Criteria for the development of the system of combined engineering calculations and tests to justify technological safety

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Abstract: The modern theory and practice of ensuring high performance characteristics of critical engineering systems use parameters describing the level of the system's protection from accidents and catastrophes as well as parameters of technological risks, safety, damage tolerance, reliability, service life and strength. To fulfill these requirements and avoid the occurrence of limit states various safety factors are introduced by research institutions, design organizations and supervising agencies. These safety factors are established by conducting analytical and numerical calculations and experiments focused on assessment of stress-strain states and through tests carried out on laboratory specimens, models, test benches and full-scale structures. The amount of calculations and tests are determined by the level of novelty and criticality of the designed and used equipment.

Keywords: strength, service life, safety, mechanical characteristics, safety factor

1 Introduction

Basic research in the field of risk theory, mechanics of catastrophes, deformation and fracture mechanics [1-3] forms the basis of modern approaches to insuring safe operation of high-load engineering facilities. At the same time the criterion base for developing and improving approaches to ensuring the required conditions for accident-free operation includes standard-based parameters of risk and safety. These parameters are substantiated by sets of criteria of strength, service life, reliability, and damage tolerance. Safe and reliable operation of high loaded facilities can be ensured through experimental and calculation formation of an appropriate criteria base for risk regulation and management. This criteria base should take into account both normal operating conditions and the possibility of occurrence of various incidents, accidents and catastrophes [1, 2, 4-7]. With regard to the practice of operating engineering facilities (*EF*) in Russia, they can be divided into the following categories: facilities subjected to technical regulation (*TRF*), this category numbers $10^6 \div 10^7$ facilities; hazardous production facilities (*HPF*), $10^4 \div 5\ 10^5$ facilities in total; critically important facilities (*CIF*) with the number $10^3 \div 5\ 10^3$; and strategically important facilities (*SIF*) with the number $10^2 \div 10^3$.

In historical retrospective ensuring structural integrity and safety of engineering facilities is characterized by solving the following sequence of problems: strength → stiffness → resilience → service life → reliability → damage tolerance → safety → risk → protection. Each of these problems requires accumulation of basic scientific knowledge, developing a criteria base, elaborating engineering design and testing methods, creating norms and rules for *EF* designing and manufacturing that would allow one to ensure *EF* operation within the specified limits of design modes and parameters. In other words when analyzing the problem of ensuring structural integrity and safety in the most general form, the following governing parameters should be considered:

R_σ is strength determined by the capacity of the load carrying (structural) components that are subjected to normal and extreme impacts to resist fracture;

R_λ is stability determined by the capacity load-carrying components to resist buckling under normal and abnormal loading;

R_δ is the rigidity determined by the resistance of the load-carrying components to the unacceptable deformations δ under the impact of normal and abnormal loads;

$R_{N\tau}$ is a service life determined by the time τ or the number of cycles *N* before either fracture, or loss of stability occurs;

P_{QR} is reliability determined by the ability of an facility (in its normal or damaged state) to fulfill its functions under given loads *Q*;

L_{ld} is damage tolerance (or flaw resistance) determined by the ability of the facility with damage *d* (or defect size l) that exceeds the acceptable level to fulfill (at least partially) its functions;

S is safety determined by the ability of the facility avoid catastrophic states;

R is risk determined by the probability of the occurrence of unfavorable situations at the facility and possible consequences of these situations;

Z_c is protection level determined by the ability of the facility to resist the occurrence and development of adverse consequences in normal and emergency situations.

Parameters R_σ, R_λ, R_δ should be used for assessment of facilities subjected to technical regulation; R_σ, R_λ, R_δ, $R_{N\tau}$ should be estimated when hazardous production facilities are considered; R_σ, R_λ, R_δ, $R_{N\tau}$, P_{QR}, L_{ld}, *S* should be included into consideration for critically important facilities; R_σ, R_λ, R_δ, $R_{N\tau}$, P_{QR}, L_{ld}, *S*, *R*, Z_c are characteristics of strategically important facilities.

2 Analysis of limit states

Modern trends in the design and operation of high-load equipment are focused on increasing strength and service life of its load-bearing elements in order to ensure operational safety. It means that strength assessment should be carried out not only in linear elastic, but also in nonlinear elastoplastic formulation [2]. Since the considered *EF* along with static loading are also subjected to cyclic nonstationary loading, both static and cyclic elastic and elastoplastic strains in stress concentration zones should be analyzed [2, 8]. In the view of the above the analysis of conditions and the formation of the criteria base of reaching limit states is a necessary step for justifying parameters of EF safe operation [2, 7, 9].

The assessment of accumulated damage of engineering facilities for various stages of their lifecycle and estimation of conditions for their transition to critical states due to the application of multifactor loading regimes are generally based on application of computational and experimental methods for determining strength, service life, reliability, resilience, and safety (Fig. 1). At the same time, the development of proposals related to various design schemes and design cases for all stages of *EF* life cycle is implemented using the criteria that take into account the changes of the mechanical properties of materials at all stages of the facility life cycle.

At the design stage, the initial mechanical properties of the material are included in the calculations of strength and service life. Estimates of the current state of the considered structural components are made with the account of the actual mechanical properties of the material obtained during control experiments. Assessment of the remaining service life according to the criteria for reaching limit states are carried out using current mechanical properties of the material and their estimated (predicted) values [2, 10]. In this case, the operational loads that influence the current mechanical properties of structural materials at various stages of EF life cycle are determined by the following main parameters: the number of cycles *N,* the loading time τ, temperature *t*, level of accumulated damage (size of the defects) *l*, environmental conditions β. Moreover, the parameters *N* and τ affect the lifetime of the facility as a whole, and *t* affects its heat resistance.

The scientific substantiation of strength, service time, damage tolerance, and safety requires an analysis of the results of complex basic and applied research in an interdisciplinary formulation with the formation of relevant criteria and governing equations. Some of these equations that use safety factors for strength and service life assessment were initially quite simple. But the development of new formulations that take into account the conditions of impact, sustained and cyclic loadings, and also high-speed, high-temperature, and low-temperature loading requires more complicated governing equations.

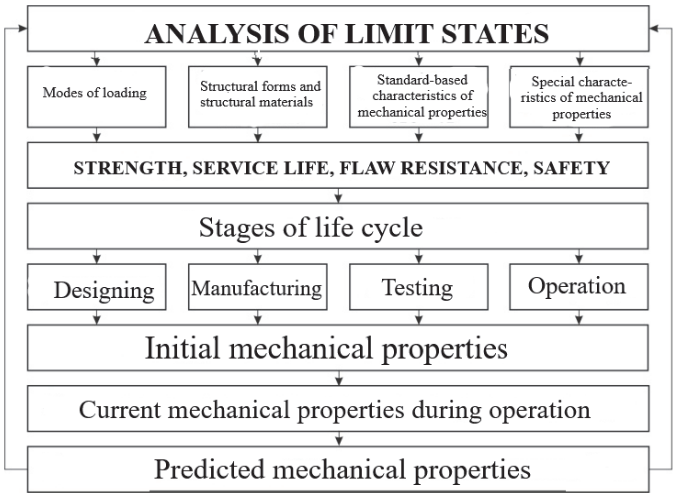

Figure 1 – The flowchart of the analysis of the conditions for attaining limit states

The analysis of processes of deformation and fracture in the elastoplastic formulation requires a transition from the traditional stress based approach which is adequate for solving the problems of linear mechanics of deformation and fracture to the strain-based approach. This formulation of the problem has been introduced into a number of design standards, including standards adopted in the nuclear industry. It will be certainly developed further when the problems of ensuring safe operation of engineering facilities in extreme situations will also be included in the scope of consideration with the detailed assessment of parameters of stress σ, strain *e*, durability according to the number of cycles *N* and time τ, as well as the effects of the environment *Φ*.

The criteria base and the system of design equations for assessment of limit states at all (design, manufacture, operation) stages of the *EF* life cycle that should be considered for justification of the strength, service life, reliability, survivability, safety, risks and security of facilities become more complex. The effects of stress concentration, boundary problems of the theory of elasticity and plasticity have now been transformed into an analysis of very complex scientific, design, technological, social and economic problems. This requires analytical, numerical and experimental methods to be applied for the stages of nonlinear behavior of materials and structures when their mechanical properties start to vary in the process of *EF* manufacture and operation.

3 Determination of the parameters of limit states

The basic tasks of substantiating the design characteristics and the formation of relevant criteria in the framework of theoretical and experimental mechanics, deformation and fracture mechanics, and catastrophe mechanics include three main ones:

- calculated-experimental analysis of stress-strain states (σ, e) taking into account mechanical Q^s, thermal Q^s_t, aero-hydrodynamic Q^s_{ah} impacts as well as impacts of external radiation and corrosive environment Q^s_{rc}. In this case, local stresses σ^s_{max} and strains e^s_{max} prove to be dependent on the number of loading cycles N^s, time τ^s, and temperature t^s;

$$\left\{\sigma^s_{\max}, e^s_{\max}\right\} = F_s\left\{P^s, Q^s_t, Q^s_{ah}, Q^s_{rc}, N^s, \tau^s, t^s\right\}; \tag{1}$$

- analysis of the trends of static, dynamic, cyclic and sustained elastic and elastoplastic deformation for varying frequencies f_τ, amplitudes of stresses and strains e_a^s, temperatures t^s and time τ^s;

$$\left\{\sigma^s_{\max}, e^s_{\max}\right\} = F_{1s}\left\{f_\tau, \left(\sigma^s_a, e^s_a\right), t^s, \tau^s\right\}; \tag{2}$$

- analysis of the criteria and conditions for the accumulation of damage d^s, as well as cyclic durability N_c^S for the stages of crack initiation and propagation:

$$\left\{d^s, N^s_c\right\} = F_{2s}\left\{f_\tau, \left(\sigma^s_a, e^s_a\right), t^s, \tau^s\right\} \tag{3}$$

The results of experimental and numerical studies on specimens, models and full-scale constructions make it possible to determine safety factors for stresses n_σ, strains n_e, number of cycles n_N, time n_τ, exposure to environment n_Φ and crack size n_l:

$$\left\{n_\sigma, n_e, n_N, n_\tau, n_\Phi, n_l\right\} = \left\{\frac{\sigma_c}{\sigma^s_{\max}}, \frac{e_c}{e^s_{\max}}, \frac{N_c}{N^s}, \frac{\tau_c}{\tau^s}, \frac{\Phi_c}{\Phi^s}, \frac{l_c}{l^s}\right\}, \tag{4}$$

where the subscript "*c*" refers to the critical (limit) value of the relevant characteristics of strength, durability, crack resistance, and the index "*s*" refers to the corresponding values during operation.

The available computational and experimental information on the loads Q, temperatures t, stresses σ and strains e, as well as the criterion values of safety factors for stresses of the resistance to deformation and fracture of the structural materials forms the basis for constructing the curves of limit states:

$$Q_c = \{(\sigma_{\text{mod}}, e_{\text{mod}})_{\max k}, t, \tau, N\}, \tag{5}$$

where Q_c is the critical (limit) combination of mechanical, temperature and other types of impacts for different loading modes fot time τ, number of cycles N, temperature t.

The values of Q_c, as a rule, are established according to the criterion values of local stresses $(\sigma_{\text{mod}})_{\max k}$ or strains $(e_{\text{mod}})_{\max k}$. The following equations are used for this purpose:

- curves of isothermal low- or high-cycle fatigue for corresponding materials

$$\{(\sigma_{\text{mod}})_{\max k}, (e_{\text{mod}})_{\max k}\}_c = f_N \left\{ \frac{N, \sigma_b, \psi_c, S_c}{\sigma_p, m} \right\}, \tag{6}$$

Where σ_b is the ultimate strength, σ_p is the yield strength, S_c is stress at fracture, ψ_c is the relative narrowing in the neck of the specimen at fracture, m is the stress hardening exponent in the elastic-plastic region;

- curves of sustained isothermal strength

$$\{(\sigma_{\text{mod}})_{\max k}, (e_{\text{mod}})_{\max k}\}_c = f_\tau \left\{ \frac{\tau, \sigma_b, \psi_c, S_c}{\sigma_p, m} \right\}, \tag{7}$$

- static strength curves at varying temperatures t

$$\{(\sigma_{\text{mod}})_{\max k}, (e_{\text{mod}})_{\max k}\}_c = f_t \left\{ \frac{t, \sigma_b, \psi_c, S_c}{\sigma_p, m} \right\}. \tag{8}$$

The curves described by expressions (6) and (7) for metal structural materials, have as a rule, a monotonic form: when the values of N and τ go up the limit values of stresses and strains at fracture decrease.

According to expression (8) the temperature dependences of the critical stresses and strains in the low temperature region can be non monotonic: for radiation brittle or cold brittle metal states, strength and plasticity in this case can decrease.

The limit curves constructed in accordance with expressions (6) - (8) for a given loading mode defined by the values $\{(\sigma_{\text{mod}})_{\max k}, (e_{\text{mod}})_{\max k}\}_i$ are used for determination of the limit (critical) values of parameters N_{ci}, τ_{ci}, t_{ci}, Φ_{ci}.. If the values of N_i, τ_i, t_i, Φ_i, for the specific loading mode are known then using the curves of fatigue, crack resistance, long-term strength and resistance to external impacts, one can estimate the level of the accumulated damage.

In the general case spatial three-dimensional surfaces of limit and allowable states can be constructed to analyze the conditions of critical damage occurrence (Fig. 2). The space that contains these surfaces has the following coordinate axes:

- axis of operational loading factors (forces Q, nominal stresses σ_n, stress intensity factors K_I, maximum local stresses $(\sigma_{\text{mod}})_{\max k}$ in stress concentration zones);
- the axis of temperature-time and cyclic operation parameters (temperature t, time τ, number of loading cycles N);
- the axis of the accumulated damage (dimensions l of defects with accounting for their shape and spatial location).

The occurrence of fracture, unacceptable plastic deformations or critical cracks in the analyzed structural components corresponds to the reaching of the limit state (the surface of the limit states in Fig. 2). The limit load Q in this case is a vector passing through the origin of coordinates with angles corresponding to the given state of the structure in terms of the parameters l, t, τ, N, σ_n, K_I, $(\sigma_{\text{mod}})_{\max k}$. If you introduce the necessary safety factors n against the specified parameters, then from the surface of limit states one can go, through the region between the dashed and solid curves in Fig. 2, to the surface of acceptable states and the acceptable load [Q]. In this case, the specified strength, service life and safety can be considered as ensured if the length of the vector of the operational load for certain specific conditions Q^s is less than or equal to the length of the vector of the load that is acceptable for these conditions [Q], i.e. $Q^s \le [Q]$.

Traditional methods for calculation of strength and service life were developed on the assumption of the defect-free state of the structural material (l= 0). In this case from the surfaces of limit and acceptable states (fig. 2) one can go to the limit and acceptable curves (in the plane «Q, σ_n, K_I, $(\sigma_{\text{mod}})_{\max k} - t$, τ, N» - static strength (at a predetermined temperature t), long-term sustained static strength (for a given time τ) and cyclic strength (for a given number of cycles N).

The strength and flaw resistance at the early stages were determined by the criteria of linear fracture mechanics for the plane «Q, σ_n, K_I, $(\sigma_{\text{mod}})_{\max k} - l$». For modern design methods for strength, service life and flaw resistance assessment that use the concepts of limit and acceptable states, it is important to adopt unified constitutive equations, uniform fracture criteria and uniform sets of design characteristics regardless of the type of construction, properties of structural materials and operational loading modes.

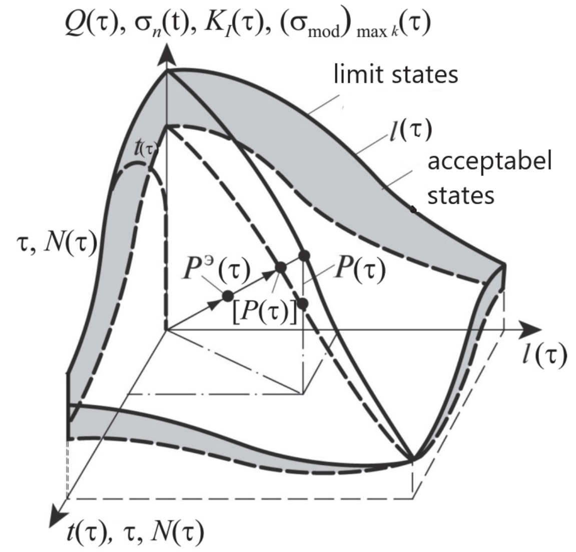

Figure 2 – Scheme of construction of the surface limit and allowable states in the analysis of strength and service life

The considered laws of deformation and fracture of structural materials are used for carrying out comprehensive risk based assessments of technological safety and protection level of the *EF* subjected to complex operational impacts. These laws that are taken into account at the design stage and combined with diagnostic and monitoring data on the current state of the *EF* forms the foundation of databases and knowledge bases for assessment of its strength, service life and durability.

4 Criterion base of technological safety

Conditions for reaching the limit states (fracture, the formation of critical cracks, loss of resilience, unacceptable plastic deformations, etc.) under a wide range of loading parameters can be characterized by the following groups of situations occurring during equipment operation [1, 5]:

- normal (regular) situations when the requirements of strength, service life, reliability and damage tolerance are satisfied at specified levels of safety factors n and material imperfection l^s; in this case the EF operation continues according to the existing rules and regulations;
- incidents or deviations from normal conditions in terms of operating impact parameters $(\sigma)^s_{max}$, mechanical properties and defectness level l^s with a decrease in safety factors n; in this case damages and failures may occur. This requires diagnostic and repair work;
- design basis emergencies when there is a significant increase in the levels of operational impacts, a decrease in strength (σ_p, σ_b) and plasticity ψ, an increase of the defectness level l_s. In these cases, the operation of the equipment should be terminated, its condition analyzed, repair and restoration, as well as residual strength and service life assessment should be carried out;
- beyond design basis emergencies when safety factors n and design characteristics are transferred to an unacceptable area ($n \leq 1$); in this case, there is a normal or abnormal shutdown of the equipment, work is underway to restore them, and decisions are made whether it is possible or not to continuer the work of the EF;
- hypothetical emergencies in the implementation of the most dangerous, unforeseen impacts $(\sigma)^s_{max}$ accompanied by significant damage ($l^s \rightarrow l_c$) of load carrying elements.

Each of these types of emergencies corresponds to a certain level of the reduction of technological safety that can be assessed by values of risk $R^s(\tau)$ at a current stage τ^s of operation. The values of risk are determined by the probabilities $P_i^s(\tau)$ of each of these i situations and economic consequences $U_i^s(\tau)$ of their occurrence:

$$R^s(\tau) = F_R\left\{P_i^s(\tau), U_i^s(\tau)\right\} \tag{9}$$

In this case the safety parameter can be quantified as a corresponding safety factor:

$$n_R = R_c(\tau) / R_i^s(\tau) \tag{10}$$

where $R_c(\tau)$ is the critical, or unacceptable risk for a specific facility; $R_i^s(\tau)$ is a design value of risk for the moment of operation τ in i-th situation; n_R is a risk-based safety factor.

The main task of the indicated above transition from traditional methods for ensuring the specified operating conditions of manmade facilities to the new ones is to solve the problem of ensuring a certain level of risks $R(\tau)$ of possible accidents and disasters, and require to use such norms of calculations and tests that would provide an acceptable level of risks. This approach determines (Fig. 3) all the main groups of the above design characteristics: protection $Z_c(\tau)$, safety $S(\tau)$, and risks $R(\tau)$; service life $R_{N\tau}(\tau)$, and damage tolerance $L_{ld}(\tau)$; strength $R_\sigma(\tau)$, stiffness $R_\delta(\tau)$, and resilience $R_\lambda(\tau)$.

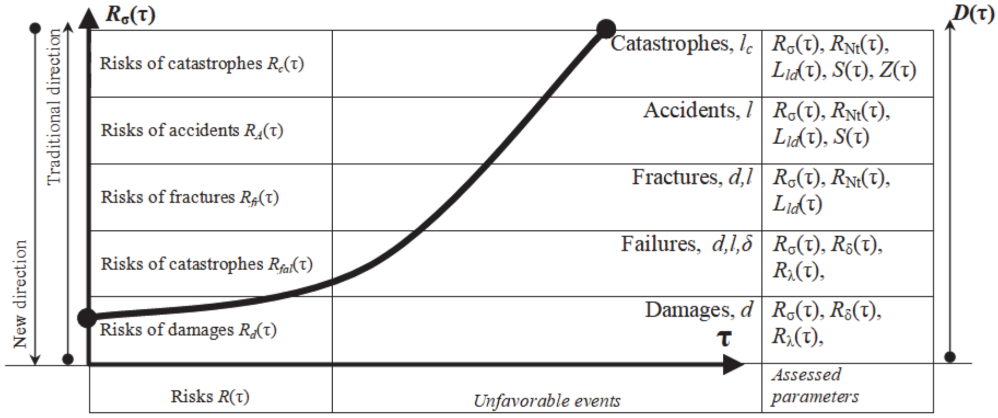

Figure 3 – Sequence of analysis of hazardous conditions of facilities and corresponding risks

At the same time, the trajectories of the development of hazardous events that lead to equipment failures can be of different type (Fig. 3), characterized by an increase of the values of risk $R(\tau)$ over the time τ.

Damage accumulation, initiation of failure, accident, and catastrophe, as well as risks $R(\tau)$ that correspond to them can be considered in time τ as both short-term and long-term processes that include various stages of deviations from the normal operating modes, the accumulation of mechanical damage, failures, as well as violation of control over the quality and state of the equipment and personnel. This is taken into account when developing a risk analysis algorithm $R(\tau)$, as well as scenarios of hazardous events development and determining the key parameters of assessed facilities.

The first stage of damage accumulation d, failures, and partial destructions with the development of local damage (cracks l) ends in an emergency situation at the facility, which may be associated with the beginning of cascade fracture and irreversible deviations from normal operation conditions. An accident or catastrophe with the occurrence of a limit state in the structural components and the formation of critical defects l_c is the final stage of unfavorable situations and is characterized by the highest, unacceptable (critical) risks $R(\tau)=R_c(\tau)$.

The limit state of a facility may be reached along different trajectories, depending on the conditions, modes, and type of loading. At certain stages of the facility life cycle (including those defined by the regulations), its current states are subjected to automated diagnostic control with determination of the accumulated damage (Fig. 4). This allows one to make decisions about the possibility of further operation of the facility [1, 11-13].

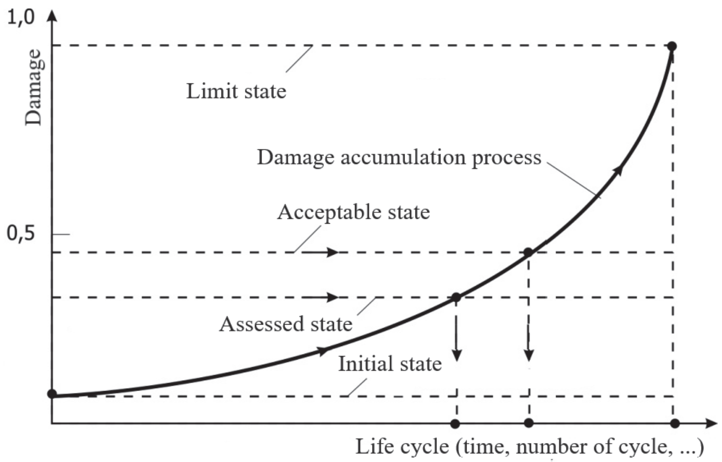

Figure 4 – Trajectories of damage accumulation at different stages of the facility life cycle

A fairly fully developed criteria and regulatory framework was developed for assessment of facilities that operate under normal operation conditions. The system of calculations of parameters characterizing design basis situations, beyond design basis, and hypothetical ones is founded on the analysis and consideration of the conditions for the occurrence of failures and damaged states leading to emergency and disastrous situations. This requires essential improvement and clarification of the criteria, approaches and methodologies that were developed for assessment of normal situations. In the transition from the assessment of normal situations to the assessment of beyond design basis situations and possible hypothetical ones that are typical for severe accidents and catastrophes, one should note that the relevant criteria and regulatory frameworks are missing.

The operating conditions of the engineering facilities and the scenarios of their changes are important for the analysis of scenarios of reaching limit states [1, 6, 14, 15]. Fig. 5 illustrates such scenarios. The horizontal axis describes factors of operation conditions (loading cycles, times, temperatures, corrosive environments) F^s, while the vertical axis describes the system response to these conditions S^*.

The lower area in fig. 5 up to the dotted line corresponds to the acceptable states. It includes normal situations with the operation of the facility within the parameters assigned in accordance with the design standards. In this area the Each point «S^s-F^s» of this area characterizes the current operational state of the EF.

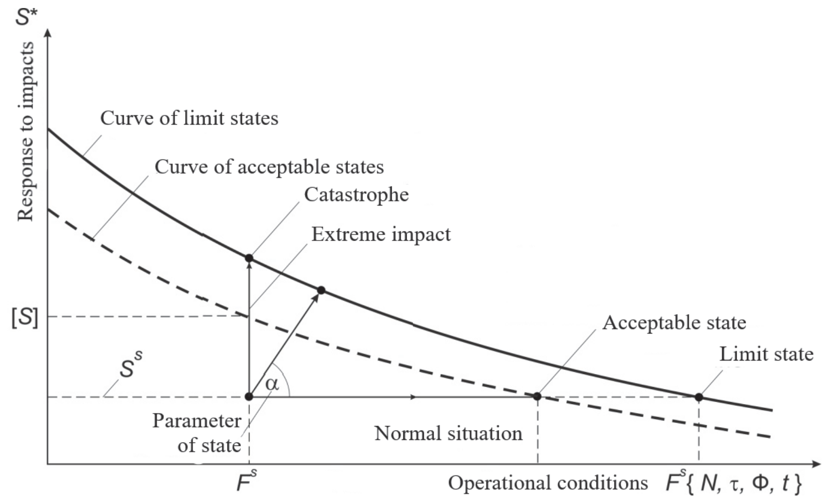

Figure 5 − States, scenarios and factors of operation of facilities with the possibility of accidents and disasters

A critically loaded element of the facility can transit from this point into dangerous (limit) states along different paths characterized by an angle α (scenario parameter). For example, moving from it current position to the right (when $\alpha = 0$) one can assess the acceptable service life with respect to N or τ (up to the crossing with the dotted line) and limit service life (up to crossing with solid line). Rising from the current point upwards (at $\alpha=90^0$), a facility can reach the limit state beyond which a disaster occurs. In this case the task of analyzing safety of the facility in such a scenario should be solved according to a completely different methodology. At the same time, the existing regulatory stress-based design approach that uses standard mechanical properties determined using the existing experimental base is insufficient.

5 Experimental determination of design characteristics

As noted above, the results of mechanical tests play an important role in calculations of strength, service life and safety under various modes of loading of engineering facilities. They are included as the main parameters in the corresponding criteria expressions [2, 3, 7, 10, 16, 17]. As machines and structures are being improved and their loading conditions become more complex, the range of structural materials, technologies and types of mechanical tests expanded in order to obtain characteristics of their mechanical properties as basic criteria parameters (Table 1).

Already at the stage I (according to Table 1) the basic approaches to the assessment of the main characteristics became established. Their essence is that the maximum operational impacts Q^S_{max} on the load carrying elements should not exceed the acceptable values $[Q]$ that in turn are determined by critical values of Q_c with the introduction of the corresponding safety factors n_Q.

$$Q^s_{\max} \le [Q] = \frac{Q_c}{n_Q}. \qquad (11)$$

When the problem of ensuring strength is considered, the term dangerous loads Q_c reefers to loads causing destruction Q_b or plastic deformations (fluidity) Q_p. Then condition (11) can be rewritten as:

$$Q^{э}_{\max} \le [Q] = \min\left\{\frac{Q_c}{n_Q}, \frac{Q_p}{n_{Qp}}\right\} \qquad (12)$$

If it is necessary to satisfy stiffness conditions then the critical forces Q_c in expression (11) are the forces Q_ε that cause the specified critical strains ε_c.

If the condition of resilience should be ensured then the critical forces Q_c in (11) are the forces Q_{st} that cause the loss of resilience. In these cases safety factors against strain $n_{Q\varepsilon}$ or stability n_{Qst} are introduced into expression (12). Safety factors n in all the considered cases should be greater than one (n>1).

Table 1 - Types of methods of mechanical tests and criterial characteristics of materials obtained using these methods

Stage	Types of materials	Calculation section	Test type	Material characteristic
V	Metals, composites, ceramics, nano-materials	Safety	Testing for fracture and catastrophe	Q_c, l_c, N_c, τ_c (Q^s, N^s, τ^s)
IV	Metals, composites, ceramics	Resilience	Tests for crack resistance	K_{Ic}, K_{Iec}, δ_c, J_c (K_I^s, δ^s, J^s)
III	Metals, composites	Reliability	Combined safety tests	v_{σ_p}, v_{σ_b}, $v_{\sigma_{-1}}$ (v_σ^s)
II	Metals	Durability	Cyclic, long-term tests	σ_{-1}, N_0, σ_{lt}, τ_0 (σ^s_{an}, $\sigma^s_{a\,\max}$)
I	Strength, rigidity, resilience		Static, dynamic tests	σ_b, σ_p, E, μ (σ_n^s)

Expressions (11) and (12) are valid for each of individual load carrying component, its dangerous sections *S*, geometric shape and size, loading conditions and the type of structural material. There is an infinite number of such combinations of impacts, forms, loading conditions and types of materials. In this regard in order to get an invariant conditions of strength, rigidity and resilience, the calculations by expressions (11) and (12) are replaced by calculations at maximum nominal stresses $\sigma_{\max n}$, determined using the equations of the strength of materials.

$$\sigma^{э}_{\max n} = \frac{Q^{э}_{\max}}{S} = \left\{ \frac{N}{F}, \frac{M_b}{W_{ax}}, \frac{M_t}{W_p} \right\}, \tag{13}$$

where *F* is the area cross section, *N* is axial force, W_{ax} is area moment of inertia, M_b is bending moment, W_p is polar moment of inertia of area, M_t is torsion moment). Then using equations (11) and (13):

$$\sigma^{э}_{\max n} \le [\sigma] = \frac{\sigma_c}{n_\sigma}. \tag{14}$$

The criterion values of critical stresses σ_c are the ultimate strengths σ_b, yield strengths σ_p, stresses σ_ε at the given strain ε, stresses σ_{st} at the loss of resilience.

The main types of mechanical testing of structural materials to ensure the conditions of strength, rigidity and resilience are standard static tests of smooth laboratory specimens under tension (compression), bending or torsion. Moreover, for most engineering products the following conditions are met:

$$1 \le n_p \le n_{st} \le n_\varepsilon < n_b \le (2{,}5 \div 3). \tag{15}$$

For dynamically loaded machines, as a rule, an increase in the impacts $Q^s_{\max d}$ and the corresponding stresses $\sigma^s_{\max d}$ is observed.

$$\sigma^s_{\max d} = \sigma^s_{\max n} \cdot K_d, \tag{16}$$

where K_d is a dynamic factor of loading (usually $1 \le K_s \le 2{,}5$).

In simplified calculations of the strength of dynamically loaded elements of machines and structures it was allowed to use static characteristics of mechanical properties in a deterministic formulation and to apply lower values safety factors than indicated in expression (15). When the statistical dynamic tests of specimens were mastered, the values of safety factors used in (15) were preserved taking into account the growth of σ_p, σ_b, σ_ε, σ_{st} due to the increase of dynamic loading and scatter of mechanical properties.

Methods of mechanical tests and calculations based on expressions (11) - (16) have previously been widely used in the automotive industry, agricultural machinery, machine tool industry, power engineering. Later on these approaches were generally retained, but as the calculations were refined, safety factors n_σ gradually decreased (by about 15% within one decade). The use of probability theory and mathematical statistics in this case made it possible to estimate the probability and risks of accidents and catastrophes [1, 2, 5].

For many decades, there has been a continuous improvement in the methods of mechanical testing of structural materials. The following groups of mechanical tests are currently being implemented: laboratory tests on specimens, bench tests on models, and field tests on full-scale components and real facilities (Fig. 6a,b). At the same time, laboratory tests are carried out [2, 3] on test equipment controlled by automated computer systems (Fig. 6a, b) using various types of materials of specimens (Fig. 6c) or full-scale model components of the facility under study (Fig. 6b).

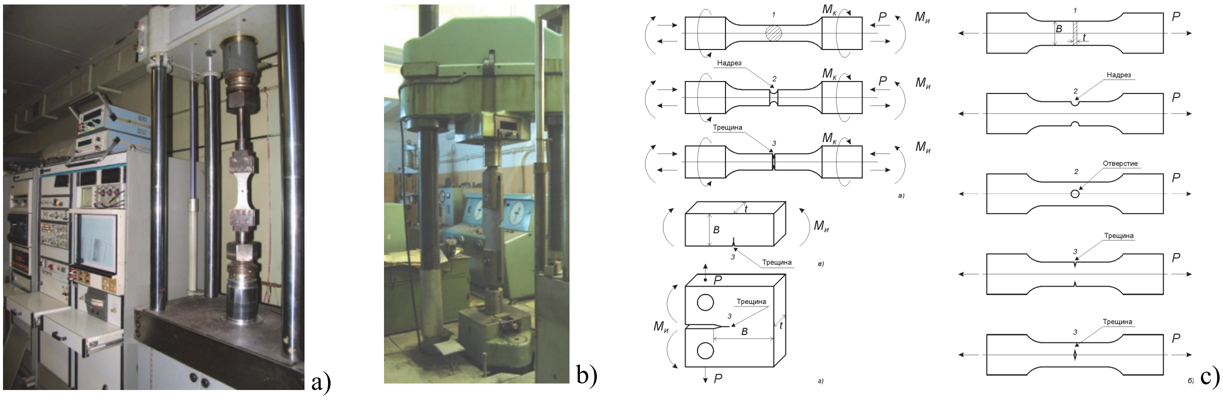

Figure 6 – Testing of samples (a) and full-scale models (b); types of test specimens (c)

So, for example, experimental studies of stress-strain states of components of a liquid-propellant rocket engine (Fig. 7,a) and its turbine and pumping unit of fuel supply (Fig. 7b) are realized on models made of optically sensitive materials (Fig. 7c) of such highly loaded elements as the impeller of a high pressure hydrogen pump, with determination of stresses at various points of its elements (Fig. 7, d) [18].

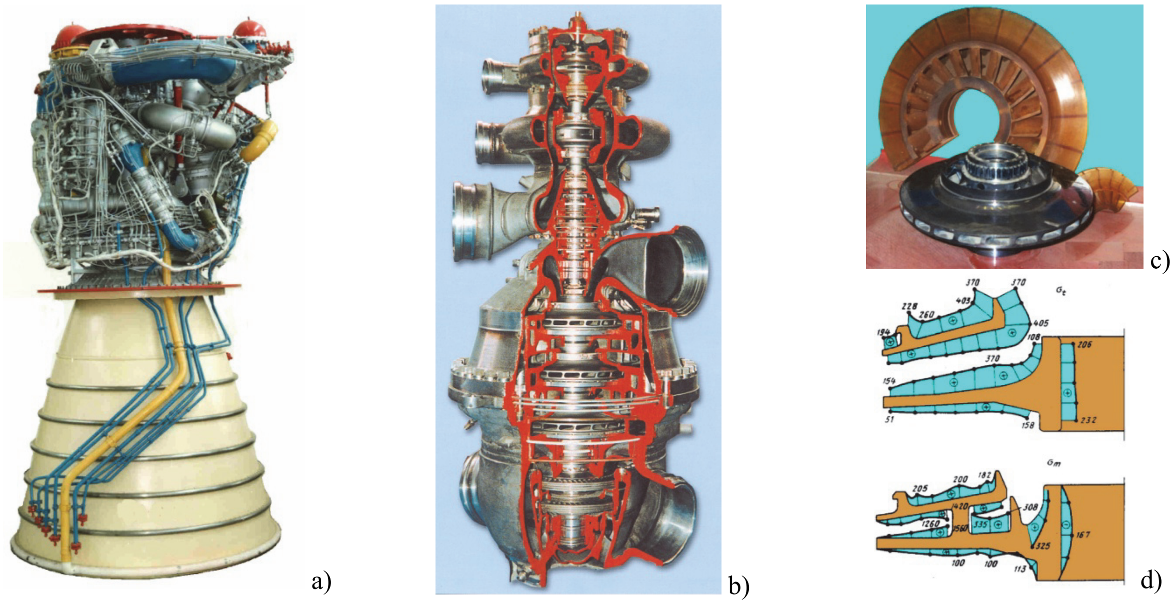

Figure 7 – Experimental study of the stress-strain state of the components of liquid-propelled rocket engine (a) and its turbo pump unit using the pump disk model (c) and data on stress distribution (d)

When studying the dynamics of loading of the water-cooled power reactor components (Fig. 8, a) it is also important to use detailed models of their connecting components (Fig. 8, b) allowing one to carry out the experimental determination of stress distribution [19, 20] and automated registration of diagrams of dynamic response (Fig. 8, c) to the corresponding operational impacts with their analytical computer processing.

In general, the types of mechanical tests are divided into standard (regulated by standards), unified (carried out according to the guidelines) and special (according to the relevant methodological recommendations). The data obtained by tests on stress-strain states and characteristics of mechanical properties are used in two main types of calculations: basic ones (with a selection of the main dimensions of load carrying structural components and types of materials according to established design schemes and design cases); and refined ones (with the verification of the validity of the choice of design parameters accounting for design, technological and operational factors).

The formation of automated databases on the characteristics of the mechanical properties of materials is carried out with the experimental studies of static and cyclic (including low-cyclic) strength of materials that are controlled by experimental computation systems. Automated experimental research systems should provide:

- comprehensive automation of tests for the implementation of specified loading modes with control of the loading process and the initial processing of the obtained data;
- the formation of an array of experimental information to be included into data banks for further processing and issuing the required parameters for the relevant requests.

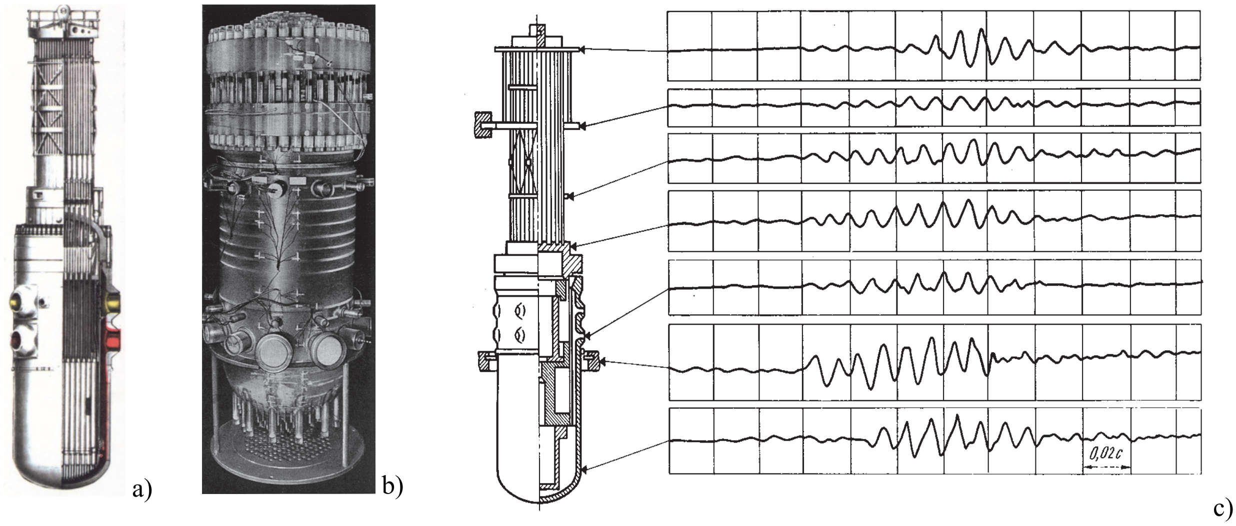

Figure 8 – Experimental study of the dynamics of a water-water energetic reactor (a) elements on its model (b) with registration of response diagrams (c)

Obtaining a significant amount of experimental data through automated test systems requests its systematic storage and processing. In this regard, a certain role in the automation of the storage, retrieval and processing experimental information is played by data banks, that are formed both on the general principles of collecting standard information on the mechanical properties of materials, and on the problem-oriented trends of solving the problems stated. The main task of the data bank on the physical and mechanical properties of materials is the accumulation and storage of the information received on the basis of a special input form. For example, automating cyclic testing in an elastic and plastic deformation area, taking into account all the features inherent in this type of experiments, allows us both to reproduce various modes of loading , such as simulating conditions in the stress concentration zone; or high-temperature tests with separation of mechanical deformations from the thermal ones. Moreover, it provides the possibility of recording large volumes of specific experimental data, including data on kinetics of the deformation processes, the parameters of cyclic deformation diagrams and others that are used as the criteria parameters in the above equations of state for assessing strength, service life and safety.

Generalized dependencies of the properties of the structural materials for a specific loading conditions as well the list of materials corresponding to a given mechanical properties; standardized characteristics of the studied materials, and other data can be obtained as a result of the automated search, as an output of the functioning of the data bank. Such data on the mechanical properties of a material form the criterion basis of a comprehensive analysis of the conditions for reaching the limit states corresponding to parameters of strength, service life, flaw resistance and safety of engineering facilities [1-10] at all stages of their life cycle (Fig. 1) for a subsequent automated assessment of current states in the process of their diagnostics and monitoring through the problem-oriented computing systems.

The problem-oriented automated information systems used in the analysis and determination of the safe operation parameters of high-risk engineering facilities are intended mainly for the in-depth solution of relevant problems of ensuring strength, service life and safety using experimental information and methods of its processing for determination of design characteristics. These systems use specific software to implement the required comprehensive engineering assessments of conditions of safe operation of load carrying components. This software is developed taking into account the considered above constitutive laws and the corresponding criteria base (expressions (1) - (16)) describing the conditions for reaching the limit states (Fig. 2, 4) and the scenarios of their development (Fig. 5) in connection with the kinetics of accumulation of damage in the engineering facilities (Fig. 3).

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