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COMPOSITES THEORY AND PRACTICE

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# THE APPLICATION OF PZT SENSOR NETWORKS IN DEGRADATION MONITORING OF COMPOSITE AERONAUTICAL STRUCTURES

**One of the ideas to develop structural health monitoring systems is to use piezoelectric transducers generating elastic waves in a monitored structure. In the paper, we present an approach to develop such a system with the use of PZT ceramic (lead zirconium titanate - PZT) sensors embedded into the structure of a composite. Elastic waves actuated in an acoustic medium by a network of PZT transducers can be scattered on the discontinuities of the monitored structure, thus giving a possibility to detect such damages. For composites they can be debondings or delaminations caused by impacts. In that case, PZT transducers can be either bonded to the surface of an element or embedded in the internal structure of a composite. Both methods have their own advantages and drawbacks. Apart from increased sensor durability and lower energy consumption when actuating elastic waves, there are also other, more important reasons for sensor embedding. First, when considering structure repairs with composite patches, it can be hard to use PZT transducers attached to the surface due to their exposure to external conditions. Embedding may also increase the damage detection capabilities of the approach. For multilayered structures like Fiber Metal Laminates (FML), it may allow one to assess the state of each layer separately and to distinguish between inner layers delaminations and debondings between layers made of different materials. In the paper, we present an approach to detecting impact damages of composite structures which are barely visible on the surface (Barely Visible Impact Damage - BVID). The results of impact tests, signal analysis algorithms and the influence of the composite manufacturing process on chosen transducer properties are presented.**

**Keywords:** **composites, impact damage detection, structure integrated sensors**

## MONITOROWANIE DEGRADACJI KOMPOZYTOWYCH KONSTRUKCJI LOTNICZYCH Z WYKORZYSTANIEM SIECI PRZETWORNIKÓW PZT

**Jednym z rozwijanych sposobów monitorowania stanu konstrukcji jest zastosowanie przetworników piezoelektrycznych wzbudzających w diagnozowanym elemencie fale sprężyste. W artykule zaprezentowano propozycję budowy takiego systemu z wykorzystaniem ceramicznych przetworników PZT (cyrkonia-tytanian ołowiu - PZT) wbudowanych w strukturę kompozytu. Fale sprężyste wzbudzone w elemencie kompozytowym poprzez sieć czujników są rozpraszane na nieciągłościach struktury, np. rozwarstwieniach lub odklejeniach, spowodowanych udarami, dając możliwość detekcji tego rodzaju uszkodzeń. Przetworniki PZT mogą być trwale związane z powierzchnią monitorowanego elementu lub - w przypadku kompozytów - wbudowane w jego strukturę. Obydwie metody mają swoje zalety i wady. W przypadku kompozytów, oprócz większej trwałości czujników i lepszego sprzężenia akustycznego, za ich wbudowaniem w strukturę przemawiają również inne powody. Jednym z nich jest trudność w zastosowaniu przetworników umocowanych na powierzchni kompozytowych napraw poszycia samolotów ze względu na bezpośrednie narażenie na czynniki zewnętrzne. Wbudowanie czujników w wewnętrzną strukturę kompozytu może również zwiększyć możliwości diagnostyczne tej metody. W przypadku struktur wielowarstwowych o różnorodnej budowie, np. laminatów metalowo-włóknistych FML, może to umożliwić ocenę stopnia uszkodzeń poszczególnych warstw lub rozróżnienie pomiędzy uszkodzeniami wewnątrz- i międzywarstwowymi. W artykule zaprezentowano wyniki monitorowania uszkodzeń udarowych, stosowane metody analizy sygnału oraz wpływ procesu wytwarzania kompozytów na wybrane parametry przetworników PZT.**

**Słowa kluczowe:** **kompozyty, detekcja uszkodzeń udarowych, czujniki zintegrowane**

## INTRODUCTION

The current methods of assuring the integrity of structures used in aerospace may become insufficient because of safety as well as economic issues. Nowadays, the most commonly adopted approach when designing aircrafts is so-called damage tolerance. It relies on profound knowledge of fatigue durability and other material properties used in aircraft manufacturing, an assumed load spectra of the structure and damage detection capabilities of non-destructive testing methods. However, the way in which a particular aircraft is operated after it enters into service can be significantly different from its assumed - averaged form. The reliability of non destructive tests (NDT) is assessed in so-called PoD studies [1] under laboratory conditions. Such studies, while properly assessing the devices and methodology used in NDT, cannot fully encompass the human factor, especially when considering hard-to-access areas. Furthermore, the introduction of broad NDT programs as a necessary compound of the damage tolerance approach greatly affects aircraft maintenance costs. Therefore, conventional nondestructive testing techniques are nowadays supposed to be supported by systems of structure integrated sensors continuously monitoring the health of the structure. The application of such methods would definitely increase safety, especially when considering difficult-to-access 'hot-spots', and it could also cut the necessary inspection time by up to 50%, depending on the aircraft type [2].

In the paper, an approach to detect BVIDs with the use of an embedded PZT transducer network is presented. In the following section, an overview of the approach is presented, then the influence of the composite manufacturing process on the basic parameters of the embedded transducers is investigated and finally the results of impact tests are provided.

## STRUCTURE MONITORING VIA PZT TRANSDUCERS

The approach to structural health monitoring with the use of PZT transducers is based on analysis of the excited displacements propagation in a given element [3-7]. Elastic waves can be scattered on discontinuities, thus structural damages can result in observable changes of signals acquired by the sensors of a given network. The state of a monitored structure is assessed based on chosen signal characteristics called Damage Indices (Damage - Index DI). The signal can also be influenced by factors other than damages, thus posing a risk of false indications. Therefore, DIs used for structure assessment need to be balanced between sensitivity to damages and stability under varying transducer working conditions. In the adopted approach, the DIs carry marginal signal information content. Denoting as $f_{gs}^{env}$ the envelope of a signal generated by transducer $g$ and received by 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 DIs are given as follows [8]:

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

where $\operatorname{cor}\left(f_{gs}^{env}, f_{gs,b}^{env}\right)$ stands for the sample correlation of $f_{gs}^{env}, f_{gs,b}^{env}$. Both of the proposed DIs 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 dissipate the wave energy due to wave scatterings on delaminations but can also alter its time redistribution due to local stiffness changes and the 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 further analysis, the above DIs are greatly changed whenever a damage occurs on a direct path of wave propagation between the generator and sensor. Such a path is called a sensing path. The information from all of the sensing paths forming a given network can be merged in Averaged Damage Indices (Averaged Damage Index - ADI), defined as follows:

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

where $n$ is the number of transducers in a given node of the network. ADIs are better suited for damage size estimation due to their decreased dependence on the damage location.

## EMBEDDING PZT TRANSDUCERS INTO A COMPOSITE STRUCTURE

One of the parameters related to the electromechanical and geometric properties of transducers having influence on their performance is their electric capacitance. The signal is usually much stronger for sensors having a higher electric capacitance. The composite manufacturing process, i.e. long exposure to the temperature and pressure may affect the transducer physical properties and geometry, resulting in particular in a change in its capacitance. The plot (Fig. 1) shows the mean decrease in that parameter after the manufacturing processes of different structures. Al-G, Al-C denote fiber metal laminates (FML) reinforced with glass (G) or carbon (C) respectively. In addition, for Al-C specimens the transducers need to be isolated by a non conductive coating. This was achieved by embedding the transducers in a GFRP laminate prior to Al-C manufacturing. The structures were manufactured using prepreg technology with a Heatcon control unit and heating blanket. This method provides only under-pressure down force and one side heating, nevertheless, it is often used in Composite Patch Bonded Repair. The working temperature was about 130°C which is significantly lower than the Curie temperature - 320°C for the transducers used. One way ANOVA analysis shows a statistically significant decrease in capacitance in all of the cases. The change also differs significantly between all of the groups. The smallest decrease for the 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 to that of the Al-G specimens and was about 40% of the initial capacitance. Despite the described changes, the performance of the embedded transducers compared to a surface attached PZT of the same kind in terms of signal to noise ratio is still better.

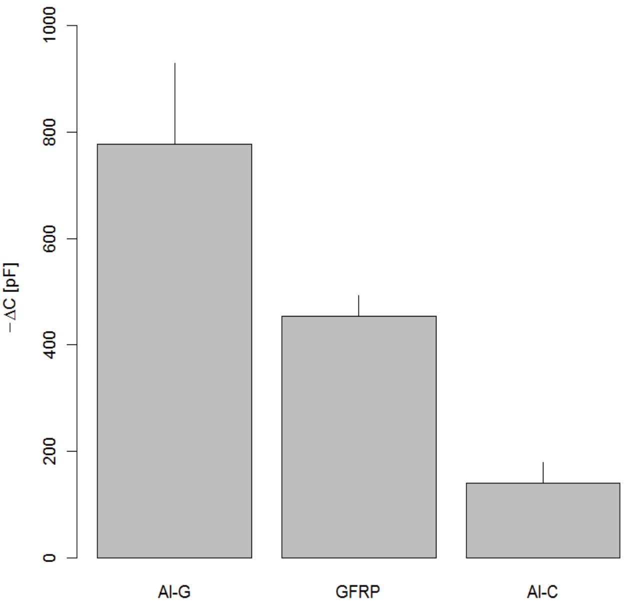

Fig. 1. Mean capacitance change of PZT transducers and its standard deviation after embedding in different structures

Rys. 1. Średnia zmiana pojemności przetworników PZT oraz jej odchylenie standardowe w zależności od rodzaju materiału, z którym są integrowane

## IMPACT TEST RESULTS

In order to test the BVID detection capabilities of the presented approach, impact tests on CFRP (Carbon Fiber Reinforced Plastic) and Al-C-Al-C-Al specimens assembled with embedded PZT sensor networks were performed. The CFRP specimen was equipped with a network of 4 PZT transducers.

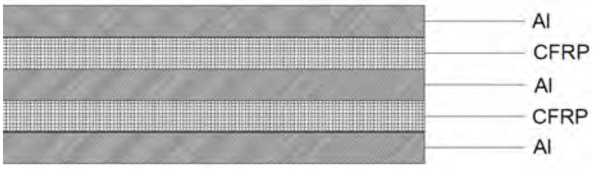

Fig. 2. Scheme of Al-C-Al-C-Al specimen

Rys. 2. Schemat próbki Al-C-Al-C-Al

The Al-C-Al-C-Al is an FML structure (Fig. 2) reinforced with 2 layers of CFRP laminate (C) separated by an aluminium alloy layer (Al), whose surfaces are also Al layers. Each C layer of the Al-C-Al-C-Al structure was equipped with independent networks of 4 PZT transducers embedded in the layer. Before embedding in the described structures, the PZT transducers were coated with a GFRP laminate. The impacts on both specimens with energies 9, 6 and 3 J, were performed subsequently by dropping a mass from different heights. Before the experiment and after each impact, signals generated by the PZT networks were collected. Figures 3-6 present the locations of the impacts for the CFRP structure as well as changes in the proposed DIs for all of the network sensing paths. The color of a data point on the plot corresponds to the generator number, whereas its shape encodes the information about the sensor. It is evident that the changes in the Damage Indices are the effect of the BVIDs. For each impact, the change in the DIs occurs only for the sensing path in the proximity of the resultant damage. The value of this change depends on the impact energy and thus it is correlated with the extent of BVID.

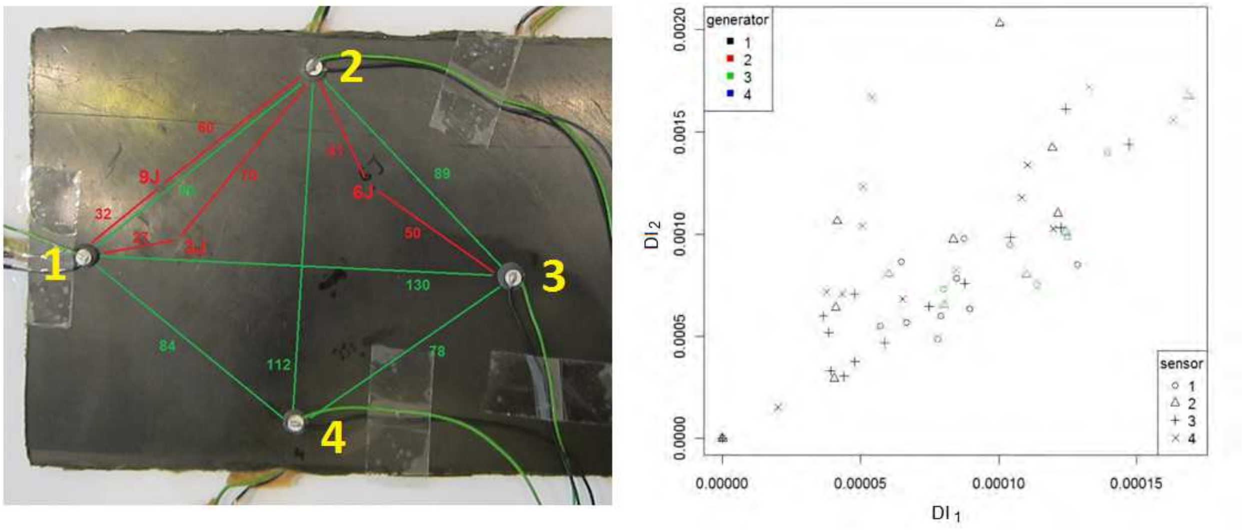

Fig. 3. Damage Indices for initial state of structure

Rys. 3. Wskaźniki uszkodzeń dla wyjściowego stanu struktury

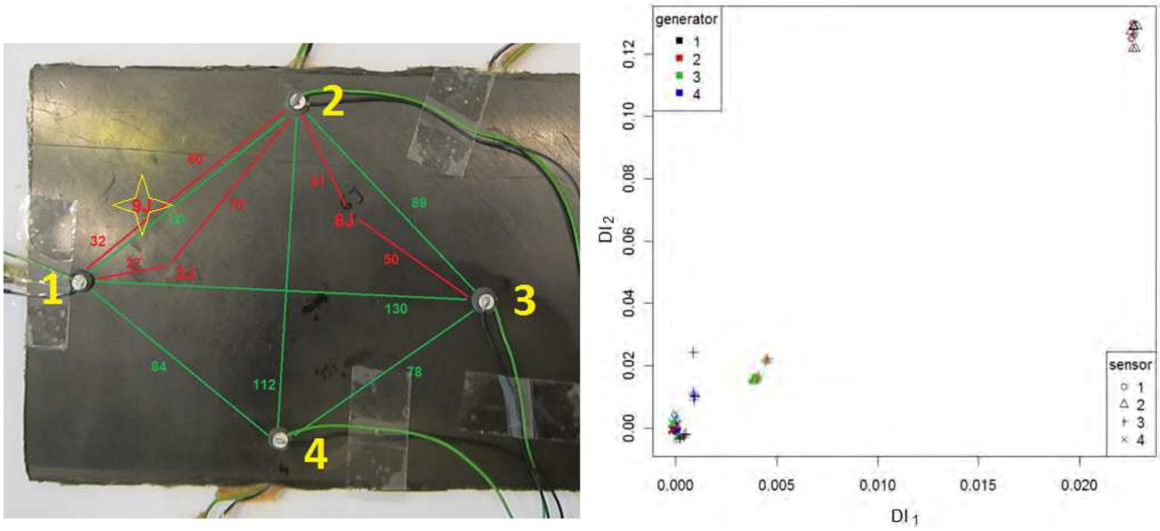

Fig. 4. Damage Indices after 9 J impact

Rys. 4. Wskaźniki uszkodzeń po uderzeniu o energii 9 J

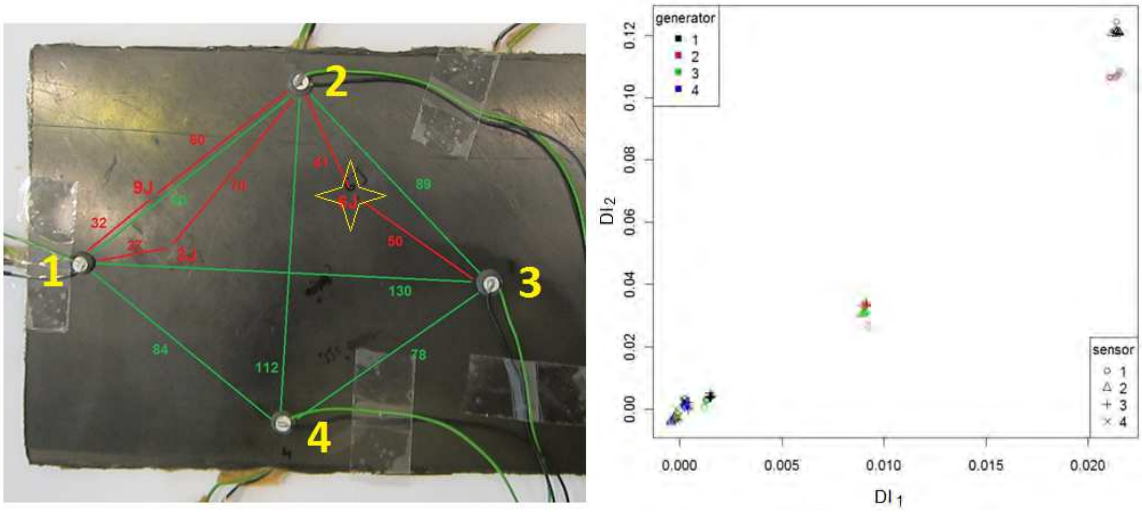

Fig. 5. Damage Indices after 6 J impact

Rys. 5. Wskaźniki uszkodzeń po uderzeniu o energii 6 J

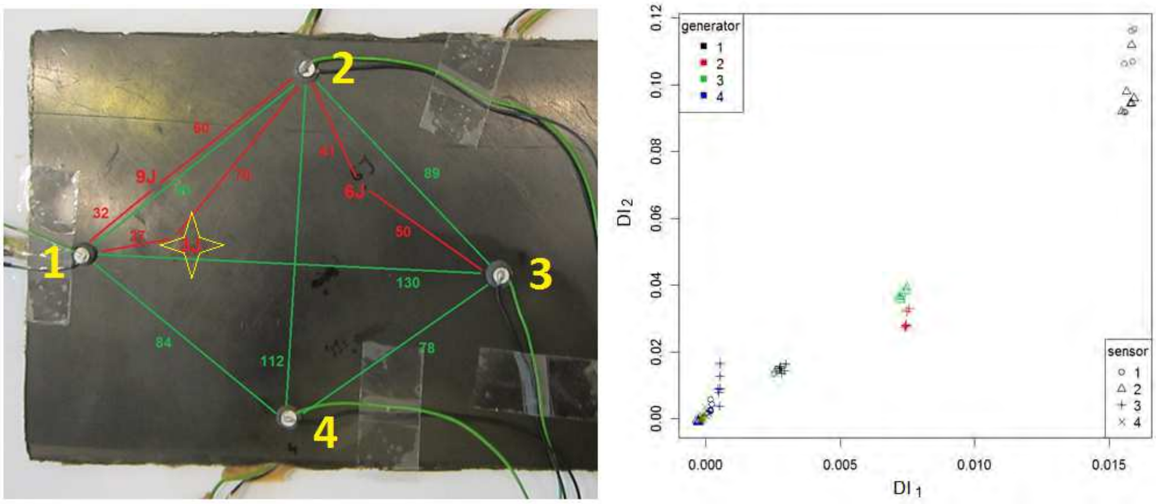

Fig. 6. Damage Indices after 3 J impact

Rys. 6. Wskaźniki uszkodzeń po uderzeniu o energii 3 J

The plot (Fig. 7) shows the Averaged Damage Indices with respect to cumulative energy: 9, 15 and 18 J of the subsequent impacts. Both the data corresponding to the 9 J impact and the 6 J impact are well separated from the initial state of the structure as well as from each other. The impact of 3 J results in a slight ADI change which provides a hint about the damage detection capabilities of the system. Tests were also performed on an FML specimen with an embedded PZT network.

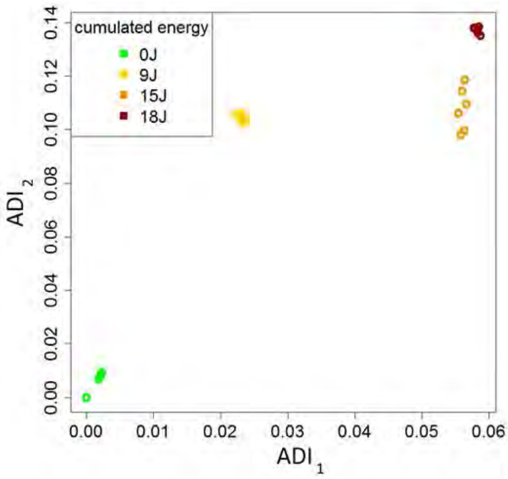

Fig. 7. Averaged Damage Indices for CFRP specimen

Rys. 7. Uśrednione wskaźniki uszkodzeń dla próbki CFRP

Figure 8 shows the Al-C-Al-C-Al structure with impact locations and the geometry of the PZT networks. The network formed by sensors S.2–S.4–S.6–S.8 was embedded in the top CFRP layer (Fig. 2) of the specimen. The other sensors were embedded in the bottom CFRP (Fig. 2) layer. Both of the networks had virtually the same geometry (Fig. 8) in order to compare the results.

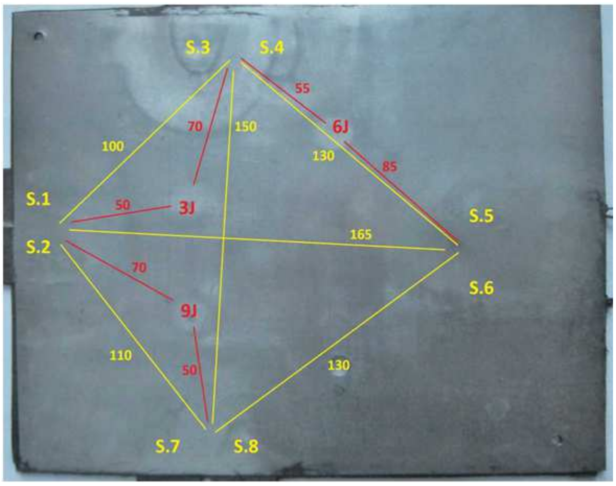

Fig. 8. FML specimen with transducers embedded in two different layers with indicated impact locations - network geometry and impact location given in millimeters

Rys. 8. Próbka FML z przetwornikami wbudowanymi w dwóch różnych warstwach z zaznaczeniem lokalizacji uderzeń - wymiary sieci oraz lokalizacja uszkodzeń podana w milimetrach

The plot (Fig. 9) presents the ADIs obtained for the bottom (Fig. 9a) and the top (Fig. 9b) PZT networks. In that case, a baseline signal was collected for each impact separately. Similar to the case of the CFRP specimen (Fig. 7), the ADIs obtained for the impact of 3 J are indistinguishable from the undamaged state, whereas the 9 J impact is clearly visible in both cases. However, the 6 J impact is better separated from the undamaged state for the network placed in the top CFRP layer of the specimen (Fig. 9b) than for the bottom one (Fig. 9a). This can be due to the more severe damage in the top layer which was directly exposed to the impact.

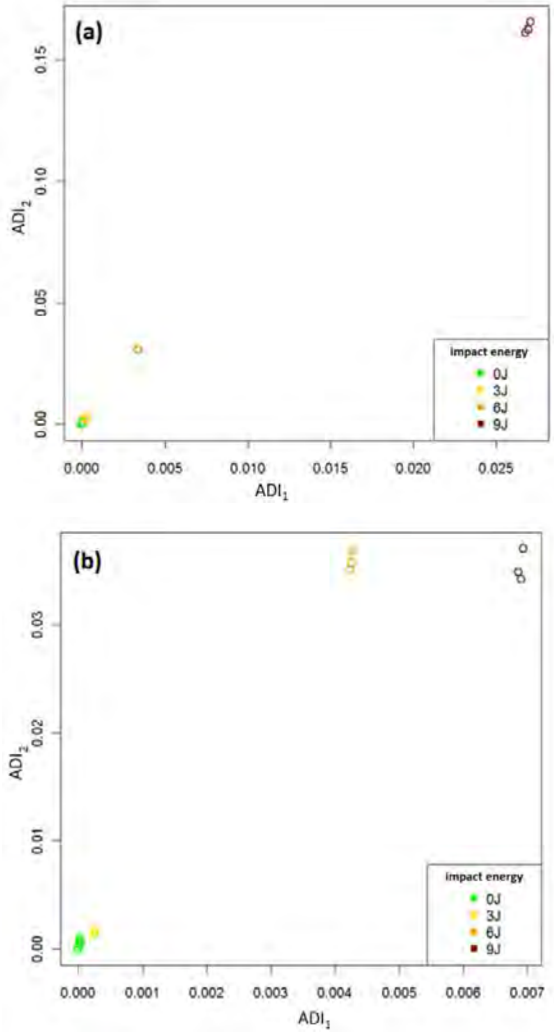

Fig. 9. Averaged Damage Indices with respect to impact energy for FML specimen: a) network embedded in bottom layer, b) network embedded in top layer

Rys. 9. Uśrednione wskaźniki uszkodzeń w zależności od energii uderzenia otrzymane dla próbek FML: a) sieć wbudowana w spodnią warstwę próbki, b) sieć wbudowana w wierzchnią warstwę próbki

## SUMMARY

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

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