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Effects of coatings on water intrusion and strain gauge durability in submerged fatigue conditions

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Abstract

Marine energy structures are typically made using composite materials and are repeatedly loaded by currents and waves. Submersion and repeated loading lead to two environmental effects: moisture intrusion and mechanical fatigue. To understand their combined effects, submerged fatigue testing can be used. Submerged fatigue testing often requires submerged instrumentation to validate component manufacturing methods and models. Strain measurements are critical for understanding marine energy component loads. One common method for measuring strain is by using foil strain gauges, but the durability of strain gauges in submerged fatigue conditions is not well-understood. To increase strain gauge durability and protection from contamination, delamination, and water intrusion, strain gauge coatings may be applied over strain gauges and wire connections. In this study, strain gauges were adhered to composite coupons, coated, and mechanically tested in a water tank. Cycles to composite failure, cycles to strain gauge failure (SGF), strains, and SGF modes were used to measure the effects of strain gauge coatings on composite fatigue life and strain gauge durability. The coatings did not have significant effects on composite fatigue life or strain gauge durability. The methods developed and measurements taken at the coupon scale in this study will be used to inform methods and designs for subsequent submerged subcomponent testing, full-scale testing, and standards development. The benefits of designing marine energy structures to informed standards and designs are decreased lifetime costs and increased reliability and energy production, ultimately leading to a sustainable and low-carbon energy system.

Keywords: strain gauge durability; marine energy materials; strain gauge coatings; flexural testing; composite fatigue testing

1. Introduction

Marine energy structures are typically made using composite materials and are repeatedly loaded by currents and waves. Submersion and repeated loading lead to two environmental effects: moisture intrusion and mechanical fatigue. To understand their combined effects, submerged fatigue testing can be used. Lusty, Murdy, and Gionet-Gonzales [1] fatigue tested thermoplastic and vinyl ester composites in dry and fatigue conditions. The composites were strain gauged, but no strain results were reported. This paper reports the strain gauge durability for the submerged fatigue-tested thermoplastic and vinyl ester composites from [1], along with epoxy composites. Strain gauge durability was first evaluated by measuring the number of cycles to SGF. Then, strain gauge durability was compared to the strain values measured for different composite types. Finally, optical microscopy was used to observe strain gauge resistive grid failure. Prior to submerged fatigue testing, the strain gauges were coated with two different strain gauge coatings:

Micro-Measurements M-Coat A and M-Coat JA. M-Coat A is a polyurethane coating typically brushed over strain gauges for composite testing in dry conditions. M-Coat JA is a two-part polysulfide liquid polymer protective coating typically applied over strain gauges and wire connections in lieu of M-Coat A to prevent water intrusion into strain gauges in submerged conditions. M-Coat JA was used with strain gauges on the Verdant Power blades deployed in New York in [2], which motivated its use in this study. In [2], however, the strain gauges were adhered on the internal faces of the turbine blade where strains are lower and not directly exposed to water. Future submerged subcomponent and full-scale testing plans will likely include adhering strain gauges to the external composite faces where strains are higher and strain gauges are more susceptible to moisture intrusion. Strains will also be higher when testing distributed embedded energy converter technologies such as those described in [3]. It is possible that, in addition to protecting the strain gauges from water ingress, the coatings could affect the fatigue lives of composite materials by mitigating water intrusion where the coatings are applied. Coated strain gauges are commonly used in marine energy structural testing but may not be commonly used in final marine energy structure deployments, so understanding the effects of strain gauge coatings on composite material properties will be beneficial for the transition from laboratory testing to final deployment stages. The composite and strain gauge durability results from this study will be used to inform future marine energy structural instrumentation plans and standards development. Improved testing methods and standards will lead to the design of marine energy devices that can withstand repeated loading in underwater environments.

2. Experimentation

2.1. Materials selection

Three fiberglass composite panels were manufactured using vacuum-assisted resin transfer molding. Two layers of quadriaxial (0°, 45°, 90°, -45°) Vectorply E-QX 9000 fabric were used. The resin systems used were Derakane 411C-350 vinyl ester epoxy, Arkema Elium 188-O thermoplastic, and Hexion 035 epoxy, respectively termed vinyl ester, thermoplastic, and epoxy. The respective volume fractions for the vinyl ester, thermoplastic, and epoxy panels were 57%, 58%, and 58%. Panels were cut into 175 mm × 15 mm coupons. Micro-Measurements CEA-06-250UWA-350 strain gauges were adhered to the center of the top and bottom faces of coupons using M-Bond AE-10 epoxy adhesive. The top faces were those in contact with peel ply during manufacturing, while the bottom faces were those in contact with the glass table. During testing, the top faces were in compression and the bottom faces were in tension. The strain gauge coatings used were either M-Coat A polyurethane or M-Coat JA polysulfide (Fig. 1).

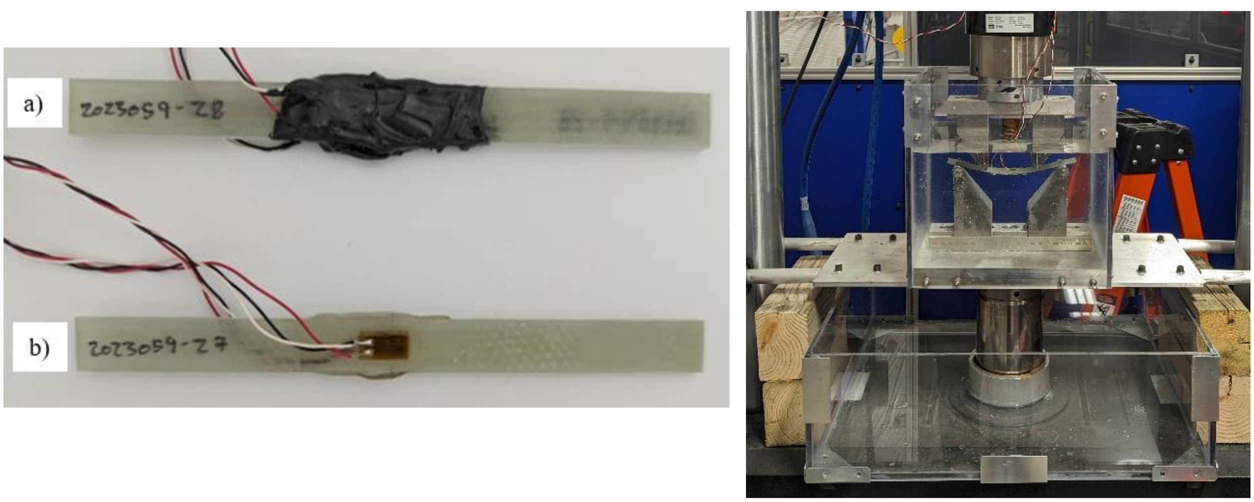

Fig. 1. Composite coupons with (a) polysulfide and (b) polyurethane strain gauge coatings (left) and submerged four-point bend load frame assembly (right).

2.2. Fatigue testing procedures

Lusty, Murdy, and Gionet-Gonzales [1] can be referenced for the fatigue testing procedures used for this study. Specimens were tested in the load frame setup in Fig. 1.

3. Results

The effects of strain gauge coatings on composite moisture intrusion and strain gauge durability were assessed for fatigue-tested, strain-gauged composites with polysulfide and polyurethane strain gauge coatings in submerged conditions.

3.1. Effects of strain gauge coatings on moisture intrusion into composites

Cycles to composite failure did not vary significantly between the two coating types (Table 1), indicating that the strain gauge coatings did not prevent moisture intrusion into the composites. Based on the top face sheet wear locations shown in Fig. 2, it is likely that most water intrusion into the composite occurred under the loading noses rather than in the gauge sections.

Table 1. Cycles to coupon failure for polyurethane and polysulfide coating types for submerged composites. Five coupons were tested for each combination of composite and coating types.

Composite Type	Polyurethane	Polysulfide
Vinyl Ester	4,545 ± 4,987	4,511 ± 2,536
Thermoplastic	47,823 ± 27,618	58,670 ± 24,140
Epoxy	12,602 ± 7,212	12,584 ± 2,666

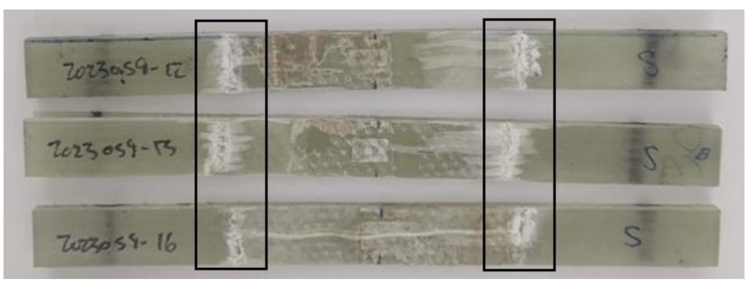

Fig. 2. Epoxy specimens with rectangles indicating top sheet crush locations from loading noses.

3.2. Effects of strain gauge coatings on strain gauge durability

Cycles to SGF were compared for the two coatings and three composite types. Strain gauges failed prior to composite failure for each test. SGF was calculated in two steps. First, the ratio *R* of peak-valley strain and peak-valley displacement was calculated. Then, the slopes of *R* between each cycle were calculated and plotted. Strain gauges were considered failed when the plot of the slopes of *R* spiked (Fig. 3). Strain values past SGF were considered inaccurate.

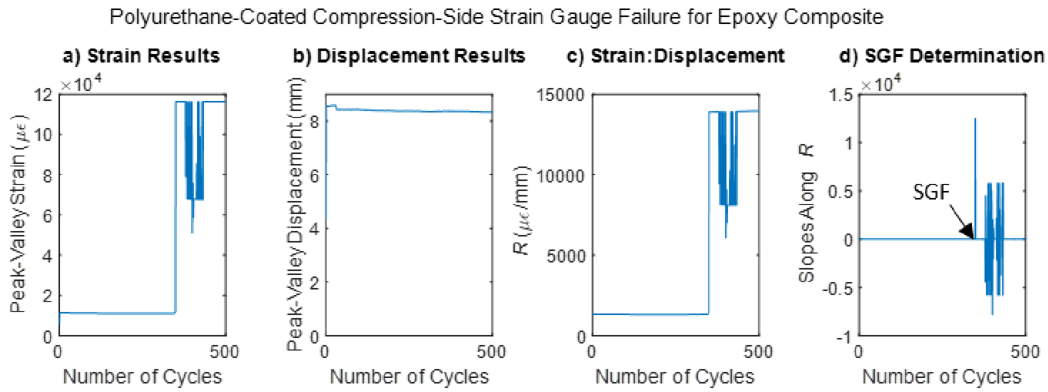

Fig. 3. Plots of a) peak-valley strain, b) peak-valley displacement, c) *R*, and d) the slopes along *R*. The number of cycles to SGF was 346 and was determined by the initial spike in plot d). SGF occurred at a peak-valley strain of 1.5×10^4 με and a peak-valley displacement of 8.34 mm.

Values for cycles to SGF were combined for the top and bottom gauges to examine the overall effects of coatings on strain gauge durability (Table 2). Some strain gauges failed within the first loading cycle and were omitted from the averaged results.

Table 2. Cycles to SGF for submerged composites with top and bottom gauges summed together. The number of gauges that were included in each average are in parentheses.

Composite Type	Polyurethane	Polysulfide
Vinyl ester	1,012 ± 716 (8)	525 ± 568 (8)
Thermoplastic	1,092 ± 722 (9)	1,237 ± 831 (9)
Epoxy	294 ± 177 (9)	368 ± 665 (8)

T-tests with α = 0.05 were performed to determine if differences between averages were significant. None of the cycles to SGF averages were significantly different between the coating types, which suggests that the polysulfide coating did not prevent more water intrusion into the strain gauges than the polyurethane coating.

There was a significant difference in the cycles to SGF results between thermoplastic and epoxy composite types, indicating that strain gauge durability was more affected by the composite type than the coating used. The variation in strain gauge durability among composite types could be explained by the differences in resulting strain values among composite types (Fig. 4), as the epoxy had both the lowest strain gauge durability and the highest strains. SGF likely occurred when the metal in the strain gauges cracked (Fig. 5).

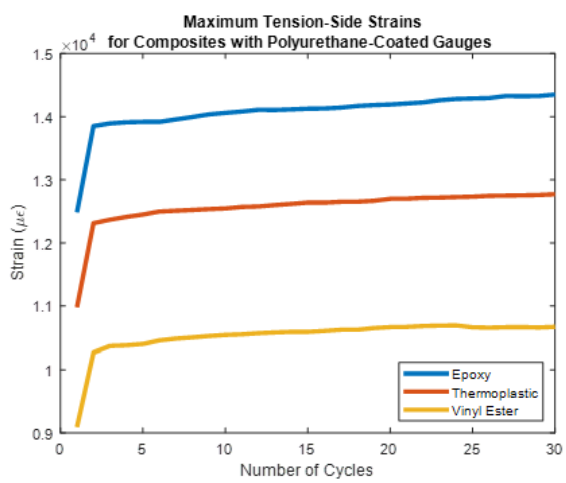

Fig. 4. Maximum strain values for each submerged composite type for the first 30 cycles.

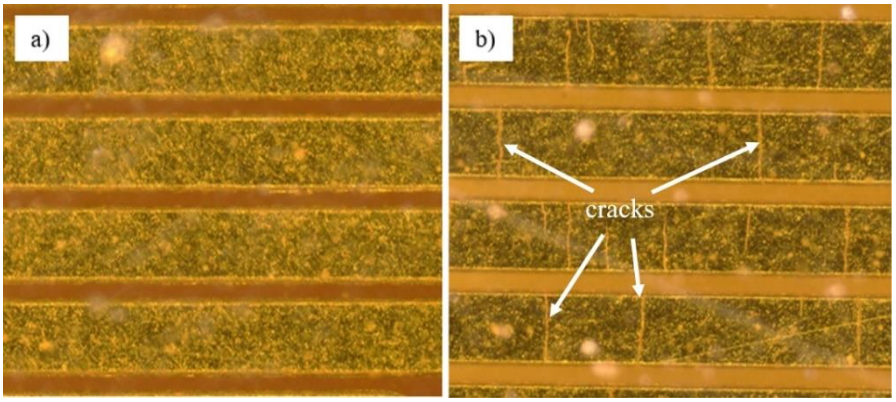

Fig. 5. Optical microscopy images (300 × magnification) of polyurethane-coated strain gauge Constantan foil resistive grid (a) before and (b) after submerged fatigue testing. The white arrows in (b) point to some of the cracked Constantan locations.

Cycles to SGF averages for all submerged composites were 817 ± 677 for gauges coated with polyurethane and 703 ± 777 for gauges coated in polysulfide, which indicates that the polysulfide coating did not extend the overall life of the strain gauges. Hand sanding is used during composite surface preparation prior to strain gauge adhesion, which can cause variability in surface adhesion properties. The variability from hand sanding could explain the failure of some of the strain gauges prior to testing.

4. Conclusions, recommendations, and future work

Thirty composite coupons with 60 strain gauges were fatigue tested in submerged conditions to measure the effectiveness of two different coating types on strain gauge durability. The coatings did not have an apparent effect on the number of cycles to failure of the composite materials, likely because most of the water intrusion occurred where the loading noses were in contact with the composites. Future work could examine loading nose wear mitigation by incorporating support and load tabs into fatigue testing methods such as those used in [4]. In addition to incorporating loading nose wear mitigation methods, testing composites that are fully surrounded by coatings would provide a better understanding of the different levels of moisture intrusion mitigation by different coating types on composite structures. The strain gauges did not last for the duration of testing, which was expected because the coupons were tested at strain levels that were 8 times higher than the strain gauge manufacturer's recommendations for fatigue testing [5]. Future testing at strain levels past manufacturer recommendations should include comparisons to displacements like those done in this study to understand strain measurement accuracy and cycles to SGF. Strain gauges lasted longer for composites that had lower strains, which indicates that strain gauge durability was more dependent on strain values than the coating types used in this study. Similar values of cycles to SGF between coating types further supports that strain levels have a more pronounced effect on strain gauge durability than the coating type used. Additional submerged studies at lower strain levels could provide a better understanding of which coating type is more effective in mitigating moisture intrusion into strain gauges. Strain gauge durability results from this study will be used for future submerged fatigue subcomponent and full-scale instrumentation methods. Submerged fatigue tests with adequate instrumentation methods will lead to effective validations of marine energy structural components, which will ultimately help marine energy become a more viable form of renewable energy production.

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