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MECHANICS OF MATERIALS: STRENGTH, SERVICE LIFE, SAFETY

Experimental-Computational Methods for Determination of the Stress-Strain State of Structural Components

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Abstract—Results of scientific achievements in the development of experimental and computational methods for study of stress-loading parameters of structural components are reported. Special attention is paid to theoretical and long-term developments based on the methods of inverse problems of experimental mechanics. The paper provides examples of solutions of transient thermal conductivity problems with a limited amount of experimental data on determination of high-gradient inhomogeneous residual stress fields and flaw detection in structural components.

Keywords: stress loading of structures, flaw detection, experimental mechanics, inverse problems

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The development of experimental methods for determination of the stress-strain state (SSS) is inseparably associated with Professor N.I. Prigorovskii, an honored scientist of the Russian Federation who worked at the Institute of Machine Science from 1940 to 1988. He played a leading part in the development and practical application of experimental methods and facilities for determination of displacements, deformations, stresses, forces, and loading in complicated structures such as full-scale tensometry under extreme conditions, polarization optical and holographic methods for recording of strain fields and displacements, and the brittle coating technique. The researchers of his school of thought such as S.E. Bugaenko, A.K. Preis, G.Kh. Khurshudov, and M.L. Daichik created the theoretical basis of simulation and variation of the SSS parameters, methods for processing and analysis of experimental data, and assessment of the accuracy of results and developed instruments and equipment for laboratory and full-scale measurements. Simultaneously, researchers at the laboratory of the Institute for Machine Science (IMASh) of the Russian Academy of Sciences headed by Academician S.V. Serensen (N.A. Makhutov, V.V. Larionov, O.A. Levin, etc.) successfully developed methods for analysis of the plastic deformation processes and damage accumulation and propagation in metals such as light-sensitive coating and moiré techniques. The scientific foundation for these developments and the results of their successful application for estimation of the stress-loading, strength, and service life are represented in numerous publications by researchers at IMASh [1–9, etc.].

A steady trend toward enhancing the operational characteristics of structures posed fundamentally new challenges to the experimentalist. In recent years, a rapid development of computer engineering has provided great opportunities for computational analysis of the SSSs and strength of structures on the basis of the finite element method (FEM), which has a great impact on development of experimental mechanics. Thus, methods for experimental study of the SSSs based on physical modeling did not win the competition with the computational FEM-based analysis and lost their practical value.

Owing to modern computer technologies, the experiment has gained efficiency in data acquisition and interpretation of the results.

New promising lines of experimental analysis of the SSSs such as methods of digital electronic speckle pattern interferometry (ESPI), digital holography (DH), and digital image correlation (DIC) have come into existence, which enables real-time recording of the displacement fields and creation of systems for monitoring force loading and heat strain of full-scale structures [10–13]. Computer technologies have opened new opportunities for a correct interpretation of experimental results and development of fundamentally new approaches to analysis of the SSSs and diagnostics of structural components by the methods of inverse problems of experimental mechanics. Let us consider approaches of this kind by the examples of developments made by researchers at IMASh in recent years.

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† Deceased.

METHODS FOR STUDY OF RESIDUAL STRESSES

The methods used in practice until recently, both destructive and nondestructive, were aimed at analysis of locally homogeneous residual stress (RS) fields and did not enable investigation of high-gradient RS fields when the stresses on the base varied considerably on the order of about 1 mm with the exception of the cases of a one-dimensional distribution of the RSs. Determination of RSs of this type, however, is often a necessary condition for evaluation of the strength and the service life of structures with weldments, dissimilar components, etc.

In this connection, the researchers at IMASh have developed experimental-computational techniques for study of high-gradient—to the point of discontinuous—residual stress fields in components fabricated of homogeneous and piecewise-homogeneous materials by cutting. Approaches to such investigations are based on the formulation of the problem of analyzing the RSs as an inverse problem of the elasticity theory and are reduced to solutions of Volterra or Fredholm integral equations. Unlike the well-known techniques, they do not suppose knowledge of a priori relations between the distribution of the sought RSs and the parameters of the deformation response caused by recesses of different types in the component under investigation. Practical implementation of such approaches involves mathematical processing of a large amount of experimental data, which necessitates use of optical interference techniques as a way to record the deformation response caused by cutting the component.

When using the Volterra integral equation method [14], a rectilinear slit in a flat component of an arbitrary shape with a residual stress field is lengthened in discrete steps; at each step, a certain stress-state parameter is measured at the characteristic point that allows tracking the movement of the slit's tip (Fig. 1a). The relation between residual stresses $s_y(\xi)$ and an experimentally determined variation in stress-state parameter $\mu(x)$ along the cut line can be presented in the form of a Volterra equation of the first kind:

$$\int_0^x B(x, \xi)\sigma_y(\xi)d\xi = \mu(x), \qquad (1)$$

$$0 \le \xi \le x \le L,$$

where $\sigma_y = -s_y$ and L is the maximum length of the slit. Operator kernel $B(x, \xi)$ corresponds to the values of $\mu(x)$ at point x from action δ at point ξ and the domain of its determination is a triangle; i.e., at $\xi > x$, we obtain $B(x, \xi) = 0$.

When the Volterra integral equation method used in practice, the magnitude of the increment in the slit length is determined during the preparation for the experiment on the basis of numerical simulation considering the sensitivity of the experimental method and the character of function $B(x, \xi)$. This requires a preprocessing of the experimental source information and construction by discrete data of certain continuous and differentiable analogs within a range of errors comparable with the experimental errors. In selecting procedures for processing the input data, preference is given to the regularization methods.

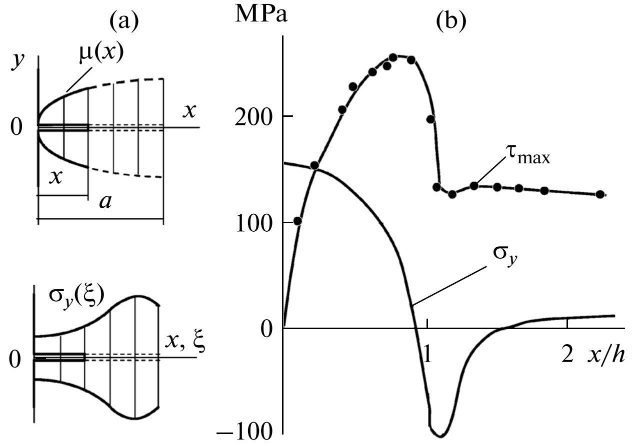

Fig. 1. (a) Scheme of the sequential lengthening of the rectangular slit, an indicator of residual stresses, and (b) a high-gradient residual stress field detetmined by the Volterra integral equation.

Figure 1b shows an example of an investigated high-gradient RS field that occurs in a flat specimen cut out from a bimetal VVER-1000 reactor vessel shell. The vessel is made of high-strength alloyed steel; on the inner surface of the shell, there is a built-up weld seam with width $h \approx 9$ mm from stainless austenitic steel.

However, despite all possibilities for solving the general problem of determination of residual stresses, the complexity and laboriousness of the proposed approach restrict its application in solving practical problems.

The crack lengthening method can be interpreted as a particular case of the above general approach. In this case, a mathematical slit, a crack, is considered as a slit on the faces of which residual stresses are relieved; the distribution of the opening mode stress $K_I(x)$ and transverse-shear stress $K_{II}(x)$ intensity factors is considered as stress-state parameter $\mu(x)$. In such a definition, the governing equation of a number of boundary problems is reduced to a Volterra equation of the first kind with the Abel kernel, which enables their closed analytical solutions. As a result, a stable procedure for computation of residual stresses on the basis of experimental data becomes sufficiently simplified. However, the experimental study is more laborious since, to obtain the function of the stress-state parameter, it is necessary to determine quantities K_I and K_{II} at each step. In [15], relations were obtained that allowed application of the crack lengthening methods to investigations of the RSs in the near-surface areas of the components (the edge crack method) and in piecewise-homogeneous structural elements. This method has been effectively applied to study the RSs in modern engineering structures [9, 16, etc.]. Further developments were the techniques for investigating the RSs based on experimental-analytical approaches to solutions of the problem [17, 18] that can be interpreted as updating of the Fredholm integral equation of the first kind.

SOLUTION OF INVERSE THERMAL CONDUCTIVITY PROBLEMS

One of the problems of ensuring and enhancing the service life of the VVER reactor equipment at nuclear power plants is determination of the SSSs of the structural components under real operating conditions that allow transient temperature impacts.

Direct strain measurements of internal tube surfaces that are the most stressed reactor components under transient temperature impacts in real conditions are in practice not feasible. This necessitated development of methods for solution of inverse thermal conductivity and thermal elasticity problems that suppose restoration of transient boundary conditions on the inner surface of the structures by the data on the temperature and heat-flow (or stress) distribution on the outer surface.

The problem under consideration, for example, for structures in the form of plates, cylindrical tubes, and spherical shells, in the one-dimensional formulation with regard to the spatial coordinates is reduced to the solution of the Volterra integral equation of the first kind

$$\int_0^t B(t-\tau)T(\tau)\mathrm{d}\tau = T^*(t) - T^0(t), \qquad (2)$$

$$0 \le \tau \le t \le t_0,$$

where $B(t-\tau)$ is the integral operator kernel that is the system's transfer function, $T(\tau)$ is the sought temperature function on the inner surface, $T^*(t)$ is the measured temperature values on the outer surface, and $T^0(t)$ is the temperature on the outer surface corresponding to consideration of the impacts of the initial temperature conditions and the thermal insulation of the outer surface.

Integral equation (2) is an incorrectly formulated problem and is solved using regularization algorithms that ensure a stable procedure for restoration of the sought temperature distribution on the inner surface [19–21].

For numerical implementation, the Inverse special-purpose software package was designed to determine transient boundary temperature conditions on the internal surfaces of structures in the form of plates, cylindrical tubes, and spherical shells by the known temperature distribution on the heat-insulated outer surface [22, 23]. The structural material can be composed of both homogeneous and inhomogeneous materials with different thermophysical and mechanical properties. The problems are solved in both the linear formulation when the material's thermophysical characteristics do not depend on the temperature and in the nonlinear formulation when the temperature has a considerable effect on the material's thermophysical characteristics.

The package also comprises the solution of an inverse thermal elasticity problem [24] that consists in determination of the transient boundary temperature conditions on the inner surface by the measured temperature and thermal stress values on the outer surface. The problem can be solved in both the linear and the nonlinear formulation.

The package consists of the basic Inverse program and four external procedures in the subroutine format:

(i) Subroutine Thermal for solution of the inverse thermal conductivity problem for homogeneous structures,

(ii) Subroutine Contact Teploprovodnoct for solution of the inverse thermal conductivity problem for compound structures,

(iii) Subroutine Nonlinearthermal for solution of the inverse thermal conductivity problem in the nonlinear formulation, and

(iv) Subroutine Termolast for solution of the inverse thermal elasticity problem. Each external procedure has its own internal procedures that work in their medium's environment and can be activated only from it.

When solving the inverse thermal conductivity and thermal elasticity problems, one should bear in mind that the temperature distribution on the inner surface of the equipment has slight oscillating fluctuations caused by high-frequency heat flux density components. When solving the direct thermal conductivity problem, the distributions with different fluctuations may cause outer surface temperatures practically indistinguishable from each other. This means that the inverse thermal conductivity problem does not have a unique solution; therefore, reduction of an incorrectly formulated problem to a correctly formulated one should correspond to physically achievable heat transfer conditions.

To assess the errors of the restoration of the temperature boundary conditions and thermoelastic hoop stresses on the inner surface obtained with the help of the Inverse package, a reference experiment was carried out. The study was conducted on a laboratory setup by the experimental design bureau OKB Gidropress that represents a model of a VVER reactor pipeline, a 200-mm-long tube 12.5 mm in diameter of 08Kh18N10T steel coated with two-layered thermal insulation with a total thickness of 30 mm. The tube was fitted with 13 primary temperature converters at an equal depth apart from the outer and inner surfaces in the central cross section of the model.

As heating elements, a hot air gun and a ceramic heater were used. The inner surface of the model under investigation was cooled by either natural convection or blowing compressed air from the VVER-1000 hot operational test stand by OKB Gidropress.

In the course of testing, several experiments in the temperature range of 20–380°C were carried out in which both uniform heating–cooling of the model under investigation and cyclic temperature variations at a maximum rate of 4°C/s were performed.

Comparison of the solutions of the linear and nonlinear inverse thermal conductivity problems enabled determination of the application limits for the software package in question in terms of the rate and the direction of the transient process.

The maximum relative error of the solution of the inverse problem obtained as a result of testing the Inverse software package did not exceed 10% at 48°C, which was 5°C, and the absolute maximum error of the solution of the inverse problem was 7% at 125°C, which was 9°C. The mean error of the solution of the inverse problem in all experiments was 2–3%, which means 2–4°C.

The following phases in mastering the software package were processing of full-scale measurement data to determine the fields of application of the algorithm and making recommendations on its operation. Different temperature conditions studied in the course of this work that were implemented at the stages of first criticality and startup and operation of the first unit of the Tianwan NPP are presented in Fig. 2. Here, panels (a)–(e) correspond to the following conditions:

(a) a thermal shock in the makeup branch tube of the makeup–purging system, the temperature impact rate of 5.1°C/s;

(b) thermal pulsation in the feedwater branch tube, the temperature impact rate of 0.2°C/s;

(c) cooling down, the temperature impact rate of 0.1°C/s;

(d) temperature compensation in the junction line, the temperature impact rate of 0.76°C/s; and

(e) temperature compensation in the injection branch pipe of the pressurizer, the temperature impact rate of 0.76°C/s.

The hoop stresses shown in Figs. 2a–2c are caused only by temperature factors; the real stresses appear to be higher than the given values, which should be taken

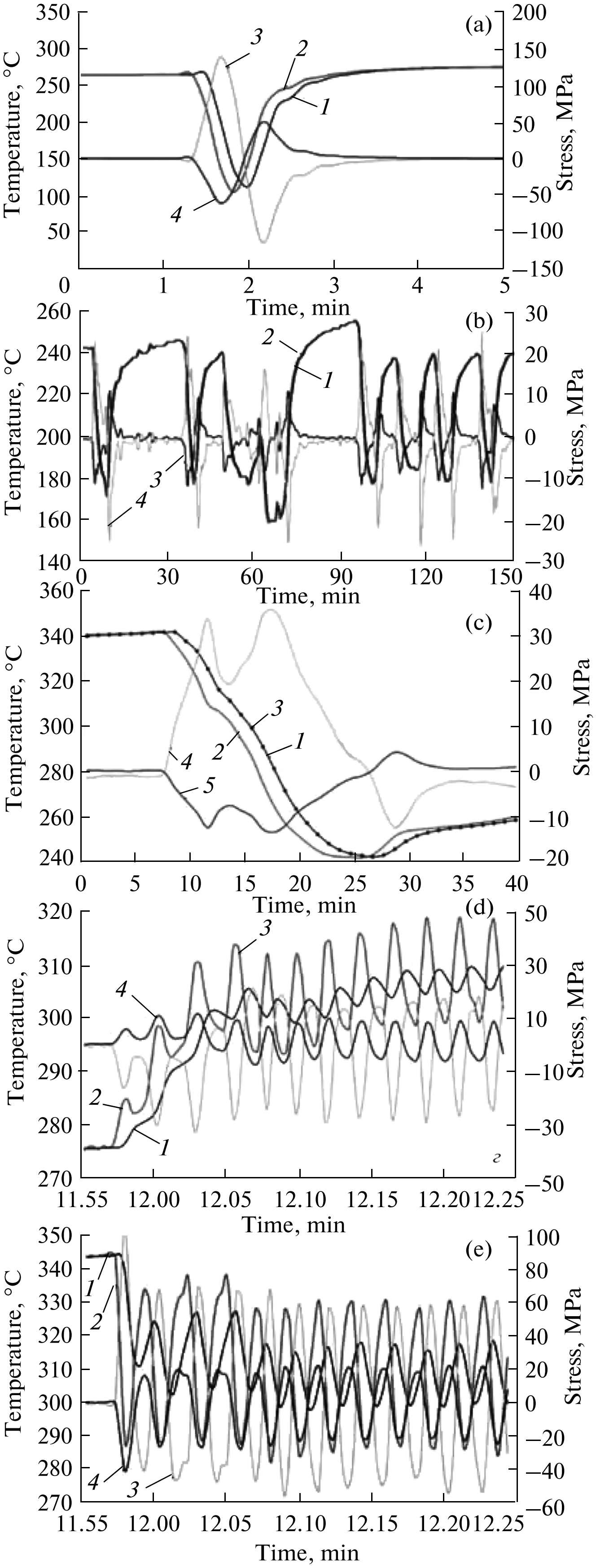

Fig. 2. Dependences of the temperature and the stresses on the time in correspondence with different phases of the first criticality and MCRP implementation in unit 1 of Tianwan NPP: (*1*) the measured outer surface temperature, (*2*) the predicted outer surface temperature (inverse problem), (*3*) the outer surface temperature (direct problem), (*4*) the predicted outer hoop stress, and (*5*) the predicted inner hoop stress.

into consideration when proving the strength of the structure affected by transient temperature impacts. The processed full-scale measurement data on smooth temperature variations at a rate of 0.1°C/s and on thermal shocks at a rate of 5.1°C/s showed the workability of the software within the entire temperature range under investigation.

The problem being solved is especially topical within the framework of the program of development of the Russian nuclear power engineering in terms of proving the strength and enhanced service life of VVER reactor equipment. It is known that the NPP commissioning phase accounts for a considerable extent of the equipment wear. This is proven by a high level of design thermoplastic stresses that occur in the makeup–purging system branch tube with a range of variation of ~250 MPa caused by various thermal pulsations in the components of the pressurizer system that reach a range of 45 MPa (see Fig. 2a) and a thermal shock of 55°C at a temperature variation rate of 5.1°C/s (see Fig. 2e).

Testing and checking of the Inverse software as applied to solution of inverse thermal conductivity and thermal elasticity problems of various classes showed that the methodological principles of practical applications of numerical solutions to inverse thermal conductivity and thermal elasticity problems to analyze the results of the full-scale tensometry of VVER reactor equipment are practicable when used in a package for acquisition, processing, and analysis of sensor readings and assessment of stress-strain states in the structures.

DETERMINATION OF THE SSS PARAMETERS AND DEFECTIVENESS OF FULL-SCALE STRUCTURES

As a rule, the methods for determination of the SSS parameters and other characteristics necessary for assessment of the strength and the service life of structural components (localization and sizes of defects and degradation of the material's properties) are based on a uniform methodological approach that uses a priori known dependences between the sought parameters and the experimental results. These dependences are found using analytical or numerical solutions close in formulation of boundary problems. Approaches of this kind are applied to determine the internal force factors, strains and stresses (including residual stresses), parameters of fracture mechanics, and deformation characteristics of the materials. At present, this problem is solved by processing two-dimensional information on the fields of the deformation response that is triggered upon stressing and under other impacts on the object under investigation. Obviously, the corresponding techniques have a restricted field of application and may cause certain errors in construction of models for solution of particular problems. In this connection, the researchers at IMASh have developed a methodological approach [25, 26] that, unlike traditional approaches, does not have any fundamental limitations with regard to the types of determined force factors; moreover, this approach enables determination of the geometry of defects in the investigated area and assessment of the degradation of the mechanical properties of materials.

The method is based on determination of the sought parameters of the problem P_j, for example, load magnitudes, internal force factors, stresses, and defect sizes, from the minimum condition of criterion function I that describes the divergences between the predicted data on deformation response fields e_i and the corresponding experimental data arrays e_i^*. A condition necessary for practical implementation of this approach is use of considerable amounts of experimental information in the form of displacement or deformation fields, which, in turn, supposes use of this information to devise the above ESPI, GH, and DIC methods.

The method is implemented in a "flexible" computational complex that comprises the following control programs with a graphic interface in the MATLAB environment:

(1) A program for compilation of experimental data array e_i^* that enables an interactive indication of measurement points (MPs) against the background of the patterns of experimental deformation response fields and automatic generation of the information on the MP localization with regard to the model of the object under investigation to be used further on.

(2) A program for solution of the direct problem that consists in calculation of deformation response values e_i in the assigned MPs with arbitrary preset values of parameters P_j by the FEM using the ANSYS program package on the basis of which the SSS fields are computed that result from stressing the investigated area or from other impacts on already stressed area, for example, from boring openings or cracking.

(3) A program for solution of the inverse problem of evaluation of parameters P_j that minimizes criterion function $I(e_i, e_i^*)$. As criterion functions, root-mean-square I_{RMS} or maximum $I_{\max}$ deviations can be used, as well as functions of a special type. To solve the inverse problem, the simplex-element (of a deformed polyhedron) or the Newton methods can be used. Since such an approach does not involve solution of integral equations (which can lead to ambiguous solutions), but is based on "direct" calculations of the physical model; as a result, such P_j can be fitted at which e_i will be in the best agreement with the experimental data e_i^*.

(4) A program that allows estimation of the effect of errors resulting from different factors, such as the experiments, the amount of experimental informa-

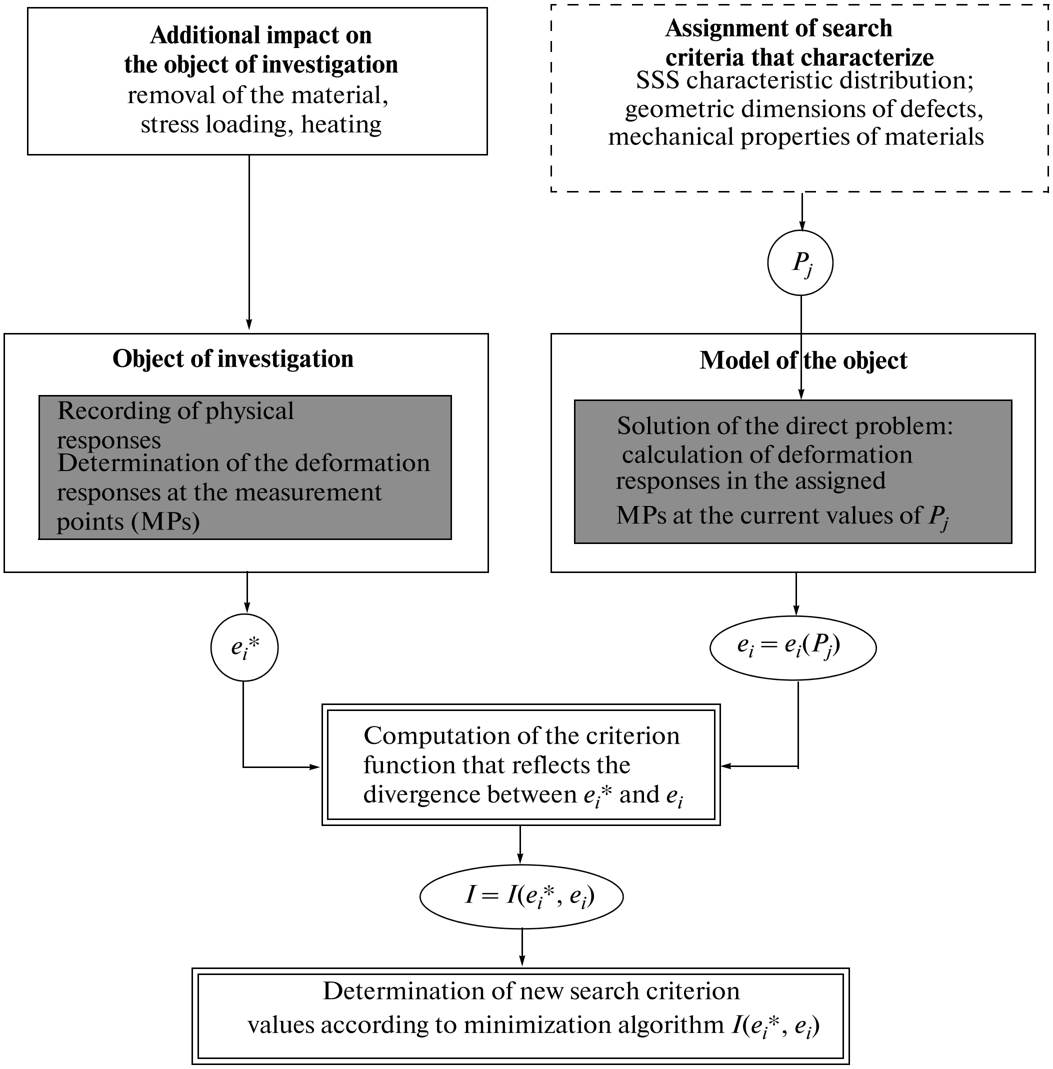

Fig. 3. Schematic block diagram of determination of the SSS parameters and defectiveness and degradation of the properties of materials based on mathematically processed experimental data.

tion, and selection of the localization of MPs, on the solution of the problem in a semiautomatic mode.

Thus, the computational complex ensures a complete solution of the problem of determining the sought parameters starting from acquisition of experimental data to analysis of the stability of the solution and its validation. The structure of the computational complex enables automatic solution of the defined problem, consolidating the control of different components under the “leadership” of the control programs. The schematic block diagram of determination of the SSS parameters, defectiveness, and degradation of the properties of materials on the basis of mathematical processing of the data is shown in Fig. 3.

In [27, 28], the results of the method applied to

—evaluate stress loading of thin-walled structures;

—carry out complex analysis of the structural components with a surface crack that involves simultaneous determination of the crack depth and applied stresses; and

—evaluate residual stresses nonuniformly distributed over the component’s depth (by boring a gradually deepening opening, etc.)

are reported.

ASSESSMENT OF THE CRACK DIMENSIONS ON THE INTERNAL SURFACE

A successful application of the proposed method for determination of the surface crack depth enabled setting a more complex problem of dimensioning of the defects on the inner surface of thin-walled components by the deformation fields or disturbances that occur on the outer surface as a result of stressing or partial stress relieving of the object under consideration. For this purpose, the following model problem was analyzed. A thin-walled component was consid-

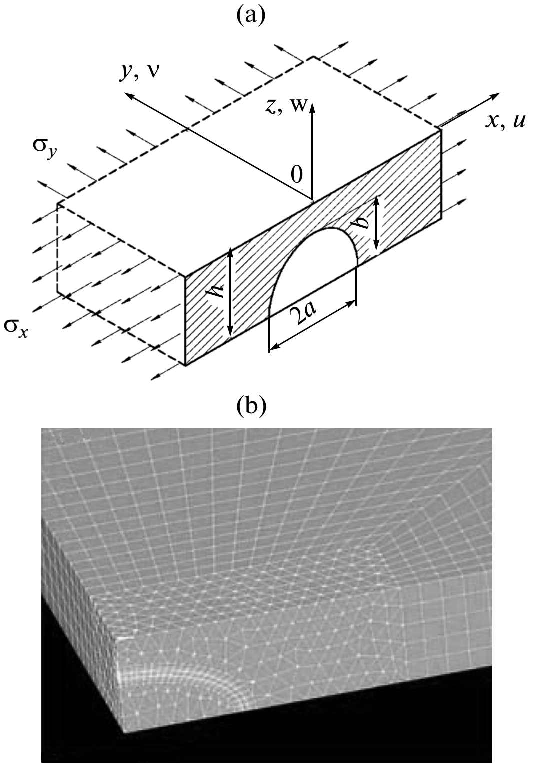

Fig. 4. (a) A thin-walled component with an internal crack and (b) its mesh spacing.

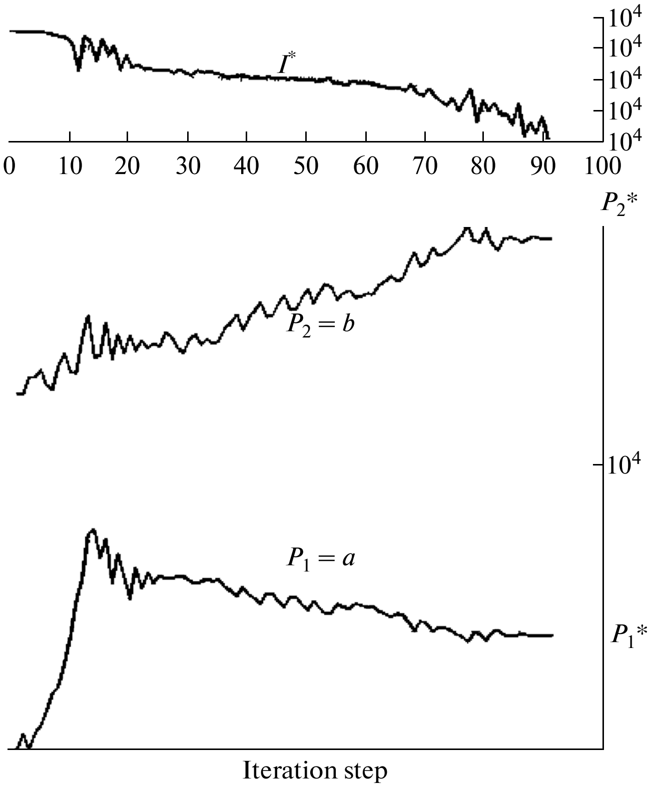

Fig. 5. Variations in the values of sought parameters P_1, P_2, and I^* depending on the iteration step.

ered (Fig. 4) on the inner side of which a flat elliptic crack was located in the direction orthogonal to the surface; the dimensions of the crack (a and b) had to be determined. On a part of the outer surface (planes $z = 0$), displacement fields u, v, and w resulting from stresses σ_x and σ_y of known magnitudes were recorded by the ESPI and DIC methods. The stresses were caused by an additional impact on the investigated area of the object or the object as a whole. For example, when analyzing the defectiveness of a pipeline, the pressure in it can be increased or reduced by a known value.

The effect of experimental data spread δ_e, i.e., displacement values u, v, and w, and of a potential measurement error in the value of load δ_σ (stresses σ_x and σ_y) on the accuracy of determination of the dimensions of an elliptic crack (parameters $P_1 = a$ and $P_2 = b$) was studied. The calculated results of the model problem for the case $b/h = 0.6$ obtained at different values of the spread of the experimental data, stresses, σ_x/σ_y ratios, and the types of displacement fields used (u, v, and w) showed that criterion functions I_{RMS} and $I_{\max}$, when used to solve the minimization problem, yield relative errors in determination of sought parameters P_1 and P_2 equal to about 20% and above, with the relative error of the initial data being about 10%. To enhance the accuracy of the results, as a criterion function, a special function based on ordering of quantities $\tilde{e}_i$ (the relative difference of e_i^* and e_i) was used that enables finding the global minimum with heavily "noisy" data [28]:

$$I^* = \sqrt{\frac{1}{N}\sum_m (N - m + 1)d_m^2},$$

where $d_m = \begin{cases} \tilde{e}_m - \tilde{e}_{m-1}, & m \neq 1; \\ \tilde{e}_1, & m = 1 \end{cases}$ is the vector of difference between the values of adjacent vector components $\tilde{e}_m$ ($\tilde{e}_{m+1} \geq e_m$) that results from ordering the relative divergences of $\tilde{e}_i$ ($m = 1, ..., N$).

The obtained results showed that, even in the case of a considerable error in determination of the deformation responses $\delta_e = 20\%$ and load value spread $\delta_\sigma = 10\%$, processing of the measured values of the three displacement vector components u, v, and w using function I^* enables determination of parameters a and b with an error of 7.5% at most. With a relative error of the experiment of about 10%, the error of the results does not exceed 6.5% even on the basis of the processed measurement results for two displacement vector components, u and v.

Figure 5 shows an example of variations in the values of sought parameters P_1 and P_2 during minimization of criterion function I^*. A well-convergent process is observed when the sought parameters tend to accurate values of P_1^* and P_2^* and the criterion functions rapidly decrease.

After determining parameters a and b, the question of estimating the crack resistance of the structural component under investigation always arises. For this purpose, a special macro in the computational complex was developed to calculate the distribution of the stress intensity factors and the J-integral along the crack front by the found problem parameters such as load, depth, and crack shape [29].

Consequently, computations of model problems of different types showed a high efficiency of the applied techniques and the developed computational complex for study of stress loading, defectiveness, and residual stresses. Owing to their universal character, the developed algorithms and programs open further possibilities for expansion of the scope of problems of diagnosing NPP structural components, including elastoplastic problems and analysis of degradation of the properties of materials. To solve the latter problem, the computational complex provides means for consideration of parameters P_j as mechanical characteristics of the material that vary in the preset areas of the structural components. Moreover, it is intended to explore spherical hardness indentation as a means of exerting a force on the investigated object along with additional stressing and boring openings.

The experimental-computational methods based on solution of inverse problems of experimental mechanics are an important and promising tool to diagnose the stress loading and the defectiveness of the components of machines and structures. The problems of this class have been put forward in practice in a natural way and serve as a supplement to and a further development of traditional approaches established in the field of processing and analyzing experimental data.

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