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Evaluation of composite materials for wave and current energy technologies

Bernadette A. Hernandez-Sanchez, James Nicholas, Budi Gunawan, David A. Miller, George T. Bonheyo, Francisco Presuel-Moreno, and Scott Hughes

Abstract—**Composites are promising materials that could provide lightweight marine durable structures for wave and current (tidal/instream) energy conversion technologies. However, some composite materials are expensive and unproven under marine renewable energy (MRE) conditions. To reduce uncertainty in using composites, Sandia National Laboratories along with Pacific Northwest National Laboratory, National Renewable Energy Laboratory, Montana State University, and Florida Atlantic University have partnered to investigate carbon and glass reinforced composites. Using samples provided by industry (U.S. Marine and Hydrokinetic (MHK), composites/coatings manufacturers), the effects of marine environmental exposure on performance was evaluated. Coupons were submersed in actual and simulated seawater to determine the effects of biofouling, metal-carbon fiber interconnect corrosion, and potential strategies to mitigate them. Tensile static and fatigue testing on 33 different laminates, from five suppliers, was also conducted. Testing was performed on unconditioned and simulated seawater conditioned coupons of each laminate. In addition, a larger scale testing effort at sub-component size to provide insight on the operational load challenges for composite materials is currently being designed with input from developers. It is expected that the outcome of this project will provide industry a better understanding of the materials science and engineering behind MHK composite structures, to optimize designs and avoid costly redesigns. Resulting data from this study can be found in the open source U.S. DOE MHK Materials & Structures Database. This paper focuses on the current results obtained from this program.**

Keywords—**Biofouling, Corrosion, Composites, Fiber Reinforced Polymer (FRP), Wave Energy, Current Energy.**

I. INTRODUCTION

THE extreme marine environment presents a challenge to the design, manufacture, operation and maintenance of marine renewable energy (MRE) technology. Materials and coatings are sought that are amenable to the environment and will meet design requirements. To address the need for using high-strength, lightweight structures for MRE that can withstand corrosion, interest in using fiber reinforced polymers (FRPs) composites has grown. Composite materials are also of interest because they lend themselves to advanced manufacturing methods with the potential for cost reduction opportunities.

During the 2015 U.S. Department of Energy Marine and Hydrokinetic (MHK) program, U.S. industry expressed interest in using composites but noted the need for materials research to overcome uncertainty in using composites for MHK applications. While MHK developers anticipate a benefit from the strength, weight, and potentially greater durability of composites in the marine environment (compared with steel or aluminum), most MHK devices have remained as steel structures due to more mature fabrication methods, the relative low cost of the materials and manufacturing, wide availability of resources, and greater characterization of steel alloys' performance in marine environments. In addition, it was recognized that there are also significant design and load challenges that are specific to marine energy that would impact material and coating selection. The next section briefly outlines some of these issues related to composites and their use.

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B. A. Hernandez-Sanchez is with Sandia National Laboratories, Advanced Materials Laboratory, P.O. Box 5800, Albuquerque NM, 87185-1349, USA (e-mail: baherna@sandia.gov);
J. Nicholas is with Sandia National Laboratories, Advanced Materials Laboratory, P.O. Box 5800, Albuquerque NM, 87185-1349, USA (email: jnicho@sandia.gov).
B. Gunawan is with Sandia National Laboratories, Water Power Technologies, P.O. Box 5800, Albuquerque NM, 87185-1349, USA (e-mail: bgunawa@sandia.gov).
D. A Miller is with Montana State University, P.O. Box 173800 Bozeman, MT, 59717, USA (e-mail: davidmiller@montana.edu).
G. T. Bonheyo is with Pacific Northwest National Laboratory, Marine Research Laboratory, 1529 West Sequim Bay Road, MSIN: SEQUI Sequim, WA 98382, USA (e-mail: George.Bonheyo@pnnl.gov).
F. Presuel-Moreno is with Florida Atlantic University, 777 Glades Road, ST 239 Boca Raton, FL, 333431, USA (e-mail: fpresuel@fau.edu).
S. Hughes is with National Renewable Energy Laboratory, National Wind Technology Center, 15013 Denver West Parkway Golden, CO, 8040, USA (e-mail: scott.hughes@nrel.gov).

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A. MHK design challenges

In comparison to the wind industry, MHK technologies have multiple design configurations leading to a wide range of criteria to consider. Examples of structural geometries include a surging flap, floating hull point absorber, axial flow and cross flow turbines. For these design configurations both carbon and glass fiber-based composites are being evaluated. For example, composites research on the influence of salt water on MRE materials properties and manufacturing using resin transfer molding and other strategies were conducted on tidal technologies [1, 2, 6]. Reports show that only recently (2014) have studies begun to investigate the combined effect of the applied cyclic load and seawater submersion [1]. As such, there is a dearth of knowledge on the coupling between cyclic loads and seawater, and how these might degrade material performance. The current U.S. program has made a similar, but smaller effort to examine combined effects of load, diffusion and material performance [3,4,5].

Judicious choice of reinforcing fiber selection needs to be applied in design considerations. As higher quality carbon fiber becomes more accessible and affordable, MHK developers must understand how to mitigate galvanic corrosion between carbon fibers and metal interconnects often observed within the aerospace and automobile industries. Composite materials, and component interconnections between metallic and composite materials, must be carefully designed and validated given the unique and demanding environmental operating conditions of MHK systems. Thus, activities focused on the materials science of composites/metal interconnects was initiated in the U.S. program. Finally, it must be recognized that MHK operational conditions will lead to unique device designs where not all commercial marine materials can be transferred without preliminary performance testing.

B. MHK specific load challenges

MHK marine composite structures must withstand significant periodic loading due to their interaction with (1) the power take-off and control system, and (2) site conditions that include wave and current, over their service life. The design standard developed by International Electrotechnical Commission [8] requires developers to describe structural performance of a device based on a specific set of limit states, including the ultimate and fatigue limit states, beyond which the device no longer satisfies the design requirement. Therefore, knowledge on composite materials performances under operational marine energy environments is required to determine and certify whether the wave/current energy converter (WEC/CEC) is structurally sound and complies with standards. MHK systems may not realize the benefits of composite materials until the structural behavior of composite materials under extreme marine loading and environmental conditions is adequately understood and quantified.

C. Coating challenges

Commercial antifouling coatings are formulated for various operational conditions and locations specific to the established marine industry but not to marine renewable energy. For example, foul release coatings have shown outstanding performance with ships navigating at high speeds >10 kn (5.1 m/s), but these same coatings did not demonstrate the same performance under simulated MHK wave conditions for laboratory testing at Pacific Northwest National Laboratory (PNNL). Marine energy devices typically experience velocities <10 kn or even <5 kn (2.6 m/s). In addition, environmental regulations can also impact coating selections.

D. Joined materials challenges

It is expected that composites will be joined together through various methods that include adhesives and metallic interconnects. Environmental effects on these features must be understood to provide insight into operation & maintenance, reliability, and safety. Thus, salt water and biofouling effects on joined dissimilar materials are being evaluated.

II. U.S. MHK COMPOSITES PROGRAM

To reduced uncertainty and provide the fundamental research required to support industry, the U.S. Materials Program has focused on addressing the following areas listed below. A short description on the evaluation type is listed for reference. The next sections will detail each area and progress made for these respective studies.

1) Salt Water Effects on Composite Performance Testing. Coupons of composites were immersed until saturation in simulated seawater prior to testing.
2) Biofouling & Environmental Effects on Composites. Coupons of various alloys and composites were coated with commercial or research grade antifouling coatings. Samples are being immersed in unfiltered actual sea water for 2 to 22-month periods.
3) Metal – Carbon Fiber Composite Interconnects in Seawater. Carbon fiber composite coupons were coupled with titanium, sacrificial anodes, nickel and stainless steel and immersed in actual seawater to examine galvanic behavior and calcaerous deposits.
4) Industry Directed Sub-Scale Elements & Joined Coupon Fabrication/Testing. Test coupons using metallic interconnects and adhesives are being fabricated and immersed (simulated & actual seawater) prior to testing.
5) Industry Directed Full-Scale Subcomponent Testing. Agnostic subcomponents, identified through industry surveys, will be fabricated and immersed (simulated & actual seawater) prior to testing.

These studies were conducted between 2017 and 2019. Some results are stored in the U.S. DOE Wind & Water Materials & Structures Database [3].

III. U.S. DOE Wind & Water Materials & Structure Database

To provide designers a tool to aid in materials selection, the U.S. DOE Wind & Water Materials & Structures Database was developed. Fig. 1 illustrates the current user community for this public resource established by Sandia National Laboratories (SNL) and Montana State University (MSU).

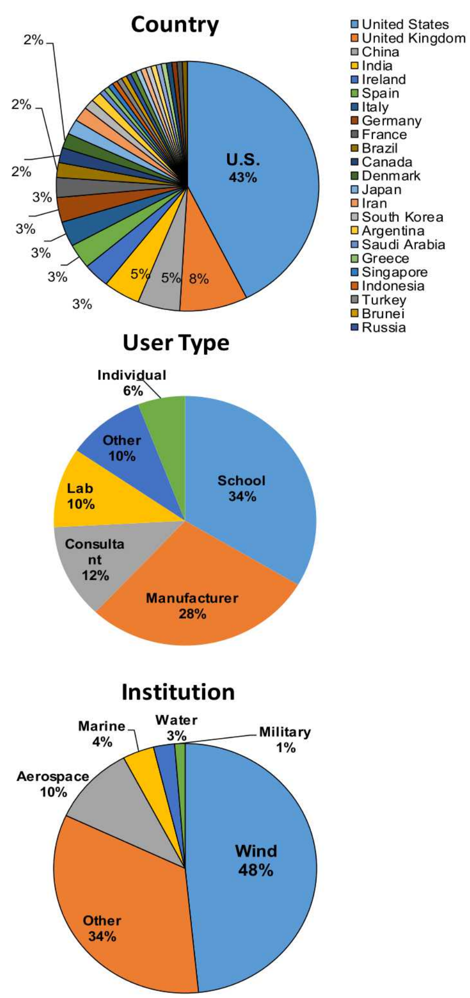

Fig 1. Example of database user community for marine composite resources.

Born from the discovery of wind blade materials, the database has expanded to include materials considered for wave and current energy converters. The database is being used to fill knowledge gaps and to provide critical links between the materials science of composites, system & component design, and the performance of materials & substructures.

A critical outcome is to provide a better understanding of the materials science and engineering behind MHK composite structures to avoid costly redesigns. Details on the studies used to understand the current wind and water data sets are distributed within journal publications and dissertations. Recent data includes results from coupon and coatings samples submitted by industry for evaluation. The database is beginning to move beyond the coupon level and will include substructure data sets. For the future, composite long-range data needs are represented in Fig 2.

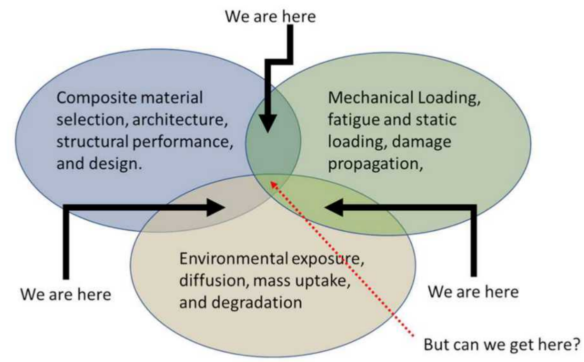

Fig 2. Long range data needs to reduce composite uncertainty.

Here, aspects of the materials type & architecture, their mechanics & damage behavior, and environmental robustness are evaluated. Separate data collected in these areas are beginning to provide a snapshot of how these areas interact, but the real long-term challenge is to understand the intersection of where these areas overlap. For example, this would represent the simultaneous exposure and mechanical testing of full-scale or substructure components.

E. Salt water effects on composite performance testing

Recent 2018 updates to the Water Materials & Structural database includes results from tensile static and fatigue testing on 33 different laminates (Thermosets & Thermoplastics). Five suppliers from the U.S. program provided samples that were immersed in artificial salt water. Full details on testing can be found in the database.

In brief, the following testing was applied:

- Tensile static and fatigue, R = 0.1, testing on 33 different laminates, from five suppliers.
- Testing was performed on unconditioned and simulated seawater conditioned coupons of each laminate.
- The static and fatigue tests on the 33 different laminate configurations required over 175 machine days (4148 hours) of continuous testing time after 90+ days of moisture conditioning.
- Thermoset and thermoplastic coupon sets were measured.
- Acoustic emission data were collected to investigate damage propagation in both dry and saturated coupons.
- The longest saturated samples tested were carbon fiber vinyl ester laminates immersed in seawater for 5 years at room temperature.
- Table I gives an example of a portion of data housed within [3].

TABLE I
EXAMPLE OF DATABASE RESULTS FOR CE THERMOSET

MSU Material	Layup	Average V_F for static tests %	% Moisture	Longitudinal Direction			Transverse Direction		
				E, GPa	UTS, MPa	% strain	E, GPa	UTS, MPa	% strain
CE1	$[V/(+/-45)g/0c]_S$	40.9	0	56.1	786	1.38	10.7	98.3	3.17
			1.2	58.3	787	1.33	8.54	68.3	1.84
CE2		35.8	0	54.8	773	1.40	9.02	83.3	3.26
			1.33	55.3	725	1.30	7.79	58.9	1.84
CE3		40.7	0	54.1	792	1.43	9.96	95.3	3.67
			1.1	52.1	691	1.31	8.62	68	1.92
CE4		36.1	0	53.7	774	1.36	8.91	83.9	3.69
			1.2	53.1	712	1.30	8.18	60.5	1.82
CE5		36.4	0	56.5	733	1.29	9.69	77.8	3.54
			0.34	57.9	695	1.15	8.05	63.6	2.05
CE6	[V/0/45/-45/0/V]	42.3	0	29.2	695	2.69	12.0	109	2.52
			0.36	28.7	590	2.36	16.6	126	2.36

The material examined in Table I, (labelled as CE#) is a hybrid thermoset made from both carbon and glass. This snap shot illustrates how moisture diffusion within the laminate affects the longitudinal and transverse mechanical behavior. Similar degradations in strength and increase in failure strain was observed across almost all the 33 material systems, as seen in the snapshot of ultimate tensile stress for uniaxial samples shown in Fig 3. Here unconditioned materials (blue) are compared to conditioned (red) for the 33 samples.

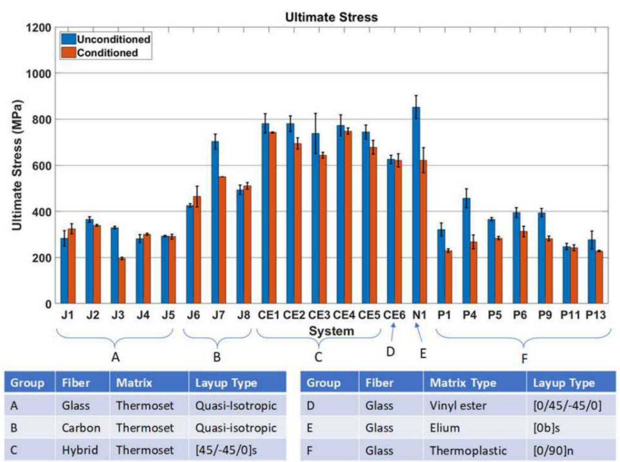

Fig 3. Ultimate Stress for dry (blue) and conditioned (red) samples showing strength drop after saturation. A: Glass Thermoset; B: Carbon Thermoset; C: Hybrid Thermoset; D: Glass Vinyl Ester; E: Glass Elium; F: Glass Thermoplastic.

F. *Biofouling & environmental effects on composites*

Biofouling and environmental effects can have a profound effect on MHK performance. Increased drag can occur from large growth on a surface, thereby reducing the energy harvesting motion of WECs and CECs. Extra strain on moorings can also occur, and fouling can also accelerate corrosion. Other impacts include increased costs, sensor failure, safety issues, toxins from coatings, as well as the introduction of invasive species or attraction of artificial reef formation.

To assess the effects of biofouling on composites, 500 coupons with commercial coatings and composites were examined. Table II summarizes the materials received which were provided by composites and coatings manufactures along with MHK developers. For these studies, investigations were made on the rate and extent of biofouling accumulation, any potential impact on the material, self-swelling, weight gain, and corrosion.

TABLE II
MATERIALS EVALUATED FOR BIOFOULING

Glass fiber reinforced plastic (GRP)
Polystyrene (PS)
Polyethylene (PE)
G10 Garolite fiberglass (G10, aka FR4)
Poly(phthalazinone ether amide) (PPEA)
Poly(2,6-dimethyl-l,4-phenylene ether) (PPE)
Nylon 11 (polyamide) (PA11)
Polyamide 6 (PA6)
Polyethylene terephthalate (PETG)
Poly(ethylene terephthalate) (PET)
Carbon-carbon composite (HDP)
Aluminum
Sanded aluminum
Stainless steel
Carbon steel
Glass fiber reinforced plastic (GRP)
Polystyrene (PS)

Testing was conducted at PNNL's Marine Science Laboratory under the following conditions:

- Unfiltered actual seawater was used (low flow & static tanks).
- Tests under MRE-relevant velocities (0.1 m/s and 2.6 m/s) using a track.
- Exposure testing from 2 to 22 months is currently underway
- Total organic carbon and nitrogen analysis was conducted.

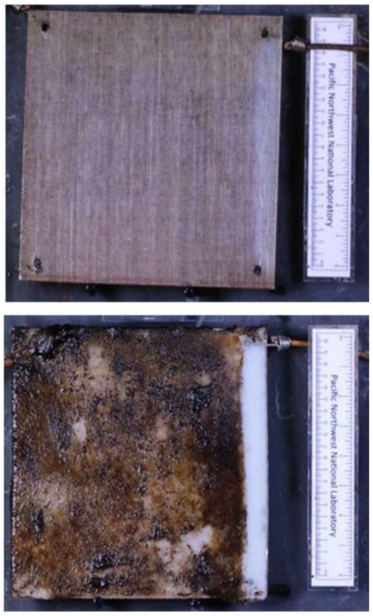

Fig 4. (Top) FRP samples with an effective antifouling coating after 18 months of exposure. (Bottom) A polymer material and coating showing ineffective fouling protection. The right edge of each sample was wiped clean to expose the underlying substrate.

An example of some of the FRP samples after 18 months of exposure can be seen in Fig 4. Light to heavy slime on can be found on the surfaces. For a few samples, the slime seems to be penetrating the coupon itself working its way into the fibers. Full characterization is underway.

In additions to basic coupon testing, samples being developed in *subsection G, H, and I* (listed below) will also undergo similar immersion conditions. These studies will provide insight into how fouling and other environmental conditions impacts substructure and joined materials performance.

G. Metal – Carbon fiber composite interconnects in seawater

Future manufacture of WEC and CEC designs might require these devices to be manufactured in one location and later assembled in another. This will require a good understanding of the potential reliability issues of interconnects used in designs that could arise due to corrosion and MRE loading conditions. Past efforts on metal-carbon fiber composite interconnections were focused on ship applications [9–14] and provide much of the basis for understanding and mitigating corrosion issues. Due to galvanic coupling, past issues include blistering of composite, accelerated metal corrosion, and calcareous deposits formed on the surface of the composite.

Investigations for MRE conditions were initiated with carbon fiber vinyl ester (CF/VE) composites that were separately interconnected to three different types of alloys. For this study, a titanium alloy, a nickel alloy, and a sacrificial anode alloy were used. Electrical connections were then made by individually interconnecting the alloys to CF/VE coupons (Cu wire was attached to one edge of each coupon and the all edges were coated). The samples were then immersed in seawater either at room temperature or elevated temperature (100 °F). Fig. 5 shows the experimental setup, heater and samples, prior to interconnection.

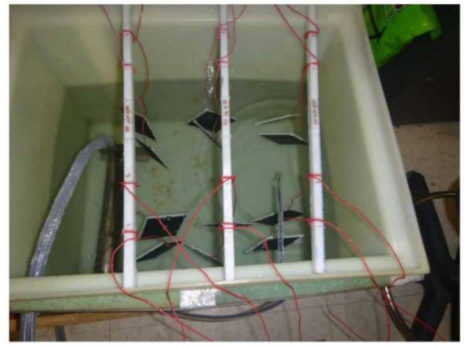

Fig. 5. Test setup for metal-carbon fiber composite interconnects at Florida Atlantic University.

After immersion till saturation, several monitoring measurements were conducted. This includes: (1) potential vs. time, (2) electrochemical impedance spectroscopy, (3) anodic and cathodic polarization and (4) visual inspection.

Examples of scanning electron microscopy (SEM) data from this study are shown in Fig. 6. The images present the top view and cross section of the calcareous deposits formed on one of the carbon fiber composites interconnected to a sacrificial anode. The presence of these deposits acted as a coating (once full coverage took place) that reduced the amount of oxygen reaching the carbon fibers, thus lowering the cathodic capacity of the carbon fibers. A second study on crevice corrosion, which is often observed with bolted joints is underway.

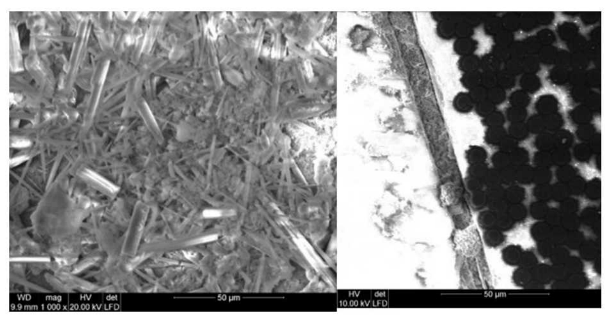

Fig. 6. Calcareous deposits observed on a CF/VE8084 sample interconnected to a sacrificial anode. (Left) top view of deposit, (Right) cross section.

H. Industry directed sub-scale elements & joined coupon fabrication/testing.

Understanding the load behavior and potential impacts of environmental effects on joined materials is also critical to future manufacturing. An early study for this program looked at the IC technical specifications and the Wave Energy Scotland Loads and Structures reports to

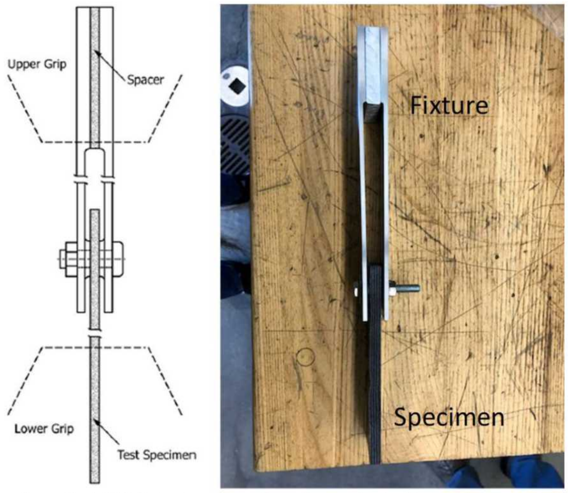

Fig. 7 ASTM test setup for through bolt testing on CE materials.

understand MRE needs [6,7,8]. Calculations following these technical strategies are being made at SNL with the understanding that the strength of the collective material being analyzed should always be greater than the design load. To investigate physical loads on joined materials being evaluated, samples are being prepared following ASTM [15] procedures (Fig. 7). Hybrid CE materials, Table I, were used to prepare the ASTM test samples. A comparison of the results between: (1) dry (unconditioned) composites, (2) artificial salt water conditioned composites joined with non-corroded through bolts, and (3) seawater conditioned composites joined with corroded through bolts will be made.

I. Industry directed full-scale subcomponent testing

The intent of subcomponent composite material research is to provide data and information necessary to establish design guidelines and best practices for the implementation of composite materials and structures used for MHK devices. Development and validation of composite subcomponents subjected to realistic operating environments and realistic loading conditions enable MHK designers to utilize composites cost effectively with reduced levels of risk. Building upon coupon and element characterization found in [3], subcomponent composite research will provide structural performance data critical to informing the design of durable and cost-optimized full-scale MHK systems. Data and information obtained through this research will inform designs with structural properties at near net-scale, including scale and environmental effects on composite structural performance.

Based on communication with the U.S. MHK industry and R&D from the wind industry, a series of agnostic subcomponents were selected (Fig 8.). The test articles are currently being fabricated at MSU and will be made from glass-epoxy and glass-vinyl ester. Both static fatigue and relaxation testing will be conducted at NREL's National Wind Technology Center.

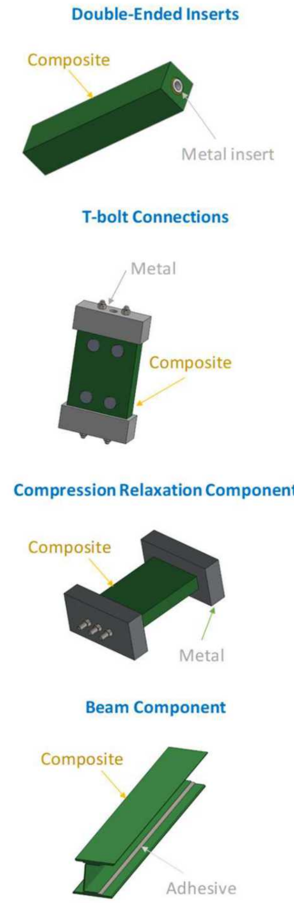

Fig. 8. Examples of agnostic substructure articles being developed. Static fatigue and relaxation testing will be conducted on both dry and seawater conditioned samples.

IV. CONCLUSION

- Salt water absorption into composites negatively impacts the material's properties (e.g., degradation of strength/mechanical properties, accelerated corrosion of alloy interconnected to carbon composite).
- Not all antifouling coatings are created equal. MHK devices operate under conditions not encountered by other marine industries.
- A subset of agnostic subcomponents is being tested under actual sea water and dry conditions to support industry design needs.
- Designers must consider corrosion issues even when working with composites. Metallic coupling between carbon fiber composites do experience corrosion (of the alloy) and calcareous deposits can form on the interconnected composites. Corrosion of any metallic interconnect should be inspected.
- Load characterization and measurement testing are being conducted to advance understanding of MHK condition effects on composite materials.

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