Incorporation of Residual Stress Effects in a Plasticity, Fracture, and Fatigue Crack Growth Model for Reliability Assessments of Aluminum Ship Structures

1.0 OBJECTIVE.

1.1 The objective of this project is to develop an experimentally calibrated and verified, computational tool which accurately predicts the plastic response and failure due to fatigue and ductile fracture under the influence of residual stresses of a structural aluminum alloy. This numerical tool will not only be able to be used in reliability assessments and survivability analyses of aluminum ship structures, but also in development of fracture control plans for ship design and optimization.

2.0 BACKGROUND.

2.1 Rapid progress in computational mechanics in recent years has allowed engineers to analyze complex ship structures, to assess structural reliability and optimize structural designs. Consequently, the need for more accurate material models becomes increasingly evident; particularly when minimizing design margins becomes the approach for weight optimization or life-extension efforts.

2.2 Ship structures may be subject to extreme loading conditions caused by heavy seas or accidents, such as collisions and groundings. Military vessels are also subject to severe loading in combat scenarios. Under extreme conditions ship structures may experience large plastic deformation, which may be monotonic or cyclic, leading to structure failure.

2.3 To date, an overwhelming majority of structural analyses employ the classical J2 plasticity theory to describe the plastic response of metallic alloys. This theory assumes hydrostatic stress and the third invariant of the stress deviator do not affect the plastic behavior. However, increasing experimental evidence shows that the assumptions made in the J2 plasticity theory are invalid for many materials. Gao et al. (2009) noticed that the plastic response of a 5083 aluminum alloy is stress-state dependent and proposed an I1-J2-J3 plasticity model.

2.4 The equivalent strain-to-fracture is often used as a ductile fracture criterion and it is widely accepted that its value depends on the stress triaxiality (Johnson and Cook, 1985). However, recent studies demonstrate that the stress triaxiality alone cannot sufficiently characterize the effect of stress state on ductile fracture. Gao et al. (2009) developed a stress-state dependent ductile fracture model, where the equivalent strain to failure is expressed as a function of both the stress triaxiality and the third invariant of the stress deviator, and calibrated this fracture model for an ABS Grade DH36 steel.

2.5 Previous research by Gao’s group (Jiang, Gao and Srivatsan; 2009) developed an irreversible cohesive zone model to simulate fatigue crack growth. The model was successfully calibrated for a 7075 aluminum alloy and predicted fatigue crack propagation in the compact tension-shear specimens. The numerical results capture the effects of loading mode and overload on fatigue crack growth rate.

2.6 Welded joints are widely used in ship structures. However, they present great complications for modeling and analysis, such as different material behavior and properties for base metal, weldment and the heat affected zone; geometrical discontinuity at the weld toe (which modifies stress distribution and causes high stresses at the weld toe), and residual stresses. These factors compound the local stresses applied to the underlying material, diminishing the accuracy of material models that do not consider such contributions. Welds are not commonly modeled with this level of detail on the structural scale, yet failure often initiates in this region because of these
factors. Improved accuracy in structural reliability prediction requires robust material models that incorporate the contributions of residual stresses that are so common to welds.

2.7 We propose to extend the stress-state dependent plasticity model, the ductile fracture model and the fatigue crack growth model developed by Gao and co-workers by introducing well-characterized and reproducible residual stresses into laboratory specimens machined from a 5083 aluminum plate. As it is difficult to prevent residual stresses in a material during construction welding, it is also difficult to control them in a weldment for research purposes. One technique for introducing such residual stresses is the controlled application of local compression to the point of permanent set to the sides of a test specimen cut from base plate. Numerical analysis of the mechanical testing quantifies the internal stress field.

3.0 REQUIREMENTS.

3.1 Scope.

3.1.1 The approach for model development involves experimental work and finite element modeling. Tensile testing, torsion testing, fracture testing, and fatigue crack growth testing are needed for development of the plasticity, ductile fracture and fatigue crack growth models. The local out-of-plane compression technique will be used to create different residual stress fields in compact tension specimens and to study the effect of residual stresses on plastic deformation, ductile fracture resistance, and fatigue crack propagation.

3.1.2 The Contractors shall develop appropriate plasticity, ductile fracture and fatigue crack growth models for a 5083 aluminum alloy.

3.1.3 The Contractors shall evaluate the effect of residual stresses on ductile fracture resistance.

3.1.4 The Contractors shall evaluate the effect of residual stresses on fatigue crack propagation.

3.1.5 The Contractors shall develop a computational tool for reliability assessments of aluminum 5083 ship structures, which includes the stress-state effect on plasticity and takes into account the effects of residual stresses on ductile fracture and fatigue crack growth.

3.2 Tasks.

3.2.1 The test matrix will be finalized and specimens will be machined and prepared.

3.2.2 Tensile testing, torsion testing, fracture testing, and fatigue crack growth testing will be conducted.

3.2.3 Finite element analyses will be performed on all specimens tested.

3.2.4 The models developed in this project will be implemented into a finite element code.

3.2.5 A final report will be prepared and submitted.

3.3 Project Timeline. See Enclosure (A).

4.0 GOVERNMENT FURNISHED INFORMATION.
4.1 Standards for the Preparation and Publication of SSC Technical Reports.

5.0 **DElIVERY REQUIREMENTS.** (Identify the deliverables of the project).

5.1 The Contractors shall provide quarterly progress reports to the Project Technical Committee, the Ship Structure Committee Executive Director, and the Contract Specialist.

5.2 The Contractors shall provide electronic copies of test data and source code generated.

5.3 The Contractors shall provide a print ready master final report and an electronic copy, including the above deliverables, formatted as per the SSC Report Style Manual.

6.0 **PERIOD OF PERFORMANCE.**

6.1 Project Initiation Date: date of award.

6.2 Project Completion Date: 12 months from the date of award.

7.0 **GOVERNMENT ESTIMATE.** These contractor direct costs are based on previous project participation expenses.

7.1 Project Duration: 12 months.

7.2 Cost Estimate:

7.2.1 Machining and expenses, NSWCCD: $20,000
7.2.2 Labor & travel, NSWCCD: $65,000
7.2.3 Labor & travel, U. Akron: $65,000
7.2.4 Total Estimate: $150,000

8.0 **REFERENCES.**


9.0 **SUGGESTED CONTRACTING STRATEGY.**

9.1 The Naval Surface Warfare Center, Carderock Division will perform the mechanical testing and analysis. The University of Akron will carry out the software implementation and finite element analyses. Both organizations will contribute to the model development and reporting.
## Enclosure A: Project Timeline

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