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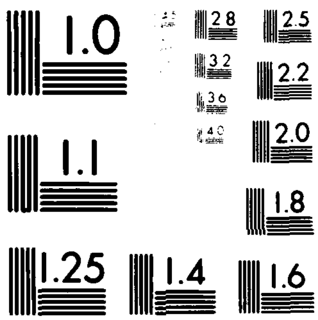

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International Union of Theoretical and Applied Mechanics: 3rd Symposium on Creep in Structures

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15 December 1980

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The 3rd Symposium on Creep in Structures was held September 8-12, 1980, at the University of Leicester, Leicester, UK. The Symposia in this series occur once every ten years with the aim to review developments in the area of creep and creep mechanics. As such, this Symposium, with a total attendance of about 70, attracted many prominent workers in this field. Over the years, emphasis in this field has shifted from analysis of creep mechanics toward the problems of cavitation, void formation, creep cracking and rupture. This change is in part a result of metallurgical

developments leading to stronger, more creep resistant materials but also less ductile materials. This was reflected in this Synposium as half the papers dealt with the various problems in the areas of cavitation, creep crack propagation and rupture. Futhermore, there was a significant input from Metallurgy and Materials' Science and the promotion of interaction between the Mechanics and Materials' Science approaches to the subject of creep was an important secondary aim of this Symposium.

INTERNATIONAL UNION OF THEORETICAL AND APPLIED MECHANICS:
THIRD SYMPOSIUM ON CREEP IN STRUCTURES

The Third Symposium on Creep in Structures, sponsored by the International Union of Theoretical and Applied Mechanics (IUTAM) with financial support by both industrial and governmental organizations, was held September 8-12, 1980, at the University of Leicester, UK. The city of Leicester, although it is in the industrial Midlands, is nevertheless attractive and prosperous. The University is young by UK standards, having opened in 1921 as the University College of Leicester and having gained a full charter as a degree-awarding university only in 1957, but it is mature, with an excellent staff and program in engineering.

There were approximately 70 delegates attending the symposium; about 30 were from the UK with the balance being roughly distributed as follows: US, 6; Poland, 7; FRG, 5; France, 3; Japan, 9; Sweden, 5; Netherlands, 2; and Italy, 2. Most delegates stayed in a university residence hall about 4 miles from the main campus and a bus was provided to and from conference sessions. Since most social functions were held in the residence hall, there was plenty of time for conversation and exchange of ideas amongst the delegates outside of the scheduled sessions and, with the limited attendance, in a very intimate atmosphere. The local organizing committee, chaired by Prof. A.R.S. Ponter (Univ. of Leicester) did an excellent job of organizing the facilities, schedule, and services for the conference.

Aim of the Symposium

The first symposium was held at Stanford University in 1960 and the second at Chalmers University, Gothenberg, Sweden, in 1970. The third symposium had the same goal as the first two, namely to review the developments of the preceding decade in the application of mechanics to creep in structures. The most prominent theme in the sumposium was, indeed, the use of mechanics in understanding the phenomena involved in deformation and fracture in structures operating at elevated temperatures. Recent developments, however, in areas such as cavitation, creep-crack propagation, creep-fatigue interaction and thermal fatigue have required a closer interaction between structural mechanics and materials science. This interaction was reflected by a significant number of papers in this symposium by metallurgists and materials scientists. The promotion of such interaction was an important additional theme of the symposium, but it was also evident that there is a way to go before such interaction becomes harmonious.

The symposium was organized into 5 sessions, each of 1 day's duration: Sessions I and II were entitled "Creep of Materials and Structures"; Session III, "Creep Buckling"; Session IV, "Constitutive Equations"; and Session V, "Creep-Crack Growth and Rupture". Each session featured papers by both structural engineers and materials' scientists. The full text of all papers will be published by Springer-Verlag in 1981.

Creep of Materials and Structures

The first two sessions saw papers on a wide range of topics under this general heading. B. Wilshire (Swansea Univ., UK) discussed creep of multi-phase alloys and noted the common observation that with such materials the stress exponent, n, and activation energy, Q_C, are generally larger than the corresponding values for single-phase (that is, unreinforced) metals and alloys. He then described how, by stress-reduction tests, a parameter σ_o could be measured such that the creep rate would now depend on $(\sigma - \sigma_o)$, where σ is the applied stress, rather than σ alone. The "friction stress" σ_o experimentally was found to be both stress and temperature dependent and to be a large fraction of σ for multiphase alloys but a small fraction of σ for pure metals and alloys. By incorporating σ_o into analysis of data on creep rate versus stress in Cu-Co alloys the stress exponents and activation energies for both the single- and multi-phase alloys were found to be the same. Two other observations made were, first, that deformation on the two-phase alloy (Cu-Co) at low stresses tended to concentrate in grain boundaries but at high stresses was more uniform throughout the microstructure; deformation remained uniform in single-phase material (Cu). Second, the theory would appear applicable to some ferritic steels if aging and coarsening of carbides is taken into account. More general applicability to such metallurgical instabilities was suggested. This paper served to highlight some of the differences in approach taken by structural analysts and metallurgists to the problem of creep. For the metallurgists, it seems necessary greatly to simplify experiments to get at microstructural effects. Such experiments are typically accomplished at constant temperature and constant uniaxial tensile stress or under conditions where perhaps one variable is changed in the course of a test. Resulting constitutive equations become more complicated by introduction of parameters such as σ_o. Structural analysts, on the other hand, are seeking mathematically simpler constitutive equations, or at least those which describe material behavior under more realistic engineering conditions wherein loads and temperatures are not constant.

A subsequent paper by I. Goodall, R. Hales, and D. Walters (Central Electricity Generating Board, Berkeley, UK), described a series of tests on Type 316 stainless steel. The experiments were directed toward development of constitutive equations applicable to the interaction between short-term plastic deformation and subsequent creep deformation and also to the interaction between fatigue and creep during static-dwell periods. Given the degree of complexity involved in such loading, analysis becomes much more difficult if recourse must be made to parameters determined at the microstructural level. Additional problems outlined which are receiving attention are the effect of cyclic deformation on void formation and growth and also on creep crack initiation and growth. With interaction between creep and fatigue, do the "classic" creep or "classic" fatigue failure mechanisms dominate the fracture process? It was noted that, as expected, fatigue mechanisms dominate for relatively short dwell periods and creep mechanisms dominate for relatively long dwell periods. Appropriate constitutive laws with predictive ability beyond the experimental conditions actually investigated have yet to be developed.

Several papers dealt with analysis of structures experiencing creep deformation. R. Anderson (Atomic Energy Auth., Preston, UK) reviewed his work on reference stresses, skeletal points, limit loads and application of these to finite element analysis. These concepts, as applied to creep, are related to the idea of an equivalent elastic solution to a beam undergoing plastic deformation in, say, bending. In some cases, this may enable analysis of a structure to be simplified to analysis of behavior at a single (reference) stress. The first of the two problem areas that exist in the development of this approach is the incorporation of residual stresses into the analysis. The limit load approach is applicable for residual stresses much smaller than applied stresses, while the residual stress becomes the reference stress for applied stresses much smaller than the residual stresses. The intermediate case represents the most difficult area. The second problem area is found in structures which fail locally rather than extensively. For both problem areas it was suggested that incorporation of the reference stress and skeletal point concept into finite element methods might assist in overcoming these difficulties.

It was noted several times in this symposium that current computing capacity is far short of that necessary for large-scale solutions of structural problems wherein creep predominates. J. Boyle and J. Spence (Univ. of Strathclyde, UK) focused on this problem and reviewed the development of generalized structural models, for instance, to treat problems involving time-independent plasticity, which reduce three-dimensional problems to one- or two-dimensional problems. In contrast to the previously discussed paper, this paper was concerned with the problems involved in developing generalized constitutive equations relating generalized measures of stress and strain. Several possible generalized models were reviewed and discussed and progress was noted in overcoming several problems. This effort is now being directed toward incorporation of material deterioration in the form of tertiary creep; this will require damage laws and several forms for such laws were discussed.

An interesting paper on model creep work was given by T. Hyde and H. Feesler (Univ. of Nottingham, UK). Model in this context means a scale model of an actual structure, not a mathematical model of a physical process. Creep testing is difficult and interpretation and application of its results are often problematic. Why not, then, build a scale model of the structure in question and test it? Even better, why not build the model with a lead-base alloy such that laboratory ambient temperature corresponds to the same homologous temperature ($T \simeq 1/2\ T_m$) encountered in the actual structure? The paper was largely devoted to the problems related to the manufacture, heat treatment, and calibration of such models. Lead-based alloys were used, employing antimony and arsenic for grain refinement and strengthening. Such alloys exhibit a North-Bailey stress exponent $n \simeq 4$ at low stresses, giving way to $n \simeq 15$ at high stresses, thus approximating the behavior of several constructional steels at temperatures between 500°C and 600°C. The models were made by chill casting, and this necessitated careful design of molds and fixtures to avoid casting defects and yet allow removal of the as-cast model without damage of distortion. Models have been made of structues as complex as a pressure vessel with cn' hemispherical end wherein wall thickness differs from side wall to end ' 'p. Special fixtures for clamping and bolting were developed as the alloy: necessarily creep extensively under loads developed in tightening bolts prior to testing. The testing of such models has revealed them to be useful for validating both analytical and computational creep-prediction methods. It was also proposed that a reference stress method may be applicable to direct prototype predictions of creep behavior.

In summary, the first two sessions covered a wide range of topics but two points kept recurring. The first was the need for improved constitutive relations coupled with simplified analytical techniques. This would avoid the problems and expense associated with direct computational methods for which computer capacity is presently insufficient in many cases. The second was materials characterization under more representative conditions. This latter point was strongly made by J. Holmes (Fast Reactor Div., Nuclear Power Co., UK). In his talk, he noted that most stresses in nuclear power systems are thermal in nature rather than resulting from direct load. This being so, too little is known about material response in thermal gradients and under conditions of thermal fatigue and shock. Other speakers noted these same problems and suggested as well that knowledge of creep-fatigue interaction and thermal fatigue is inadequate; the need for improved understanding of damage and failure processes is especially important.

Creep Buckling

A short session on the third day of the symposium was devoted to this subject. A concise review of the area was given by B. Hayman (Leicester Univ., UK). Spring—dashpot models may be incorporated into structural analysis to simulate components exhibiting both limited and unlimited creep. The essential effect of creep is to reduce the load for buckling below what it would be if creep were not to occur, and this may be represented by a locus or surface of critical points. For materials which exhibit limited creep, one can identify an elastic load below which buckling will never occur.

In another presentation in this session, D. Griffin (Advanced Reactors Div., Westinghouse, US) discussed the new rules concerning creep buckling as contained in Case N-47 of the ASME Boiler and Pressure Vessel Code. Griffin distinguished between load-controlled and strain-controlled buckling, the former being of greater concern. Essentially, load factors are imposed on service loads to provide a factor of ten on component design life. Load factors are thus made large enough to ensure that there is a margin against instability and to avoid the necessity to calculate creep buckling loads. The comments made earlier regarding constitutive equations can be made again here. Direct computation of structural response is not reasonable without more accurate constitutive equations; hence, more simplified approaches must be taken, even to the extent of imposing factors as large as ten on lifetime.

Constitutive Equations

This session was, perhaps, misnamed; rather, most of the papers dealt with either physically or mathematically based investigations of damage and failure via cavity and crack growth. L. Svensson and G. Dunlop (Chalmers Univ., Sweden) presented a review on growth of intergrannular creep cavities and examined several models for this phenomena. The various models imply several regimes for cavity growth and thus suggest cavity growth mechanism maps analogous to the Ashby deformation mechanism maps. The various models generally assume a normal tensile stress acting on a grain boundary. Vacancy diffusion toward and atom diffusion away from a growing cavity establishes the rate of increase of cavity size. Under conditions of stable diffusion growth there will be conditions of control by bulk as well as grain boundary surface diffusion and concurrent deformation may result in either constraint or enhancement of cavity growth. A. Cocks and M. Ashby (Cambridge Univ., UK) continued this theme and presented models developed to apply to power-law creep-controlled void growth and boundary-diffusion-controlled void growth. This model was developed incorporating multiaxial stresses as well. An important result of this work is a representation for stress versus time-to-rupture, based on void growth, which provides excellent correlation of such data as is normally represented by time-temperature parameters like Larson-Miller or Sherby-Dorn. This representation was not directly compared to other time-temperature parameters but it is notable that a model essentially based on the failure process rather than the creep process itself may provide good correlation of rupture data.

Both of the previously discussed papers considered void growth but not void nucleation. It was noted that the nucleation process would be most difficult to examine experimentally as it certainly would involve defects no more than a few atoms in diameter located in a grain boundary, itself a "defect" in the structure. The importance of stress state, however, was examined further in a paper presented by B. Dyson and M. Loveday (National Physical Lab., UK). Specimens of Nimonic 80A with a Bridgman notch geometry were creep tested at 750°C over a range of stress. At high stresses the fracture was initiated at the center of the specimen in the plane of the notch while at low stresses the fracture began at the notch root. At all stresses the fracture was a result of creep cavitation and all fractures were intergrannular in nature. It was suggested that several factors contribute to this behavior. First, the fracture strain is dependent on the stress state. Second, the spatial variation of strain across the notch throat depends on n, the Norton-Bailey stress exponent, and on the applied stress. The stress-state dependence of the fracture strain results from variation in cavity spacing with stress state. Given this, the fracture strain is reached in the center of the specimen at high stresses, that is, the nucleation rate and subsequent growth rate are highest. At low stresses, the fracture strain is first attained nearer the notch root. This kind of experiment would be worth pursuing for a variety of materials which exhibit different apparent void nucleation and growth characteristics.

Still another approach to this problem was presented by W. Trampcyynski (Polish Acad. of Sciences, Warsaw), and D. Hayhurst (Leicester Univ., UK). Three materials, tough-pitch, copper, an aluminum-magnesium-silicon alloy, and Nimonic 80A, were investigated under non-proportional loading conditions. First, damage was defined as the volume fraction of voids and this void volume fraction was determined as a function of strain for several different stresses during uniaxial tensile creep. Subsequent experiments, using thin-walled tubes of the above materials, were conducted to determine the stress-state dependence of the fracture behavior of each material. Copper, which showed extensive cavitation, failed according to a maximum principle stress law; the aluminum alloy, which showed no tendency to cavitate, failed according to an effective stress law; the Nimonic 80A was intermediate. This behavior could be modeled using an appropriate strain-rate versus stress law, expressed in terms of multiaxial stresses and strain-rates and incorporating the damage parameter as $(1 - \omega)^{-n}$, where ω is the damage as defined above and n is the appropriate Norton-Bailey stress exponent.

It was recognized that such factors as material purity or cleanliness were important, but even so, there are still important differences in failure mechanisms among the several discussed in this session. Considerable insight has been gained in the area of void growth but the connection between this and crack initiation and growth is still not clear. Other papers presented in this session were more mathematically based and addressed such questions as the tensorial nature of damage. No clear conclusions were drawn from these; even such questions as the appropriate rank of the damage tensor were not clearly established. Another question raised but not answered was the physical meaning of damage under compressive loading and its meaning in non-metallics, for example concrete.

Creep Crack Growth and Rupture

The final session of the symposium was devoted to papers on crack growth and rupture under creep conditions and thus followed nicely the preceding session. G. Webster and K. Nikbin (Imperial Col., London, UK) reviewed the various formulations from fracture mechanics which have evolved to treat the problem of fracture at elevated temperature. For materials which are brittle, the conveniently-defined stress intensity factor K appears adequate, even for materials undergoing creep. For more ductile materials the most promising parameter appears to be C*, the creep equivalent of the J-contour integral. The J-contour integral applies to materials exhibiting plasticity prior to crack extension and essentially is determined from load-deflection curves for varying crack length. The parameter C* is analogously determined from load- deflection rate curves for varying crack lengths. For materials which exhibit power law strain hardening, the H-contour integral is simply related to the strain-hardening index; similarly, C* is simply related to the Norton-Bailey stress exponent for materials exhibiting power-law creep. For very ductile materials σ_{ref}, the reference stress, appears to correlate fracture data. For materials of intermediate ductility under creep conditions, for example Cr-Mo-V ferritic steels, crack extension rate $\dot{a}$ correlates well with C* for conditions of steady load.

H. Riedel (Max-Plank Inst., Dusseldorf, FRG) modeled macroscopic crack growth under creep conditions by considering the response of cavities to the crack-tip stress field of a crack in a creeping material. It was assumed that cavities were nucleated if the local stress exceeded a critical value. For diffusion-controlled cavity growth, the growth rate was assumed to depend on the grain boundary diffusivity and the difference between the local stress and the nucleation stress. The cavity growth law for creep deformation control was assumed to depend on strain rate. A damage parameter was defined as the ratio of void size to void spacing; when this parameter attained a value of one, crack extension was assumed to occur. The results of such analysis were, first, an incubation period for crack growth initiation and second, crack growth rate expressions for both creep controlled and difussion controlled conditions involving C*, the stress exponent and crack length. These expressions provided excellent correlation of crack extension rate versus C* for Type 304 stainless steel. The model was considered applicable to cyclic loading if load varied slowly enough that the stress at the crack tip remained dominated by creep deformation. More rapid load variation would result in larger stresses at the crack tip than predicted by this analysis and hence acceleration of crack growth. This paper was particularly well received as the proposed model appeared to have rather general applicability to many important constructional materials and to provide ample justification for the use of the parameter C* to correlate crack growth rates for many materials. In particular, the model appeared to provide a means for defining the range of creep control of crack frowth for materials experiencing cyclic deformation at elevated temperatures.

The problems involved in investigation of creep-fatigue interaction were reviewed by B. Tomkins and J. Wareing (Atomic Energy Auth., Preston, UK). Most studies involve cyclic loading with periodic holds at maximum stress. During these holds, creep occurs involving mechanisms such as grain boundary sliding, cavity nucleation, and cavity growth. Regarding fatigue, the three stages normally observed also occur at elevated temperature. Stage I, initiation, is followed by Stage II growth and Stage III final rupture. Holds during Stage I do not appear to alter normal transgrannular shear band formation and propagation. During Stage II, holds leading to creep cavitation interact with intergrannular crack propagation and result in increased rate of subsequent fatigue crack propagation. In particular, intergrannular fatigue crack growth becomes unstable when crack opening displacement is about equal to the spacing of cavities in the material. The metallurgical state of the material is particularly important at this point; for example, instabilities such as precipitation and coarsening of carbides in austenitic steels will generally enhance fatigue crack growth. It was noted, however, that as material ductility increases as determined by creep rupture strain, the acceleration of creep and fatigue failure processes under creep-fatigue conditions becomes less noticeable. In particular, cavitation and its associated effects are present to a lesser degree in more ductile materials, thus illustrating the importance of cavitation and void formation in creep-fatigue interaction.

The importance of cavitation damage to creep crack growth was further illustrated in a paper by R. Pilkington (Univ. of Manchester, UK). Crack growth test specimens experiencing either no prestrain or prestrain up to 0.6 percent at elevated temperature were used to measure crack growth rates. Samples subjected to prestraining had higher crack growth rates and shorter rupture lives due to cavitation damage resulting from prestraining. Crack growth rates were best correlated by the C* approach. D. Hayhurst, C. Morrison and P. Brown (Leicester Univ., UK) presented a review of the most widely used theories for crack growth in creeping materials and noted several problems. Essentially, experiments show that cracks grow into deteriorating material but the mechanisms by which such growth occur are not clear. The incorporation into a physically consistent mechanistic model of stress state, cavity growth, and linkage of cavities to a growing crack, has yet to be accomplished. This point received further attention in a summary of the final session by B. Bilby (Sheffield Univ., UK). Advances in fracture mechanics have led to development of approaches such as C* but the role of creep damage in the fracture process is not yet clear. It would appear that much remains to be learned about damage processes such as cavitation before they properly can be assimilated into models for crack initiation and growth under creep conditions.

Closing

There were 36 papers and 5 summaries presented over the 5 days of the symposium. Many approaches to this problem area were discussed and the aim of the meeting was fulfilled. Especially notable was the interaction between structural mechanics and materials science and metallurgy. While the two fields still remain largely separate, one does sense that better communication is evolving and the symposium certainly contributed to this evolution.

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