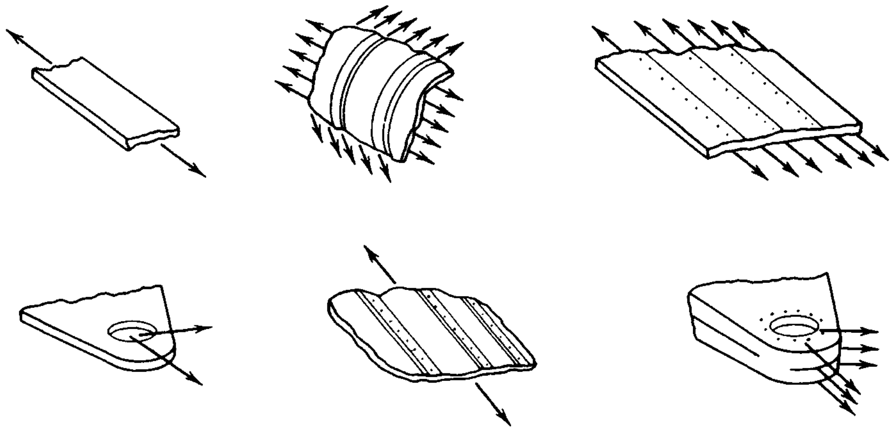

Fig. 18.61 Structural arrangements. (After Ref. 74.)

2 structures, including pressurized cabins and pressure vessels, relatively large amounts of damage may be contained by providing tear straps or stiffeners. There is usually a high probability of damage detection for a class 2 structure because of fuel or pressure leakage, that is, "leak-before-break" design is characteristic of class 2 structures. Class 3 structures are usually designed to provide a specified percentage of the original strength, that is, a specified residual strength, during and subsequent to the failure of one element. This is often called "failsafe" type of structure. However, the preexisting flaw concept requires that all members, including every member of a multiple load path structure, be assumed to contain flaws. It is usual to assume a smaller initial flaw size for class 3 structures because it is appropriate to take a larger risk of operating with cracks if multiple load paths are available.

The development of inspection procedures is an important part of any fracture control program. Appropriate inspection procedures must be established for each structural element, and regions within elements may be classified with respect to required NDI sensitivity. Inspection intervals are established on the basis of crack growth information assuming a specified initial flaw size and a "detectable" flaw size that depends on the NDI procedure. Inspection intervals are established to ensure that an undetected flaw will not grow to critical size before the next inspection, with a comfortable margin of safety. The intervals are usually picked so that two inspections will occur before any crack will reach critical size.

A good fracture-control program should encompass and interact with design, materials selection, fabrication, inspection, and operational phases in the development of any high-performance engineering system.

18.6 CREEP AND STRESS RUPTURE

Creep in its simplest form is the progressive accumulation of plastic strain in a specimen or machine part under stress at elevated temperature over a period of time. Creep failure occurs when the accumulated creep strain results in a deformation of the machine part that exceeds the design limits. *Creep rupture* is an extension of the creep process to the limiting condition where the stressed member actually separates into two parts. *Stress rupture* is a term used interchangeably by many with creep rupture; however, others reserve the term stress rupture for the rupture termination of a creep process in which steady-state creep is never reached, and use the term creep rupture for the rupture termination of a creep process in which a period of steady-state creep has persisted. Figure 18.62 illustrates these differences. The interaction of creep and stress rupture with cyclic stressing and the fatigue process has not yet been clearly understood but is of great importance in many modern high-performance engineering systems.

Creep strains of engineering significance are not usually encountered until the operating temperatures reach a range of approximately 35–70% of the melting point on a scale of absolute temperature. The approximate melting temperature for several substances is shown in Table 18.2.

Not only is excessive deformation due to creep an important consideration, but other consequences of the creep process may also be important. These might include creep rupture, thermal relaxation, dynamic creep under cyclic loads or cyclic temperatures, creep and rupture under multiaxial states of stress, cumulative creep effects, and effects of combined creep and fatigue.

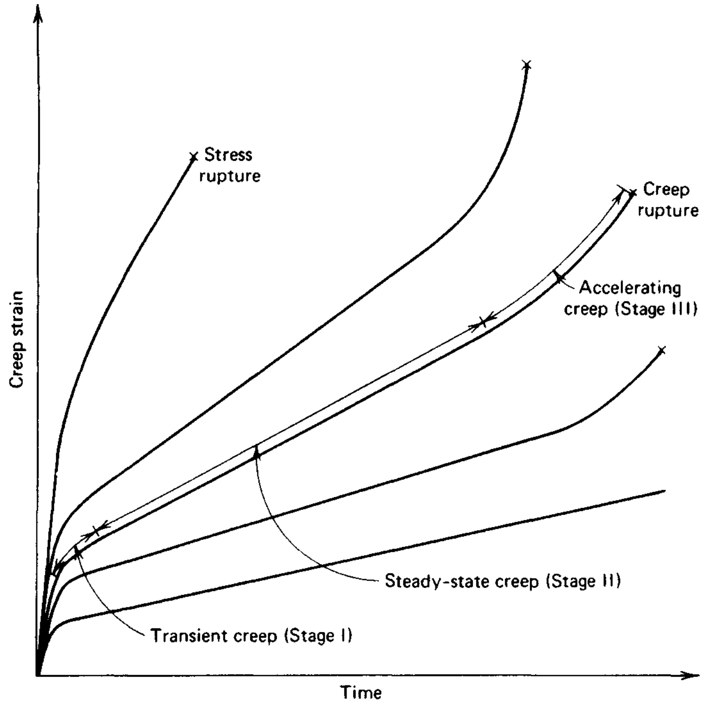

Fig. 18.62 Illustration of creep and stress rupture.

Table 18.2 Melting Temperatures[49]

Material	°F	°C
Hafnium carbide	7030	3887
Graphite (sublimes)	6330	3500
Tungsten	6100	3370
Tungsten carbide	5190	2867
Magnesia	5070	2800
Molybdenum	4740	2620
Boron	4170	2300
Titanium	3260	1795
Platinum	3180	1750
Silica	3140	1728
Chromium	3000	1650
Iron	2800	1540
Stainless steels	2640	1450
Steel	2550	1400
Aluminum alloys	1220	660
Magnesium alloys	1200	650
Lead alloys	605	320

Creep deformation and rupture are initiated in the grain boundaries and proceed by sliding and separation. Thus, creep rupture failures are intercrystalline, in contrast, for example, to the transcrystalline failure surface exhibited by room-temperature fatigue failures. Although creep is a plastic flow phenomenon, the intercrystalline failure path gives a rupture surface that has the appearance of brittle fracture. Creep rupture typically occurs without necking and without warning. Current state-of-the-art knowledge does not permit a reliable prediction of creep or stress rupture properties on a theoretical basis. Furthermore, there seems to be little or no correlation between the creep properties of a material and its room-temperature mechanical properties. Therefore, test data and empirical methods of extending these data are relied on heavily for prediction of creep behavior under anticipated service conditions.

Metallurgical stability under long-time exposure to elevated temperatures is mandatory for good creep-resistant alloys. Prolonged time at elevated temperatures acts as a tempering process, and any improvement in properties originally gained by quenching may be lost. Resistance to oxidation and other corrosive media are also usually important attributes for a good creep-resistant alloy. Larger grain size may also be advantageous since this reduces the length of grain boundary, where much of the creep process resides.

18.6.1 Prediction of Long-Term Creep Behavior

Much time and effort has been expended in attempting to device good short-time creep tests for accurate and reliable prediction of long-term creep and stress rupture behavior. It appears, however, that really reliable creep data can be obtained only by conducting long-term creep tests that duplicate actual service loading and temperature conditions as nearly as possible. Unfortunately, designers are unable to wait for years to obtain design data needed in creep failure analysis. Therefore, certain useful techniques have been developed for approximating long-term creep behavior based on a series of short-term tests. Data from creep testing may be cross plotted in a variety of different ways. The basic variables involved are stress, strain, time, temperature, and, perhaps, strain rate. Any two of these basic variables may be selected as plotting coordinates, with the remaining variables treated as parametric constants for a given curve. Three commonly used methods for extrapolating short-time creep data to long-term applications are the abridged method, the mechanical acceleration method, and the thermal acceleration method. In the abridged method of creep testing the tests are conducted at several different stress levels and at the contemplated operating temperature. The data are plotted as creep strain versus time for a family of stress levels, all run at constant temperature. The curves are plotted out to the laboratory test duration and then extrapolated to the required design life. In the mechanical acceleration method of creep testing, the stress levels used in the laboratory tests are significantly higher than the contemplated design stress levels, so the limiting design strains are reached in a much shorter time than in actual service. The data taken in the mechanical acceleration method are plotted as stress level versus time for a family of constant strain curves all run at a constant temperature. The thermal acceleration method involves laboratory testing at temperatures much higher than the actual service temperature expected. The data are plotted as stress versus time for a family of constant temperatures where the creep strain produced is constant for the whole plot.

It is important to recognize that such extrapolations are not able to predict the potential of failure by creep rupture prior to reaching the creep design life. In any testing method it should be noted that creep testing guidelines usually dictate that test periods of less than 1% of the expected life are not deemed to give significant results. Tests extending to at least 10% of the expected life are preferred where feasible.

Several different theories have been proposed in recent years to correlate the results of short-time elevated-temperature tests with long-term service performance at more moderate temperatures. The more accurate and useful of these proposals to date are the Larson–Miller theory and the Manson–Haferd theory.

The Larson–Miller theory[75] postulates that for each combination of material and stress level there exists a unique value of a parameter P that is related to temperature and time by the equation

$$P = (\theta + 460)(C + \log_{10} t) \tag{18.64}$$

where P = Larson–Miller parameter, constant for a given material and stress level
θ = temperature, °F
C = constant, usually assumed to be 20
t = time in hours to rupture or to reach a specified value of creep strain

This equation was investigated for both creep and rupture for some 28 different materials by Larson and Miller with good success. By using (18.64) it is a simple matter to find a short-term combination of temperature and time that is equivalent to any desired long-term service requirement. For example, for any given material at a specified stress level the test conditions listed in Table 18.3 should be equivalent to the operating conditions.

Table 18.3 Equivalent Conditions Based on Larson–Miller Parameter

Operating Condition	Equivalent Test Condition
10,000 hours at 1000°F	13 hours at 1200°F
1,000 hours at 1200°F	12 hours at 1350°F
1,000 hours at 1350°F	12 hours at 1500°F
1,000 hours at 300°F	2.2 hours at 400°F

The Manson–Haferd[76] theory postulates that for a given material and stress level there exists a unique value of a parameter P' that is related to temperature and time by the equation

$$P' = \frac{\theta - \theta_a}{\log_{10} t - \log_{10} t_a} \tag{18.65}$$

where P' = Manson–Haferd parameter, constant for a given material and stress level
θ = temperature, °F
t = time in hours to rupture or to reach a specified value of creep strain
θ_a, t_a = material constants

In the Manson–Haferd equation values of the constants for several materials are shown in Table 18.4.

18.6.2 Creep under Uniaxial State of Stress

Many relationships have been proposed to relate stress, strain, time, and temperature in the creep process. If one investigates experimental creep strain versus time data, it will be observed that the data are close to linear for a wide variety of materials when plotted on log strain versus log time coordinates. Such a plot is shown, for example, in Fig. 18.63 for three different materials. An equation describing this type of behavior is

$$\delta = At^a \tag{18.66}$$

where δ = true creep strain
t = time
A, a = empirical constants

Differentiating (18.66) with respect to time gives

$$\dot{\delta} = aAt^{(a-1)} \tag{18.67}$$

or, setting $aA = b$ and $(1 - a) = n$,

$$\dot{\delta} = bt^{-n} \tag{18.68}$$

This equation represents a variety of different types of creep strain versus time curves, depending on the magnitude of the exponent n. If n is zero, the behavior, characteristic of high temperatures, is termed *constant creep rate,* and the creep strain is given as

Table 18.4 Constants for Manson–Haferd Equation[76]

Material	Creep or Rupture	θ_a	$\log_{10} t_a$
25–20 stainless steel	Rupture	100	14
18–8 stainless steel	Rupture	100	15
S-590 alloy	Rupture	0	21
DM steel	Rupture	100	22
Inconel X	Rupture	100	24
Nimonic 80	Rupture	100	17
Nimonic 80	0.2 percent plastic strain	100	17
Nimonic 80	0.1 percent plastic strain	100	17

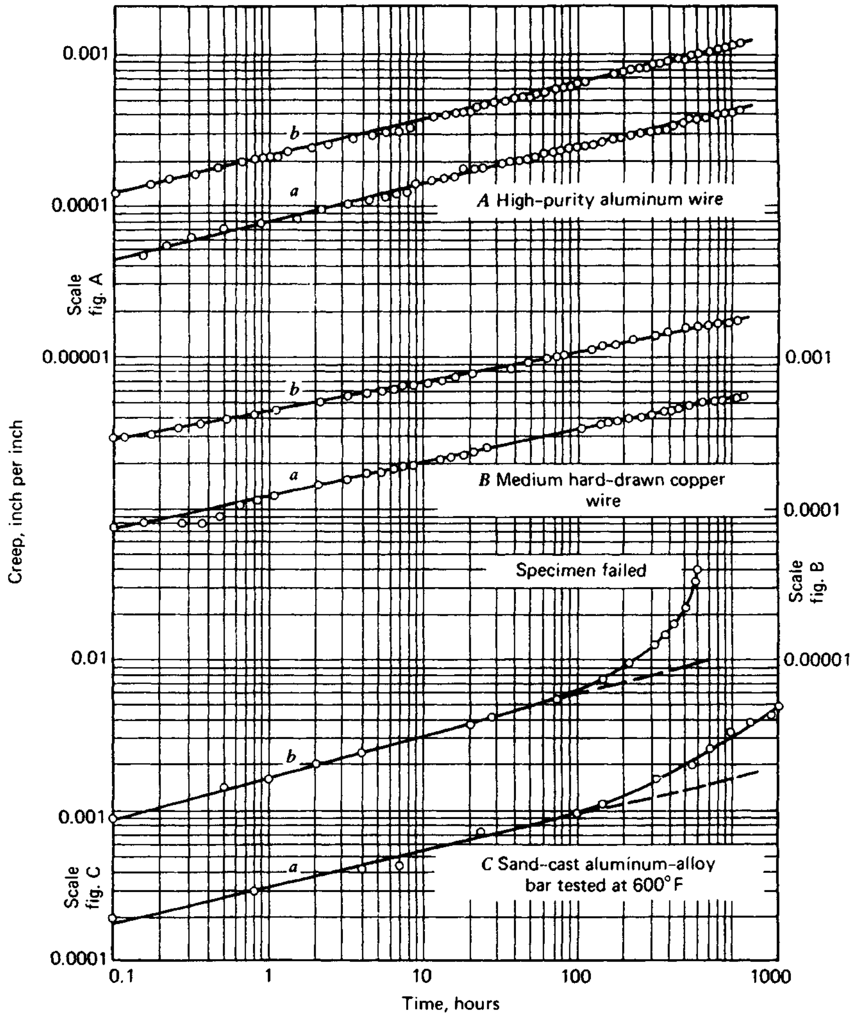

Fig. 18.63 Creep curves for three materials plotted on log–log coordinates. (From Ref. 77.)

$$\delta = b_1 t + C_1 \tag{18.69}$$

If n lies between 0 and 1, the behavior is termed *parabolic creep*, and the creep strain is given by

$$\delta = b_3 t^m + C_3 \tag{18.70}$$

This type of creep behavior occurs at intermediate and high temperatures. The coefficient b_3 increases exponentially with stress and temperature, and the exponent m decreases with stress and increases with temperature. The influence of stress level σ on creep rate can often be represented by the empirical expression

$$\dot{\delta} = B\sigma^N \tag{18.71}$$

Assuming the stress σ to be independent of time, we may integrate (18.71) to yield the creep strain

$$\delta = Bt\sigma^N + C' \tag{18.72}$$

If the constant C' is small compared with $Bt\sigma^N$, as it often is, the result is called the *log–log stress–time creep law,* given as

$$\delta = Bt\sigma^N \tag{18.73}$$

As long as the instantaneous deformation on load application and the stage I transient creep are small compared to stage II steady-state creep, (18.73) is useful as a design tool.

If it is necessary to consider all stages of the creep process, the creep strain expression becomes much more complex. The most general expression for the creep process is (see p. 438 of Ref. 78)

$$\delta = \frac{\sigma}{E} + k_1\sigma^m + k_2(1 - e^{-qt})\sigma^n + k_3t\sigma^p \tag{18.74}$$

where δ = total creep strain
σ/E = initial elastic strain
$k_1\sigma^m$ = initial plastic strain
$k_2(1 - e^{-qt})\sigma^n$ = anelastic strain
$k_3t\sigma^p$ = viscous strain
σ = stress
E = modulus of elasticity
m = reciprocal of strain-hardening exponent
k_1 = reciprocal of strength coefficient
q = reciprocal of Kelvin retardation time
k_2 = anelastic coefficient
n = empirical exponent
k_3 = viscous coefficient
p = empirical exponent
t = time

To utilize this empirical nonlinear expression in a design environment requires specific knowledge of the constants and exponents that characterize the material and temperature of the application. In all cases it must be recognized that stress rupture may intervene to terminate the creep process, and the prediction of this occurrence is difficult.

18.6.3 Creep under Multiaxial State of Stress

Many service applications, such as pressure vessels, piping, and turbine rotors, may involve creep conditions under a multiaxial state of stress. To determine creep strain and deformation under a multiaxial state of stress, the techniques of proportional deformation theory may be combined with the distortion energy theory of failure to give the expressions

$$\delta_1 = Bt(\sigma_1')^N[\alpha^2 + \beta^2 - \alpha\beta - \alpha - \beta + 1]^{(N-1)/2}\left[1 - \frac{\alpha}{2} - \frac{\beta}{2}\right] \tag{18.75}$$

$$\delta_2 = Bt(\sigma_1')^N[\alpha^2 + \beta^2 - \alpha\beta - \alpha - \beta + 1]^{(N-1)/2}\left[\alpha - \frac{\beta}{2} - \frac{1}{2}\right] \tag{18.76}$$

$$\delta_3 = Bt(\sigma_1')^N[\alpha^2 + \beta^2 - \alpha\beta - \alpha - \beta + 1]^{(N-1)/2}\left[\beta - \frac{\alpha}{2} - \frac{1}{2}\right] \tag{18.77}$$

where $\delta_1, \delta_2, \delta_3$ = principal true strains
$\sigma_1', \sigma_2', \sigma_3'$ = principal true stresses
$\alpha = \sigma_2'/\sigma_1'$
$\beta = \sigma_3'/\sigma_1'$
B, N = experimentally determined uniaxial creep parameters

These three equations completely define the principal creep strains in terms of the principal creep stresses and the experimentally determined uniaxial tensile creep parameters B and N. Predictions of creep behavior in any multiaxial state of stress can be made by these equations, based only on the results of a simple uniaxial creep test.

18.6.4 Cumulative Creep

There is at the present time no universally accepted method for estimating the creep strain accumulated as a result of exposure for various periods of time at different temperatures and stress levels. However, several different techniques for making such estimates have been proposed. The simplest of these is a linear hypothesis suggested by Robinson.[79] A generalized version of the Robinson hypothesis may be written as follows: If a design limit of creep strain δ_D is specified, it is predicted that the creep strain δ_D will be reached when

$$\sum_{i=1}^{k} \frac{t_i}{L_i} = 1 \tag{18.78}$$

where t_i = time of exposure at the ith combination of stress level and temperature
L_i = time required to produce creep strain δ_D if entire exposure were held constant at the ith combination of stress level and temperature

Stress rupture may also be predicted by (18.78) if the L_i values correspond to stress rupture. This prediction technique gives relatively accurate results if the creep deformation is dominated by stage II steady-state creep behavior. Under other circumstances the method may yield predictions that are seriously in error.

Other cumulative creep prediction techniques that have been proposed include the time-hardening rule, the strain-hardening rule, and the life-fraction rule. The time-hardening rule is based on the assumption that the major factor governing the creep rate is the length of exposure at a given temperature and stress level, no matter what the past history of exposure has been. The strain-hardening rule is based on the assumption that the major factor governing the creep rate is the amount of prior strain, no matter what the past history of exposure has been. The life-fraction rule is a compromise between the time-hardening rule and the strain-hardening rule which accounts for influence of both time history and strain history. The life-fraction rule is probably the most accurate of these prediction techniques.

18.7 COMBINED CREEP AND FATIGUE

There are several important high-performance applications of current interest in which conditions persist that lead to combined creep and fatigue. For example, aircraft gas turbines and nuclear power reactors are subjected to this combination of failure modes. To make matters worse, the duty cycle in these applications might include a sequence of events including fluctuating stress levels at constant temperature, fluctuating temperature levels at constant stress, and periods during which both stress and temperature are simultaneously fluctuating. Furthermore, there is evidence to indicate that the fatigue and creep processes interact to produce a synergistic response.

It has been observed that interrupted stressing may accelerate, retard, or leave unaffected the time under stress required to produce stress rupture. The same observation has also been made with respect to creep rate. Temperature cycling at constant stress level may also produce a variety of responses, depending on material properties and the details of the temperature cycle.

No general law has been found by which cumulative creep and stress rupture response under temperature cycling at constant stress or stress cycling at constant temperature in the creep range can be accurately predicted. However, some recent progress has been made in developing life prediction techniques for combined creep and fatigue. For example, a procedure sometimes used to predict failure under combined creep and fatigue conditions for isothermal cyclic stressing is to assume that the creep behavior is controlled by the mean stress σ_m and that the fatigue behavior is controlled by the stress amplitude σ_a, with the two processes combining linearly to produce failure. This approach is similar to the development of the Goodman diagram described in Section 18.5.4 except that instead of an intercept of σ_u on the σ_m axis, as shown in Fig. 18.38, the intercept used is the *creep-limited static stress* σ_{cr}, as shown in Fig. 18.64. The creep-limited static stress corresponds either to the design limit on creep strain at the design life or to creep rupture at the design life, depending on which failure mode governs. The linear prediction rule then may be stated as

Failure is predicted to occur under combined isothermal creep and fatigue if

$$\frac{\sigma_a}{\sigma_N} + \frac{\sigma_m}{\sigma_{cr}} \geq 1 \tag{18.79}$$

An elliptic relationship is also shown in Fig. 18.64, which may be written as

Failure is predicted to occur under combined isothermal creep and fatigue if

$$\left(\frac{\sigma_a}{\sigma_N}\right)^2 + \left(\frac{\sigma_m}{\sigma_{cr}}\right)^2 \geq 1 \tag{18.80}$$

The linear rule is usually (but not always) conservative. In the higher-temperature portion of the creep range the elliptic relationship usually gives better agreement with data. For example, in Fig. 18.65*a* actual data for combined isothermal creep and fatigue tests are shown for several different