STRUCTURAL HEALTH MONITORING OF COMPOSITE STRUCTURES WITH USE OF EMBEDDED PZT PIEZOELECTRIC SENSORS

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Abstract
One of the ideas for structural health monitoring systems built is based on the measuring of the mechanical properties of materials used for aircraft structural elements. In the paper we present an approach to develop such system with use of sensors embedded into the composite structure. Beside the sensors durability and less energy loss when generating an elastic wave, the reasons for the sensor embedding are twofold: there is virtually no possibility to use them in a different way when considering structure repairs with composite patches but also in the case of FML like structures it improves damage detection capabilities, e.g. allows for distinction between inner layers delaminations and debondings between layers made of different materials. The results of impact tests, the signal analysis algorithms and the influence of composite manufacturing process on various transducer properties are presented.

1. Introduction

The current methods of assuring integrity of structures used in the aerospace may become insufficient because of the safety as well as economic issues. The foundations of the most commonly adopted *damage tolerant* design philosophy relies on profound knowledge of fatigue durability and other material properties used in the aircraft manufacturing, an assumed load spectra of the structure and damage detection capabilities of non-destructive testing methods. However the way in which the particular aircraft is operated after it enters into the service doesn't necessarily fit to its statistical representation. The reliability of non destructive tests (NDT) is assessed in the so called PoD studies [1] under laboratory conditions, thus does not fully encompassing the human factor. Furthermore introduction of broad NDT programs as a necessary compound of the *damage tolerance* approach heavily affects the aircraft maintenance costs.

Therefore conventional nondestructive testing techniques are nowadays supposed to be complemented by systems of structure integrated sensors continuously monitoring its health. Application of such methods would definitely increase safety, especially when considering hardly accessible 'hot-spots', but also it could save up to 50% of necessary inspections time depend-

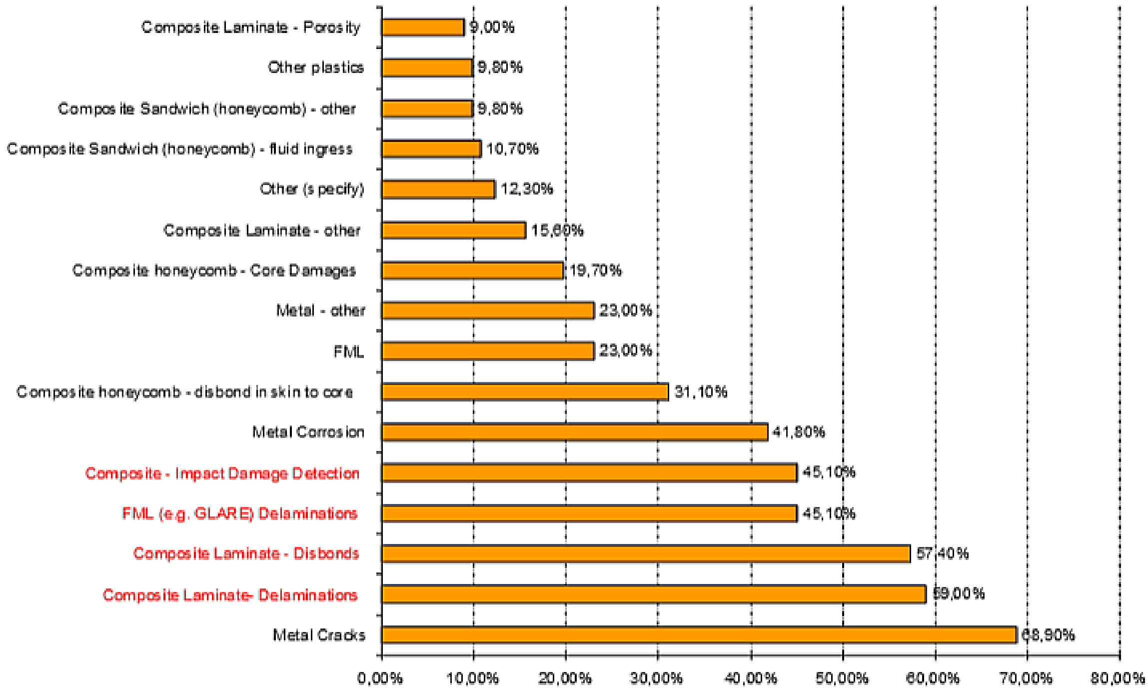

Figure 1. Potential SHM applications with respect to the aerospace industry needs [3].

ing on the aircraft type [2]. The figure 1 shows a survey of the aerospace industry needs [3] regarding Structural Health Monitoring (SHM) systems. The fact that composite structures are in the top of the industry demands list is not a coincidence. This is precisely the case focusing both the safety and economic issues. First composites are vulnerable to random in nature impact damages, burdening the determined time interval between subsequent inspections with additional risk factor. Their wear-out process is to a high extent unknown, at least comparing to metallic structures which has another adverse effect on the safety. Furthermore even impacts of low energy can form an extensive network of cracks and delamination deployed under the surface of an element causing severe loss to their strength. Such damages are invisible or barely visible on the boundaries hindering the use of low cost NDI methods, therefore a reliable SHM system allowing for automated detection of such damages is highly desired.

In the paper an approach to detect Barely Visible Impact Damages (BVID's) with use of embedded PZT transducers network is presented. In the following section the overview of the approach is presented, then the influence of composite curing process on basic parameters of the transducers is investigated and finally the results of impact tests are provided.

2. Structure monitoring via PZT transducers

One of the ideas for structural health monitoring systems built is based on the measuring of the mechanical properties of materials used for aircraft structural elements. The approach is based on analysis of small displacements propagation excited in the element by a network of PZT piezoelectric actuators [4, 5]. Solution for small deformation dynamics of the medium strongly depends on the boundary conditions, in particular the geometry of the object and its

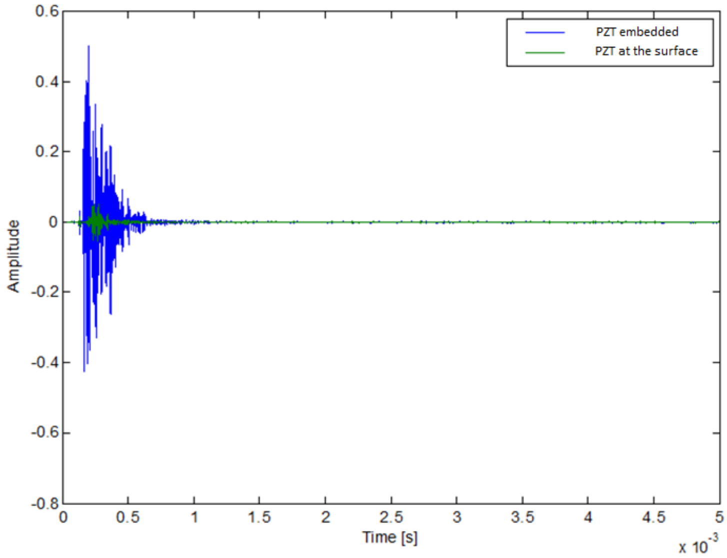

Figure 2. The signal comparison for PZT transducers embedded into the structure and bonded to its surface.

distortions caused by discontinuities and deformations. Structural damages can thus result in observable changes of the signal generated by the network sensors. The state of a monitored structure is assessed based on chosen signal characteristics called the Damage Indices (DIs). The acquired signals can be also influenced by factors other than damages thus posing a risk of false indications. Therefore DI's used for the structure assessment needs to be balanced between sensitivity to damages and stability under varying working conditions of transducers. In the adopted approach the DI's carries marginal signal information content. Denoting as f_{gs}^{env} the envelope of a signal generated by the transducer g and received by the sensor s and as $f_{gs,b}^{env}$ the envelope of the corresponding baseline, i.e. the reference signal obtained for the initial state of the structure, the proposed Damage Indices are given as follows [6]:

$$DI_1(g,s) = 1 - cor(f_{gs}^{env}, f_{gs,b}^{env}), \qquad DI_2(g,s) = \left| \frac{\int (f_{gs}^{env} - f_{gs,b}^{env})^2 dt}{\int (f_{gs,b}^{env})^2 dt} \right|, \tag{1}$$

where $cor(f_{gs}^{env}, f_{gs,b}^{env})$ stands for the sample correlation of the two signals. Both of the proposed DI's are correlated with the total energy received by a given sensor but also with its distribution in time during the measurement. Structure discontinuities caused by BVID's dissipate the wave energy due to wave scatterings on delaminations but can also alter its time redistribution due to local stiffness changes and related propagation speed shift of the incoming wave packets. Both of the effects can be captured by the proposed Damage Indices. As will be shown in the following, the above DI's are changed the most whenever a damage occurs on a direct path of wave propagation between a generator g and sensor s, i.e. a sensing path. The information from all of the sensing paths consisting a given network can be merged in Averaged Damage Indices (ADI's), defined as follows:

$$ADI_j = \frac{1}{n(n-1)} \sum_{g,s:g \neq s} DI_j(g,s), \qquad j = 1,2, \tag{2}$$

where n is the number of transducers in a network measurement node. ADI's are better suited for damage size estimation due to their decreased dependence on the damage localization.

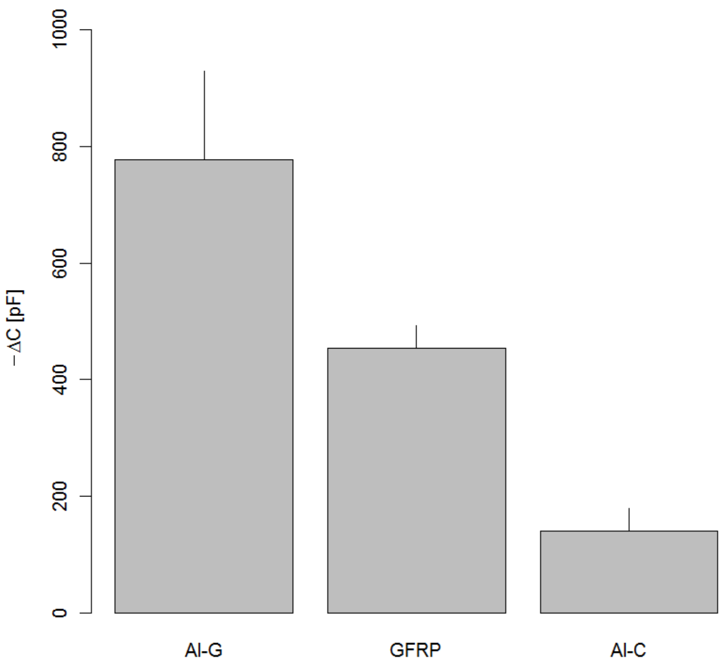

Figure 3. The mean capacitance change of PZT transducers and its standard deviation after different curing cycles.

3. Embedding PZT transducers into a composite structure

Regular PZT piezoelectric transducers generates in plate like structures the so called Lamb waves. The displacement field in this solution along the direction orthogonal to the plate surface is stationary. In metallic structures such stationary initial conditions can be delivered by the transducers mounted at the surface of an element. In the case of composites also their embedding is possible. The drawback of the last approach is that from the mechanical point of view the transducers can be considered as foreign object inclusion having an adverse effect on the strength. However Lamb waves generated by PZT sensor can travel a significant distance thus they can be placed where other structural reinforcements are present. Transducers embedding provides much better coupling with the medium, thus the signal amplitude and its ratio to the noise (SNR) are much better in that case. The figure 2 shows the signal acquired for two pairs of transducers for the same parameters of the excitation: one embedded into the composite structure and the other bonded to its surface over the embedded PZT's. The energy consumption can therefore be lowered when embedding which may be an issue in some applications. Furthermore in some cases, e.g. for composite patches repairs bonding transducers to the element surface is not allowable.

One of the parameters related to electro-mechanical and geometric properties of transducers having impact on their performance is the capacitance. The signal is usually much stronger for sensors having it higher. The curing process of the composites, i.e. long exposition on the temperature and the pressure may affect transducer physical properties and the geometry resulting in particular in change of its capacitance. The plot (Fig. 3) shows the mean decrease of that parameter after different curing cycles. The Al-G, Al-C was a process of manufacturing fiber metal laminates (FML) reinforced with glass or carbon respectively. In addition for Al-C specimens the transducers needs to be isolated by non conductive coating. In that case PZTs were embedded in thin GFRP laminates prior to Al-C manufacturing. The one way ANOVA analysis shows statistically significant decrease of capacitance in all of the cases. The change also differs significantly between all of the groups. The least decrease for Al-C specimens may be connected with the fact that one curing process for the transducers had already been done before their final manufacturing. However the joint effect was similar as for Al-G specimens and was about 40% of the initial capacitance. Despite the described changes, the performance of the embedded transducers is still much better (Fig. 2).

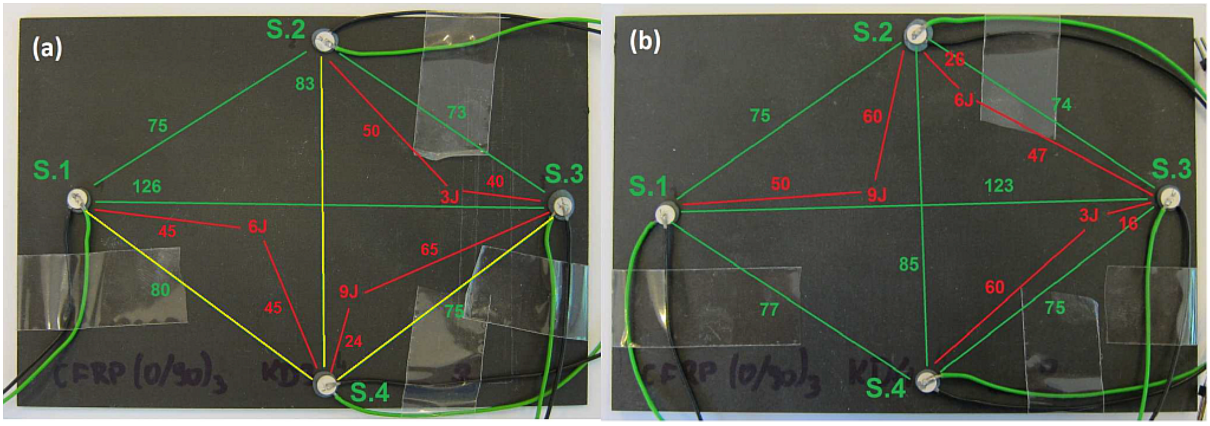

Figure 4. The PZT sensor network geometry with indicated impact localizations for the specimens: (a) specimen no. 1 and (b) specimen no. 2.The dimensions are given in millimeters and the sensing paths neglected in the analysis are marked in yellow.

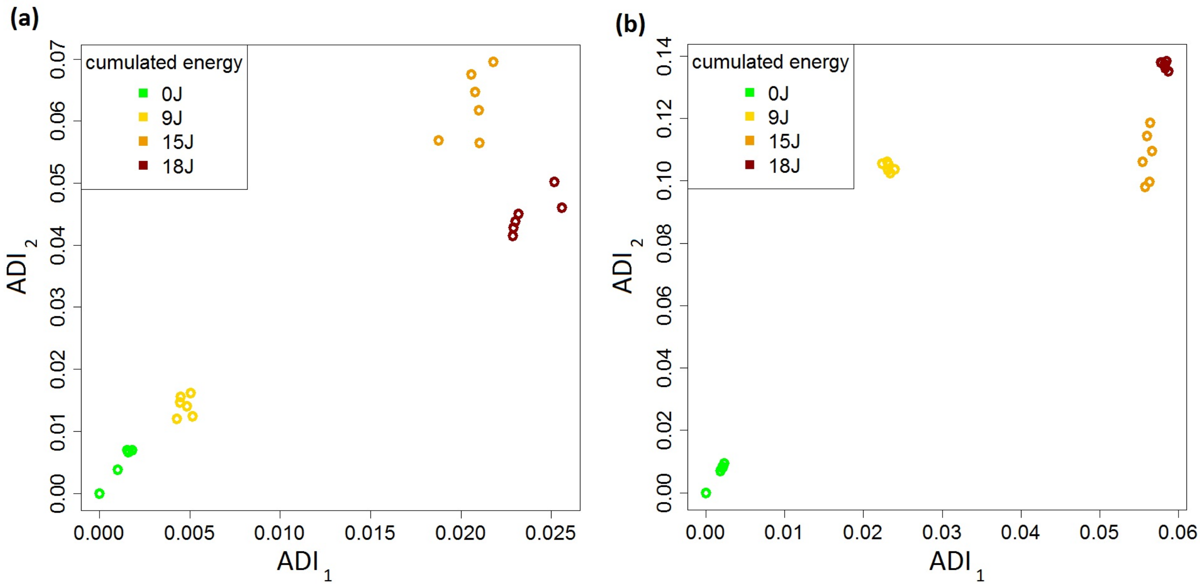

Figure 5. Averaged Damage Indices with respect to cumulated energy of impacts: (a) the specimen no. 1 and (b) the specimen no. 2.

4. Results of impact tests

In order to test BVIDs damage detection capabilities in this approach, impact test of CFRP specimens were performed with PZT sensor network attached to the surface. Impacts with energies: 9J, 6J and 3J were carried out subsequently and after each of them a series of signals generated by the PZT network were collected. The following figures presents the network geometries with indicated impact localizations (Fig. 4) and Averaged Damage Indices with respect to the cumulative energies of impacts (Fig. 5). In the case of the specimen no. 1, the sensor S.4 was damaged during the test, therefore it was neglected in calculating ADIs. The changes of ADIs depends on the length of the cross sections between delaminations and network sensing paths. This is the most evident comparing the data corresponding to impacts of 9J energies for both specimens. For the specimen no. 1 such BVID is located near sensing paths originated from the neglected sensor. The only contribution to ADIs value can come from the path conformed by sensors S.1, S.3 running slightly through the damage, therefore there is a little change of ADIs for that group of data (Fig. 5 (a)). In the case of the specimen no. 2 the 9J impact is located precisely along active sensing paths 1 – 3, 2 – 4 thus resulting in significant change of ADIs (Fig. 5 (b)) and the same occurs for the 6J impacts for both of the specimens. However the separation of data is less evident for delaminations caused by 3J impacts, despite they are located in direct vicinity of operating sensing paths, providing a hint about damage detection capabilities of the system.

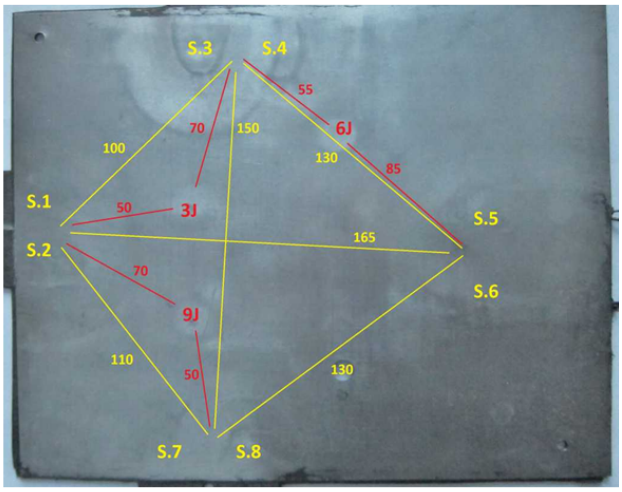

Figure 6. The FML specimen with transducers embedded in two different layers with indicated impact localizations. The network geometry and impact localization given in millimeters.

The tests were also performed for FML specimens with embedded PZT network. The figure 6 shows a FML structure having an inner aluminum layer separating two CFRP laminates with embedded PZT transducers. The PZT networks had 4 transducers each, the network consisted from sensors S.2–S.4–S.6–S.8 was placed in the upper layer of the specimen. Both of the networks had virtually the same geometry (Fig. 6). The plot (Fig. 7) presents the ADIs obtained in that case. The results are shown with respects to the impact energy meaning that new baseline signals were collected after each impact. Higher SNR for embedded transducers results in better measurement repeatability revealed here in lower dispersion within each group of data. Similarly as in the case of sensors attached to the surface (Fig. 5) the impact of energy 3J is indistinguishable from the undamaged state whereas the 9J impact is well clearly visible in both cases. However the 6J impact was better separated from undamaged state for the network placed in the top layer of the specimen (Fig. 7(b)) than for the bottom one (Fig. 7(a)). This can be due to higher damage severity in the layer directly exposed on the impact.

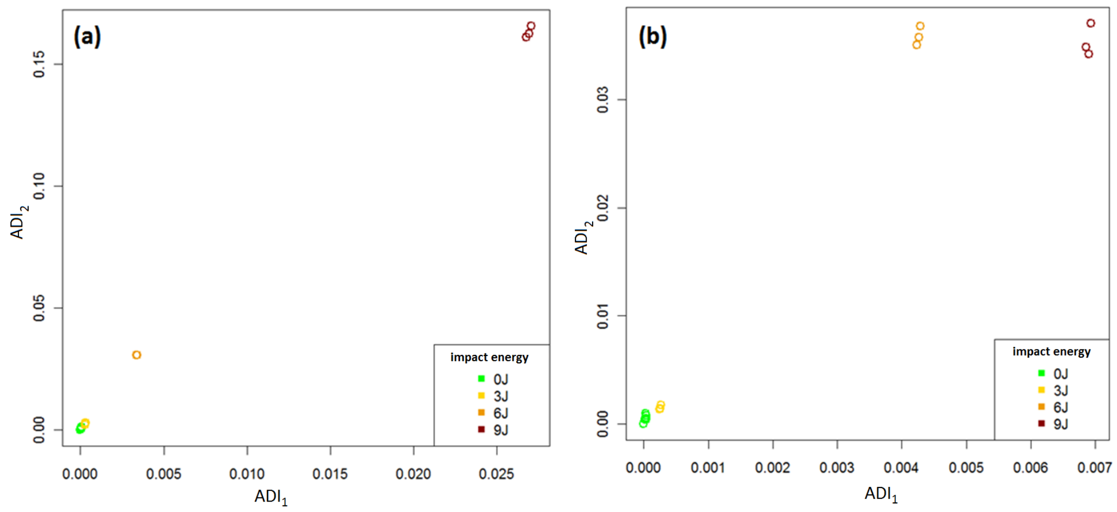

Figure 7. Averaged Damage Indices with respect to the energy of impacts for FML specimen: (a) the network embedded in the bottom layer (b) the network embedded in the top layer.

5. Summary

In the paper an approach to monitor barely visible impact damages of composite structures with use of piezoelectric transducers was presented. The impact of composite curing process on capacitance of structure embedded sensors was investigated. The technique allowed for the detection of impacts with energy higher than 3J. In the case of structures consisted of many layers equipped with the transducers separated by media of distinct acoustic impedance it opens an opportunity to differentiate the damage severity across them.

References

[1] United States Department of Defence. *MIL-HDBK-1823A: Nondestructive evaluation system: reliability assessment*, 2009.

[2] C. Boller and W.J Staszewski. Aircraft structural health and usage monitoring. In W.J. Staszewski, C. Boller, and Tomlinson G.R., editors, *Health Monitoring of Aerospace Structures*, pages 29–73. John Wiley and Sons, Ltd, 2004.

[3] D. Roach. Industry survey of structural health monitoring technology and usage. Sandia National Laboratories, 2012.

[4] V. Giurgiutiu. *Structural health monitoring: with piezoelectric wafer active sensors*. Academic Press, 2007.

[5] Z. Su and L. Ye. *Identification of damage using lamb waves: from fundamentals to applications*. Springer, 2009.

[6] K. Dragan, M. Dziendzikowski, S. Klimaszewski, S. Klysz, and A. Kurnyta. Energy correlated damage indices in fatigue crack extent quantification. *Key Engineering Materials*, 569:1186–1193, 2013.