Novel Design and Performance Evaluation Tool for Crack Arrestor Enhanced Aluminum Marine Structures

1.0 OBJECTIVE.

1.1 The objective of the present research project is to improve the existing modeling capability to efficiently and reliably capture the effect of a crack arrestor on the improved fatigue and fracture performance of a welded aluminum marine structure and explore an optimal deign of a crack arrestor to achieve a design requirement. The design of a large aluminum high-speed vessel under hostile operating environments requires the welded structure to withstand sub-critical growth of manufacturing flaws and service-induced defects against failure. Studies have shown that the arrest of crack propagation can be achieved through either insertion of a local high fracture toughness material or reduction the crack growth driving force. The lack of crack arrester design procedures for aluminum structure has precluded an optimal selection of a mechanical arrester device to stop the crack before reaching its critical state. The purpose of this study is to develop and implement a novel computational tool for simulation of a curvilinear crack growth and its associated residual strength and life of welded aluminum marine structures in the presence of crack arrestors, residual stress, and welding induced material heterogeneity and nonlinearity.

2.0 BACKGROUND.

2.1 Weight and performance needs for the current and future ship manufacturers demand optimal lightweight aluminum ship structural systems. Different from conventional vessels, an aluminum vessel experiences a high strain rate loading resulting from extreme loading events such as the wave slamming. A stable fatigue crack growth can become unstable in an aluminum ship structure after experiencing a dynamic loading event. In order to prevent a catastrophic failure, various forms of crack arresters have been implemented through the use of a riveted skin-stringer, local insertion of high toughness material, welded patch or stiffener, or an expanded hole. While extensive study has been performed for evaluation of crack arrestors in steel structures, both the modeling and design procedures of crack arrestors have not been fully explored for aluminum ship structures.

2.2 Design of aluminum marine structure is severely limited by a lack of information on the fatigue strength of typical structure details used in aluminum high-speed vessels. The fatigue strength of aluminum structural details published in the existing design codes cannot be directly used since these published design details do not reflect many of the structural details currently used or to be used in construction of high-performance aluminum marine vehicles with reduced fuel consumption. There is an immediate need to develop an efficient and reliable analysis tool for fatigue and fracture assessment of an arbitrary welded aluminum structure in the presence of stress concentrators, structural discontinuities, flaws, material heterogeneity, and residual stress.

2.3 Design and selection of an optimal crack arrestor in aluminum marine structures are very important since the fatigue crack growth rate in 5083 Aluminum is about 30 times higher than that of H 36 steel. An accurate prediction of crack path and its growth driving force is very crucial in the placement of various kinds of mechanical arrester devices in the path of a fast-moving crack. In order capture the interaction of an evolving crack and its surrounding arrestors, the resulting problem domain is quite large and the presence of 3D stress field will make the crack growth path curvilinear. At the intersection of the base structure (skin plate) and its arrestor (stiffener), a crack will be branched into its different segments with their different growth directions. The use of a conventional finite element modeling approach with 3D solid elements will make the computational cost prohibitively large. In addition, any modification of an initial flaw and arrestor configuration will force an analyst to develop a new model along with the tracking of the crack growth.

2.4 Failure prediction of crack propagation in welded aluminum structure with arrestors is a challenging problem because of the presence of residual stress, material heterogeneity, and material nonlinearity. To capture the distinct crack growth behavior, fracture and fatigue properties associated with each material zone have to be quantified for selected marine aluminum alloys. Residual stress induced variation in crack growth driving force has to be included in a stress ratio dependent fatigue damage accumulation model. Accurate extraction of components of crack growth driving force is essential for the crack growth rate and direction prediction.

2.5 To evaluate the residual strength of an aluminum ship structure subjected to an unexpected extreme loading event such as the wave slamming or ship grounding, a dynamic crack growth prediction has to be performed for the welded structure after experiencing a given number of cycles. The fatigue induced damage needs to be stored and used as an initial damage configuration for the subsequent dynamic crack prediction in the presence of a crack arrestor.

3.0 REQUIREMENTS.

3.1 Scope.

3.1.1 The Contractor shall improve and extend the current state-of-the-art modeling and prediction capability for residual strength and life prediction of a welded aluminum structure with a selected crack arrestor. Novel element technology will be implemented to able to efficiently characterize crack initiation and growth in a large scale welded structure with crack arrestors. A hybrid computational framework will be established to characterize the fatigue driven static analysis followed by the dynamic crack growth prediction under an extreme loading event.

3.1.2 The Contractor shall collect fracture and fatigue properties for a selected aluminum alloy and implement fatigue damage accumulation models for a heterogeneous welded structure with a distribution of residual stress field. The effects of residual stress field on the crack growth driving force will be incorporated in a stress-ratio dependent fatigue damage accumulation model.

3.1.3 The Contractor shall select multiple benchmark problems and perform a tradeoff study on the application of different types of crack arrestor for the enhancement of fatigue life and residual strength. Key issues will be addressed such as potential crack re-initiation and re-distribution of residual stress after insertion of a crack arrestor.

3.1.4 The Contractor will perform toolkit verification and validation study at component level using the collected test data from the existing literature and testing labs

3.1.5 The Contractor will prepare a detailed report of all work undertaken.

3.2 Tasks.

3.2.1 Take 1 – Literature review. A review of the literature on (a) current design practice of crack arrestors in aluminum structures, (b) fracture and fatigue properties of welded aluminum structures, and (c) fatigue damage accumulation in the presence of residual stress and variable amplitude loading.

3.2.2 Task 2 – Advanced toolkit for performance evaluation of a crack arrestor. Novel element and material models will be implemented within a hybrid computational framework for simulation of fatigue crack growth and its subsequent dynamic failure of welded aluminum structures with an initial defect, a crack arrestor, structural discontinuity, and material heterogeneity. Advanced modeling techniques will be implemented to simulate crack initiation, crack branching, curvilinear crack path, interaction of a crack with a crack arrestor.

3.2.3 Task 3 – Toolkit application and demonstration. Verification tests will be performed to explore the accuracy and solution efficiency of the developed toolkit for crack growth simulation in the presence of various kinds of mechanical arrester devices in the path of a growing crack. Three crack arrest mechanisms will be examined via 1) reduction of crack growth driving force; 2) increase of the local fracture toughness; and 3) a combination of (1) and (2). Practicability and feasibility will be examined in terms of current design specification, cost of materials, installation and fabrication costs, potential crack initiation, and residual stress introduced.

3.2.4 Task 4 – Validation of the toolkit. Available component level test data will be collected from marine industries and testing labs for the toolkit validation study.

3.2.5 Task 5 – Reporting: Biannually and final reports are prepared

3.3 Project Timeline.

	Month																	
Tasks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	X	X																
2		X	X	X	X	X	X	X	X									
3									X	X	X	X	X	X	X	X		
4										X	X	X	X	X	X	X		
5						X						X					X	X

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

5.2 The Contractor 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: 18 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: 18 months.

7.2 Total Estimate Funding from SSC: $70,000.0

The total cost of this 18-month program is estimated to be $140,000.0. The Contractor will seek a 50/50 cost sharing (matching) fund from ONR to reach a fully funded program of $140,000.0.

7.3 The Independent Government Cost Estimate is attached as enclosure (*x*).

8.0 <u>REFERENCES</u>.

NOTE:

- Please do not submit any proprietary information in this outline. This will be posted on the SSC Website regardless if the project is selected to be funded.