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Research Article

Structural Health Monitoring Application of Aviation Composite Materials Using Microscopic Techniques

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ABSTRACT

Structural Health Monitoring (SHM) is a process that involves the observation and analysis of a system over time using periodically sampled response measurements to monitor changes to the material and geometric properties of engineering structures such as bridges, buildings, and aerospace composite structures. The goal of SHM is to detect changes in the structural behavior or condition that may indicate damage or degradation before a catastrophic failure occurs. SHM involves the implementation of damage detection strategies for structures of high importance. It is commonly used in civil engineering, aerospace engineering, and mechanical engineering applications to ensure the safety and reliability of structures. It improves the safety of aerospace composite structures by detecting damage at an early stage, preventing damage from occurring, improving reliability, and extending the life of the structure. SHM applications enable aircraft to spend less time on the ground and carry more passengers and cargo, thereby reducing operational costs. It can be utilized in various fields such as monitoring the health condition of aircraft tail and wing areas in the aviation industry, preventing damage and deterioration of car parts and components under operating conditions in the automotive sector, monitoring the health condition of bridges and tunnels in the transportation sector, and monitoring the health condition of wind turbines and other structures in the energy sector. Aerospace composite structures can suffer from several complex nonlinear damage modes, including impact damage, delamination, matrix cracking, fiber breakage, and voids. This study provides general and useful information on how structural health applications of aviation composites can be supported by microscopic techniques. In order to better understand the subject, an example aircraft composite structural component containing impact damage, which was mentioned above, was examined using microscopic techniques. In this investigation conducted using Stereo and Scanning Electron Microscopes (SEM), the identification of potential damage sources and the assessment of damage severity are explained in detail.

Keywords: *Aerospace, Composite materials, Microscopy, Structural Health Monitoring*

Havacılık Kompozit Malzemelerinde Mikroskobik Teknikler Kullanılarak Yapısal Sağlık İzleme Uygulamaları

ÖZ

Yapısal Sağlık İzleme (YSİ), mühendislik yapıları arasında köprüler, binalar ve havacılık kompozit yapılar gibi yapıların malzeme ve geometrik özelliklerindeki değişiklikleri izlemek için düzenli aralıklarla alınan tepki ölçümlerini kullanarak zaman içinde bir sistemin gözlem ve analizini içeren bir süreçtir. YSİ'nin amacı, yapısal davranışta veya koşullarda meydana gelen değişiklikleri tespit etmek ve felaketle sonuçlanmadan önce hasar veya bozulma belirtebilecek olanları saptamaktır. YSİ, yüksek öneme sahip yapılar için hasar tespiti stratejilerinin uygulanmasını içerir. Genellikle sivil mühendislik, havacılık mühendisliği ve makine mühendisliği uygulamalarında yapıların güvenliği ve güvenirliğini sağlamak için kullanılır. Havacılık kompozit yapıların

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güvenliğini artırarak erken aşamada hasarı tespit eder, hasarın meydana gelmesini önler, güvenilirliği artırır ve yapının ömrünü uzatır. YSİ uygulamaları, uçakların daha az süreyle yerde kalmasını ve daha fazla yolcu ve yük taşımasını sağlayarak işletme maliyetlerini azaltır. Bu uygulamalar, havacılık endüstrisinde uçak kuyruk ve kanat bölgelerinin sağlık durumunu izlemek, otomotiv sektöründe işletme koşullarında araç parçalarının ve bileşenlerinin hasarını ve bozulmasını önlemek, ulaşım sektöründe köprülerin ve tünellerin sağlık durumunu izlemek ve enerji sektöründe rüzgar türbinleri ve diğer yapıların sağlık durumunu izlemek gibi çeşitli alanlarda kullanılabilir. Havacılık kompozit yapılar, darbe hasarı, delaminasyon, matris çatlama, lif kırılması ve boşluklar dahil olmak üzere çeşitli karmaşık olmayan hasar modlarına maruz kalabilir. Bu çalışma, havacılık kompozitlerinin yapısal sağlık uygulamalarının mikroskopik tekniklerle nasıl desteklenebileceği hakkında genel ve faydalı bilgiler sunmaktadır. Konuyu daha iyi anlamak için yukarıda bahsedilen darbe hasarı içeren bir örnek uçak kompozit yapısal bileşeni, mikroskopik teknikler kullanılarak incelenmiştir. Bu araştırma, Stereo ve Taramalı Elektron Mikroskopları (SEM) kullanılarak potansiyel hasar kaynaklarının tanımlanması ve hasarın şiddetinin ayrıntılı açıklamasını içermektedir.

Anahtar Kelimeler: *Havacılık, Kompozit malzemeler, Mikroskopi, Yapısal Sağlık İzleme*

I. INTRODUCTION

Structural Health Monitoring (SHM) is a systematic process involving the continuous observation and analysis of a system over time, utilizing periodically sampled response measurements to track alterations in the material and geometric characteristics of engineering structures, such as bridges, buildings, and aerospace composite structures. The primary objective of SHM is to discern modifications in the structural behavior or condition that might signify damage or deterioration before an impending catastrophic failure emerges [1], [2]. SHM necessitates the utilization of permanently affixed sensors on the structure, enabling the ongoing collection of data from the structure. Subsequently, this data is subject to analysis to identify changes within the structural system, including structural degradation, damage, and potential hazards. It exhibits the capability to identify various forms of damage modes within aerospace composite structures, encompassing impact-induced damage, delamination, matrix cracking, fiber breakage, and voids. The output from SHM comprises periodically refreshed information concerning the structure's ability to fulfill its intended function considering the inevitable aging and degradation stemming from operational environments. It is widely deployed across domains such as civil engineering, aerospace engineering, and mechanical engineering to ensure the safety and reliability of structural assets [3], [4].

SHM systems have a broad range of applications in real-world scenarios. Their primary purpose is to monitor structural health and promptly detect any signs of damage [5]. These systems are used to continuously monitor the structural health of aircraft components. For example, a real-time SHM system was developed to identify debonding flaws during ground testing of aircraft [6]. It plays a crucial role in monitoring the structural condition of bridges. One notable example is the application of SHM to the Forth Road Bridge in Scotland, where it monitors cable tension and detects any changes that may indicate structural damage [7]. They are also essential for monitoring the structural health of wind turbine components. A typical use case involves the development of SHM systems for wind turbine blades to detect alterations in their structural behavior that may indicate damage [8]. SHM systems are also employed to monitor the structural health of pipelines. An illustrative instance is the development of a SHM system for pipelines, which can identify shifts in their structural behavior signaling potential damage [9].

Aerospace composite structures are susceptible to a range of intricate nonlinear damage modes, all of which can be effectively detected by SHM systems. By detecting damage early, it is possible to take corrective action and prevent further damage, improving the safety and reliability of the aerospace composite structure. Impact damage transpires when a composite structure experiences an external impact, such as a bird strike or hail. This form of damage can instigate delamination, matrix cracking, and fiber breakage [10]. Delamination manifests as the separation of layers within a composite structure. It can occur due to various factors, including impacts, fatigue, or other environmental conditions [6],

[10]. Matrix cracking arises when the resin matrix that binds the fibers within a composite structure undergoes cracking. Matrix cracking can result from fatigue, impacts, or other relevant factors [10], [11]. Fiber breakage takes place when the individual fibers within a composite structure fracture. This type of damage can be attributed to impacts, fatigue, or other contributing factors [12]. Voids represent regions within a composite structure where the resin or fiber is absent. Their presence may stem from manufacturing imperfections or structural damage.

The use of composite components, primarily carbon fiber, in critical areas like aviation where structural health monitoring is necessary, is increasing day by day. Therefore, after the detection of any potential damage on these materials through sensors placed on the structure, a detailed examination is required. This way, damages on the structure can be thoroughly characterized, and a correlation can be established between the type and severity of damage with the information obtained from the sensors on the structure. In various studies, metallographic cross-sections have been prepared to evaluate the condition of the sensors in the composite structure or to examine the damage in detail [13], [14]. However, in situ examination of the damage directly with a stereo microscope provides rapid, useful evaluation.

A composite aircraft structural component containing impact damage is used to demonstrate the capability of microscopic techniques. The damaged part was examined using Stereo and Scanning Electron microscopes (SEM), the identification of potential damage sources and the assessment of damage severity are explained in detail.

This experimental study focuses on demonstrating the application possibilities of SHM using microscopic techniques to detect composite defects on aircraft composite fuselage parts. Using microscopic techniques, it has been shown that not only the severity of defects on composite parts can be determined, but also the type and root cause of damage.

II. MATERIALS AND METHODS

A. EXPERIMENTAL PROCEDURE

This section outlines the procedures employed for assessing the damaged component through microscopic techniques. Initially, a visual inspection and stereo microscope examination were conducted to obtain a comprehensive overview of the damage, providing general information.

Following this, a SEM equipped with an Energy Dispersive X-ray Spectroscopy (EDX) attachment was employed to perform an in-depth assessment of the outer skin. This advanced imaging and elemental analysis technique facilitated a comprehensive characterization and potential identification of the underlying cause(s) of the damage.

B. BACKGROUND

During the service life of an aircraft, a section of the outer skin of the body encountered impact damage. The impact resulted in visible damage, which was subsequently identified during routine inspections. The dimensions of the affected area were measured in terms of width, length, depth, and total area.

Following an assessment in accordance with the pertinent Technical Order (TO) documents, it was determined that the damage exceeded the established usage or repair limits. Consequently, the damaged part was disassembled and disposed of. Subsequently, the part was forwarded to a laboratory for a comprehensive analysis aimed at elucidating the potential root cause(s) and obtaining a more detailed characterization of the type and severity of the damage.

The composite pre-preg material utilized in this study is manufactured by HexcelTM, consisting of an epoxy matrix with plain-weaved carbon fibers. The component is constructed from six layers of 0-900 oriented carbon fibers.

C. MICROSCOPIC EVALUATION

The component was initially subjected to direct examination under a stereo microscope at its original dimensions. During the inspection, the entire damaged surface was examined at different magnifications ranging from 5 to 50x. The stereo microscope was equipped with an image analyzer, enabling the capture and measurement of images during the inspection process. The accuracy of the measurements made with the image analyzer is periodically verified with calibration blocks.

Following the stereo microscope evaluation, a section of the part surrounding the damaged area was excised for further examination using SEM. A masking procedure was implemented during the cutting process to safeguard the integrity of the damaged surfaces.

SEM/EDX analyses were additionally conducted, wherein the SEM Backscatter detector was employed to gain a deeper insight into elemental distinctions within the component. The accuracy of the analysis performed with the EDX unit is verified by calibrating blocks containing the elements to be measured. EDX measurements are performed at least 3 times to ensure the elemental distribution in the analyzed region.

III. RESULTS

The general appearance of the damage is illustrated in Figure 1.

Figure 1. *The general appearance of the damage*

Figures 2, depict the damaged area as observed under the stereo microscope. This inspection disclosed that the initial three layers of the composite exhibited damage, with numerous fragmented fiber particles observed on the part's surfaces. The boundaries of the damage were sharply delineated, with no evidence of similar damaged regions detected elsewhere on the surface of the component. The dimensions of the damaged area measured approximately 16.2 mm in maximum length and 4.3 mm in maximum width, with a depth of approximately 0.6 mm. Notably, the damage extends to a depth nearing half of the part's total thickness. It is worth emphasizing that the utilization of stereo microscopes permits a more comprehensive collection of information and facilitates precise measurements, surpassing the capabilities of on-site visual inspections conducted at the aircraft's location.

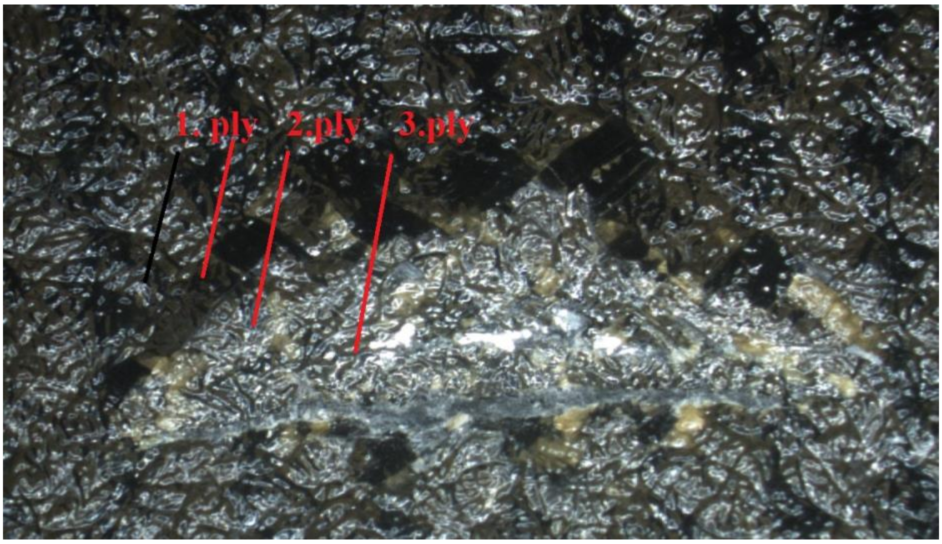
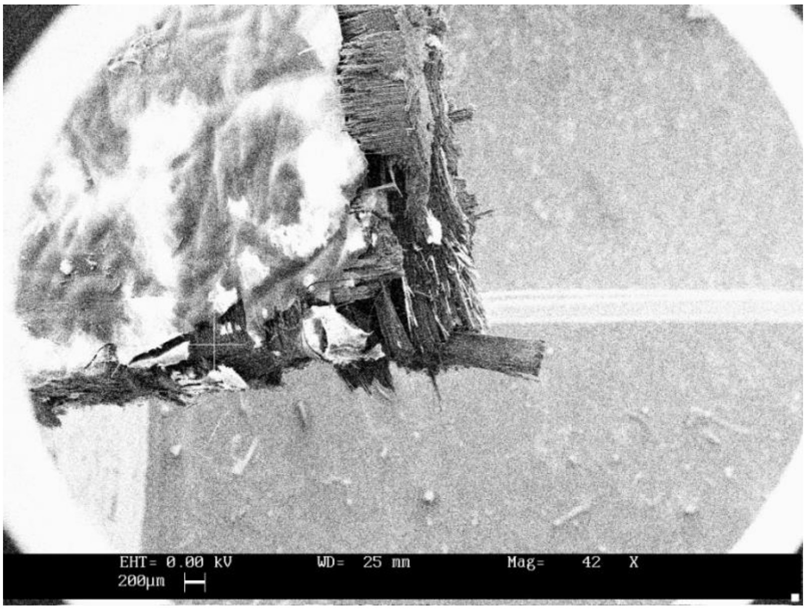
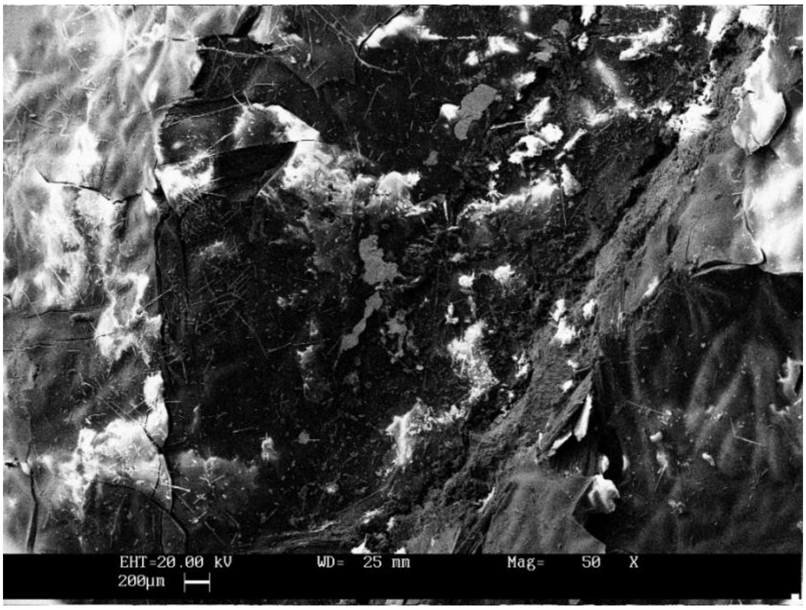


Figure 2. *General appearance of the damage_16x*

The SEM examination unveiled the presence of fiber breakage, delamination, and matrix cracking at the site of damage. Additionally, broken fiber particles were observed in SEM Secondary detector images. These specific damages are depicted in Figure 3a and b.



(a)



(b)

Figure 3. *(a) and (b) the SEM secondary detector images of the damage area_50x.*

Notably, white-colored spots were identified on the damaged surfaces through the backscatter detector, and subsequent EDX micro spot analysis was carried out on these identified spots. The corresponding backscatter images and EDX analysis are presented in Figure 4 and 5, respectively.

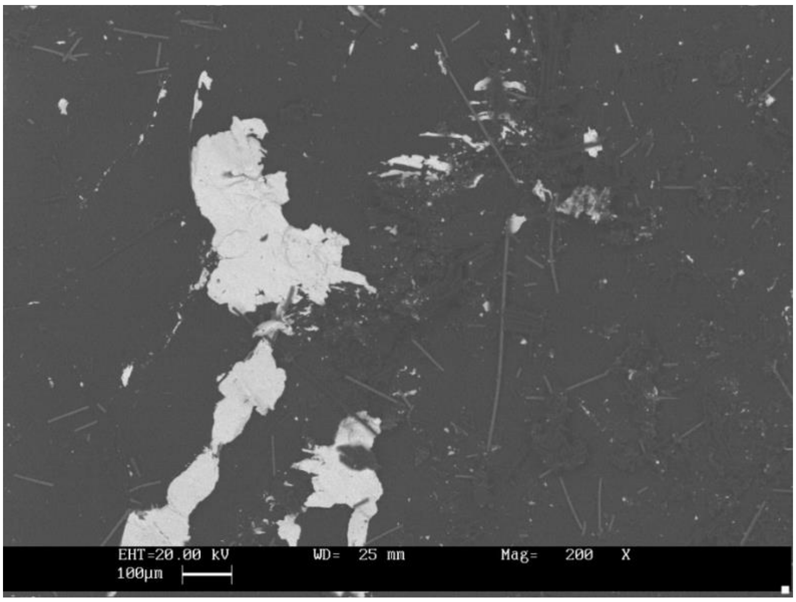


Figure 4. *Backscatter SEM image from the damage area*

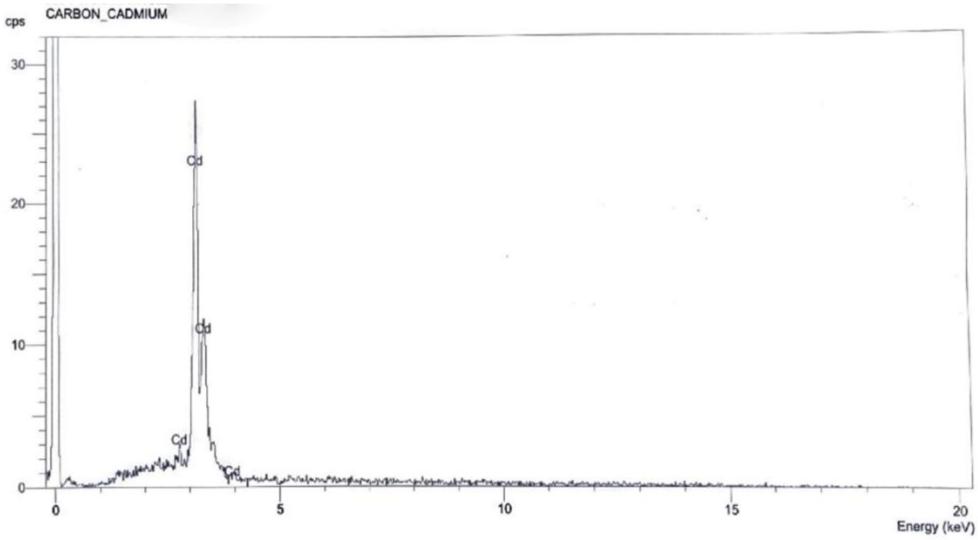


Figure 5. *The EDX analysis*

The investigations conducted on the damaged component have yielded valuable data regarding the mechanism of damage initiation and its effects on the part. The examination using a stereo microscope has provided significant insights. The well-defined and localized boundaries of the damage, coupled with the absence of any external damage in the proximity, suggest that the part has incurred damage characteristic of a hard-body impact.

Furthermore, the preliminary assessment through stereo microscopy, later confirmed by SEM analysis, has revealed that the damage extends to a depth of approximately half the thickness of the part. The SEM examination has also confirmed the presence of fiber breakage, delamination, and matrix cracking within the part.

Moreover, the SEM/EDX examination has detected residues of cadmium on the damaged surfaces. Cadmium is commonly employed as a corrosion-resistant coating in aircraft structural components. Consequently, it can be inferred that the object responsible for the impact damage possesses sharp-edged contours, likely a metallic object associated with possible aircraft structural components.

IV. CONCLUSION

In this study, the utilization of microscopic examination techniques has provided valuable data that can support structural health monitoring of composite components. This data can facilitate correlation studies between sensor data and the type and severity of damage. By examining the impact site with a stereo microscope and SEM, the type of damage could be determined as hard body impact. The determination of the type of damage is of great importance for the implementation of corrective actions such as repair, part replacement, etc. Furthermore, the rapid assessment of composite airframe damage will ensure that the aircraft can be quickly prepared for the next flight. This means significant economic benefits in terms of maintenance costs. The use of SEM/EDX provides useful information about the elemental composition of the impacting object in impact damage events.

The insights gained from this research can contribute significantly to enhancing the effectiveness of future SHM applications. By replicating and expanding upon such studies, we can anticipate more successful outcomes in SHM applications in the future. For example, in future studies, examining impact damage to structures containing sensors such as accelerometers and acoustic emissions with microscopic techniques will provide a detailed examination of the relationship between sensor data and damage.

Consequently, this can lead to improved flight safety, reduced maintenance costs, and extended component lifespans, among other beneficial outcomes.

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