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DEFORMED SOLID MECHANICS AT THE SIBERIAN BRANCH, ACADEMY OF SCIENCES OF THE USSR

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UDC 531

From the creation of the Siberian Branch in 1957 in determining the main directions for development of mechanics its organizers have devoted considerable attention to deformed solid mechanics. This was connected both with the solution of a series of important dynamic strength problems and with general problems of developing engineering. It turned out that from the first plan for developing this direction at the Institute of Theoretical and Applied Mechanics (ITAM) (Academician S. A. Khristianovich) a new plan was born, i.e., development as a basis for the whole subject of an experimental section of deformed solid mechanics at the Institute of Hydrodynamics (IG) (Academician Yu. N. Rabotnov). The plan for studying solid mechanics realized in this section was creation of experimental equipment based on the newest technology, systematic experimental study of modern materials, phenomenological description and its comparison with experimental data, creation and development of resolving strength problems and the stability of structural elements taking account of irreversible strains, and finally introduction of these methods into design bureau.

Forms of organization were determined for theoretical and experimental studies of deformed solid mechanics in institutes of the Siberian Branch of the Academy of Sciences of the USSR (SO AN SSSR), a department was organized at Novosibirsk State University (NSU), as well as work of the Council for Defending Dissertations in this subject at the Presidium of the SO AN SSSR. In these decisions it is possible to see the breadth of organizational questions, i.e., from strengthening and developing scientific contacts with the main schools in Moscow, Leningrad, Kiev, and with large groups of applied subjects, to systems for training groups of highly qualified specialists. It is necessary to say that not all of this was possible: some important specialists did not arrive for the work: theoreticians and experimentors did not develop the test design base with sufficient quickness. Nonetheless, at the present time thirty years after the creation of the SO AN SSSR, it is possible to note that now in the Siberian Branch the groups of different institutes are developing forcefully almost all of the main important themes of this scientific subject. It is necessary to refer to the following:

— creation of mathematical models for the deformation of solid deformed bodies including a study of irreversible strains (plasticity, creep) and failure; creation of a set of test installations making it possible to study the main connections between stresses and strains with different types of static and dynamic loads equipped with automatic control and recording;

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— development of analytical and numerical methods for solving boundary problems of statics and dynamics for the deformed solid intended for using modern computing techniques (in particular in a packaged regime);

— use of deformed solid mechanics methods in mining, machine building, geophysics, in order to solve topical problems of industry. Currently scientific studies of different problems of solid mechanics are being carried out in the Institute of Hydrodynamics (IG), the Institute of Mining (IGD), Computing Centers (VTs) in Novosibirsk and Krasnoyarsk, the Institute of Theoretical and Applied Mechanics (ITPM), the Institute of Physicotechnical Problems of the North (ITPTS), the Institute of Geology and Geophysics (IGG), and also in higher educational establishments in Novosibirsk: Novosibirsk State University (NGU), Novosibirsk Electrotechnical Institute (NETI), Novosibirsk Institute of Railroad Transportation Engineering (NIIZhT), Sibstrin.

1. Mathematical Models of the Deformed Solid [1-47]. Material models should satisfy two requirements: a) quite completely and correctly describe material deformation by forces in a prescribed range of stresses, strains, and temperature; b) there should be sufficiently simple formulation of the basic equations, boundary and initial conditions, the main physical relationships in order that on the basis of the model it would be possible to solve practical problems. Models created recently are as a rule orientated towards solving problems with the use of modern computing techniques. Mathematical models correctly reflecting the actual behavior of solids and structures help the constructor and technologist to use and change the properties of materials and structures; models are constantly being improved.

The basis of model construction is establishing functional relationships between stress and strain tensors, increments of these values, general characteristics of the stressed and strained state in structures. These relationships may contain additional parameters: temperature, time, structural damage parameters, etc.

A. Effective use of deformed solid mechanics methods in strength analysis for materials and structural elements is impossible without an all-round study of the mechanisms of inelastic deformation with a complex stressed state. A knowledge of inelastic properties makes it possible to use completely the supporting capacity of structural elements, and to find optimum ways for developing new structural materials exhibiting improved strength and deformation properties.

In order to calculate the stress-strained state of structural elements models (variants) are required for plasticity theory substantiated reliably by the results of experimental studies. Classical plasticity theories, resting on the idea of an isotropic material, are applied as a rule for classes of simple loading and some complex loadings which are nearly simple. This situation leads to the requirement of building up new models for plastic deformation suitable for describing complex stress—strain states [1-5].

Development of work for building mathematical models of elastoplastic bodies has attracted constant interest in different groups. Here it is necessary to note two features of this development: 1) experimental and theoretical study of the effects of complex loading in the IG and ITPM, and then also in the IGD; 2) building of models based on ideas about plastic (generally irreversible) strain in connection with surfaces of maximum tangential stresses and shears. The second feature implies a return to the ideas of St. Venant and Karman, and it has markedly expanded mathematical ideas into singular loading surfaces or even made it possible to carry out building of closed models without this usual example.

Experimental data accumulated up to the present time with complex loading indicates that an initially homogeneous and isotropic material becomes anisotropic. Anisotropy for the plastic condition of a material element depends both on the stress—strain state achieved and deformation history, and also on the direction of the last loading [2, 4, 5].

The process of loading a material element may be represented as a sequence of loadings when apart from active loading and unloading processes there is an intermediate condition of partial unloading. In this condition, in one of the directions there is active loading and active unloading is accomplished in the other. Results available for an experimental study of the mechanisms of elastic deformation for material with partial unloading under complex loading conditions are extremely limited [20-29]. It has been established that material strengthening under loading with partial unloading without strengthening in the unloading direction [2, 20] has the same character as with simple loading. Partial unloading with strengthening leads to restoration of the elastic mechanism for the second principal strain tensor component, and an increase in strain intensity corresponds to a reduction in stress intensity. Experimental results have been provided which detect nonconformity with the delay principle and the hypothesis of local definiteness [24, 27]. Directions have been revealed for an increase in material stiffness causing a marked increase in limiting strength and deformation characteristics in relation to limiting characteristics with pure shear [20, 24].

Starting from work in [6, 7] and embracing a series of aspects of experimental and theoretical directions [8-16], a separate direction has been isolated in the mechanics of loose materials which are historically connected with work on models with internal friction and dynamic problems [6, 7]. This direction has received further recognition and development in view of the extensive important applications in rock mechanics [11-15].

B. The study of loose material mechanics is carried mainly at the IGD. In recent years interest in this classical section of mechanics has increased strongly. In problems of loose material mechanics there is analysis of a broad class of technological processes of mining, powder metallurgy, building, the chemical industry, and a study of different processes occurring in natural conditions. Problems of loose material mechanics also have considerable theoretical importance. As is well known, a fundamental role in mechanics is played by theory describing the behavior of the simplest representatives of classes of materials. This relates to theories of elasticity, an ideal and viscous liquid, and classical variants of plasticity theory. A granular material without adhesion may also be related to the simplest fundamental material. A study of it makes it possible in "pure form" to carry out analysis of a number of effects of deformation of soils, rocks, and uncompacted metals.

In theoretical studies a considerable role is played by questions of building mathematical models for deformation. Above all, models should rely on data from special (model) experiments. As is well known, the main requirement for these experiments is sufficient homogeneity for the stress—strain state. For the study of plastic materials there is extensive use of the classical method of thin-walled tubular specimen deformation. Although they exhibit many features of plastic materials, this procedure is not applicable to granular materials.

In order to set up model experiments a procedure and instrument for uniform shear and complex loading has been developed in the IGD [8-10]. Experiments carried out have made it possible to detect new dilation mechanisms (a change in volume during shear). In the general case with alternating loading dilation accumulates from two parts: an irreversible change in the relative volume of packing defects and natural dilation with a capacity for defect-free packing. According to this, all particle packing may be divided into two classes: reversible, for which there exists a plastic loading path trajectory returning them to the original condition, and irreversible. It would appear that with shear greater than a certain critical value the plane parallel flow of loose material loses stability and it changes into a new regime in which the material is broken down by an almost regular set of slip lines into individual blocks (Fig. 1). In stress diagrams there is a changeover into a descending branch [11].

Sufficient evenness is assumed for velocity and displacement fields in solid mechanics. Besides this, the nature of plastic deformation of loose materials is connected in fact with the discontinuity of the original velocity field (with slippages of length dimensions at contacts). In formulating closed models the original broken velocity field is averaged. However, information about breaks is important and it is retained by introducing internal kinematic and force variables. In this way the paradoxes of classical models are removed naturally, and in addition the required criteria of adequacy for any mathematical model of a granular material are formulated: the rate of energy dissipation does not depend on the material dilation properties and it should tend towards zero with changeover towards ideally smooth particles [12].

Within the scope of the models constructed algorithms and programs have been developed for numerical solution of elastoplastic boundary problems in which consideration is given to possible unloading, a changeover into a limiting condition, nonlinear boundary conditions of the inequality type (dry friction), and the case when boundary displacements are prescribed as a function of boundary stresses (reaction of the material with yielding boundary structures). Questions have also been studied of constructing approximate calculation schemes. Problems have been considered of the stress—strain state of material in bunkers, ore chutes, pressure compliance sensors, boundary structures, and the problem of slip line development (shear cracks) etc. [13, 14].

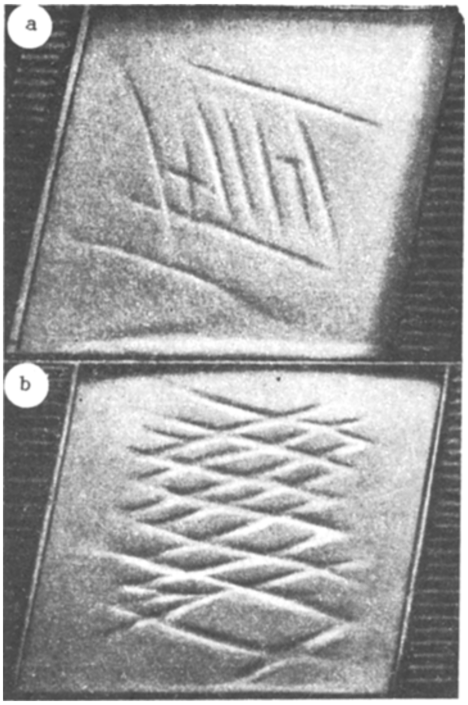

Fig. 1

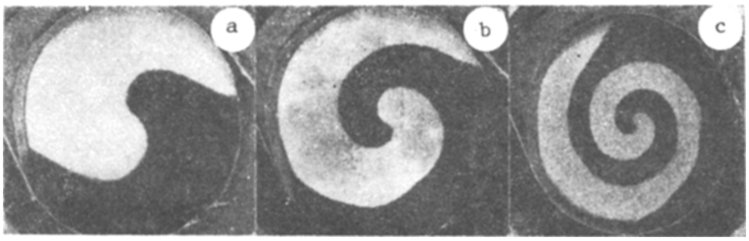

Fig. 2

One of the most universal problems applied over a wide range of fields is plastic flow in converging channels (discharge of materials from vessels, rolling, and extrusion). In particular, for radial symmetrical channels it is normal to assume that flow will be symmetrical and radial in character. Special experiments have shown that for some classes of materials that is not so. At a certain stage radial flow becomes stable and it changes over into a new regime which is characterized by shear localization through a set of discrete surfaces and a considerable reduction in strains outside these surfaces [15, 16].

We note the results obtained in studying complex loading. It was shown in [5, 10] that it is possible to approach an ideal uniform process if as one of the simplest situations, consideration is given to deformation of an elliptical region when at the boundary a velocity vector is prescribed constant in value and direction over the tangent to the boundary, so that the region turns into itself all the time. For loose, viscous, and a series of other inelastic materials the effect of directional transfer is observed: with the return of boundary points to the original position, internal points do not return to the original position. This leads to the situation that with an increase in the number of cycles "residual displacements" accumulate and internal deformation becomes unlimited (Fig. 2, in the original condition the boundary of materials with different colors is a straight line). Possible applications for this effect were indicated in [10].

C. A systematic experimental study has been carried out for modern metallic materials under conditions of high temperature and nonsteady loading with the aim of establishing certain relationships. It has been established that in a certain temperature and loading range there is creep without strengthening, and in so doing over a period of several tens to hundreds of seconds there is marked accumulation of plastic strain (short-term creep).

Equations of the flow theory type with constants depending on temperature and substantiated by experiment have been suggested. These constants have been determined for a large group of modern structural materials. Engineering methods have been developed for solving the problem of taking account of short-term creep [29-31].

A large cycle of works have been carried out directed at verification of the main hypotheses of creep theory and specific equations emerging from them [32-39]. It has been shown that in order to describe steady-state creep a potential of the Mises type and the associated flow rule are suitable; it is noted that the potential for steady-state creep is independent of loading prehistory.

It has been established that for anisotropic materials initial anisotropy is retained during creep. For steady-state creep simple forms of potential are suggested containing correspondingly three or two quadratic invariants of the stress tensor, and one or two isotropy tensors which may be assumed to be constant. It has been shown that for anisotropic material the measure of strengthening may be selected the same as for isotropy. Thus, initial and strain-induced anisotropy are clearly separated.

For materials creeping under tension and compression in a different way, a potential has been constructed depending on the first and second, or second and third stress tensor invariants, and another method for description has also been suggested based on combining two potential functions [40]. Use of the Druker stability postulation for studying certain creep theory equations has been suggested [41]. An experimental study has been carried out on creep surfaces [42, 43].

In order to describe the creep process and stress-rupture strength of metals Rabotnov has suggested the idea of a mechanical equation of state with a set of kinetic equations for determining structural parameters q_i characterizing the state in question. For uniaxial creep they have the form

$$\begin{gathered} dp/dt = f(\sigma, T, q_1, q_2, \ldots, q_n), \\ dq_i = a_i dp + b_i d\sigma + c_i dt + h_i dT. \end{gathered} \tag{1.1}$$

Coefficients a_i, b_i, c_i, h_i in the general case depend on creep strain p, stress σ, time t, temperature T, and also on q_i. Use of relationships (1.1) extends the possibility of known theories for qualitative and quantitative description of different experimental results. Use as q_i of different creep characteristics makes it possible to describe many effects observed in an experiment. In particular, Rabotnov has used a single structural parameter ω characterizing the degree of material damage (degree of reduction in effective cross-sectional area). At the start of the deformation ω = 0, and specimen failure corresponds to the value ω = 1. The simplest form of relationships (1.1) for describing creep in the steady-state and accelerating stages is written as

$$\frac{dp}{dt} = A\left(\frac{\sigma}{1-\omega}\right)^n, \quad \frac{d\omega}{dt} = B\left(\frac{\sigma}{1-\omega}\right)^k, \tag{1.2}$$

whence the value of failure time t^* with constant stress $t^* = B^{-1}(k+1)^{-1}\sigma_0^{-k}$ is obtained. In [44] for the spatial case the amount of scattered energy was selected as a damage parameter

$$A = \int_0^t \sigma_{ij}\eta_{ij}dt, \tag{1.3}$$

where σ_{ij} and η_{ij} are stress and creep strain velocity tensors respectively. A certain limiting value of A^* was taken as a condition for failure under creep. By generalizing relationships (1.1) taking account of (1.3) in the spatial case an energy variant of creep theory and stress-rupture strength was obtained. Experimental verification of this variant was carried out for a series of structural alloys applied to alternating temperature—force effects under both uniaxial and plane stressed state conditions [44, 45]. Methods have been developed for solving creep and stress-rupture strength problems on the basis of the energy variant [46, 47].

2. Mechanics of Composites [48-77]. Recently there has been considerable use in technology of artificial materials consisting of two or more components rigidly bonded to each other. Depending on the nature of component distribution, materials are subdivided into

layered, fiber, and dispersion reinforced composites. Layered and fiber composite materials and structures are as a rule anisotropic: the greatest stiffness and strength are realized in certain selected directions. Dispersion-reinforced composites are quasiisotropic materials.

In order to study deformation and failure of structures, classical models of anisotropic inhomogeneous elasticity and plasticity are used in which the tensor characteristics of the material are expressed in terms of mechanical and geometric characteristics of the composite. This makes it possible to determine certain average characteristics of the stress—strain state, which then allows determination of the local stress—strain state in individual composites on whose basis local failure conditions are determined (structural method).

Constructions having a layered structure normally consist of rigid supporting layers and a soft filler. Classical Kirchhoff hypotheses, i.e., rectilinearity, nondeformability, and orthogonality of fibers normal to the central surface, making it possible to reduce the three-dimensional problem of elasticity or plasticity theory to a two-dimensional problem, do not make it possible to account for transverse shears and strains normal to the central surface which are marked with deformation of layered structures consisting of materials with sharply differing mechanical properties.

A theory has been constructed for linear and nonlinear deformation of multilayered plates and shells based on generalizing the Kirchhoff hypotheses: for each layer it is assumed that the normal to the central surface before deformation also remains rectilinear after deformation, but not orthogonal to the deformed central surfaces of the layer [48-52]. Theoretical and experimental proof of this hypothesis [53, 54] and its generalization [55] have been given. A new variant of multilayer shell theory has been developed [56].

A wide range of practical problems of multilayer plate and shell deformation have been resolved. In particular, critical deformation parameters have been found for cylindrical and conical shells under the action of hydrostatic pressure [52].

Structures prepared by winding high-strength filaments and filled with polymerizing binders make it possible to provide an optimum article for strength and stability.

It has been demonstrated that the elastic behavior of a flat glass-reinforced plastic element with two mutually orthogonal reinforcement lay-up directions is satisfactorily described by a model for an elastically orthotropic body

$$\varepsilon_x = \frac{1}{E_1}\sigma_x - \frac{\nu_2}{E_2}\sigma_y,\ \varepsilon_y = -\frac{\nu_1}{E_1}\sigma_x + \frac{1}{E_2}\sigma_y,\ \gamma_{xy} = G^{-1}\tau_{xy}. \tag{2.1}$$

Here x and y are directions along the reinforcement lay-up; elastic constants E_1 and E_2 are proportional to the amount of filament in a unit area of cross section; G is elasticity modulus of the matrix. Creep of this element is also described by relationships (2.1) with a change of constant G to a shear creep operator [57-59].

Structural models have been built for a reinforced layer [60-62]. Based on them a general theory for strength analysis of reinforced thin-walled structures and principles for their rational design has been developed, which has made it possible to consider the operating efficiency of each substructural element, to predict the area and nature of failure, and to determine failure loads. Specific calculations have been carried out for rod structures, shells, and panels with different loading conditions. The theoretical and experimental results obtained have been compared. Practical recommendations have been developed for creating articles which are efficient for conditions of strength and stability [61-65] (Fig. 3, where typical lay-up schemes are shown for uniformly stressed reinforcement in circular plates).

A large group of static and dynamic problems has been resolved for unidirectional glass-reinforced plastic based on a shear model close to relationship (2.1) [66-72].

A polymerized mixture of epoxy resin with finely cut glass fiber is used extensively as a randomly reinforced composite. The strength of this plastic is higher than that for unreinforced material. Articles of randomly reinforced plastic are prepared quite simply by forming, extrusion, and casting. A mechanical model has been constructed for deformation and failure of a randomly reinforced composite which has been used as the basis of a solution for a series of deformation and failure problems and the optimum design of some structures [73-77].

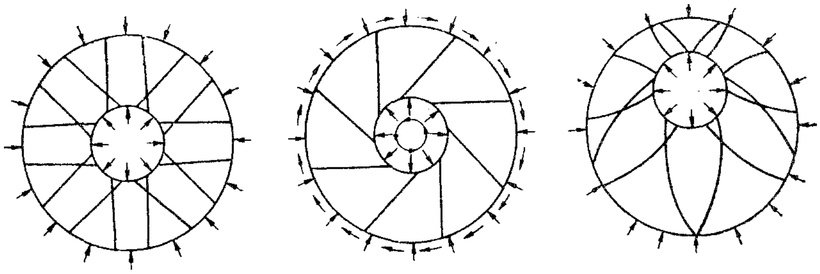

Fig. 3

3. Development of Methods for Solving Solid Mechanics Problems [78-139].

A. Elastoplastic deformation theory is the basis of strength analysis in technology. Methods have been developed based on the theory of analytical functions, and solution of axisymmetric and other spatial problems of elasticity theory [97].

A theory has been developed for the plane problem of static elasticity theory within the scope of a model for physically and geometrically nonlinear elasticity. A generalized Kolosov–Muskhelishvili equation has been obtained for the Novozhilov variant. A solution has been found for a series of problems concerning stress concentration around a hole [98-101].

Group analysis by the Li–Ovsyannikov method has been carried out for elasticity equations in [102, 103]. An asymptotic solution has been constructed for a series of boundary problems of elasticity when a small parameter enters into the Hooke's law relationship [104-106, 109, 110]; a solution for a series of elasticity problems in stresses has been given in [107, 108, 111].

Elastoplastic problems have found extensive use in designing structures and estimation of their operating capacity in fracture mechanics and rock mechanics.

The main difficulty for this group of problems consists of the fact that in elastic and plastic regions there are different sets of equations, and the boundary separating these regions is unknown. In rock mechanics there is considerable interest in the problem of stress concentration around a hole by means of which it is possible to estimate the zone of inelastic deformation around a working. Assuming that the hole is completely embraced by a plastic zone in which the stressed state is assumed to be known, the problem is reduced to finding three analytical functions $\varphi(\zeta)$, $\psi(\zeta)$, $\omega(\zeta)$ outside a unit circle of plane ζ which with $|\zeta| = 1$ satisfy conditions

$$\begin{gathered}\varphi(\zeta)+\overline{\varphi(\zeta)}=H(\omega(\zeta),\overline{\omega(\zeta)}),\\ \overline{\omega(\zeta)}\varphi'(\zeta)/\omega'(\zeta)+\psi(\zeta)=F(\omega(\zeta),\overline{\omega(\zeta)}).\end{gathered}\tag{3.1}$$

Here $H(\omega, \bar{\omega})$ and $F(\omega, \bar{\omega})$ are known functions; $\omega(\zeta)$ is a representative function which determines the elastoplastic boundary. Methods and examples are given in [112-115, 118] for solving system (3.1) by determining the corresponding equations for $\omega(\zeta)$ which is found from (3.1) by excluding functions $\varphi(\zeta)$, $\psi(\zeta)$. A condition has been obtained for the rationality of representative function

$$F(\omega(\zeta),\overline{\omega(\zeta)})=N(\zeta)+\overline{\omega(\zeta)}M(\zeta),$$

where $N(\zeta)$, $M(\zeta)$ are analytical functions with $|\zeta| > 1$ [115].

An accurate solution has been found for system (3.1) for an exponential flow condition [116] which gives a good approximation of the limiting condition for a series of rocks, for the Sokolovskii flow condition, and other flow conditions. The case has been considered when the elastoplastic boundary is close to a circle [114, 122], and the nature of the solution close to an elastoplastic boundary has been studied [121]. Using ideas about the acquisition of anisotropy for an elastoplastic condition [1] displacements in the classical Galin problem have been found [119, 120]. A series of quasistatic elastoplastic problems for finite thin-walled bodies of rotation have been considered [124, 125] where new numerical algorithms for their solution are given.

A new approach has been suggested in [117] for solving the classical problem of elastoplastic torsion making it possible to prove a theorem for the existence and uniqueness of the solution, and to build up an effective numerical algorithm for its solution.

Methods of variational inequality are used successfully for proving the theorem for the occurrence of spatial elastoplastic problems in [123].

B. In thin-walled structural elements (plates and shells) one of the measurements (thickness) is markedly less than the other two. The extent of using thin-walled structures in aircraft construction, shipbuilding, and other areas gives rise to the necessity of considerable engineering calculations. This has led to creation of different approximation theories for elastoplastic deformation and stability based on using a naturally small parameter, i.e., the ratio of thickness to the characteristic length of a plate or shell. A variant of the theory for thin flat elastic shells of variable thickness has been suggested for which a set of differential equations is consistent with natural boundary conditions. For plates and spherical shells of constant thickness in explicit form a general integral for a set of differential equations has been expressed by means of analytical functions of a single complex variable [78]. Spectra in problems of stability and the behavior of thin-walled structures with intense loading have been studied by an asymptotic method. The existence of points of concentration for characteristic values in problems of shell stability with existence of perturbations has been detected. An essential role for the density of characteristic values in problems for the development of dynamic forms of loss of stability has been demonstrated [79-83]. The contemporary state of questions about the stability of elastic and elastoplastic shells has been studied in [84, 139]. With arbitrary rotations and deformations, the three-dimensional linear problem of shell deformation has been reduced to a two-dimensional problem of deformation for its basal surface [85, 86].

Methods have been developed for solving problems of structurally inhomogeneous plates and shells. Plasticity conditions [87] and equations for elastoplastic bending of secured shells [88, 89] have been obtained.

Axisymmetric buckling of asymmetrically secured shells with the combined action of internal pressure and an axial compressive force has been studied assuming that longitudinal and circumferential ribs operate independent of each other [90].

A solution has been obtained for a series of dynamic problems of plate fastening on the basis of a rigidly plastic analysis scheme [91, 92]. Equations have been constructed connecting the deformation rate of plates and shells with forces and moments [93, 94]. Refined equations for the deformation of inhomogeneous plates and shells have been found on the basis of a method using expansion of functions by a Legendre polynomial [95, 96].

C. Optimization of structures in accordance with selected quality criteria (strength, weight, and amplitude—frequency characteristics) is a strongly developing section of solid mechanics. Work in [126-129] has been devoted to development of methods for designing elastic and elastoplastic bodies with a varying internal structure, shape of the body, and other structural parameters.

Interesting results have been obtained in problems for optimizing layered structures composed of a prescribed collection of materials [130-137]. The main feature of these problems is the fact that piecewise-constant functions with a discrete range for values serves as a control characterizing the structure of layered systems. This in turn leads to the possibility of constructing small variations of control normally used in variation calculus, since in the final selection there may not be materials with similar properties. Therefore, in order to yield the required conditions for optimality, which is important for organizing the computation algorithm, it is necessary to use finite control variations in a small set (needle-type variations). The optimum structures obtained in the optimization process will be layered with specific dimensions and structure, although the number of layers in the structure, thickness, and layer materials were previously unknown.

4. Dynamic Problems and Fracture Mechanics [140-212].

A. The study of wave propagation in deformed solids is carried out in different groups of the Siberian Branch, including VTs and IGG. Some combined results for these problems are given in [140-142, 201].

A study of stress wave damping in hard rocks has demonstrated the unsuitability of the elastic model for quantitative calculations. In order to solve damping problems for spherical and cylindrical waves, models have been suggested with internal friction [6, 7, 28], and a solution of the problem has been built up by the method of Khristianovich "short" wave theory.

If the ratio of maximum principal stresses in a spherical stress wave is determined from the Coulomb rule with a side pressure factor $\alpha(\sigma_\nu = \alpha\sigma_r)$, then damping of maximum radial stresses σ_r^{max} over distance r proceeds by the rule $\sigma_r^{max} \sim r^{-(2-\alpha)}$.

The effect of unloading for a "weak" wave appears to be insignificant [26]. It is interesting to note that for "short" and "weak" waves an approximate relationship between radial stresses and particle velocity v is valid:

$$-\sigma_r \approx \rho_0 va,$$

where ρ_0 is density; a is sound velocity ($a \approx v_\rho$, v_ρ is longitudinal wave velocity). This relationship is accurate for a plane elastic wave, and accurate for a shock wave if instead of α shock wave velocity D is substituted (for a weak wave $D \approx \alpha$). It is often used in treating experimental data, and it appears to be true in short-wave theory [6, 7, 26].

New results in problems of nonsteady wave propagation in elastic materials and structures were obtained in 1965-1970 [142, 144]. A method developed for combined application of two-stage integral transforms has made it possible to obtain new qualitative effects governing the main structure of wave processes in cylindrical systems with local moving effects, to establish a principle for conformity of steady-state and nonsteady-state solutions, to analyze and describe quantitatively quasisteady regimes. An important result in direct practical applications is the detection of typical features of resonance processes forming in a cylindrical system during propagation of a load with a critical velocity along its axis.

The method of integral transforms and different methods for treating the original problems and solutions of a series of new dynamic problems for hydroelastic bodies and structures has been developed in [144, 149].

The study of nonsteady deformation processes is based on analytical and numerical methods [149, 151] developed in [142, 146], specially adapted to the calculation of frontal zones. A study was made in [152-154] of the features of wave processes in anisotropic materials and structures with different loading regimes. Steady-state and nonsteady-state wave fields in composite constructions and layered structures were studied in [149, 153] with analysis of the spectral properties of piecewise-homogeneous bodies of periodic structure (including the effects of transmission (nontransmission), resonances, antiresonances, pulsations). Due to a method for mechanizing numerical dispersion in algorithms for implicit finite-difference schemes developed in [153], it has been possible to obtain [154-156] almost exact solutions for nonsteady state dynamics problems for composite structures reacting with elastic and acoustic media.

Mention should also be made of work connected with studying different definitions of the problem of elasticity and linear viscoelasticity theory. They have been carried out mainly in VTs SO AN SSSR, and are connected with developing and proving effective numerical algorithms for solving problems of elastic body statics and dynamics. To begin with, definition of the dynamic problem for elastic theory in "velocities and stresses" is noted [162]:

$$\frac{\partial \mathbf{W}}{\partial t} + \sum_{i=1}^{3} A_i \frac{\partial \mathbf{W}}{\partial x} = \mathbf{f}. \tag{4.1}$$

System (4.1) is symmetrical according to Friedrichs and in combination with the method of splitting for spatial variables it has been possible to construct and prove quite effective difference schemes for dynamics problems [158].

A new definition of dynamic and static problems of elasticity theory in terms of "stresses" has been studied in [159, 161].

In order to solve problems of high-velocity and shock-wave loading and deformation Godunov has formulated a model for a viscoelastic body of the Maxwellian type with a nonlinear dependence of tangential stress relaxation time on parameters characterizing the stress—strain state of the material [162]. A model has been developed, proved, and realized in specific calculations. A procedure for constructing the relationship for tangential stress relaxation time was given in [163, 164]. A method for numerical solution of problems in this model has been suggested [165]. Work in [167] was devoted to studying the toughness of metals with high-speed loading.

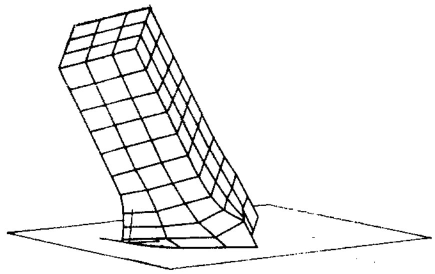

Fig. 4

A model has been considered in [168] for penetration of a striker into a deforming material based on ideas about a rigidly plastic body. In order to solve multidimensional problems of high-speed reaction in a gas-dynamic approximation, use was made of a modified method of particles in cells [169, 170] which made it possible to reduce the calculation variations for local flow parameters and to reduce the calculation time markedly. Creation of a theory for differential analyzers of shock waves, and shock waves with relaxation, has made it possible to suggest practical criteria for determining the position of the shock-wave front for a given class of problems from calculated results [171]. This has markedly simplified the volume and treatment of calculated results.

In solving problems within the scope of Prandtl–Reiss models use has been made of a modified Wilkins method [172] whose modification consisted of local rebuilding of the difference network with fulfillment of all of the rules for conservation in the calculation process, which made it possible to carry out calculations with large material deformations reducing the overall calculation time in a computer, and to carry the solution of practical problems to an end. Currently the possibilities for this method are being considerably expanded [173].

Given in Fig. 4 is a deformation network of initially rectangular elements in the problem of impact of a yielding striker with a rigid barrier.

B. In [175], apart from the series of basic works on fracture mechanics listed, there is discussion of some fundamental questions of crack mechanics and failure criteria. Analysis is carried out in [176] for typical problems of crack theory within the limits of linear and nonlinear elasticity theory, and cracks in an elastoplastic material are also considered.

Solutions obtained on the basis of linear elasticity theory do not satisfy the conditions for applying this theory since rotations of the crack are large and strains are not limited. On the basis of nonlinear theory an estimate has been made of the region at the edge of a crack where there is marked nonlinearity. It appears that for quite stiff materials physical nonlinearity should have an effect at greater distances from the edge of the crack than geometric nonlinearity. Whence it follows that use of geometrically linear theories for analyzing the failure problems in question makes real sense. Typical plane problems of crack dynamics in a linearly elastic body have been studied: nonsteady, steady state, self-modelling.

Considerable attention has been devoted to deriving and discussing the applicability of the most generally used criteria for crack growth, i.e., force and energy. Their non-equivalence is noted (e.g., with crack rotation in an elastic body) as well as the considerable generality of the force criterion in the form suggested by Novozhilov. In view of this, a requirement arises for taking account of material structure (failure at the microlevel) in order to normalize stresses in failure criteria.

Failure at the microlevel, and the correlation between material microstructural properties and the microscopic characteristics of failure have been considered in [66, 178, 180]. For this purpose problems have been solved for movement of cracks in discrete materials and a comparison has been carried out with similar solutions for continuous material.

The problem of failure for composites was resolved in [180] in a nonlinear arrangement on the basis of numerical methods. A study was made in planar and spatial arrangements of breaking crack propagation and shear processes, and localization of failure zones with instantaneous breakage of a single fiber. A theory was created in [181] for fatigue crack growth on the basis of analyzing the Dugdale–Panasyuk elastoplastic solution under cyclic loading conditions. Methods for solving dynamic problems of crack theory and a simplified approximate model for these problems were considered in [178-180].

An approximate solution has been obtained for equilibrium of a set of parallel cracks [191] on whose basis the instability of front development for these cracks has been proven [192]. Perturbation growth characteristics together with data for damping of loading waves during an explosion have been suggested as a basis of an equation for the average lump size occurring during breaking of rocks with blasting [193]. Crack development mechanisms in acrylic plastic have been studied experimentally [197]. A dependence connecting crack velocity and stress intensity factor has been suggested as a material characteristic. Data obtained have been used in evaluating the breaking effect of blasting in brittle rock [192, 195, 197].

A model of breaking for the Earth's crust by a main shear crack is the currently generally accepted model for the site of origin of an earthquake. There is dynamic release of stresses at the edges of a growing crack. Unloading waves proceeding from the origin cause shaking of the daylight surface of a half-space. This problem, which may also be applied in mining for estimating, the sequence of a rock burst, has been considered in [183].

Failure criteria for solids with spalling, in particular taking account of the damage factor, have been considered in [140, 185, 186]. This approach is natural in studying the phenomenology of failure occurring in a certain region [187, 188], and also in developing numerical methods in mechanics problems for brittle failure. In turn these calculations make it possible to select criteria for the failure of solids with dynamic loading [140, 185, 186] in the form of invariant relationships for critical values of failure process macrocharacteristics (stresses and strains), although information is also appearing in mechanics about failure kinetics at the microlevel [140, 190]. For the source of microfailure consideration is being given to solutions in the vicinity of antiplanar strain, and closed solutions have been obtained linking origin "dimensions", energy, and displacement at crack edges [189].

C. Questions important for science and the national economy are connected with application to geophysics, in particular to seismic studies (a study of the internal structure of the Earth, the search for economic minerals, earthquake prediction, volcanic eruptions, tsunami, and monitoring of nuclear tests).

In the SO AN SSSR (VTs, IM, IG, IGD) two classes of problems have been studied: direct and reverse problems of wave propagation theory (elastic, electromagnetic, hydroacoustic). In direct problems it is assumed that the mechanical structure of the material and vibration sources are known, i.e., the material vibration regime is predicted; in reverse problems the material structure is synthesized from the prescribed oscillation regime for a certain number of points and prescribed sources.

The most common method for solving direct problems for complex material models is an asymptotic (with high frequencies) "ray method" developed theoretically by a group of Leningrad and Siberian scientists [201], and realized numerically in VTs SO AN SSSR in 1967 [202]. It has found extensive practical application in seismology and seismic surveying. Limitations arising in view of the asymptotic nature of the ray method have been overcome due to development of numerical methods and use of computers.

Numerical methods have been found for solving direct dynamic seismic problems in a precise arrangement based on the idea of combining analytical approaches with finite difference methods. The Lamb problem has been resolved for inhomogeneous material models and new types of seismic wave have been discovered which do not obey geometric seismic rules [203]. This approach has been developed for inhomogeneous anisotropic, inelastic, and porous materials [203, 204], and also for solving problems of elasticity theory in velocities and stresses [203]. A numerical—analytical approach has also appeared to be effective in solving problems of seismic wave propagation theory for two and three-dimensional inhomogeneous material models [203, 208]. Methods of vibrational inspection [204, 205] have been developed for solving problems of deep seismic sounding.

For more detailed study of seismic wave distribution processes in complexly built materials and in order to overcome the effect of different inhomogeneity in the formation and propagation of seismic wave fields, apart from methods for solving direct dynamic seismic problems (i.e., problems for evaluating seismic waves), it is also necessary to arrange methods for solving problems, i.e., problems of determining the structure of a body from the vibration regime prescribed for some of its surfaces, which makes it possible to create a closed device for mathematical modelling of wave processes, and thus to carry out a detailed and all-round study.

Over thirty years in the SO AN SSSR (IG, IM, VTs) a wide range of studies have been carried out in this direction for analyzing the correctness of stating reverse problems, the existence and uniqueness of solutions [206, 207], and also development of numerical methods for determining the structure of the bodies in question [202, 206]. Methods and algorithms have been studied in detail and realized for determining the structure of layered-inhomogeneous materials, which have been proved both by numerical results and in actual field experiments.

Experience of developing deformed body mechanics in the SO AN SSSR has shown that development of the main model representations in dynamics and statics, development of numerical and combined research methods, supplemented by limited but purposeful experiments, has made it possible to resolve successfully problems posed in practice. Time is necessary for further development of knowledge at the junction of deformed body mechanics and solid physics, and this relates to studying inelastic strains and failure, selection of new materials, and optimization of structures. Examples of these studies are work in the ISTPM, Yakut Branch of the SO AN SSSR for cold brittleness [209-211] and the Institute of Strength Problems and Material Science, Tomsk Branch of the SO AN SSSR [212]. Solution methods should be aimed at extensive use of modern computing techniques and means of automation, both in the formation of experimental work and in carrying the results into sensible applications.

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