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MODERN LEVELS FOR STRUCTURAL STRENGTH ASSESSMENT AND THE ALGORITHM FOR IMPLEMENTATION OF THE RISK ANALYSIS METHODOLOGY IN THE OPERATION OF WELDED METAL STRUCTURES

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ABSTRACT

Three levels of assessment of indices of structural strength, reliability and durability of welded metal structures are considered for the construction of the integrity management system (IMS) of welded metal structures. Level 1 uses the criteria of the limit state of welded metal structures based on safety margin factors and is implemented by us using a failure assessment diagram. Level 2 of probabilistic analysis of safety and reliability involves the formulation and evaluation of the values of probabilistic indices used to assess the structural strength, reliability and durability of welded metal structures in the presence of uncertainty and lack of completeness of input data. For level 3 of the risk analysis of the operation of welded metal structures, an algorithm for its realization is proposed and an implementation option in the form of an IMS is prescribed. The two-criteria failure assessment diagram is the basis of the implementation of all three levels.

KEYWORDS: risk, failure probability, consequences, two-criteria approach, failure assessment diagram, probabilistic safety analysis, risk matrix, integrity management system

INTRODUCTION

Modern high-efficient diagnostic tools, for instance, in-pipe diagnostic technologies, allow detecting and identifying thousands and even hundred thousand defects which are monitored in the main pipeline. After performance of in-pipe diagnostics the question arises about defect classification by the degree of their influence on the reliable and safe service. It is necessary to develop a rational and substantiated procedure for taking improvement measures (repair, revision of operating regulations), planning subsequent inspections (with determination of their terms and scope), and to prioritize areas for repairs. As a large numbers of defects which can be qualified as admissible ones, remain in service, it is probably inappropriate to talk about absolute reliability of such a structure. Under such circumstances there will always be a certain probability of the structure failure. In its turn, the failure probability should be regarded in combination with such an important characteristic as failure consequences, which require expert assessment. It is obvious that at the same failure probability the consequences of failure of the primary circuit pipeline in the power unit of a nuclear power plant (NPP) and of a petroleum processing plant will be different. Thus, different reliability levels should be used for different structural elements within the scope of consideration of one object. The product of failure probability by the index of failure consequences determines the risk which may be used as a universal measure of reliability and effectiveness of the object operation.

The probabilistic risk analysis is usually performed for potentially hazardous productions, chemical and technogenically-hazardous technological processes, to assess the reliability of nuclear power plants and their equipment, as well as in the aerospace industry. There are two causes, which somewhat restrain the introduction of risk analysis ideology: first, a range of factors which may cause a failure or accident, is so wide that it requires computerized object certification, qualified processing of the statistical material and operating with various laws of random value distribution to obtain valid evaluation data of the reliability, and, secondly, the majority of improvement measures aimed at increasing the object safety, which are based on outdated diagnostic methods can be effective even without knowing the real risk, associated with object operation. The latter approach has the right to exist, but it should be the methodological component of the general strategy of management of the reliability and efficiency (also, economic efficiency) of critical objects with rather convincing substantiation of their application.

Considerable activity, observed in the world in the field of ensuring the reliability of engineering systems and introducing the risk analysis ideology [1], is caused, on the one hand, by competition — optimization of the technological process towards lowering its cost, and on the other — by more stringent safety regulations, specified by state regulatory bodies (reg-

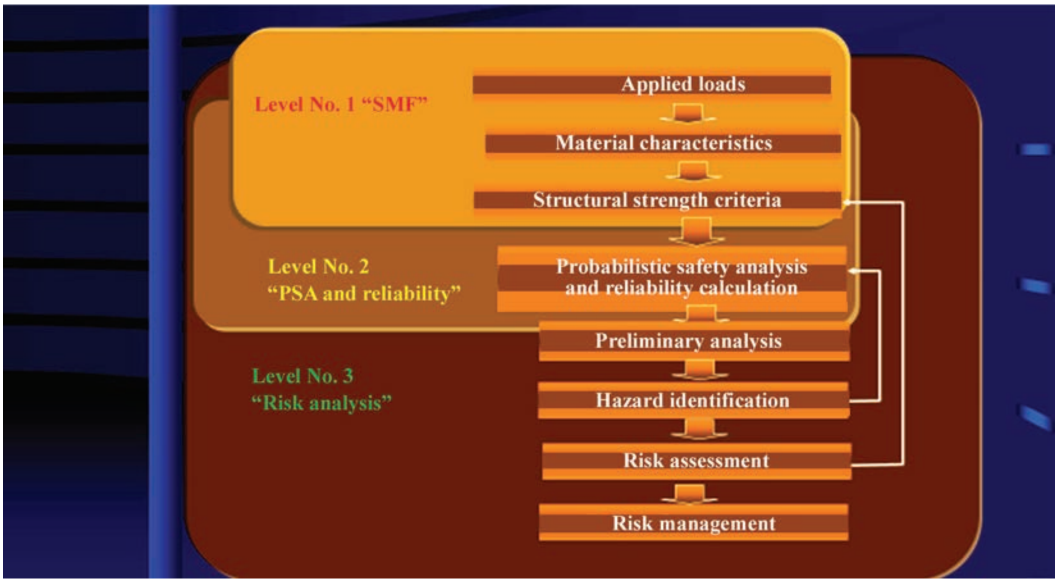

Figure 1. Modern levels of assessment of the indices of structural strength, reliability and durability of welded metal structures

ulator, for instance State Nuclear Regulatory Inspectorate of Ukraine, Derzhgirpromnaglyad, etc.).

It follows from the above-said that in the general case it is necessary to use a three-level approach for assessment of the indices of structural strength, reliability and durability of welded metal structures: pressure vessels, bridges, cylinders, tanks, pipelines, etc. (Figure 1).

LEVEL 1

uses the criteria of limit state of welded metal structures based on the safety margin factor (SMF), and it envisages formulation and use of the traditional deterministic indices of structural strength with determination of the limit state criteria at brittle, quasi-brittle and ductile fracture. On this level we recommend using a two-criteria approach, namely two-criteria failure assessment diagram (FAD) and its expansion [2]. Figure 2, *a* shows a modified FAD, the boundary curve of which is used as the fracture criterion of the main pipelines with defects [3]. A feature of FAD proposed by us and its temperature-load expansion (Figure 2, *b*) is explicit use of point T_b — critical brittleness temperature, which separates the brittle fracture zone from the quasibrittle fracture, and it is uniquely defined by coordinates of point B on FAD as follows B $(1; \xi = 0.7P_{YL}/P_{LL})$ (Figure 2, *a*). The abscissa of the point of quasibrittle transition B, which corresponds to T_t — toughness temperature, in Figure 2, *b* is determined from the condition of breaking load achieving limit load P_{LL}. The ordinate of point B based on the available experimental data corresponds to value

$\mu = \dfrac{K_I}{K_{IC}} \approx 0.4 - 0.7$. As one can see from Figure 2, *a*, at $K_r = \dfrac{K_I}{K_{IC}} \prec \mu$ the ductile fracture criterion is realized: $S_r = 1$ or $P = P_{LL}$, where P is the generalized load applied to cracked structural element (CSE).

FAD, which in the general case is a certain boundary area II, separates area I of safe operation of CSE from fracture area III, using the admissible SMF k.

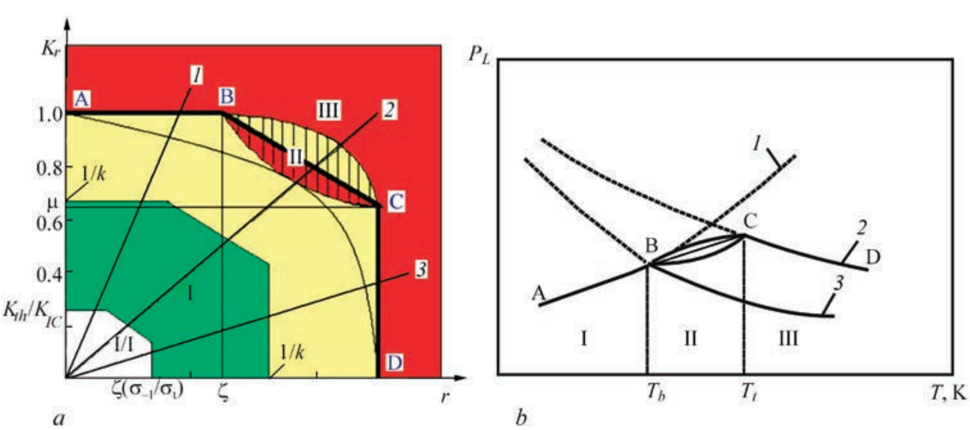

Figure 2. Two-criteria FAD (*a*): $S_r = \dfrac{P}{P_{LL}}$; $\xi = 0.7\dfrac{P_{YL}}{P_{LL}}$ and its loading-temperature expansion (*b*): *1* — P_L (K_{IC}); *2* — P_{LL} (σ_t); *3* — P_{YL} (σ_y), where σ_y is the yield strength and P_{YL} is the value of the load at the yield point of the entire net cross-section of the structure

In area II we will select the boundary line ABCD, in order to, first of all, simplify and perform the engineering assessment of the limit state of the cracked structural element, and secondly, be able to predict the brittle (ray 01 crosses area AB of FAD boundary line in Figure 2, *a*), quasibrittle or mixed (ray 02 crosses area BC of FAD boundary line in Figure 2, *a*) and ductile (ray 03 crosses area CD of FAD boundary line in Figure 2, *a*) fracture mode.

Green colour in Figure 2, *a* highlights admissible area I of CSE operation, which is determined allowing for admissible SMF *k*. Admissible SMF is a normative value by static strength criterion, which is specified by standards, norms, regulations, normative-technical documentation, etc. So, for NPP critical equipment [4] $k = 2.5$, and for main pipelines *k* is specified in keeping with SNiP 2.05.06–85 [5]:

$$k = \frac{0.9 k_1 k_R}{m}, \quad (1)$$

where *m* is the coefficient of operating conditions; k_1 is the coefficient of reliability, depending on material; k_R is the coefficient of reliability depending on purpose.

Yellow colour in Figure 2, *a* is used to highlight the zone of SMF validity II, requiring application of appropriate improvement measures as to the possibility of further safe operation of this CSE and it corresponds to subcritical controlled crack growth, the red colour shows the inadmissible zone III of CSE operation.

White color in Figure 2, *a* highlights the area IV, which is defined by coordinates $K_r = \frac{K_{th}}{K_{IC}}$ and $S_r = \zeta\left(\frac{\sigma_{-1}}{\sigma_t}\right)$,

where K_{th} is the fatigue crack propagation threshold of stress intensity factor (SIF) at cyclic loading; σ_{-1} is the limit of endurance, σ_t is the tensile strength. This area corresponds to the stage of defect initiation and propagation by the fatigue mechanism up to dimensions controlled by fracture mechanics laws.

LEVEL 2

of probabilistic analysis of safety (PSA) and reliability envisages formulation and assessment of probabilistic indices $\bar{x} = (x_1, x_2, \ldots, x_n)$ in the form of mathematical expectation $M(F,[R])$ and mean-root-square deviation $C(F, [R])$ of the generalized stochastic loading (applied load), scatter of measurements of structural element geometry and interpretation (schematization, classification, description of the geometry and location) of the defects detected by NDT means and scatter of experimental data on the mechanical properties and crack resistance characteristics of the materials and their welded joints.

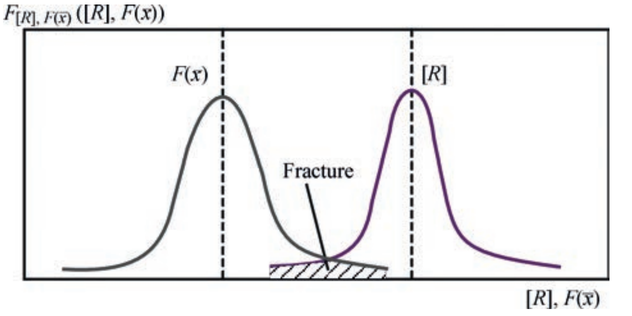

Figure 3. Fracture probability P_f, which is determined by the area of intersection of the parameters of the structure stressed state $F(\bar{x})$ with the generalized stochastic fracture resistance $[R]$

In the general case, the function of the metal structure limit state $g(\bar{x})$ can be expressed in the following form:

$$g(\bar{x}) = [R] - F(\bar{x}), \quad (2)$$

where $[R]$ is the generalized stochastic fracture resistance that is characterized by admissible parameters, which are determined by the mechanical properties and crack resistance characteristics, allowing for the normative safety factors (SMF); $F(\bar{x})$ are the maximal, equivalent as to the selected strength criteria stochastic parameters of the structure stressed state, which were established by construction of a computational model and uncertainty analysis.

Then, the probability of metal structure destruction, as illustrated by Figure 3, is calculated by the following equation:

$$P_f = \int_{g(x)\le 0} f_{[R],F(\bar{x})}([R], F(\bar{x}))dRdF(\bar{x}). \quad (3)$$

The following can be used as an integral function for indices of metal structure operation reliability RN^* [9, 10]:

- mathematical expectation and mean-root-square deviation of the appropriate indices of metal structure reliability $M(F,[R])$ and $C(F,[R])$, respectively;
- probability of the value of the respective reliability index *R* not being lower than the specified (normative) value R_{sp}. Let us denote this probabilistic index as $P(R \ge R_{sp})$.

Depending on the research objectives and tasks solved at the main stages of the structural element life cycle (design, construction (repair) or operation [7]), the conditions of optimality or suitability, which are also called “fitness-for-purpose” criterion, can be imposed on each of the considered indices $M(F, [R])$, $C(F, [R])$, $P(R \ge R_{sp})$ [11]. So, for $P(R \ge R_{sp})$ index the fitness-for-service criterion will have the following form:

$$P(R \ge R_{sp}) \ge P_g, \quad (4)$$

where P_g is the guaranteed probability of the value of the respective reliability index R not being lower than the normative value R_{sp}.

We based the construction of the algorithm of simulation model of metal structure destruction on the indirect method of statistical probabilistic modeling (Monte-Carlo method [8]), which consists of the following steps:

1. In keeping with the known distribution laws $f_i(x_i)$ generate a sample of implementations N: $XN^* = (x_1^*, x_2^*, \ldots, x_n^*)_i$, $i = \overline{1,N}$ of random values $x_1, x_2, \ldots, x_n$, which belong to the specified range of values (of parameters, characteristics).

2. Substitute the formulated implementations $(x_1^*, x_2^*, \ldots, x_n^*)_i$, $i = \overline{1,N}$, into (2) and obtain the respective sample of implementations of reliability indices F, $[R]$: $RN^* = (F_i, [R]_i, i = \overline{1,N})$.

3. Based on the sample of implementations of reliability indices $RN^* = (F_i, [R]_i, i = \overline{1,N})$ obtain a sample of estimated values of the respective probabilistic reliability indices $(M^*(F, [R]), C^*(F, [R]), P^*(R \geq R_{sp}), \ldots)_i$, $i = \overline{1,N}$.

4. Proceeding from the sample of estimated values of the respective probabilistic reliability indices $M^*(F, [R])$, $C^*(F, [R])$, $P^*(R \geq R_{sp})$, $i = \overline{1,N}$ make conclusions as to the structural strength and truth of the values of these indices.

Implementation of the first step is based on standard methods of modeling the random values and vectors, using the algorithmic sensors of random values [8].

Special attention in the second step should be paid to application of a correct deterministic fracture model (criterion). We use a two-criteria approach [2] and two-criteria failure assessment diagrams developed on its base.

Implementation of the third step is based on obtaining point estimates of the probabilistic reliability indices $M^*(F, [R])$, $C^*(F, [R])$, $P^*(R \geq R_{sp})$, $i = \overline{1,N}$ using a sample of implementations of deterministic indices $RN^* = (F_i[R]_i, i = \overline{1,N})$. Point values of estimates of the first two indices (mathematical expectation and mean-root-square deviation) are determined as follows:

$$M^*(F,[R]) = \sum_{i=1}^{j} \frac{(F,[R]}{j}, \; j = \overline{1,N}; \quad (5)$$

$$C(F,[R]) = \sqrt{D(F,[R]_j}, \; j = \overline{1,N}, \quad (6)$$

where $D(F, [R]_j)$ is the estimation of the dispersion of sample values:

$$D(F,[R])_j = \sum_{i=1}^{j} \frac{(F,[R]-M(F,[R]))}{j}, \; j = \overline{1,N}. \quad (7)$$

International standard ISO 16708:2006 can be an example of implementation of level 2 for the main oil and gas pipelines [6]. In limit states, when the structure experiences additional loads or loss of quality and violates the safety standards in keeping with the deterministic approach, the deterministic approach proper can no longer be applied to determine if the structure still is sufficiently safe. Limit states in this context are, for instance, material aging, considerable corrosion and additional loads, not allowed for in the initial design.

In this case, a probabilistic approach can be used, calculating the structure failure rate. It was introduced approximately 20 years ago during structure design. Compared to the deterministic approach, failure rate calculation is a complex process. The problem is establishing the generally accepted limitations for the failure rate.

The International Standardization Organization (ISO) has worked on this issue for many years and ISO 16708 standard "Petroleum and natural gas industries — Pipeline transportation systems — Reliability-based limit state methods" [6] was often changed in the draft status for a long period of time. In 2006 it was accepted as DIN EN ISO 16708, as the National Standard of Germany.

The scope of application of DIN EN ISO 16708 standard allows using the deterministic and probabilistic approaches in parallel. The standard has a high level of recognition among the authorities, experts and specialists-engineers.

In modern practice DBN V.1.2-14:2018 [11] is used for ensuring the reliability and structural safety of buildings and constructions, which is applied when searching for, designing, building and liquidation of buildings and structures, irrespective of their purpose. Thus, level 2 of probabilistic safety analysis (PSA) and reliability is applied for complicated issues of uncertainty when compiling the "Objects", "Defects", "Loads", and "Properties" data bases, which are required for construction of a computational model, identifying the potentially critical cross-sections of a welded metal structure and assessment of structural strength, using a two-criteria approach based on Monte-Carlo method [8–10].

LEVEL 3

At this level it is necessary to formulate and assess the above-mentioned probabilistic indices of structural strength, reliability and durability with guaranteed or confidence level, which allow for failure consequences [10, 12].

Selection of a particular level of assessment of the indices of structural strength, reliability, durability of structural elements will depend on such main factors as: importance of the assessed structure; stage of its life cycle under consideration; input data used to obtain the respective estimates of the indices and the level of confidence in them.

In order to introduce the methodology of risk assessment at operation of welded metal structures, it is first of all necessary to develop a risk assessment program. The operator should take into account all the features of his metal structure, operating in a certain system (for instance, a power unit of a nuclear power plant should be regarded as such a system, etc.) and should decide, which of the approaches is the most suitable. The main objective of risk assessment consists in identifying the greatest risks in the system so that the operator could decide how, where and when to take the repair and improvement measures, so that it would increase the integrity of the metal structure of the mentioned system in the most effective manner. The operator should decide which information can be useful for assessment, and how this information should be used, so that the accuracy and effectiveness of the estimates were maximal. A simplified scheme of risk analysis performance is shown in Figure 4 [12, 13].

It is obvious that risk analysis includes three main components: risk analysis, which considers and analyzes the possibility of accidents (destruction) with their consequences; risk assessment, which compares the obtained risk with the available criteria of its admissibility; risk management which envisages and defines the measures for risk reduction.

A substantiated methodology of risk assessment should be:

Structured. Risk assessment procedures usually use the input data of the systems of technical condition monitoring (sensors, controllers, etc.) or are formulated by experts in the field of assessment of strength, corrosion protection, welding, technological production processes, etc. All the methods of risk assessment, however, determine and use the logical schemes in order to determine how the data being considered influence the risk in the terms of probability of an accident or its potential consequences.

Supported by sufficient resources. Sufficient number of staff and adequate time should be allocated to successfully fulfill all the stages and detail the risk analysis.

Based on real experience. The frequency and severity of the consequences of previous events (in this or a similar welded metal structure) should be considered, as well as understanding and taking into account all the improvement measures, implemented to prevent such situations. Risk assessment methods should take into account the specific history of functioning of this welded metal structure.

Predictive. By its nature the procedure should be exploratory, i.e. it should identify the earlier not taken into account threats to the integrity of the welded metal structure. Accident scenarios which had never occurred before in this metal structure, should be considered.

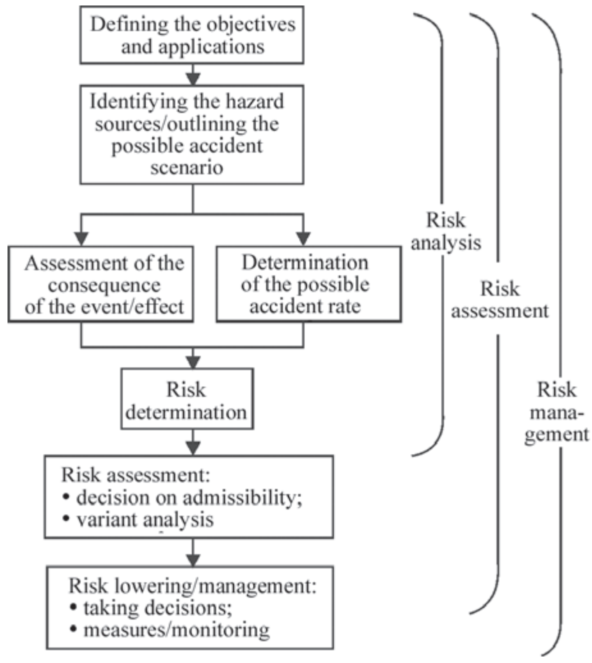

Figure 4. Simplified scheme of risk analysis

Use adequate data. Some risk analysis decisions are just subjective expert statements. Therefore, adequate input data of the systems of monitoring the technical state of the metal structure are just mandatory to take objective decisions and estimates.

Capable of supporting feedback. Risk analysis is an interactive process. Real events and data on the condition of the welded metal structure should be used to confirm or correct the made assumptions.

FIRST STEPS DURING RISK ASSESSMENT

Generally accepted start of the assessment process consists in formation of a representative group of company experts for identification of the events or conditions (risk analysis) which may lead to failure of this metal structure, for assessment of the accident consequences, as well as for determination of the measures, which reduce the risk for this metal structure. This group should include the representatives from the departments of management, operation, units of control of metal, corrosion, safety, engineers from the construction site, representatives of the regulator (supervisory) bodies, etc. The purpose of this group consists in outlining and incorporating the experience of different expert groups into the risk assessment method so that these methods could use the experience and information, not yet taken into account in the data bases of integrity management system (IMS) [1, 7, 13, 14].

The following generally accepted methods can be used to conduct systematic and complete investigation:

- free-form brainstorming technique for potential risk analysis;
- performing segment-by-segment analysis (area-by-area) of the metal structure using geoinformation systems;

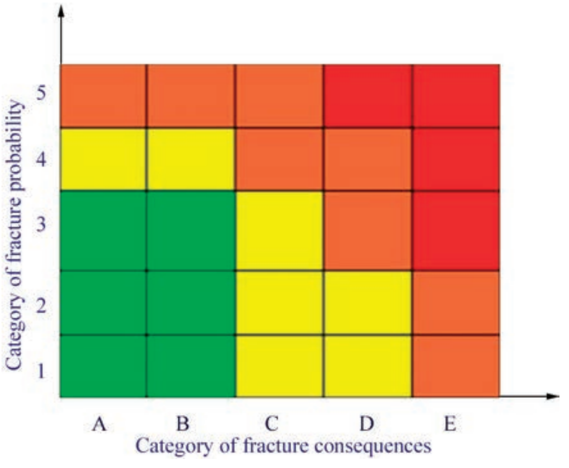

Figure 5. Risk matrix [1, 13]

- use of a list of structured questions, pertaining to the complete list of possible hazards and problems of metal structure integrity;
- application of simple risk matrices, shown in Figure 5 for illustration, for qualitative analysis of the probability and consequences of possible events [1, 13].

MAIN COMPONENTS OF RISK ASSESSMENT METHODOLOGY

Risk assessment is a process of combining the estimates of accident frequency and consequences into a unified risk value. The risk value can be quantitative, qualitative or a combination of the two, depending on the assessment procedure, or the objective set by the operator during IMS development [1, 7, 13, 14]. The sensitivity and accuracy of risk assessment methods is a function of the number of variables used, and the ability to determine the change in the risk along the coordinates of the welded metal structure.

Some methods require the user to assess the risk in individual areas of the metal structure, using similar characteristics, while other take into account the local effects of the change of functioning conditions. For instance, as regards the main pipelines, it can be the values of cathode protection indices, presence of defects, number of diagnostic anomalies, fracture modes, etc. In many methods the event probability is assessed using variable values and indices, pertaining to:

- external corrosion;
- internal corrosion;
- third party damage;
- soil movement (shifts, subsidences, ground undermining in mining areas, etc.);
- design conditions and material characteristics;
- metal structure functioning in the system.

The consequences are assessed using variables belonging to the following categories:

- environmental impact;
- influence on population;
- economic consequences.

The more such variables are used, the more quantitative is the analysis. The quantitative analysis accuracy is enhanced with further specifying of the variables (effect of interaction with the supports, foundation, soil type, age (aging) of the metal structures, protective coating quality, etc.).

RISK VALIDATION AND IDENTIFICATION

Irrespective of the process of risk assessment performance, the operator must analyze the information so as to guarantee that the accepted technology yields the results, which on the whole correspond to analysis purpose. This can be achieved involving either a specialist on risk analysis having experience of analysis of similar systems, or a multifaceted team of specialists on functioning of similar diagnostics objects. If the obtained results do not correspond to the operator's perception of the real risk, he should study the causes for such differences, and if required, revise the methods, input assumptions or data.

After validation of the risk assessment methods, the operator has the necessary information for ranging the risks. The segment with a greater degree of risk should be given greater priority at identification of areas where the improvement measures should be applied (priority of diagnostics, repair, etc.). To reduce the overall risk, the operator first has to analyze the causes for appearance of a high risk in this segment. This can be due either to a high probability of the event (destruction) or significant consequences. This information is important to take decisions as to the scope and list of improvement measures.

RISK MANAGEMENT AND IMPROVEMENT MEASURES

Risk assessment methods are an important tool to support the operator when taking economically and technically sound solutions on reducing the risks for their systems. As soon as the potential risk has been indentified and the means for its reduction have been determined, the methods of risk assessment can be applied again to determine the risk reduction value and obtaining material benefit. These methods can be constantly used at assessment of the rationality of the proposed improvement measures. In combination with analysis of the cost for introduction of these measures, risk analysis allows the company to select the most effective measures which can be applied in this period.

Figure 6 shows the algorithm for introduction of the methodology of risk assessment in welded metal structures, which was implemented by us using program-procedural complex (PPC) "Probabilistic risk analysis" of "Strength" expert system [7, 12].

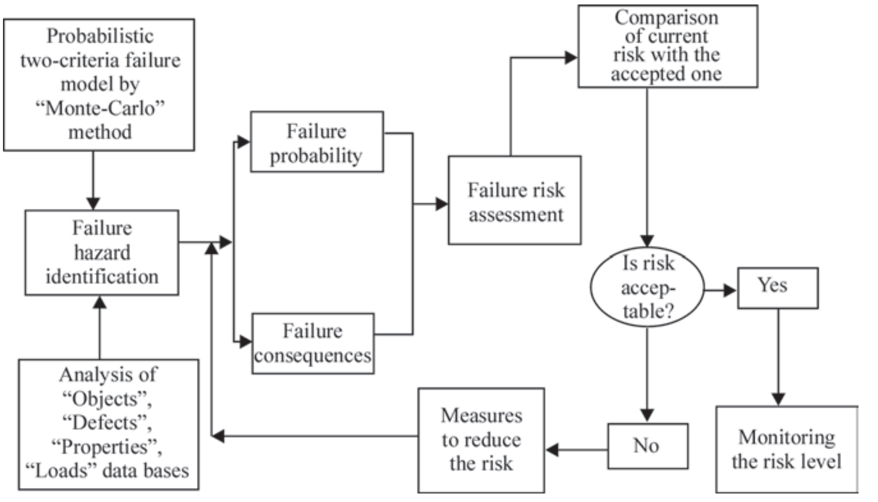

Figure 6. Algorithm for introduction of the methodology of welded metal structure risk assessment

CONCLUSIONS

1. Three levels of assessment of the indices of structural strength, reliability and durability of welded metal structures were considered for construction of an integrity management system, which uses a two-criteria fracture assessment diagram.

2. An algorithm was proposed for introduction of risk assessment methodology based on the system of management of welded metal structure integrity.

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