has been carried out. The ratios for social, industrial and environmental risks used in the calculation practice are given. The acceptable values of risks are considered. A safe operation criterion in the form of an inequality is proposed, in which the structural risk does not exceed an acceptable value, multiplied by a coefficient determined by the calculated and acceptable values of industrial, social and environmental risks. The criterion is a theoretical generalization of the known relationships used in design practice of investment projects on the construction and operation of various structures of product pipelines.

Keywords Structural reliability · Safe operation · Failure probability

24.1 Introduction

The purpose of this study is to develop the experimental and theoretical foundations of the stochastic method for assessing of longevity and diagnostic periods of the technical conditions of various long structures whose elements are at the internal pressure of the pumped product, the action of mass forces, temperature field and natural-climatic and technogenic influences. The methodological basis for the

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G. Lesiuk et al. (eds.), *Structural Integrity and Fatigue Failure Analysis*, Structural Integrity 25, https://doi.org/10.1007/978-3-030-91847-7_24

proposed method of durability estimation is the works of scientists on the fundamental scientific problem of the technogenic safety of structure operation [1–5]. Here are considered three main technogenic spheres such as people, constructions and the environment, and, accordingly, are introduced the concepts of technogenic and anthropogenesis risks, namely the probability of injury to people (the social risk), the probability of destruction of industrial objects (the industrial risk) and the probability of flora and fauna destruction (the ecological risk) located in a potentially dangerous zone near the structure at destruction. The modern problems of safety estimation are to formulate the criteria of structural reliability, to study of the probabilities of the appearance and spread of injury factors at the structure destruction, to estimate of technogenic and anthropogenesis risks based on the operation data, to establish the acceptable risks, to develop of numerical modeling for durability and residual life finding taking into account the risks, to create of longevity management methods and to calculate of potential economic damage at the construction and operation.

The nature of the change in operating loads, a significant heterogeneity of the mechanical characteristics of materials, a variation in design technological factors, as well as the need to take into account of technological and operational defects, leads to need to use the probabilistic methods for estimation of the durability and crack resistance of structural elements. The probabilistic parameters of material properties (characteristics of crack opening, Woehler curve, Coffin-Manson equation and Paris relation, yield stress, etc.) are entered in the durability calculation, and random stationary loading processes are considered.

One of the main modern directions is the creation of algorithms for predicting the residual life of structural elements based on the established patterns of failure processes at the micro-, meso- and macro-levels.

24.2 The Criterion of Structural Reliability

Here is introduced the function $Q = Q(\tau), 0 \le Q \le 1, \quad \tau \in [0, t]$ is determined as a probability of structure failure (the structural risk) at a time τ.

Structures such as product pipelines are divided into sections according to the functional and design principle: linear sections with branches and looping, crossings over natural and artificial obstacles (roads, railways, air crossings over water obstacles, ravines, underwater crossings, etc.), connection nodes of other structures, construction of gas and oil metering stations, gas recovery units, units of starting and receiving of cleaning devices, design of head and intermediate pumping stations, etc. So there is considered the probability $Q_k = Q_k(\tau)$ of k-section failure, $k = 1, \ldots K$. The sections consist of a large number of similar q-elements $n_{k,q}, q = 1, \ldots \mathbb{Q}$, of the same type (base metal, longitudinal and ring welded joints, tee connection, diversion, adapter, bottom) for which the probability $Q_{k,q} = Q_{k,q}(\tau)$ of q-element k-section failure is introduced. It is assumed that the failure probability $Q = Q(\tau)$ is determined through the failure probabilities $Q_k = Q_k(\tau)$ of k-section failure according as follows:

$$\text{optimistic scenario } Q(\tau) = \sum_{k=1}^{K} \left(\frac{Q_k(\tau)}{1 - Q_k(\tau)} \right) \prod_{k=1}^{K} [1 - Q_k(\tau)] \tag{24.1}$$

$$\text{pessimistic scenario } Q(\tau) = 1 - \prod_{k=1}^{K} [1 - Q_k(\tau)] \tag{24.2}$$

Relation (24.1) determines the sum of independent events, namely k-section failure in the absence of the remaining section failure, relation (24.2) is the sum of independent events at least of k-section failure. Analogically we have the following:

$$\text{optimistic scenario } Q_k(\tau) = \sum_{q=1}^{\mathbb{Q}} \left(\frac{Q_{k,q}(\tau)}{1 - Q_{k,q}(\tau)} \right) \prod_{q=1}^{\mathbb{Q}} \left[1 - Q_{k,q}(\tau)\right] \tag{24.3}$$

$$\text{pessimistic scenario } Q_k(\tau) = 1 - \prod_{q=1}^{\mathbb{Q}} \left[1 - Q_{k,q}(\tau)\right] \tag{24.4}$$

Let k-section consists of $n_{k,q} q$-elements of linear dimensions l_q, $q = 1, \ldots \mathbb{Q}$, with life $t_{f,k,q}$. It is proposed to describe the probability $Q_{k,q} = Q_{k,q}(\tau)$ by a function of the Poisson distribution type on the first failure of q-element:

$$\begin{aligned} Q_{k,q}(\tau) = \varphi_{k,q}(\tau) e^{1-\varphi_{k,q}(\tau)}, \quad & \varphi_{k,q}(\tau) \\ & = \lambda_q l_q n_{k,q} \frac{\tilde{t}}{t_{f,k,q}} \tau, \; q = 1, \ldots \mathbb{Q}, \; k = 1, \ldots K. \end{aligned} \tag{24.5}$$

In the relation (24.5) a parameter $\tilde{t}$ is the economically and socially acceptable structure life, assigned by the design standards. For example, it lies within 35–45 years for main pipelines, 60–65 years for tie pipelines, 15–20 years for field pipelines. Parameter λ_q is the intensity of the q-element failure flow, namely the number of q-element failure per unit of time (year) and per unit of length (km), known from the statistics of destruction at operation of similar structures in similar natural and climatic conditions. For tee connections, the number of failures per unit time attributed to the total number of elements is considered as λ_q, and relation (24.5) does not include the value l_q.

Relation (24.5) includes the durability of q-element k-section $t_{f,k,q}$, which is determined using a stochastic model of scale-structural fatigue [6–8]. The durability at operation loading is described by random processes taking into account the potential stochastic element failure, random mechanical loading, random environmental influences, etc. Therefore, a stochastic approach and methods of the theory of random processes and statistical analysis are chosen. As a toolkit for numerical experiments and solving practical problems, finite element methods of the ANSYS are used. There is proposed a stochastic method of safe operation assessing on the basis of a system of safe operation criteria for long structures, taking into account the determination of the structural element life using a stochastic model of fatigue scale-structural failure [9–12]. The model predicts the probability that a certain function of the structure, depending on the density and size of multilevel defects, reaches the limiting values during loading. The basic experiments for identifying of material functions are based on the standard tests of materials for long-term and fatigue strength.

The criterion of structural reliability is formulated as follows:

$$Q(\tau) \le \tilde{Q}, \tag{24.6}$$

on condition $t_{f,k,q} \ge \tilde{t}, \ \ k = 1, \dots K, \ \ q = 1, \dots \mathbb{Q}$, the probability $Q = Q(\tau)$ is determined by (24.1)–(24.5), $\tilde{Q}$ is acceptable structural risk according to design standards. The structure life is determined by the equation:

$$Q\left(t_f\right) = \tilde{Q} \tag{24.7}$$

The probability of failure $Q_R = Q_R(\tau)$, $t_R \le \tau$ (t_R is the total time of all R standard diagnostics), after carrying out R diagnostics and replacing structural elements with unacceptable defects is determined through the function of the probability $Q_{k,R} = Q_{k,R}(\tau)$ for k-section is expressed through functions (24.1), (24.2) as follows:

$$\text{optimistic scenario} \ \ Q_R(\tau) = \sum_{k=1}^{K} \left(\frac{Q_{k,R}(\tau)}{1 - Q_{k,R}(\tau)} \right) \prod_{k=1}^{K} \left[1 - Q_{k,R}(\tau) \right] \tag{24.8}$$

$$\text{pessimistic scenario} \ \ Q_R(\tau) = 1 - \prod_{k=1}^{K} \left[1 - Q_{k,R}(\tau) \right] \tag{24.9}$$

Correspondingly for $Q_{k,R} = Q_{k,R}(\tau)$ here can be written the following:

$$\text{optimistic scenario} \ \ Q_{k,R}(\tau) = \sum_{r=1}^{R} \left(\frac{Q_{k,r}(\tau)}{1 - Q_{k,r}(\tau)} \right) \prod_{r=1}^{R} \left[1 - Q_{k,r}(\tau) \right] \tag{24.10}$$

$$\text{pessimistic scenario} \ \ Q_{k,R}(\tau) = 1 - \prod_{r=1}^{R} \left[1 - Q_{k,r}(\tau) \right] \tag{24.11}$$

where the probability of k-section failure revealed during r-diagnostics $Q_{k,r} = Q_{k,r}(\tau)$ is expressed through the probability of q-element k-section failure revealed during r-diagnostics $Q_{k,r,q} = Q_{k,r,q}(\tau)$ in the form:

$$\text{optimistic scenario}\quad Q_{k,r}(\tau) = \sum_{q=1}^{\mathbb{Q}} \left(\frac{Q_{k,r,q}(\tau)}{1 - Q_{k,r,q}(\tau)} \right) \prod_{q=1}^{\mathbb{Q}} \left[1 - Q_{k,r,q}(\tau) \right] \tag{24.12}$$

$$\text{pessimistic scenario}\quad Q_{\kappa,r}(\tau) = 1 - \prod_{q=1}^{\mathbb{Q}} \left[1 - Q_{k,r,q}(\tau) \right] \tag{24.13}$$

The failure probability $Q_{k,r,q} = Q_{k,r,q}(\tau)$ for q-element of k-section on all defects detected by r-diagnostics, $1 \le r \le R$, is set through $Q_{k,r,q,j} = Q_{k,r,q,j}(\tau)$ as follows:

$$\text{optimistic scenario}\quad Q_{k,r,q}(\tau) = \sum_{j=1}^{J} \left(\frac{Q_{k,r,q,j}(\tau)}{1 - Q_{k,r,q,j}(\tau)} \right) \prod_{j=1}^{J} \left[1 - Q_{k,r,q,j}(\tau) \right] \tag{24.14}$$

$$\text{pessimistic scenario}\quad Q_{\kappa,r,q}(\tau) = 1 - \prod_{j=1}^{J} \left[1 - Q_{k,r,q,j}(\tau) \right] \tag{24.15}$$

The probability $Q_{k,r,q,j} = Q_{k,r,q,j}(\tau)$ of failure of $n_{k,q}q$ element k-section due to defects of j-type, $j = 1, \ldots J$, revealed by r-diagnostics, $r = 1, \ldots R$, is determined by the following relations:

$$\begin{aligned} Q_{k,r,q,j}(\tau) &= \varphi(\tau) e^{1-\varphi(\tau)}, \quad \varphi(\tau) \\ &= \lambda_{r,q,j} l_q n_{k,q} \frac{\tilde{t}}{\Delta t_{f,k,q,j}} \tau, \quad q = 1, \ldots \mathbb{Q}, \quad k = 1, \ldots K. \end{aligned} \tag{24.16}$$

In (24.8) l_q is the linear size of q-element, $\lambda_{r,q,j}$ are the coefficients of failure flow, i.e., the number of q-element failure on a defect of j-type, revealed by r-diagnostics or known from the failure statistics of failure (in this case $r = 1$) per unit of time (year) per unit of length (km), $\Delta t_{f,k,q,j}$ is the residual life of q-element of k-section on j-failure.

The criterion of structural reliability for structure after regulatory R diagnostics and replacing structural elements with unacceptable defects is also determined by (24.6) as follows:

$$Q_R(\tau) \le \tilde{Q}, \tag{24.17}$$

where $Q_R = Q_R(\tau)$ is the structural risk of k-section in the loading interval $[t_R, t]$ according (24.8)–(24.16), $\tilde{Q}$ is acceptable structural risk according to design standards.

Finally the residual life after regulatory diagnostics and replacing structural elements with unacceptable defects is determined from the Eq. (24.7) on the equation:

$$Q_R\left(\Delta t_f\right) = \tilde{Q} \tag{24.18}$$

24.3 The Safe Operation Criterion

Based on the analysis of literature and regulatory documents, the following main negative factors of damage from pipeline destruction are identified: toxic effects from the outflow of pumping toxic liquids and gases ($i = 1$); thermal effect from ignition of a gas jet flowing out from a through crack ($i = 2$); thermal effect when a cloud of gas-air mixture ignites ($i = 3$); shock air waves from gas and gas combustion product expansion ($i = 4$); defeat from the scattering of destroyed structure fragments ($i = 5$). These factors arise with a probabilities J_i, $i = 1, ...5$, accordingly, which are determined by the regulatory statistics of the appearance of negative factors at destructions of similar structures.

Here are considered the known notions of the social risk $I_1 = I_1(\tau),\ \ 0 \le I_1 \le 1,\ \tau \in [0, t]$ (the probability of injury to people, located in a potentially dangerous zone near the failure structure), the industrial risk, $I_2 = I_2(\tau),\ 0 \le I_2 \le 1,\ \tau \in [0, t]$ (the probability of destruction of industrial objects) and the ecological risk $I_3 = I_3(\tau),\ \ I_4 = I_4(\tau)\ \ 0 \le I_3 \le 1,\ \ 0 \le I_4 \le 1,\ \ \tau \in [0, t]$ (the probability of flora and fauna destruction accordingly) located in a potentially dangerous zone near the structure at destruction. Standards for structures determine the acceptable values of social, industrial and environmental risks $\tilde{I}_m,\ \ m = 1, \dots 4,\ m = 1, ...4,$ during the acceptable life $\tilde{t}$.

According to the developed approach [6–9] the safe operation criterion into account social, industrial and environmental risks according during the structure operation

$$Q(\tau)\mathrm{I}_m(\tau) \le \tilde{Q}\tilde{\mathrm{I}}_m, \quad m = 1, \dots 4, \tag{24.19}$$

$$\text{optimistic scenario}\ \ I_m = \sum_{i=1}^{5}\left(\frac{J_i I_{m,i}}{1 - J_i I_{m,i}}\right)\prod_{i=1}^{5}\left[1 - J_i I_{m,i}\right], \tag{24.20}$$

$$\text{pessimistic scenario}\ \ I_m = 1 - \prod_{i=1}^{5}\left[1 - J_i I_{m,i}\right], \tag{24.21}$$

$$I_{m,i} = \max\left\{\int_0^R \int_0^{2\pi} \rho_m(r,\theta) I_i(r,\theta,\tau) r \mathrm{d}r \mathrm{d}\theta :\ \ 0 \le \tau \le t_i\right\}, \quad m = 2, 3, \tag{24.22}$$

$$I_{m,i} = \max\left\{\int_0^R \int_0^{2\pi} \rho_m(r,\theta,\xi) I_i(r,\theta,\tau) r \mathrm{d}r \mathrm{d}\theta :\ 0 \le \xi \le t_p;\ 0 \le \tau \le t_i\right\}, \quad m = 1, 4, \tag{24.23}$$

$$I_1(r,\theta,\tau) = a_1 * \ln\left\{\left(\frac{D(r,\theta,\tau)}{D_1}\right)^2 \frac{\tau}{t_1}\right\}, \quad 0 \le \tau \le t_1, a_1, D_1 = \text{const}, \tag{24.24}$$

$$I_2(r,\tau) = a_2 * \ln\left\{\left(\frac{q(r,\tau)}{q_2}\right)^{4/3} \frac{\tau}{t_2}\right\}, \quad 0 \le \tau \le t_2, a_2, q_2 = \text{const}, \tag{24.25}$$

$$I_3(r,\tau) = a_3 * \ln\left\{\left(\frac{q(r,\tau)}{q_3}\right)^{4/3} \frac{\tau}{t_3}\right\}, \quad 0 \le \tau \le t_3, a_3, q_3 = \text{const}, \tag{24.26}$$

$$I_4(r,\tau) = a_4 * \ln\left(\left(\frac{p_0}{p(r,\tau)}\right)^{\alpha} + \left(\frac{I_0}{I(r,\tau)}\right)^{\beta}\right),$$
$$0 \le \tau \le t_4, a_4, p_0, I_0, \alpha, \beta = \text{const}, \tag{24.27}$$

$$I_5(r) = a_5 + b_5\left(\frac{mv(r,\tau)^2}{I_0}\right), \quad 0 \le \tau \le t_5, a_5, b_5, I_0 = \text{const}, \tag{24.28}$$

where (r, θ) is the polar coordinate system centered at the point of $i-$negative factor origin, $\rho_m = \rho_m(r, \theta, t)$ is the distribution function of people, objects, flora and fauna density in the zone $[0, R]$ depending on time, R is the radius of $i-$negative factor action, t_1 is time period of $i-$negative factor action. Function $D = D(r, \theta, \tau)$ in (24.24) is the concentration (referred to a unit of volume) of toxic substance at a point (r, θ) at a time τ, depending on gas density, average wind speed, intensity and duration of emissions and are determined by hydro-aerodynamics methods, constants (a_1, D_1, t_1) lie in the following range: $0.2 \le \alpha_1 \le 2.5, \quad 7 < -\alpha_1 \ln\left(D_1^2 t_1\right) < 60$. Function $q = q(r, \tau)$ in (24.25) is the heat flow (per unit surface) at the point r at the time τ, t_2 is the total time of jet burning. In (24.26) $q = q(r, \tau)$ is the heat flow (per unit surface) at the point r at the time τ, t_3 is the life of the fireball, constant a_3 is chosen equal $a_3 = 2.5$. In (24.27) functions $p = p(r, \tau)$ and $I = I(r, \tau)$ are the impulse and the maximum overpressure on the wave front, t_4 is the life of the fireball, constants are chosen as follows: $a_4 = -0.2, \quad p_0 = 40$ MPa, $I_0 = 450$ kg*m/s, $\alpha = 7.5, \quad \beta = 11.5$. In (24.28) m and $v = v(r, \tau)$ are, respectively, the mass and velocity of the fragment, t_5 is the time of fragment flight, and they are found on the solution of the problem about the shock destruction of pressure vessels, parameters a_5 and b_5 are chosen in the view $a_5 = 10.5$, $b_5 = -21$.

For gas pipelines of the Russian Federation, the federal acceptable risks of operation during an acceptable life are as follows: $I_1^* = \left(2 \times 10^{-4} - 2 \times 10^{-5}\right)\left[\frac{\text{number of people}}{\text{km}}\right] * L_0$, $I_2^* = \left(10^{-3} - 10^{-4}\right)\left[\frac{\text{number of objects}}{\text{sq. km}}\right] * S_0$, $I_3^* = \left(10^{-1} - 10^{-2}\right)\left[\frac{\text{number of flora representatives}}{\text{sq. km}}\right] * S_0$, $I_4^* =$

$\left(10^{-2} - 10^{-3}\right)\left[\frac{\text{number of fauna representatives}}{\text{sq. km}}\right] * S_0$, L_0 is the pipeline length, S_2 is the area of a potentially dangerous zone.

The time of dangerous operation of structure is found as a solution of the following equation according to (24.19):

$$Q\left(t_{f,m}\right) = \frac{\tilde{\mathrm{I}}_m}{\mathrm{I}_m}\tilde{Q} \quad m = 1, \ldots 4, \tag{24.29}$$

In this case, the following inequality: $t_{f,m} \le t_f$ is fulfilled, where t_f is the structure life, determined by Eq. (24.7) without taking into account the social safety of its operation. The life $t_{f,m} \quad m = 1, \ldots 4$, the risk-adjusted longevity considered social, industrial and environmental risks correspondingly.

The proposed safe operation criterion was applied for predicting of the longevity of oil and gas pipelines. A number of Conclusions on the life and residual life of various designs of gas and oil pipelines with a certain level of accumulated defects were prepared [6–9].

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