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The effect of embedded devices on structural integrity of composite laminates

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ABSTRACT

Integration of functional devices within structural materials is an efficient method to implement and design multifunctional materials and structures. However, embedded devices in composite structures typically cause a geometric discontinuity, which results in a significant effect on the structural integrity of the composite. Herein, we have presented an experimental and numerical investigation into the effect of embedded devices on the tensile properties of carbon/epoxy laminates. The embedded devices considered in this study are embedded thin film lithium energy cells within composited laminates to form energy storage structural composites. During static tensile testing, the damage evolution was monitored by acoustic emission measurement and several specimens were observed through optical micrograph at different load levels to determine the progressive damage. Testing results demonstrate that delamination at the interface between composite and integrated device is a significant damage mechanism in tensile performance degradation and the delamination propagation depends on the ply angle of the SUS/θ interface. A two-dimensional plane strain finite element model using ABAQUS code was developed to study damage initiation using stress analysis and the behavior for delamination propagation using a fracture mechanics approach. Numerical results demonstrate that the different effects of "slipping" and "frictional forces" on crack propagation can be modeled to introduce different critical release rate.

1. Introduction

The concept of multifunctional structures (MFS) has become more noticeable over the last several years with a number of definitions being accepted. The most popular is a material, structure, or material system with the ability to perform multiple functions through an advisable combination for structure function with one or more additional functional capabilities as dictated by system requirements [1,2]. It encompasses traditional composite materials that provide high specific stiffness, strength, and incorporates other functions such as energy absorption, electromagnetic properties, sensing and actuation, power harvesting and repair [3–6]. However, its application to the aerospace and other engineering industries is infeasible until their integrity issues are completely understood. Mechanical response and integrity of multifunctional structures/materials under various operating conditions, such as static loads, cyclic loads, temperature variations, radiation, corrosion, humidity, impact etc., is imperative before real world application.

The embedded device in a composite structure typically causes discontinuity that usually results in a significant effect on the structural integrity. Inclusions not only result in the net area loss of the material, but interlaminar stresses may also arise at, or near, this discontinuity of the host composite structure [7]. These phenomena may result in a reduction of the load carrying capability of the host structure. Furthermore, interlaminar stresses may also result in the failure of the interface between the sensor/actuator [8], hence the embedded device may lose its ability to perform its sole role in the adaptive structure or, alternatively, the embedded device itself may fail due to the high stresses that are associated with inclusion. These aforementioned factors have motivated this investigation.

Previous publications [9–17] have focused on the feasibility of the embedment of different types of sensors and devices and evaluating the durability of the integrated transducers and quantifying the strength and fatigue life of the host material. From these studies it appears that in cases where the thickness of the inclusion does not significantly alter the through-the-thickness geometry

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of the host material, the resulting stress concentration is rather negligible, and thus has no observable effects on the material's integrity. However, in cases where the integrated devices are not relatively small (e.g. 40 mm × 25 mm and various thicknesses), the strength reduction as well as the resulting damage mechanisms have not been quantitatively investigated.

Shivakumar et al. [12,13] presented the effects of embedded fiber-optic sensors on the integrity of carbon/epoxy laminates. They primarily focused on the damage initiation and propagation within different materials. According to their experimental observations, the in-plane properties of the material were unaffected by the fiber-optic sensors and a small reduction (10%) of the tensile strength was observed. In addition, the compressive strength was drastically reduced (40%). A key feature of their study was the investigation of the material microstructure and inspection of the progression of the damage at different levels of applied stress. The site of damage initiation was found numerically to be at the tip of the eye-shaped resin pockets located around the integrated sensor. The researchers attributed the failure to delamination growth due to high values of transversal stress.

Warkentin et al. [14] studied the feasibility of embedding active integrated circuits on silicon chips within graphite/epoxy laminates. They explored the material manufacture as well as the durability of the sensors and composite under different testing conditions. The presence of the integrated device appeared to have no effect on the longitudinal mechanical properties and a 15% reduction of the maximum bearable stress was observed.

In recent years, an ongoing project at TJU, TUS, and JAXA aims to investigate the feasibility study of the process of physically embedding solid-state thin-film lithium energy cells into carbon fiber reinforced plastic composites (CFRP) and the performance of the resulting power composites for various functions, as well as evaluate the implications of the composite's mechanical performance (see Fig. 1). With regard to the effects on the material strength and failure, several experimental studies have been performed with both simulated and embedded devices [18–22].

The research work presented herein is the continuation of these previous studies with the intent of characterizing monotonic tensile behavior of CFRP-laminated structures with embedded device. A standard tensile testing of a cross-ply laminate coupons with and without embedded devices was performed as a characterization technique. Their responses were compared using several metrics, such as first ply failure, transverse crack density, delamination, modulus, and ultimate strength. Acoustic emission (AE) technique and the micrographic inspections were utilized to assess the damage initiation and propagation at different stages of loading. A two-dimensional plane strain finite element model using ABAQUS code was developed with emphasis on the numerical simulation for damage initiation and delamination propagation.

2. Experimental

2.1. Materials and manufacturing

In order to investigate the effects of embedded devices on the tensile performance of laminated composites, the steel use stainless (SUS) film with a thickness of 0.1 mm was selected as the embedded device in a composite structure. The composite panels with and without embedded device were 8-layer cross-ply lay-ups laminates, which were fabricated via vacuum hot pressing technique (Feng Yuan electronics Co. Ltd., MD400-100T-H); the nominal dimension of composite panels was 240 × 240 mm. *In order to create the embedded specimens, the SUS surface was scuffed with sandpaper and chemical cleaning was conducted to provide greater adhesion with the neighboring plies. Subsequently the SUS was simply co-cured with the fiber composite prepreg, with no added adhesive.* The host composite structures consisted of a carbon/epoxy, T700/7901 unidirectional prepreg from Guang Wei carbon fiber Co., Ltd., and fiber volume fraction was found to be 58–62%. The curing temperature and cycle were followed by the manufacturer's recommendations and was achieved by hot pressing the material at 120 °C under 0.65 MPa pressure. All specimens were cut into the same overall length of 200 mm, a width of 40 mm, and an average thickness of 1.1 mm for a rectangular sample, as shown in Fig. 2. To determine the interlaminar fracture behavior of SUS/θ interfaces ($\theta = 0°, 90°$) in various laminates, four types of specimens were proposed in this study: Type A1: $[0/90_2/0]_S$, blank specimens (without embedment); Type A2: $[0/90_2/0/\underline{SUS}/0/90_2/0]$, with embedment; Type B1: $[90/0_2/90]_S$, blank specimens (without embedment); and Type B2: $[90/0_2/90/\underline{SUS}/90/0_2/90]$, with embedment.

A specified quantity of specimens were subjected to optical microscopic detection before the loading test that revealed no internal defects in the material attributable to the manufacturing process; microscopic examples of the pre-impregnation lay-ups

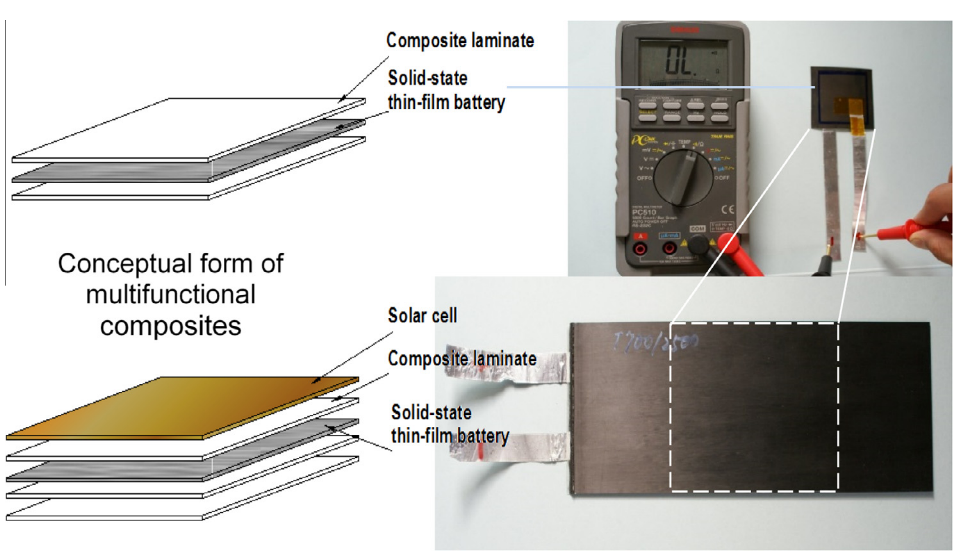

Fig. 1. Embedding solid-state thin-film lithium energy cells into carbon fiber reinforced plastic composites.