Experimental Quantification of the Tensile Strength and Ductility of Under-Matched Aluminum Welds

1. OBJECTIVE.

a. This project will experimentally test aluminum marine structural connection details with under-matched welds to better understand the capabilities of these connections and create a test database for future design method verification.

2. BACKGROUND.

a. Aluminum structures offer potential structural weight-savings of up to 50% for many marine vehicles, thereby reducing fuel consumption and improving economics in many time-sensitive or draft-limited applications.

b. A key challenge in designing aluminum structures is dealing with the under-matched fusion welds used to assemble the structure. Unlike most steels, marine aluminum alloys suffer a reduction in strength in the heat affected zone (HAZ) of welds reaching as much as 50 percent of the strength of the prime material. However, little work has been done on the strength of welded aluminum ship structures in tension. A preliminary assessment was made which concluded that present methods were inadequate for design of complex connections. The offshore and civil engineering community have made more extensive studies of this issue yet these studies did not address marine details.

c. The primary concern with under-matched welds is that under extreme tensile loading, plastic deformation localizes in the under-matched region, leading to high strains and eventual ductile failure in these regions. Given that the rest of the structure is often still in elastic response, the overall structural deformation to failure appears startlingly small. Additionally, compared to monolithic structures, the energy absorption until rupture is also much smaller which has significant implications for accidental limit states such as collision or grounding response.

d. The traditional approach to design has been to use the minimum strength of the HAZ as the design strength and treat the structure as monolithic. This approach may seriously underestimate the strength of welded structure while overestimating its ductility and energy absorption capabilities. Marine structures have many unique topologies of under-matched weld regions under tension, including stiffener to transverse frame joints, watertight bulkhead connections, and load-carrying fillet welds at the end of complex hollow-core extrusions.

e. While the marine industry has extensively explored compressive strength design methods for aluminum tensile design methods have been comparatively ignored. The inability to efficiently predict the strength and ductility of tensile connections has serious implications to using modern limit-state design to develop lightweight aluminum structures. Progressive collapse methods such as the Smith method require the prediction of both the load-shortening and load-extension curves of structural elements, yet we lack any realistic way of predicting the load-extension curve for welded aluminum structures. Direct application of finite element methods has proven to be a difficult approach requiring mesh discretization much smaller than the plate thickness. Furthermore, custom element enrichment is required if shell elements are going to be used in the model. Such techniques are not yet practical outside of academic research groups or specialized consultancies. The techniques developed to date have only been validated on the types of details common to civil engineering structures. Thus, the marine structural engineer currently lacks practical tools and experimental data to design structures with the impact of under-matched welds fully accounted for.

3. REQUIREMENTS.

a. Scope.

i. The Contractor shall conduct a literature review of existing experiments and modeling techniques for the strength of under-matched aluminum welds.

ii. The Contractor shall design and fabricate a series of test specimens containing under-matched welds

iii. The Contractor shall test these specimens under tension until failure, recording relevant strains, stresses, and the evolution of failure for validating future modeling approaches.

iv. The Contractor shall document the results of the project in a report.

b. Tasks.

i. The Contractor shall review the literature to determine previous studies on aluminum welds in tension for marine-grade alloys, typical marine structural connection details, and experimental procedures for conducting tests on assemblies with under-matched welds.

ii. The Contractor shall design three representative connection details, starting with simple non-load carrying fillet weld attachments representing frames to shell plating joints, stiffener and frame intersections, and extruded hollow-core panel joints. Specimens shall be designed in conjunction with the available test apparatus and will be modeled by finite element analysis, including non-linear materials and geometry, but excluding fracture.

iii. The Contractor shall fabricate the representative connection details. The as-built fit-up and condition of the specimens shall be documented.

iv. The Contractor shall instrument and test the representative connection details.

v. The Contractor shall post-process the test results into a format suitable for validating both simplified failure models and more advanced finite element simulations. Particular attention shall be placed on making a high-quality data set available for future use via the Ship Structure Committee website.

vi. The Contractor shall perform a discussion and limited analysis of the results and their implications for current marine design standards and limit state approaches.

c. Project Timeline.

i. Literature review and specimen design 4 months
ii. Fabrication and testing: 6 months
iii. Analysis and report writing: 2 months

4. GOVERNMENT FURNISHED INFORMATION.

a. Standards for the Preparation and Publication of SSC Technical Reports.

5. **DELIVERY REQUIREMENTS.**

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

b. 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.

c. The Contractor shall provide validation data from the experiments in digital form for archiving on the Ship Structure Committee website

6. PERIOD OF PERFORMANCE.

a. Project Initiation Date: date of award.

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

7. <u>GOVERNMENT ESTIMATE</u>. These contractor direct costs are based on previous project participation expenses.

a. Project Duration: 12 months.

b. Total Estimate: $100,000.

8. <u>REFERENCES</u>.

i. Benson, S., J. Downes, and R.S. Dow. 2011. "Ultimate Strength Characteristics of Aluminium Plates for High-speed Vessels." *Ships and Offshore Structures* 6 (1-2): 67–80.

ii. Chan, T., and R. Porter Goff. 2000. "Welded Aluminium Alloy Connections: a Simplified Plastic Model." *Proceedings of the Institution of Civil Engineers. Structures and Buildings* 140 (May): 161–168.

iii. Collette, M. 2007. "Impact of Fusion Welds on the Ultimate Strength of Aluminum Structures." In *10th International Symposium on Practical Design of Ships and Other Floating Structures (PRADS 2007)*, 2:944–952. Houston, Texas.

iv. ———. 2011. "Rapid Analysis Techniques for Ultimate Strength Predictions of Aluminum Structures." In *Advances in Marine Structures*, 109–117. Hamburg, Germany: CRC Press.

v. Dørum, C., O.-G. Lademo, O.R. Myhr, T. Berstad, and O.S. Hopperstad. 2010. "Finite Element Analysis of Plastic Failure in Heat-affected Zone of Welded Aluminium Connections." *Computers and Structures* 88 (9-10): 519–528.

vi. Paik, J. 2009. *Buckling Collapse Testing of Friction Stir Welded Aluminum Stiffened Plate Structures*. Washington, DC, USA: Ship Structure Committee.

vii. Paik, J.K, Anil K. Thayamballi, J. Ryu, C. Jang, J. Seo, S. Park, S. Soe, C. Renaud, and N. Kim. 2007. *Mechanical Collapse Testing on Aluminum Stiffened Panels for Marine Applications*. Washington, DC, USA: Ship Structure Committee.

viii. Paik, J.K, S. van der Veen, A. Duran, and M. Collette. 2005. "Ultimate Compressive Strength Design Methods of Aluminum Welded Stiffened Panel Structures for Aerospace, Marine and Land-based Applications: A Benchmark Study." *Thin-Walled Structures* 43 (10). Thin-Walled Struct. (UK) (October): 1550–66.

ix. Rigo, P., R. Sarghiuta, S. Estefen, E. Lehmann, S. C. Otelea, I. Pasqualino, B. C. Simonsen, Z. Wan, and T. Yao. 2003. "Sensitivity Analysis on Ultimate Strength of Aluminium Stiffened Panels." *Marine Structures* 16 (6) (August): 437–468. doi:16/j.marstruc.2003.09.002.

x. Wang, T., O.S. Hopperstad, O.-G. Lademo, and P.K. Larsen. 2007. "Finite Element Modelling of Welded Aluminium Members Subjected to Four-point Bending." *Thin-Walled Structures* 45 (3): 307–320.