COMPLEX-STRESS CREEP RELAXATION OF METALS AT ELEVATED TEMPERATURES

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SUMMARY

Many engineering components, such as bolted flanges, press-fit elements and springs are subject to creep relaxation, the initial loading strain remaining constant with time, and subsequent creep strain manifesting itself by an interchange of elastic strain for creep strain, resulting in diminishing stress with time. Further it is recognised that understanding of the behaviour of components under conditions of thermal stress, stress relieving treatment, and stress redistribution in complex and welded elements must involve a knowledge of the manner by which complex-stress conditions are altered by creep relaxation processes. Thus methods for the prediction of complex-stress relaxation of metals are a prerequisite for advanced design such as might be expected for the nuclear reactor industry.

The programme of investigation reported in this paper represents virtually the only comprehensive study undertaken in the field.

The four metals tested at elevated temperatures are considered to span a reasonable spectrum of engineering alloys; these are a 0.24%C Steel at 450°C, a Commercially Pure Copper at 250°C, on aluminium alloy at 200°C and a magnesium alloy at 50 and 20°C. Two questions were primarily considered in the work:

(a) Could simple tensile relaxation tests provide an acceptable prediction of complex-stress relaxation behaviour?
(b) Could simple tensile creep data form the basis of a similar prediction of relaxation under complex-stresses?

Combined tension-torsion relaxation tests were made on thin-walled tubular specimens of the metal concerned which, with the conventional assumptions of volumetric constancy, enabled those tests to be considered representative of complex-stress conditions in general.

The study has shown that simple, manually-controlled tensile relaxation-tests can provide a satisfactory prediction of complex-stress relaxation. Where only tensile primary creep data are available, however, the strain-hardening form of the appropriate complex-stress creep equation, derived from the tensile data, leads to reasonably accurate prediction of the complex-stress relaxation results.

NOTATION

A	Test constant
A', A_1, A_2, K m, n, n_1, n_2	Isothermal constants
C_a	Axial creep rate
C_{ij}	Creep rate tensor
C_o	Octahedral shear creep rate
C_1, C_2, C_3	Principal creep rates
E	Tensile modulus of elasticity
E_o	Octahedral shear strain
E_{oo}	Total elastic octahedral shear strain at $t = 0$
E_{ot}	Elastic octahedral shear strain at $t = t$
E_1, E_2	Principal elastic strains
F, f_1, f_2, ϕ	Functions
J_2	Second order invariant of stress deviation tensor
J_{20}	Value of J_2 at $t = 0$
J_{2t}	Value of J at time t
S_{ij}	Stress deviation tensor
S_1	Maximum principal stress deviator
t	Time
δ_{ij}	The Kronecker delta which equals unity when $i = j$ and zero when $i \neq j$
ε_a	Axial creep strain
ε_{ij}	Creep strain tensor
ε_{ot}	Octahedral shear strain at $t = t$
ν	Poisson's ratio
Σ	Sum of such terms as
σ	Tensile stress
σ_{ij}	Stress tensor
σ_v	Spherical stress tensor or hydrostatic stress
$\sigma_1, \sigma_2, \sigma_3$	Principal stresses
τ_o	Octahedral shear stress
τ_{oo}	Initial octahedral shear stress
τ_{ot}	Octahedral shear stress at $t = t$

INTRODUCTION

A considerable range of engineering components, such as bolted flanges, press-fit elements, and springs, operating in the temperature range at which creep occurs for the metal involved incur creep relaxation. Under these circumstances, the initial loading strain remains approximately constant with time, and developing creep strain manifests itself by an interchange of creep strain for elastic strain with a consequent diminishing stress history. In addition, many engineering elements operate under conditions of creep stress redistribution or thermal stress or are subjected to stress relieving treatment, for all of which a knowledge of complex-stress creep relaxation is a prerequisite for satisfactory understanding of the time-dependent behaviour of such components. The present paper gives the results of an investigation begun several years ago at NEL into the complex-stress relaxation of metals at elevated temperature. The four metals investigated are considered to be sufficiently different in both composition and form to justify the expectation that any conclusions found to apply to all four may be considered to be acceptable for metals in general.

Two questions were primarily considered:

a whether complex-stress relaxation properties could be predicted from simple tensile relaxation tests, and

b how far tensile creep data could be used for similar predictions.

Complex-stress relaxation tests were performed on thin-walled tubular specimens under conditions of combined tension and torsion. The test machines, specimens, and preparation of specimens have been described elsewhere by Henderson and Snedden [1] and Johnson and Frost [2].

Corresponding relaxation tests were performed on solid cylindrical specimens under axial loading conditions; similarly, the same test machines, Denison double-lever 5-tonne load capacity units, were used for tensile creep tests on specimens of the same size.

THEORY

1 Prediction of Complex-Stress Relaxation from Tensile Relaxation

The complex-stress primary creep rate equations for all the metals considered in the present paper have been shown by Johnson, Henderson, and Khan [3] to be of the form

$$C_{ij} = F(J_2)S_{ij}\phi(t) \tag{1}$$

where C_{ij} = creep rate tensor,
J_2 = second invariant of stress deviation tensor $= \frac{1}{6}\Sigma(\sigma_1 - \sigma_2)^2$,
S_{ij} = stress deviation tensor $= \sigma_{ij} - \delta_{ij}\sigma_v$,
$\phi(t)$ = time function, and
$\sigma_1, \sigma_2, \sigma_3$ = principal stresses.

$F(J_2)$ was usually found to be of the form

$$A'(J_2)^n \quad \text{or} \quad \{A_1(J_2)^{n_1} + A_2(J_2)^{n_2}\}$$

where A', A_1, A_2, n, n_1, n_2, are constants for a given metal and temperature.

Thus, as for creep, complex-stress and pure tensile relaxation tests are considered equivalent on the basis of similarity of the second stress invariant J_2 or the octahedral shear stress τ_o, where

$$\tau_o = \tfrac{1}{3}\{\Sigma(\sigma_1 - \sigma_2)^2\}^{\frac{1}{2}} = (\tfrac{2}{3} J_2)^{\frac{1}{2}}.$$

Tensile and complex-stress relaxation tests of the same initial octahedral shear stress, τ_o, should accordingly develop similar octahedral shear stress/time curves. An experimental investigation of the validity of this premise is described in this paper.

2 Prediction of Complex-Stress Relaxation from Tensile Creep Data

The mechanical theories of creep are considered to provide a relationship whereby constant-stress creep equations or data may be converted to a form suitable for describing changing stress conditions of creep and relaxation.

The equation (1) $\qquad C_{ij} = F(J_2)S_{ij}\phi(t)$
known as the time-hardening equation, may be re-written in the strain-hardening form

$$C_{ij} = f_1\{F(J_2)S_{ij}\}/f_2(\varepsilon_{ij}). \tag{2}$$

Equation (1) assumes that, for isothermal conditions, creep rate is dependent only on current stress and time; equation (2), that creep rate depends on current stress and strain. It is assumed that the current creep rate is unaffected by the stress and strain history. Further the effect of creep recovery is also neglected, although this has been shown by Henderson [4] to be significant. The neglect of stress or strain history and recovery must in theory be an impediment to the completely successful application of the mechanical equation of state to the prediction of complex-stress relaxation, compared with the equivalent tensile relaxation method. The present work examines this supposition. Simplification of the complex-stress system and the consideration of relaxation are obtained by referring the general stress system to the octahedral shear stress (see Appendix). Thus the general creep rate equation

$$C_{ij} = F(J_2)S_{ij}\phi(t)$$

is related to the octahedral plane to give the equation

$$C_o = 2\sqrt{\tfrac{2}{3}}\{F(J_2)\}(\sqrt{J_2})\phi(t). \tag{3}$$

The normal stress on this plane is equal to the hydrostatic stress and, since volumetric constancy is assumed for primary creep, must be ineffective under creep conditions. Similarly, since the normal creep strain for this plane is proportional to the sum of the principal creep strains, it too is zero from the assumption of volumetric constancy.

For elastic conditions, the octahedral shear strain E_o is given by

$$E_o = \tfrac{2}{3}\sqrt{\{\Sigma(E_1 - E_2)^2\}} = \tfrac{2}{3}\left(\frac{1+\nu}{E}\right)\sqrt{\{\Sigma(\sigma_1 - \sigma_2)^2\}}$$

where E_1, E_2 etc = principal elastic strains;

thus $$E_o = \frac{2}{E}\sqrt{\tfrac{2}{3}}(1+\nu)\sqrt{J_2} = K\sqrt{J_2}.$$

The complex-stress total strain equation, where only elastic and creep conditions are considered, is given by

$$E_{oo} = E_{ot} + \varepsilon_{ot} \tag{4}$$

where the suffix o refers to zero time and t to current time;

that is E_{oo} = total octahedral shear strain (elastic) at t = 0,

E_{ot} = elastic octahedral shear strain at t = t, and

ε_{ot} = octahedral shear creep strain at t = t.

Differentiating equation (4) with respect to time gives

$dE_{oo}/dt = 0$ for relaxation conditions (that is E_{oo} constant);

thus $$0 = \frac{dE_{ot}}{dt} + \frac{d\varepsilon_{ot}}{dt},$$

that is $$\frac{d\varepsilon_{ot}}{dt} = C_o = -\frac{dE_{ot}}{dt} = -K\frac{d\sqrt{J_2}}{dt}.$$

By equations (1) or (2) and (3)

$$-K\frac{d\sqrt{J_2}}{dt} = 2\sqrt{\tfrac{2}{3}}F(J_2)\sqrt{J_2}\phi(t) = F_1(J_2)\sqrt{J_2}\phi(t), \tag{5}$$

or $$-K\frac{d\sqrt{J_2}}{dt} = f_1\{2\sqrt{\tfrac{2}{3}}F(J_2)\sqrt{J_2}\}/f_2(\varepsilon_{ot}) = \{F_2(J_2)\sqrt{J_2}\}/f_2(\varepsilon_{ot}). \tag{6}$$

(When $F_2(J_2)\sqrt{J_2} = f_1\{2\sqrt{\tfrac{2}{3}}F(J_2)\} = \frac{1}{m}F_1(J_2)\sqrt{J_2}$ for $\phi(t) = t^{m-1}$.)

Integrating equation (5) gives

$$\int_0^t (t)\,dt = -K \int_{\sqrt{J_{20}}}^{\sqrt{J_{2t}}} \frac{d\sqrt{J_2}}{F_1(J_2)\sqrt{J_2}};$$

for the metals tested $\phi(t) = t^{m-1}$,

thus

$$t^m = mK \int_{\sqrt{J_{2t}}}^{\sqrt{J_{20}}} \frac{d\sqrt{J_{2t}}}{F_1(J_2)\sqrt{J_2}}.$$

Similarly, for equation (6)

$$-K\frac{d\sqrt{J_2}}{dt} = C_o = m\{F_2(J_2)\sqrt{J_2}\}^{\frac{1}{m}} \Big/ \varepsilon_{ot}^{\frac{1}{m}-1}$$

and since

$$\varepsilon_{ot} = E_{oo} - E_{ot} = K(\sqrt{J_{20}} - \sqrt{J_{2t}}),$$

$$-K\frac{d\sqrt{J_2}}{dt} = m\{F_2(J_2)\sqrt{J_2}\}^{\frac{1}{m}} \Big/ \{K(\sqrt{J_{20}} - \sqrt{J_{2t}})\}^{\frac{1}{m}-1}.$$

Thus

$$t = \frac{K^{\frac{1}{m}}}{m} \int_{\sqrt{J_2}}^{\sqrt{J_{20}}} \frac{(\sqrt{J_{20}} - \sqrt{J_{2t}})^{\frac{1}{m}-1}}{\{F_2(J_2)\sqrt{J_2}\}^{\frac{1}{m}}}\, d\sqrt{J_2}$$

$$= \frac{K^{\frac{1}{m}}}{m} \int_{\sqrt{J_{2t}}}^{\sqrt{J_{20}}} \frac{(\sqrt{J_{20}} - \sqrt{J_{2t}})^{\frac{1}{m}-1}}{\{F_2(J_2)\sqrt{J_2}\}^{\frac{1}{m}}}\, d\sqrt{J_2}$$

and

$$t = \left[mK \int_{\sqrt{J_{2t}}}^{\sqrt{J_{20}}} \{F_1(J_2)\sqrt{J_2}\}^{-1} d\sqrt{J_{2t}} \right]^{\frac{1}{m}} \qquad (7)$$

by Time Hardening theory,

and

$$t = \frac{K^{\frac{1}{m}}}{m} \int_{\sqrt{J_{2t}}}^{\sqrt{J_{20}}} \{F_2(J_2)\sqrt{J_2}\}^{-\frac{1}{m}} (\sqrt{J_{20}} - \sqrt{J_{2t}})^{\frac{1}{m}-1}\, d\sqrt{J_2} \qquad (8)$$

by Strain Hardening theory.

MATERIAL

The metals studied were a 0.24%C steel at 450°C, a commercially pure copper at 250°C, an aluminium alloy (RR59) at 200°C and a magnesium alloy (2%Al) at 20 and 50°C. Details of the metals and heat treatment are given in Table I.

TEST RESULTS

Table II lists the tests performed on each metal, and Table III shows the constants and functions obtained for the various metals and used in the formation of the equations described in the section on theory. The constants in the complex-stress creep rate equations were derived from data obtained in appropriate tensile creep tests, except for the magnesium alloy at 20°C, where the complex-stress creep equation derived previously by Johnson, Henderson, and Khan [5] was used. The octahedral relaxation curves derived by both theories, using the complex-stress equation, were compared with the experimental complex-stress relaxation tests. Similarly comparison was made between test curves and those derived from corresponding tensile relaxation tests. The method is fully exemplified for the case of 0.24%C steel at 450°C in the Appendix.

Finally, Table IV shows the degree of error found between the variously predicted and actual complex-stress relaxation test curves.

DISCUSSION

The combined tension-torsion stress relaxation test results for the four metals were predicted from the results of equivalent tensile relaxation tests on solid cylindrical specimens and by the mechanical equations of state derived from tensile creep tests on similar solid cylindrical specimens.

The conclusions are considered to apply to complex-stress systems in general, restricted only by the acceptability for creep and relaxation of conventional assumptions in plasticity theory of volumetric constancy and ineffectiveness of hydrostatic stress. The range of tension to torsion ratios of about 0.3 to 3.0 and the consideration of several distinctly different metals reinforces confidence in the justification of extending the common conclusions to general stress conditions.

The complex-stress tests on the aluminium and the magnesium alloy at 50°C were of 150 hours duration. In view of the evidence that about 60-70 per cent of the relaxation of stress occurred in the first 8 hours it was considered that no great advantage would be served by extending those tests to much longer times; in fact, it was decided that for the 0.24%C steel, the copper, and the magnesium alloy at 20°C, complex-stress tests of only 8 hours duration would be acceptable for the remainder of the research programme. Tensile relaxation tests on the 0.24%C steel confirmed that 66 per cent of the relaxation in the 150 hours indeed occurred in the initial 8 hours for this metal at 450°C. Turning to the results of the investigation, the percentage errors shown in Table IV were calculated as the difference at various times between predicted and observed relaxed stress values, divided by the observed stress, averaged over the series of complex-stress tests for a particular metal. The average range of test errors and maximum errors for each metal is included. Statistically a larger sample of tests would have been an advantage; however, against the background of limited testing available from a single complex-stress unit and the similarity of conclusions for four different metals, the implications are quite unambiguous. It is apparent from Table IV that the best prediction of the complex stress relaxation test results is afforded by the equivalent tensile relaxation tests. It is incidentally noted that tensile relaxation tests on the steel at 450°C indicated that reasonably similar results (within 5 per cent) were obtained by manually controlled relaxation as compared with automatic (continuous) control.

That the equivalent tensile relaxation test (based on the octahedral shear stress or von Mises criterion) is superior to the mechanical equation of state, with tensile creep data, in predicting the complex-stress relaxation tests is not altogether surprising since (a) initial inelastic loading strain, if present, (b) creep recovery (reverse creep at reduced stress), and (c) Poisson's ratio for elastic conditions differing from 0.5, are all complicating factors automatically allowed for in the replication of the complex-stress relaxation test by an equivalent tensile test. These often significant effects are ignored when using creep data and transposition is made, via the mechanical theories, to relaxation under complex-stress.

Nonetheless it may often be the case that only tensile creep data are available for complex-stress relaxation prediction and that no additional testing is possible. It is important therefore, for those circumstances, to know the degree of error which may be involved in such equation of state predictions. Table IV shows that, of the two methods, the strain hardening form is in general better in providing a prediction of the complex-stress tests, average errors ranging from -6 to +9 per cent for all four metals. The time hardening errors range from -11 to +4 per cent and it is open to question whether the slightly more complex calculations associated with the strain hardening equation justify the marginally improved prediction. In this regard it is to be noticed that prediction by equivalent tensile relaxation test is not only superior to both the foregoing methods but requires virtually no mathematical calculations or formulation of equations and furthermore can be performed by relatively inexperienced staff using a simple double-lever creep testing machine.

For the four metals examined, it is concluded that a satisfactory prediction of complex-stress relaxation may be obtained from tensile relaxation tests with the added advantages of simplicity of testing and minimal computation.

Where only tensile primary creep data are available, however, the mechanical equations of state offer only slightly less accurate, though considerably more laborious, predictions of the complex-stress relaxation tests than the tensile relaxation method. Extension of the findings to metals and stress systems in general is considered to be permissible within the creep regime of the metal concerned.

The present paper indicates how the quantifying of complex-stress relaxation behaviour in components and structures may be made; the effect as it affects stress redistribution in creep fracture, stress relief damage, and pure relaxation problems is the subject of further study.

ACKNOWLEDGEMENTS

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A P P E N D I X

COMPLEX-STRESS RELAXATION OF 0.24%C STEEL AT 450°C USING TENSILE CREEP DATA

Primary creep curves obtained from tests shown in Fig. 1 are, from linearity displayed in $\log\varepsilon_a/\log t$ plots, of the form

$$\varepsilon_a = At^{0.27}.$$

Plots of A against stress (Fig. 2) lead to the primary creep equation for tensile tests

$$\varepsilon_a = (4.4 \times 10^{-7}\sigma + 5.98 \times 10^{-11}\sigma^3)t^{0.27}$$

$$= (6.6 \times 10^{-7} + 8.97 \times 10^{-11}\sigma^2)(\tfrac{2}{3}\sigma)t^{0.27} \quad (\sigma \text{ in MN/m}^2) \; (t \text{ in hours})$$

$$= \{6.6 \times 10^{-7} + 2.69 \times 10^{-10}(J_2)\}(\tfrac{2}{3}\sigma)t^{0.27}$$

where $$J_2 = \frac{1}{6}\,\Sigma(\sigma_1 - \sigma_2)^2 = \tfrac{1}{3}\sigma^2 \text{ for pure tension}$$

and $$C_a = \{1.78 \times 10^{-7} + 7.26 \times 10^{-11}(J_2)\}(\tfrac{2}{3}\sigma)t^{-0.73}$$

or $$C_1 = \{1.78 \times 10^{-7} + 7.26 \times 10^{-11}(J_2)\}(S_1)t^{-0.73}.$$

Thus the general complex-stress creep rate equation is

$$C_{ij} = \{1.78 \times 10^{-7} + 7.26 \times 10^{-11}(J_2)\}(S_{ij})t^{-0.73}$$

and represents a form of equation which satisfies the complex-stress primary creep behaviour of the metals considered in the present report, that is

$$C_{ij} = F(J_2)S_{ij}\phi(t).$$

Thus for the 0.24%C steel at 450°C

$$F(J_2) = 1.78 \times 10^{-7} + 7.26 \times 10^{-11}(J_2)$$

and $$F_1(J_2) = 2.9 \times 10^{-7} + 1.18 \times 10^{-10}(J_2)$$

$$F_2(J_2) = F_1(J_2)/0.27$$

$$m = 0.27, \quad E = 166\,400 \text{ MN/m}^2, \quad \nu = 0.30, \quad K = \frac{2}{E}\sqrt{\frac{2}{3}}\,(1 + \nu) = 1.275 \times 10^{-5}.$$

Introducing these constants and functions into equations (7) and (8) provides the form of equation for the prediction of the relaxation of the tension-torsion tests by the time hardening and strain hardening forms of the equation of state.

The predicted relaxation test for an initial value of octahedral shear stress is obtained by substituting this stress in the form of the second order invariant of the stress deviation tensor, that is $\sqrt{J_{20}} = \sqrt{\tfrac{3}{2}}\tau_{oo}$ in the developed equation and proceeding with the integration either graphically or by computer of a preselected number of intervals of $\sqrt{J_2}$. Thus for each complex-stress test, the initial value of $\sqrt{J_{20}}$ or τ_{oo}, a series of times corresponding to diminished values of τ_{ot} were obtained by the time or strain hardening theories respectively. A typical comparison of predicted and actual test relaxation curves is illustrated in Fig. 3 together with the corresponding curve derived from the equivalent tensile relaxation test.

T A B L E   I

DETAILS OF PRODUCTION, HEAT TREATMENT, AND CHEMICAL COMPOSITION OF MATERIALS

Material	Details of production and dimensions	Details of heat treatment	Details of chemical composition (per cent)									
			C	Si	S	P	Ni	Cr	Mo	Cu	S~~M~~n	Mn
0.24% carbon steel	Core from an ingot 406 mm in diameter and 876 mm in length	Three hours at 950°C followed by air cooling, then 15 minutes at 930°C followed by air cooling and finally a stress relieving treatment of 3 hours at 575°C with furnace cooling.	0.24	0.22	0.036	0.033	0.27	0.09	0.03	0.16	0.005	0.69
Copper	Rolled bar of 381 mm diameter	400°C for 1 hour and furnace cooled.	Commercially pure									
Aluminium alloy To specification BS 2L42 (RR59)	Billet 457 mm long and 305 mm diameter, continuously cast	525°C ± 5 degC for 8 hours and quenched in boiling water. 24 hours at room temperature, heated at 250°C for 16 hours and air cooled.	Cu	Fe	Si	Mn	Mg	Ni	Sn			
			1.97	1.19	0.86	0.05	1.45	1.06	0.06			
Magnesium alloy	Billet 305 mm long and 305 mm diameter	420°C ± 5 degC for 4 hours, furnace cooled to room temperature in about 10 hours. Heat treatment carried out in an atmosphere of sulphur dioxide.	Zn	Al	Si	Cu	Mn	Fe	Sn			
			<0.05	2.0	0.02	<0.01	0.03	<0.04	0.03			

T A B L E   I I

DETAILS OF TESTS

Metal	Temperature (^{o}C)	Tests	Stress τ_o range (MN/m^2)	No	Duration
0.24%C steel	450	CS Relaxation	66.6-92.7	4	500 min
		Solid Tensile Creep	36.4-92.7	9	10 000 min
		Solid Tensile Relaxation	50.9-9.27	7	9 000 min
Commercially pure copper	250	CS TR TC	19.4-25.5 19.4-25.5 12.5-29.1	5 5 6	500 min 1800 min 1800 min
Aluminium alloy	200	CS TR TC	24.5-44.9 14.1-42.4	7 7	168 h 200 h 20-200 h
Magnesium alloy	20	CS CSC TR	20.4-22.5 - 20.4-11.5	6 - [illegible]	500 min previous study 500 min
	50	CS TC	0.17-16.3 7.00-14.4	7 3	168 h 168 h

T A B L E   I I I

CONSTANTS IN CREEP RATE EQUATION AND ELASTIC CONSTANTS

$$C_o = \{A_1(J_2)^{n_1} + A_2(J_2)^{n_2}\} \sqrt{J_2}\, t^{m-1}$$

$$\text{or} \quad C_o = A'(J_2)^{n}(\sqrt{J_2})\, t^{m-1}.$$

Elastic constants: ν = Poisson's ratio, and

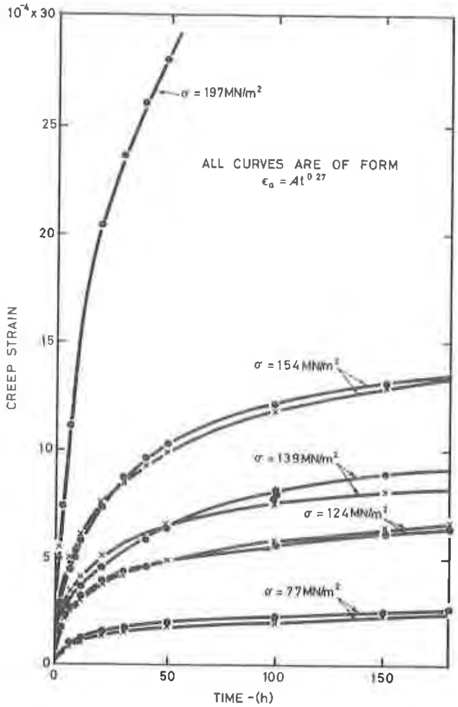
E = modulus (Young's) of elasticity (stresses in MN/m^2).

Metal	A_1	A_2	A'	n_1	n_2	n	m	ν	E (MN/m^2)
0.24%C steel 450°C	2.9×10^{-7}	1.18×10^{-10}		0	1		0.27	0.03	166 400
Aluminium alloy 200°C	1.83×10^{-7}	7.18×10^{-10}		0	1		0.27	0.45	64 300
Commercially pure copper 250°C	2.18×10^{-6}	5.48×10^{-18}		0	4.11		0.51	0.44	93 700
Magnesium alloy 20°C			3.49×10^{-8}			0.50	0.23	0.30	41 700
Magnesium alloy 50°C			2.81×10^{-8}			0.75	0.29	0.39	34 450

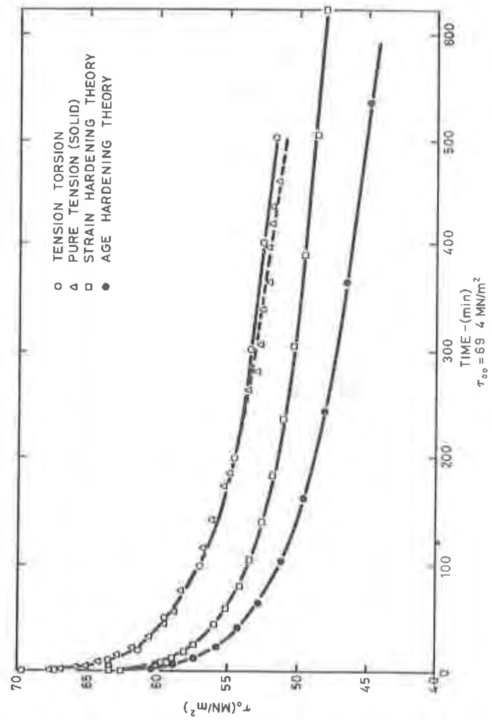
T A B L E   I V

SUMMARY OF PERCENTAGE ERRORS IN PREDICTION OF COMPLEX-STRESS RELAXATION TESTS

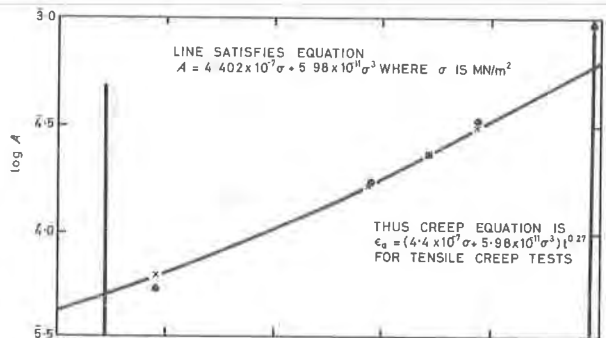
Metal	Theory								
	Time hardening			Strain hardening			Tensile relaxation		
	Av. error	Max. error	Range	Av. error	Max. error	Range	Av. error	Max. error	Range
0.24%C steel, 450°C	-11	13	13	-6	7	8	+1	3	3
Aluminium alloy, 200°C	-1	6	2	+1	6	2	+5	7	3
Commercially pure copper, 250°C	-8	15	16	-3	6	8	-2	5	6
Magnesium alloy, 20°C	-3	5	3	-2	4	2	-6	7	3
Magnesium alloy, 50°C	+4	13	11	+9	19	17			



1 Tensile creep curves (solid specimens) for 0.24%C steel at 450°C



2 Creep stress dependence



3 Experimental and predicted octahedral relaxation curves.