Deep Dive into Marine Energy Composites and Manufacturing

Webinar Series: March-April 2021
Event Series Listed In WPTO R&D Deep Dive Webinar Series

- Crevice Corrosion in Seawater Using CFRP/Hybrid Composite as Part of a Novel Crevice Former, March 19, 1-2 pm ET

- Summary of Marine and Hydrokinetic (MHK) Composites Testing at Montana State University, March 26, 1-2 pm ET

- Leveraging the Advantages of Additive Manufacturing to Produce Advanced Composite Structures for Marine Energy Systems, April 9, 1-2 pm ET

- Marine Energy Composites & Manufacturing Workshop, April 16, 10-2 pm ET

Crevice Corrosion in Seawater Using CFRP Composite as Part of a Novel Crevice Former

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Materials Team

George Bonheyo: Biofouling
David Miller: Composite Performance
Francisco Presuel-Moreno: Corrosion
Scott Hughes: Substructure Testing
Bernadette A. Hernandez-Sanchez: Materials Chemistry
Budi Gunawan: Loads & FBG Sensors

Marine Science Laboratory
Pacific Northwest National Laboratory
Sandia National Laboratories
Materials Challenges for Marine Renewables

Proper structural/component materials and coatings are critical to reducing engineering barriers, COE, and commercialization time.

Design Challenge: Several Design Configurations & Operational Conditions

Significant Periodic Loading:
- Interaction with PTO & Control System
- Site Conditions
- IEC Design Standard (Fatigue/Ultimate)

Composites Research Needed
- Composite material selection, architecture, structural performance, and design:
  - Mechanical Loading, fatigue and static loading, damage propagation,
  - Environmental exposure, diffusion, mass uptake, and degradation

Coating & Environmental Challenges
- Corrosion
- Biofouling
- Joined Materials

Adhesive joint beams

http://www.roseocks.ca/

Hernandez-Sanchez et al 13th EWTEC Proceedings
Environmental Effects on Composites

Corrosion can occur on metals connected to carbon fiber composite materials (i.e., CF composite to metal interconnects).

Calcereous deposit from corrosion study CF/VE8084 + anode

Corrosion Studies on Connections

Biofouling Studies on Composites & Coatings

MRE relevant Velocities
0.1 m/S and 2.6 m/s
0-22 month Exposures
Corrosion can occur on metals connected to carbon fiber (CF) composites. A special case is crevice corrosion for bolted CF composite immersed in seawater.

A portion of a carbon fiber composite mast is shown, with metal couplings attached to it.

Cathodic Polarization Scans on CFRP after immersion in seawater interconnected to Al anode

Evidence of cathodic kinetics reduced due to calcareous deposits formed on samples connected to anodes. Smaller $i_L$
**Experimental**

**Materials Systems**

- **CF/VE**
- **Hybrid Composite**

**Environmental conditions**

- Sea Water /RT
- Sea Water 100°F

**Metal Hardware**

Stainless Steel (18% Cr)
Monel (NiCu alloy)
Ti alloy

<table>
<thead>
<tr>
<th>Number of samples prepared indicating immersion tank</th>
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<tbody>
<tr>
<td>CF/VE RT</td>
</tr>
<tr>
<td>Stainless Steel</td>
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<tr>
<td>Monel</td>
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<tr>
<td>Ti alloy</td>
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<table>
<thead>
<tr>
<th>Number of samples dis-assembled</th>
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<tbody>
<tr>
<td>CF/VE RT</td>
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<tr>
<td>Stainless Steel</td>
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<td>Ti alloy</td>
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<table>
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<th>Number of days at which samples were removed from immersion and dis-assembled</th>
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<tbody>
<tr>
<td>CF/VE RT</td>
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Crevice assembly using composite as the plate 9.4 mm diameter drilled at the center.
Torque: 20 lb-in (2.26 N.m)

CF/VE panels 1.8 mm thick (6/8 plies unidirectional)
Hybrid (both carbon and glass fiber) 7.5 mm thick
Immersion started November 8, 2018

CFRP 7.5 cm × 7.5 cm
Hybrid 3.5 cm × 3.5 cm

Visual inspection at 55, 98, 197, 273, and 600+ (remaining specimens) days.

Samples removed from immersion and dis-assembled starting at day 273, last set at day 806. Stereo microscope and selected samples observed on SEM.
Location where crevice corrosion could develop

The specimen as shown in Figure can lead to the following crevice geometries:

- C1: Between the washer/smooth side of the carbon fiber
- C2: Between the washer/rough side of the carbon fiber
- C3: Between the nut and the washer
- C4: Between the bolt head and the washer
- C5: Between the threads of the bolt and the matching threads of the nut.

These tight occluded regions are sites prone for crevice corrosion to occur. In here the focus is on C1 and C2 geometries, as it corresponds to the composite to metal contact. However, a few examples for C3, C4 and C5 geometries are included.
Differential aeration cell - Fundamentals

The oxygen reduction reaction occurs at drastically different rates inside the crevice where oxygen is depleted.

- oxygen depleted inside
- ferrous ion hydrolyze
- Fe activates inside, remains passive outside.

- Corrosion rate inside becomes large with anode (inside) and cathode (oxygen reduction outside)

- At first corrosion is actually worse on the outside because of ready supply of $O_2$
Crevice Corrosion - Fundamentals

Stage I

- Oxygen is readily depleted in crevice
- Anode and cathode become separated
- Metal ions hydrolyze, and chloride migrates to maintain electro-neutrality
- Severe crevice chemistry depassivates metal inside crevice, active corrosion occurs
Stainless Steel/CFRP composite fastened samples

Room Temperature
Observations after 55 days of immersion

Elevated Temperature
after 55 days of immersion

Observations after 273 days of immersion

Observations after 55 days of immersion

after 273 days of immersion
Elevated Temperature
Monel, immersed for 55 days

Monel or Ti /CFRP composite fastened samples
Ti, immersed for 55 days

Monel

Monel, immersed for 273 days

Ti

Left
Hybrid- Monel

Right
Hybrid - Ti
Room temperature immersed in Seawater

Stainless Steel Washers in contact with the CFRP composite, top row smooth side, bottom row rough side

302 days  365 days  799 days  806 days

C1

C2
806 days
Washer in contact with smooth composite
**Room temperature immersed in Seawater**

Monel washer surfaces in contact with the CFRP composite, top row smooth side, bottom row rough side
799 days, on the left in contact with smooth CFRP composite, below in contact with rougher CFRP composite surface
Room temperature immersed in Seawater

Ti washer surfaces in contact with the CFRP composite, top row smooth side, bottom row rough side

330 days  448 days  806 days
Elevated Temperature – Stainless Steel

Stainless Steel Washers in contact with the CFRP composite, top row smooth side, bottom row rough side

273 days
8084-2019

323 days
510-2019

729 days
8084-2020

652 days
510-2020
Elevated Temperature

Monel Washers in contact with the CFRP composite, top row smooth side, bottom row rough side

288 days

330 days

659 days

739 days
Elevated Temperature

Titanium washers in contact with the CFRP composite, top row - smooth side, bottom row - rough side

316 days

448 days

806 days
Elevated Temperature

Washers in contact with the Hybrid composite, top row - smooth side, bottom row - rough side

316 days, 708 days
704 days, 713 days

Stainless Steel
Monel
Titanium
Interior Smooth Side

Composite corresponds to samples fastened with Monel

Interior Rough Side

708 days
SEM observations

323 days
Monel
Elevated Temperature – Stainless Steel

Stainless Steel Washers in contact seawater, top row bolt, bottom row nut side
Elevated Temperature – Monel

Stainless Steel Washers in contact seawater, top row bolt, bottom row nut side
Elevated Temperature

Washers in contact with the Hybrid composite, top row – bolt side, bottom row – nut side

316 days 708 days

704 days 713 days

Stainless Steel  Monel  Titanium
Example of a C3 site (crevice corrosion between nut and washer surfaces)

Nut side in contact with washer

Washer in contact with nut
Example of a C3 site (crevice corrosion between nut and washer surface) Stainless Steel (652 days)
Example of a C3 site (crevice corrosion between nut and washer surfaces)
Example of a C4 site (crevice corrosion between bolt and washer surfaces)

739 days
Example of a C5 site (crevice corrosion between threads of bolt and nut)

Elevated Temperature – Stainless Steel (652 days)

Pitting Corrosion
On the left two close-up images of the composite surface on the bolt side, with calcareous deposits. Below, the composite surface on the nut side. Note the washer inprint and that there are almost no calcareous deposits. Possibly due to the rougher surface of the composite.
Conclusions

Crevice Corrosion of type C1 and C2 were observed on Monel and Stainless steel washers.

Crevice corrosion appears to be more pronounced on samples exposed in the elevated temperature seawater.

C1 corrosion occurred with large surface coverage on stainless steel, and most corrosion products leached out.

C2 corrosion occurred as different sizes of pits on stainless steel and as brown corrosion products that flaked easily on Monel washers.

No corrosion took place on the Titanium washers within the time monitored.
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