DAMAGE EVALUATION OF SMART CFRP-PIEZOCERAMIC-MATERIALS USING NON-DESTRUCTIVE METHODS

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SUMMARY: Manufacturing and exploitation of adaptive material systems consisting of carbon fibre reinforced plastics (CFRP) with embedded piezoceramic sensors and actuators require sophisticated production techniques. Non-destructive methods are needed to detect manufacturing defects and to monitor the damage evaluation in a self-diagnostic manner. First, the paper presents in-situ bending tests accompanied by microscopic and acoustic observations showing damage mechanisms. Second, eddy current, ultrasonic and radiographic imaging techniques are presented as a powerful tool to characterize structural imperfections. Results are given for typical manufacturing and load induced damages. Third, first steps to a health monitoring system are discussed using ultrasonic and thermographic techniques.

KEYWORDS: carbon fiber reinforced plastics, piezoceramic actuators, failure mechanisms, non-destructive characterization, eddy current imaging, ultrasonic imaging, thermography, health monitoring

INTRODUCTION

Smart materials based on carbon fiber-reinforced plastics with integrated PZT sensors and actuators are expected to be a favorite composite for vibration damping and noise reduction [1]. Figure 1 presents the material system. Significant differences between mechanical and thermal properties of the ceramic patches and the matrix demand sophisticated manufacturing techniques. Various damage mechanisms may reduce or even destroy the sensing and actuating capabilities of the piezoceramic material. To improve the performance and to predict the reliable life-time of adaptive structures it is necessary to analyze and describe quantitatively the damage process as a complex microscale interaction between the embedded patches and the host structure. The major challenge is to create a suitable damage tolerance concept integrating a damage mechanics methodology combined with advanced non-destructive diagnostics. In extension of conventional non-destructive evaluation (NDE) after manufacturing and during inspection breaks, a smart material can be used in a self diagnostic manner to detect early damage stages. This approach results in more intelligent NDE procedures. Its successful application requires fundamental knowledge of nature, size and

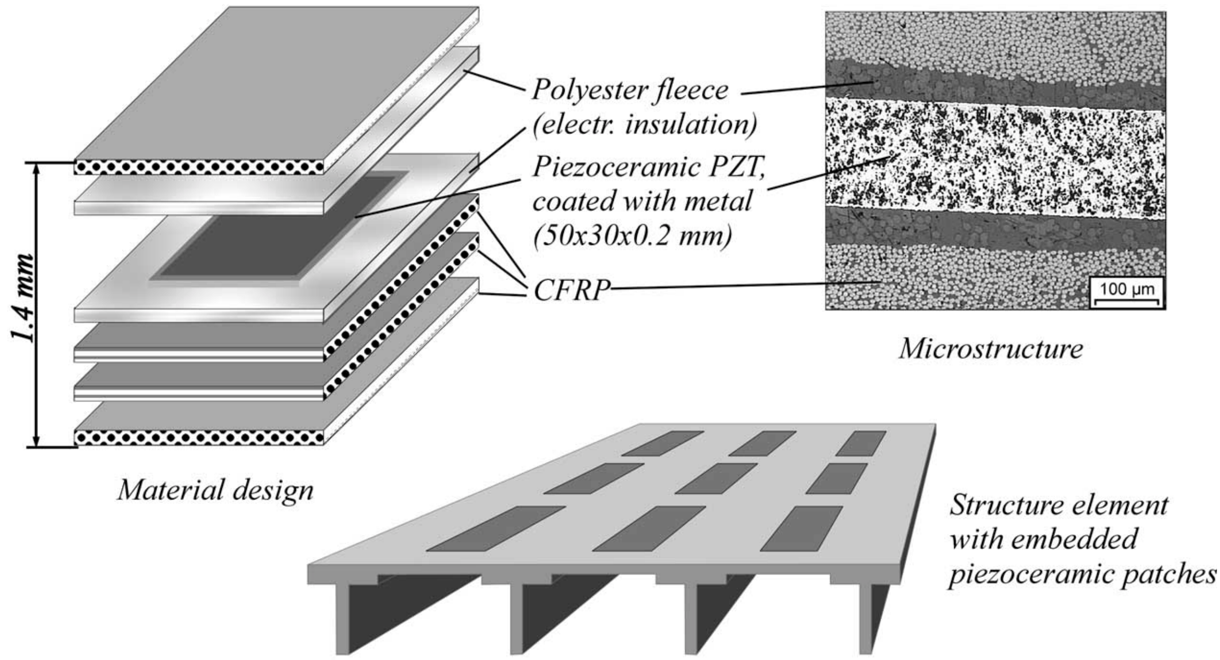

Fig. 1: Design of the adaptive structure

location of damage as well as extensive data acquisition and processing [2]. The real-time health monitoring techniques should provide reduced maintenance costs and offer many unique opportunities to assess the structural integrity [3].

The scope of properties to be evaluated includes the internal structure of the composite (fiber orientation, ply sequence, sensor and actuator position, local fiber or epoxy concentrations), planar flaws oriented parallel to the surface (delamination, ceramic debonding), perpendicular oriented flaws (cracks of the matrix or of the patches) and volume imperfections (pores, voids, inclusions). Some typical imperfections in the smart material system are shown in Figure 2.

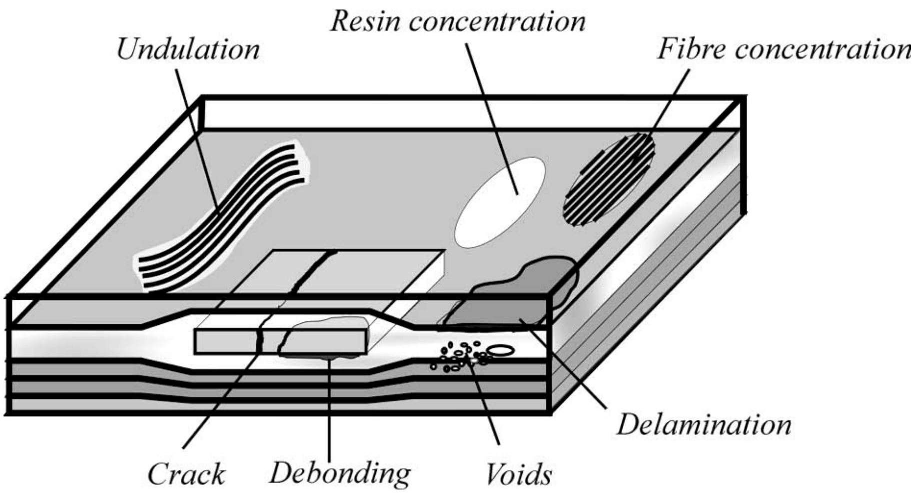

Fig. 2: Typical imperfections after manufacturing of a CFRP laminate with embedded piezoceramic patch

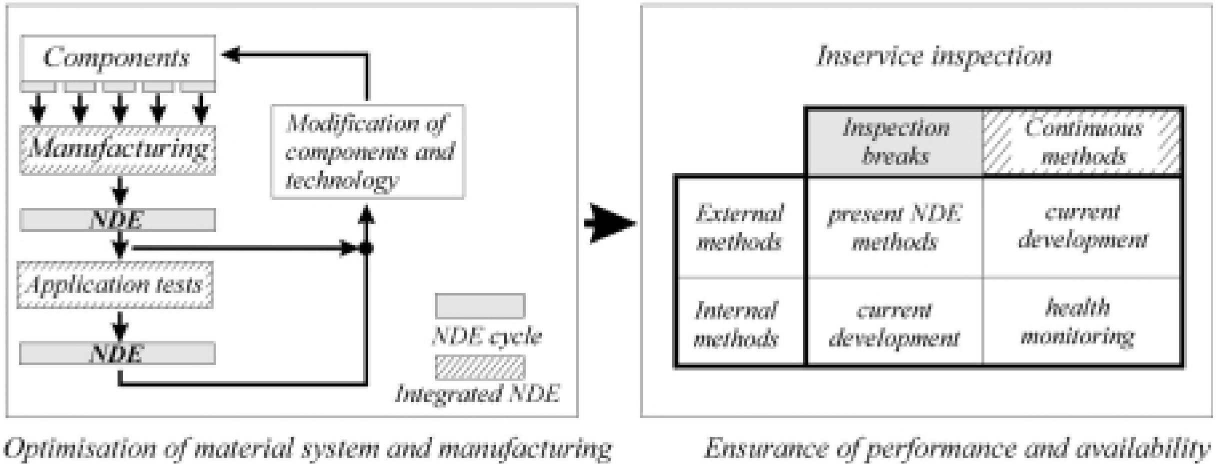

Fig. 3: Contribution of NDE to the damage tolerance concept of adaptive structures

Figure 3 outlines the contribution of NDE to the development and application of adaptive materials. In research and development, it helps to find out suitable components and to optimize the manufacturing process. During and after manufacturing, NDE brings up the structural state of the composite and visualizes imperfections. Additionally, NDE accompanies mechanical testing. Non-destructive in-service inspection of the material system can be accomplished during inspection breaks. Current work is focused to the development of methods using the active capabilities of the embedded actuators and sensors for NDE purposes. Furthermore, continuous methods with external as well as internal approaches are created.

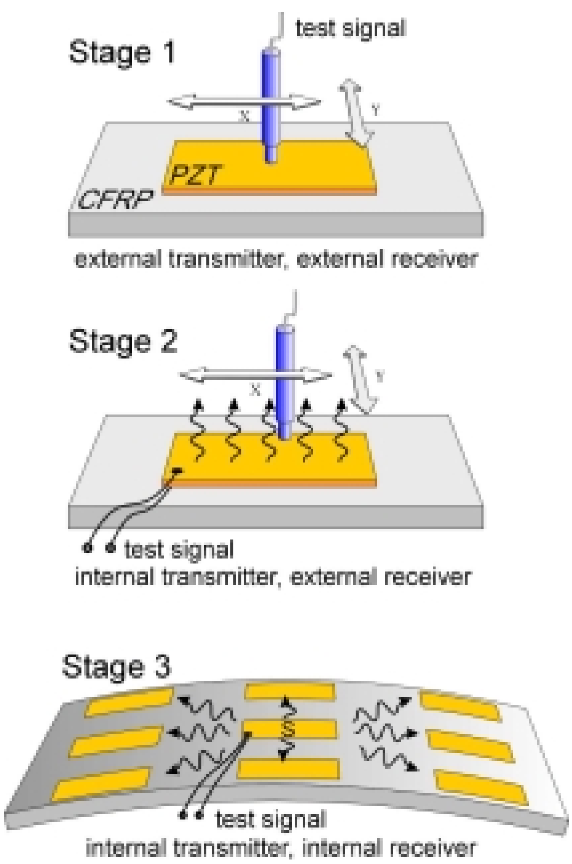

Fig. 4: Three stages to health monitoring

Fig. 4 presents these stages from the signal generating point of view. At first stage, a transmitting and receiving probe scans the object. The object may be either passive or active. At second stage, the internal actuators are used as transmitters for the test signal. An external scanning sensor (or sensor array) receives the signal characterizing the transmitter (actuator) as well as the channel (structure). Of course, this principle may be inverted. Both stages create images as the inspection result. Finally, third stage is aimed to avoid any external sensors or transmitters. Here, the internal sensors and actuators perform as transmitters and receivers. To get information about local distribution of structural properties the transmitting function may be switched to various actuators. Unfortunately, no clear images can be expected and it is a matter of further investigations to find out the chances and limitations of this approach.

FAILURE MECHANISMS

Specimens (46x11x2 mm^3) with a structure according to Figure 1 but with two symmetrically embedded piezoceramic patches on each side were loaded in three-point bending tests for microscopic and in-situ Scanning Electron Microscope (SEM) examination. The primary goal was to identify initial damage by acoustic emission (AE) and SEM images. A load-displacement curve and the cumulative energy of acoustic emission can be seen in Figure 5.

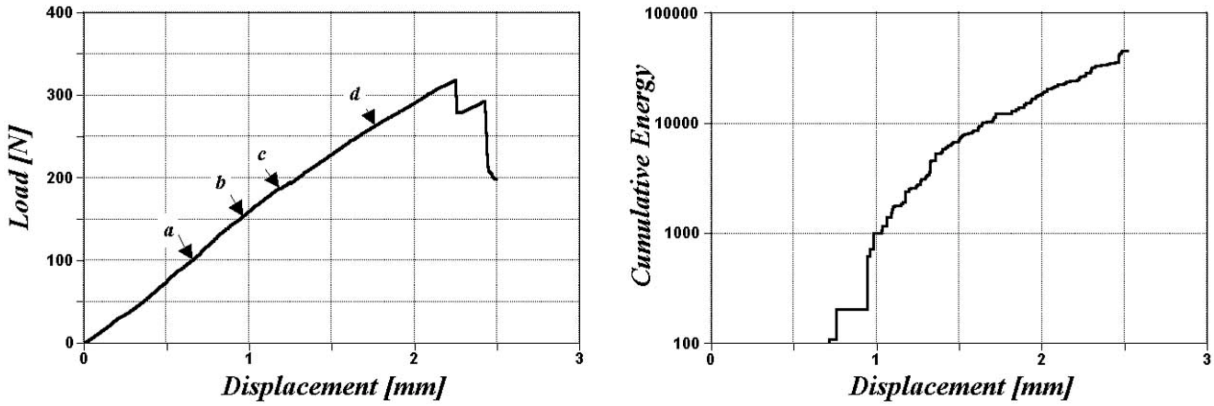

Fig. 5: Load-displacement curve and AE cumulative energy-displacement curve

The bending test yields information on the behavior of the piezoceramics and the surrounding interface under tension and compression load. From the SEM images in Figure 6 the damage progress with increasing load (see marks in Figure 5) can be described as follows:

a) crack initiation in the tension stressed piezoceramic patch accompanied by first acoustic emission (AE) signals,

b) delamination without cracking in the compression zone with increasing AE,

c) crack initiation in the insulation fleece and propagation into the matrix and the carbon fibers,

d) crack propagation in the compression stressed piezoceramic patch.

Comparing the results of specimens containing piezoceramic patches with specimens without any ceramics, the AE method seems to be well suited to monitor the early damage development in the piezoceramic patch.

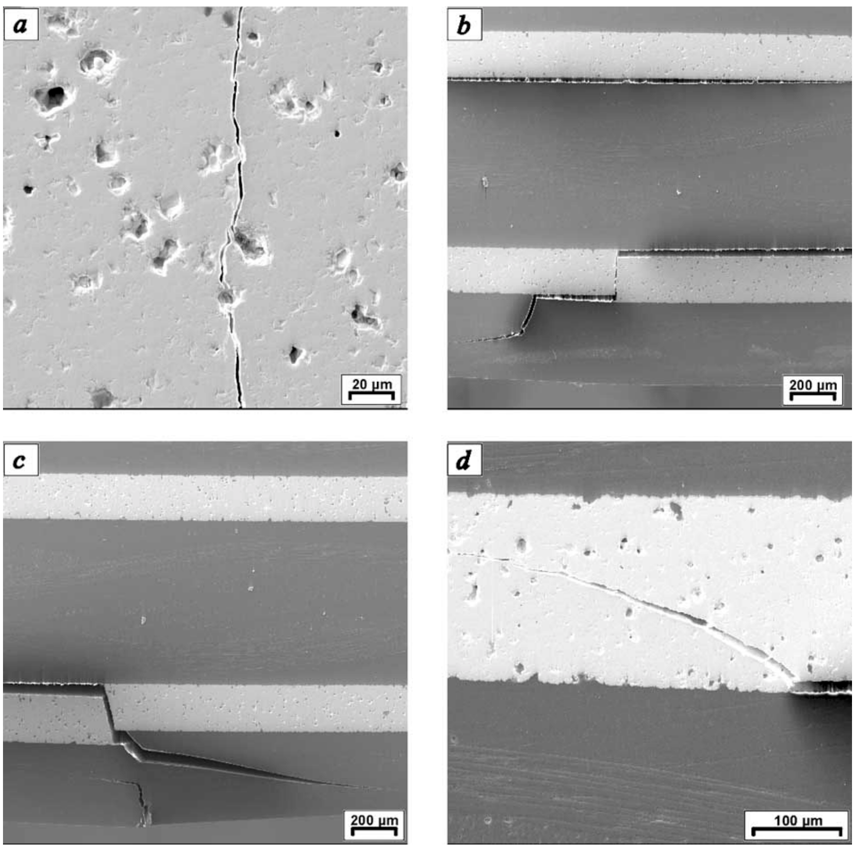

Fig. 6: SEM images of damage propagation within CFRP containing two embedded piezoceramic patches during in-situ bending

IMAGING NON-DESTRUCTIVE CHARACTERIZATION

Eddy current (EC) method: The essential idea is to use the anisotropic conductivity of the material. Along the carbon fibers much better conductivity is found than across the fibers. Additionally, the piezoceramic patches are coated with thin copper-nickel layers providing electrical contacting. This layer is able to carry eddy current. In case of patch cracking the coating also cracks thus interrupting current paths [4].

Ultrasonic (US) method: Ultrasonic testing is based on the reflection and transmission behavior of elastomechanic waves at internal structures and so different reflection and transmission testing techniques are applicable [5]. The perpendicular incidence of longitudinal waves corresponds to the existence of pure longitudinal wave mode and admits the detection of most structural flaws. For testing of smart CFRP structures, the problems of the materials anisotropy, heterogeneity and layered structure have to be kept in mind [7].

Radioscopy (X): X-radiation is suitable to study both surface and internal damage of the laminate as well as of the piezoceramic. Digital X-ray imaging using a special differential technique was used to detect cracks in the piezoceramic.

Thermography: Thermal fields generated by external heating or internal processes are used for thermographic methods. Temperature gradients which can be detected using infrared thermography are caused by local heating as well as by the existence of defects which can prevent the heat dissipation. The infrared thermography is a suitable method for a active detection of those temperature gradients [6,8].

NDE OF MANUFACTURING DEFECTS

Figure 7 presents images of a cracked actuator in the laminate. The patch was broken before embedding into the laminate. Figure 7a results from an X-ray procedure using special aperture to limit the radiation to the actuator area. The eddy current image 7b reflects the metallic coating of the actuator and the CFRP layer. Since the metallic layer does not cover the ceramic patch completely, crack areas in the upper part remain unnoticed. The ultrasonic image 7c shows rectangular areas near the edges of the piezoceramic patch from adhesive tapes for fixing the broken actuator. Furthermore, the crack-network becomes partly visible.

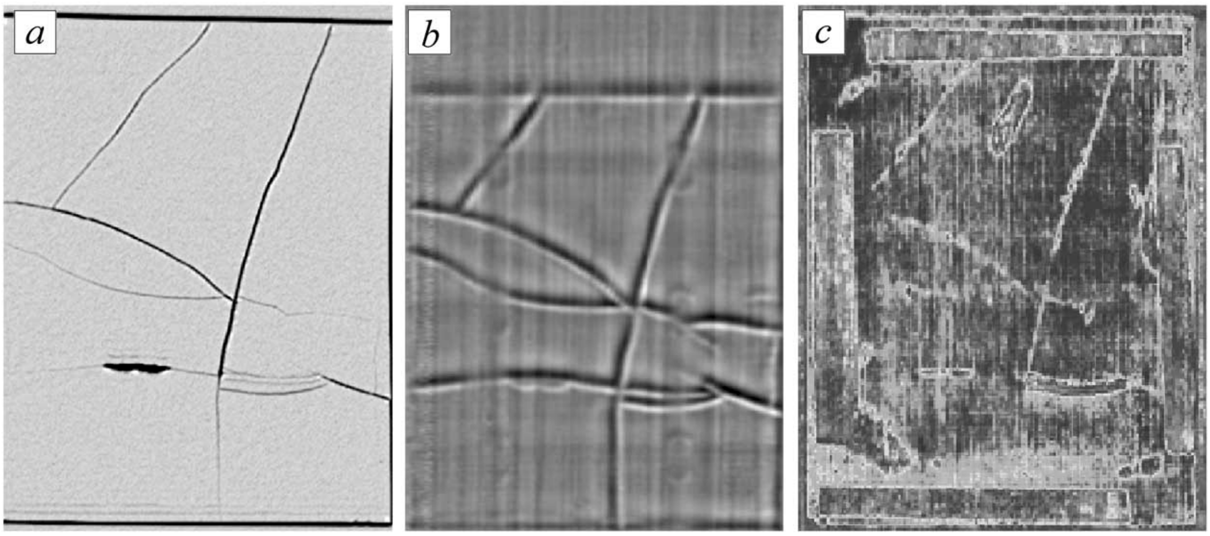

Fig. 7: Fracture of embedded piezoceramics: a) x-ray, b) eddy current and c) ultrasonic images

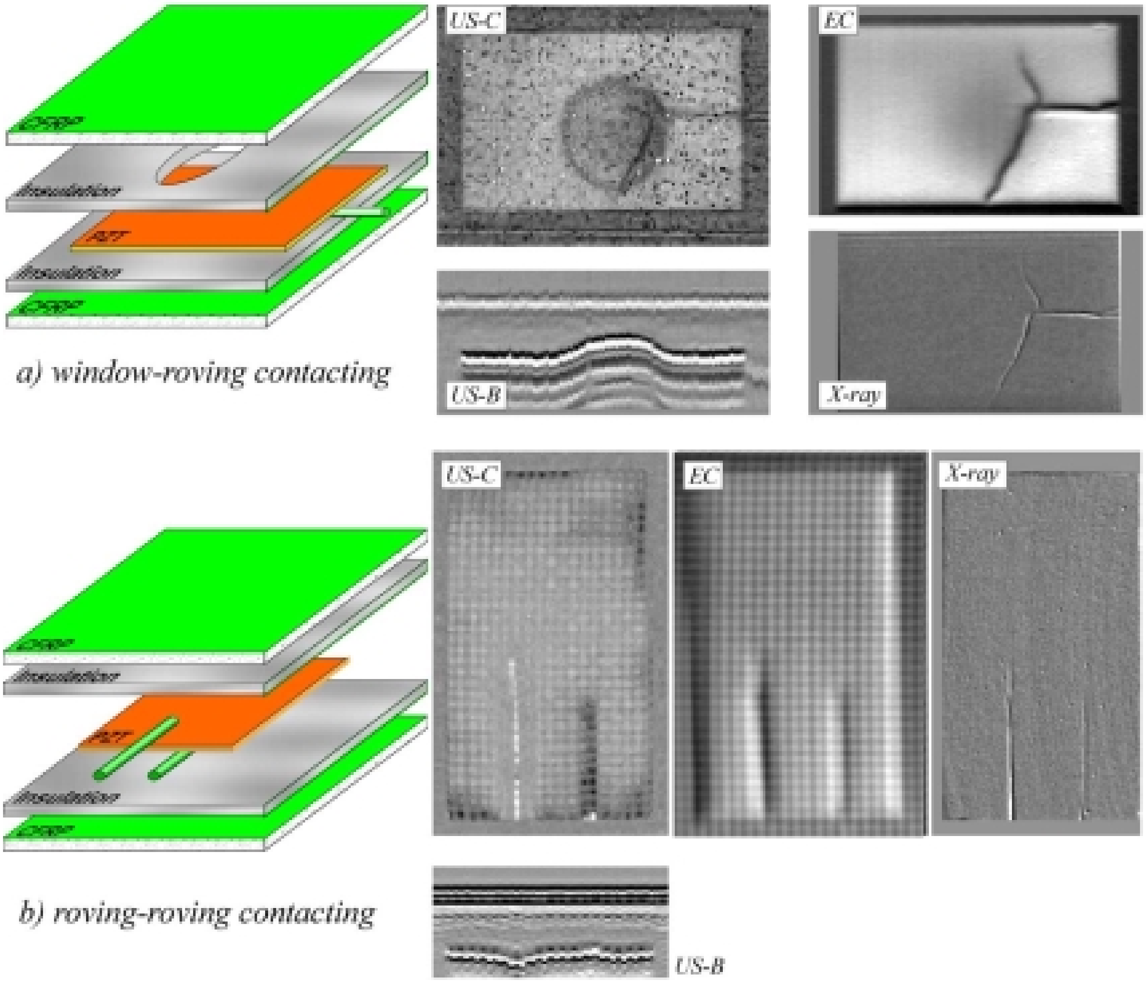

Fig. 8: Actuator deformation and cracking caused by conductor rovings

A very sensitive point is the contacting of actuators because it also may damage them during autoclave curing. First kind of contacting are dedicated windows in the insulation fleece as shown in figure 8a. The conducting CFRP layer acts as the common electrode for some actuators. The contact window causes an actuator deformation at curing. The resulting stresses deform the actuator and even may induce cracks. US-C-scan indicates this deformed area due to reduced time of flight of longitudinal waves. The degree of deformation can be measured in the US-B-scan with an accuracy up to 20 µm. Additionally, US-C-scan shows some branches of a crack and the contacting carbon fiber roving. EC image clearly makes visible the cracks and indicates the deformation as dark area due to the reduced distance between the actuator and the probe. X-ray image brings up the cracks but cannot detect the deformation.

A second kind of contacting are dedicated rovings (fiber bundles). Figure 8b presents the ply sequence around an actuator. Although being very thin and flexible, these rovings also lead to an inhomogeneous pressure distribution during manufacturing. Local pressure concentration around the rovings may induce cracks in the ceramic patches. US-C-scan shows the contacting carbon fiber roving above and below the piezoceramic as bright and dark lines [7]. This is even better visible in the US-B-scan which permits reconstruction of the layer structure in a cross section plane. Here, the obvious changes in actuator direction indicate cracking. EC technique indicates good conducting metal coating of the actuator as bright square. Cracks can be seen as dark lines. Although remaining unaffected by carbon fiber material, the X-ray image clearly shows both cracks.

NDE OF LOAD INDUCED DAMAGE

Electrical overload

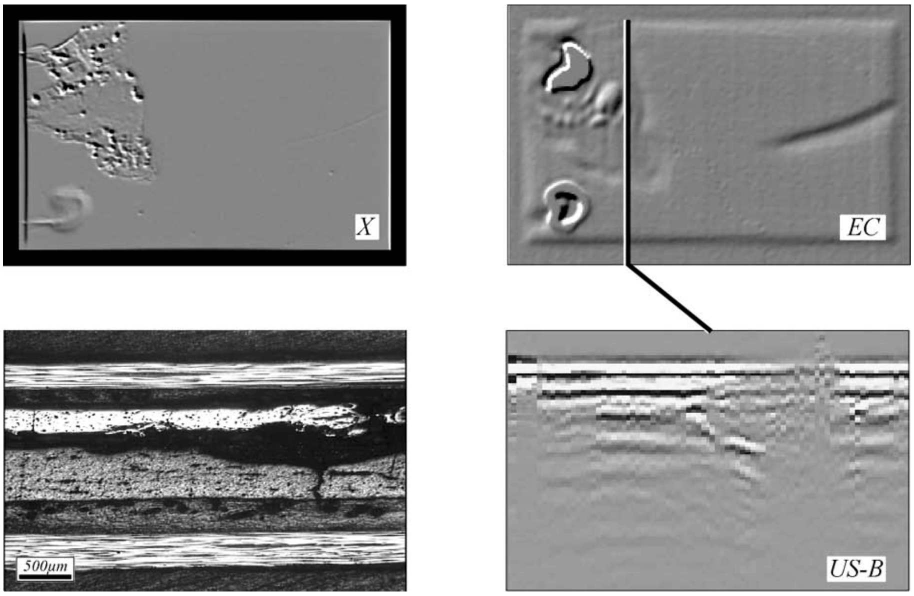

Fig. 9: Blown actuator, non-destructive imaging techniques indicate burned areas in the ceramic patch (X-ray), areas of redistributed metal coating and cracks (eddy current), destruction of the material (ultrasonic).

Figure 9 presents NDE results of a blown actuator. Electrical overload has caused burn out of ceramic parts spreading from one of the terminals (wire). Holes can be recognized in the X-ray. The EC image in its differential mode shows the termination and visualises the damage front starting from the upper terminal downward. Around this terminal a chain of well conducting spots was built by the redistributed metal coating. Additionally, a crack on the right side becomes visible. US-B-scan proves a high degree of material destruction in different depths. The longitudinal waves are screened by delaminated areas and broken material being unable to transmit elastic waves. The micrograph validates severe damage of the actuator, the insulation fleece, the inner CFRP layers and their debonding.

Impact damage

Impact investigations were conducted using a 5 Joule energy drop weight impactor. Figure 10 shows EC and US images from top and bottom sides and, additionally, an X-ray image. The top views indicate a wide delamination between 0° and 90° CFRP layers. EC and US images correspond very well at this type of damage. The reason for eddy current indication is the interrupt of interlayer circular currents [8]. EC bottom image indicates cracks in the actuator and nearly a circular damaged zone. US-C-scan shows a rectangular shaped area between insulation fleece and actuator corresponding with a delamination being caused by a pore-enriched zone in the insulation layer. The X-ray image brings up two large straight cracks and a circular cracked area confirming the EC image.

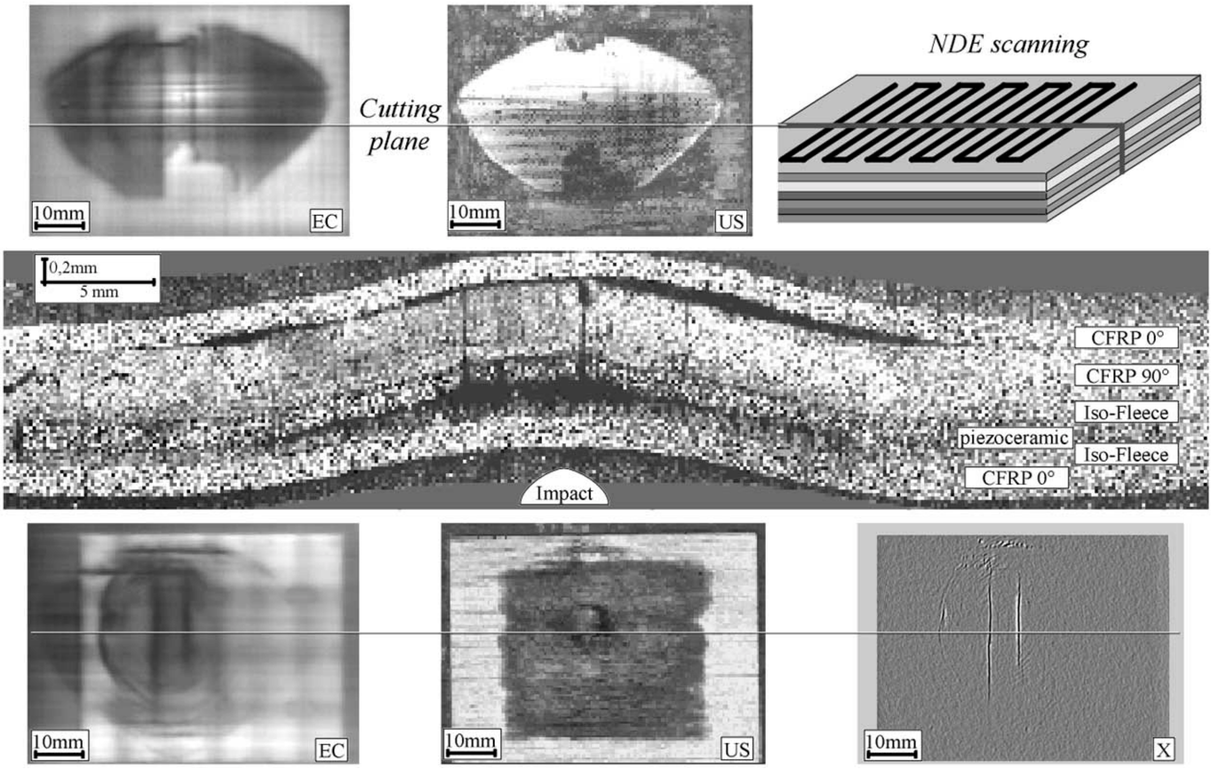

Fig. 10: 5 Joule impact in CFRP laminate with embedded piezoceramic patch. Above: NDE images from top, middle: cross section of the laminate along the indicated line, below: NDE images from bottom.

SELF-DIAGNOSTIC NDE TECHNIQUES

The active capabilities of adaptive materials can be used for evaluation of the integrity and functionality of the structure in a self diagnostic manner [9,10]. Using ultrasonic and thermographic techniques, the piezoceramic patches of the structure are excited by electric stimulation and react with energy conversion into mechanical waves or heat which gives information about structural or functional features.

The self diagnostic ultrasonic testing technique is explained more in detail in Figure 10. The embedded piezoceramic is driven by an electrical pulse and transmits ultrasonic waves in a broad frequency range. A scanning probe receives these signals generated from the structure and after an appropriate data processing the spatial distribution of the piezoceramic activity becomes visible. Additionally, flaws of the piezoceramic and in the covering CFRP and insulation layers are detectable. Furthermore, structural features (here a local bending of the piezoceramic patch) become visible, too.

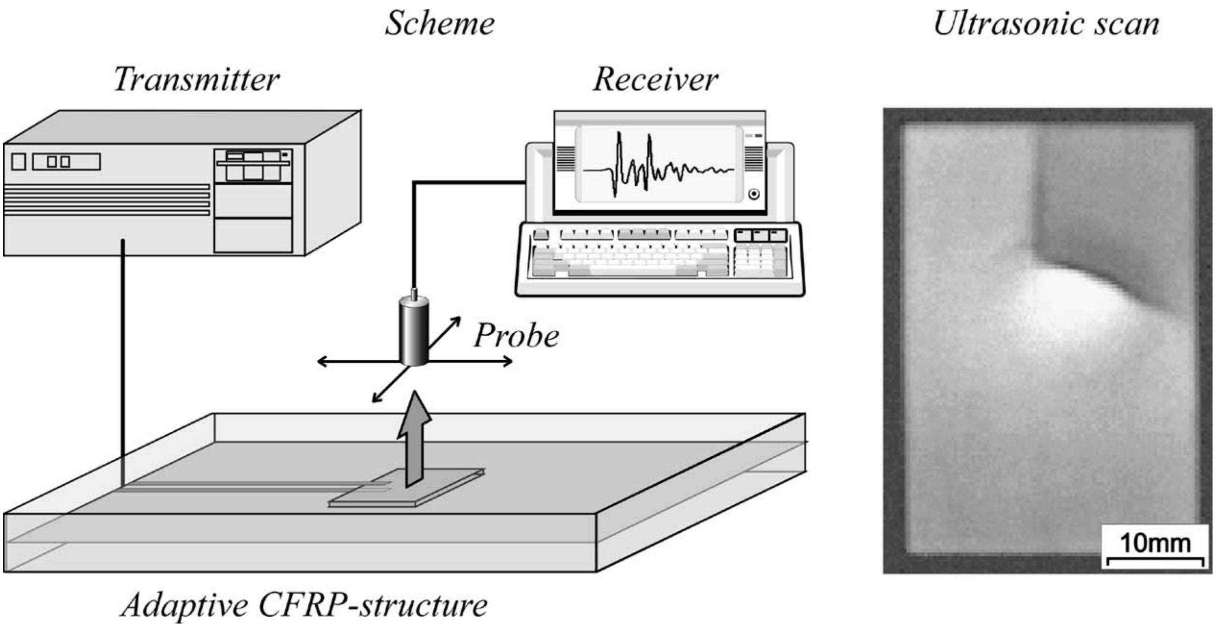

Fig. 11: US testing technique using embedded piezoceramics

Figure 12 shows some examples of thermographic investigation with active excitation of a CFRP strip with three embedded piezoceramic patches and received by an infrared-camera. Figure 12a displays the stacking sequence of the specimen. Every actuator can be stimulated separately. The harmonic electrical stimulation results in vibration heating in the piezoceramic patches and resistance heating in the conductor rovings. In Figure 12b, the form and the position of the three piezoceramic patches become clearly visible at a frequency of 50 Hz. Furthermore, it is also possible to characterize other typical features of the material system. In Figure 12c, a single excitation of the piezoceramic patches with a frequency of 80 kHz was chosen resulting in a predominant resistance heating of the conductor rovings (due to the decreasing capacitive resistance of the piezoceramic patches at higher frequencies). The bright lines show the track of the heated rovings and the bright shining points indicate weak spots.

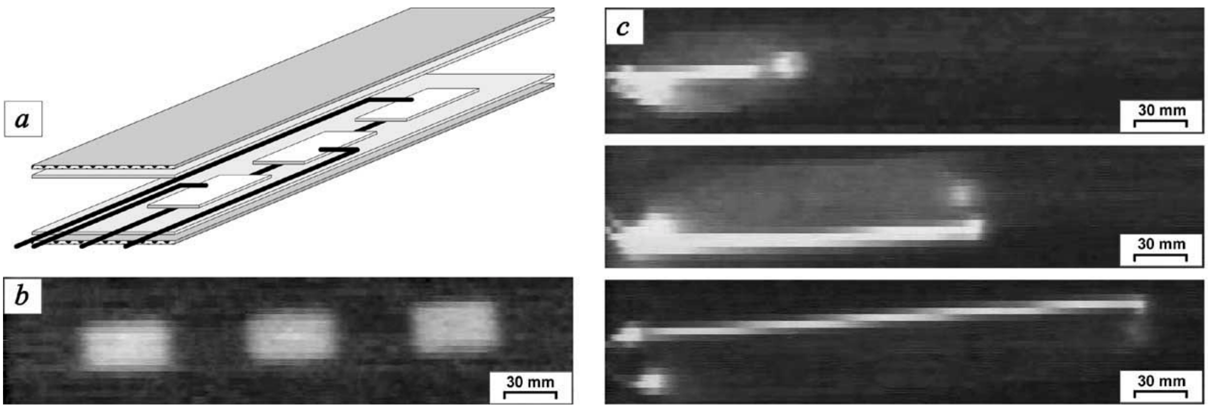

Fig. 12: Thermographic images of an electrically excited adaptive CFRP structure (a: tested structure, b: patches at excitation frequency 50 Hz, c: conductor rovings at excitation frequency 80 kHz) [8]

These techniques admit a very comprehensive characterization of the structure and are further steps on the way to health monitoring techniques.

CONCLUSIONS

Recent advances in smart materials offer many unique opportunities of adaptive structures technology. However, to improve the manufacturing process and the reliability of such structures a comprehensive non-destructive characterization is necessary. High resolution techniques are able to visualize manufacturing imperfections as well as defects induced by operational conditions. The wide variety of physical properties of CFRP and piezoceramics demands a combination of different NDE methods. Together with mechanical methods, eddy current, ultrasonic, X-ray, acoustic emission techniques and thermography help to improve the adaptive material system. Experimental investigations indicate that microcracking of the embedded piezoceramic patches and delaminations at interfaces govern the degradation of this class of materials. Based on these results, the future development is aimed onto direct application of the embedded active elements for health monitoring of adaptive structures.

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