Chapter 11
Summary and Future Study

11.1 Main Conclusion

The applicability of several classical plasticity models to ultra-low-cycle fatigue loading of structural steels and aluminum is validated, and a new plasticity model for large strain reversals is proposed. Ductile fracture models for cyclic incremental and constant-amplitude loading are also proposed. Approaches to calibrate the model parameters of the plasticity models and the fracture models only from monotonic tension coupon tests are proposed. The models with the calibration methods are validated by a series of cyclic tests on hourglass-type specimens and applied to structural steels, steel connections, structural aluminum, and aluminum buckling-restrained braces successfully. The detailed findings are given in the following.

11.1.1 Cyclic Plasticity Models for Cyclic Large Strain Loading

Based on the experimental and numerical studies on a series of hourglass-type steel specimens and double-edge-notched aluminum specimens, the following main conclusions can be drawn:

(1) A modified weighted average method is proposed to obtain the true stress–true strain till fracture from the test result of a tension coupon.
(2) A modified Yoshida–Uemori model is proposed, and the model is found to be able to trace the cyclic plasticity of structural steels at very large plastic strain ranges. The model parameters can also be obtained from a tension coupon test by carrying out an optimization analysis.
(3) The Chaboche model with isotropic hardening (IH) can well simulate the cyclic plasticity of structural steels under cyclic large strain loading, and the model

L.-J. Jia and H. Ge, *Ultra-low-Cycle Fatigue Failure of Metal Structures under Strong Earthquakes*, Springer Tracts in Civil Engineering,
https://doi.org/10.1007/978-981-13-2661-5_11

slightly overestimates the stress for the case under constant-amplitude loading due to a lack of the memory surface.

(4) A simple method using representative mechanical parameters of aluminum is proposed to obtain the true stress–true strain till fracture, and the proposed method can be applied to evaluating hysteretic properties of aluminum coupons and buckling-restrained braces under cyclic loading with good accuracy.

11.1.2 Ductile Fracture Models for Cyclic Large Strain Loading

(1) A monotonic fracture model with only one model parameter for structural steels is proposed by applying the Rice–Tracey model and the Miner's rule in incremental form.
(2) A crack propagation rule based on the energy concept is proposed for structural steels, and the method performs well for high-strength steel, where the correlated parameter can be obtained through monotonic tension coupon test.
(3) A cyclic fracture model developed from the monotonic fracture model in combination with the Chaboche model with IH, or the modified Yoshida–Uemori model, can generally well simulate the ductile fracture of structural steels under cyclic large strain loading.
(4) Experimental tests on stub box columns under ULCF loading are carried out to calibrate both the cyclic fracture model and the Chaboche model with IH. The numerical simulation results using the models agree well with the corresponding test results.
(5) Ultra-low-cycle fatigue (ULCF) loading tests on structural steel and aluminum are conducted, where a transition fracture mode from low-cycle fatigue to ductile fracture is observed.
(6) An approach to evaluate the ULCF life of ductile metals is proposed, which can be correlated with the corresponding tension coupon test results. The theory has been validated using aluminum coupons under ULCF loading.

11.2 Future Work

It is suggested that the following items require further study on ductile fracture of metals under ULCF loading.

(1) The damage rule within negative stress triaxialities under cyclic loading at large plastic ranges close to fracture of metals is found to be underestimated in this study, and a more accurate rule is required based on more experimental results.

(2) Ductile crack propagation simulation of cracked bodies under cyclic loading should be further studied, since the final sudden loss for specimens under ULCF loading sometimes cannot be well captured.
(3) Effects of residual stress and strain on buckling modes and fracture processes of steel members need further study.
(4) Though the transition between brittle fracture and ductile fracture is not the concern of this study, it is of great importance in practice, since the brittle fracture is found to be triggered by ductile fracture. It is still an open issue and needs further study.
(5) The tests carried out in this study is only on structural steels and aluminum, and the validity of the fracture model and the plasticity models for other ductile metals should be further validated.
(6) The welded structures are still difficult to be predicted due to the complicated material properties within the heat-affected zone, and a number of factors affect the mechanical properties and defects of the welds. There are still no straightforward and accurate approaches to evaluate the welded structures, where further study is necessary.
(7) The effect of strain rate on ductile fracture of structural steels has not been comprehensively studied yet. Ductile fracture mechanisms of structural steels under dynamic ULCF loading require further study.
(8) Study on seismic performance of large-scale whole structures has seldom employed such elaborate plasticity models and fracture models as used in this study. Ductile fracture simulation of whole structures under seismic loading requires further study, and performance of metallic structures at the ultimate failure stage can be re-evaluated to ensure a safer design.
(9) More elaborate simulation of the cracking process is necessary, e.g., closure and contact of the neighboring cracked parts; more realistic simulation of the cracking path using advanced approaches such as the XFEM, while convergence and simulation efficiency are also greatly concerned for large-scaled structures.