SSC Project Recommendation for FY 2016

FLAWS: Fatigue – Longevity of Aluminum Welded Structures

Submitted by: Delft University of Technology, The Netherlands

1.0 OBJECTIVE.

To extend and to demonstrate the Total Stress concept as a design method for a more accurate aluminum hull structure welded joint fatigue strength and life time estimate.

2.0 BACKGROUND.

2.1 Introduction

Crew transfers, surveillance duties as well as security, rescue and interception operations at sea typically require high-speed craft. Aluminum is quite often selected as hull structure material because of its weight saving potential in comparison to steel, aiming for a reduction of installed power and fuel consumption. However, the fatigue strength may become a point of concern because of the increased strain levels associated with the lower Young's modulus.

Continuous wave loading as well as repeating wave impacts are typically identified as dominant, meaning fatigue is a governing limit state in aluminum high-speed craft design. Particular attention in that respect is paid to arc-welded joints connecting the hull structural members, since the weld geometry introduces notches; fatigue sensitive locations.

Fatigue physics cover an extensive range of scales and accurate process modeling requires a multi-scale approach. Adopting a global intact geometry structural response parameter *S* at macro scale may seem attractive since *S* controls plasticity required to facilitate fatigue damage at macro (structural)- as well as meso and micro (material) scale, but pays off in fatigue resistance data scatter and life time estimate uncertainty. Incorporating physics at smaller scales should improve the accuracy. A continuous increase of the considered scale range of physics as observed in fatigue assessment concepts developed over time is however typically associated with increased (computational) effort and concept complexity. At the same time, similarity; proper scaling, meaning equal parameter values should yield the same fatigue resistance, seems still incomplete since all concepts available involve multiple fatigue resistance curves rather than one.

From medium and high cycle fatigue design perspective, a local (macro) continuum mechanics approach seems sufficient and a Total Stress concept (den Besten, 2015) is developed to balance accuracy, effort and complexity. Similarity is improved at the same time to obtain one (family of) aluminum arc-welded joint fatigue resistance curve(s) and involves weld notch stress distribution, stress intensity, crack growth and fatigue resistance elements. The Battelle Structural Stress concept involves the same elements (Dong and Hong, 2004), but in a different way.

2.2 Total Stress concept

The weld geometry introduces a notch at the weld toe and depending on penetration level another one at the weld root. Cracks may initiate at both fatigue sensitive locations, grow principally in plate thickness direction because of the structure orthotropic stiffness characteristics and continue to propagate in the plate plane, suggesting a thickness based (leakage and detectable repair) criterion to be an appropriate fatigue design parameter. The total through-thickness weld notch stress distribution along the expected crack path, including both the wave induced cyclic remote mechanical loading- and welding process related quasi-constant thermal residual part, is assumed to be a key element. The predominant remote mechanical loading mode-I contribution involves a self-equilibrating weld geometry stress – consisting of a local V-shaped notch- and weld load carrying part – and equilibrium equivalent global structural field stress component; a refinement of a well-known definition. The semi-analytical formulations are related to the welded joint far field stress, calculated using a relatively coarse meshed plate FE model as typically available for fatigue design purposes. Exploiting (non-)symmetry conditions, a generalised formulation demonstrating stress field similarity has been obtained and extends to the welding induced thermal residual stress distributions. Fatigue scaling requires both the (zone 1) peak value and (zone 2 notch affected and zone 3 far field dominated) gradient to be incorporated, meaning a damage criterion should take the complete distribution into account.

The stress intensity factor K seems to meet this criterion, though, the intact geometry related notch stress distributions should be correlated to crack damaged equivalents; fatigue is assumed to be a crack growth dominated process. At the same time, hull structure arc-welded joints inevitably contain flaws or crack nuclei (defects) at the weld toe- and root notches, i.e. using the damage tolerant mode-I parameter K_I seems justified since fatigue associated to the medium and high cycle fatigue life time range at both locations will predominantly be a matter of micro- and macro-crack growth. The zone 3 related equilibrium equivalent stress contribution has been used to obtain a far field factor, distinguishing different type of cracks related to (non-) symmetry conditions for both (quasi) 2D- and 3D configurations. A notch factor incorporates the zone 1 and 2 governing self-equilibrating stress. Remote mechanical weld toe- and weld root stress intensities show the zone 1 and 2 notch affected- and zone 3 far field dominated parts define a micro- and macro-crack region, turning the stress field similarity into a stress intensity similarity. Each stress component dominates a certain crack length range: the notch stress the micro-crack region, the structural field stress the macro-crack region; the weld load carrying stress determines the transition (i.e. apex) location. The welding induced and displacement controlled mode-I residual stress intensity factor K_I^r is acquired for both weld toe and weld root notches to complete the total weld notch stress intensity similarity factor formulation K_I^T.

Cyclic remote mechanical- and quasi-constant thermal residual loading turn K_I^T into a crack growth driving force ΔK_I^T and defects may develop into cracks. The crack growth rate of micro-cracks emanating at notches show – at least for constant amplitude loading – elastoplastic wake field affected anomalies, i.e. monotonically increasing or non-monotonic behavior beyond the material threshold. Modifying Paris' equation, a two-stage micro- and macro-crack growth law similarity is developed to include both the weld notch- and far field characteristic contributions, elastoplasticity as well as remote mechanical and thermal residual mean stress effects.

Crack growth model integration yields a medium cycle fatigue single slope resistance relation, a joint S_T-N curve correlating arc-welded joint life time N and the total stress parameter S_T; a line equivalent point criterion to estimate hull structure longevity ensuring welded joint fatigue resistance similarity between small scale specimen, large scale specimen and the full scale structure. A random fatigue limit formulation has been adopted to incorporate high cycle fatigue taking the transition in fatigue damage mechanism (i.e. growth dominant turns into initiation controlled for decreasing load level), a slope change, into account. As-welded small scale specimen constant amplitude data has been used to establish a family of (damage tolerant engineering) joint S_T-N fatigue resistance design curves to be able to estimate the fatigue life time N of welded joints knowing the joint geometry and far field structural response. Full scale structure representative constant amplitude large scale specimen data has been examined to verify a small scale specimen data scatter band fit. Since constant amplitude small and large scale specimen fatigue resistance is principally used to estimate a variable amplitude full scale structure value adopting the Palmgren-Miner hypothesis, variable amplitude small scale specimen data is examined and a scatter band fit is observed. The involved equivalent total stress parameter $S_{T,eq}$ is obtained adopting an extended rain flow counting algorithm to capture the damage cube.

2.3 Total Stress concept advances

The two-stage crack growth law involves an elastoplasticity coefficient, allowing notch affected crack growth behavior to turn from non-monotonic to monotonically increasing for decreasing load level, since the notch and crack tip elastoplastic response turns into an elastic one. For the S_T-N curve an average elastoplasticity coefficient value has been determined using aluminum arc-welded joint fatigue resistance data. To increase understanding at crack growth level as well, it is proposed to investigate the (yield stress /

far field stress) ratio dependency experimentally using crack growth measurements to improve the S_T parameter formulation and finally the hull structure longevity estimate (i.e. fatigue design strength and life time accuracy) by reducing the fatigue resistance data scatter band for the benefit of total ownership costs (Stambaugh, 2014).

To capture the stress intensity factor as governing crack growth parameter experimentally, its notch and far field information – respectively crack size/length (crack tip position) and (linear) stress distribution – is required and is proposed to be obtained using Digital Image Correlation (DIC); a non-destructive, non-contact, direct optical observation method and surface displacement measurement technique. The displacement field kinematic basis is a key issue. Since a general (e.g. polynomial) one as typically used in commercial DIC software is not able to capture the displacement discontinuity over the crack faces accurately, a dedicated one is proposed to be adopted, i.e. an Airy stress function like Williams' (generalised) asymptotic solution and an X-FEM based displacement field decomposition (Roux, Réthoré and Hild, 2009). One of the popular measurement methods using a clip gauge or DC potential drop – providing only crack size information – will be used as back-up.

3.0 REQUIREMENTS.

3.1 Scope. (Identify the phases of the project).

3.1.1 Modeling: development of a 2D and 3D DIC displacement field kinematic basis using Airy stress functions and X-FEM as well as advancement of a crack growth model incorporating (yield stress / far field stress) dependent notch and crack tip elastoplasticity.
3.1.2 Testing: to conduct constant and variable amplitude crack growth experiments using Al5083H321 Single Edge Notch specimen involving DIC and a back-up system (e.g. a clip gauge or DC potential drop).
3.1.3 Validation: analysis of crack growth data to investigate notch and crack tip elastoplasticity effects in order to advance the Total Stress parameter.
3.1.4 Exemplification: application of the Total Stress concept with and without notch and crack tip elastoplasticity correction to hull structure welded joints for demonstration purposes.

3.2 Tasks. (Identify the tasks to carry out the scope of the project).

3.2.1 Develop a 2D and 3D DIC displacement field kinematic basis using Airy stress functions and an X-FEM formulation.
3.2.2 Model notch and crack tip elastoplasticity affected crack growth.
3.2.3 Conduct Al5083H321 Single Edge Notch Tension (SENT) specimen crack growth measurements involving DIC and a back-up system.
- Constant amplitude loading: 6 specimens (3 load levels, repeating twice).
- Variable amplitude loading: 2 specimens (2 load levels; characteristic spectrum).

3.2.4 Analyze (DIC based) crack growth data.
3.2.5 Investigate crack growth notch and crack tip elastoplasticity effects.
3.2.6 Advance the Total Stress parameter incorporating load level dependent notch and crack tip elastoplasticity and re-establish the aluminum welded joint fatigue resistance data scatter band.
3.2.7 Demonstrate the Total Stress concept as design tool, estimating hull structure longevity (i.e. aluminum welded joint fatigue strength and life time) with and without notch and crack tip elastoplasticity correction.

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 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 as posted on the website http://www.shipstructure.org.

6.0 PERIOD OF PERFORMANCE.

6.1 Project Initiation Date: January 1st, 2017.

6.2 Project Completion Date: *12* months from the project initiation date.

7.0 GOVERNMENT ESTIMATE. Contractor direct costs are based on previous project participation expenses.

7.1 Project Duration: *12* months.

7.2 Total Estimate: 100k$

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

8.0 REFERENCES.

8.1 Besten, J. H. den (2015). Fatigue resistance of welded joints in aluminium high-speed craft: A TOTAL STRESS CONCEPT. PhD thesis, Delft University of Technology, The Netherlands. Link: http://repository.tudelft.nl/view/ir/uuid%3A370b3d44-f4a6-403e-9629-d36174c3aca4/.

8.2 Dong P., Hong, J.K. (2004). The master S-N curve approach to fatigue evaluation of offshore and marine structures. Proc. of the 23rd Int. Conf. on Offshore Mech. & Arctic Eng., OMAE 2004.

8.3 Roux S., Réthoré J. and Hild F. (2009). Digital image correlation and fracture: an advanced technique for estimating stress intensity factors of 2D and 3D cracks. J. of Applied Physics D: Applied Physics, vol. 42, No. 21.

8.4 Stambaugh K. (2014). Naval ship structure service life considerations. ASNE Fleet Maintenance and Modernization Symposium, FMMS 2014.

ENCLOSURE *A:* Project Timeline

Month	1	2	3	4	5	6	7	8	9	10	11	12
Task 1: displacement field kinematic basis development	■	■	■									
Task 2: notch and crack tip elastoplasticity modeling			■	■								
Task 3: single edge notch specimen crack growth tests					■	■	■					
Task 4: crack growth data analysis							■	■	■			
Task 5: investigate crack growth elastoplasticity effects								■	■			
Task 6: Total Stress parameter advancement									■	■		
Task 7: Total Stress concept exemplification											■	■

ENCLOSURE *B:* Costs Estimate

Phase 1: modeling	20 k$
Phase 2: testing	30 k$
Phase 3: validation	30 k$
Phase 4: exemplification	20 k$
Total	**100 k$**