MATHEMATISCHES FORSCHUNGSINSTITUT OBERWOLFACH

T a g u n g s b e r i c h t 1/1986

Kontinuumsmechanik fester Körper

5.1. bis 11.1.1986

Die Tagung wurde von den Herren G. Herrmann (Stanford) und H. Lippmann (München) geleitet. Das rege Interesse an ihr wird durch die unvorhergesehen große Teilnehmerzahl unterstrichen. Auf Bitten der Tagungsleitung verzichteten mehrere prominente Gäste auf einen Vortrag. Daher blieb genug Zeit für ausführliche Referate insbesondere der jüngeren und ausländischen Teilnehmer sowie für angeregte Diskussionen. Von den Anwesenden wird eine möglichst baldige Wiederholung bzw. Fortsetzung gewünscht, wozu auch die unübertreffliche Gastfreundschaft des Instituts beiträgt.

Zweck des allgemein gehaltenen Tagungsthemas ist es, einen Überblick über verschiedene aktuelle Forschungsschwerpunkte auf dem Gebiet der Kontinuumsmechanik zu ermöglichen, was durch die Mannigfaltigkeit der Vorträge in der Tat gelang. Stickwortartig lassen sich nennen: Neue physikalische Überlegungen und Rechenverfahren in der Bruchmechanik und verwandten Bereichen, experimentelle und mathematisch beschreibende Methoden zur Erfassung des komplexen plastischen Verhaltens, mathematische Problemstellungen der klassischen Elastizitätstheorie mit Anwendungen im Ingenieurwesen, technische Anwendungen von Rechenverfahren der Plastizität. Als Resumee kann festgestellt werden, daß die Entwicklung der mathematischen, physikalischen und experimentellen Grundlagen der Kontinuumsmechanik keineswegs abgeschlossen ist, und daß auch die Anwendungsmethoden in der Technik weiterentwickelt werden.

Im Verlauf der Tagung fand unter der Leitung von G. Herrmann (Stanford) und K. Ikegami (Tokio) eine Diskussion über die Zukunft der Mechanik statt. Die Beiträge vermitteln folgendes Bild: Die Mechanik nimmt z. Zt. im öffentlichen und wissenschaftspolitischen Raum zwar keine exponierte Stelle ein. Nichtsdestoweniger leistet sie unersetzliche Beiträge zur technologischen Entwicklung und deren grundsätzlichem Verständnis, wobei immer wieder neue Forschungszweige heranwachsen. Man beobachtet allerdings, daß sich die im Rampenlicht stehenden Wissenschaften und Technologien Teilgebiete der Mechanik einverleiben.

Vortragsauszüge

A. BALTOV:

Visco-plastic response of flexible structural elements

Flexible, dynamically loaded plates with visco-plastic response are considered. The geometric nonlinearity is described by means of the von Karman approach. The energetic visco-plastic model is used to describe the behaviour of the plate material during the deformation process. A special numerical procedure, called "Finite System Method" is applied to obtain the process measures. Particular attention is given to the residual deflexions and to the possibility of crack initiation. Some numerical examples are given to illustrate the energetic model and the FSM.

J.F. BESSELING:

Three-dimensional analysis of elastic lines with large rotations

The differential equations that can be formulated for a description of large deformations of an elastic line are not a suitable starting point for a numerical computation of large displacements and large rotations. While the simplest and most transparent description in terms of differential equations is obtained by the use of three rotation parameters (such as Euler angles), for numerical computation the use of the four Euler parameters proved to be more efficient. Furthermore in the finite element model it is possible to take a formulation that recognizes the large difference in stiffness against elongation as compared to bending and torsion right from the start. The finite element, that is presented, reproduces in the limit the differential equations of the elastic line, but could not be obtained directly from the differential equations.

Applications of the finite element model are found in pipe-laying analysis at sea, in the analysis of manipulators and robots with flexible and rigid links, etc.

J.P. BOEHLER:

On off-axis testing of anisotropic materials

In experimental investigations of the mechanical properties of anisotropic materials specific difficulties arise. A typical example is that where the principle directions of the applied agencies do not coincide with the material symmetry directions (off-axes tests) as well in the elastic as in the plastic range, in such tests the principle directions of the stress and the kinematic tensors cannot coincide; a direct consequence is that the boundary conditions imposed in the classical testing procedures are incompatible with the development of homogeneous stress and strain fields; the so-obtained experimental data are unsuitable for proper specification of anisotropic constitutive laws. Thus, it is necessary to imagine and to develop new experimental techniques, which are appropriate for anisotropic materials and which produce homogeneous stress and kinematic fields in off-axes tests.

We propose such a new testing device for tensile tests on anisotropic solids. It consists of hinged fixtures with knife-edges allowing the ends of the specimens to rotate. Numerical simulations in the elastic range on composite materials (finite element method) and experimental studies in the plastic range on rolled sheet-steel (stereo photogrammetric method) show that the proposed new testing device produces effectively homogeneous stress and kinematic fields in off-axes specimens. With this procedure reliable experimental data for the directional properties of anisotropic solids can be obtained.

F.-G. BUCHHOLZ:

Über nützliche Zusammenhänge zwischen elastischer Verzerrungsenergie und Energiefreisetzungsrate bei quasistatischer Rißausbreitung in Festkörpern

Bei Voraussetzung eines ebenen Verzerrungszustandes läßt sich die elastische Verzerrungsenergie eines Festkörpers in zwei entkoppelte Anteile gemäß der Verzerrung in der Ebene sowie infolge der verhinderten Dehnung senkrecht dazu aufspalten. Da nur der erstgenannte Anteil zur Entstehung und Ausbreitung ebener Risse beitragen kann, ist damit eine obere Schranke für die insgesamt zu Verfügung stehende Rißenergie gegeben. An verschiedenen Beispielen wird gezeigt (z.B. homogener Körper mit geradem Riß, diskontinuierlich inhomogener Körper mit gekrümmtem Grenzflächenriß), wie mit Hilfe dieses Schrankenwertes sich ein quantitatives Genauigkeitsmaß für unterschiedliche numerische Methoden angeben läßt, mit denen die Energiefreisetzungsrate bei quasistatischer Rißausbreitung ermittelt werden kann.

G. FICHERA:

Plane stress in classical elasticity

Theory of plane strain is nowadays considered as a well-settled chapter of classical elasticity. Analytic problems arising from elastostatics connected with a two-dimensional deformation have been deeply investigated by using complex methods, biharmonic equation and the two-dimensional system of elasticity. Very little is known about problems connected with plane stress which are of a quite different analytical nature with respect to the ones concerning plane strain. A review of recent work done in connection with plane stress:

$$\sigma_{11} = \sigma_{xx}(x, y), \quad \sigma_{12} = \sigma_{21} = \sigma_{xy}(x, y), \quad \sigma_{22} = \sigma_{yy}(x, y),$$

$$\sigma_{13} = \sigma_{31} = \sigma_{23} = \sigma_{32} = \sigma_{33} = 0$$

is outlined.

The following problems are considered:

1) How to give the surface forces or the boundary of a cylinder in order to have a system of plane stresses.

2) To investigate the boundary value problem which arises when only one component (with respect to a given variable direction) is given on the boundary Σ of the cross-section of the cylinder.

3) To consider problem 2) in the particular case that the given variable direction is orthogonal to Σ at each point of Σ.

Results obtained in Rome and by W. Hayman (London) are desribed and the physical interpretation of these results (some very unexpected) is proposed like a new problem.

F.D. FISCHER:

Zur Stabilität von Strukturen bei Folgelasten

Das beschreibende Gleichungssystem für eine Struktur bei Berücksichtigung von großen Verformungen und nichtlinearem

Materialverhalten lautet $^{m}\underline{\underline{K}}\ \delta\underline{u} = \delta\underline{R}$, $^{m}\underline{\underline{K}}$ Tangentensteifigkeitsmatrix, $\delta\underline{u}$ Inkrement der Verschiebungen, $\delta\underline{R}$ Inkrement des Lastvektors. Im Fall von Folgelasten ist $^{m}\underline{\underline{K}}$ nicht symmetrisch. Wenn geprüft wird, daß bei einer Laststufe m für das Eigenwertproblem $(^{m}\underline{\underline{K}} - \omega_i^2\ \underline{\underline{M}})\ \underline{\phi}_i = \underline{0}$, $\underline{\underline{M}}$ Massenmatrix, ω_i^2 Eigenwert (Quadrat der Eigenfrequenz) keine kongugiert komplexe Lösung besteht, ist Flatterinstabilität auszuschließen. Dann kann nach Symmetrisierung von $^{m}\underline{\underline{K}}$ die begleitende Eigenwertanalyse (Ramm et al) angewandt werden, da sicher ist, daß ein Stabilitätsverlust zufolge Verzweigung zu erwarten ist.

U. GAMER:

The elastic-plastic deformation of shrink fit

An interference for which Tresca's yield condition predicts vanishing of the circumferential stress at the bore of the hub of an elastic-plastic shrink fit is called critical. It is shown that Tresca's criterion does not admit a solution of the supercritical shrink fit problem for perfectly plastic materials. For hardening materials, stress, displacement and plastic strain in the shrink fit with supercritical interference are derived. The occurence of a supercritical interference as well as the range of validity of the results presented are discussed.

The angular speed for which Tresca's yield criterion predicts vanishing of the radial stress at the elastic-plastic border in the hub of a shrink fit is called critical. Beyond the critical speed, the plastic zone is composed of two parts, and at the common border, the image points in the principal stress plane migrate from one side regime through the corner into the adjacent side regime of Tresca's hexagon. Stress, displacement as well as plastic strain in the shrink fit rotation with supercritical angular speed are discussed.

E.W. HART:

Steady crack extension rates in ductile materials

It is well known that the stress analysis of cracks in ductile materials under remote loading shows that the local stress singularity, when there is one, is not of the reciprocal square-root type and so the Irwin crack propagation force J is no longer defined. In the present work it has been shown that a finite value of J is recovered if the crack is considered to be propagating with velocity v in a material that flows with a real-time rate under the action of the local stress. The case of a semi-infinite crack such that the remote load implies a stress intensity factor K_A results in a steady local value of K at the crack tip that is generally smaller than K_A. If now the crack velocity v is required to depend on the local value K, it is possible to compute the dependence of v on K_A. The results show that generally there are two distinct stable brandies of v (K_A). One branch is a low velocity branch, and the other is a high velocity branch that shows little effect of deformation. The upper K_A limit of the lower branch defines the usual critical fracture toughness K_c. It is shown from the temperature dependence of the flow rate and the crack extension rate that at sufficiently low temperature the loading system cannot access the low velocity branch and so the high velocity branch supercedes. This generally happens at a lower value of K_A than the value of K_c at sligthly higher temperature. This represents a brittle-ductile transition.

K. IKEGAMI:

The experimental results on inelastic behaviour of metals in high temperature

The following three effects are discussed on the basis of experimental results of metals under combined stress state.

1) Effects of complex loadings on plastic behavior in high temperature.

2) Effects of plastic prestain on subsequent plastic behaviour in various temperatures.

3) Effects of creep prestrains on subsequent plastic behaviour in various temperatures.

The testing is conducted by subjecting the specimen of thin walled tube to combined axial load and torsion. The material of the specimen is stainless steel of 304 type. The testing temperature is from room temperature to 600 °C. Concerning the effects of complex loading the loading along the path with a corner and the cyclic loading superposed on the steady load are conducted. The effect of the corner angle or the ratcheting behaviour are discussed. Concerning the effects of plastic prestrains in various temperature tensile-stress strain curves under variable temperature and Bauschinger curves under variable temperature are discussed. The history of high temperature is not easily faded in Bauschinger curves. But in the tensile curves the temperature history is faded. Concerning the effect of creep prestrain, the plastic and creep prestrains are given to the specimen. The subsequent loadings are conducted under constant temperature and variable temperature. The effect of creep straining on the hardening depends on the testing temperature. The obtained results are unified by the multi-loading surfaces.

H. ISHIKAWA:

Constitutive equation of cyclic plasticity considering induced anisotropy

The motion of the center of the loading surface and the plastic deformation induced anisotropy are incorporated in the loading function of the constitutive equation for cyclic plasticity. The associated plastic flow law is derived from the so called normality of the plastic strain increments to the loading surface. The Ziegler type of assumption is used as the evolution equation of the center of the loading surface. All the stress-strain curves in cyclic loading are also assumed to be represented well by the modified Ramberg-Osgood law which should be applied from the current center of the loading surface. The computer simulation based on this model is verified by virtue of several kinds of experiments on type 304 austenite stainless steel. As a result, this model is recognized, by that simulation, to be adequate to describe the essential features of cyclic plasticity.

R. KIENZLER:

Ähnliches Verhalten von engbenachbarten Löchern und Rißspitzen

Es wurde eine einfache Formel vorgestellt zur Berechnung der Umfangsspannungen an Kreislöchern in beliebig belasteten linear-elastischen Scheiben. Die Anwendung der Formel wurde an einfachen Beispielen erprobt.

Zum zweiten wurde eine Doppellochkonfiguration betrachtet. Wann der dimensionslose Lochabstand ε gegen Null geht, streben die Spannungen am Lochrand mit $1/\sqrt{\varepsilon}$ gegen Unendlich. Aus Analogieproblemem mit der Bruchmechanik wurde eine alternative Methode vorgeschlagen zur Bestimmung der Bruchzähigkeit.

R.J. KNOPS:

Continuous dependence in elastodynamics on unbounded regions by means of the Lagrange identity

By combining the Lagrange identity (as used by Brun (1969) and Levine (1977) in bounded region) with a weighted energy approach, estimates are established for continuous initial data dependence in the initial boundary value problem of linear elasticity on unbounded domains. The boundary of the domain need not necessarily be compact so that, besides exterior regions, the half-space may also be included in the analysis. Furthermore, the conclusions do not depend upon sign-definiteness of the elasticities.

This work has been undertaken in collaboration with Professor G.P. Galdi (Ferrara) and Professor S. Rionero (Naples).

J. KRATOCHVIL:

Problem of stability of dislocation structure in deformed metals

The most distinguished feature of plastic deformation is its spontaneously developed inhomogeneity. It appears at different scales and has two principle reasons. One reason is the tendency of plastic deformation to localize (necking, macroscopic shear bands, kink bands, at smaller scale this tendency appears as a "pateky" slip). The other reason is the instability of homogeneous dislocation distribution in deformed metals. The high and low dislocation density regions are formed at the scale of µm. In the lecture both tendencies are described and analysed. The forces governing the instability of the dislocation structure are identified as interactions between mobile dislocations and dislocation dipoles assisted by the applied stress fiels. A simple model of formation of periodic dislocation structure by an autocatalytic process is discussed.

K. MARKOV:

New bounds on the bulk properties of composite materials

A general method of placing bounds on the bulk properties of composite materials of random constitution is proposed. The method, displayed in the context of heat conductivity, utilizes truncated functional series, generated by the random conductivity field, as classes of trial functions for the classical variational principles. As an illustration, new bounds for the bulk conductivity of a rigid suspension of equisized spheres are obtained which hold to the order c^2, c being the volume fraction of the spheres. The bounds are optimal for a given two-point distribution function f_2 for spheres centres; they contain a statistical parameter which can be simply evaluated by means of f_2.

M. MATCZYNSKI:

Crack extension due to heat source

The infinite elastic plane contains a single crack of length 2a. At any arbitrary point of a plate (outside the crack) a heat source/sink is located. It is assumed that crack's surfaces are thermally insulated and free of stresses. In addition we assume that temperature and strain fields are uncoupled and the problem is reduced to static case.

To estimate the direction in which we may expect the crack will propagate two fracture criteria were used, namely maximum normal stress criterion and strain energy density criterion.

M.J. MIKKOLA

Dynamic stability of an elastic-plastic arch model under multiple loads

A simple model of an inelastic arch is investigated. It consists of four rigid bars, three hinges, and two deformable cells. The two outer bars are in an inclined position. The central two bars are horizontal initially and connected by a hinge in the middle. A deformable cell connects an outer bar and an inner bar. The structure is symmetrical with respect to the vertical central line. The cell consists of two parallel springs which have a circular pin which is allowed to slide and rotate in a central channel between the springs. A rigid rod is connected to the pin, perpendicular to the inner bar. When the pin slides and rotates, the springs exert tensible or compressive forces on the rods. The springs obey a bi-linear elastic-plastic force-elongation relationship. The model is loaded by vertical point loads applied at the upper ends of the outer bars.

The model has four degrees of freedom. The equations of motion are derived using the principle of virtual power. In deriving the inertia forces, uniform distribution of mass along the rigid bars are assumed. The solution of the equations of motion was achieved by direct integration methods. The explicit central difference scheme proved to be more economical than the implicit trapezoidal rule with equilibrium iteration at each time step. As the dynamic stability criterion the degree of growth of the displacement norm as function of the load intensity according to the suggestions by Budiansky and Hutchinson (1969) is used. Stability boundaries for step load and for impulsive load were computed.

J. NAJAR:

On continuum modelling of rock fragmentation at blasting

Experimental data on elastic waves attenuation, slap-on measurements with rock specimens etc. indicate energy dissipation at stress levels fairly below the tensile strength, which can be ascribed to intrinsic damage development from the very beginning of the dynamic tensile loading. A phenomenological model of damage developement with tensile straining is proposed in order to describe this phenomenon. The deviation from linear elastic behaviour is assumed to be proportional to the damage induced, measured as a ratio of the deviation energy to its limit value at complete failure. Energy of dissipation at loading turns out be of twin nature: a small part goes into the formation of surfaces of fracture , a larger one has the nature of frictional losses proportional to the amount of the damage and the state of stress in the matrix material of the rock. Secondary losses of same kind occur at unloading. High unloading modulae can be predicted at early stages of reversal, decreasing gradually at later stages. Cyclic loading behaviour of the type of low cycle fatigue can be predicted. The damage model is associated then with a fragmentation mechanism, based on a modifation of the Weibull's flaw statistic. The speed of fragmentation can be computed as a function of time, for a given straining function. The condition of limiting crack velocity puts a necessary condition on the damage energy capacity. The resulting dependence of strength on the strain rate in the form: $\sigma_z \sim \dot{\varepsilon}$, where m is the Weibull's exponent, agrees very well with the data for various rock materials.

Z.S. OLESIAK:

Certain simple solutions for mixed boundary value problems of the theory of elasticity and coupled fields

The contact and crack problems are considered in the case when there is a field of temperature and that of linear diffusion. It has been proved that a contact problem of the theory of elasticity with the conduction of heat and diffusion taken into account can be reduced to a mixed boundary value problem of the theory of elasticity and superposed simple problem of the coupled fields.

We proved a lemma which consists in solving an auxilary problem saying that the stresses normal to the boundary plane are proportional to the distribution of temperature and/or to that of diffusion.

Also a crack problem can be reduced in a similar way to a superposition of a mixed boundary value problem of the theory of elasticity and the use of the result following from the lemma.

H. PETRYK:

On the concept of stabilty of plastic deformation processes

Difficulties in adapting the usual stability concepts to quasi-static processes of plastic deformation of continuous bodies are discussed. Next, the postulate of stability in the energy sense is introduced for such processes in the case of conservative loading. It is demonstrated that various observable instabilities in plastically deformed solids may be consistently regarded as symptoms of instability in the unified energy sense. Several stability conditions derived from the postulate are shown to be closely related to or even coincide with the known criteria based on the bifurcation approach or dynamic stability concept.

K. TANAKA:

Phase transition of metallic materials: an engineering view

Thermomechanical behaviour of metallic materials during the transformations is formulated by means of the internal variables theory in continuum mechanics. It is first explained that the well-defined fractions of phases can be regarded as the internal state variables. The constitutive equations and the transformation kinetics are determined. The theory is applied to the analysis of the superplastic deformation in pure iron in the process of the austenite-ferrite (A_3) transformation. The transformation pseudo-elasticity and the shape memory effect are also discussed.

D. WEICHERT:

The influence of geometrical changes on shakedown and stability of elastic-plastic bodies under variable loads

The incremental collapse of elastic-plastic bodies due to the unlimited accumulation of plastic strains is often accompanied by finite displacements so that geometrically linear theories give only rough and incomplete predections of the real structural behaviour.

Here an extension of MELAN's shakedown-theorem was presented by which certain geometrical effects due to the successive deformation of the considered body can be taken into account. Thin elastic-plastic shells undergoing moderate rotations about tangents and small rotations about normals to the mid-surface were considered as example for the presented theory. A numerical illustration was given for a von-Karman type plate.

J.R. WILLIS:

Fairly short cracks

A "fairly short crack" in this lecture means a crack whose length is much greater than a microstructural length (a grain diameter, say), but not so large that microstructural dimensions have no influence. First, a quick review of the application of matched asymptotic expansions is given, including some new results for power-law hardening materials and a discussion of the truth (or otherwise) of the relation " $J = -\partial U/\partial a$". The main part of the talk, however, considers two competing microscopic mechanisms for fracture: cleavage, postulated to occur when normal stress a critical distance r_c from the crack tip attains a critical value, and ductile, postulated to occur when a void is estimated by the Rice-Tracey formula to have reached a critical size. The void is assumed to be centred a distance r_d from the crack tip (r_d is comparable to r_c) and at some angle ϑ from the plane of the crack. At low temperature, the flow stress is high and the cleavage condition is reached first; at high temperature, the flow stress is low and ductile failure occurs. It is demonstrated that, at a given temperature, the value predicted for the fracture toughness, and the preferred mechanism of fracture, is sensitive to crack size, with smaller cracks tending to display higher toughness and lower transition temperature than longer ones. This sensitivity is present for cracks as large as $100\,r_c$, which could be $\sim$1cm for some structural materials. Results for particular specimens are correlated via calculations based on matched expansion procedures, which suggests a rule for characterizing the predicted phenomenon, independently of specimen type.

W. WINTER:

Elastisch-plastische Stabwerke mit kinematischer Verfestigung als Modell für vielkristallines Werkstoffverhalten unter Wechselbeanspruchung

Die plastische Verformung eines vielkristallinen Werkstoffes beruht insbesondere bei zyklischer Beanspruchung auf komplizierten mikro-physikalischen Vorgängen wie der

Bewegung von Versetzungen, den durch sie bedingten Abgleitungen längs kristallographischen Ebenen sowie den damit verbundenen Wechselwirkungen der Körner untereinander. Wenn man an den mikro-physikalischen Vorgängen als solchen nicht interessiert ist, sondern lediglich die durch sie bedingten makroskopischen Effekte studieren will, so kann man das einzelne Korn als homogen Baustein auffassen und es modellmäßig durch eine elastisch-plastischen Stab modellieren, wobei die Korn- und Gleitebenenstruktur dann im Modell durch die einfacher vorstellbare Struktur eines technischen Stabwerkes ersetzt werden kann. Unter Einbeziehung der Stabwerverformung zeigen bereits einfache Stabkombinationen Effekte, wie sie auch bei zyklisch beanspruchten vielkristallinen Werkstoffen beobachtet werden.

Berichterstatter: V. Mannl

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