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Non-destructive evaluation and Structural Health Monitoring of impact induced damage in composite structures using ultrasonic approaches and shearography

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Abstract. Composite structures are massively used thanks to the high strength-to-weight ratio, making them ideal for lightweight and durable structures in aviation. However, impact may arise at any time during lifetime on composite aerostructures and ensuring their structural integrity via fast inspection is essential to meet airworthiness criteria. Multimodal NDT (Non-Destructive Testing) inspection and characterization of composite structures is a critical process to verify the quality of the composite material and identify any defects. In this context, the paper shows a comparison of different techniques as nondestructive methods: shearography, and phased array ultrasonics. In particular, using shearography as non-contact approach can increase the inspection speed and reliability compared to the state of the art phased array ultrasonics, which is the standard approach used in the aerospace field. For this reason, a sample of interest to the aerospace industry is subject to a debonding, simulated as the result of low velocity impact. The results show the capabilities of both approaches in identifying small emerging defects along with the advantage and drawbacks of both methodologies through a critical review of performance thereof evaluating the parameters of their use. In addition, the same specimen is equipped with piezoelectric transducers to carry out continuous health monitoring. In this regard, NDT approaches are demonstrated useful to validate and enhance damage assessment after SHM warnings.

Keywords: guided ultrasonic waves, aerospace structures, airframes, Phased array ultrasonic testing, laser shearography, debonding detection, structural health monitoring

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Introduction

Composite airframe suffer of barely visible impact damage which might result in critical debonding where the thin-walled host structure is stiffened by stringers [1]. The damage consists of a disconnection between those parts which reduces the load bearing capabilities with a significant impact on safety [2]. Hence, it is of outmost importance detecting this type of damage, ideally through continuous and/or detailed non-destructive inspections. In this context, Structural Health Monitoring (SHM) can meet the safety requirements through permanent condition monitoring system to control damage phenomena through a set of distributed sensors that are able to detect damage. However, lack of reliability assessment and reduced details in the achievable diagnosis still requires to put in place and deploy a multimodal health monitoring system including classic non-destructive testing (NDT).

Various approaches have been proposed so far to detect, localize, and quantify damage in composite structures. Among them, ultrasonic guided waves based methods are particularly suitable for debonding detection in composite stiffened structures and many approaches are available in the literature using probabilistic imaging [3], ray tracing reconstruction [4], fusion-based damage diagnostics [5], and learning approaches [6, 7]. In addition, an amount of emerging techniques is also available to detect this type of damage, including ultra-wideband (UWB) guided electromagnetic waves (GEMWs) travelling through hollow structures [8].

However, to achieve a reliable and detailed assessment of possible flaws occurring in the structure and enable predictive maintenance, a large number of transducers is often needed, with a negative impact on aircraft performance due to additional weight [9]. An alternative medium term approach to deploy SHM consists in combining continuous monitoring with acceptable performance and compare fast non-contact non-destructive testing to estimate the severity of damage in detail. Non destructive inspection (NDI) is a widely used method for quality control and materials inspection across various industries, especially in the aerospace field where the introduction of composite materials has revolutionized inspection techniques [10]. Due to the high quality performance, in-service ultrasonic inspection (UT) is mostly used for preventive maintenance purposes. One of the biggest challenges of such techniques is the need to use a coupling medium, which can often be a critical issue. For this reason, considerable effort has been made in the aerospace field in recent years to employ innovative techniques that do not require the use of coupling media, either still based on the physics of ultrasound [11], or different ones like infrared thermography [12].

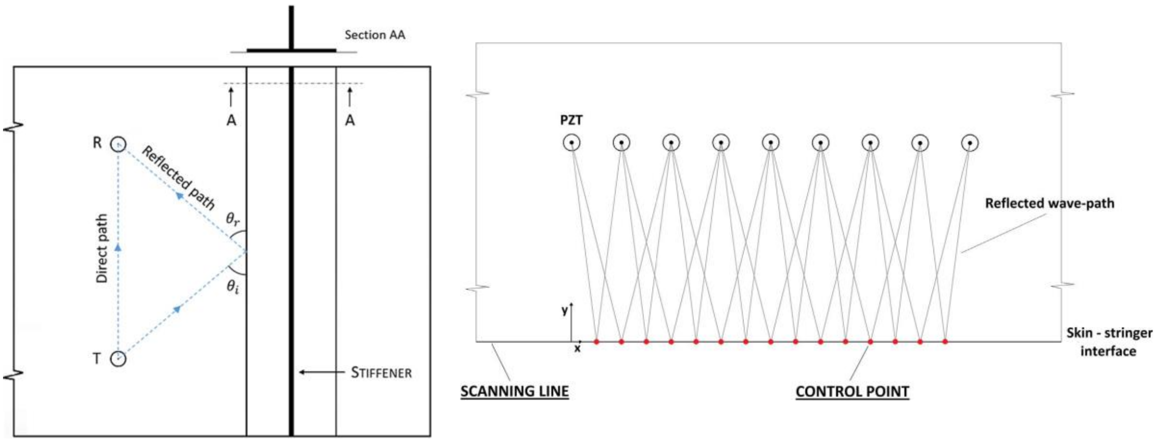
Another proposed technique is the Laser Shearography (LS), an optical non-destructive testing based on the principle of laser -speckle pattern interferometry that provides information about failure in composites by analyzing stress concentration typically distributed around critical defects. The deformation of the surface caused by stress/loading is measured and the defects are detected only by their mechanical response, making not simple the interpretation of results. In addition, it requires special inspection condition (surface condition and illumination) and the loading of the specimen which may be further damaged. As a consequence, it is extremely difficult to characterize defect and it can be adopted mostly for the fast identification of certain flaws. On the other hand, shearography provides large area testing capabilities, non-contact properties and good performance for a wide variety of materials and combination thereof, which is a big challenge for traditional nondestructive testing methods. In addition, its relative insensitivity to environmental disturbances makes this method suitable for less skilled users (less training needed). Finally, it is applicable for a large range of applications including detection of delamination as well as debondings, which are of major concerns in barely visible impact damage.

Implementing this multimodal approach, a comprehensive experimental campaign is conducted on a full-scale wing stiffened plate made of carbon composite. The real scenario representative structure is damaged via simulated barely visible impact damage leading to stiffener debonding and then inspected through permanently installed transducers working in SHM mode as well as via non-destructive inspection. The results allow to highlight strengths and drawbacks thereof and to conceive a multimodal inspection procedure exploiting synergically complementarity thereof to achieve cost-effective predictive maintenance.

1. Materials and Methods

1.1 Ultrasonic Guided Waves based local monitoring approach

Figure 1 shows the concept of the local approach for debonding detection in stiffened composite structures. In principle, given a couple of transducers located alongside the stringer, one works as transmitter (T) and excites Lamb wave propagation, which is sensed by the other transducer working as receiver (R). In this case the stringer is merely a reflector so that exciting the wave from a single location in the pristine structure, a receiver bonded on the same side senses the amount of energy reflected from the stringer. When a debonding occurs, the same receiver senses a lower energy as most of the incident wave flows down to the stiffener and gets transmitted across the skin. Replicating this by a cluster of transducers alongside the stringer (see Figure 1 (b)), each transducer is actuated to excite Lamb wave propagation which is sensed by all other sensors along the line. Such receivers are able to primarily detect the direct wave propagating parallel to the stringer and then the wave reflected from the stringer at a specific (control) point. The valuable information which can be further derived analyzing the wave portion reflected from the stiffener is related to the physical problem of scattering when interacting with discontinuities. The stiffener region is an area characterized by a strong mismatch of structural impedance. When the stringer is bonded to the surface, the excited wave propagating within the plate is partially reflected from the stringer while another amount of energy is transmitted allowing the wave mostly to penetrate into the stringer web. When the disbanding occurs, the impedance mismatch approaches zero and most of the incident wave travels across the skin with a limited interaction with the stringer. That is where the propagation behavior can be exploited for damage detection comparing over time the quantity of energy transmitted by T and reflected from the stringer to R.



(a) (b)

Fig. 1. Geometric configuration for a sensor pair exploited for local approach (a) and its implementation through a sensor network for debonding detection (b). The stiffener works as a scattering mirror and ultrasonic wave propagation interacts with debonding showing a reduction of reflected energy.

1.2 Phased Array Ultrasonic Testing

A first non destructive inspection is carried out by a Phased Array Ultrasonic Testing (PAUT) by Olympus OmniScan SX flaw detector (Figure 2) equipped with a 16:64PR phased array unit able to perform pulse-echo, pitch-catch or TOFD inspection. An encoded 5 MHz, 64 elements linear array probe with a straight wedge is used, coupling the probe and the inspected panel surface with a specific water based gel (Figure 2 b). No calibration blocks are used and the specimen thickness on the unstiffened skin is considered as reference. Tests are carried out with the phased array positioned over the smooth (outer) surface of the specimen, the probe is moved physically along the longitudinal axis while the ultrasonic beam electronically scans along the transverse direction. A mini wheel encoder is used to maintain a precise geometric correspondence of the B-,S-, and C-Scan images with the scanned part. In principle, when detecting debondings, the echo in the A-scan from the interface between skin and stringer is slightly visible when bonding is ensured while its amplitude gets higher when disconnection occurs.

(a) (b)

Fig. 2. Olympus OmniScan SX flaw detector (a) equipped with a 16:64PR phased array unit (b) able to perform pulse-echo, pitch-catch or TOFD inspection on composite structures.

1.3 Shearography Testing

Shearography analysis is performed using a FlawExplorer Laser Shearography sensor from Dantec Dynamics, that is a lightweight and fully integrated device, requiring only two connections: one for power and one for camera data. It’s equipped with a standard 3.2 MPx or optional 5 MPx CMOS camera, offering a maximum frame rate of 37 and 24 Hz, respectively. The sensor includes a varifocal zoom lens, eight laser diodes with automatic cut-off, auto- projection calibration and phase-shift piezo functions. The selected method for apply mechanical stress to the thick panels was heating by lamps, halogen (short-wave) heat excitation system. When heat is applied to an object, the temperature increases and surface starts to swell and expand, this approach was chosen to generate controlled deformations on the surface of the specimens, allowing for detailed evaluation.
Moreover, the instrument is supported by the advanced laser shearography software Istra D4, very intuitive and simple to use. The users could control all the relevant measurement setup parameters, including brightness, cut, projection and display settings, and could easily perform real-time measurements and also advanced post-processing analyzes of the acquired results. Laser Shearography has one of the highest inspection rates compared to any NDT method, specifically because it utilizes a large Field-of-View (FoV) from the use of multiple coherent laser diodes as shown in Figure 3.

Fig. 3. Laser Shearography system with the FlawExplorer sensor and thermal excitation system.

1.4 Experimental setup and SHM dataset

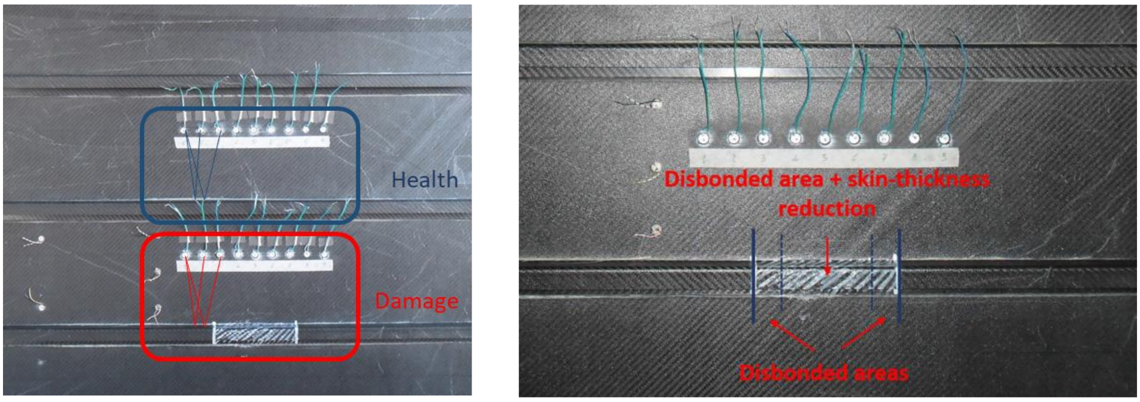
A full-scale wing stiffened panel of a regional aircraft is used to validate the local SHM approach in detecting the stringer debonding and compare the results with ST and PAUT.
The specimen is a composite panel fully made of carbon/epoxy material and designed for the lower panel of a regional aircraft wing box. The thin walled structure is stiffened with five C-type stringers made of the same material and bonded together with the plate during the manufacturing process to ensure structural continuity without any other splice. The panel dimensions are 1200 mm× 900 mm× 25 mm and the stringers are placed with an equal spacing of 200 mm along the long side. Nine lead zirconate-titanate (PZT) disks made of ferroelectric soft piezo material (PIC255) by Physik Instrumente (PI), 10 mm diameter and 0.25 mm thickness, are bonded on the plate surface through a vacuum based secondary bonding procedure commonly used by aircraft industries (See Figure 4). The diagnostic signal is emitted by an arbitrary waveform generator (HP/Agilent 33120A), as a 4.5 sine-cycles burst with 10 V peak-to-peak tension and windowed using Hanning function to obtain a narrow-bend curve in the spectral domain. The carrier frequency of 60 kHz is chosen to obtain an excitation ensuring the best compromise between tuning of the first antisymmetric Lamb wave mode A_0, A_0 /S_0 amplitude and optimal design geometrically constrained by the bay dimension [4]. An amplifier is used to boost the voltage with up to 80 Vpp increasing the signal to noise ratio. The ultrasonic signal is then digitalized and recorded with a four channel digital oscilloscope with up to 1 GHz sampling rate (Agilent InfiniiVision DSO7104A). Finally, the digitized ultrasonic signals are downloaded to a personal computer for data post processing.
To carry out damage detection and size assessment, it is assumed that:

- The wave signal is reflected by the stringer web with the same incident angle (Snell's law).
- The incident A_0 mode is reflected as A_0 mode only (i.e. the A_0 to S_0 conversion is negligible).

Starting from the expected velocity measured through direct wave propagation from T to R, the stringer reflections are time windowed from digitized signals for each considered reflected path. The window size is that ensures to totally include the portion of signal redirected by the stringer defining an opportune time interval. Thus, the damage indicator, DI, is computed to monitor each control point on the base of generalized energy contained by the wave supposed to be reflected from that point. The feature is extracted from current (damage structure) and baseline (pristine structure) signal as follows:

$$DI = \frac{|f_{CS} - f_{BS}|}{f_{BS}};\ f_{BS} = \int_{t_i}^{t_f} s_{BS}^2(t)\,dt;\ \ f_{CS} = \int_{t_i}^{t_f} s_{CS}^2(t)\,dt$$

where t_i and t_f are the time window delimiters, while s_{BS} and s_{CS} are the UGW signals acquired on the pristine (left) and debonded (right) region, respectively. Other than UGW signals acquired for the SHM dataset, non-descructive inspections are performed using both PAUT and LS.



(a) (b)

Fig. 4. Experimental setup for UGW local monitoring aiming at stringer debonding assessment. Composite panel made by carbon/epoxy material and stiffened with five C-type stringers uniformly spaced. Area A is used for preliminary testing, while area B is used for SHM validation.

The stringer debonding, highlighted in Figure 4 (b), is obtained through hand pressure and simulates different damage severities typically shown in barely visible impact damage. The disbonded area shows two characteristic regions. Two side regions (A and C) exhibit disconnection between stiffener and skin only, while the central region (B) also exhibits delamination which results in skin thickness reduction. This second type and more severe damage usually characterizes the area around the impact zone.

2. Results

The identification of the stringer debonding in the stiffened composite structure is based upon SHM measurements and compared to non-destructive testing using PAUT and LS, respectively. Figure 5 shows the damage indicator trend versus the scanning line, X, whose zero is set at the coordinate of the first PZT. It is worth noting that the SHM reveals the three different regions clearly. The damage indicator increases when the debonding occurs (A, and C) and further increases when the skin is also damaged (B). A very low DI is instead obtained where the stiffener is correctly bonded, which is mostly due to noise level in the measurements.

From PAUT NDE in Figure 6 it is possible to define clearly the three different characteristic regions. Starting from the left (X= 0), it is possible to detect a first undamaged region where the through thickness phased array investigation correctly returns the plate interface (blue regions) and the stiffener interface (i.e. the central red region). Then a first damaged area (A) can be assessed between X= 55 mm and X= 100 mm, where the disboding is increasingly evident due to the central area that returns a different echo amplitude confirmed by the mixed orange and dark blue area. From X= 100 mm to about X= 160 mm the echo response changes and defines the dark blue and orange big spots, according to the increasing severity of damage which characterizes the third region (B). In this area it is indeed present a skin thickness reduction which is confirmed by visual inspection and due to the forced manual disbanding which pulled part of the skin. Following, the region (C) between X= 160 mm and X= 190 mm is quite similar to the first damaged area observed. Finally another undamaged area is correctly detected after X=190 mm.

Instead, laser shearography inspection result is depicted in Figure 7, which shows clear evidence of the debonding occurring at the right stringer. The size of the damage and also its shape can be detected clearly. In addition, even though the quantitative assessment is hard achieving, the severity of the damage can be qualitatively interpreted from the diagnostic image, showing a more severe debonding in the middle of the damage area.

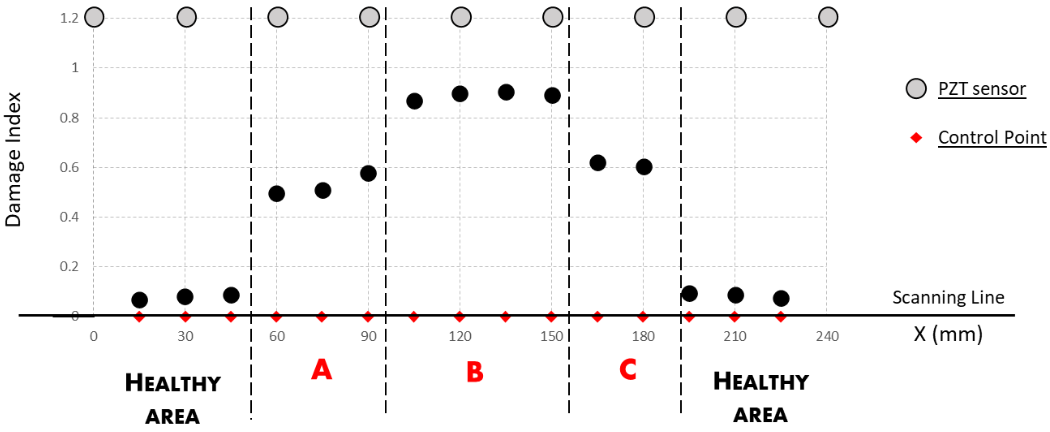


Fig. 5. Distribution of Damage Index vs. X, which provides the coordinate along the scanning line

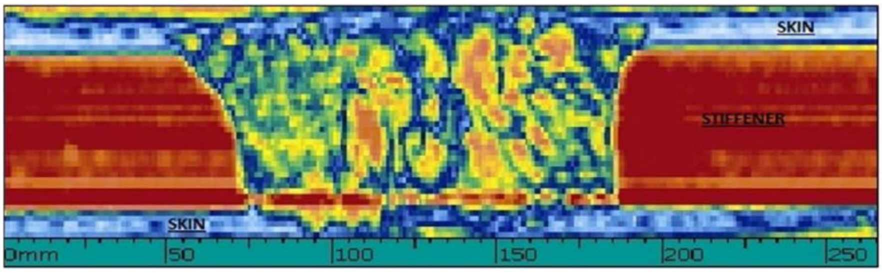


Fig. 6. C-scan report obtained by phased array ultrasonic testing. X coordinate in accordance with SHM

Fig. 7. In plane view of LS map carried out on a whole panel bay consisting in one intact (left) and one debonded (right) stringer.

3. Discussion

Table 1. Damage assessment obtained with proposed SHM and classic NDE based on PAUT and ST.

Approach	Overall Length [mm]	A length [mm]	B length [mm]	C length [mm]
SHM	135 ± 15	45 ± 15	60 ± 15	30 ± 15
PAUT	135 ± 1	45 ± 1	60 ± 1	30 ± 1
ST	135 ± 0.1	~	~	~

Table 1 summarizes the results obtained by different approaches and showed in Figures 5, 6, and 7, respectively. They are proposed in this paper for multi-modal damage assessment having different advantages and drawbacks. Compared to PAUT, which is the standard NDT technique in composite aerostructures, SHM approach shows a very good size capability and severity assessment at the cost of an increased uncertainty. Nonetheless, it does not require any on-site inspection or skilled personnel, provide a cost-effective maintenance solution. Otherwise, ST shows a very good diagnostic capability with a more simple non-contact setup, ensuring both fast inspection and quality of results. Nonetheless, it cannot achieve the quantitative assessment ensured by PAUT, which also allows to look into the damage severity through a variety of data post-processing techniques resulting in A-, B-, S-, and C-Scan diagnostic maps. However, the synergistic use of these three techniques can be exploited to enable efficient predictive maintenance; continuous monitoring through the lifetime can be demanded to UGW SHM, whose damage warning can be efficiently assisted by the a first fast shearography scanning and, when needed, by a second more demanding round of inspection through PAUT. This procedure can alleviates the demand for expensive an time consuming inspections. Otherwise, multimodal inspection can be settled to enhance the diagnosis implementing a reasonable reasoning approach to effectively combine uncertain information and make use of such complementary approaches.

3. Concluding remarks

This paper presents non-destructive evaluation and Structural Health Monitoring of impact induced damage in composite structures using ultrasonic approaches and shearography. The results obtained from full-scale composite specimen with induced debonding showed the ability of these techniques to recognize debonding accurately and the complementarity thereof. In addition, advantages and drawbacks of these approaches allow to conceive an inspection procedure where SHM and two level NDT is exploited to achieve cost-effective predictive maintenance.

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