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Damage detection of carbon fiber reinforced polymer composites via electrical resistance measurement

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ABSTRACT

Carbon fiber reinforced polymer–matrix composites (CFRPs) are widely applicable in various important structural components. One of the critical issues in the successful application of CFRPs is the assessment of damage state in a particular structural component. Electrical resistance measurement is a merging non-destructive evaluation technology for real-time/on-board damage detection in CFRPs. This paper overviews the recent advances in damage detection in CFRPs using the resistance measurement. Besides the discussions on various experimental methods for self-sensing and damage detection, modeling from microscale to continuum levels for the predictions of resistances change due to the mechanical damages are also presented. Future directions in damage detection of CFRPs using the resistance method are provided.

1. Introduction

Carbon fiber reinforced polymer composites (CFRPs) are manufactured by mixing carbon fibers and plastic resin under prescribed conditions. These materials are distinguished by their high strength and rigidity, low density, excellent damping properties and high resistances to impacting and corrosion combining with modifiable thermal expansion to complement complex characteristics profile. Because of their excellent mechanical properties, CFRP materials have been widely used for critical components and structures, such as aircraft fuselage and wing structures, helicopter rotors and windmill blades, road and marine vehicle body structures, and, bridges and large civil infrastructures. CFRPs can significantly reduce weight while increase strength and durability which can result in large improvement in efficiency of the vehicles and/or structural facilities. For example, the application of composites in the new Boeing 787 has reached 60% of the total components used, which results in a 20% increase in fuel efficiency.

One of the critical issues in the successful application of CFRPs is on-board or in-situ assessment of the damage state and accurate prediction of the remaining service life of the CFRP components. The damage identification and remaining life prediction of CFRP components exposed to complex loading states play a key role in the service function and safety of the systems. Under complex environments and loading states, damage in the form of penetration, delamination and/or transverse cracking may occur in these materials during service. In-situ on-line health monitoring can enable prediction of remaining life, and, in turn can provide life extension control or damage mitigation which results in improved safety and reliability of structural components, and the prevention of catastrophic failures. Presently, there are various non-destructive evaluation (NDE) methods that could be used for the assessment of the damage state. Most conventional NDE techniques such as ultrasonic C-scan [1], X-ray [2], thermography [3] and eddy current [4] are not on-line based techniques and usually require the targeted component to be taken out of service for a prolonged length of time for post-damage inspection and assessment. Other techniques, such as piezoelectric sensor [5], optical fiber [6], can be used for on-line health monitoring of CFRP structures, but they all involve the attachment of external sensors or additional fiber input in CFRPs.

CFRPs are multifunctional materials in which the damage is coupled with the material electrical resistance, providing the possibility of real-time information about the damage state through monitoring of resistance. The uniqueness of this resistivity technique lies in its capability of in-situ self-sensing of damage criticality of composite materials without any additional sensors to be embedded within composites. Currently, much experimental work has been conducted relying on the electrical conductive characteristics of carbon fibers for damage detection in CFRPs. By comparison with classical non-destructive evaluation techniques such as acoustic emission, it has been shown that resistance measurement allows for the monitoring of the in-situ evolution of various internal damage nucleation and growth phenomena such as fiber fractures, interply matrix cracks and interply delamination [7,8]. Changes in electrical resistance of carbon fiber composite damages have been established by a number of experimental studies in the

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last decade [5,9]. However, until recently, numerical work on the modeling of mechanical damage in CFRPs via electrical resistance has been carried out at the micro and macroscale levels. Very little work has been conducted on multiscale modeling efforts at various scales to predict the electrical response for damage assessment under various loading conditions.

This literature review covers recent advances in damage detection of CFRP materials by the electrical resistance method. Section 2 of this paper will briefly present the fundamental structural properties and the damage and failure mechanisms in CFRPs. Section 3 will review the experimental methods of damage detection, particularly, the electric resistance measurement techniques, and their application to the detection of damages under various loading conditions. The modeling work, including micromechanical models, finite element models, and coupled electro-mechanical models are discussed in Section 4. Section 5 will present the existing and future directions for the application of the electrical resistance methods.

2. Brief overviews of structure and properties of CFRPs

2.1. CFRP structures

The simplest structure of CFRPs is unidirectional composites in which all fibers run in the same direction parallel to each other in polymer matrix, as shown in Fig. 1a. The most common form of CFRPs is the cross-ply laminate, such as laying up a sequence of unidirectional plies. Usually the cross-ply laminates, as shown in Fig. 1b, suffer from the complex damage processes involving debonding of the fiber–matrix, transverse cracks, delamination and fiber failure. In other structural models, such as woven CFRPs shown in Fig. 1c, the fibers are braided around each other. This special structure improves the damage tolerance of the composites. In addition, the three-dimensional orthogonal woven CFRPs, as shown in Fig. 1d, has also been developed, in which fibers are placed in three orthogonal directions with each other. Due to the cross-over pattern, this multi-directional structure endows the CFRPs a better delamination resistance.

Besides the reinforcement, carbon fiber, CFRPs consist of epoxy matrices, which fix the pattern of CFRPs. Although epoxy matrix is not as strong as the carbon fiber, it helps transfer loads within the composites.

2.2. Mechanical properties

CFRPs are widely used in many areas because of their excellent mechanical properties. This material has very high elastic modulus and high tensile strength of approximately 7 GPa. Low density and low thermal expansion are also the reasons of its popular use. In addition, CFRPs have high chemical inertness and can serve under the corrosive environment. Although failure under fatigue loading can sometimes be observed, CFRPs have better fatigue behavior than metals. The CFRPs endurance limit reaches about 60–80% of the fracture stress, but the metals endurance limit only reaches about 30% of the fracture stress [9]. However, the CFRPs are relatively brittle comparing with metallic materials. During fatigue, delamination may occur in CFRPs. A study, discussing the influence of moisture on CFRPs, was carried out [10]. The mechanical properties of CFRPs become worse due to moisture.

2.3. Electromechanical properties

CFRPs are electrically conductive because of the high conductivity of carbon fibers. Although the epoxy matrix has high electrical resistivity, which can be taken as an insulator, the fiber–fiber contact in the matrix forms an electrical network, which makes the CFRPs conductive in transverse and through-thickness directions. The electrical resistance in CFRPs relays on the volume fraction, the loading and the size of carbon fibers and the laminate sequence. The resistance change is linearly proportional to strain due to the conductive fibers. However, fiber fracture in CFRPs results in sudden increasing of resistance because of breakage of

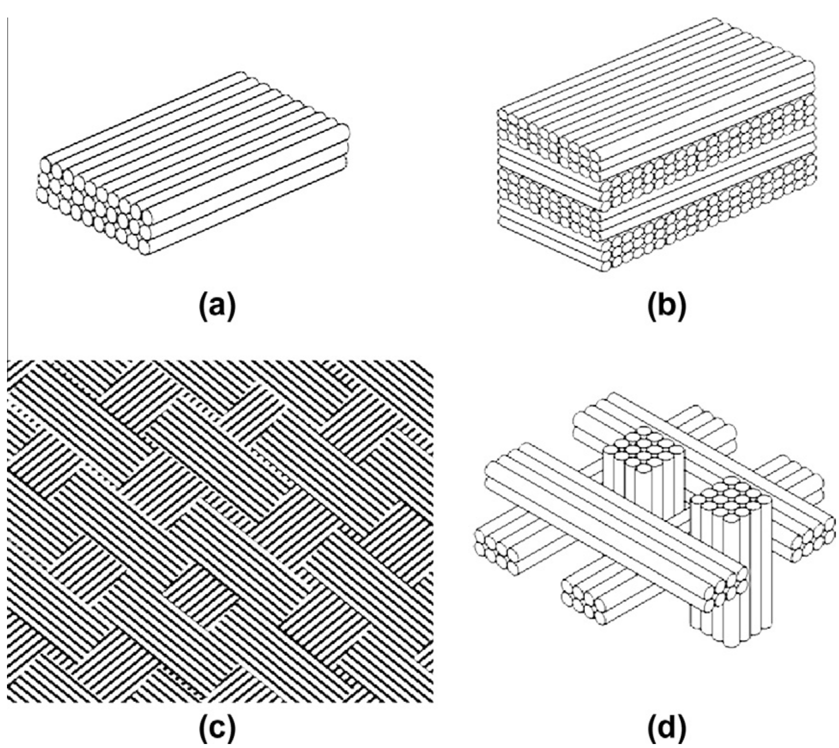

Fig. 1. Four types of CFRP structures: (a) unidirectional composites, (b) cross-ply composites, (c) 2D woven CFRP, and (d) 3D orthogonal woven CFRP.