Structural Health Monitoring of CFRP Structures Using Electromechanical Behavior

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ABSTRACT

Whereas the number and the fields of carbon fiber reinforced plastics (CFRPs) are vastly increasing, studies about in-situ real-times self-sensing are limited. Thus, our research group investigated the CFRP self-sensing capability using the electromechanical behaviors of CFRPs. Both elastic region and failure of CFRPs can be monitored by electrical resistance change ratio. Therefore, structural health monitoring (SHM) and prognostic health management (PHM) are feasible for both elastic deformation and delamination.

1. INTRODUCTION

Carbon fiber reinforced plastic (CFRP) has enormous advantages in both physical and electrical properties. CFRP has ~12 times higher strength-to-weight ratio than that of stainless steel. Electrical conductivity of carbon fiber is $\sim 5.9\times10^6\ \mathrm{S/m}$ so that CFRP can be conductive.

As various fields consider energy efficiency as well as structural strength, CFRPs are widely adopted for large structures such as aerospace, vehicle, vessel, and civil infrastructure. To avoid enormous sensing elements and invasive data handling, Kumagai *et al.* investigated self-sensing capability of CFRP structures monitoring electrical resistance changes. Gallao and Thostenson characterized the electrical properties of CFRPs and CNTs, as well as FEM analysis to detect cracks in micro-scale. Roh *et al.* reviewed the self-sensing capabilities of carbon-based structures.

Elkjaer *et al.* developed piezopaint in arrays for large-scale-SHM. Baskar *et al.* compared the sensing performance of strain gauges and fiber Bragg grating (FBG) sensors, and suggested integration of the FBG sensors into large-scale-SHM. However, they lack the strategies for large-scale coverage as well as data handling. Thus, this paper presents the PHM system of CFRPs using electrical resistance. This study is not limited to specific potential application, but to every fields.

2. EXPERIMENTAL

2.1. Materials

Thermoset matrix (RF-1001MV, Epovia) was supplied from JetKorea, Korea. DBLT, quad-axially non-woven 850-E uni-directional glass fiber, was supplied from JetKorea, Korea. Plain-woven 3k-carbon fiber and that of glass fiber was provided from JMC, Korea.

2.2. Specimen manufacturing

Between DBLTs on the top and the bottom of a composite, 6 plies of carbon fiber were located at the center. The size of the composite was 200 mm by 100 mm, and A PTFE (Polytetrafluoroethylene, Teflon) film was inserted in the mid-plane of a composite as an initial crack as Fig.1 describes. Electrodes were located near the PTFE film at the top and the bottom surfaces of carbon fiber plies, and silver paste was applied at the conjunction of the electrodes and carbon fiber to minimize contact resistance.

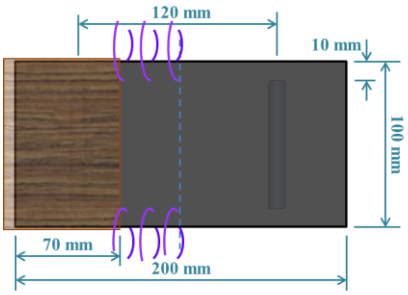

Figure 1. PTFE film at the mid-plane and 12 electrodes.

Specimens were manufactured by vacuum-assisted resin transfer molding (VARTM). The final sample geometry and electrode numberings are demonstrated in Fig. 2. (CF indicates carbon fiber)

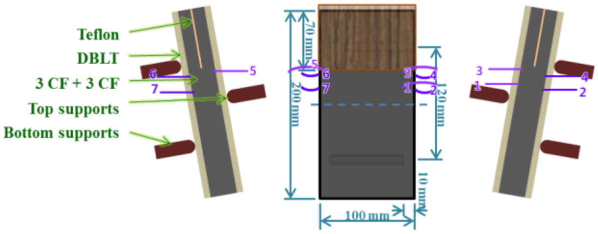

Figure 2. Sample geometry and electrode numbers.

2.3. Loading condition

Universal testing machine (INSTRON 5982, USA) was utilized for 3-point bending tests at the loading rate of 2 mm/min with 0.5 N preload. The support span was 120 mm as shown in Fig. 1, and the specimen under bending is represented in Fig. 2. A multimeter and a switching system (Keithley 2002 and 7001, USA) were used to investigate electromechanical behavior under the bending.

3. RESULTS AND DISCUSSION

Mechanical property of the specimen was plotted with grey lines in Fig. 3, and Fig. 4 magnified the initial part (From 0 to 0.02 strain). Electrical resistance showed linear behavior under elastic region, whereas abrupt change was captured at the fracture near 0.012 strain.

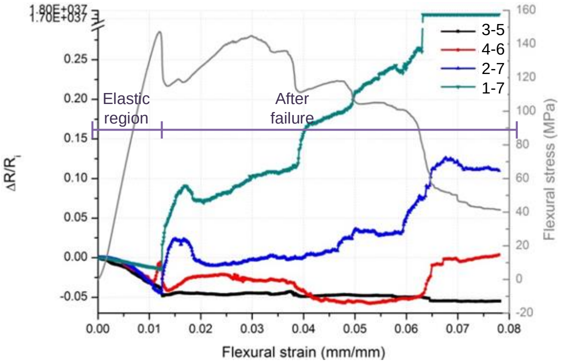

Figure 3. Electromechanical behavior of the CFRP under the 3-point bending test.

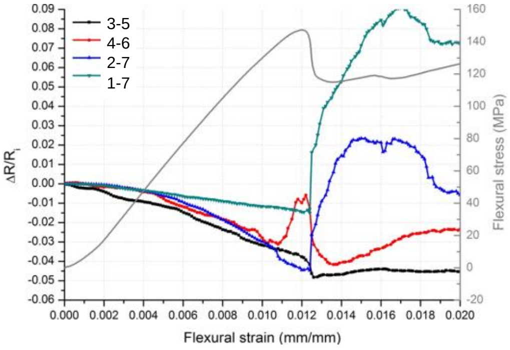

Figure 4. Magnified view Figure 3.

3.1. Elastic region

Under elastic region, negative electrical resistance was monitored as the flexural strain and the stress increased. The more the plate was bent, the more shear strain might be applied to carbon fiber parts so that electrical resistance change was represented. The extent of the bending can be speculated from the proportional correlation between the electrical resistance and the flexural strain.

3.2. After failure

Near the composite failure, electrical resistance showed deviation from the correlation. Eccentric slopes of the electrical resistance can be indicators of the structural failure.

After the stress drop at the failure, all the electrical resistance channels showed abrupt pop-up except the channel 3-5. Beyond the flexural strength of the composite, delamination was initiated at the mid-plane from the PTFE film.

The abrupt electrical resistance pop-up was caused from the electrical path interference by the delamination. Even though the delamination does not cut the shortest electrical path, it can affect the electrical conductivity of the composite. For example, channel 4-6 does not across the mid-plane, but the change was observed as shown in Fig. 4, because non-zero electrical current density part near channel 3-5 were separated by the delamination. At this point, we could catch out that delamination detection is available even when an electrical path does not across the mechanical failure.

4. CONCLUSIONS

Investigating electromechanical behavior of the CFRP, authors can conclude that in-situ real-time SHM and PHM of CFRP is enabled by monitoring electrical resistance change.

Under elastic region, electrical resistances were linearly decreased following the increasing flexural strain as well as flexural stress regardless of the electrode placement. At the end of elastic region, around 0.011 strain, the slopes of electrical resistance change ratio were changed.

With the flexural stress drop at the failure, around 0.012 strain, electrical resistance was increased abruptly. The abrupt change was due to the electrical path change, which is equal to the carbon fiber contour change.

From this study, our group concluded that electrical resistance change observation enables the SHM and PHM of CFRP only with electrodes, but not external devices such as strain gauge or fiber Bragg grating optical fiber. Therefore, the system for in-situ real-time SHM and PHM of CFRPs was achieved by electrical resistance change monitoring, and this system can serve as the basis for effective large-scale SHM and PHM system in various fields.

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BIOGRAPHIES

Hyung Doh Roh is a graduate student in UNIST, Ulsan, Republic of Korea. Research field is the electromechanical behavior of carbon fiber investigating piezoresistivity, and electrically equivalent circuit modeling of CFRPs. He had been a visiting researcher at Georgia Tech in 2012 summer, and was an undergraduate researcher in UNIST. He received B.S. at UNIST in 2014, and now he is in the 4th year of M.S.-Ph.D. combined program.

Young-Bin Park is an Associate Professor of Mechanical Engineering at UNIST. His research interests are in the field of advanced composites and nanocomposites for smart, functional applications. In particular, his research focus is on the application of high-performance carbon-based materials, especially graphene, carbon nanotubes and carbon fibers, to multifunctional composites and structures. More recently, he has expanded his scope of research into novel technologies for rapid, affordable manufacturing of fiber-reinforced composites, particularly targeted for automotive industry. Professor Park received his B.S. and M.S. from Seoul National University in 1995 and 1997, respectively, and Ph.D. from Georgia Tech in 2003.