Abstract

Plasticity plays an important role in the manufacturing, design, and failure investigation of components/structures made up of metallic materials. Such components may be subjected to a complex state of stress and may undergo finite deformation under monotonic/cyclic loading. Based on the literature review, it is found that the covariant formulation of nonlinear kinematic hardening, the effects of stress triaxiality, and Lode parameters on ductile response/failure, viscoplasticity, and their coupling with phase field theory are not adequately dealt with. In the present thesis, isotropic plasticity is investigated by considering nonlinear kinematic hardening, multi-invariants dependence, and viscoplasticity with coupling to phase field theory for small and large deformations, along with the examination of numerical implementation aspects.

A covariant formulation of hyperelasto-plasticity, including the nonlinear kinematic hardening, is presented in finite deformation plasticity. A nonlinear kinematic hardening equation is proposed in the spatial configuration using the Lie

derivative of the kinematic hardening tensor. A method is proposed to compute the deviatoric and trace parts of the elastic left Cauchy Green tensor and the deviatoric part of the kinematic hardening tensor, satisfying the incompressibility of plastic deformation. The integration of the local governing equations using the covariant backward Euler integration scheme is presented along with the closed-form expression of the algorithmically consistent spatial tangent constitutive tensor.

A ductile failure theory is presented by coupling the developed covariant formulation of kinematic hardening finite deformation plasticity with phase field theory. To capture the correct physical response of the material after crack initiation, the fracture driving function is modified by an energy release controlling function. A neural network optimization procedure is presented to calibrate the material parameters. The capability of the model is demonstrated by simulating the crack path in complex three-dimensional geometries.

Implicit and semi-implicit integration schemes are formulated for multi-invariants dependent finite deformation plasticity. In the implicit integration scheme, the backward Euler difference approximation of equivalent plastic strain is coupled with the exponential approximation of return mapping in principal Kirchhoff stresses space. In the semi-implicit integration scheme, the forward Euler difference approximation of equivalent plastic strain is coupled with the logarithmic approximation of return mapping in Kirchhoff stress space. The computation time involved in the simulations using these two schemes is compared.

The multi-invariants dependent plasticity is coupled with phase field theory to investigate the effects of stress invariants on crack initiation and propagation in ductile materials. The threshold energy in the phase field variable evolution equation is proposed as a function of the stress triaxiality and normalized Lode angle parameters based on the Mohr-Coulomb fracture initiation criterion. A Hosford equivalent stress-dependent Drucker-Prager yield function is used to describe the ductile response of the material, which provides stress invariants dependent energy release during the crack propagation. The experimental responses of different specimens with varying degrees of stress triaxiality and Lode angle parameters available in the literature are used to calibrate model parameters. The simulated crack propagation path in these specimen is compared with that observed in available experimental studies.

To consider the rate-dependent behavior of materials, an accurate and computationally efficient integration scheme is proposed for small deformation viscoplasticity by combining the backward Euler difference approximation of the stress rate equation and the exponential integration scheme for the kinematic hardening equation. The accuracy and computational cost of the proposed integration scheme are compared with the integration schemes based on either backward Euler difference approximation or exponential integration. Finally, a preliminary study involving small deformation viscoplasticity coupled with phase field theory is carried out to investigate low cycle fatigue and creep interaction.