MECHANICAL BEHAVIOR OF MATERIALS AND
STRUCTURAL ELEMENTS AT ELEVATED TEMPERATURES

Progress Report
for Period
June 1, 1976 - May 31, 1977

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Report of Equipment Purchased
or Fabricated

<u>Equipment</u>	<u>Status</u>	<u>Cost</u>
Autodata Nine + Magnetic Tape Recorder (Acurex Autodata Inc.)	purchased	\$10,505.00
4-DC LVDT's (Schaevitz Engineering) (GCD-121-125)	purchased	1,230.00
1 - Load Cell (Transducers Inc.) (BTC-FF62H-CS-226.8 kg)	purchased	440.00
3-power supplies (Kepco 2, Trans-Tek 1) (ABC 10-0.75M)(D15.200) (ABC 30-0.75M)	purchased	460.00
1-Airconditioner (Murray Co.)	purchased	223.50
1 Heater with Controller	purchased	150.00
Drum Device (Machine Shop)	fabricated	1,000.00
Load Fixtures and Pulling Rods (Machine Shop)	fabricated	1,500.00
Load Frame (Machine Shop)	fabricated	500.00
Environmental Chamber Temperature controller	estimate	2,500.00

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ABSTRACT

This report summarises the research performed between June 1, 1976 and May 31, 1977 on the project Mechanical Behavior of Materials and Structural Elements at Elevated Temperatures. The analytical research performed includes solutions of boundary value problems for several structural elements using Hart's constitutive relations with and without the presence of anelastic strains. Research is in progress on the use of boundary-integral equation methods to solve inelastic deformation problems for planar bodies. The design and fabrication of a creep testing facility with auxilliary force, temperature and displacement transducers and data acquisition system is complete and creep experiments on beams at room temperature are in progress.

1. Analytical research on inelastic deformation using Hart's theory.

The research of the previous contract period (June 75-August 76) has been successfully continued during the present period (September 76-August 77). Research on the response of structural elements - spheres, cylinders, discs, beams, plates etc. - subjected to relatively steady loads, obeying Hart's constitutive relations has been completed [1-7]. Results have been obtained both for the case of uniform temperature and steady thermal gradients. The response of structural elements to time varying loads using Hart's complete constitutive relations including anelastic strains is being studied [8] and further numerical results for different loading histories on spheres and cylinders are expected by the end of this contract period. The boundary-integral equation method was applied for the first time to creep problems [9] last year and work is in progress on a two-dimensional plane stress and plane strain computer program capable of predicting the inelastic response of arbitrary shaped bodies (simple and multiply connected) to various loading histories. This program, capable of using classical creep or Hart's constitutive equations without anelastic strain, is expected to become operational by August 77. Some serious errors in the plane strain BIE formulation of plasticity problems by other researchers were discovered in course of this investigation and these have been corrected [10]. Research on the generalization of the equation of state theories to creep problems involving large deformation and strains will be started this summer.

a. Response of structural elements to relatively steady loads.

This phase of the research has been completed [1-7]. The response of various structural elements - spheres, cylinders, beams, plates, etc. -

to relatively steady loads, have been calculated using Hart's constitutive equations in the absence of anelastic strains. According to this formulation, the (recoverable) anelastic strain is assumed to remain at a steady saturated value throughout the deformation process and all the nonelastic strain is the (irrecoverable) permanent strain. Of primary interest is the effect of the initial state defined by the hardness on subsequent stress redistribution and creep. Figs. 1 and 2 show the effect of initial hardness on stress redistribution in the pure bending of a rectangular beam. The stress distribution across the beam thickness changes from the initial linear distribution (elastic solution) to the final nonlinear distribution. As expected, stress redistribution is more rapid in the softer beam (Fig. 2). Plates, as members of more complete structures, often confine fluids, some of which may be regarded as incompressible. Such a structural element is easily studied experimentally. Creep in such a plate has received little attention in the literature, and was therefore chosen as the topic of an analytical study. The major results are reported in [7].

Of special interest in this study are the deformation histories of plates sealing an incompressible fluid with a central, distributed pressure. One remarkable result of the calculations is that a plate with a "hardness" at a level comparable to 10% cold work, and under a lateral uniform pressure over a central circle with radius one-half the plate radius, undergoes larger deformation, for fixed time, than an identical plate with smaller hardness. This is illustrated in Fig. 3. A more detailed discussion of this phenomenon is given in [7].

b. Response of structural elements to time varying loads.

The analysis of inelastic deformation of structural elements using Hart's complete constitutive equations including anelastic strain is underway [8]. Inclusion of the recoverable anelastic component of the nonelastic strain enables one to calculate the response of structural elements to arbitrary time-varying load histories. Some computational difficulty was encountered in the relatively flat region of the $\ln \sigma - \ln \dot{\epsilon}^p$ curves [11-12]. In this region, $\sigma^a \approx \sigma^*$ (see [8]), so that the equation for the permanent strain rate invariant (eqn. 4.10 of [8]).

$$\dot{\epsilon}^p = \dot{\epsilon}^* [\ln(\sigma^*/\sigma^a)]^{-1/\lambda} \quad (1)$$

gives rise to numerical instability. This difficulty was partially overcome by the introduction of the so called viscoplastic limit. In this limit, $\dot{\sigma}^* = \dot{\sigma}^a$, so that eqn. (1) can be replaced by

$$\dot{\epsilon}^p = \frac{s_{ij}^a \dot{\epsilon}_{ij}^n / \sigma^a}{1 + \frac{\sigma^* \Gamma(\sigma^*, \sigma^a)}{M}} \quad (2)$$

In the above, σ^* is the hardness, σ^a the anelastic stress invariant, s_{ij}^a the deviatoric component of the anelastic stress tensor, $\dot{\epsilon}_{ij}^n$ the nonelastic strain rate, Γ the hardening function, $\dot{\epsilon}^*$ a reference strain rate and λ and M are parameters.

Fig. 4 shows the creep of the inside radius of a nickel sphere subjected to various values of steady internal pressure for a fixed value of initial hardness corresponding to 3% cold work. Hart's full constitutive equations are used. The anelastic effect is evident in that the displacement grows rapidly to a value of about three times the

elastic displacement in about one second. Fig. 5 shows the expected saturation of the anelastic stress invariant. Since in this example the initial hardness exceeds the stress invariant $\sigma(r,0)$ everywhere, the anelastic stress, which is initially zero rapidly approaches $\sigma(r,t)$ throughout the sphere. There is little permanent strain since $\dot{\epsilon}^*$ in Nickel, for these values of pressure, temperature and hardness, is too low (see eqn. 1), and most of the creep strain is anelastic (transient). Calculations are currently in progress for other values of hardness and other loading histories, and these results will be reported in a subsequent report at the end of this contract period.

The study of "cross effects" in the torsion of thin walled tubes is being conducted in the viscoplastic limit. Here the theory predicts that extension necessarily accompanies the torsion of these elements, which is in agreement with existing experiments. The extension of these calculations to more complicated combinations of loads is underway.

c. Boundary-integral equation formulation in two-dimensions

The boundary-integral equation formulation was used for time-dependent inelastic deformation problems for the first time last year [9]. Research is in progress this year on a general two-dimensional (plane stress or plane strain) computer program capable of calculating the response of arbitrary shaped bodies subjected to arbitrary loading histories. The existing literature on BIE methods in plasticity problems was surveyed and some serious errors in the plane-strain formulation by other researchers were discovered. These have been corrected [10]. Riccardella's [13] BIE computer program for planar problems in plasticity has been studied in detail. A general purpose two-dimensional BIE computer

program (plane stress and plane strain) for time-dependent inelastic deformation should be operational by the end of this contract period. It will be capable of handling classical theories of creep as well as Hart's constitutive equations in the absence of anelastic strains. Several geometrical configurations for structural elements will be considered. Whenever possible, results will be compared with those obtained by direct analytical methods. These results will be presented in a forthcoming report [14].

d. Equation of state theories for large deformations.

Research will be initiated this summer on the generalization of equation of state theories of inelastic deformation to problems involving large deformations.

2. Experimental research

The design and fabrication of the creep testing facility, with auxiliary force temperature and displacement transducers and data acquisition systems, is complete. The basic machine frame is shown in Figs. 6 and 7, which are reproduced from [15]. Several proof tests of the system have been completed and are reported in detail in the aforementioned report. Representative samples of beam creep response are given in Fig. 8.

The load application system was designed to apply uniaxial step loads to the structure being loaded. Steps of less than one-second duration have been achieved; typical load histories on the beam loading fixture are shown in Fig. 8. The data acquisition system is fully capable of recording detailed load histories during such step loads.

Temperatures in the testing facility enclosure and at specimen level are fully controllable, with ranges at room temperature of $\pm 0.2^{\circ}\text{C}$. A high temperature test chamber, for conducting experiments on specimens at temperatures up to 250°C is available (on loan from another test facility) but the temperature controller has not yet been acquired. This is now on order and should be ready for service later in the summer.

In the mean time we intend to conduct fully controlled experiments, at room temperature, on beam specimens of pure nickel, which is the material about which most is known.

Inevitable delays in equipment delivery, and failure of electronic equipment to perform to specifications, have retarded the progress we anticipated a year ago. Nevertheless, we are at a point where significant data can now be collected with ease. Step loading studies of beam and plate behavior will be the first priority experiments we shall conduct

this summer. As noted above, elevated temperature proof tests will also be conducted, when a controller has been delivered.

References

1. Kumar, V., and Mukherjee, S., "Creep analysis of structures using a new equation of state type constitutive relation", Journal of Computers and Structures, Vol. 6, August/October 1976, pp. 429-437.
2. Kumar, V., and Mukherjee, S., "Time-dependent inelastic analysis of metallic media using constitutive relations with state variables", Nuclear Engineering and Design, Vol. 41, March 1977, pp. 27-43.
3. Kumar, V., and Mukherjee, S., "Creep analysis of metallic structures in the presence of thermal gradients using newer constitutive relations", Journal of Pressure Vessel Technology, Trans. ASME, Vol. 99, Series J, May 1977, pp. 272-280.
4. Waung, Y.C., and Lance, R.H., "Creep of beams using a state variable approach". ERDA Report No. C00-2733-6 Department of Theoretical and Applied Mechanics, Cornell University, Ithaca, N.Y., July 1976.
5. Waung, Y.C., and Lance, R.H., "Creep of circular plates using a state variable approach," ERDA Report NO. C00-2733-7, Department of Theoretical and Applied Mechanics, Cornell University, Ithaca, N.Y., August 1976.
6. Waung, Y.C., and Lance, R.H., "Theory of creep bending - a state variable approach", ERDA Report No. C00-2733-8, Department of Theoretical and Applied Mechanics, Cornell University, Ithaca, N.Y., September 1976.
7. Chang, K.J., and Lance, R.H., "Creep of circular plates sealing an incompressible fluid", ERDA Report No. C00-2733-9, Department of Theoretical and Applied Mechanics, Cornell University, Ithaca, N.Y. April 1977.
8. Kumar, V., and Mukherjee, S., "Elevated temperature inelastic analysis of metallic media under time-varying loads using state variable theories," Proceedings of the Fourth International Conference on Structural Materials in Reactor Technology, San Francisco, Calif., August 1977 (to appear).
9. Kumar, V., and Mukherjee, S., "A boundary-integral equation formulation for time-dependent inelastic deformation in metals", ERDA Report No. C00-2733-4, Department of Theoretical and Applied Mechanics, Cornell University, Ithaca, N.Y., April 1976.
10. Mukherjee, S., "Corrected boundary-integral equations in planar thermoelastoplasticity", International Journal of Solids and Structures, Vol. 13, April 1977, pp. 331-335.
11. Hart, E.W., Li, C.Y., Yamada, H., and Wire, G.L., "Phenomenological Theory - A guide to constitutive relations and fundamental deformation properties", in "Constitutive equations in plasticity", (e.g. A.S. Argon 1, M.I.T. Press, Cambridge, Mass., 1976, pp. 149-197.

12. Hart, E.W., "Constitutive relations for the nonelastic deformation of metals", Journal of Engineering Materials and Technology, Trans. ASME, Vol. 98, No. 3, 1976, pp. 193-202.
13. Riccardella, P.C., "An implementation of the boundary-integral technique for planar problems in elasticity and elasto-plasticity". Ph.D. Thesis, Department of Mechanical Engineering, Carnegie Institute of Technology, Carnegie-Mellon University, Pittsburgh, Pa. April 1973.
14. Mukherjee, S., and Kumar, V., "An implementation of the boundary-integral equation method for time-dependent inelastic deformation in metals." ERDA report under preparation. Department of Theoretical and Applied Mechanics, Cornell University, Ithaca, N.Y.
15. Chang, K.J. and Lance, R.H., "Design of a uniaxial creep testing machine", ERDA Report No. C00-2733-10, Department of Theoretical and Applied Mechanics, Cornell University, Ithaca, N.Y., May 1977.

List of Contract Reports to Date

1. Kumar, V., and Mukherjee, S., "Creep of a thick-walled spherical shell - An equation of state approach," ERDA Report No. C00-2733-1, Department of Theoretical and Applied Mechanics, Cornell University, Ithaca, N.Y. July 1975.
2. Kumar, V., and Mukherjee, S., "Creep analysis of structures using a new equation of state type constitutive relation", ERDA Report No. C00-2733-2, Department of Theoretical and Applied Mechanics, Cornell University, Ithaca, N.Y., September 1975.
3. Kumar, V., and Mukherjee, S., "Inelastic analysis of metallic structures in the presence of thermal gradients using newer constitutive relations," ERDA Report No. C00-2733-3, Department of Theoretical and Applied Mechanics, Cornell University, Ithaca, N.Y., February 1976.
4. Kumar, V., and Mukherjee, S., "A boundary-integral equation formulation for time-dependent inelastic deformation in metals," ERDA Report No. C00-2733-4, Department of Theoretical and Applied Mechanics, Cornell University, Ithaca, N.Y., April 1976.
5. Lance, R.H., and Mukherjee, S., "Mechanical behavior of materials and structural elements at elevated temperatures - Progress Report June 1, 1975-May 31, 1976", ERDA Report No. C00-2733-5, Department of Theoretical and Applied Mechanics, Cornell University, Ithaca, N.Y., May 1976.
6. Waung, Y.C., and Lance, R.H., "Creep of beams using a state variable approach". ERDA Report No. C00-2733-6, Department of Theoretical and Applied Mechanics, Cornell University, Ithaca, N.Y., July 1976.
7. Waung, Y.C., and Lance, R.H., "Creep of circular plates using a state variable approach", ERDA Report No. C00-2733-7, Department of Theoretical and Applied Mechanics, Cornell University, Ithaca, N.Y., August 1976.
8. Waung, Y.C., and Lance, R.H., "Theory of creep bending - a state variable approach", ERDA Report No. C00-2733-8, Department of Theoretical and Applied Mechanics, Cornell University, Ithaca, N.Y., September 1976.
9. Chang, K.J. and Lance, R.H., "Creep of Circular plates sealing an incompressible fluid", ERDA Report No. C00-2733-9, Department of Theoretical and Applied Mechanics, Cornell University, Ithaca, N.Y., April 1977.
10. Chang, K.J. and Lance, R.H., "Design of a uniaxial load creep testing machine", ERDA Report No. C00-2733-10, Department of Theoretical and Applied Mechanics, Cornell University, Ithaca, N.Y., May 1977.

List of Publications to Date.

1. Kumar, V., and Mukherjee, S., "Creep analysis of structures using a new equation of state type constitutive relation", Journal of Computers and Structures, Vol. 6, August/October 1976, pp. 429-437.
2. Kumar, V., and Mukherjee, S., "Time-dependent inelastic analysis of metallic media using constitutive relations with state variables", Nuclear Engineering and Design, Vol. 41, March 1977, pp. 27-43.
3. Mukherjee, S., "Corrected boundary-integral equations in planar thermoelastoplasticity", International Journal of Solids and Structures, Vol. 13, April 1977, pp. 331-335.
4. Kumar, V., and Mukherjee, S., "Creep analysis of metallic structures in the presence of thermal gradients using newer constitutive realtions", Journal of Pressure Vessel Technology Trans. ASME, Vol. 99, Series J, May 1977, pp. 272-280.
5. Kumar, V., and Mukherjee, S., "Elevated temperature inelastic analysis of metallic media under time varying loads using state variable theories", Proceedings of the Fourth International Conference on Structural Materials in Reactor Technology, San Francisco, Calif., August 1977 (to appear).

TRANSIENT CREEP IN PURE BENDING

Fig. 1

(Fig. 2 from [4])

TRANSIENT CREEP IN PURE BENDING

Fig. 2

(Fig. 3 from [4])

Fig. 3 Creep displacement and radial stress relaxation in an Aluminum plate sealing a fluid for various values of initial hardness. $T = 250^\circ\text{C}$, $\sigma_0 = 1,000$ psi, $n = 1/2$ (with fluid) [Fig. 3 from [7]].

Fig. 4 Creep of the inside radius of a Nickel sphere subjected to various levels of constant internal pressure. $T = 400^\circ\text{C}$, $\sigma_o^* = 22,000 \text{ psi}$ (3% cold work) $b/a = 2$)

Fig. 5 Redistribution of stress invariants in a creeping Nickel sphere. $T = 400^\circ\text{C}$, $p = 6,000 \text{ psi}$, $\sigma_o^* = 16,000 \text{ psi}$, $b/a = 2$

Figure 6 Uniaxial Creep Testing System
(Fig. 2 from [15])

Figure 7 Instruments Used in Creep Tests
A: Auto Data Nine Digital Data Logger
B: Cipher's 85H Magnetic Tape Recorder
C: Power Supplies
D: Room Temperature Controller
(Fig. 3 from [15]).

Fig. 8 Second Proof Test
 Temperatures, Load and Curvature
 (Fig. 20 from [15]).