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COMPOSITES THEORY AND PRACTICE

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COMPOSITE AEROSPACE STRUCTURE IN-SITU DIAGNOSTICS WITH THE USE OF NETWORK PZT SENSORS

In the article, an approach for damage characterization in composite aerospace structures for the linear acoustic non destructive evaluation technique is presented. The damages which affect the structural integrity of such components among others are: disbonds, delaminations and foreign object inclusions. One of the significant damages which may occur during structure operation is low energy impact damage (BVID - Barely Visible Impact Damage). BVID may decrease the stiffness of the component due to the creation of internal damages resulting in impact energy dissipation across the material. In the paper an approach for their diagnostics is presented. The approach is based on structure integrated PZT piezoelectric sensors. The application of such sensors enables acoustic and local distortion fields propagation based on the physics of small displacements in continuous media. This can be affected by local geometry changes caused by BVID which opens an opportunity for their detection. The signal processing methods which may enable damage detection and their classification are presented in the article. The results of low energy impact detection based on the PZT sensor network approach as well as their full characterization using classical NDE are also provided.

Keywords: composites, impact damage, structure integrated sensors

DIAGNOZOWANIE KOMPOZYTOWYCH KONSTRUKCJI LOTNICZYCH Z WYKORZYSTANIEM CZUJNIKÓW PZT ZINTEGROWANYCH Z KONSTRUKCJĄ

Przedstawiono metody charakteryzacji uszkodzeń w kompozytowych strukturach lotniczych z wykorzystaniem liniowych akustycznych technik badań nieniszczących. Uszkodzenia mające wpływ na integralność struktury lub jej poszczególnych komponentów to: odklejenia, rozwarstwienia, wtrącenia ciał obcych oraz wiele innych. Jednym z istotnych uszkodzeń mogących wystąpić podczas eksploatacji są uszkodzenia od uderzeń o niskich energiach (nazywane BVID). BVID mogą obniżyć sztywność elementu poprzez tworzenie uszkodzeń wewnętrznych powstałych w wyniku rozpraszania energii uderzenia w materiale. Autorzy przedstawiają podejście do diagnostyki oparte na strukturze zintegrowanych czujników piezoelektrycznych PZT. Zastosowanie takich czujników umożliwia akustyczną i lokalną propagację pola zakłóceń w oparciu o fizykę niewielkich przemieszczeń. Może to wpływać na lokalne zmiany geometrii spowodowane BVID, co umożliwia ich wykrywanie. W artykule zaprezentowano metody przetwarzania sygnałów, które mogą umożliwić wykrycie uszkodzeń oraz ich klasyfikację. Przedstawiono wyniki wykrywania uszkodzeń od uderzeń o niskich energiach przy pomocy klasycznych metod NDT oraz za pomocą sieci czujników PZT.

Słowa kluczowe: kompozyty, udary mechaniczne, czujniki zintegrowane

INTRODUCTION

The condition of a structure has a direct impact on its service capability, which is the main parameter defining safety and airworthiness. Excessive structure degradation may cause the necessity for its repair. To optimize maintenance costs, repairs can be carried out in the early stages of damage development or alternatively one can decide to postpone repairs until a scheduled overhaul, if they do not jeopardize the safety of the aircraft operation. In some cases, it may be necessary to modify operation routines in order to slow down the damage growth rate. Sufficient knowledge about the damage extent allows one to implement health and usage monitoring methods, which are a part of condition based maintenance. The degradation of composite structures due to, e.g. impact, is less predictable than in the case of metals. In particular, damages caused by low energy impacts can be especially dangerous due to the fact that they are invisible or barely visible on the surface of the composite. Such damages are called BVID (Barely Visible Impact Damage). Although small in size and almost invisible, BVIDs are dangerous for the structure [1]. These defects form an extensive network of cracks and delaminations deployed under the surface of the composite (Fig. 1).

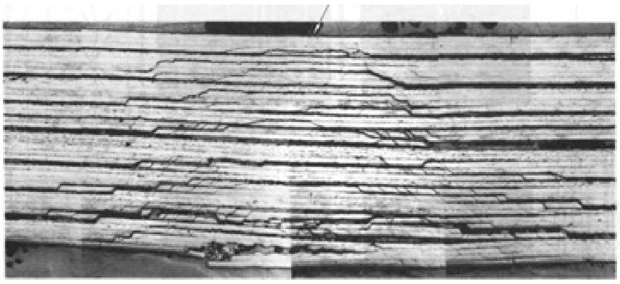

Fig. 1. BVID in CFRP composite structure [2]

Rys. 1. Uszkodzenie BVID w kompozycie CFRP [2]

The use of technology called Structural Heath Monitoring (SHM) allows for early detection of even minor damages, which becomes a very important factor in aviation safety. Moreover there is a strong need from the users: airlines, the Air Force and industry to develop systems for impact damage detection [3]. The main goal of the article is to present an approach for early BVID detection in a composite structure. A monitoring system description based on an embedded PZT piezoelectric sensor network as well as the results of specimen impact tests, correlated with Non Destructive Testing (NDT) methods are provided in the paper. First the experimental procedure is described, followed by a short NDT methods description and the results discussion. The long-term goal is to implement such sensors as the integral part of the structural elements which would enable in-situ diagnostic capabilities of aircraft.

EXPERIMENTAL PROCEDURE

The test was performed on two kinds of specimens: GFRP (Glass Fiber Reinforced Plastic) and CFRP (Carbon Fiber Reinforced Plastic). The GFRP samples were prepared at Lublin University of Technology using prepreg technology and a Scholz Maschinenbau autoclave. This method of specimen preparation gives better results since it provides uniform underpressure and overpressure downforce as well as temperature distribution. A glass-epoxy prepreg was used, and the fibers orientation was [0,90,0,90,0,90] for specimen numbers 1 and 2. The total thickness of the manufactured specimen was 1.6 mm.

The CFRP specimens were prepared in AFIT in prepreg technology using a Heatcon control unit and heating blanket. This method provides only underpressure downforce and one side heating, nevertheless, this method is often used in Composite Patch Bonded Repair for aerospace components and guarantees material properties assuring safe operation. Unidirectional carbon-epoxy prepreg tape was used. The orientation of the carbon layers was [-45,45,-45,45,-45,45,-45] for specimen number 1 and [0,45,-45,0,90,0,-45,45,0] for specimen number 2. The total thickness of the manufactured specimens was 1.2 mm. The prepared specimens were subjected to NDT tests in order to detect defects which might occur during the manufacturing process. No damages were found during that process. For each CFRP and GFRP specimen, a network of six piezoelectric sensors (PZT) was installed (Figs. 2, 3) in the so-called 'clock like' configuration in order to take into consideration the acoustic anisotropy of the composite.

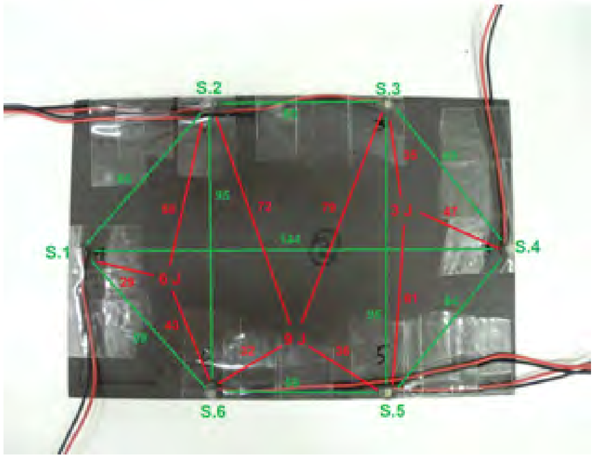

Fig. 2. PZT network on CFRP specimen number 1 (dimensions are in millimeters)

Rys. 2. Sieć czujników PZT zainstalowana na próbce CFRP nr 1 (wymiary podane w milimetrach)

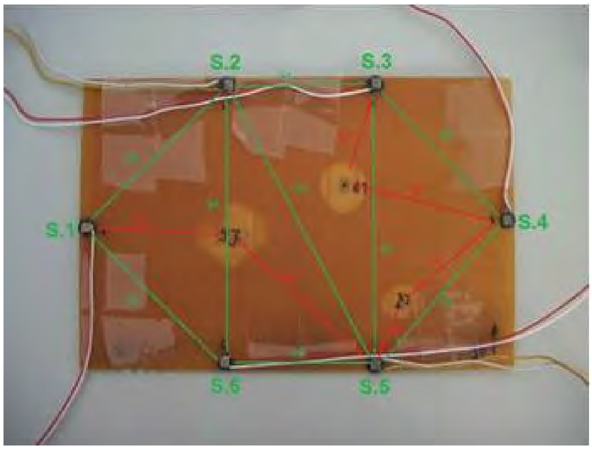

Fig. 3. PZT network on GFRP specimen number (dimensions are in millimeters)

Rys. 3. Sieć czujników PZT zainstalowana na próbce GFRP nr 1 (wymiary podane w milimetrach)

Then impacts with energies: 9, 6 and 3 J were carried out subsequently. The method based on the impactor drop on the sample was used. The mass of the impactor was chosen to obtain founded energies. The specimen used in the tests was 100 x 150 mm, which is the standard introduced by Boeing [4]. After installing the network of sensors and after each impact, the series of signals generated by the PZT network were collected. After all the impacts, NDT were taken again to illustrate the defects and to determine their sizes. NDT tests were performed with use of pulse thermography and ultrasound.

INSPECTION OF LAMINATE AFTER IMPACT - PULSE THERMOGRAPHY

The basic principle of the pulsed thermography method is to heat the specimen surface in a short time (a few milliseconds) by means of a heat impulse coming from a flash. A thermal imaging camera connected to a computer records the time-dependent thermally induced reactions of the sample surface. During the one-sided impulse thermography test, the heat flow over the defects from the sample surface toward its inside is completely or partially blocked causing a temporary local temperature increase on the surface. In the cooling stage, the temperature changes more slowly in the damaged area due to the less intense heat dissipation caused by material discontinuities. The instantaneous thermal excitation method is most effective when the size of the defect is larger than its position underneath the specimen surface. Below are the results of tests carried out on carbon epoxy and epoxy-glass samples using the pulsed thermography method (Figs. 4-7). The results of the thermography method are shown as thermal images. This method allowed the detection of all the defects caused by impacts with different energies.

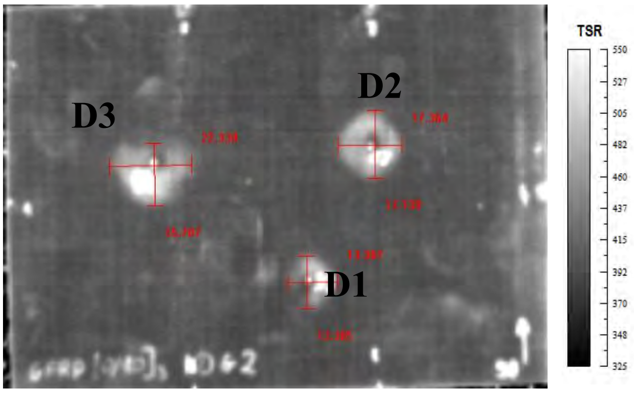

Fig. 4. Test results for GFRP specimen number 1 after impact - thermography method

Rys. 4. Wyniki badań metodą termografii dla próbki epoksydowo-szklanej nr 2 po impaktach

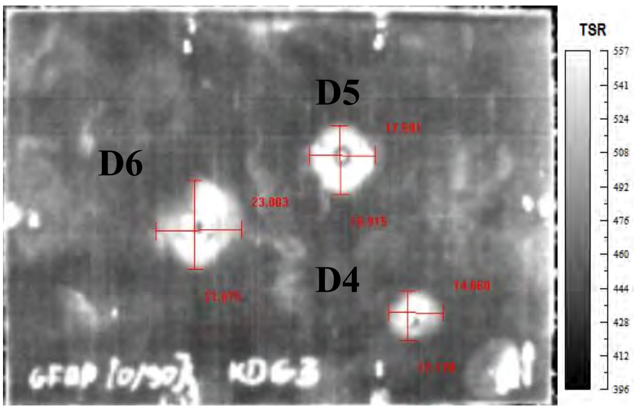

Fig. 5. Test results for GFRP specimen number 2 after impact - thermography method

Rys. 5. Wyniki badań metodą termografii dla próbki epoksydowo-szklanej nr 2 po impaktach

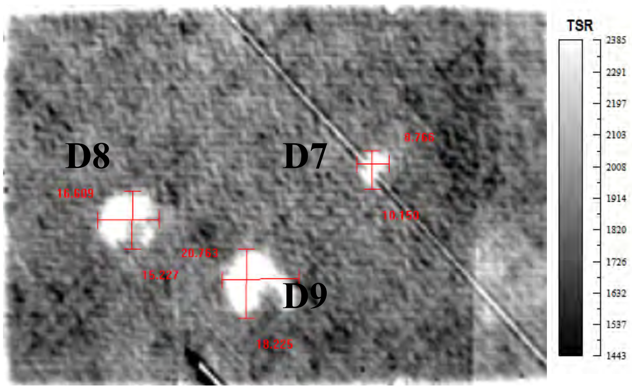

Fig. 6. Test results for CFRP specimen number 1 after impact - thermography method

Rys. 6. Wyniki badań metodą termografii dla próbki epoksydowo-węglowej nr 1 po impaktach

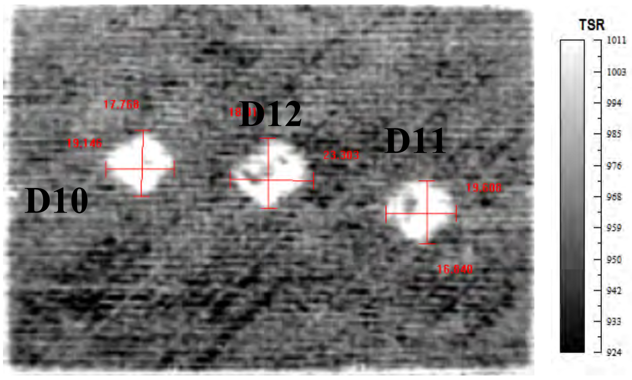

Fig. 7. Test results for CFRP specimen number 1 after impact - thermography method

Rys. 7. Wyniki badań metodą termografii dla próbki epoksydowo-węglowej nr 2 po impaktach

INSPECTION OF LAMINATE AFTER IMPACT - ULTRASONIC TESTING

Ultrasonic tests use sound waves in the frequency range above 16 kHz (in practice 5 MHz), and the phenomena associated with the spread of the sound wave in the material to diagnose the structure of the material, inter alia, in order to detect the delamination of composites. Locating defects is based on the measurement of flight time, and changes in its amplitude. The main advantage of ultrasonic testing for composites is the high sensitivity of the typical faults occurring in them, along with high precision for determining the position (depth) and the size of defects.

The results of ultrasonic tests, presented in the form of so-called C-scans, are presented in Figures 8-10.

The UT method allowed detection of all the defects. The detected delaminations of the composite structure are characteristic for the damages caused by impact (multiple damages located at different depths). The appearance of delaminations in several composite layers is indicated by the measured depths of the damages, which are found throughout the whole thickness of the sample (Table 1).

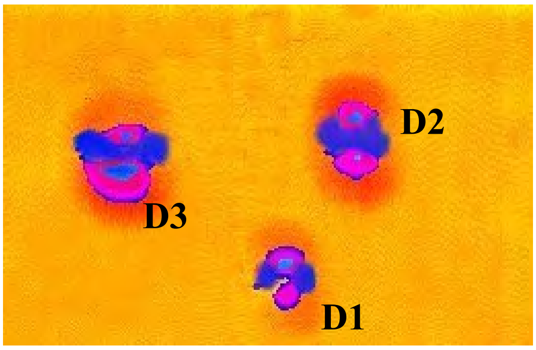

Fig. 8. Test results for GFRP specimen number 1 after impact - UT method

Rys. 8. Wyniki badań metodą UT dla próbki epoksydowo-szklanej nr 1 po impaktach

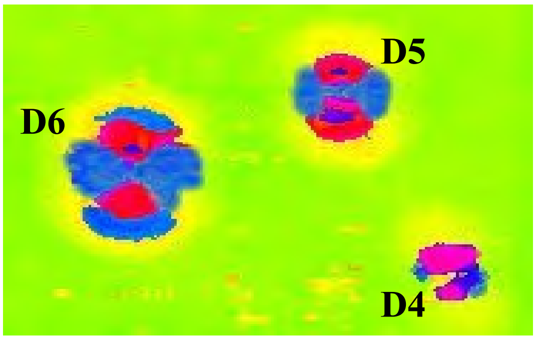

Fig. 9. Test results for GFRP specimen number 2 after impact - UT method

Rys. 9. Wyniki badań metodą UT dla próbki epoksydowo-szklanej nr 2 po impaktach

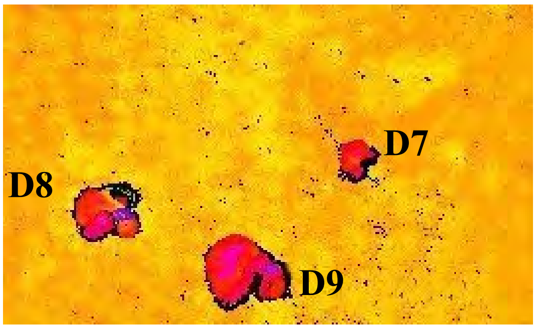

Fig. 10. Test results for CFRP specimen number 1 after impact - UT method

Rys. 10. Wyniki badań metodą UT dla próbki epoksydowo-węglowej nr 1 po impaktach

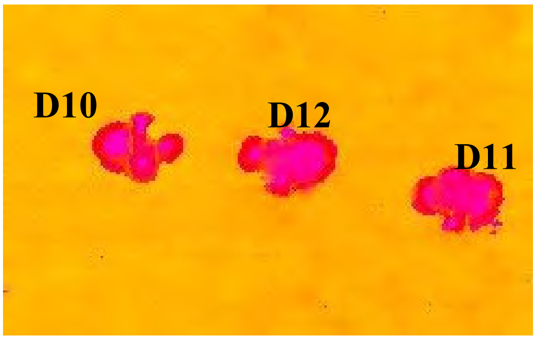

Fig. 11. Test results for CFRP specimen number 2 after impact - UT method

Rys. 11. Wyniki badań metodą UT dla próbki epoksydowo-węglowej nr 2 po impaktach

TABLE 1. **Size of damages**
TABELA 1. **Wielkości uszkodzeń**

Specimen	Number of damage	Energy [J]	Surface of damage [cm^2]	Depth of damage [mm]	Thickness of specimen [mm]
GFRP number 1	D1	3	0.7	0.08÷ 1.6	1.6
	D2	6	1.8		
	D3	9	2.8		
GFRP number 2	D4	3	1.8	0.05÷ 1.6	1.6
	D5	6	2.3		
	D6	9	2.6		
CFRP number 1	D7	3	1.9	0.06÷ 0.9	1.0
	D8	6	2.5		
	D9	9	3.8		
CFRP number 2	D10	3	1.7	0.07÷ 1.2	1.24
	D11	6	2.8		
	D12	9	5.3		

INSPECTION OF LAMINATE AFTER IMPACT - PZT SENSOR NETWORK APPROACH

One of the ideas for structural health monitoring systems is based on measuring the mechanical properties of materials used for aircraft structural elements. It is based on the analysis of small displacements propagation excited in the element by a network of PZT piezoelectric actuators [5, 6]. The solution for small deformation dynamics of the medium strongly depends on the boundary conditions, in particular, the geometry of the object and its distortions caused by discontinuities and deformations. Damage caused by impact can thus result in observable changes of the signal generated by the network sensors. In fact, the signal can be also influenced by many other factors. Apart from environmental conditions, whose variability should be compensated, a significant difference in signal can be also caused by the relative geometry changes of the network, i.e. the damage location and its orientation with respect to the sensors of the network. Therefore in the adopted approach, the Damage Indices (DIs) [5], i.e. signal transformation used for structure evaluation, carries a residual 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 Damage Indices are given as follows:

$$DI_1(g,s) = 1 - \mathrm{cor}(f_{gs}^{env}, f_{gs,b}^{env})$$

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

The pair (g, s) consisting of a generator g and sensor s is called a sensing path, and the Damage Indices above are defined for each sensing path. In order to decrease the dependence of DIs on the damage location the Averaged Damage Indices (ADIs), utilizing joint information from all of the sensing paths, can be defined [7, 8]:

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

where is the number of transducers in the network measurement node. The averaged damage indices (ADIs) are better suited for damage size estimation and remaining structure evaluation ability as well as in the case of improper functioning of several transducers of the network.

The Figures 12 and 13 present the proposed Averaged Damage Indices obtained for the test specimens. In all of the cases, one can observe a significant separation of data corresponding to the pristine and the damaged state of the structures. The separation of different groups within the data corresponding to the damaged structures depends on the specific configuration of the impacts. This can be noticed comparing the results obtained for the CFRP specimens. The first damage D8 caused by a 9 J impact is located on the sensing path spanned by sensors 4, 6 and the corresponding cross section of the delamination and the path is significant, therefore the group of data labeled as "9J" is well separated from the undamaged structure - "0J" (Fig. 12 left).

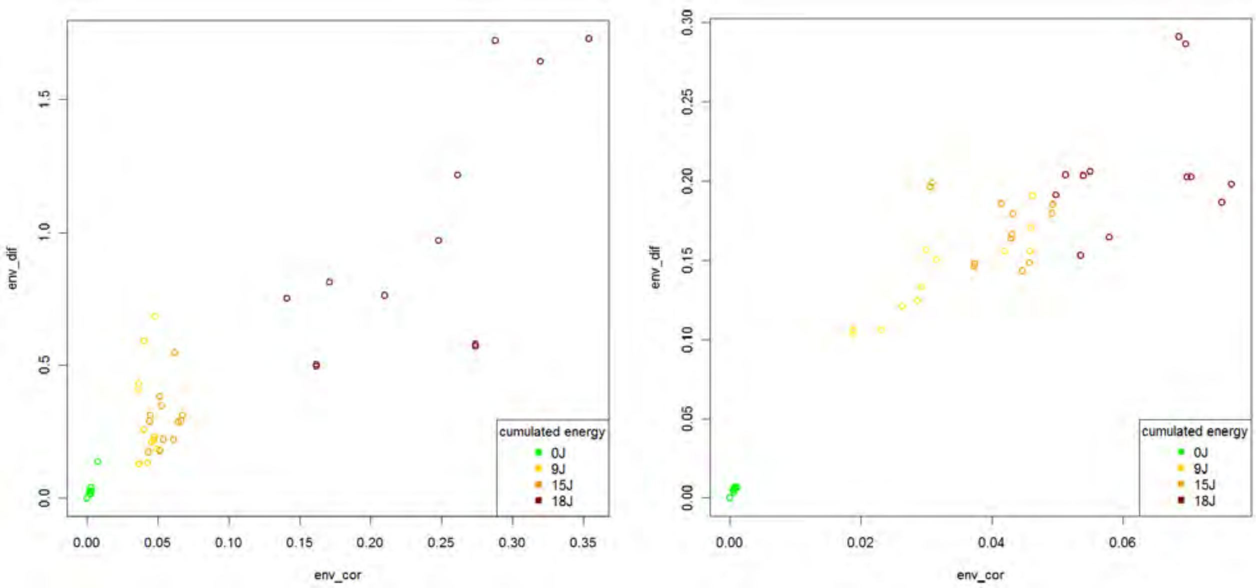

Fig. 12. Average damage indicators for CFRP specimen: number 1 (left graph) and number 2 (right graph)

Rys. 12. Uśrednione wskaźniki uszkodzeń dla próbek epoksydowo-węglowych: próbka nr 1 (z lewej) oraz próbka nr 2 (z prawej)

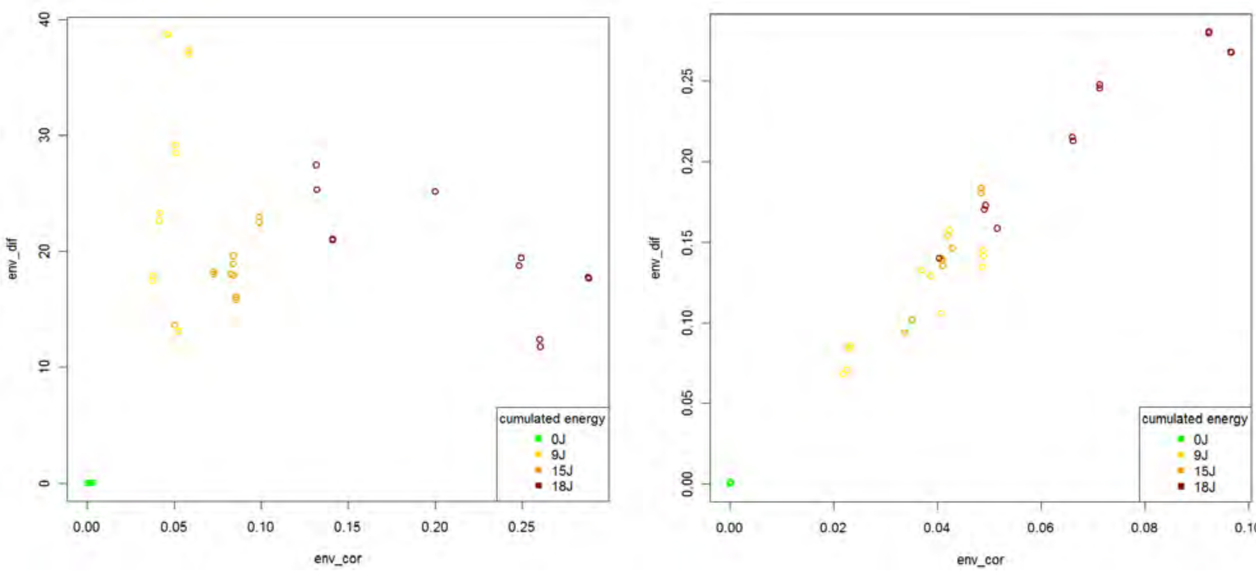

Fig. 13. Average damage indicators for GFRP specimen: number 1 (left graph) and number 2 (right graph)

Rys. 13. Uśrednione wskaźniki uszkodzeń dla próbek epoksydowo-szklanych: próbka nr 1 (z lewej) oraz próbka nr 2 (z prawej)

Damage D9 barely intersects sensing paths 1-6 and 1-4, so the corresponding data - "15J" are not separated from the previous group - "9J" (Fig. 12 left). The third damage D7, although the smallest one, is located across a new sensing path 1-4 (Fig. 2), causing significant changes in ADIs (Fig. 12 left). In the case of the second CFRP specimen, only a single sensing path 1-4 is essentially crossed by all of the damages (Fig. 2, Fig. 7), therefore there is significant separation between the damaged and the healthy structure, while separation between damages of different severity is less evident (Fig. 12 right).

The obtained results indicate that the resolution of the presented method for BVID monitoring depends on the geometry of the network used. The changes of the damage indices proposed depends on the length of the cross sections between the delaminations and network sensing paths. Furthermore the system indication is more evident if new sensing paths are involved when a new damage occurs.

SUMMARY

Taking into account the results presented above, the following conclusions can be made:

1. All the damages created by impacts have been detected both by thermography and ultrasound methods.
2. The depth of the defects (almost the entire depth of the specimen) indicate that the obtained delaminations are characteristic for Impact Damage.
3. The analyzes have shown the possibility of using the PZT sensor network for monitoring BVIDs in composite structures. The resolution of a system is related to a specific BVID configuration within the network, however, even relatively small damages can cause significant changes in the Damage Indices when located on the intersection of two or more sensing paths. It is recommended to conduct further research in order to increase the resolution of the proposed method. In particular, it is important to develop defect indicators which are more sensitive to signal changes caused by damages located on a sensing path, however, they should still be invulnerable enough to other signal influencing factors in order to obtain reliable indications of the system.
4. NDI methods were used for the validation of PZT sensors indications as well as damage sizing.

Acknowledgment

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