Self-Sensing Health of Carbon Composite Pultrusion Strength Members

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ABSTRACT

In applications such as race boat rigging, offshore umbilicals and energy kite tethers which require light weight and high stiffness strength members, there is no better material choice than carbon composite pultrusion. However, designing an optimized termination profile for fatigue driven applications is time consuming and generating stress versus cycle to failure (S-N) curves is expensive. Fortunately, owing to electrical properties inherent in carbon pultrusions, self-sensing techniques can be correlated to microscopic damage to provide useful new metrics on which to base design specifications. This paper presents a new technique for self-sensing health via 4-wire method of carbon composite pultrusion materials in gauge and termination region of a full-scale system. This self-sensing method sheds light into system stress state and permits measurement of damage from crack propagation due to fatigue using robust and widely available tools. These self-sensing signals have clear potential utility for speeding design tasks, defining lifetime ratings and providing real-time system diagnostics of high performance strength members.

INTRODUCTION

Composite uniaxial carbon fiber rods fabricated by the pultrusions process have advantages against steel wire and braided polymer (Dyneema®, Vectran®) in applications where stiffness and low weight are of utmost importance [1-3]. However, demonstrating long term reliability of carbon pultrusion strength members in applications where fatigue loads may exceed 1e7 tension-tension cycles within five years remains a challenge [4]. While carbon composites have great fatigue characteristics in semi-static or otherwise ideal circumstances [3], bodies of literature point to difficulties in designing a pultrusion termination which can sustain high magnitude fatigue loads [2]. Furthermore, the termination of strength

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members tend to be the most vulnerable point of the assembly. Chung et. al. has described techniques for self-sensing in composite material coupons which can give insight into damage and stress/strain state. These techniques are taken a step further and adapted to real world hardware representative of a functional offshore umbilical or energy kite tether.

In this study, a carbon pultrusion rod is terminated and loaded in tension fatigue up to 220kN peak for over 7.3e4 fatigue cycles while collecting self-sensing measurements in several directions. The results show that 4-wire signals exhibit distinct load rate dependent viscoelastic behavior and increases over 300% possibly due to fretting and longitudinal crack propagation.

Pultrusion

The carbon fiber reinforced rods under study are fabricated by continuous pultrusion process. This process consists of tows of high performance carbon fiber guided through a saturating bath of thermoset epoxy, and into a heated die for cure. A pulling mechanism and coiler allows cured rod to be manufactured in lengths up to thousands of meters. Cross section of typical pultrusion product is shown in Figure 1.

Termination stress state

Stress state in the termination is described in literature and modeled using finite element techniques. Bradon and Kerstens et. al. have shown that resin socket terminations generally transfer wedging compression loads through friction forces, and that the termination nose point sees a high radial compression, shear and tensile forces with a correspondingly higher degree of crushing and compression damage [5-6]. Peak compression forces at the termination nose are represented as a stress riser in the Figure 1 schematic. In some circumstances, premature failure is shown to be caused by bending due to high compressive forces at the nose of a typical conical termination socket [6]. Gamstedt et. al. described damage to individual strands in a uniaxial composite in tensile fatigue as being characterized by matrix cracks and debonding, followed by fiber breaking and further propagation of broken fibers adjacent to the damage site [7].

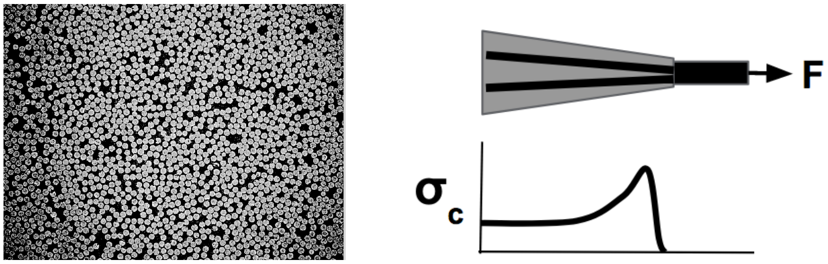

Figure 1. Cross section of pristine carbon pultrusion (left). Typical compression force distribution in a conical termination (right).

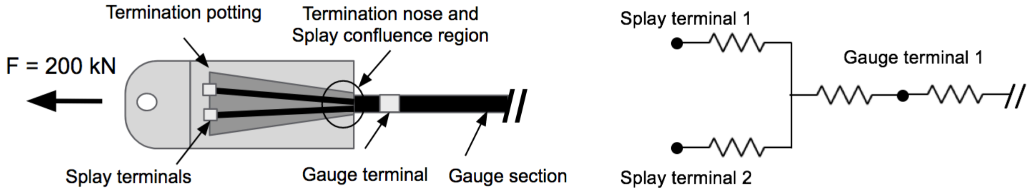

Figure 2. Schematic of strength member (left) and simplified circuit depiction (right). Three 4-wire circuits exist: gauge terminal to opposing gauge terminal (not shown), splay terminal to gauge terminal, splay terminal to adjacent splay terminal.

METHODS

Single rod testing

The unit under test is made of a short length of 12mm diameter pultrusion approximately 1.5 meter in length with the termination length splayed into quadrants. Each splayed end is aligned inside of a split-mold termination made of two halves of a machined aluminum block. Each half of the split mold termination is pinned together using preloaded bolts. The splayed core is potted in the termination with a thermoset epoxy selected for high compressive strength. Following epoxy cure, 4-wire probes are installed and the section is ready for use. Figure 2 shows the termination schematic overview and name of all measurement circuits discussed in this work.

Each terminated end of the pultrusion is contained via clevis attachment in a custom steel load frame where tensile forces are applied. Pressure is developed by fixed displacement pump and controlled with proportional relief valves. A hydraulic cylinder delivers displacement. All control and data acquisition is administered via National Instruments hardware with LabVIEW virtual instrument and universal analog input module for resistance measurements. The frame and hydraulic power is rated to deliver tensile forces up to 500kN (56 ton) with programmable load profiles approximating sine wave. Test temperature was held at 25°C with uncontrolled ambient humidity. For the majority of fatigue testing, load frequency was around 30 seconds per cycle with load ratio near zero.

Self Sensing

Carbon pultrusion materials are self-sensing by their electrically conductive nature such that no other transducers such as optical or ultrasonic are required to gain insight into the strain or damage state. Chung et al. and others have demonstrated the 4-wire method of measuring electrical resistance as a viable means of estimating tensile, compressive and flexural strain in plate, rod and dogbone geometries, as well as damage in woven and uniaxial members [8-10]. Carbon composite members are also a viable material for strain transducers in microelectronic applications [11]. Self-sensing stress/strain should be distinguished from self-sensing damage. The former is typically a result of reversible Poisson effect or piezoresistive effects, whereas damage detection is the result of broken carbon elements [8]. Piezoresistivity is the underlying mechanism behind high gauge factor carbon fiber cements and likely plays a role in resistance value during tensile and compression stress states of uniaxial pultrusions [12, 13].

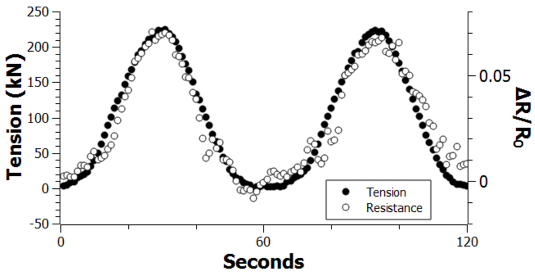

Figure 3. Pultrusion gauge terminal to opposite gauge terminal during fatigue cycles.

In any self-sensing measurement, the direction of continuity is an important consideration. Longitudinal resistance of bulk rod depends on carbon cross sectional area thus is sensitive to Poisson contraction from tension, piezoresistive effects or damage which reduces cross sectional area, such as from fretting or crushing from high compression forces [5]. Transverse resistance depends on electrical conduction through adjacent filament contact and interstitial gaps, commonly referred to as percolation, thus is sensitive to longitudinal cracks and the compression state of the uniaxial rod. The 4-wire self-sensing probes are attached via silver epoxy, a robust method common in existing studies [8]. Splay terminal consists of silver epoxy capped splay end, while gauge terminal consists of a circular ring painted on the outside of the rod. Since termination splay to splay and splay to gauge measurements both rely on longitudinal (such as through straight rod sections) and transverse conduction (such as across the splay confluence region), these circuits are a good indicator of overall health and will be sensitive to carbon fiber damage running in any preferred direction.

RESULTS AND DISCUSSION

Gauge Section

Longitudinal resistance is measured via gauge to opposite gauge circuit, as described in Figure 3. The resistance response of this circuit matches tension in phase and shape, with resistance change partially explained by cross sectional geometry change due to Poisson effect and changes in volume resistivity. Gauge factor is estimated to be 6. Considering the instantaneous response of the gauge to gauge circuit and signal magnitude, this circuit offers a potential route of system diagnostics like load sensing.

Quasi-step stress

Health of the carbon within the termination is of particular interest and can be estimated via splay to splay and splay to gauge circuit. Contributions to circuit resistance can be separated into instantaneous effects on geometry or resistivity, or effects which exhibit temporal mismatch of stress-strain state, also called also called viscoelastic effects. Relaxation in polymers is an example of viscoelastic

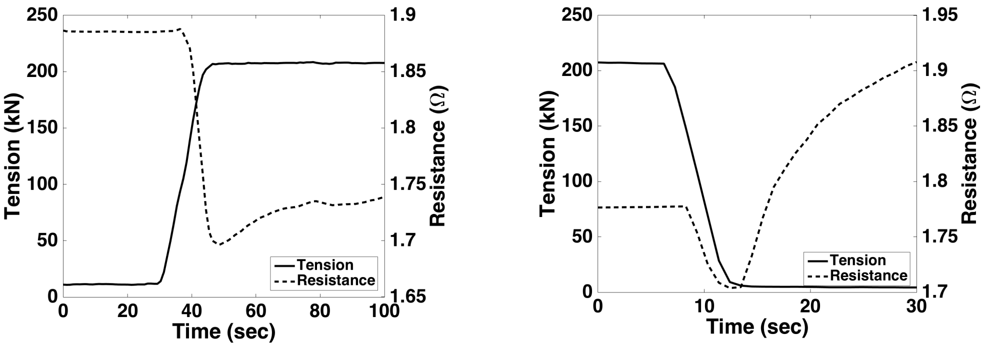

Figure 4. Time-resistance response in splay-splay circuit to a quasi-step function in tension from zero to full tension (left) and from full tension to zero tension (right).

behavior. Quasi-step stress is a useful way to see the contributors of each effect on termination circuits, shown in Figure 4.

In tensile loading, the resistance shows a small bump upwards due to Poisson effects near second 30 to 35, however, the magnitude of this bump is shadowed by termination compression wedging forces that reduce transverse resistance, lowering bulk resistance to a local minimum at 45 seconds. Resistance drop at time 35 to 45 sec is due to compression in the termination reducing carbon filament interstices and increasing microscopic contact areas within the transverse conduction dominated splay confluence region. From time 45 to 60, resistance increases could be explained by viscoelastic relaxation relieving compression stress.

When tension is released rapidly as in Figure 4 (right), both instantaneous effects and time delayed effects are shown clearly. Resistance shows a drop immediately after tension is released, due to fibers rapidly regaining their original diameter and lowering bulk resistance. The drop is consistent in magnitude to gauge-gauge circuit resistance in Figure 4. There is an increasing trend in resistance after second 13, as compression within the termination is removed and the carbon rod relaxes back into a state of lower compression with higher transverse resistance.

Future measurement of quasi-step stress should be improved in a few ways: matching tension load to unload speed would likely make the Poisson increase effect more prevalent upon load ramp, and precise data of termination nose and gauge displacement would shed light on relaxation.

Termination sinusoid stress

Sinusoid stress profiles are a common load case in strength member applications. The force versus resistance response is seen in Figure 5 and exhibits a unique “double hump” shape, of which the magnitude and phase relative to the stressing function is exhibits load rate dependency. The general tendency is for resistance response to be greater in magnitude when loaded quicker, which may suggest greater stress to the carbon rod. The resistance measurements may be useful in accelerating high cycle fatigue testing by informing acceleration factors or cumulative damage models. More work must be done to validate this approach.

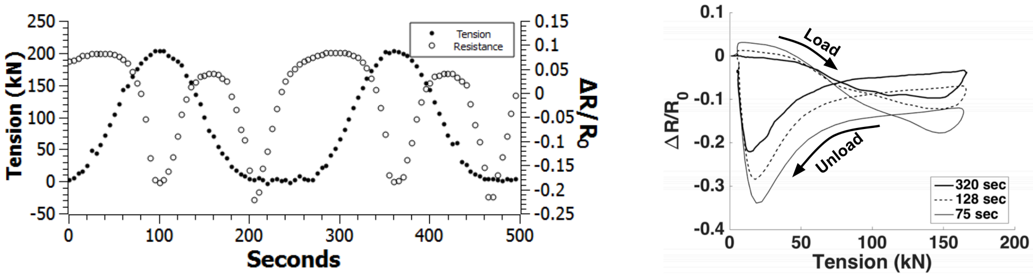

Figure 5. Time-resistance measurement of splay to adjacent splay (left), and resistance-tension plot of the same circuit under different load frequencies (right).

Damage Detection

SETTLING

The strength member under test exhibits unique settling behavior as measured across all circuits within the termination. Shown in Figure 6, settling is characterized by large magnitude initial resistance followed by a steep drop to a local minimum around 250 cycles. The mean strain of the first 250 cycles increases 6%, while mean strain of the subsequent 2000 cycles grows less than 1%. The settling behavior likely explained by localized yielding inside the termination structure, pressure relief as a result of fabrication imperfections and compression damage to the carbon core.

LIFETIME DAMAGE

Cumulative increase in resistance is measured over the course of longer fatigue testing up to 7.3e4 cycles, shown in Figure 6, with splay-splay resistance growing over 300%. Resistance shows periodic jumps up and down, possibly indicating sudden crack propagation or sudden fiber crushing. Peak load remained constant at 150kN until 5e4 cycles where it was stepped up gradually reaching peak of 220kN at the conclusion of the test.

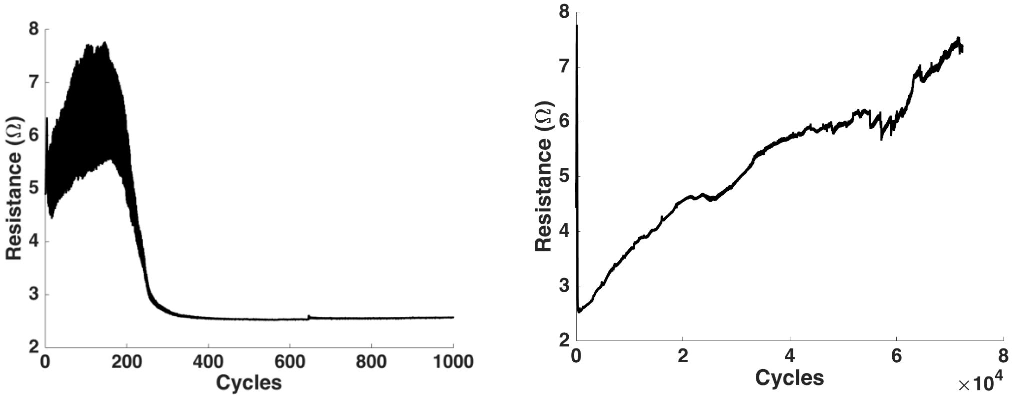

Figure 6. Settling behavior of splays-splay circuit inside the termination (left). Longer fatigue life data for splay to splay resistance up to 7.3e4 cycles (right).

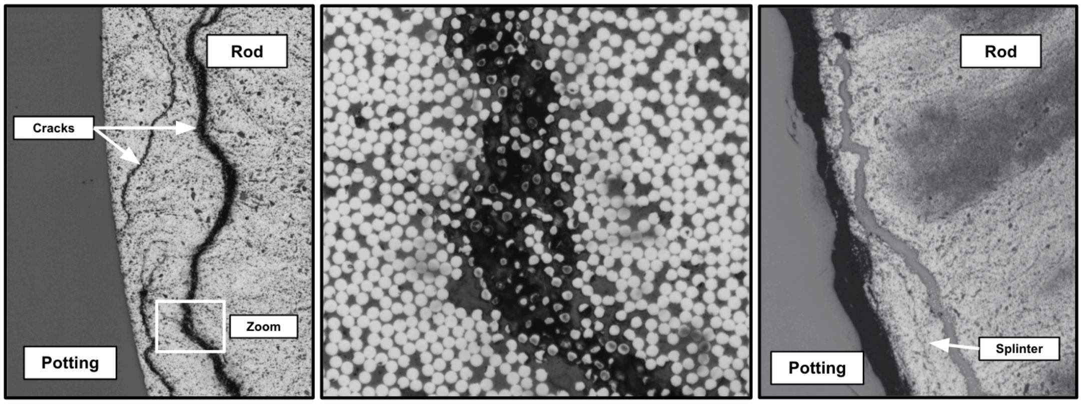

Figure 8. Cross section of the rod further from the nose of the termination showing deep cracks with rod to potting interface in good condition (left). High magnification of the crack shows broken and crushed fibers (center). Closer to the nose of the termination, the pristine circular rod to potting interface is replaced with cracked potting, crushed CFRP and longitudinal splinters (right).

This specimen was not fatigued until failure, allowing collection of high quality cross section images. Cross sections shown in Figure 8 show the condition of two places within the termination. Most interesting to note is the propagation of longitudinal cracks measuring up to 100 micrometers wide. High magnification images show that these cracks are filled with carbon fibers which have been broken or crushed into non-circular shapes. In parts of the termination 80mm closer to the nose, the clean circular pultrusion to potting interface is fretted away eliminating up to 1mm of the outer diameter. While it is not known if these cracks run continuously, it is reasonable to assume that the cracking is distributed over a long region within the termination from before splay confluence to the termination nose, with damage reaching a maximum around the expected point of maximum compression within the termination. The end result of these cracks is an increase to the continuity path length and decrease in cross section area, resulting in an increase in resistance. Thus, bulk resistance from splay and gauge terminals is a useful means of detecting damage to the structural carbon. Ultimate failure of the strength member in fatigue is expected to be characterized as exponential growth in resistance. Ultimate failure stage is not captured in this study.

CONCLUSION

A technique of self-sensing health within gauge and termination locations of a carbon fiber pultrusion strength member is presented using the 4-wire method. By relying on electrical properties inherent in carbon pultrusions, circuits are identified such that electrical continuity depends both on longitudinal and transverse conduction within the rod, thereby affording sensitivity to damage running in any preferred direction. The electrical signal provides avenues towards novel system diagnostic tools and insights to the termination stress state. Most importantly, damage to the carbon core is likely correlated to irreversible increase in strength member electrical resistance within the termination.

In one long term fatigue specimen, circuit resistance grows over 300% over the course of 7.4e4 fatigue cycles. After careful dissection of the specimen, the resistance growth may be attributed to deep cracks running in the longitudinal direction along with damage from crushing and fretting. This damage is located in the termination region where maximum compression forces are expected.

This method offers advantages over common methods of damage detection such as imbedded fiber optics or acoustic emission, since the 4-wire method is self-sensing and support equipment is robust and widely available. The 4-wire technique also offers avenues towards strain sensing in the gauge and termination, which is not possible with acoustic emission techniques. With further investigation, this method could show promise in understanding the fatigue life and design parameters of a new generation of carbon composite strength members useful in undersea umbilicals and light weight high stiffness strength members.

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