

INELASTIC STRESS ANALYSIS AND FAILURE LAWS

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SUMMARY

For severely stressed nuclear reactor components operating at elevated temperature, design by analysis is frequently required. It consists of the stress analysis part (a calculation of the stresses (strains) as a function of location and time) and the failure analysis part (determination whether the calculated stresses (strains) are safe). In the areas of interest to high temperature reactor design both stress and failure analysis may involve inelastic deformation of structural metals (creep, relaxation and low-cycle fatigue loading).

Traditionally, the stress analysis part rests on the established three dimensional theories of elastic-plastic and creep behavior and is being performed using sophisticated finite element software. The failure analysis part is evolving gradually from a limiting strength concept. Aside from creep, low-cycle fatigue is now being considered as possible failure mode and failure laws using rather complicated loading histories in the uniaxial state of stress are now being established in high temperature laboratory tests. However, very little effort is devoted to the three dimensional aspects.

For design by analysis stress and failure analysis must be viewed as one total system. Both require the idealizations of material behavior in suitable mathematical expressions. In the former constitutive equations are necessary whereas failure laws are essential for the latter. From a total system viewpoint an oversophistication in one part does not contribute if the other part is neglected. This viewpoint forms the basis of our analysis of presently used approaches. Owing to the nature of the tasks constitutive equations and failure laws are developed by people trained in different disciplines, e.g. mathematics on one side and materials on the other. It is argued that the design by analysis process could be economized if constitutive equations, failure laws and the associated software would be developed with the system point of view. As one means of accomplishing this, education of engineers has to include stress and failure analysis as well as the total system viewpoint.

As an example of the interdependence of constitutive equations and failure laws we discuss the formulation of three dimensional expressions from mostly uniaxial information using mathematical concepts and the influence of superposed hydrostatic pressure on deformation and failure. Under hydrostatic pressure levels equivalent to the stresses encountered in stress analysis deformation is largely unaffected by hydrostatic pressure whereas failure is not. This observation leads to different three dimensional formulations of constitutive equations and failure laws for creep and fatigue.

Next the evolution in time of constitutive equations and failure laws are considered. Both can be idealized for the time independent case (no rate-effects, no creep, no relaxation; no frequency and hold-time effects) and the time dependent case (the former effects are included). In the absence of a suitable repository for deformation induced permanent microstructure changes (plasticity effects) cyclic hardening, creep-plasticity interactions cannot be reproduced in the constitutive equations. A similar repository is necessary in the failure law if sequence effects should be modelled.

The development will be demonstrated using a first order, nonlinear differential constitutive equation and a failure law based on a differential equation form of damage accumulation. The approach is continuum oriented and is restricted to infinitesimal deformations and homogeneous states of stress (strain). A possible extension to inhomogeneous conditions is suggested.

