Structural materials sciences in problems of life time and safety of technical systems

Vladimir Moskvichev

SCTB "Nauka" KSC SB RAS, Mira 53, Krasnoyarsk, 660049, Russia

moskvich@icm.krasn.ru

Keywords: structural materials, life time, safety, technical systems.

Abstract. The achievements in science of structural materials (physics of strength, fracture theories, fracture mechanics, materials science, and mechanics of heterogeneous materials) are the basic for solving the safety problems of technical systems (TS). Interrelationship of requisition to materials, structures and technologies predetermine common requirements to safety of TS and the necessity to solve direct and inverse problems of materials science. The direct problems represent the making of new materials with higher mechanical properties and crack resistance for certain class of TS. The inverse problems include the design of materials with specified structure and properties for perspective and special TS according to their functionality. In this context the complex researches on material structure, mechanical properties, crack resistance and limit conditions have been carried out. The tasks of life design and safety have been solved. The work was supported by RFBR, grant 11-08-00945.

Introduction

Modern development of technics and technology is characterized by high rate of growth and scientific achievements in aerospace, nuclear, energy, chemical and other industries. At the same time this gives rise to initiation and intensification of non-existent previously potential and real threats to human society and environment from technical objects.

Failure of complex technical systems and engineering structures is the main source of man-caused disasters. This fact has led to developing new methods to design and analyze GTS. In 1970-1980, further to conventional methods of calculating the strength, durability and reliability of structural components, new approaches for assessment of the fracture toughness have been implemented. Later on parameters of residual life, risk and safety have been included in design procedure. Quantitative assessment of these parameters requires numerous experimental and calculation efforts to study the causes and mechanisms of failure, to formulate the limit states and to model the emergency conditions.

Failure analysis of quarry machines and excavators, cranes, pressure vessels, heat-and-power equipment, technological and trunk pipelines shows that technological defects, fatigue andcorrosion cracks, low quality of metals, residual stress and aggressive environment are the main causes of fracture (Fig.1). Specific weight mentioned above factors depends on type of CTS.

In most cases, failure of CTS relates to initial technological defects in welded joints. Statistical analysis of weld defects typical for various industries has allowed determining the distribution functions of the defect types and sizes corresponding to different technologies of welding. These distributions have been found to be determined predominately by manufacturing methods rather than the type of a structure.

To make engineering estimates on the safe life of structures considering initial defects and operational damages distinctive types of the limit states have been marked out (Fig. 2) [1].

In general, the constitutive equations for the limit states include parameters of stress-strain state a (e), defect size l, characteristics of the static (K_c, J_c, K_{ec}) and cyclic (C, n) fracture toughness of materials:

$$\Phi\{\sigma, e, l, K_c, J_c, K_{ce}, C, n\} = 0 \qquad (1)$$

Calculations according to the equation (1) can be carried out using either deterministic or probabilistic approaches. In the former case, quantitative assessments of the fracture toughness and residual life of CTS are carried out applying experimental and calculation methods of the fracture mechanics. In probabilistic approach, the methods developed are based on a combination of the fracture mechanics criteria and the reliability theory. Since the parameters of the equation (1) are stochastic variables, the possibility to reach the limit state of a system within a given service time *t* can be estimated by a probabilistic measure - the risk function *R(t)*:

$$R_i(t)=P\{\Phi(x,t)=0\}=1-\exp\left\{-\sum_{\Phi}\lambda_{\Phi}(t)dt\right\}, \qquad (2)$$

where λ_Φ is the intensity of occurrence of a given limit state.

The safe life of a structure is determined as an average time *T* required for the structure to reach a given limit state:

$$T=\int_0^\infty t\left[1-R_j(t)\right]dt. \qquad (3)$$

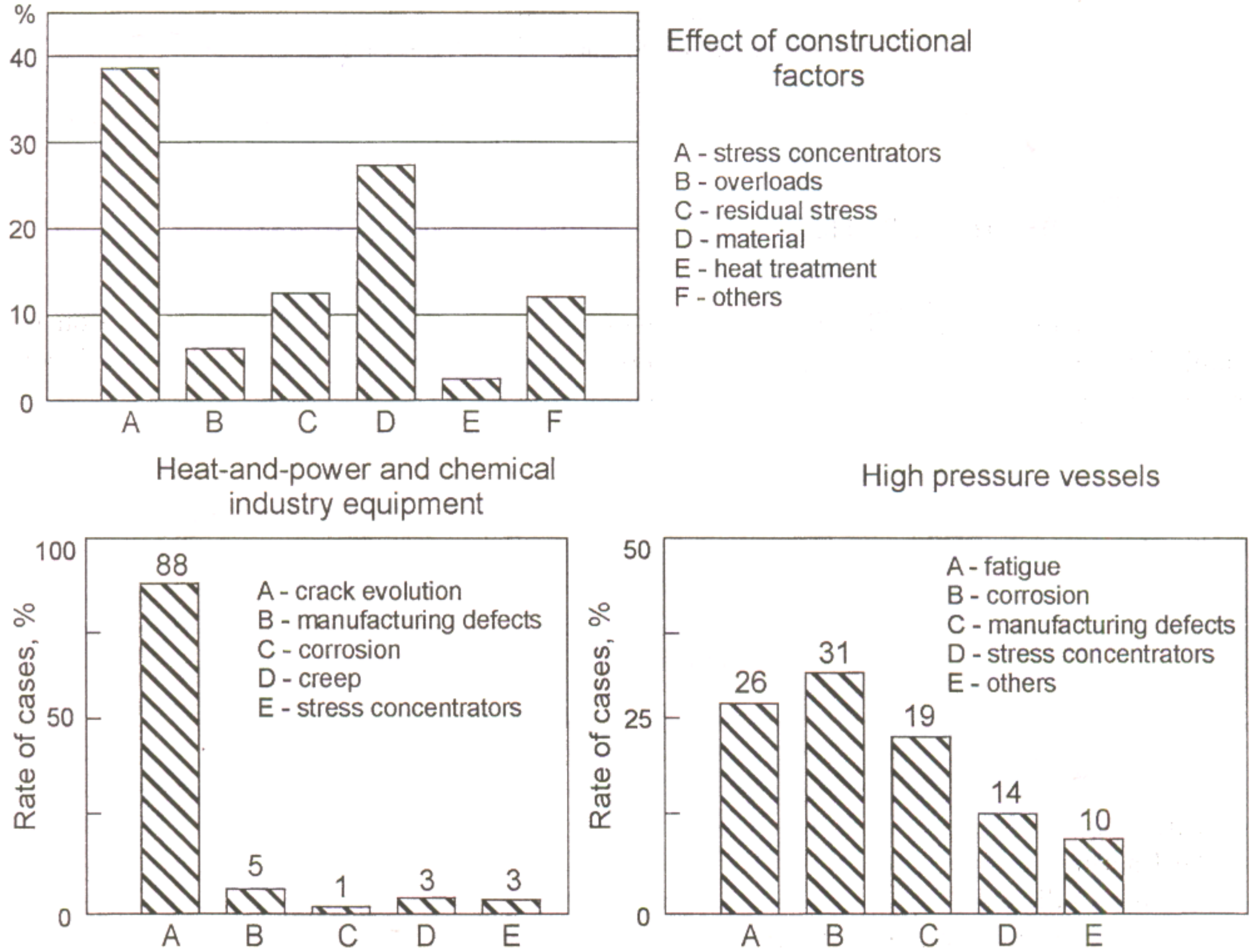

Fig. 1. Fracture causes of technical systems

Primary limit states	Additional limit states
• PLS1 - strength breakdown at maximal loads (static and dynamic loadings) • PLS2 - breakdown of regular operation at fatigue cracks initiation (cyclic loading) • PLS3 - evolution of intolerable plastic deformation • PLS4 - overall or local buckling	• ALS1 - brittle, quasi-brittle, ductile fracture due to technological defect or crack • ALS2 - initiation and evolution of fatigue cracks • ALS3 - initiation and evolution of corrosion-mechanical cracks

Limit states of emergency conditions
• ELS1 - ductile or brittle fracture accompanied by drastic drop (50…90%) of bearing ability • ELS2 - fracture under cyclic loading accompanied by drastic drop (1..2 orders) of durability • ELS3 - fracture due to secondary factors of developing emergency conditions • ELS4 - thermal damages due to primarily and secondary damaging factors.

Fig. 2. Limit states of technical systems

Elaboration of this methodology opens up possibilities to analyze and solve problems of CTS safety, to develop and implement new methods of CTS risk assessment [2].

Problems of structural materials science

1. Design of new structural materials with increased crack and failure resistance considering the operational factors.
2. The basics of the problems are the experimental studies of the structure, mechanical properties and fracture kinetics and crack resistance of structural materials.
3. Multicriteria choice of materials for certain limit states on the basis of calculation to ensure the strength, service life, reliability, survivability and security.
4. The transition from direct (experimental) methods to experimental and calculated basics for choosing the structural materials.

The study of fracture toughness

Evaluation of limit state parameters is impossible without comprehensive knowledge on mechanical properties of materials. For this purpose, a large number of tests on static and cyclic fracture toughness of various structural materials have been carried out [3]. Effect of different parameters, such as scale factor, loading scheme and operational conditions, on characteristics of elasto-plastic fracture of low-carbon and low alloyed steels was of the most interest (Fig. 3). Distribution functions for the critical value of J-integral J_c and strain intensity factor K_{ce} under elasto-plastic deformation of the materials have been obtained. Determined relationship between these measures of the material crack resistance facilitates the analysis of CTS limit states. Large experimental database combined with new method base on J-integral is powerful tool for the fracture toughness calculations of structural components.

Statistical investigations on the static and cyclic fracture toughness of different zone of welds have allowed to derive the probability distribution functions for wide used structural steels: St3, 09G2S, 10XCHD and others (Fig. 4). Based on this study the generalization of cyclic fracture diagrams for low-carbon and low-alloyed steels has been completed. Characteristics of the fracture toughness for structural materials under conditions of dynamic crack growth have been studied employing developed technique. Research done on AL/B composite and ceramics, apart from detailed structural and mechanistic insights, has provided the knowledge on the resistance to crack growth of these materials, which are finding increasing application in many fields of advanced engineering. Amongst others, the obtained experimental results on the fracture behavior of aluminum alloys and clad steels are to mention.

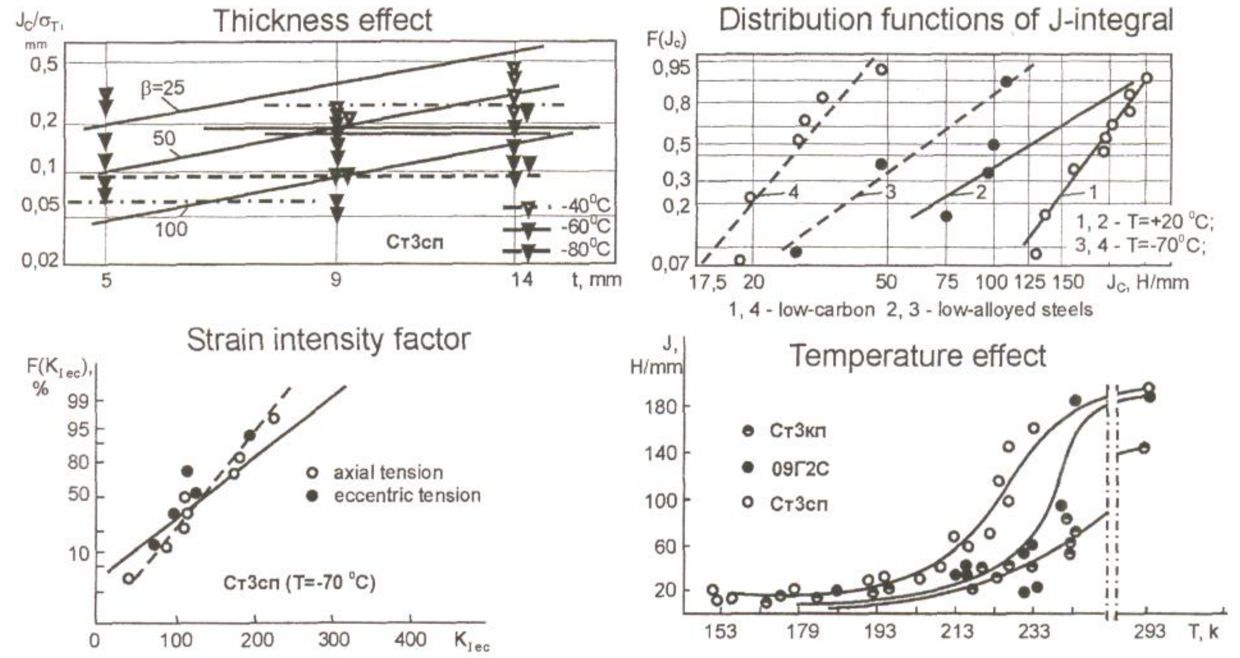

Fig.3. Research on characteristics of elasto-plastic fracture

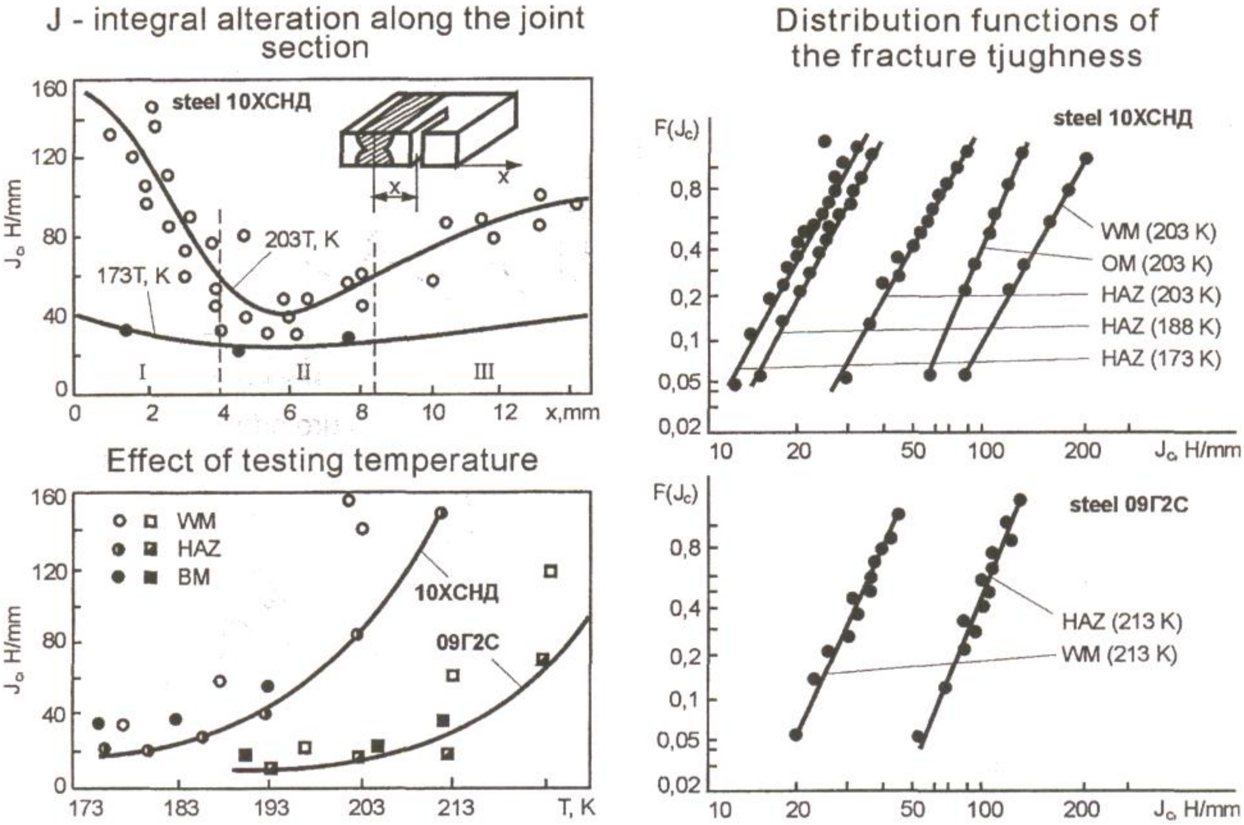

Fig. 4. The fracture toughness of welded joints

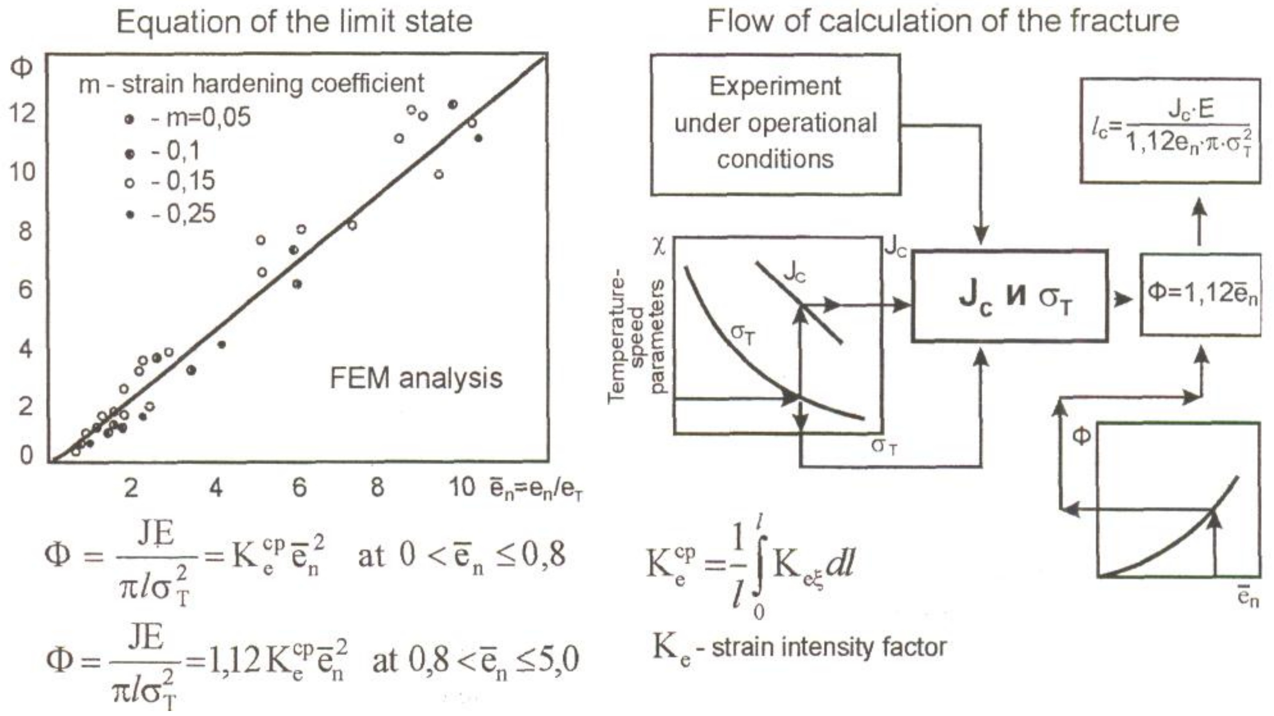

Fig. 5. Limit state analysis for elasto-plastic fracture

Development of calculation methods

Complex application of fracture mechanics methods has allowed to solve a number of important problems of strength and reliability assessment of CTS structures. Presented on Fig. 5 numerical calculations and experimental data displays the validity of the J-design curve approach used for the fracture toughness calculations of plate structural components with stress concentrators. Strength assessment for load bearing components of space apparatus made of fibrous metal matrix composite has been done assuming initial technological defects (Fig. 6) [4].

To solve problems of the service life design of welded joints a method of statistical testing has been developed. The method is based on application the defect kinetic equations coupled with numerical calculations of stress-strain state and probabilistic models of defects, loading and the fracture toughness (Fig. 7). This allows to obtain:

– reliability functions of welded joints in the presence of different types of weld defects;
– probabilistic diagrams of the residual life linking the number of loading cycles, loading level and the probability of safe life;
– probabilistic diagrams of the service life allowing to estimate the influence of loading level, defect size, component thickness and operational temperature.

Results of deterministic and probabilistic modeling of the crack growth kinetics have led to the development of a method to evaluate the safe residual life of CTS structures in the form of the equation (3) [5, 6].

Evolution of the probabilistic fracture mechanics approaches and the reliability theory has provided with a tool for the probabilistic risk analysis of structures including estimation of the risk function (2) [2]. The algorithm includes

– analysis of stress-strain state of a structure;
– modeling of a potential fracture zone considering a possible limit state;
– calculation of the fracture probability.

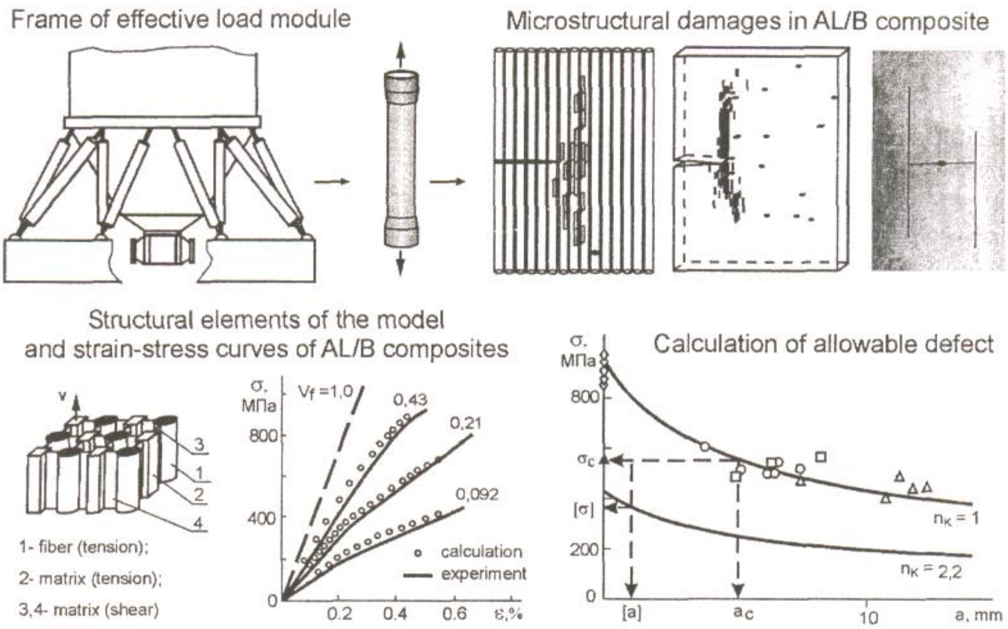

Fig.6.Failure modeling and the fracture toughness of space apparatus frame

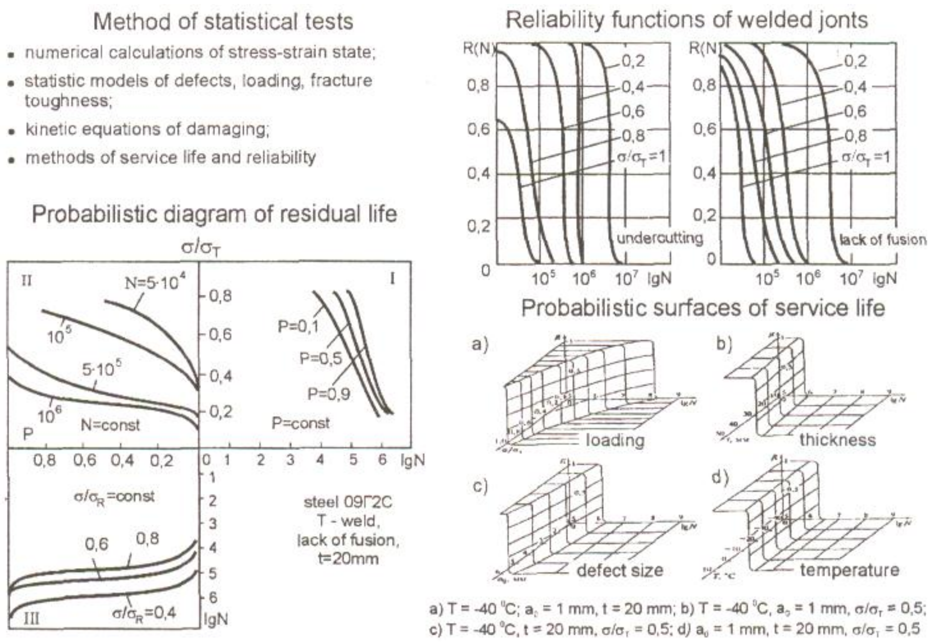

Fig. 7. Design of welded structures

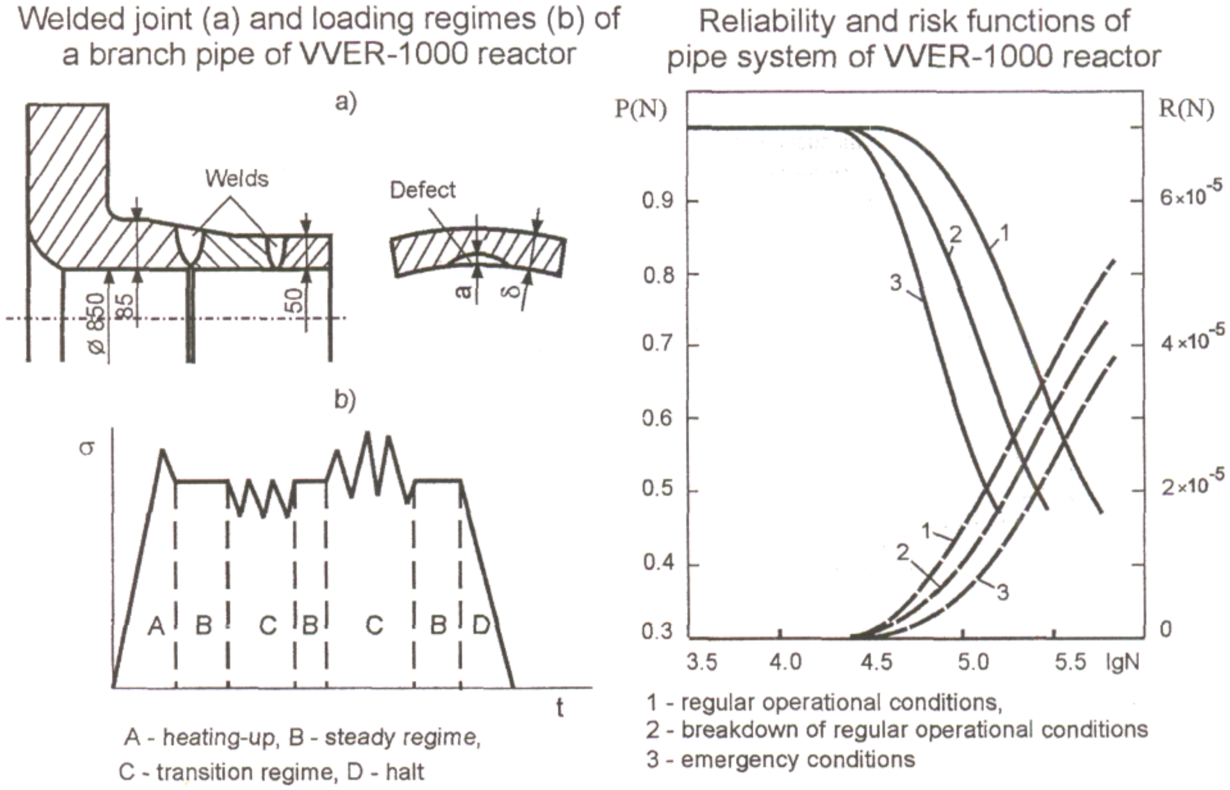

Fig. 8. Reliability and risk assessment of welded components of VVER-1000 reactor

In solving problems of the risk analysis, an important role belongs to mathematical modeling and numerical experiment. Mentioned above methods and techniques have been implemented evaluating parameters of reliability and risk of fracture for components of VVER-1000 reactor (Fig. 8), welded metal structures of quarry excavators, high lift-capacity cranes, different types of pressure vessels, piping systems, components of power equipment and building metal structures.

At present, our research is concentrated on assessing the safe residual life of machines and structures, which are out of its normative lifetime.

References

[1] V.V. Moskvichev: *Fundamentals of structural strength of technical systems and engineering structures* (Nauka, Russia 2002).

[2] A.M. Lepikhin, N.A. Makhutov, V.V. Moskvichev, A.P. Cherniaev: *Probabilistic risk analysis of technical system structures* (Nauka, Russia 2003).

[3] V.V. Moskvichev, N.A. Makhutov, A.P. Cherniaev: *The fracture toughness and mechanical properties of structural materials* (Nauka, Russia 2002).

[4] A.E. Burov, I.I. Kokcharov, V.V. Moskvichev: *Failure modeling and the fracture toughness of fibrous metal matrix composites* (Nauka, Russia 2003).

[5] A.M. Lepikhin, N.A. Makhutov, V.V. Moskvichev, S.V. Doronin: Fatigue and Fracture of Engrg. Mater. and Struct. Vol. 23 (2000), p. 395.

[6] A.M. Lepikhin, S.V. Doronin, V.V. Moskvichev: Theoret. and applied fract. mech. Vol. 29 (1998), p. 103.