Engineering materials and structures are usually subjected to multiaxial stress states loading due to geometrical effects, residual stresses, or multi-directional loading. Ductile fracture and Extremely Low Cycle Fatigue (ELCF), less than 100 cycles to fail, are two common and co-exist failure modes in many engineering structures. However, the linkage between these two failure modes under multi-axial loading conditions has never been systematically studied. This research summarizes an extensive work of experimental and numerical studies of ductile fracture and ELCF under different stress states for nickel-base superalloy material "IN718" under room temperature. Specially designed specimens and tests were used to achieve desired multi-axial loading conditions. Four types of specimens with four different shapes, total of 16 specimens, were tested until complete fracture. Two groups of tests were conducted: (a) round bar specimens with different notches; (b) plane strain specimens. Experimental data of force-displacement curves and strain-life graph were plotted for analysis.

The first part of this research focuses on a numerical study of monotonic tensile loading with different stress states. This part of the investigation deeply studies the dependency of the hydrostatic stress (related to stress triaxiality) and the normalized third invariant of the deviatoric stress (related to Lode angle parameter) in plastic behavior and ductile fracture. Constitutive plasticity model proposed by Bai & Wierzbicki and the modified Mohr-Coulomb (MMC) ductile fracture model were adapted with several extensions. The plasticity model and ductile fracture criterion were implemented into ABAQUS through a user-defined material subroutine (VUMAT). Extensive experimental results are used to calibrate the models. After setting up the parameter optimization during model calibration, the experimental results and numerical simulations were well correlated in both plasticity deformation and fracture initiation. A 3D fracture locus of Inconel 718 was constructed by knowing the strain at fracture, stress triaxiality, and normalized Lode angle of the tested samples. By introducing a suitable element post-failure behavior, not only the fracture initiation but also the fracture propagation modes are successfully predicted in finite element simulations for monotonic loading.

The second part extensively investigates ELCF on IN718. The IN718 cyclic plasticity behavior and the Bauschinger effect are studied and simulated using the well-known nonlinear kinematic hardening law by J. L. Chaboche and his co-workers under different strain amplitudes and different stress states. Moreover, the Vocé isotropic hardening law was applied in combination with the Bai-Wierzbicki plasticity model. The Bai-Wierzbicki plasticity model was used to capture the effect of different stress states on ELCF based on the stress triaxiality and Lode angle parameters. On the other hand, the modified Mohr-Coulomb (MMC) ductile fracture model for monotonic loading was extended by a new damage evolution rule to cover the ELCF regime. A new parameter was introduced to represent the effect of the cyclic loading at ELCF. The new parameter is responsible for capturing the change of non-proportional loading direction between the current stress and the backstress tensors. The model explores the underlying damage and fracture mechanisms through the equivalent plastic strain evolution under cycling loading.

Finally, the mechanism linkage between these two failure modes was studied. A comparison between the experimental data and the finite element simulation results (by Abaqus/Explicit) shows very good correlations. In addition, fractographic examinations, analysis, and finite element simulations are presented.
Alain Kassab, Department of Mechanical and Aerospace Engineering
Quanfang Chen, Department of Mechanical and Aerospace Engineering
Hansen Mansy, Department of Mechanical and Aerospace Engineering
Boo Hyun Nam, Department of Civil, Environmental, and Construction Engineering

Approved for distribution by Yuanli Bai, Committee Chair, on September 26, 2016.

The public is welcome to attend.