Experimental application of Lamb wave based SHM system at complex composite material structures

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Abstract

Due to the high sensitivity to damage and defects, the actual potential of composite materials in civil aviation is not fully exploited, resulting often in increased structural mass and expensive maintenance approaches. In the last decades, many attempts have been doing in order to reduce the conservatism of the current design approach, and to improve time and cost-saving maintenance procedures by considering the application of SHM systems tailored for composite structures. In SMAF project, the application of SHM systems is finalised to replace the current two levels of the traditional maintenance approach based on visual and NDI inspections, with only one level entirely focused on SHM inspections, and also to support the design of new structures by achieving consistent weight reductions respect to the current design methods. Under this topic, this work is concerned with numerical and experimental application of an SHM system for the detection and characterization of low-energy impact damages on composite stiffened panels. The SHM system presented is based on the elliptical triangulation method and high frequency Lamb waves. In the last years, few non-destructive techniques based on measurement of Lamb waves were developed, and on the same approach is based the elliptical triangulation method presented in this paper. Through the calculation of the Time of Flight (ToF) of the signals and the knowledge of the actuator-sensor position, the method identifies position and dimension of the damage. The effectiveness of the method has been validated for stiffened CFRP structures, via simulations and tests, and it is presented in this article. Low-velocity damage impacts have been induced in the above panels. The numerical results for damage detection, position and area measurement, have been correlated with the experimental ones. The capability of the SHM system to evaluate the position and the damaged area on complex structures has been discussed. The damage detection results (positioning and sizing of the damage) evaluated with the ellipse triangulation method have been compared with those ones obtained using the ultrasonic C-scan.

1. Introduction

The use of composite materials for civil aircrafts is nowadays a consolidated reality which arises from the aim to produce performing structures with a structural weight, production, operational and maintenance costs, lower than those ones coming from the use of the conventional metallic materials. The topics of investigation regarding the applicability of the CFRP materials in the aeronautical field, vary among the optimisation of the manufacturing processes (in terms of final costs and times),
integrated and one-shot components for reducing the number of the parts and the use of mechanical joints (with a consequent reduction of the final weight), more tailored and net-shape parts. On the other hand, the use of the composite materials implies also different and new criticalities due to their intrinsic characteristics that can limit their potential benefits. Among these limits, there is in particular their high sensitivity to low energy impact damages that can reduce dramatically their residual strength under loads. The current certification rules,(1) foresee to size the aircraft composite structures by supposing them already characterised by both manufacturing defects and impact induced damages, not detectable by the visual inspection. The upper limit of this kind of damages, Category 1 (1), is the BVID (Barely Visible Impact Damage). The structural substantiation for BVID damage includes demonstration of a reliable service life, while retaining ultimate load capability and its repair is not required. This approach obviously implies oversized structures. In the past decades, in order to avoid structural oversizing induced by certification rules, many scientists worldwide have approached the problem of the damage identification in composite structures trying to demonstrate how the reliability of the service life could be controlled even when a structural damage occurs. Hence, structural health monitoring (SHM) techniques aimed to monitoring components or structural parts to detect the damage initiation, damage propagation up to the failure of the structure, have been developed. Generally, SHM techniques aim to implement systems able to detect the damage in a nondestructive way. Moreover, based on which parameters are monitored, these techniques can be divided in “global scale methods” and “local scale methods”. The global scale methods, used generally for the full wing or fuselage, detect the damage analyzing the changes introduced by damage in the structural modal properties (natural frequencies, modal shapes, etc.) (2-6), but their limited sensibility is such to make them unusable when the detection of very small damage is required, since this doesn't introduce considerable changes into the structural modal properties. Conversely, the local scale methods allow to detect the damage also when it is still at early state, like the BVID damage condition.

The firsts local scale damage detection methods developed in 1990s (7-12) were able to detect the crack initiation based on the variation of the elastic waves and the changes in structural impedance measured into the structure. In recent years, thanks to the improvements in signal processing techniques applied in methods based on the propagation of ultrasonic waves (13-17), considerable benefits in terms of sensitivity and accuracy of the damage detection in structures have been obtained. Methods based on the analysis of the Lamb waves using the short time (STFT) and fast (FFT) Fourier transforms, as well as method-based wavelet transform (WT) were developed (18, 19). Further ultrasonic waves techniques used for damage detection are the artificial neural networks (ANN) and the probability ellipse (PE) (20-22). Starting from the damages indexes calculated on each sensing path, De Fenza et al. (22, 23) applied both methods for the damage detection. Additional method uncoupled with the calculation of the damage indexes was proposed by Sorrentino et al (23, 24). They highlighted how the elliptical triangulation method (ETM) which based on the propagation of ultrasonic waves (Time of Flight - ToF) in each actuator-sensor path, was able to identify position and dimension of the damage on both metallic and composite material flat plates first, and in stiffened composite material structures later. Under this topic, this paper shows some results obtained by the development of a dedicated off-line SHM system, based on PZT sensors/actuators, able to detect and measure the extension of impact damages using the elliptical triangulation method applied to some stiffened structures in
composite material. This system was appropriately performed in order to achieve the target of SMAF project coordinated by CIRA and funded by Italian Program for Aerospace Research: overcome the above conservative design approach and improve the current maintenance methods. The research activities were performed assuming as reference items small flat stiffened panels, representatives of the upper skins, loaded in compression, of a typical wing box of a regional aircraft. Low energy impact damages were induced in the middle of the stringer bay and for different energy levels. The small panels had a dimension of 230 mm (stringer direction) x 350 mm with two T shaped stringers.

### 2. New design approach based on SHM system

Since the beginning of their development in aircraft field, SHM systems were exclusively conceived for maintenance purposes, in order to potentially reduce through-life costs by the adoption of a Condition Based Maintenance approach. In many cases, they also could allow to monitor not accessible areas, avoiding for those parts an ultraconservative design in recognition of the inability to access the structural component. In the last decade, the aircraft manufacturers and designers have realized that the SHM systems can also to be a fundamental support to design new composite structures with a considerable weight reduction.

The high sensitivity of composite materials to the BVID penalizes the design in terms of thickness and weight of the final structure, because often the reduction of the material design allowable due to the BVID is affected by conservatisms linked essentially to the limitations of current techniques for the inspection and measurement of the BVID, including visual inspection. The reduction of the strength of a laminate in presence of BVID is a function of many parameters: the impact energy level, thickness, stacking sequence. Many aircraft composite structures are currently overdesigned due to the requirement for safe operation with this kind of undetected damage. The BVID is usually defined as damage that is “barely” visible from a distance of 1.5 meters under ambient light conditions and it has been tied to a specific indentation size: usually 0.8-1 mm deep indentation (25, 26). Currently the certification compliance of composite structures is traditionally accomplished from the civil aircraft manufacturers by mainly applying no-growth design approach for nonvisual damage and a high knock-down factor to the material strength properties to take into account the effects of BVID. Besides, the design is performed by considering the structure uniformly damaged and applying the first-ply-failure design criteria. Particularly, a BVID knock-down factor is conservatively selected even up to a value of about 0.4, reducing the material strength properties up to 60%. The use of an off-line SHM system has instead the potential to reduce many of the current uncertainties and overdesigns and could permit increased design allowable leading to lighter and more efficient structures (27). It could detect the presence of defects and damages in the structure at sizes smaller than those currently assumed for design and certification by the visual inspection (BVID). In detail, SHM systems can allow to design with higher design allowable thanks to a more reliable detection of the current BVID, improving the static strength (compression after impact) of the composite structures for a reduced damage size detection. The detection by SHM of a BVID smaller than that one identified by visual inspection (0.8/1 mm) consequently implies the adoption of a higher material allowable for the design of the composite
structure with a consequent reduction in weight. In the same time, the SHM system could reduce of relevant percentage operative costs for airlines by modifying the current damage assessment process from a 2 Level approach (visual inspections followed, if required, by NDT/C-Scan) to a single step approach based on the interrogation of the system.

3. Elliptical Triangulation Method (ETM)

The damage detection method used in this paper is the elliptical triangulation method which is based on the propagation of ultrasonic waves in each sensing paths. Once verified the effectiveness of the method on flat plates (23), the authors tested, numerically, its efficiency also when applied to complex structures affected by impact damage (24). In this work, the ETM method is applied to flat stiffened panels, representatives of the upper skins of a typical wing box of a regional aircraft, subject to low velocity impact test. As highlighted by Sorrentino et al. (23,24), the uncertainty of the waves propagation speed induced by the anisotropy of the material, that represents the main method limitation when applied to structures realized in composite material, can be overcome through an iterative approach which is based on the initialization of the waves propagation speed at first iteration.

![Figure 1. Functional scheme of the ETM method applied to flat plate, with actuator-sensor path (LS) and actuator-damage-sensor path (L1+L2)](image)

Any discontinuity inside the structure, such as the damage, generates reflected waves representing the perturbation. The perturbation path, given by actuator-damage-sensor path \((L_1 + L_2)\), can be connected with the time of flight and the wave propagation speed of the disturbance as follow:

\[
L_1 + L_2 = V_p * t_d
\]  (1)

The Equation 1, written for some sensing paths become a system of equations that solved give out the exact position of the damage. Past studies (23) have demonstrated that a minimum of three sensing paths are needed for a correct identification of the damage while, at least four are required to evaluate the dimension of the damage.
4. Numerical and Experimental application on stiffened CFRP structures

Concerning the experiments, flat stiffened panels (Figure 2), representative of the upper skin of a typical regional aircraft wing-box, were used. Two main skin layups were investigated having respectively 12 (wing tip) and 24 plies (around the middle span of the wing) with same stringers in terms of layup and thickness (Table 1). To assess the reliability in damage detection, three same 12-ply skin panels were manufactured and tested; therefore, four panels were equipped with an array of 4 PCB sensors, following the scheme reported in (23). The Lamb waves propagation data were acquired on both undamaged and damaged configurations using pitch-catch approach. The damaged configuration was obtained through low-velocity impact tests conducted with an impact tower at energy of 15 and 30 joules. The single impacts were induced in the middle of the stringer bay and centre of the panel: 15 joules for the 12-ply and 30 joules for the 24-ply.

![Figure 2. Lateral views of the 24-ply (a) and 12-ply (b) panels, with stringers top view (c)](image)

Table 1. Panels and stringers layup specifications

<table>
<thead>
<tr>
<th>n. ply</th>
<th>Layup</th>
<th>Thickness (mm)</th>
<th>n. ply</th>
<th>Layup</th>
<th>n. ply</th>
<th>Layup</th>
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<td>12</td>
<td>[45,-45,0,90,45,-45]s</td>
<td>2.23</td>
<td>12</td>
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<td>24</td>
<td>[45,-45,0,90,0,90,0,90,-45,45]s</td>
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<tr>
<td>24</td>
<td>[45,-45,0,90,45,-45]2s</td>
<td>4.46</td>
<td>12</td>
<td>[45,-45,0,90,0]s</td>
<td>24</td>
<td>[45,-45,0,90,0,90,0,90,-45,45]s</td>
</tr>
</tbody>
</table>
In order to confirm the effectiveness of the ETM method in damage detection as reported in (23, 24), the experimental results obtained on the 24 plies panel, were compared with those obtained numerically (Figure 3). The panel and stringers were considered perfectly joined. In order to ensure the correct waves simulation, the stiffened panel was modelled using the approach described in (21). By numerical point of view, an artificial damage applied in the impacted area was used to represent the damage due to 30 joules low-velocity impact (22).

![Figure 3. Stiffened panel (a) and detail of the stringer (b)](image-url)

In the following are reported the test results in terms of NDI images with the overlap of the ellipses calculated using the Elliptical Triangulation Method (ETM) for the panels subjected to impact energy of 15 joules and those obtained numerically and by test at the impact energy of 30 joules.
Figure 4. NDI and ETM results respectively on stiffened panels Exp47 (a), Exp48 (b) and Exp49 (c)

(a) (b) (c)

Figure 5. Comparison between experimental (a) and numerical results (b) on 24 plies panels

Table 2. Results overview

<table>
<thead>
<tr>
<th>Panel ID</th>
<th>n. ply</th>
<th>Impact Energy [J]</th>
<th>Damaged area measured by NDI [mm²]</th>
<th>Damaged area evaluated by ETM [mm²]</th>
<th>Diff. [%]</th>
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<tr>
<td>Exp47</td>
<td>12</td>
<td>15</td>
<td>57</td>
<td>45</td>
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<td>24</td>
<td>30</td>
<td>133</td>
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<tr>
<td>Num52</td>
<td>24</td>
<td>30</td>
<td>147</td>
<td>134</td>
<td>9</td>
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</table>

Regarding the 12-ply skin panels, the results highlighted that the ETM areas were quite close to the NDI ones; also, the positioning comparison resulted well satisfied. In detail, the damaged area evaluated by ETM, is averagely around the 25%, while the evaluated position of the affected damage zone is very close to the real one highlighting the high reliability of the method in the damage positioning detection.

Concerning the test conducted at impact energy of 30 joules (24-ply skin panel), the difference between the damaged area evaluated by the ETM and that measured by the NDI is instead about 35%, higher than the previous ones. Also, the positioning was resulted well satisfied. Currently the authors are investigating additional test cases, more wide test matrix, in order to better understand this results, in terms for example of...
influence of higher thicknesses on lamb wave propagation characteristics. The same test case analysed numerically have instead confirmed the effectiveness of the method in damage detection highlighted a 9% difference between the simulated damage area in the FE model (147mm$^2$) and those evaluated by ETM method (134mm$^2$). Additional details concerning the measured damaged areas and the evaluated ones are reported in Table 2.

6. Conclusions

For the 12-ply skin panels the average value of the damage indentation (dent depth) corresponding to the impact energy of 15 joule is resulted 0.06 mm, while the unique value for the 24-ply skin panel is resulted 0.09 mm. Both the values are very lower than the accepted threshold of 0.8/1 mm detectable by a visual inspection and that defines the standard BVID also used for the design approach (§ 2). Therefore, these damages would not be detected by the visual inspection (1$^{\text{st}}$ level) but probably only by the next application of NDT/C-Scan (2$^{\text{nd}}$ level). The SHM system, by an off-line approach could instead give the localization and entity (in terms of damage area rather than deep indentation) in a very smart and fast way and by a single intervention. On the other hand, the possibility to detect a damage lower than the BVID, with whom the current panel has been sized at the beginning of the design, could give the possibility to obtain a lighter panel, for the same design loads, by simply defining a new upper threshold of the Category 1 of damage, based on the sensitivity and reliability of the SHM system. Probably in the future could be possible to define a BSID ( Barely SHM Impact Damage) rather than using the BVID, allowing to size a panel lighter than the conventional because of using an higher compressive design allowable. Preliminary analyses developed in (2) have shown that a reduction of weight of also 10% would be achievable by redesigning the 24-ply skin panel with the BSHM. Regarding the results, the SHM system presented in this work is very promising even if more analyses and improvements are necessary to reduce the gap between the C-Scan areas and those ones measured by the SHM system. In general, the minimum gap (expected by around 10-15%) needs to be such to ensure that the gap doesn’t affect the expected compression after impact residual strength of the structure. For this reason a wider test matrix is under investigation including other panels with different layups and thicknesses and energy impact levels. Besides, more than one impact induced in the skin of the stiffened panel, and in different locations (under the stringer cap and/or the edge of the cap), will be under investigation.

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References

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