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Using a Computational Galvanic Model in a Fracture Mechanics Framework to Improve Material Degradation Prediction

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ABSTRACT

Although computational methods have been separately developed to predict corrosion and fatigue crack growth rates for metallic structures, challenges remain in implementing a methodology that considers the combined effects. In this work the output from a galvanic model is used to determine the spatial distribution of corrosion damage; providing a guide for the location of discrete corrosion damage features that can be analyzed using stress fields from structural models. In order to build confidence in this approach the galvanic models are validated by comparing predicted results to surface damage measurements from test specimens subject to ambient atmospheric exposure. There was good comparison between the predicted spatial distribution of corrosion damage and the measured surface damage profiles obtained from the galvanic test specimens. Following this exercise novel computational corrosion damage features were developed to represent simplified cracks shapes emanating from corrosion pits. Stress intensity factors (SIF) for these newly developed hybrid pit-crack features were determined and these solutions compared to cases where the pit is assumed to be an equivalent crack. The impact of the local, cavity induced stress field, on the SIF solutions is discussed. Building on these findings a fatigue crack growth simulation was performed using an initial flaw emanating from a hemispherical cavity (corrosion pit) located at the edge of hole in a plate. A reasonable comparison, of the predicted number of crack growth cycles, to available experimental test results was achieved.

Key words: Galvanic Corrosion, Atmospheric Exposure Measurements, Corrosion Pitting, Fracture Mechanics, Computational Modelling

INTRODUCTION

There is an urgent industry need to include the effects of existing corrosion damage in structural integrity analysis. By combining the results from galvanic modeling predictive tools and linear elastic fracture mechanics simulations a first-generation approach is introduced that can be used to provide a general assessment of the impact of common corrosion damage features on fatigue.

It is well known that fatigue performance is significantly reduced by corrosion; crack initiation sites are often associated with the location of corrosion damage (e.g. microscale roughness features) or second phase particles [1]. Crack formation life in corroded components, at maximum applied stress levels above 75-100 MPa, has been demonstrated to be a small percentage of total life and therefore crack growth analysis is a more relevant aspect of structural lifing [2].

Currently, engineering estimates, used to determine the impact of a corrosion pit on structural integrity, are based on assuming that the pit depth is equal to the initial crack size. It is often assumed that a fatigue crack will initiate when the stress intensity factor range (ΔK) exceeds the material fracture threshold (ΔK_{th}) and the crack growth rate (da/dN_{crack}) is greater than the pit growth rate (da/dt_{pit}). One researcher has expanded on this idea and introduced a powerful approach based on the corrosion modified equivalent initial flaw size (CM-EIFS) that uses linear elastic fracture mechanics (LEFM) to quantify the reduction in fatigue life due to corrosion [3].

In order to study corroded aircraft components, using LEFM to predict critical crack locations and fatigue life, we first need to be able to identify the corrosion severity using galvanic modeling techniques. In this current work, field exposure testing of a representative aircraft galvanic assembly, subject to ambient environmental conditions, has been used to demonstrate and validate the accuracy of these galvanic models. Once the most severe corrosion damage areas are identified it is then possible to predict critical crack locations and fatigue life using a LEFM approach. Knowledge of the spatial distribution of corrosion damage can be used to guide the location of computational corrosion damage features in structural models. Representative corrosion damage features can be analyzed to determine corrosion related SIFs under realistic loading; these SIF solutions can then be used within a fracture mechanics framework to determine the associated impact on fatigue life.

GALVANIC SPECIMEN DESIGN AND COMPUTATIONAL CORROSION MODEL

Review of an F/A-18 Outer Wing Teardown Inspection Report was used to select a structural component (aileron attachment hinge) that exhibited both galvanic and fatigue damage. Using this component, a simplified, but representative aircraft galvanic assembly was designed and used for exposure testing (Figure 1). Key considerations in the design include using multiple aerospace metal alloys for components, maintaining a similar combination of bushing and fastener geometry, and ensuring a non-symmetric layout to promote discrete areas of galvanic damage.

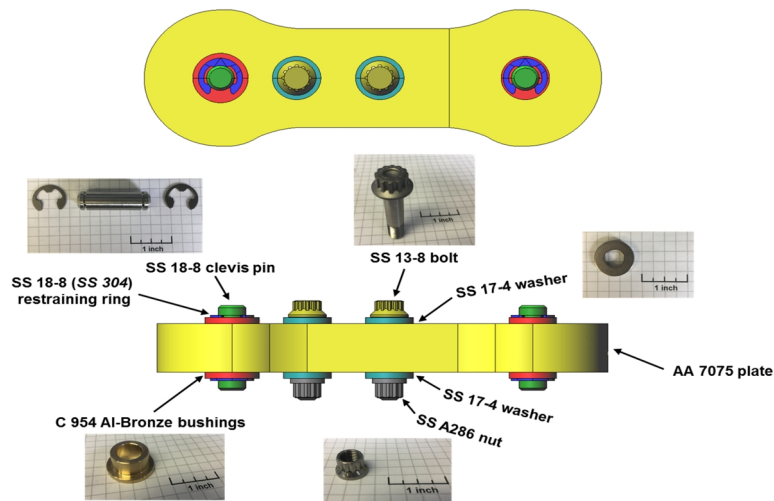


Figure 1: Representative aircraft galvanic specimen design

A BEASY[†] corrosion model was developed based on this design and used to predict areas of high galvanic stress. The model geometry is first discretized with elements using an appropriate meshing scheme. Boundary conditions based on the electrochemical kinetics (e.g. polarization curves) are then applied to represent the various component materials. Lastly, the characteristics of the electrolyte film (e.g. conductivity, film thickness) are assigned. In order to match the outdoor exposure environment as closely as possible material polarization curves (Figure 2), obtained using an artificial seawater electrolyte, were used to drive the computational model [4].

The predicted galvanic current and corrosion penetration rate for film thicknesses of 800 and 200 microns are shown in Figures 3 and 4 respectively. We should note that polarization testing was performed using immersion type (bulk) conditions. As such the potentiodynamic effects of thin film behavior for cathodic materials in the model are not reflected in the 200 micron film thickness solution (i.e. shift in the O₂ diffusion limiting cathodic current not considered). We should also note that the anodic polarization of AA 7075 does not vary significantly with film thickness. Therefore the dominant factor, controlling the more localized nature of the current density for thin film electrolytes, is the effect of increased resistance through the electrolyte layer.

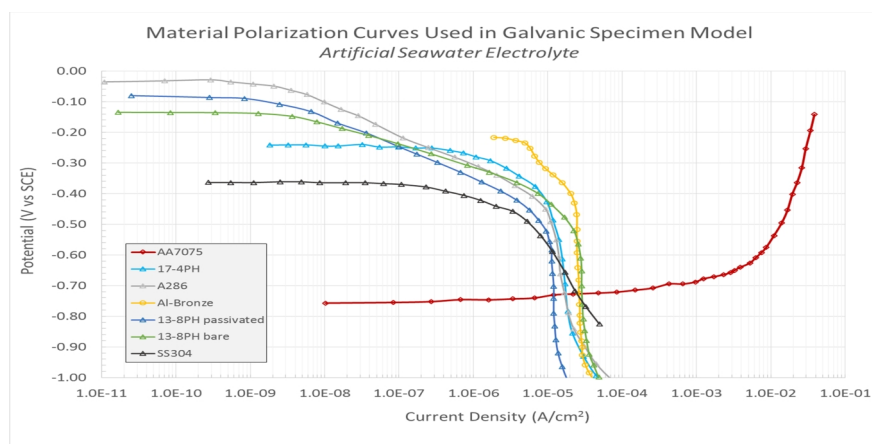


Figure 2: Material polarization curves (measured in artificial seawater)

[†] Tradename

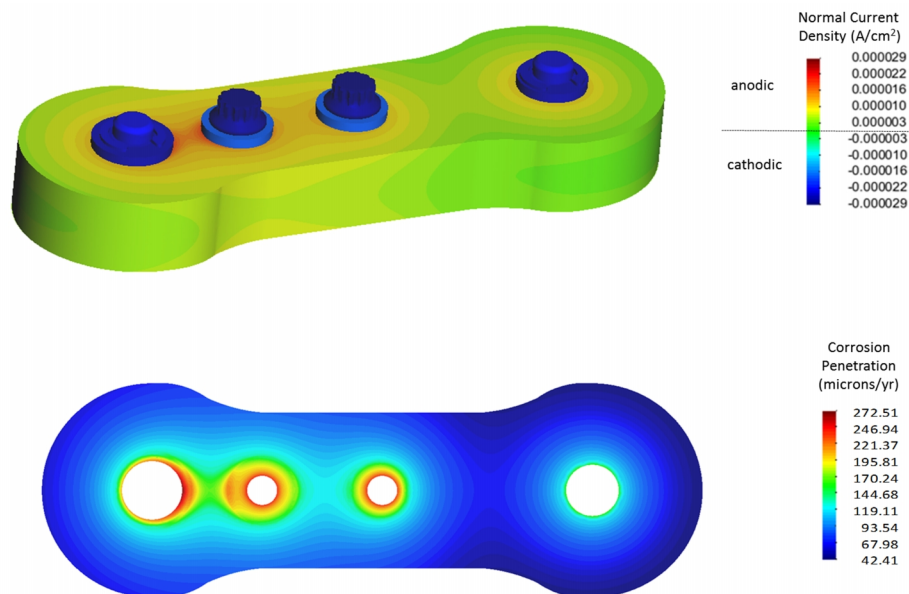


Figure 3: Prediction of galvanic currents and corrosion penetration (800 micron electrolyte layer, $K = 5.5$ S/m, material PDS curves generated using artificial seawater)

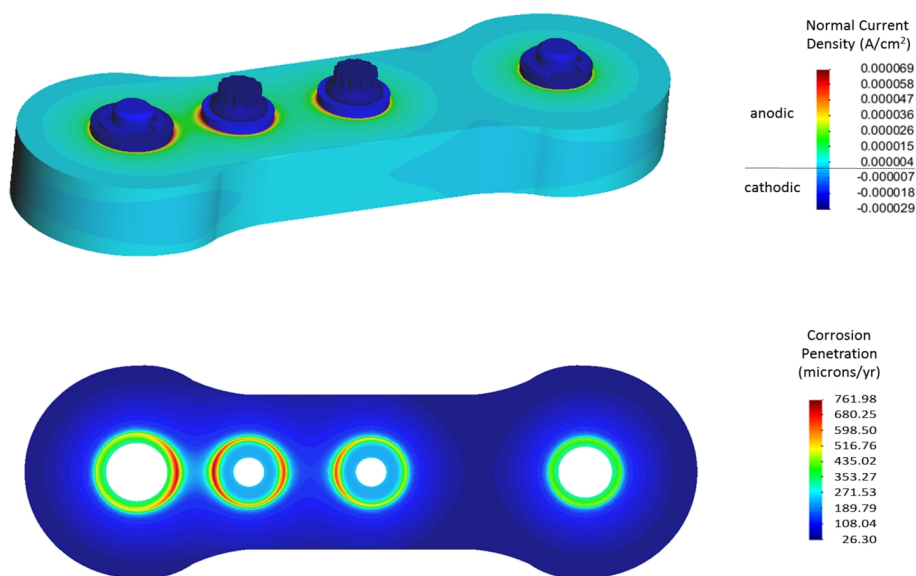


Figure 4: Prediction of galvanic currents and corrosion penetration (200 micron electrolyte layer, $K = 5.5$ S/m, material PDS curves generated using artificial seawater)

ATMOSPHERIC EXPOSURE TESTING PROGRAM

An atmospheric exposure testing program was developed to support measurement of key environmental parameters and corrosion damage on the galvanic specimens. The galvanic specimens were placed on an exposure rack at the Naval Air Station facility in Key West, FL on May 17, 2019. A photograph of the exposure rack is shown in Figures 5. The exposure test panel on this rack includes three critical components; the galvanic specimens, witness coupons (both SAE1020 carbon steel and AA7075 aluminum alloy), and an environmental sensor.

The first set of exposure samples (two galvanic assemblies and one witness coupon pair) were collected on July 17, 2019 representing a 62 day exposure period. The exposure panel was subject to ambient seacoast environmental conditions; no controlled, cyclical sea spray events,

were used during this initial 62 day exposure period. The temperature, relative humidity, and time of wetness (TOW) data at the Naval Air Station site were collected in order to characterize the environmental history [5]. The changing surface moisture conditions were determined using a Campbell Scientific Model 237-L leaf wetness sensor and this data is shown in Figure 6. The leaf wetness sensor data was used to determine the TOW which is a useful parameter in making cumulative corrosion damage estimates.

A Keyence VK-X250 3D laser scanning confocal microscope was used to measure the depth of corrosion penetration at key locations on the top and bottom surfaces of the galvanic specimens. Mass loss measurements were also performed for each of the witness coupons collected and can be used to determine self-corrosion rates for the carbon steel and AA7075 coupons.

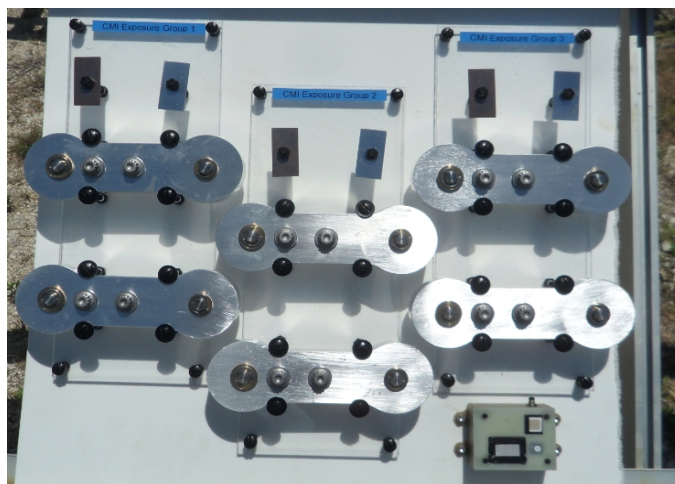


Figure 5: Atmospheric exposure test panel at Naval Air Station, Key West FL (galvanic specimens, witness coupons, corrosion sensor)

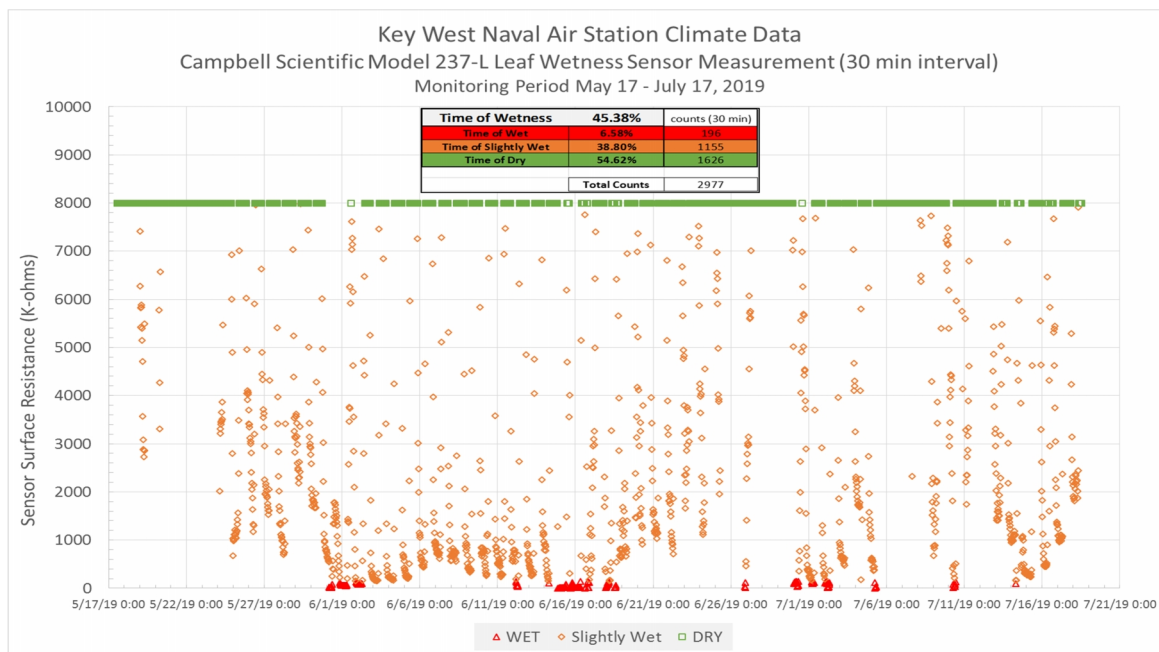


Figure 6: Leaf wetness sensor record during test period (May 17, 2019 – July 17, 2019)