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STRESS INTENSIFICATION AND CREEP RUPTURE

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The development of computer-aided finite-element and reference stress methods of time-dependent stress analysis now introduces a degree of rationale in creep design previously absent. As a consequence of such advances the hitherto neglected effect of stress raisers, discontinuities and notches has taken its place at the forefront of problems yet to be solved.

As part of a continuing programme of creep research at NEL, an investigation has been made examining, for a spectrum of engineering metals, the effect of the presence of a circular hole on the creep rupture life of a plain plate under tension.

The metals considered in the study included two alloy steels, a low-carbon steel, an aluminium alloy, a commercially pure copper, and a Nimonic alloy, each tested at a temperature typical of operational conditions for the metal involved. Thus, while only a limited number of tests were conducted for any particular metal, the span of metals and the forms from which the specimens were manufactured (wrought bar, rolled plate and ingot) would it was believed compensate for this. Further, the metals used in the investigation were chosen to adequately cover all possible combinations of multi-axial stress/creep rupture criterion and ductility features which previous research had revealed as necessary to meaningful creep rupture prediction for engineering components.

Plate specimens with or without circular holes of 2.54 mm thickness, together with conventional solid cylindrical (9.1 mm dia) specimens, were used in the investigation. The holed plate specimen contained an initial estimated elastic stress concentration factor of about 2.3.

Six metals were considered, two of which had been found in previous multiaxial stress studies to be controlled with respect to creep rupture time by the maximum principal stress; those were a commercially pure copper at 250°C and Nimonic 90 at 750°C. Those metals differed, however, in that the copper displayed considerable creep rupture ductility (>10% elongation), but the Nimonic 90 was relatively brittle in this respect (<1%).

Of the four octahedral shear stress controlled metals studied, three, the 9% Cr 1% Mo steel, the ½% Cr ½% Mo ¼% V steel and the 0.2% C steel at 525, 575, and 450°C respectively had creep rupture ductilities ranging from 5 to 50%, while the remaining metal, the aluminium alloy RR58 at 180°C, fractured with only about 1% creep strain.

The investigation revealed that, despite variations in multiaxial stress/creep rupture criterion and differences in creep rupture ductility, plate specimens containing holes, on the whole, rupture in times similar to those of plain plate specimens at a nominal stress equal to that over the minimum cross section in the holed specimens. Thus initial stress intensification has no effect on creep life in those tests. An exception to this finding was the octahedral shear stress controlled, low-ductility, aluminium alloy at 180°C; in this metal, stress intensification appears to be effective.

Corresponding tests on conventional solid cylindrical creep specimens demonstrated the importance of comparing holed plate specimens only with similar plate type plain specimens by showing for certain circumstances significantly different rupture lives from those obtained for plain plate specimens at the same stress. Initial plastic loading strain was a further factor of importance in making comparisons.

The implication of these results for the development of methods of creep analysis are discussed.

1 INTRODUCTION

Creep design has now attained a degree of rationale mainly due to the development of computer-aided finite-element and reference stress methods of time-dependent stress analysis. Relevant materials data at appropriate temperatures for a wide spectrum of engineering materials has become available(1), and constitutive equations of increasing comprehensiveness have been developed. Multi-axial stress relationships for different manifestations of creep, whether for deformation, relaxation or rupture limitations, have been established(2). Currently, elevated-temperature design of engineering components is based on elastic stress distributions or, if greater refinement is sought, steady-state stress distributions(3), in conjunction with tensile creep or creep rupture data. The afore-mentioned researches on multi-axial stress creep and creep rupture criteria and on the significance of anisotropy(4) and anelasticity(5) have extended the comprehensiveness of this approach. For the future, however, more-complex manifestations of time-dependent, elevated-temperature effects will take their place in the fore-front of research now considered of high priority; among these is the effect of stress raisers, discontinuities and notches.

Adequate ductility(6) as an indication of the suitability of a metal for components operating in the creep range is qualified by the possible reduction which may occur in the rupture ductility under conditions of multi-axial stress; evidence is required regarding this possibility.

The persistence of estimated initial stress systems set up in structures or redistribution of stresses during their life-time may play a significant role in their analysis and design and in their lives in practice.

Multi-axial creep rupture criteria and multi-axial creep and relaxation characteristics, previously established for a spectrum of metals at NEL, provided a background of suitable materials and data against which an investigation of one of the remaining imponderables, the effect of stress intensification in creep rupture, might be made. Plate specimens with and without circular holes, together with conventional solid cylindrical specimens (designated "rod" testpieces) were used in the study. The metals investigated were two alloy steels, a low carbon steel, an aluminium alloy, a commercially pure copper, and a Nimonic 90 alloy, each tested at a temperature typical of operational conditions for that metal.

Comprehensive data on the creep relaxation and creep rupture characteristics of the metals in the programme enabled estimates to be made of likely rates of stress redistribution and consequent persistence of initial stress intensification indicated by stress intensity factors for the geometry of the specimens involved.

Thus the investigation set out to answer the question "Does initial stress intensification play a significant role in the creep rupture of components where redistribution is possible?" Further, "If such an effect is significant, can it be quantified and is the degree of the effect for a particular metal related to (i) creep rupture ductility of the metal at the operative temperature, (ii) relaxation characteristics, or (iii) any other material characteristics?"

2 THEORY

For a plate of width w and thickness h containing a hole of diameter a, under axial tension, Heywood(7) developed a stress concentration equation

$$K_{tn} = 2 + (1 - \frac{a}{w})^3$$

in which K_{tn} = stress concentration factor based on the nominal stress

σN = nominal stress = $\sigma/(1 - \frac{a}{w})$

σ = applied stress, distant from hole = $\frac{P}{wh}$, and

P = applied load.

The maximum stress at the edge of the hole is given by

$$\sigma_m = K_{tg}\sigma$$

where K_{tg} = stress concentration factor based on gross stress = $\dfrac{2 + (1 - \frac{a}{w})^3}{1 - \frac{a}{w}}$

For the current plates with a circular hole such that $\frac{a}{w} = .333 \pm .006$, the values of stress concentration factor and maximum stress were thus

$$K_{tn} = 2.31$$

and $\sigma_m = 2.31\ \sigma N = \dfrac{2.31\ P}{(w - a)h}$

For an elastic/plastic stress distribution on a similar structure, Smith and Sidebottom (8) have shown that the equation

$$\frac{P}{P_e} = \frac{6}{2 + (^a/2x)^2 + 3(^a/2x)^4}$$

describes the depth of penetration of inelastic strain, where

P_e = load leading to the elastic limit at the position of maximum stress, and

x = distance of elastic/plastic boundary from centre of the hole.

Analysis leads to the stress concentration factor

K^P_{tn} = 2.00 and thus

$$\sigma_m{}^P = 2.0\ \sigma N$$

Hayhurst, Dimmer and Chernuka (9) have considered creep rupture life in plates with a central circular hole using finite element methods and have calculated normalized maximum steady-state (creep) stresses ranging from 1.11 for aluminium to 1.20 for copper.

Thus for the current tests, Table 4 shows that for four metals, the nominal stresses exceeded the yield stress, and consequently the initial stress concentration factor would be that given by Smith and Sidebottom, ie 2.0.

Assuming stress redistribution to be a partial interchange of plastic or creep strain for elastic strain under the restraints of stress gradients in a structure, some indication of a metal's capacity to redistribute stress is available in the creep behaviour and creep relaxation characteristics. A first approximation could then be obtained of the time likely to be spent at higher stress levels and the consequent creep damage, by calculating the time for pure relaxation to reduce stresses in the different metals from the maximum stress, calculated for a plate with a circular hole, to the nominal stress. Thus from primary creep equations of the form

$$\varepsilon = (A\sigma + B\sigma^n)t^m \tag{1}$$

or

$$\varepsilon = B\sigma^n t^m, \tag{2}$$

where ε = creep strain

σ = axial stress

t = time

A, B, n, m = constants,

relaxation equations were derived using the strain-hardening form of the mechanical equation of state(2).

$$t = \frac{1}{mE} \int_{\sigma_t}^{\sigma_o} \frac{(\sigma_o - \sigma_t)^{\frac{1-m}{m}}}{\left[F(\sigma)\right]^{\frac{1}{m}}} \, d\sigma \qquad (3)$$

The results of calculations of times of relaxation t_R from the maximum elastic or elastic/plastic stress to the nominal stress for the various metals are shown in Table IV.

3 MATERIALS, SPECIMENS AND TEST MACHINES

Six metals were studied, details of which are given in Table I; a ½%Cr, ½%Mo, ¼%V steel in the fully fabricated condition of a forged pipe, a 0.24%C steel which had been used in earlier studies and was known to have reasonably isotropic creep properties, a 9%Cr, 1%Mo steel currently a candidate material for reactor applications, a high temperature alloy - Nimonic 90, a commercially pure copper, and an aluminium alloy RR58, the last two typifying metals controlled in multiaxial creep rupture by a maximum principal stress and an octahedral shear stress criterion respectively.

Plate specimens of 2.54 mm thickness were used. For the plane specimens, a width of 10 mm and a parallel length of 51 mm was associated with holed specimens of width 10 mm and hole diameter of 3 mm. Conventional solid cylindrical specimens of 9.07 mm diameter, 76 mm parallel length were also tested in part of the investigation.

The creep tests were made in standard NPL-designed double-lever type creep testing machines of 50 kN load capacity.

Specimens were fitted with three platinum-platinum 13% rhodium thermocouples, and platinum resistance thermometers in conjunction with temperature controllers were used to obtain the requisite temperature and control of ± 0.5°K with a temperature gradient of less than 2°K.

4 TEST RESULTS

Table II lists the creep rupture tests performed on the different metals and the test temperatures. Nominal axial stresses σN are given in MN/m^2 and relate to initial cross sections of specimens. Rupture times are shown for tests on conventional solid cylindrical plane plate, and holed plate specimens at the same nominal stress, together with the corresponding estimate of the rupture time obtained from the relevant rupture equation for that metal and temperature.

Values of the constants for the creep rupture equation $t_f = C\sigma^{-\nu}$ and the primary creep equation $\varepsilon = (A\sigma + B\sigma^n)t_m$ are given, for the various metals, in Table III.

Table IV shows normalized operative stresses $\bar{\sigma}$ for the various types of test, the yield stress σ_y and relaxation times t_R. Average values of creep rupture ductility ε_f are also shown, as derived from the tests on solid cylindrical specimens.

5 DISCUSSION

Taking an overall view of the results of the investigation as revealed by Table II, it is apparent that for the metals and conditions investigated, the stress intensification produced by the holes, as estimated from elastic stress intensity principles, does not produce any significant effect on rupture lives compared with those shown on similar plate specimens at the same nominal stress but in the absence of stress intensification. However, there are exceptions to that conclusion and there are cautionary observations which must be made.

First it must be emphasized that the current study represents a mere reconnaissance into the general and formidable problem of creep rupture and stress concentrations. Nonetheless, by virtue of the wide variety of metals used in the study, it was considered that quite unambiguous trends could be identified.

Apart from implications for such diverse considerations as the application of fracture mechanics to elevated-temperature, time-dependent problems, crack propagation, and the relevance of continuum mechanics approaches to non-continuous conditions in engineering components, the straight-forward answer to the designers' question of "Do stress intensifications reduce and permit average stresses to be used in design for elevated-temperature applications?" is provided by the present results. In the British Standard BS806, the assumption is made that 50% of the peak stress in branch reinforcement relaxes under steady-state conditions. The test results tend to validate the assumption of adequate relaxation of peak stresses, to enable average stresses to be used in design, particularly if satisfactory creep rupture ductility is available in the material.

Considering the metals separately, the ½%Cr, ½%Mo, ¼%V steel at 575°C tested at two stress levels leading to rupture times in the hundred and thousand hour ranges respectively, showed some difference between rupture times for plate and holed specimens at the shorter times, but virtually identical lives at the lower (and therefore closer to operational) stress level. Some difference was observed between plate and solid cylindrical specimen rupture times; however, comparing rod and equation-predicted rupture times, a fair degree of scatter must, it appears, have been present between the rod tests from which the equation was derived; so that, although size effects may have been present, scatter indications would tend to reduce the significance of this.

A somewhat similar picture is presented for 9%Cr, 1%Mo steel at 525°C, in which all three types of testpiece led to almost identical results when tested at a nominal stress of 201 MN/m^2. Variation between the theoretical and test times can be attributed to the severe slope (ν between 9 and 11, Table III) in the stress/rupture time relation.

The 0.24%C steel at 450°C proved unusual compared with the two previous steels in that, although sharing the common feature of adequate creep rupture ductility, an increased life was experienced in the three holed-plate tests, compared with their plane counterparts. In the corresponding rod tests almost identical rupture time was observed in one case. The possibility of notch-strengthening is thus unlikely, particularly if comparison is made with the theoretical rupture time.

Thus creep rupture of the three steels, which earlier work has shown to be controlled in creep rupture under multiaxial stress conditions by the octahedral shear stress, is not affected by the presence of a stress raiser in the form of a circular hole.

For the high-temperature alloy Nimonic 90 at 750°C, which previous work had shown to be controlled by the maximum principal tensile stress(10) and was of extremely low ductility ($<$ 1% elongation) in creep rupture, the trend remained the same. The rupture lives, either of about 2000 or 5000 hours duration, had very little variation, whether the specimens were plane, plane holed, or solid cylindrical rod.

Commercially pure copper at 250°C had proved both ductile in creep rupture ($>$10% elongation) and obeyed a maximum principal stress criterion in multiaxial stress/creep rupture time relations. The difference between the plate and rod specimen results at the higher stress level suggested that size effect may have been present. Thus preventing any significance being placed on the difference observed between the holed and plate specimen results at the higher stress level. In addition, the similarity between plane plate and holed plate specimens at the higher stress level (where stress raiser effects had proved greatest for the other metals) tended to discount any significance in the difference at the lower stress level.

Finally, the results on the aluminium alloy RR58 at 180°C were examined. This metal had been used extensively by the authors in the past and is very well characterised in creep properties(4,5). At 180°C the creep rupture ductility had proved to be less than 1% on average, and the octahedral shear stress to control the multi-axial stress creep rupture life. At the three stress levels tested, a significant reduction in creep rupture life was observed for the holed plates. Specimens with identical nominal stresses but in one of which a circular hole was present differed by a factor of almost 2 in life times realized. Thus for the six metals examined only in the aluminium was a positive effect of stress raiser observed in creep life.

Previous consideration of the problem had suggested to the authors that stress redistribution in components, eg a bar in torsion, might be neglected in predicting creep rupture(11) and that, provided the correct complex-stress creep rupture criterion were used, the redistributed (steady state) value of that stress could be read off the basic tensile creep rupture data to provide the rupture time for the torsion bar.

The experiments had shown that such a computation led to conservative estimates of the rupture lives of solid cylindrical bars under torsion. However, although at first no effect of time spent at the higher stress levels during redistribution of bringing forward rupture times seemed to be present, it was recognised that such an effect could be masked by the counteraction of failure propagation time in these elements preventing the observation of failure initiation. Therefore, although previous evidence indicated that peak stress redistribution affected rupture time but little, the fact that experimental evidence usually involved co-existing effects which prevented isolation of the purely stress-raising effect, placed considerable doubt on accepting such evidence as final. Investigations by Hayhurst, Morrison and Leckie(12) on tension panels with circular holes had already indicated that the creep rupture of such plate structures was not significantly influenced by the magnitude of the initial elastic and steady-state stress-concentration factors. However, it appeared that in this study solid cylindrical specimens had been used to provide the basic creep rupture data and, if differences in rupture behaviour existed between plane plate and solid cylindrical specimens, then the comparison might require adjustment in the light of those differences. The current investigation used both plate and solid cylindrical specimens, and Table II indicates that at one stress level for the 0.24%C steel, the ½%Cr, ½%Mo, ¼%V steel, commercially pure copper, some size effect did appear. In the light of these results, the use of creep rupture data from solid cylindrical specimens seems justified only if at least one comparative test on plate be made. Additionally it must be pointed out that the effect for plates of lesser thickness than the present 2.54 mm could well be more severe.

Considering the isolated stress intensity effect manifested in the aluminium alloy, it remains to be discussed why this should be so and whether the behaviour could have been predicted.

As discussed in the earlier section of the paper, on theory, the times for the various calculated initial stresses to relax to the nominal stress were used to estimate creep damage relatively.

Table IV indicates that only in the case of the aluminium alloy RR58 at 180°C would stress levels materially above the nominal have been maintained for any significant time. The relaxation times for the 9% 1%Mo steel at 525°C, and the copper at 250°C were mere fractions of an hour while the 0.24%C steel at 450°C and the ½%Cr, ½%Mo, ¼%V steel at 575°C required up to about 10 hours. Again a short period against the background of 2000 hour rupture lives.

Nimonic 90 at 750°C showed a somewhat slow rate of relaxation, requiring over 100 hours to attain nominal stress, and on this basis might well have been expected to manifest some effect of time spent at the higher stress levels, by shorter lives in the holed plate specimens compared with the plane specimens. No such effect was observed, Table II showing similarity of rupture times for the two types of specimen at both stress levels.

Only for the aluminium alloy was both a stress intensification effect on creep rupture and a considerable relaxation time ($>$5000 hours) found for a stress level change from 2.3 times the nominal to the nominal. It must, be stressed that in reality creep strain will reduce the stress at a considerably slower rate than that calculated for pure relaxation. However, the implications for the different metals should remain, so that only the aluminium alloy remains suspect of inability to successfully redistribute peak stresses.

Turning attention to the influence of inelastic loading strains, (Table IV), which though present in certain of the tests was not excessive in any, it is found that despite the use (to achieve reasonable experimental rupture times of 10 000h) of substantially higher nominal stress levels than the yield stress at temperature for some of the metals studied, the rate of developing plastic loading strain with respect to stress was such that little ($<$.01%) plastic prestrain was developed at full load. Thus further explanation of the results was not to be found by consideration of initial plastic loading strain.

Finally, Table IV provides a comparison of stresses in holed and plane specimens where those stresses have been derived by referring the observed rupture times to the appropriate equation for that metal, ie

$$\sigma = \left[\frac{t_f}{C}\right]^{-\frac{1}{\nu}} \qquad (4)$$

The stresses have been normalised by division by the nominal stresses. A similar tabulation of the solid cylindrical specimen results is also presented. In the table, the aluminium alloy is the only metal for which a positive effect of the presence of a stress raiser in hastening creep rupture is observed.

The 9%Cr, 1%Mo steel and the commercially pure copper have shown values of normalized stress for holed specimens of as much as 1.14 and 1.06 respectively. However, the similar comparison for the solid cylindrical specimens range from 1.09 to 0.94 and thus indicate that the scatter in the tests leading to the equation from which the stresses have been obtained would suggest that the holed and plate specimen differences is within the creep rupture scatter band for this metal. The aluminium alloy, on the other hand, shows normalized holed specimen stresses of 1.06 to 1.12 while the corresponding solid cylindrical specimens, with a value of 1.00, show evidence of relatively unscattered test results for the creep rupture equation.

The results of the investigation have demonstrated that creep rupture of plate specimens in the presence of a stress raiser in the form of a circular hole may be adequately predicted using the average stress and conventional tensile creep rupture data provided the metal is reasonably ductile (Table IV) at the test temperature. It is further recommended that one or two tensile creep rupture tests be performed on plane plate specimens of the metal, to verify the applicability of the conventional rupture data.

Metals - such as the aluminium alloy - manifesting a relatively brittle creep rupture characteristic, in association with an octahedral shear stress creep rupture criterion must, however, be considered differently and require a further factor to be applied to allow for stress raisers. Creep ductility and relaxation calculation procedures described in the paper should enable such assessments to be made.

ACKNOWLEDGEMENTS

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NOTATION

A, B, C, K_{tn}, K_{tg}, K^{p}_{tn}, m, n	Constants
a	Diameter of hole
E	Modulus of Elasticity
F	Function
h	Thickness of plate
P	Axial load
P_e	Axial load leading to elastic limit at position of maximum stress
t	Time
t_f	Rupture time
t_R	Relaxation time
w	Width of plate
x	Depth of plastic strain on loading
ε	Creep strain
ε_f	Creep strain at rupture
σ	Axial stress
$\bar{\sigma}$	Normalised stress
σ_N	Nominal stress
σ_m	Maximum stress
σ_m^p	Maximum stress for partial plastic condition
σ_o	Axial stress at t = o
σ_t	Axial stress at t = t
ν	Constant

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TABLE I

DETAILS OF PRODUCT FORM, HEAT TREATMENT AND CHEMICAL COMPOSITION OF METALS TESTED

Metal	Product Form and Dimensions	Heat Treatment	Chemical Composition (%)
½%Cr ½%Mo ¼%V Steel	Forged pipe; 355 mm o.d. x 233 mm nominal bore	Normalised at 970°C for 2½h, cooled in still air. Tempered at 700°C for 5h, cooled in still air.*	C Si Mn S 0.12 0.30 0.43 0.024 P Cr Ni Mo V 0.014 0.36 0.21 0.57 0.23
9%Cr 1%Mo Steel	Rolled bar; 32 mm dia	Normalised and tempered	C Si Mn P 0.1 0.66 0.50 0.013 S Cr Mo Ni 0.008 8.85 0.95 0.21
0.24%C Steel	Core from ingot; 406.4 mm dia. and 876.3 mm in length	3h at 950°C followed by air cooling, then 15 min at 930°C followed by air cooling and finally a stress relieving treatment of 3h at 575°C with furnace cooling.	C Si S P 0.24 0.32 0.036 0.033 Ni Cr Mo Cu 0.27 0.09 0.03 0.16 Sn Mn 0.005 0.69
Nickel Cobalt Chromium Alloy Nimonic 90	152.4 mm cube equally forged in three directions	Standard solution treated and aged.*	C Cr Co Ti Al 0.11 21.1 18.7 2.5 1.5 Fe Si Mn Ni 1.5 0.65 0.5 Rem
Aluminium Alloy RR58	Slab 915 x 851 x 76 mm; stretched 2½%, 5h 20 min after quenching	530 ± 5°C and quenched in water not exceeding 40°C; aged for 30h at 190°C.	Cu Fe Si Mn Mg 2.60 1.05 0.07 0.06 1.50 Ni Zn 1.18 0.04
Copper	Rolled bar; 38.1 mm dia.	400°C for 1h and furnace cooled.	Commercially Pure

* Heat treated by Manufacturer

T A B L E II - CREEP RUPTURE TEST RESULTS

Material	Temp. °C	σ_N MN/m^2	Rupture Time (h)			
			Theor.	Rod	Plate	
					Plane	Holed
½%Cr ½%Mo ¼%V Steel	575	216 162	314 1918	267 2432	208 1571	136 1539
9%Cr 1%Mo Steel	525	240 201	727 2087	- 959	824 1056	145 1108
0.24%C Steel	450	235 215	1721 3800	1807 2822	1110 2217	1857 3649
Nimonic 90	750	170 147	2666 5670	2560 5591	2357 6211	2214 6370
Aluminium Alloy RR58	180	185 170 160	1644 3158 5035	1648 3251 -	1614 - 4646	930 1983 2175
Commercially Pure Copper	250	48.4 44.6	2131 3422	3019 -	1993 3422	1838 2371

T A B L E III - CONSTANTS IN PRIMARY CREEP EQUATION (1) AND CREEP RUPTURE EQUATION (4)

Material	n	m	ν	A	B	C
½%Cr ½%Mo ¼%V Steel	5.5	0.45	6.29	3.24x10^{-7}	1x10^{-16}	1.52x10^{17}
9%Cr 1%Mo Steel	5.2	0.54	†10.9 ‡9.1	0	5.62x10^{-15}	6.4x10^{28} 1.9x10^{24}
0.24%C Steel	3.0	0.27	8.9	4.4x10^{-7}	6x10^{-11}	2.18x10^{24}
Nimonic 90	1.83	0.50	5.19	0	6.7x10^{-9}	1.02x10^{15}
Aluminium Alloy RR58	7.6	0.47	7.72	*6.5x10^{-9}	6.4x10^{-24}	5.0x10^{20}
Commercially Pure Copper	5.0	0.48	5.76	2x10^{-6}	1.8x10^{-11}	1.08x10^{13}

T A B L E IV - NORMALIZED OPERATIVE STRESS - $\bar{\sigma}$ AND RELAXATION TIMES - t_R

Material	$\bar{\sigma}$			σ_y MN/m^2	t_R h	Rupt. Strain (Rod) ε_f(%)
	Rod	Plate				
		Plane	Holed			
½%Cr ½%Mo ¼%V Steel	1.02 0.96	1.07 1.03	1.14 1.04	110	0.73 9.20	33 20
9%Cr 1%Mo Steel	- 1.09	0.99 1.08	1.14 1.08	114	0.003 0.014	- 28
0.24%C Steel	0.99 1.03	1.04 1.06	0.99 1.00	127	1.69 3.03	16.5 17.5
Nimonic 90	1.01 1.01	1.02 1.01	1.04 0.98	232	108 138	0.94 0.94
Aluminium Alloy RR58	1.00 1.00 -	1.00 - 1.00	1.07 1.06 1.12	198	5,666 7,890	0.56 0.50 -
Commercially Pure Copper	0.94 -	1.01 1.00	1.03 1.06	20.1	0.002 0.004	8.74 -

* Stress exponent associated with constant A_1 = 1.65

† $\sigma > 219$ MN/m^2

‡ $\sigma < 219$ MN/m^2